

- (3) The slide-block material was followed closely by the main *surge* from the blast, which moved at speeds greater than 650 mi/hr (286 m/s). The blast left a sandy, rubbly deposit containing abundant *blast dacite*, remnants of the *cryptodome* that had intruded the mountain and pushed out the bulge. This flow deposit formed a veneer on the surfaces of some of the hummocks and was plastered on valley walls.
- (4) Within minutes after the blast swept across Johnston Ridge and into South Coldwater Creek valley, the hot, freshly deposited material started to slide off many of the slopes steeper than about 25 degrees and flowed to the valley bottom as a secondary pyroclastic flow, covering many of the deposits mentioned in (3) with a layer of sand and rocks 3.5 to 7 ft (1–2 m) thick. The surface of this redeposited blast material is fairly flat and is banked up against the valley walls and fills the swales between the hummocks of the underlying debris avalanche. The blast may have consisted of two separate explosions. Eyewitnesses north of the volcano reported two distinct pulses that were more than a minute apart (Hoblitt, 1990). If so, the first was probably magmatic and the second phreatomagmatic (a reaction of the *magma* with the water contained in the mountain).
- (5) All of the above deposits were then covered by a layer of *accretionary lapilli* that fell from the great mushroom cloud (p. 32) (including mudballs reported by some eyewitnesses) and, in areas nearer the volcano, by ash fallout from the ongoing pyroclastic flows as well.
- (6) Beginning at about 9:00 A.M. and increasing in intensity until about noon, pyroclastic flows swept down the north face of Mount St. Helens and filled low spots between the freshly deposited hummocks of the debris-avalanche deposit to depths greater than 100 ft (30 m). These flows, dominantly fresh pumice, were driven by volcanic gases and gravity. Hot clouds of ash, pumice, and gas rose out of these pyroclastic flows and became turbulent surges of this light material. The surges left bedded ash-cloud deposits as deep as 30 ft (9 m). By late afternoon on May 18, the eruption column had subsided, and pyroclastic flows were on the wane. The flat, light-tan surface formed by the overlapping sheets, tongues, and lobes of the pyroclastic deposits is called the Pumice Plain.

For a more complete overview of the events occurring on the morning of May 18, 1980, refer to p. 29.

Temperatures in the pyroclastic-flow deposits were 780°F (415°C) two weeks after the eruption. Pits as much as 200 ft (60 m) across are scattered across the surface of the Pumice Plain. These *rootless explosion craters* near the northern margins of the Pumice Plain were created when ground water came in contact with the hot pyroclastic-flow deposits, causing steam-driven explosions. The deposits remained hot (above the local boiling point) for several years after the eruption, and steam explosions continued into 1982, some generating plumes of ash and steam that rose as high as 12,000 ft (3,660 m).

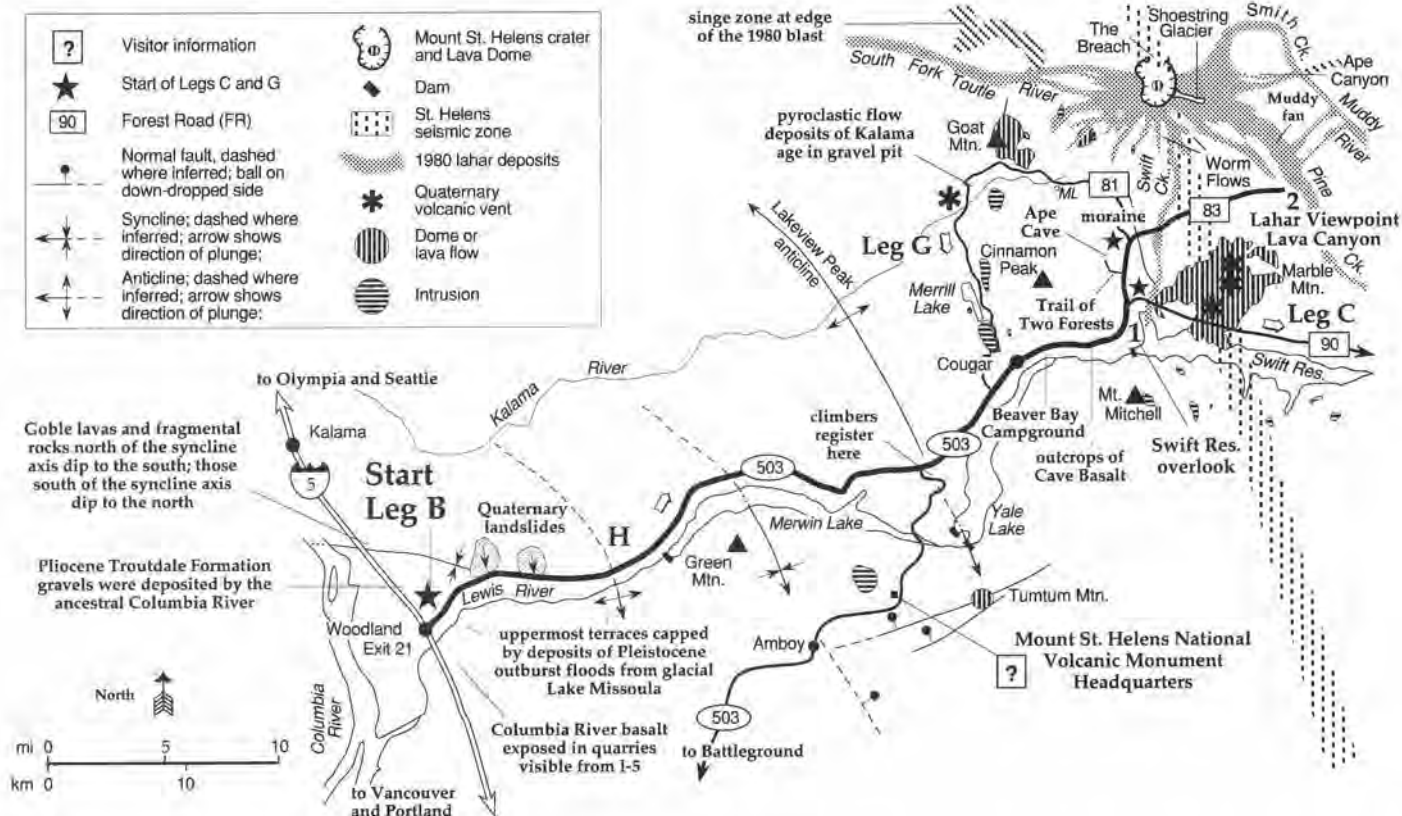


Figure 35. Sketch map of Leg B, showing numbered road stops (referred to in text) and areas of interest. Route of optional Leg G is also shown. (See p. 93.) Geologic features, structures, and deposits are shown, along with areas devastated by the 1980 lahars and blast. H, approximate maximum extent of a valley glacier that extended down the Lewis River valley about 140 ka (Hayden Creek age); ML, McBride Lake.

LEG B: SOUTHERN APPROACH—LEWIS RIVER VALLEY

Via State Route 503 and Forest Roads 25 and 83

This route to Mount St. Helens winds through the Lewis River valley and approaches the volcano from the south by way of Cougar (Fig. 35). It also provides access to Legs C and G. The route passes over ancient deposits derived from Mount St. Helens, *outwash* deposits left by alpine *glaciers*, and flat, silty and sandy terraces capped by the Missoula floods deposits. After about 9 mi (14 km), the road enters terrain carved by alpine glaciers more than 100,000 years ago and passes through a large, gentle *fold* in *Tertiary* bedrock. Conspicuous zones of red rock are ancient soils and other deposits baked by Tertiary *lava* flows.

A quarry high on the east valley wall of the Lewis River, about 0.6 mi (1 km) south of the Woodland exit on Interstate Highway 5 (I-5), has been cut into a flow of the Grande Ronde Basalt (16.5–15.6 Ma) of the Columbia River Basalt Group. This lava flow originated hundreds of miles (kilometers) to the east. The Columbia River Basalt Group is typical of a rare class of lava flows which, because of their enormous volumes, are called *flood basalt*. (See p. 19 and Fig. 12.)

Distances along the route are given in miles followed by kilometers in brackets.

Distance

0.0 [0.0] Mileage starts at I-5. State Route (SR) 503 has tight curves and truck traffic. Please drive carefully!

Terraces between 120 and 180 ft (36.6 and 54.9 m) elevation are visible on either side of the Lewis River for the first 3.5 mi (5.6 km) (Figs. 35 and 36). These terraces are composed of sand, silt, and gravel deposited by late Pleistocene *outburst floods* from glacial Lake Missoula. These enormous floods occurred between 15,300 and 12,700 yr B.P. when a large lake filling the Clark Fork valley in western Montana repeatedly breached its ice dam. The released water flooded parts of Idaho, Washington, and Oregon. (See p. 20 and Fig. 13.) More than 80 separate flood events are recorded in the sediments (although no one locality preserves evidence of all of these floods). The floodwaters racing north down the Columbia River near here were slowed by the bedrock narrows north of Kalama and formed a temporary lake at least 400 ft (120 m) deep upstream to Portland and into the Willamette Valley as far as

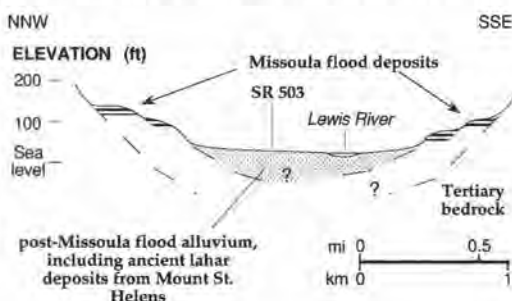


Figure 36. Diagrammatic cross section of the lower Lewis River valley about 1 mi (1.6 km) east of Woodland. Upstream view showing terraces made of Missoula flood deposits. The elevation of the deposits here indicates that the largest of more than 80 floods resulting from breakouts of glacial Lake Missoula (between 15,300 and 12,700 yr B.P.) back-flooded this valley to a depth of more than 200 ft (60 m).

Eugene, Oregon. The composite thickness of these flood deposits is as much as 100 ft (30 m) in this area along I-5.

Terraces at lower elevations are cut in flood deposits of the Lewis River that are interstratified with *lahar* and *lahar-runout* deposits from Holocene eruptions of Mount St. Helens.

- 0.8 [1.3] One of the high terraces mentioned above is visible south of the river.
- 1.4 [2.2] Another high terrace.
- 2.7 [4.3] Quaternary landslide deposits on your left.
- 7.4 [11.8] The road rises to the top of, and for a short distance follows, a Missoula flood terrace.
- 9.7 [15.5] Bedrock *outcrops* of the Goble Volcanics (Tertiary) mark the westernmost appearance of rocks of the Cascade Range along this leg. The road passes through the axes of three folds in these rocks before reaching Cougar.
- 11.8 [18.9] A pullout provides a view of Merwin Dam.
- 13.4 [21.4] Thin beds of *coal* are visible under some lava flows. This lower Tertiary coal formed when peat deposits in abandoned river channels were buried by subsequent volcanic sediments or lava flows. Strata here dip to the north or northeast—they are the northeast limb of a southeast-plunging *anticline*. Red “baked” zones are oxidized soils beneath the lava flows, which indicates that these lavas were flowing over the land surface here.
- 15.2 [24.3] The broad, U-shaped valley visible to the south was carved by a large Pleistocene glacier or glaciers that occupied the Lewis River valley. Most of Green Mountain, the east-trending ridge to the south, was buried by ice during this glaciation. *Drift* deposits are visible at 17.6 mi (28.2 km).
- 20.0 [32.0] Tumtum Mountain, a small cone-shaped *volcanic dome* complex(?), is visible in the distance to the southeast. This *dacite* dome is adjacent to, and may be younger than, a *lateral moraine* of Hayden Creek age (about 140 ka). However, a *fission-track* age of about 12.5 Ma was obtained on zircon crystals from outcrops in a quarry on the north side of the mountain.
- 23.6 [37.8] Continue straight east at the intersection with SR 503, crossing a fairly flat surface that extends to the town of Cougar. This terrace is part of an extensive fan of fragmental volcanic debris composed of Mount St. Helens lahars and lahar runouts older than those of the Pine Creek eruptive period (about 2,500 yr B.P.).
- 26.0 [41.6] Yale Lake. Mount St. Helens can be seen in the distance from along the road. A quarry in Tertiary *andesite* (north side of the road) is near the axis of the Lakeview Peak anticline, and rocks there are almost horizontal.
- 28.6 Cougar. Remnants of Amboy Drift (glacial deposits of Hayden Creek age) are visible in roadcuts to the east of Cougar. *This is the last fuel stop before the 100-mi trip to Randle via Windy Ridge or the 160-mi round trip to Windy Ridge.*

- 31.4 [50.2] Lahar deposits of Castle Creek age (2,200–1,600 yr B.P.) underlie the Beaver Bay Campground east of Cougar. From the campground, you can walk a few hundred feet to the shore of Yale Lake and examine lahar deposits exposed there. When the water level is low (controlled at the dam), older clay-rich deposits crop out below the lahar along the beach berm.
- 31.7 [50.7] The Cave Basalt flows, erupted from Mount St. Helens during the Castle Creek eruptive period, are visible on the left past the rock embankment of the Swift Reservoir spillway. The eruption of this very fluid lava is unique in the history of Mount St. Helens. (See p. 27.)

Numerous mounds on the flow surface are tumuli. A tumulus forms when a *lava tube* becomes plugged and lava pressure builds within the tube upstream of the blockage, eventually bulging the surface upwards. (See p. 64.) The pine, cedar, western hemlock, and Douglas fir trees on these flows are stunted because the soil is rocky and poorly developed.

At the Skamania County line, SR 503 becomes Forest Road (FR) 90. Continue across the hydroelectric power canal and up the hill. An ancient *debris-avalanche* deposit is exposed in the roadcuts on the left; the reddish deposits are now almost covered by alder trees. This avalanche apparently occurred during an early part of the Cougar eruptive stage (20,000–18,000 yr B.P.). Similar deposits crop out along FR 81 near McBride Lake, about 4 mi (6.4 km) from FR 83. (See p. 92.)

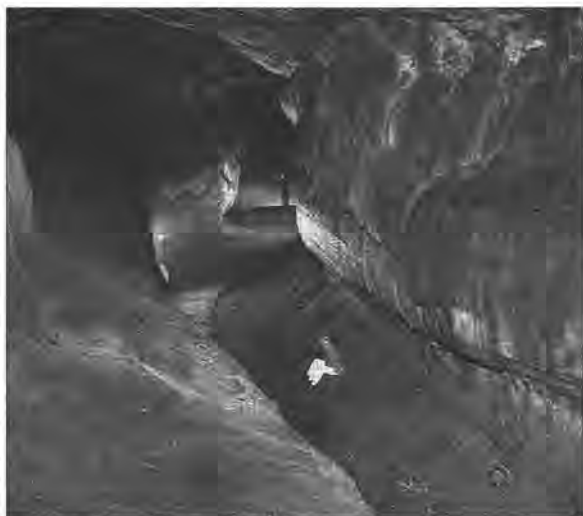
- 34.9 [55.8] **STOP B-1: SWIFT RESERVOIR OVERLOOK.** This overlook is a good place to stop and view geographic features constructed during several eruptive stages of Mount St. Helens. (See Table 3, p. 25.) The terrace on which the parking lot is situated is the remnant of a debris fan constructed during the Cougar eruptive stage. A dissected part of the fan is visible on the south valley wall downstream.

Underlying this fan is a very old Mount St. Helens lahar deposit of the Ape Canyon eruptive stage (older than 36,000 yr B.P.). It crops out in the bank of the Lewis River downstream (not visible from here). Holes drilled into the valley bottom near the Swift Reservoir dam site penetrated an even older lahar deposit whose base is 160 ft (49 m) below the surface. The debris-avalanche deposit of Cougar age mentioned at 31.7 mi (50.7 km) overlies these two lahar deposits. *Pyroclastic-flow*, lahar, and *tephra* deposits of Cougar age overlie the debris-avalanche deposit. The pyroclastic-flow deposit exposed in a borrow pit across the road to the west traveled more than 10 mi (15 km) from the mountain.

A lahar deposit underlying the terrace is visible through the fence on the east side of the parking lot. To the east and across a bay on the north side of Swift Reservoir is a lower, younger fan composed of material deposited during the Swift Creek eruptive stage (13,700–9,200 yr B.P.).

If you look to the north-northeast, you can see Marble Mountain, a *shield volcano* composed of three *scoria* cones. An *andesite* cone on the south flank of Marble Mountain was built during the last eruption from the shield about 160 ka. Marble Mountain is part of a zone of volcanoes that extends from

Figure 37. Interior of the Ape Cave lava tube, which was created during an eruption of the Cave Basalt (Castle Creek age, about 2,000 yr B.P.). The low, dissected terrace of fragmental material along the cave-floor margins contains W tephra and was probably deposited by a lahar that entered the cave during the early part of the Kalama eruptive period (late 1400s). Photo by Charlie and Jo Larson, Vancouver, Wash.



Mount St. Helens to the south more than 36 mi (60 km) toward the Columbia River and is roughly within with the *St. Helens zone* of seismicity.

Mount Mitchell, to the south, is cored by a Tertiary *granodiorite* intrusion.

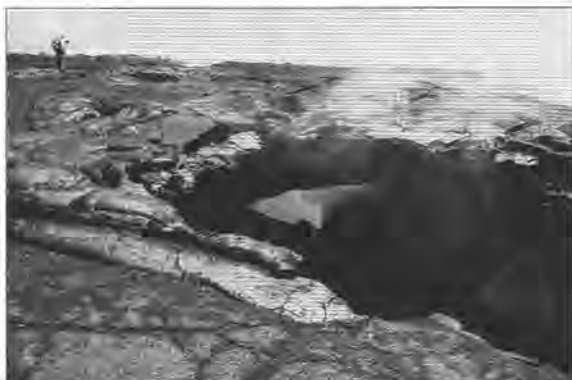
35.7 [58.7] Junction of FR 90 and FR 83. Turn left on FR 83.

37.5 [60.0] **OPTIONAL SIDE TRIP: TRAIL OF TWO FORESTS AND APE CAVE.** Round trip on FR 8303 is 0.4 mi (0.6 km) to the Trail of Two Forests or 2 mi (3.2 km) to Ape Cave. The Trail of Two Forests is a barrier-free loop (900 yd or 500 m) on Cave Basalt flows that overwhelmed a forest about 2,000 years ago. The trail winds past hollow tree molds created when the basalt solidified around fallen trees that have since rotted away.

Ape Cave lava tube, which formed in one of these basalt flows, is the longest lava tube (12,810 ft or 3.9 km) in the conterminous United States (similar tubes are found in Oregon, California, and Idaho) and one of the longest in the world. The cave was constructed by a *pahoehoe* flow (Figs. 37 and 38) that crusted over; soon after, the molten lava on the inside drained away, leaving the outer crust in place. Lava stalactites and stalagmites and flow marks can be seen on the walls and floor of the cave. Lava stalactites, conical or cylindrical deposits of lava that hang from the ceiling of a tube, are formed by dripping; stalagmites are similar in shape and are formed on the floor of the tube by the accumulation of drips from the ceiling. Some time later, a sandy lahar flowed into the cave, possibly in A.D. 1480 or 1482 because the deposit contains white *pumice* granules that resemble W tephra. During the summer, a national monument interpretive naturalist leads tours through the lower part of the cave. Be sure to read the brochure (available at the cave entrance) to find out more about the cave and the equipment you will need if you plan to explore on your own. (Sturdy shoes or boots, warm clothing, and three sources of light are recommended.)

Return to FR 83. *Note: Mileage does not include this side trip. Reset your odometer if necessary.*

Figure 38. An active lava tube at Kilauea Volcano, Hawaii, in 1987. The flow is moving from lower right to upper left. View is through a collapsed roof or “skylight” in the top of the lava tube.



- 38.9 [62.2] Junction with FR 81 (Leg G). The sinuous lava flows visible on the flanks of Mount St. Helens from this vantage point are the Worm Flows (named for their shape), erupted in the early to mid 1500s during the Kalama eruptive period. (See Fig. 3 and Table 4, p. 28.)
- 39.2 [62.7] The thick outcrop of fragmental debris on the west side of the road includes a number of pyroclastic-flow deposits of Swift Creek age (13,000–10,000 yr B.P.). Farther down the road, before it crosses the creek, the pyroclastic-flow deposits lap onto a thick, bouldery *till* of Evans Creek age (22,000–11,000 yr B.P.). USGS geologist Dwight Crandell suggested that the south-sloping surface of the till deposits might be the leading edge of a *moraine*. The till was apparently deposited after about 18,560 years ago because it is not overlain by tephra deposits of Cougar age, but by set S tephra of Swift Creek age (about 13,000 yr B.P.), which suggests that the glacier advanced between 18,560 and 13,000 yr B.P.
- 39.3 [62.9] Cross West Fork Swift Creek.
- 39.6 [63.4] Near here, one of the largest andesite lava flows recognized at Mount St. Helens (Cougar age, 20,000–18,000 yr B.P.) is overlain by a pumiceous pyroclastic flow of the same age.
- 41.9 [67.0] Marble Mountain Snowpark
- 42.8 [68.5] June Lake trailhead. The Worm Flows are visible again from this area.
- 44.0 [70.4] West Pine Creek bridge. A lahar was generated when pyroclastic material from the *blast* rushed down the southeast side of the mountain in the early stages of the May 18, 1980, eruption. The lahar washed away a bridge at this location. (An even larger lahar traveled down east Pine Creek.) The lahar left a veneer of sediment about 1 ft (30 cm) thick on the terraces adjacent to west Pine Creek. Those surfaces are now mostly covered by alder trees.
- 44.7 [71.5] The abundant white tephra exposed near the surface here is probably the We layer (A.D. 1482) whose lobe extends east of the volcano. (See Table 4 on p. 28, and Fig. 39.)
- 46.6 [74.6] **STOP B-2: LAHAR VIEWPOINT.** Lahar Viewpoint, Stratigraphy Viewpoint, and Lava Canyon Trail are clustered near the end of Leg B. This area is an interpretive cornucopia. Many of the features discussed on the

next few pages are within walking distance of the parking areas. Fragmental material and lava flows from older eruptions of Mount St. Helens and dramatic effects (deposits, scarred and killed trees, *mudlines*, and stream channel adjustments) of the 1980 eruption are visible here (Fig. 40).

Effects of the 1980 pyroclastic surge and lahar

"About 10 seconds after the avalanche was enveloped [by the blast], the cloud also began spilling over the east rim, descending the east side as a dense wall—thick, black, and rolling, but without much vertical extent."

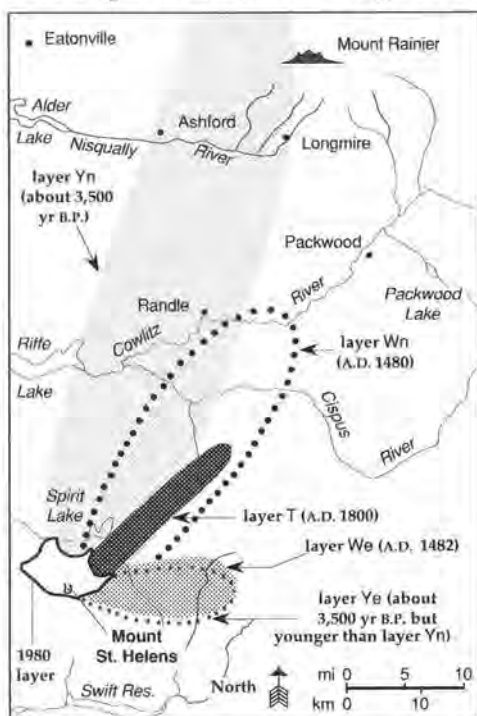
geologist Cathie Hickson,
who witnessed the eruption from
10 mi southeast of the mountain

Take a short (several hundred yards or meters) trail over bouldery terrain to the east toward a small hill. Near here the lahar split, one branch flowing down Pine Creek and the other down the Muddy River gorge. A large, lone tree south of the road is scarred on its upstream side, showing the maximum height of the lahar in this location.

Eruptive events on the east slope of Mount St. Helens were pieced together by geologists who analyzed eruption photographs taken from various vantage points and talked with eyewitnesses. Photos and satellite images were compared with tape-recorded comments of radio operators observing the eruption cloud. The following is a reconstruction of the events:

Pyroclastic surge. Within 2 minutes of the May 18 eruption, a *pyroclastic surge* consisting of rocks, ash, and volcanic gas boiled over the edge of the crater and descended the east flank of Mount St. Helens at high velocity. This turbulent cloud was funneled into the valley of Shoe-string Glacier and scoured as much as 27.4 ft (9 m) of snow and ice from the glacier. By the time it reached the base of the mountain—about 90 seconds later—it had generated a lahar. The aver-

Figure 39. Distribution of major tephra deposits of Mount St. Helens during the Spirit Lake eruptive stage (about 4,500 yr B.P. to present). Each of these relatively large eruptions deposited more than 8 in. (20 cm) of material in the respective areas shown. The 1980 eruption includes tephra fallout from the May 18 eruption column and the initial blast. Layer Wn was deposited in A.D. 1480, although Fiacco and others (1993) favor late A.D. 1479. Calendar ages of the Wn, We, and T tephra layers were established by tree-ring studies.



age velocity of the pyroclastic surge was more than 110 mi/hr (about 50 m/s) over this distance. The surge then slowed down, and after about 80 more seconds, came to a stop on the upper reaches of Muddy fan. As the solid material began to segregate from the gases, the lighter components rose into the air and dispersed (Fig. 41).

Lahar. The lahar generated by the surge left a well-defined *trimline* on a hill at the north side of the fan (Fig. 40). Farther east and along the eastern fringes of the flow are so-called bayonet trees. These trees were young and flexible when the lahar hit. They were bent over, but not snapped off. The materials in the lahar acted like liquid sandpaper and filed the tree crowns to a point. Bayonet trees also can be seen along the Lava Canyon Trail and north of the trailhead. (See p. 71.)

Stratigraphy Viewpoint

At this stop you can examine the sequence of Mount St. Helens deposits on the north edge of the fan, slightly upstream of the road. This is a well-exposed section of tephra deposits, which are locally interbedded with lahar deposits (Fig. 42).

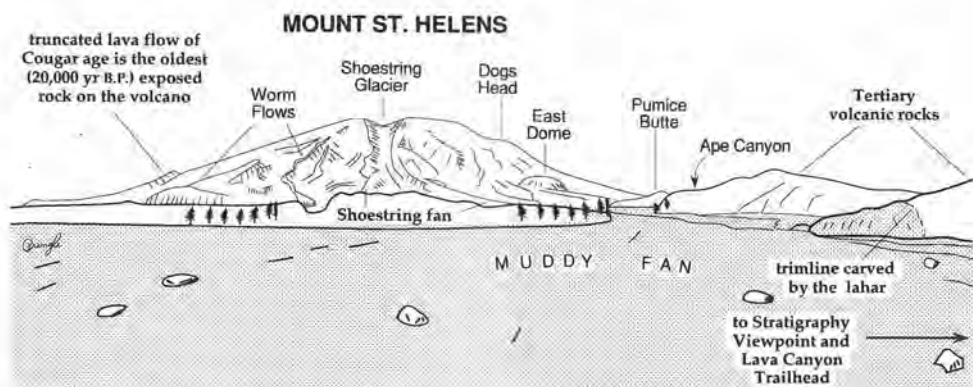


Figure 40. Panorama northeast from Lahar Viewpoint toward Mount St. Helens, 3.5 mi (6 km) away. Shoestring Glacier was decapitated during the catastrophic May 18, 1980, eruption and lost much of its zone of accumulation. A pyroclastic surge moved down the east flank of the mountain, eroded nearly 30 ft (9 m) of ice and snow from the glacier, and generated lahars that swept into Ape Canyon, across Muddy fan, and into Muddy River and Pine Creek. One lahar left a prominent trimline on the toe of a ridge composed of Tertiary volcanic rock north of the fan. The sinuous Worm Flows are rubbly andesite lava flows of Kalama age, probably erupted during the early to mid 1500s. The truncated lava flow to the left in this view is apparently an erosional remnant of a large lava flow erupted during the Cougar eruptive period (about 20,000 yr B.P.) It may be the oldest visible component of the Mount St. Helens edifice, most of which is less than 3,000 years old. Dogs Head dacite dome was erupted during the early part of the Castle Creek eruptive period. East Dome, also a dacite dome, was erupted sometime between the Castle Creek and Kalama eruptive periods. On clear days, Mount Hood volcano in Oregon is visible to the southeast, off to the left.

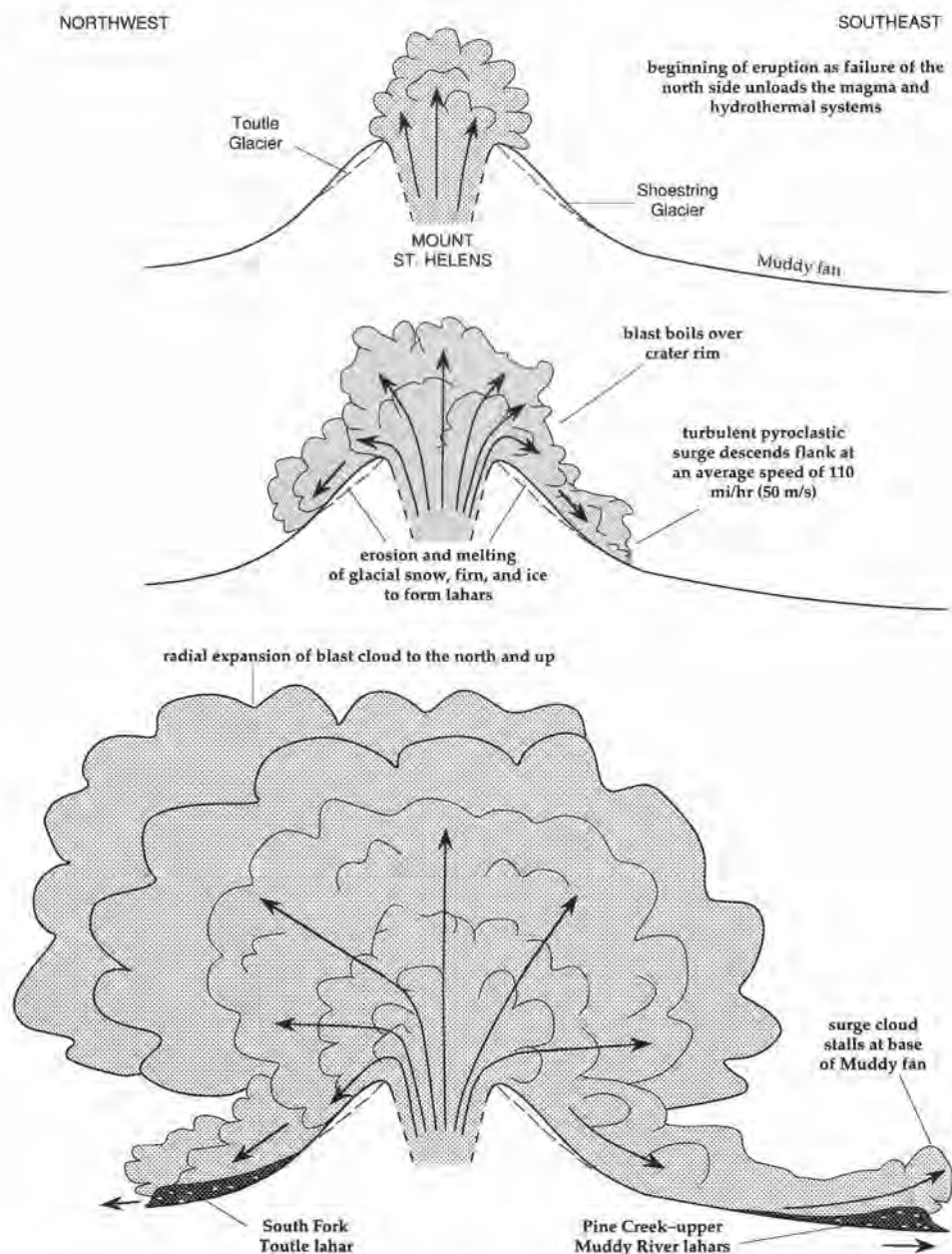


Figure 41. Diagrammatic sketch showing the May 18, 1980, blast and boiling over of pyroclastic debris onto the northwest and southeast flanks of the mountain and the resulting pyroclastic surge onto Muddy fan. Top: volcanic explosions drive material up and out. Middle: gravity takes over and drives the pyroclastic surge; as the surge ingests air, the heavier particles segregate out and the surge becomes turbulent and erosive. Bottom: a less concentrated ash cloud lifts and disperses rapidly; water derived from melted glacial snow and ice generates a lahar (volcanic debris flow).



Figure 42. This sequence of deposits at Lahar Viewpoint includes numerous fall-out-tephra layers, pyroclastic-surge layers, and two lahar deposits from Mount St. Helens. Note the May 18, 1980, lahar deposit that caps the terrace and the trees scarred by the lahar on their upstream side. The outcrop changes annually as lateral erosion cuts farther into the terrace and as the level of the streambed changes. See Tables 3 and 4 for data on individual layers indicated by initials.

Tephra is a general term for pyroclastic material of all sizes that falls from an eruption cloud. Most tephra deposits are gravel- and sand-size particles that have been ejected into the air and carried downwind. Mount St. Helens has produced scores of tephra layers in its more-than-40,000-year eruptive history, and characteristics of its explosive activity are recorded by these layers.

During the ongoing Spirit Lake eruptive stage (encompassing the last 4,000 years), Mount St. Helens has produced about 2.4 mi^3 (10 km^3) of tephra. Although the Yn tephra (about 3,500 yr B.P.) was the single largest volume erupted (0.96 mi^3 or 4 km^3), one third of the total tephra volume of all Spirit Lake eruptive events has been produced in the last 500 years. These volumes are calculated by measuring the thickness of deposits and adjusting this figure to the equivalent of solid rock (because of voids within pumice and among the particles).

The widespread tephra layers are useful to geologists and archaeologists as *stratigraphic* markers over much of the western United States. The recognition of a layer of known age in an outcrop establishes a minimum age for the materials below that layer and a maximum age for materials above it.

Figure 43. Columnar jointing in an andesite flow of Castle Creek age along the Lava Canyon Trail. Tertiary volcanic rocks are visible below the lava flow.



The Shoestring Glacier Story

The May 18, 1980, pyroclastic flow scoured the surface of Shoestring Glacier and incorporated its water, snow, and ice to form the lahars that swept down across Muddy fan. Shoestring Glacier was beheaded, and most of the glacier's snow and ice accumulation zone was removed when the upper parts of the mountain collapsed during the early moments of the eruption. As a result, the glacier has undergone significant shrinkage (*ablation*). (See p. 108.)

Fortuitously, glaciologist Melinda Brugman had begun a study of the glacier just prior to the 1980 eruption and collected data that could be used to evaluate the effects of the eruption. Contour maps of the glacier predating the eruption were compared with post-eruption surveys to determine that almost 30 ft (9 m) of ice and snow were removed by the pyroclastic surge.

Brugman noted that in the year following the eruption, the glacier first advanced rapidly (possibly because of the weight of the volcanic debris that had been deposited on its surface and a fairly heavy snow load) and then it slowed dramatically. Since 1980, the lower part of the glacier has stagnated, shrunk, and become detached from the upper part, which has also shrunk.

Erosion along the edges of Shoestring Glacier caused by the eruption exposed a layer of debris that apparently had been deposited by a throat-clearing eruption sometime between 1842 and 1857. Brugman noticed that this tephra provided a low-friction boundary layer upon which the upper part of the glacier was moving as a solid block or thrust sheet (Brugman, 1988a). (See Fig. 66.) This layer and similar thrusting along weak zones of fragmental debris were also observed at other glaciers at Mount St. Helens.

While studying Shoestring Glacier, Brugman (1988b) found that the annual volume of meltwater at the glacier terminus amounted to only about 10 percent of that which could be expected from seasonal melting of snow and ice. In the process of tracking down the missing meltwater, she discovered that its isotopic chemistry was quite similar to that of the water discharged at Moss springs (near Lahar Viewpoint). The spring water apparently originates in part from melting snow and ice high on the volcano and travels through the porous layers making up the cone before emerging at Moss springs.

The abundant water in the porous debris that composes Mount St. Helens may have contributed to the explosivity of the volcano during the May 18

eruption. Hoblitt (1990) has suggested that a second blast explosion may have included both magmatic gases and steam (a phreatomagmatic eruption) because of the scarcity of *juvenile clasts* in its deposit.

Lava Canyon Trail

This barrier-free trail leads to a view of the canyon cut by the upper Muddy River. An andesite lava flow traveled through this canyon about 1,900 years ago. The river has since cut into the weaker Tertiary volcanic deposits and left the younger, more resistant lava flow as an erosional remnant. Some of the outcrops of lava along the trail exhibit a platy *jointing* that is typical of viscous andesite lava (Fig. 43).

LEG C: EAST SIDE OF THE MONUMENT

Via Forest Roads 90, 25, and 99

Caution! These narrow roads have tight curves.

This leg takes you east along the north side of Swift Reservoir to the east side of the volcano and Forest Road (FR) 99. The destination is Bear Meadow (Fig. 44). The road is in the Lewis River watershed for most of the trip, but near the end of the route, it moves into the Cowlitz watershed at Elk Pass. *Tertiary* volcanic rocks (many altered) and lava flows from Marble Mountain *shield volcano* (Pleistocene) crop out in the stretch along the reservoir. Columnar *joints* in *basalt* flows from Marble Mountain are visible en route locally, and fossil wood can be seen in some *outcrops*.

Older Mount St. Helens deposits are visible in roadcuts toward the east end of Swift Reservoir. Slightly beyond the Pine Creek Information Station (closed in winter), FR 90 turns east and then south, but the guide route continues north on FR 25 to its junction with FR 99. FR 25 crosses Pine Creek and Muddy River, both sites of *lahars* on May 18, 1980. The road then climbs the east wall of Muddy River valley and heads north, passing outcrops of Mount St. Helens *tephra* layers and offering several views of the volcano. North of Elk Pass (closed in winter), this leg connects with Leg D, FR 99 to Windy Ridge.

Distances along the route are given in miles, followed by kilometers in brackets.

Distance

- 0.0 [0.0] Leave the junction of FRs 90 and 83 and drive east on FR 90.
- 0.5 [0.8] Deposits of volcanic debris of Swift Creek age (13,000–10,000 yr B.P.).
- 0.8 [1.3] High bridge over Swift Creek. Half a mile farther along this route, the debris fan constructed during the Swift Creek eruptive stage will be visible to the south-southwest. Some of the peaks visible to the south are Tertiary volcanic rocks, and others, such as McClellan Mountain, are *intrusive (diorite)* rocks.
- 11.3 [18.1] Swift Forest Camp.
- 12.0 [19.2] Pine Creek Information Station (closed in winter).

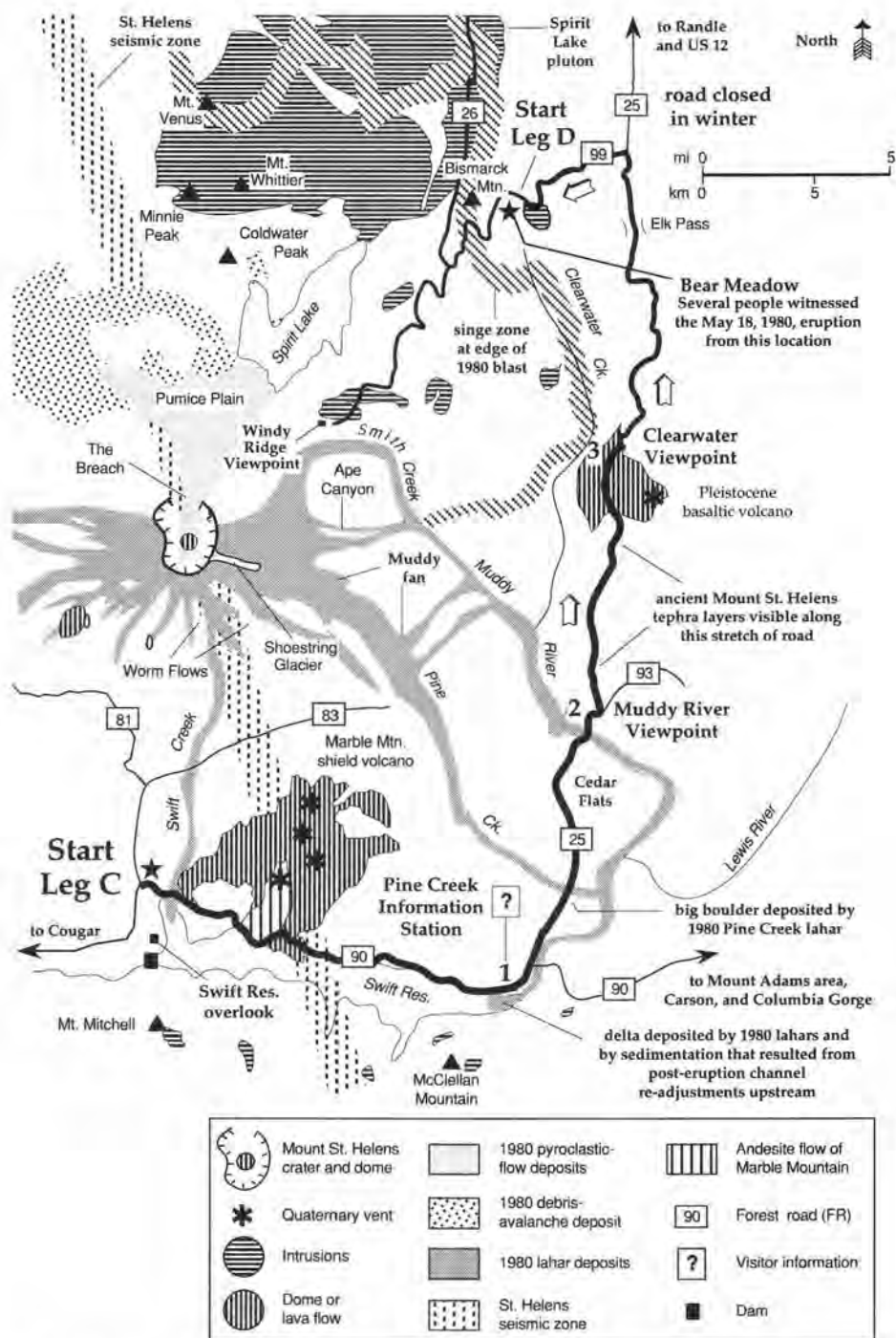


Figure 44. Sketch map of Leg C showing numbered road stops (referred to in text), geologic features and points of interest. The leg starts at the intersection of Forest Roads (FRs) 83 and 90 and continues on FRs 25 and 99 to Bear Meadow.

- 12.2 [19.5] Junction of FRs 25 and 90. Continue straight on what is now FR 25.
- 12.9 [20.6] **STOP C-1: PINE CREEK BOULDER.** Adjacent to the small turnout on the west side of the Pine Creek bridge is a 37-ton boulder that was deposited in the old roadway 33 ft (10 m) above the creek by the May 18, 1980, lahar. This lahar was generated by the *pyroclastic surge* that descended the east slope of Mount St. Helens and swept across Muddy fan. (See p. 65 and Fig. 41.) Older material in the pit on the east side of the bridge and visible upstream in the northeast bank of Pine Creek is composed of pyroclastic-flow and lahar deposits of the Pine Creek eruptive period (3,000–2,500 yr B.P.). Abundant alders and other pioneer plant species have revegetated the banks of Pine Creek since 1980.

Continue across the fan of Pine Creek age past the Cedar Flats Research Natural Area. Cedar Flats is underlain by lahars of the Pine Creek eruptive period and older deposits from the latter part of the Swift Creek eruptive stage (deposited after tephra layer S). (See Table 3, p. 25.) The fan of Swift Creek age temporarily blocked the river near here.

- 16.9 [27.2] **STOP C-2: MUDDY RIVER VIEWPOINT.** The Muddy River bridge was destroyed by a lahar on May 18, 1980. The area is now largely regrown with alders. A painted line about 10 ft (3 m) above the ground on the pole adjacent to the parking area shows the maximum height (stage) of the lahar in this area, as determined by *mudlines* on trees bordering the lahar. Large boulders of yellowish Tertiary bedrock were transported by the lahar from outcrops miles upstream and are visible along a trail to the river.

As the road climbs up the east wall of the Muddy River valley and continues north, tephra layers from Mount St. Helens become more prominent. These layers of tan, white, yellowish, and orange *pumice* and *ash* can be seen just under the modern soil layer at the tops of most outcrops.

- 17.2 [27.7] Junction of FR 25 with FR 93. FR 93 connects with FR 90 and leads to recreation sites along the Lewis River and near Mount Adams to the east. *Keep left. Stay on FR 25.*
- 22.4 [36.0] You are now entering the area covered by fallout from the Mount St. Helens We tephra plume (A.D. 1482). The deposit is noticeable as large white pumice pebbles at the top of outcrops. (See Fig. 39 for distribution of this tephra.)
- 27.1 [43.6] **STOP C-3: CLEARWATER OVERLOOK.** The broad, U-shaped valley of Clearwater Creek (Fig. 45) was carved by a *glacier* of Hayden Creek age (about 140 ka) and possibly by an earlier glacier. On May 18, 1980, the hot *blast* moved into the upper reaches of the valley, destroying most of the forest (much of it recently logged). Slope failures, mostly *debris slides*, were common during the next few years in this and nearby valleys affected by the blast. Experimental forest plots were set up to investigate the causes of the slope failures. One reason was that trees died after the 1980 eruption and their roots stopped providing cohesive strength to the soil.

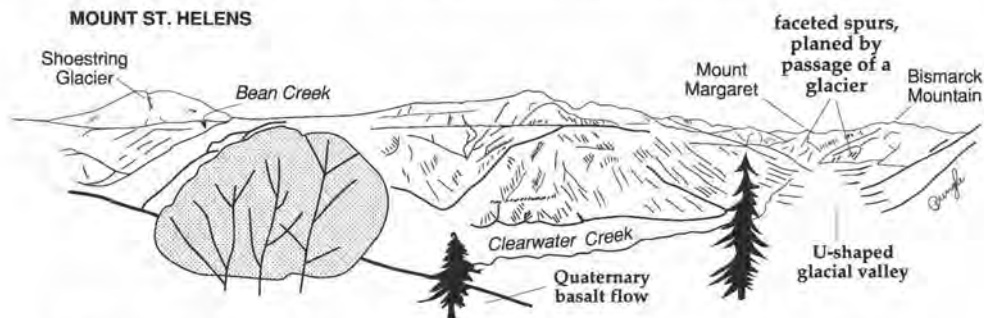


Figure 45. Panorama from the Clearwater Overlook, about 10 mi (15 km) east-northeast of Mount St. Helens. A valley glacier(s) that previously occupied the Clearwater valley carved the faceted spurs (beveled noses of ridges) and gave the valley its U shape. The Quaternary basalt flow originated at a vent immediately to the southeast and is probably an outlier of the Indian Heaven volcanic field located farther to the southeast. (See Fig. 1.)

On the east side of the road, across from the parking area, a dark basaltic *sill* of Tertiary age intrudes a lighter colored *dacite* (Fig. 46).

Gabions (cobble-filled wire mesh baskets) have been used here in an attempt to reinforce the slope at the edge of the road.



Figure 46. Tertiary basaltic sill intrudes dacite bedrock across from the Clearwater Overlook.

34.0 [54.7] Boundary Trail #1 crosses Elk Pass.

37.0 [59.5] Turn left onto FR 99. In 5.7 mi (9 km), you will reach Bear Meadow Viewpoint, the starting point for Leg D.

LEG D: FOREST ROAD 99 TO WINDY RIDGE

Reset your odometer to zero at Bear Meadow Viewpoint for the approach to Windy Ridge. This leg of the guide offers a new view of the effects of the May 18, 1980, eruption at every turn in the road (Fig. 47). Forest Road (FR) 99 passes from a verdant forest through a fringe zone of singed trees to the core of the zone devastated by the *blast*. *Tephra* layers from ancient eruptions of Mount St. Helens are visible in roadcuts along the way. These layers change in thickness as the road

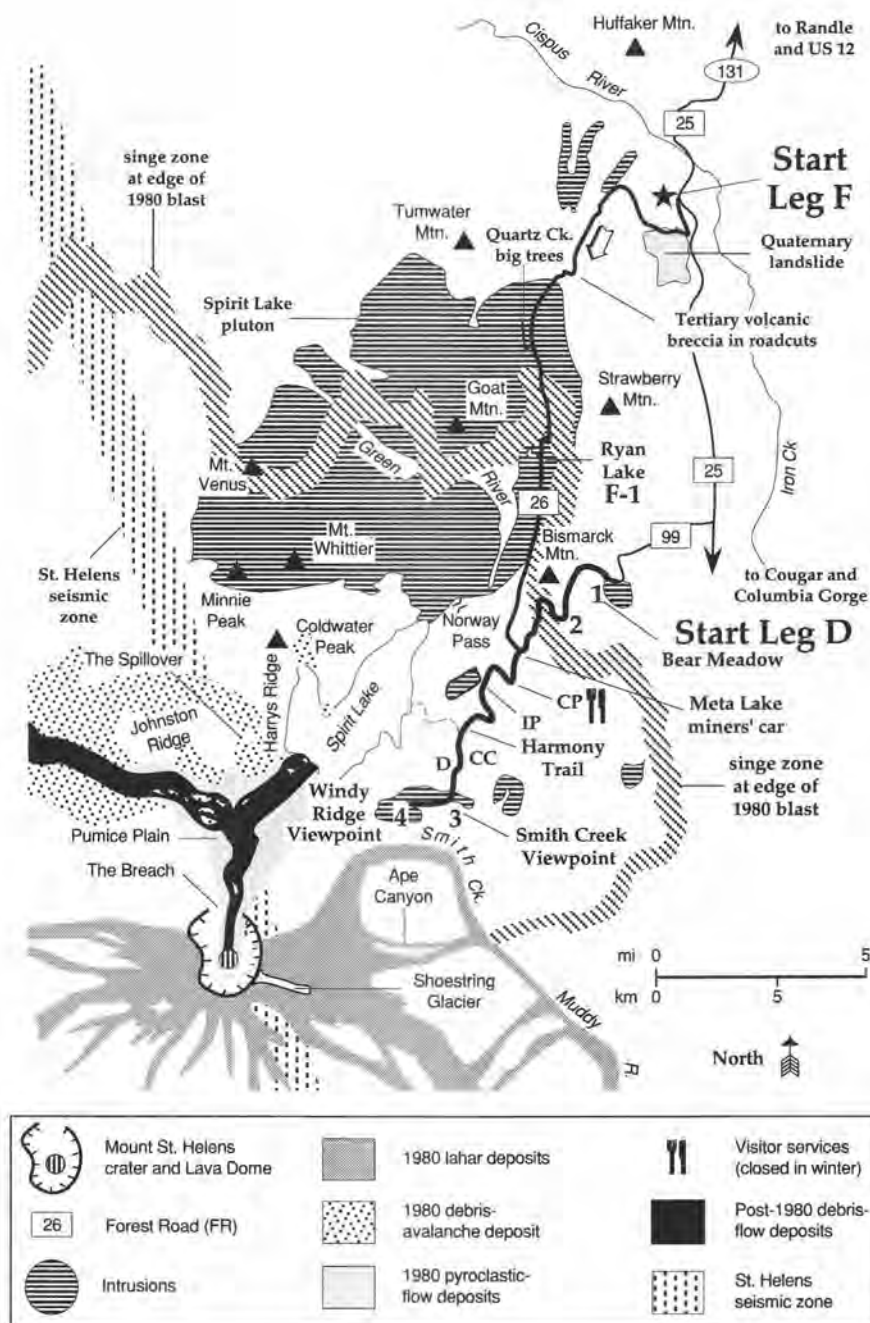


Figure 47. Sketch map of Leg D, FR 99 to Windy Ridge, and Leg F along Forest Road 26, showing numbered road stops (referred to in text) and points of interest. Optional stops also shown are CP, Cascade Peaks; IP, Independence Pass; CC, Cedar Creek Viewpoint; and D, Donny Brook Viewpoint.

travels across the axis of the tephra lobes. (See Fig. 39.) Some of the beds are more than 6 ft (2 m) thick and contain blocks and bombs as large as grapefruits—an impressive reminder that Mount St. Helens has an explosive history and that many of its ancient eruptions were larger than, or equivalent in size to the one in 1980.

Distances along the route are given in miles followed by kilometers in brackets.

Distance

- 0.0 [0.0] **STOP D-1: BEAR MEADOW VIEWPOINT.** Gary Rosenquist and Keith Ronnholm, who were camped here on the morning of May 18, took photos that recorded the dramatic initial eruptive activity that day. The photographs show the early movement of the slide blocks of the *debris avalanche* and the shape of the initial eruption cloud that developed within seconds. (See Fig. 17.) As you leave Bear Meadow and drive into the *devastated area*, note the location and severity of tree damage caused by the *blast*.

The road takes you from Iron Creek in the Cowlitz River watershed to Clearwater Creek, a tributary of the Muddy River in the Lewis River watershed. Orange-stained Tertiary dacite visible along the north side of the road as you leave the parking lot was probably part of a *dome* that was altered by *fumarolic* action while the rock cooled.

- 2.1 [3.4] **STOP D-2: BLAST-EDGE VIEWPOINT.** The road passes through an area of dead but upright trees that fringe the outer boundary of the blast zone. (See Fig. 22.) Temperatures at the edge of the zone were estimated to have been between 122°F and 482°F (50° and 250°C). Downed trees are found closer to the center of the blast zone. The orientations of the downed trees indicate the direction of the *blast density flow* as it moved across the hilly terrain. Smaller trees that survived were understory trees in the mature coniferous forest that was killed by the blast. Many of these smaller trees were protected by snow drifts and emerged undamaged later when the snow had melted. (For more information on the blast, see p. 31 and 107.)

Across the road is a sequence of tephra deposits from the Spirit Lake eruptive stage (4,500 yr B.P.–present). (See Table 3, p. 25.) The orange basal tephra layer overlying the reddish Tertiary bedrock is layer Yn, erupted from Mount St. Helens about 3,600 yr B.P. The volume (dense rock equivalent) of layer Yn deposits, calculated from its extent and thickness, is nearly 1 mi³ (4 km³), making it one of the largest eruptions from Mount St. Helens and similar in size to the A.D. 79 eruption of Vesuvius in Italy. The dark, fine-grained material overlying the orange *pumice* is composed of numerous layers of *ash* produced during a 3,000-year interval between the deposition of layer Yn and layer We (the whitish band about 2 ft or 0.6 m thick) in A.D. 1482. The dark material retains moisture because it is so fine grained. Overlying this layer is a dark forest duff and then another thin tephra layer (T) from an eruption in A.D. 1800. A similar tephra sequence is visible in many places along the road as you approach Windy Ridge.

- 4.5 [7.2] Junction of FR 99 with FR 26 (Leg F). Miners' Car. This damaged automobile belonged to a family that was killed on May 18, 1980, while working at their small mine.

4.7 [7.5] **OPTIONAL STOP: META LAKE.** A short paved trail (barrier-free) leads to Meta Lake, which occupies the bottom of a *cirque* of Evans Creek age (22,000–11,000 yr B.P.). Ice covered the lake during the eruption on May 18, 1980, so plants and animals in the water were insulated from the volcanic violence. Numerous trees and shrubs buried in snowdrifts in this area also survived the eruption. Compare the number of standing trees on the south and north sides of the valley. The platform at the lake is a good place to observe the swirls of downed trees. *Drinking water is available at this stop.*

6.0 [9.6] **OPTIONAL STOP: CASCADE PEAKS VIEWPOINT.** Many of the Cascade peaks are visible from this viewpoint, including Mount St. Helens, Mount Adams, Mount Hood, and the Indian Heaven volcanoes. (See also Fig. 50.) Across the road from this viewpoint, Mount St. Helens tephra Yn, Wn, and T crop out in sequence. T is at the top.

A refreshment stand at the viewpoint is open from mid-May to late October, depending on weather conditions.

9.7 [15.5] **OPTIONAL HIKE: HARMONY VIEWPOINT AND TRAIL.** This 3-mi (4.8 km) round trip descends the wall of a *cirque* of Evans Creek age (22,000–11,000 yr B.P.) and takes you to the east shore of Spirit Lake. Harmony Trail offers views (Fig. 48) of a wide variety of geologic features that include Tertiary welded *tuff* and Pleistocene glacial deposits, as well as a good view of the Mount St. Helens crater and the Lava Dome.

White pumice fragments from tephra layers Wn and T are exposed in cuts along the trail. The first bedrock you find on this hike is the nearly vertical outcrop of a Tertiary dacite intrusion. About halfway down to the lake, a lava flow with columnar *jointing* is exposed, but most of the bedrock along this hike is composed of fragmental volcanic rock (*breccias* and tuffs).

As the trail flattens out on the floor of the *cirque*, a *trimline* is visible on the north side of the *cirque*. This scar was left by the wall of water created when the debris avalanche slid into Spirit Lake on May 18, 1980. The giant wave stripped vegetation and soil from hillsides around Spirit Lake. The wave swept into Harmony Falls basin and scraped material off the valley walls at heights of more than 500 ft (150 m) above the present level of the lake. The water and debris then rushed back out into the Spirit Lake basin. Smaller waves probably washed into Harmony basin immediately after the first.

The trail rises slightly as it passes over a *moraine* at the mouth of Harmony basin before descending to Spirit Lake. Boulders poke out of *till* of Evans Creek age along the way. Just after the trail turns to the south (toward the volcano), smooth, glacially grooved surfaces are visible on the dark reddish welded tuff erupted by an Oligocene volcano (Fig. 49). Run your hand along this surface toward Spirit Lake to feel the grooves and polished surface. White pumice pebbles can be seen in this rock; some were flattened while still hot by the weight of overlying sediments about 30 Ma (Fig. 50). Harmony Falls is formed by this resistant rock and by a light greenish gray *dike* that cuts the tuff.

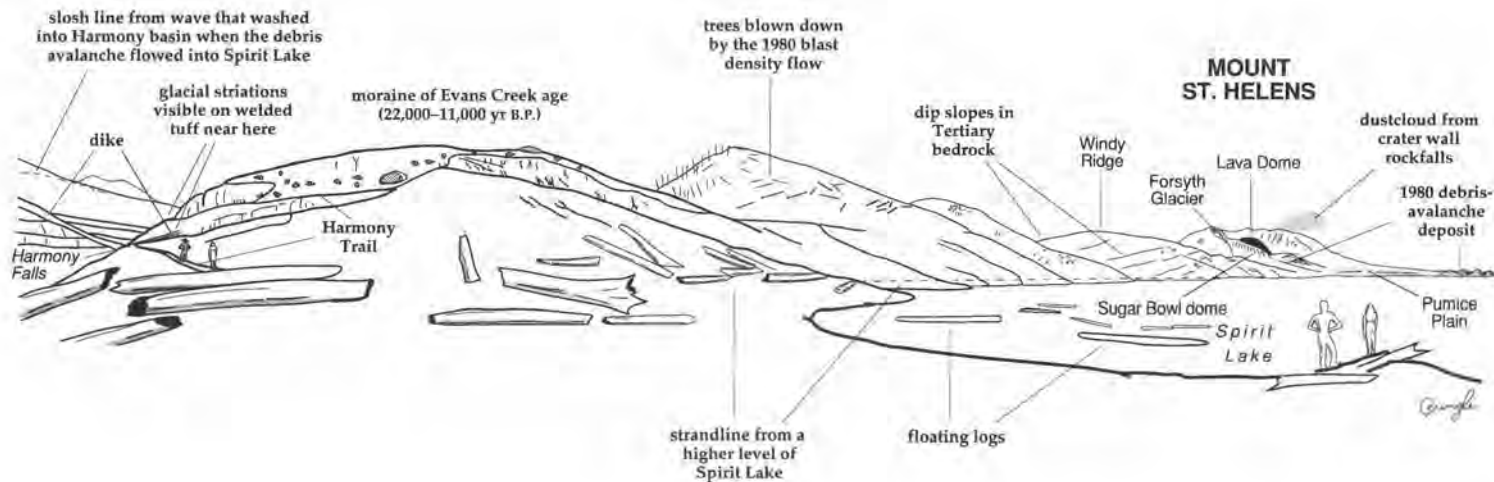


Figure 48. Panorama from the Harmony Trail at Spirit Lake, about 4 mi (7 km) northeast of Mount St. Helens. It is worth taking the 2-mi (3 km) round trip hike to Spirit Lake to see this view of the Mount St. Helens crater and the Lava Dome. Harmony Creek originates in a cirque whose glacier carved the glacial striations visible in outcrops of welded tuff (shown in Fig. 49) along the trail and also deposited the moraine, possibly of Evans Creek age (22,000–11,000 yr B.P.), shown in this sketch. Harmony Falls is formed by the resistant welded tuff and by a dacite dike. The strandline (at an elevation of about 3,420 ft or 1,043 m) was left by the highest level of Spirit Lake in 1982 before efforts to drain the lake had begun.

Figure 49. Glacial striations and smoothing on a Tertiary welded tuff along the Harmony Trail, north of Mount St. Helens.

The trail ends at Spirit Lake. A strandline of logs sits about 20 ft (6 m) above Spirit Lake, evidence of higher lake levels in 1982, before the lake level was stabilized by an outlet tunnel. The bedded pebbles and cobbles west of the mouth of Harmony Creek were deposited as a delta when the lake was at this higher level.

Continue south toward Windy Ridge. Roadcuts expose tephra layers J, Yn, Wn, and T in sequence. T is at the top.



- 10.0 [1.6] **OPTIONAL STOP: CEDAR CREEK VIEWPOINT.** The view of Spirit Lake and the denuded landscape of Tertiary rocks is the chief attraction.
- 10.1 [16.2] **OPTIONAL STOP: DONNY BROOK VIEWPOINT.** Although it presents only a partial view of the crater and dome, this site has excellent views of the debris avalanche that impounds Spirit Lake and of The Spillover, the ramp-like deposit left when the debris avalanche flowed over Johnston Ridge and down the South Coldwater valley. The outlet tunnel drilled to maintain the lake level is visible across the lake. Weather permitting, you can see Mount Adams and the Indian Heaven volcanic field to the east.
- 10.7 [17.1] **STOP D-3: SMITH CREEK VIEWPOINT.** On clear days, this site affords a view of Mount Adams, Mount Hood, Indian Heaven volcanoes, and other Cascade peaks. Also visible on the Smith Creek landscape are various features caused by the eruption and subsequent erosion and sedimentation (Fig. 51).
- A thorough study of the 1980 deposits in this area has revealed that at least four distinct flows entered the Smith Creek drainage during and immedi-

Figure 50. Flattened pumice in a Tertiary welded tuff exposed along the Harmony Trail. Beds have been tilted by gentle regional folding; true vertical is shown by the pen (black cap points down). The pumice was deposited in a molten state and squashed by the weight of the overlying sediments of the pyroclastic-flow deposit about 30 Ma.



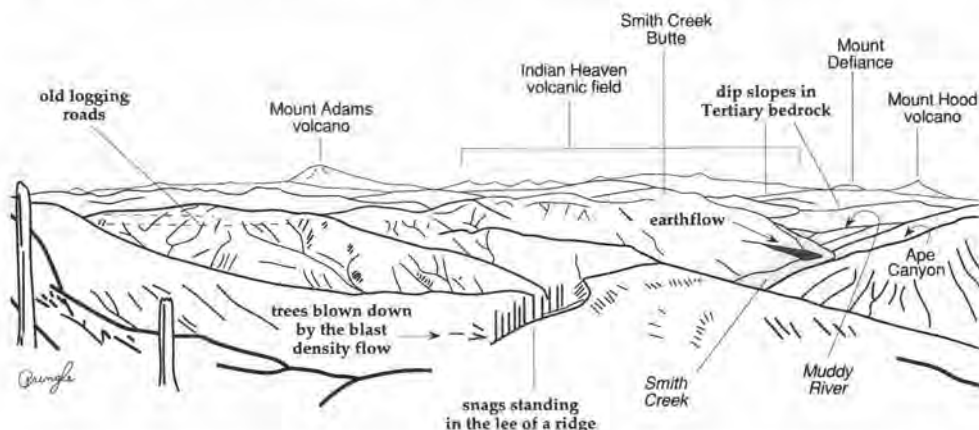


Figure 51. Panorama to the east and southeast from the Smith Creek Viewpoint, 3.5 mi (6 km) northeast of Mount St. Helens. The May 18, 1980, blast density flow swept over Windy Ridge into Smith Creek valley, leaving complex deposits and chaotic arrays of blown-down trees. Compared to pre-eruption conditions, far more material was available to be washed off the slopes. The tephra deposits were easily eroded, and the loss of soil cohesion when trees were killed meant that the slopes became more susceptible to both mass wasting and removal by rain and snowmelt. On May 18, a lahar rushed down Ape Canyon and ran up the east valley wall of Smith Creek. Another lahar flowed down the Muddy River. An earthflow constricts the channel of Smith Creek just downstream of Ape Canyon. Mount Adams (30 mi [50 km] east), the Indian Heaven volcanic field, and Oregon's Mount Hood (69 mi [115 km] south-southeast) have all erupted during the last 10,000 years.

ately after the 1980 eruption. The blast poured into Smith Creek valley from various directions, producing complex deposits. As interpreted by Brantley and Waitt (1988), this sequence was deposited as follows:

- (1) Two layers of pyroclastic debris were deposited by the blast as it swept northeastward into Smith Creek valley. The lower layer is similar to the deposit from the leading edge of the blast that is found on the surrounding hills. A thicker and much coarser layer overlying this layer is inferred to have formed as the denser rocks separated from the lighter, smaller particles and swept down the valley as a localized *pyroclastic flow*.
- (2) A *lahar* was generated by the blast as it mixed with and incorporated pyroclastic debris from the fresh basal deposits and underlying soil. It left a hummocky deposit overlying the blast layers.
- (3) Secondary pyroclastic flows swept down from the valley walls (as they did in South Coldwater valley, p. 59) and were deposited atop the lahar and blast deposits.
- (4) The blast cloud dropped a thin layer of silt-size material that capped these deposits. Mixed in as well were *accretionary lapilli* that began falling about 20 minutes after the eruption.

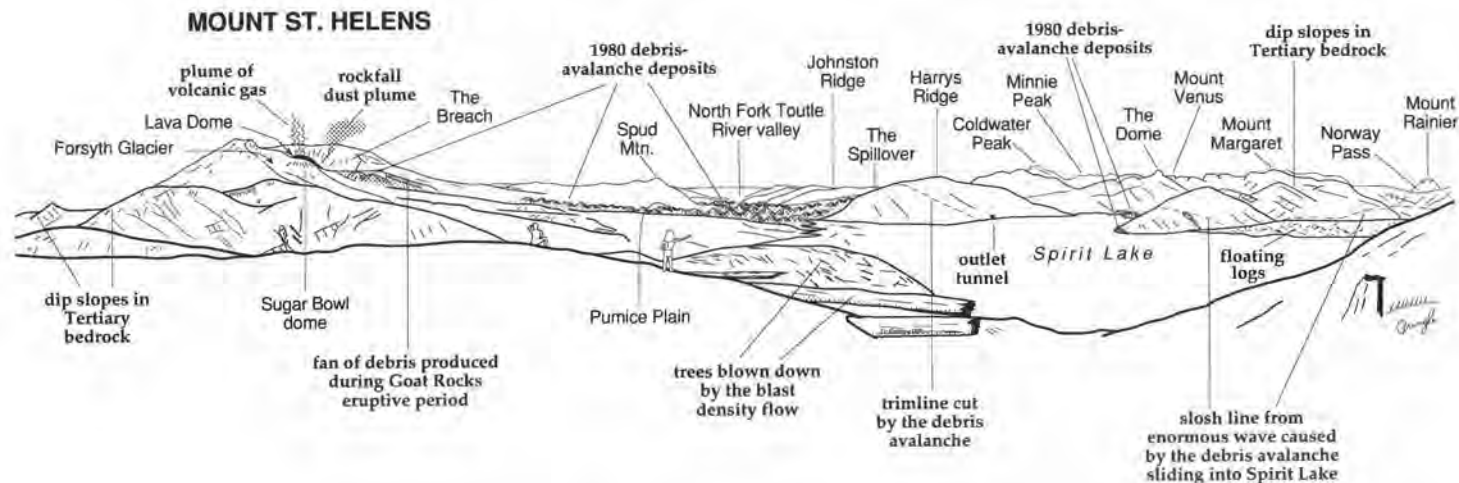


Figure 52. Panorama from the hill north of Windy Ridge, 2.5 mi (4 km) northeast of Mount St. Helens. This is an excellent place to view the devastated area immediately north of the volcano. The hummocky debris avalanche that impounds Spirit Lake and The Spillover, where the debris avalanche ran up on and spilled over Johnston Ridge into South Coldwater valley, are visible to the west. The debris avalanche also ran up onto Harrys Ridge and the south-trending ridge that plunges into Spirit Lake, stripping trees and soil and leaving a trimline. When the debris avalanche flowed into Spirit Lake, it caused an enormous translational wave that surged up onto the northern banks of the lake, leaving a slosh line. The maximum height of the wave's runup was 852 ft (260 m). The Pumice Plain is a fan of fragmental debris that was constructed on top of the debris-avalanche deposit by the pyroclastic-flow, ash-cloud, and lahar deposits of May 18, 1980, and later events. The Lava Dome, constructed by 17 eruptive episodes since 1980, is just visible behind Sugar Bowl, a 1,200-year-old dacite flank dome. Plumes of volcanic gas are commonly visible rising from the Lava Dome; dust clouds are also common because of rockfall activity from the steep crater walls. Coldwater Peak and The Dome are composed of Tertiary volcanic rocks. Minnie Peak, Mount Venus, and Mount Margaret are composed of the resistant granites and granodiorites of the Spirit Lake pluton, which intruded the Tertiary rocks between 22 Ma and 20 Ma. On clear days, Mount Rainier is visible 40 mi (70 km) to the north-northeast.

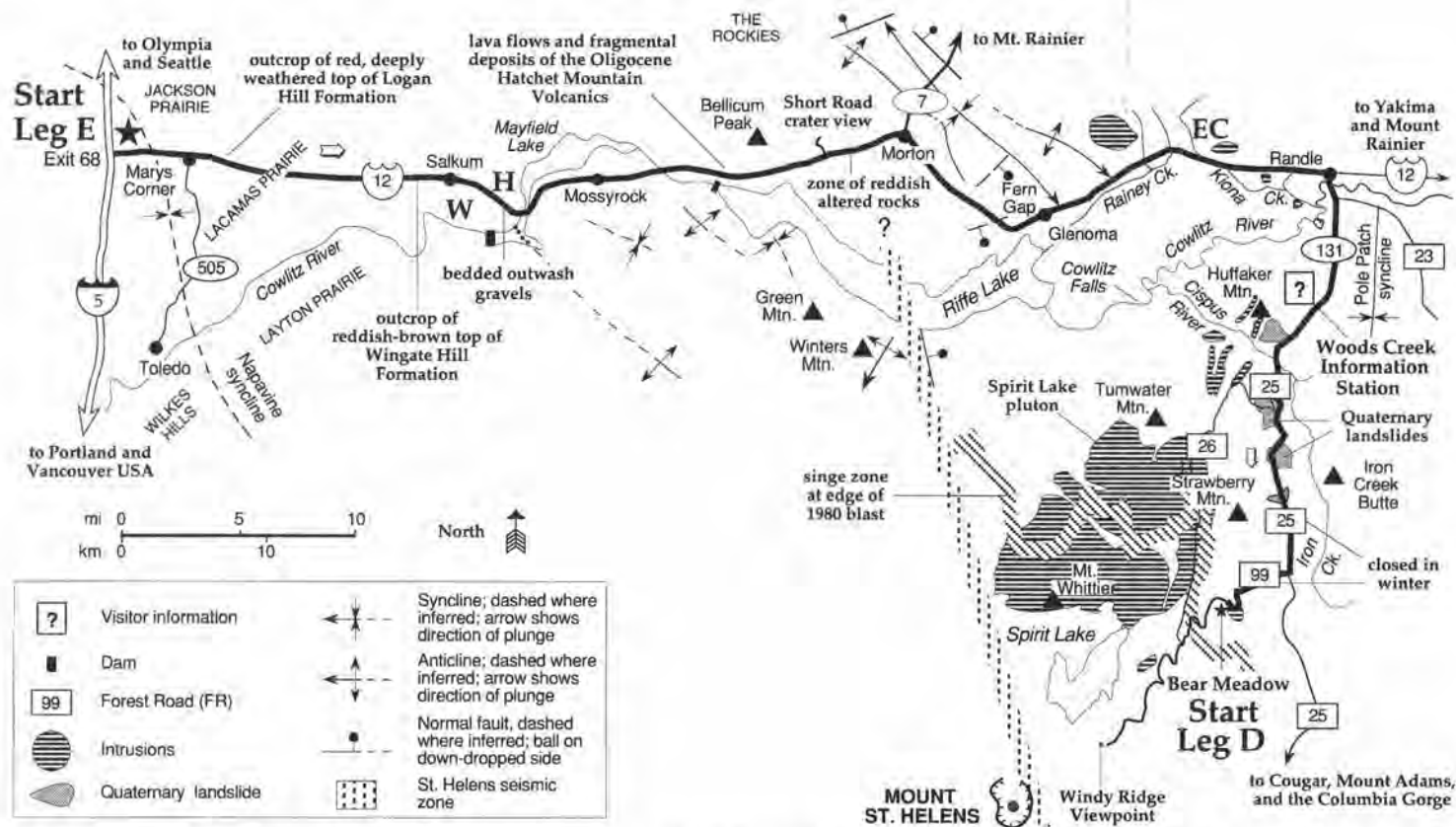


Figure 53. Sketch map of Leg E. Shown are folds (synclines and anticlines), faults, intrusions, and other features of interest. W, H, and EC show the maximum extent of a valley glacier that occupied the Cowlitz River valley during the Wingate Hill, Hayden Creek, and Evans Creek glacial advances respectively (about 500 ka, 140 ka, and 20,000 yr B.P.). The glacier originated at an extensive icecap in the Mount Rainier area that existed during each glaciation. The top of Bellicum Peak, just over 2,200 ft (671 m) elevation, was not glaciated.

- (5) Finally, a small lahar entered upper Smith Creek valley along the west margin of the hummocky lahar deposits.

11.7 [18.7] STOP D-4: WINDY RIDGE VIEWPOINT. Windy Ridge is one of the best places to get an overview of the area devastated by the 1980 eruption (Fig. 52). The landscape is littered with sand and gray rocks from that event. Deposits of the debris avalanche are visible to the west. These include the lower parts of The Spillover, where the debris avalanche traveled up over Johnston Ridge and into the South Coldwater valley.

The blast stripped most vegetation and some soil from many of the older bedrock surfaces, revealing to geologists and visitors previously hidden chapters in the geologic history of the area.

Rockfalls from the crater walls stir up ash clouds that curl over the edges of the crater rim, especially in late summer. A faint bluish-white volcanic gas plume is often visible rising from the Lava Dome, and sometimes *fumaroles* or clusters of fumaroles can be seen there.

A walk up the steps on the hill north of the parking area provides a better view of the devastated area adjacent to Spirit Lake. The 1980 debris avalanche roared over part of a ridge that protrudes into Spirit Lake from the north and carried all the downed trees off the slope and into the lake, leaving a distinct trimline (Fig. 51). The avalanche also displaced water from Spirit Lake, creating a giant wave that carved a sloch line along the shore. Many of the logs that now float in the lake were carried in by this wave; others have been eroded off the slopes since then. Wind moves the logs to different locations on the lake.

The water level of Spirit Lake is maintained at about 3,406 ft (1,038 m) by draining water through a gravity-feed tunnel completed in 1985. The 2,500-ft (762 m) -long tunnel was cut through Harrys Ridge (named for Harry Truman, the Spirit Lake resident who refused to leave his home and was killed by the May 18, 1980, eruption) to South Coldwater Creek. The portal is just visible about midway along the western shore of the lake. Had the lake level not been stabilized, its dam probably would have been breached, possibly causing catastrophic floods in the Toutle River.

LEG E: NORTHERN APPROACH — COWLITZ RIVER VALLEY

Via U.S. Highway 12, State Route 131, and Forest Road 25

This approach follows the Cowlitz River valley to the east and at Randle turns south toward Mount St. Helens (Fig. 53). U.S. Highway (US) 12 descends a series of progressively younger glacial *terraces* (named Jackson, Lacamas or Cowlitz, and Layton prairies) in stairstep fashion. The older surfaces are at higher elevations, the younger nearer the valley floor because erosion, possibly combined with a minor component of regional tectonic uplift, has deepened the valley before each succeeding episode of deposition. About 4 mi (6.4 km) west of Morton, the road crosses a divide into the Tilton River drainage and remains in that watershed for

about 9 mi (14.4 km) before descending back into the Cowlitz River valley near Fern Gap.

East of Mayfield Lake, dark-colored rocks of the Hatchet Mountain Formation (*Tertiary*) crop out along the highway, indicating that you have entered the eroded Cascade mountains. *Lava* flows and fragmental volcanic rocks of this age crop out all along the route.

South of Randle, State Route (SR) 131 crosses the wide glacial valley of the Cowlitz River and climbs the valley wall to a terrace of hummocky glacial deposits (end *moraine* and ice-marginal deposits) of Evans Creek age (22,000–11,000 yr B.P.). The road becomes Forest Road (FR) 25 when it crosses the National Forest boundary. It then follows the Cispus River and its tributary, Iron Creek, south through forested terrain. Outcrops of Miocene volcanic rocks are visible en route, as are ancient deposits of Mount St. Helens tephra that get thicker as the road nears the volcano.

Distances along the route are given in miles followed by kilometers in brackets.

Distance

- 0.0 [0.0] Mileage starts at the junction of Interstate Highway 5 and US 12. The road passes east over Jackson Prairie, a gently rolling terrace of the lower(?) Pleistocene Logan Hill Formation. This surface, which may be about a million years old, displays as much as 40 ft (12 m) of relief. Here the Logan Hill Formation consists mainly of a compacted mixture of cobbles and pebbles in a sandy clay matrix. The sediment is *outwash* from an ancient *glacier* whose source was in the southern Washington Cascade mountains near Mount Rainier.
- 2.4 [3.8] Marys Corner.
- 3.0 [4.8] Roadcuts expose the clayey, reddish, deeply weathered top of the Logan Hill Formation. Weathering reaches depths greater than 50 ft (15 m).
- 4.5 [7.2] Descend from the Jackson Prairie to Lacamas Prairie, the surface of a middle(?) Pleistocene Wingate Hill outwash deposit. Notice that Lacamas Prairie is flatter than the older Jackson Prairie—it displays relief of only a few feet. The Wingate Hill *Drift* is thought to be between 300 ka and 600 ka.
- 9.3 [14.9] Wingate Hill outwash is exposed in a roadcut about 300 ft (90 m) west of milepost 76. The reddish-brown weathering of this deposit extends to depths that range from 16 to 32 ft (5 to 10 m) and does not have the deep red hue of the older Logan Hill deposits.
- 11.4 [18.2] Near Salkum, the road descends to a terrace underlain by outwash deposits of Hayden Creek age (about 140 ka) and then crosses Mill Creek. *Till* of Wingate Hill age (about 500 ka) is visible to the right just after you pass Mill Creek. The Wingate Hill terminal moraine is about a mile (1.6 km) west of here, whereas the maximum extent of the Hayden Creek glacier was about a mile (1.6 km) to the east. The hills and mountains of the Cascades come into view as you continue farther east.
- 15.2 [24.3] Cross Mayfield Lake (a reservoir). The concrete arch dam was completed in 1962. Glacial outwash deposits are visible north of the highway on

both sides of the reservoir. Dark Cascade Range volcanic rocks begin to crop out in roadcuts near here.

21.0 [33.6] Cross the Cowlitz River.

23.1 [37.0] **OPTIONAL STOP: RIFFE LAKE VIEWPOINT.** Riffe Lake (a reservoir) is situated in the glacially carved valley of the Cowlitz River. In this area, the Goble Volcanics (Tertiary) are visible in roadcuts on the north side of the highway; the layers dip to the east at the viewpoint. Beds of fragmental volcanic rocks crop out about 0.5 mi (0.8 km) farther to the east. *Vugs* in the lava contain opal. Opal is composed of amorphous (non-crystalline) silica and commonly contains a small percentage of water. The opal was deposited by ground water that percolated into cavities in the rock. Vertical *dikes* of *basaltic andesite* are also visible locally.

The road climbs past glacial drift, out of the Cowlitz drainage, and then crosses a drainage divide into the Tilton River watershed.

27.2 [43.5] **OPTIONAL STOP: SHORT ROAD CRATER VIEW** (1.3 mi or 2 km round trip). If the weather is good, this viewpoint affords a distant view of the Mount St. Helens crater, neighboring mountains, and the glacially carved valley of the Cowlitz River. Bellicum Peak, the sharp mountain to the northwest as you climb Short Road, was not covered by glaciers during the Pleistocene Epoch. Imagine this lonely peak sticking up in the middle of a broad sheet of glacial ice during the extensive Hayden Creek glaciation.

29.4 [47.0] As the road descends into Morton, a zone of reddish altered rocks is exposed on the left. *Slickensides* are common on these rocks, although there is no evidence of a *fault*.

The smooth southwest-facing hillslope visible northwest of Morton is the dip slope of a limb of a northwest-trending *anticline*. Folding near Morton is more complex and tightly spaced than the gentle folding typically found in the region. Whereas the crest spacing (wavelength) of the *folds* in the older rocks north of Rainey Creek ranges from about 2 to 6 mi (3–10 km), the spacing in the younger rocks south of Rainey Creek ranges from about 6 to 18 mi (10–30 km). Because of this more intense folding, the rocks are generally more shattered and altered, and erosion has cut a window through the volcanic rocks into the older sedimentary rocks of the Eocene Puget Group. Landslides abound in this area, which lies between two active, north-northwest-trending seismic zones, the *St. Helens zone* and the West Rainier zone. The West Rainier zone is about 12 mi (20 km) north-northeast of the St. Helens zone. (See p. 111.)

31.9 [51.0] Junction of US 12 with SR 7 at Morton. Continue east on US 12.

33.8 [54.1] Sedimentary rocks of the Puget Group crop out on the south side of the highway. These rocks for the most part predate the Cascades, but they do interfinger with the earliest Cascade volcanic rocks.

33.5 [53.6] About 3.5 mi (5.6 km) past the SR 7 junction, the road crosses a north-east-trending *normal fault*, and you are back in the Goble Volcanics. Although the fault motion was down-to-the-southeast, the topography is

inverted and the down-dropped rocks now stand higher than those rocks across the fault, perhaps because the Goble Volcanics are more resistant to erosion than the sedimentary rocks of the Puget Group.

The highway starts to climb once it reaches the volcanic rocks, passes again into the Cowlitz River drainage and the valley of Rainey Creek at Fern Gap, and then descends to Glenoma.

The south valley wall (the elongated ridge south of Glenoma) along Rainey Creek is composed of upper Oligocene basaltic rocks, mostly lava flows. These rocks were derived from a volcanic center south of Riffe Lake.

- 43.0 [68.8] Deposits of yellowish *tephra* are visible in roadcuts and stream banks near where the road crosses Rainey Creek. The pebble-size *pumice* is the Yn tephra layer from Mount St. Helens, erupted about 3,600 yr B.P.
- 44.6 [71.4] Cross the drainage divide between Rainey and Kiona Creeks, located on coalescing alluvial fans from those two creeks.
- 46.6 [74.6] Cross Kiona Creek. Slightly east of here the highway passes through a terminal moraine of the Cowlitz River glacier of Evans Creek age.
- 49.0 [78.4] Randle. *Note: There are no service stations between here and Cougar (about 100 mi or 160 km), so make sure you have plenty of fuel.*

Turn right on SR 131 to reach the east side of the Mount St. Helens National Volcanic Monument. The road crosses the Cowlitz River, the main fork of which originates on Mount Rainier. The greenish gray color of the water is caused by rock flour, the silt and clay carried in suspension by the river. Rock flour is created by the grinding action of rocks at the bed of a glacier.

- 49.7 [79.5] A swampy area east of the highway about 0.8 mi (1.2 km) south of Randle is the remnant of an oxbow lake. The Cowlitz River has meandered back and forth across the valley in this reach. At some time in its past, the river abandoned a channel here and moved farther to the north, plugging its old channel and leaving an oxbow lake. In this stretch from Randle west to Cowlitz Falls, the Cowlitz River meanders for some 14 river miles (23 km) to travel only 9 mi (14 km). It then abruptly changes its character at Cowlitz Falls and flows in a nearly straight course for 3.2 river miles (5 km) to cover the 3.0 mi (4.8 km) from Cowlitz Falls to Riffe Lake. The Cowlitz River has cut into the Tertiary rocks at Cowlitz Falls, forming an entrenched meander. Resistant lava flows and *flow breccia* and at least two northeast-trending *porphyritic* dikes have created the falls and may also have established a base level that controls the gradient and thus the meandering course of the Cowlitz River upstream of the falls. Holocene lahar deposits from Mount Rainier underlie this flood plain, but none are exposed nearby.
- 50.0 [80.0] Junction of SR 131 and FR 23. Bear to the right and follow SR 131.
- 50.6 The road climbs the south wall of the Cowlitz River valley. After about 0.8 mi (1.3 km), the road passes through hummocky terrain on a prominent terrace, an ice-marginal area of the Evans Creek glacier.

The road crosses into the Woods Creek drainage and follows a fairly flat surface on Evans Creek drift.

54.7 [81.0] **OPTIONAL STOP: WOODS CREEK INFORMATION STATION.** You can stop here to pick up maps and interpretive, weather, road access, and miscellaneous information about the national monument. This facility is operated by the U.S. Forest Service.

57.6 [92.2] After crossing the Cispus River, SR 131 becomes FR 25. Leg F, an alternate approach to Windy Ridge, takes off to the right (nearly straight ahead) here on FR 26, a one-lane road with turnouts. *Trailers and large recreational vehicles are advised not to take FR 26.*

61.0 [97.6] **OPTIONAL STOP: IRON CREEK CAMPGROUND.** This is a good place to camp the night before a visit to Mount St. Helens.

As the road winds up a series of switchbacks, white and yellowish layers of tephra from ancient eruptions of Mount St. Helens are increasingly evident in roadcuts. Because prevailing winds blow to the east, greater amounts of tephra are deposited on this side of the volcano than on the west.

At the beginning of the second sharp switchback to the right, and for the next 1.5 mi (2.4 km), the road climbs smoothly across a large Quaternary landslide deposit that originated on the northeast side of Strawberry Mountain. Deposits of a similar landslide crop out on the right side of the road north of Benham Creek at 61.5 mi (98.4 km).

FR 25 continues south up the west valley wall of Iron Creek, a north-flowing tributary of the Cispus River. Outcrops of bedrock are scarce in this heavily wooded area, but upper Oligocene to lower Miocene lava flows, fragmental deposits, and *intrusive* rocks and deposits of glacial drift of at least two episodes of alpine glaciation can be seen in roadcuts along this stretch.

Geologists have been able to study extensive exposures of these rocks in the steep streams draining Strawberry Mountain. *K-Ar* dates on rocks in this area are about 23 Ma. The Strawberry Mountain rocks include *dacite* dikes and small *domes* and breccia that appear to be relics of an ancient dacite eruptive center. These Strawberry Mountain domes may have been emplaced in much the same way as those on the flanks of Mount St. Helens, such as East Dome and Sugar Bowl dome. *Lapilli-tuff* breccia and andesite flows stratigraphically above this volcano are exposed near a small turnout at about mile 68 (109 km).

Iron Creek Butte, a mesa having nearly horizontal bedding, is visible on the ridge top to the east-southeast from this turnout, across the valley of Iron Creek. The flat-lying rocks of that mesa are about 2.5 mi (4 km) west of the axis of the Pole Patch *syncline*. (See also Stop A-4, p. 51.)

68.1 [109.0] Strawberry Mountain Viewpoint turnout.

70.4 [112.6] Junction of FR 25 with FR 99. Turn right on FR 99.

76.1 [121.8] End of Leg E. Starting point for Leg D. (See p. 77.)

LEG F: ALTERNATE NORTHERN APPROACH

Via Forest Road 26

Forest Road 26 is a winding, one-lane road with turnouts. It is not recommended for recreational vehicles or trailers.

Those who approach the *devastated area* via Forest Road (FR) 26 will be treated to spectacular evidence of the dynamics of the Mount St. Helens *blast*. The route of this leg is shown in Figure 47 on page 76.

FR 26 winds around the north toe of Strawberry Mountain and heads south up the valley of Quartz Creek, which drains north into the Cispus–Cowlitz River system. The road continues south into the area devastated by the 1980 blast and crosses a low divide into the glacially carved upper reaches of the Green River watershed, tributary to the Toutle–Cowlitz River drainage system.

Along this route, the road passes from volcanic rocks (25 Ma–23 Ma) into the rocks of the Spirit Lake *pluton*. The pluton is a cooled magma chamber formed from 23 Ma to 20 Ma. It may have produced some of the volcanic material a few miles to the east, but those rocks have not been firmly correlated with the pluton, and there is little evidence for a vent. Copper deposits prospected locally were created by shallow *hydrothermal* activity during, and for several million years after, the intrusion of the pluton. Vegetation covers much of this rock for the first several miles (or kilometers) of this leg. As the road enters the devastated area, however, the amount of exposed rock increases dramatically.

Distances along the route are given in miles followed by kilometers in brackets.

Distance

- 0.0 [0.0] Mileage starts at intersection of FRs 25 and 26. In the first 1.5 mi (2.4 km), FR 26 traverses the northern part of a large landslide that originated on Strawberry Mountain. The road then passes through layers of *volcaniclastic* rocks and *lava* flows (mostly hidden by vegetation) that were erupted from several nearby lower Miocene volcanoes, including Strawberry Mountain to the south and Tumwater Mountain to the north.
- 3.0 [4.8] About here the road enters a zone of rocks that have been baked and altered by the intrusion of the Spirit Lake pluton (between 23 Ma and 20 Ma). Roughly 0.3 mi (0.5 km) farther along, the road enters a zone of coarse, poorly sorted *breccia* and other fragmental volcanic rocks several hundred yards (or meters) thick. Geologists have interpreted these deposits as possible *caldera* fill.
- 4.0 [6.4] The first of two roadcuts in the caldera-fill(?) deposits. These rocks have been hydrothermally altered. They typically appear dark green and have white flecks.
- 4.3 [6.9] This is the second of two roadcuts in the caldera-fill(?) deposits; here you can see *pumice* in an altered tuff.
- 6.2 [9.9] The light-colored rock in this outcrop is a *dacite dike* that cuts *granite* of the Spirit Lake pluton.

- 8.3 [13.3] **OPTIONAL STOP: QUARTZ CREEK ROAD (FR 2608).** The 2-mi (3.2 km) round trip to the Quartz Creek Big Trees Trail provides a glimpse of the old-growth forest that once covered much of this area. This grove is just outside the area devastated by the blast of May 18, 1980. However, many of the trees in this grove and in nearby forests were within the fallout zone for older *tephra* layers Wn, We, and T, and they experienced physical and thermal damage caused by the *ash* and *pumice* from those respective eruptions. The evidence of that damage was first noted in tree rings and later used to date the eruptions precisely. (See discussion of tree-ring dating, p. 97.)

About halfway to the grove, the road crosses Quartz Creek. Most of the large rocks in the stream bed are granite and *granodiorite* of the Spirit Lake pluton. Cross-bedded layers of mostly pre-1980 pumice are exposed in the bank of the stream.

Continue south on FR 26 into the blast zone.

Note: Mileage does not include the side trip to Quartz Creek Big Trees. Reset your odometer if necessary.

- 9.2 [14.7] Three Mount St. Helens tephra layers are visible here in roadcuts: Yn, Wn, and T. (See Fig. 39.) T is at the top. This site is near the north edge of the tephra deposit from the May 18, 1980, eruption.

At about 10 mi (16 km), the road enters the zone of blown-down trees in the valley bottom. The effects of the blast have been visible higher up on the slopes for the last mile. The *singe* zone is quite evident here and to the north toward Tumwater Mountain (on the skyline).

Like Strawberry Mountain, Tumwater Mountain is a stack of lower Miocene lava flows, *flow breccias*, and pyroclastic deposits that composed the flanks of an ancient volcano. These lavas include basaltic *andesite*, *porphyritic andesite*, and dacite domes.

- 10.3 [16.5] Where the road makes a sharp left-right S-turn, the jointed rock to the north is granite of the Spirit Lake pluton. This rock has a porphyritic texture; the large crystals (*phenocrysts*) are *feldspar* and *pyroxene*.

En route to Stop F-1, notice the shallow landslides on the steep hillsides. The deterioration of trees in the downed forest and the resulting loss of root strength contributed to slope instability.

- 13.2 [21.1] **STOP F-1: RYAN LAKE VIEWPOINT AND LOOP TRAIL.** Ryan Lake Viewpoint and the 0.5-mi (0.8 km) loop trail provide a good overview of the effects of the blast at a point 12 mi (19 km) north of the crater (Fig. 54).

Research on the effects of heat on conifer needles shows that the temperature of the blast at this site reached an estimated 300°C (572°F). As much as 6 in. (15.2 cm) of ash fell here. Two people died in this area on May 18, 1980, as a result of asphyxiation caused by inhaling the ash. Another person somehow hiked nearly 10 mi (15 km) farther north and then succumbed, also to asphyxiation.

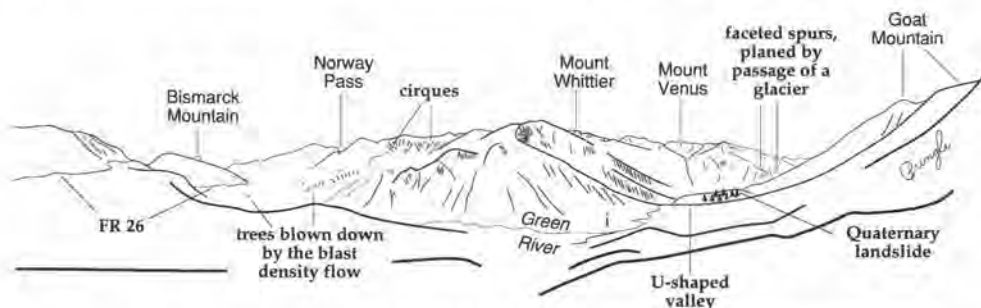


Figure 54. Panorama from the Ryan Lake trail, about 10 mi (15 km) northeast of Mount St. Helens. The blown-down trees show the intensity and turbulence of the May 18, 1980, blast density flow that swept into the Green River valley from the Spirit Lake basin to the south. The blast was apparently segregating into a lower, denser flow phase and an upper, more buoyant and less concentrated surge phase in this area. The basal portion ran out of energy just north of here, as indicated by the marginal singe zone and green trees beyond. The wide U-shaped valley of the Green River was carved by Pleistocene glaciers that originated in an ice cap on the resistant granite and granodiorite highlands of the Spirit Lake pluton. Mount Whittier, Mount Venus, and Goat Mountain are composed of those rocks. Bismarck Mountain is part of a Tertiary volcano.

Notice that trees on the lower parts of the valley wall were blown down locally, whereas those on upper parts of the valley wall still stand (Fig. 55). By the time the blast reached this location, particle segregation within it had created a heavier “flow” phase, which blew down trees in lower areas, and a lighter “surge” phase, which left trees standing in higher areas. (See also p. 31 and 105.)

Mount St. Helens tephra layers Y, W, and T crop out in cuts along this trail. Rock of the Spirit Lake pluton was quarried for road construction at a site on the south edge of the parking area.

- 14.1 [22.6] Goat Mountain, to the northwest, is composed of *granodiorite* of the Spirit Lake pluton. This area contains a large, low-grade deposit of copper and molybdenum. (See p. 14.)
- 14.7 [23.5] More tephra is visible in this roadcut; it lies over granodiorite.
Bismarck Mountain, to the east, is a thick pile of lower Miocene lava flows and *flow breccia* that is probably a remnant of an old *andesite* cone like Tum-water Mountain and Strawberry Mountain.
- 15.1 [24.1] The downed trees in this area display extraordinary swirled patterns, evidence of the turbulence in the blast.
- 17.0 [27.2] **OPTIONAL STOP: NORWAY PASS TRAIL.** Norway Pass Trail, a segment of Boundary Trail #1, is a 2.2-mi (3.5 km) hike through the blown-down forest to Norway Pass and impressive views of Mount St. Helens crater and Spirit Lake. The north-ascending slosh line on the valley walls at the extreme northern end of Spirit Lake was created when a lobe of the *debris*

Figure 55. Southwest view of the Green River valley wall south of Ryan Lake showing trees blown down and damaged by the blast. In the blowdown area here, only the weaker trees were leveled. Stronger trees or those shielded by hills were left standing.



avalanche flowed into the lake on May 18, 1980, and generated a huge wave that stripped soil and trees from the hillslopes as much as 850 ft (260 m) above the original lake level.

After 1.5 mi (2.5 km), the trail passes near the site of the old Chicago mine. The Norway and Sweden mines were down the ravine south of Norway Pass. Beginning in 1900, minor amounts of copper, gold, silver, and zinc were mined from these and other nearby mines of the St. Helens mining district. (See Fig. 10 and mining history on p. 14.) The entrance or portal to the 2,291-ft (699 m)-long Sweden mine tunnel was at an elevation of 3,340 ft (1,019 m). It is now below the waters of Spirit Lake (elev. 3,406 ft or 1,039 m).

17.9 [28.6] Junction of FR 26 with FR 99. End of Leg F.

LEG G: ALTERNATE SOUTHERN LOOP

Via Forest Road 81

This 18-mi (29 km) side trip (Fig. 35) traverses the south and southwest flanks of Mount St. Helens and provides access to Ptarmigan Trail and Climber's Bivouac (starting point for the Monitor Ridge climbing route), Forest Road (FR) 8123 to the Goat Marsh area, hiking trails on the volcano's west side, and Merrill Lake. The route of this leg is shown in Figure 35 on page 60.

The road leaves the Swift Creek watershed and crosses into the Kalama River watershed; then it heads south past Merrill Lake and back into the Lewis River drainage. The route passes through an end *moraine* of Evans Creek age (22,000–11,000 yr B.P.), exposures of Cave *Basalt*, an *outcrop* of a *debris avalanche* of Cougar age (20,000–18,000 yr B.P.) from Mount St. Helens, and across a debris fan of Kalama age (A.D. 1480 to late 1700s). The road skirts Goat Mountain, a Pleistocene *dacite dome* complex. South of Merrill Lake the road passes through several outcrops of *Tertiary* bedrock and *till*.

Distances along the route are given in miles followed by kilometers in brackets.

Distance

0.0 [0.0] Mileage starts at the intersection of FRs 83 and 81. Take FR 81.

0.5 [0.8] Pass through an end moraine of Evans Creek age.

- 1.8 [2.9] FR 830 to Ptarmigan Trail and Climber's Bivouac. *Lahar* deposits of Kalama age buried a mature forest in this area, and the tree *snags* are visible locally in stream cuts or gravel pits.
- 2.5 [4.0] Exposure of Cave Basalt (Castle Creek age, 1,900 yr B.P.).
- 4.0 [6.4] McBride Lake area. Deposits visible on the northeast side of the road include a debris avalanche of Cougar age, which is overlain by *pyroclastic-flow* deposits of Cougar age and till of Evans Creek age.
- 4.4 [7.0] Some of the trees in this area were killed by a small lahar from the south flank of Mount St. Helens that was generated by the May 18, 1980, eruption.
- 5.2 [8.3] Junction of FR 81 with FR 8123. FR 8123 provides access to Goat Mountain and Goat Marsh Lake, as well as to Sheep Canyon and the upper South Fork Toutle River. Goat Mountain is a *dacite* plug dome. *Radiometric ages* range from 3.2 Ma to 0.8 Ma, so the dome is interpreted to be either of late Pliocene or early Pleistocene age. Goat Marsh Lake and Blue Lake were created when debris of Kalama age dammed or altered the drainage of the small streams that feed into them.

Note the distinct *terraces* of a debris fan of Kalama age in this area. The vegetation on the fan is similar to, but more mature than, vegetation on the slightly younger Old Maid Flat debris fan west of Mount Hood along the Ramona Falls Loop Trail (a few miles northeast of Zigzag in the Mount Hood National Forest). The sandy, well-drained deposits composing large areas of both fans support a forest assemblage that can survive under conditions of limited soil moisture: salal, huckleberry, pinemat manzanita (bearberry or kinnikinnick), lodgepole and white pine, and Douglas fir, for example. Forest succession on the 1980 debris fan in the upper reaches of the South Fork Toutle River could develop in a similar way.

- 8.6 [13.8] Pyroclastic flows of Kalama age crop out in this quarry. Blocks of dome rock in one of the deposits suggest the flow may have occurred early in the Kalama eruptive period, possibly as early as A.D. 1482.
- 9.2 [14.7] The small dome visible to the west about 0.3 mi (0.5 km) from the road apparently postdates the Evans Creek glaciers. Its petrographic similarity to dacite of the Swift Creek eruptive period (13,000–10,000 yr B.P.) suggests it may be 13,000 yr B.P. or less.
- 10.5 [16.8] Cave Basalt crops out north of the road near here. Tumuli (pressure ridges) are visible on the surface of the flows.
- 11.4 [18.2] Merrill Lake. Geologists have suggested the lake was formed when a short tributary to the Kalama River was dammed about 1,900 yr B.P. by Cave Basalt flows and underlying fragmental deposits from Mount St. Helens.
- 12.1 [19.4] Entrance to Merrill Lake Campground, managed by the Washington Department of Natural Resources. The primitive campground is closed November through April. *Drinking water is available.*
- 17.7 Return to SR 503. End of Leg G.

PART III: A GEOLOGIC PRIMER — PROCESSES AND ROCK TYPES

WHAT IS GEOLOGY?

Geology has traditionally focused on the study of planet Earth—the materials of which it is made, the processes that shape its surface, and its history and life forms. The technical advances of the space age have broadened the scope of geology to include the study of our solar system.

To the casual observer, the rocks that compose the Earth may appear to be unchanging materials that have existed since the beginning of time. Looking more closely, however, those with a trained eye can “read” these rocks and uncover many clues to their age and origin.

Understanding geology can give us an appreciation of the scenery around us, and it can provide a historical perspective, a perception of the duration of geologic time. In addition, it can help us visualize the complex processes that have shaped the Earth and the interconnection of those processes with life on our planet. Because geology is a science whose chief laboratory is the outdoors, our knowledge is transferable anywhere in the world. When we learn to read the rocks in one area, we can recognize similar rocks and geologic processes at work in other areas and piece together their geologic history.

Although it is Mount St. Helens volcano that draws us to this spectacular, denuded and scorched landscape, the lava flows and fragmental deposits produced by Mount St. Helens throughout its more-than-40,000-year history are dwarfed by the volume of deposits laid down during the previous 40 m.y. of volcanic and tectonic activity in the southern Cascades. The 1980 eruption of Mount St. Helens is only the most recent episode in the volcanic history of the Cascade Range.

The following geologic primer reviews the types of rocks in the area, how they were formed, and how they have been transported, rotated, deformed, and changed. Because Pleistocene *glaciers* were responsible for much of the relief in the landscape around Mount St. Helens, we will briefly examine glacial processes as well as other erosional processes. Words defined in the glossary at the end of Part IV have been italicized on first usage in the text.

ROCK TYPES

Rocks are aggregates of one or more *minerals*. Geologists have categorized rocks into three major groups, based on their mode of formation: (1) *igneous* rocks, (2) *sedimentary* rocks, and (3) *metamorphic* rocks.

Igneous Rocks

Igneous rocks are rocks that have solidified from a molten state. They are subdivided into *intrusive* igneous rocks and *extrusive* igneous rocks. Specific rock types, such as granite or basalt, are typically classified by grain size, silica content, and mineral composition. Terms for various types of igneous rocks are shown in Tables 6 and 7. Igneous rocks predominate in the Mount St. Helens area.

Intrusive rocks. Intrusive igneous rocks form when *magma* solidifies before reaching the Earth’s surface. Intrusive rocks cool slowly; thus large crystals have time to grow. Pre-Mount St. Helens intrusive rocks crop out mainly along Forest Roads (FRs) 26 and 99, where erosion has exposed them. Several types of intrusive features are shown in Figure 7. These include *dikes*, which cut across the layers of intruded rock, and *sills*, which parallel the layers of intruded rock.

Extrusive rocks. Extrusive igneous rocks cool on the surface of the Earth, typically as *lava* flows or fragmental volcanic deposits (also known as *volcaniclastic* rocks) (Table 7); the latter include *pyroclastic density currents* (flows of hot rock and gas from a volcano). Extrusive rocks are fine grained compared to intrusive rocks because they cool quickly. The textural difference between intrusive and extrusive igneous rocks can be seen with a magnifying glass. Extrusive rocks at Mount St. Helens commonly have a *porphyritic* texture (Fig. 56). This texture, which has larger crystals (*phenocrysts*) in a very fine-grained matrix (the *groundmass*), indicates a compound cooling history. It shows that the magma was not totally molten, but existed as a kind of slush in which minerals with higher melting points remained solid as crystals in the molten magma and had time to grow. When an eruption occurred, the molten magma chilled quickly, and the fine texture of the groundmass was created. Quick cooling also causes *joints* and *columns* (Fig. 57). Most *Tertiary* rocks (66 Ma to 1.6 Ma) that predate Mount St. Helens are extrusive, and these rocks can be seen on all approaches to the mountain.

Sedimentary Rocks

Sedimentary rocks are rocks that have been deposited in layers by water, wind, or ice, or precipitated by chemical means. Most sedimentary rocks in this area contain volcanic debris. Some of this volcanic material can be seen along Interstate Highway 5 (I-5), along State Route (SR) 503, east of Morton on U.S. Highway 12, west of Cougar, and on the western approach along the new Spirit Lake Memorial Highway, SR 504.

Metamorphic Rocks

Metamorphic rocks are rocks that have been altered by heat, pressure, or fluids deep within the Earth’s crust. Metamorphic rocks result when pre-existing

Table 6. Simplified classification scheme for igneous rocks found in the Cascades

Intrusive rock	Extrusive rock	Silica content
granite	rhyolite	>69%
granodiorite	dacite	62-69%
diorite	andesite	54-62%
gabbro	basalt	45-54%

Table 7. Classification of fragmental volcanic rocks found in the Cascades

Clast size	Unlithified	Lithified
<2 mm	ash	tuff
2-64 mm	lapilli	lapillistone
>64 mm	bombs/blocks	volcanic breccia

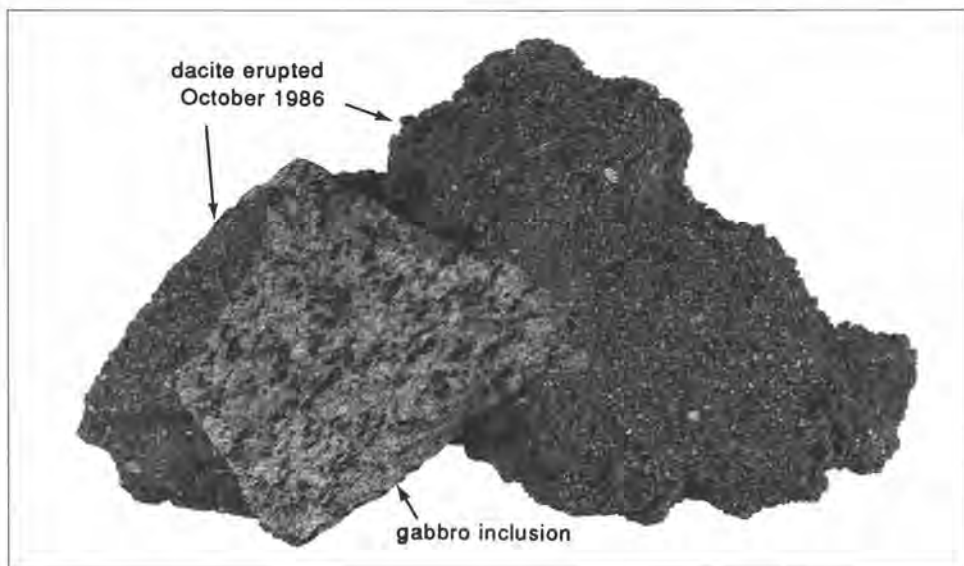
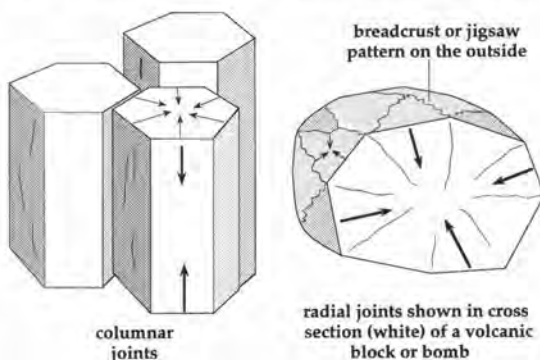


Figure 56. Fragment of Mount St. Helens dacite containing a gabbro inclusion that was incorporated into the magma as it rose in the volcano. The gabbro has a phaneritic texture (meaning that all crystals are visible), which indicates it cooled fairly slowly. The dacite has a porphyritic texture (larger crystals in a finer grained groundmass), indicating a compound cooling history. The light-colored plagioclase crystals (phenocrysts) grew as the magma was stored below the volcano; during the eruption, the darker colored groundmass chilled too quickly for large crystals to form in the liquid part of the magma.

rocks are deeply buried, squeezed by tectonic forces, or baked by nearby intrusions of molten rock. Most metamorphism of rocks in the Mount St. Helens area is "low grade" (formed in low-temperature and (or) low-pressure environments), although rocks that have been totally recrystallized, called *hornfels*, are found nearby.

In this area, the rocks that have undergone low-grade metamorphism have been partly altered to chlorite (a mica) and other clay minerals by hot fluids passing through tiny cracks in the rock mass both during and after the intrusion of magma. They typically have the greenish color of chlorite. Good examples of altered volcanic rocks are found in the Elk Rock and Johnston–Coldwater Ridge areas along SR 504, and along FRs 26 and 99

Figure 57. Sketch of columnar jointing in a lava flow and prismatic or radial jointing in a volcanic bomb/block. Small arrows show the direction of contraction during cooling; thicker arrows show the direction of cooling. Joints are caused by contraction.



where those roads enter and exit the area intruded by the Spirit Lake *pluton* or other Miocene intrusions.

GEOLOGIC TIME: THE FIRST REVOLUTION IN GEOLOGY

One of the great challenges of compiling a history of the Earth has been establishing the ages of the various rocks, sediments, and geological events. For thousands of years, people have speculated about the age of the Earth and the universe. But during the nineteenth-century, geologists observed geologic processes that suggested the Earth was older than previously accepted. They pondered the great length of time it must have taken for the Earth to cool down from an initial molten state; for salt to form in the oceans; for the formation of igneous, metamorphic, and sedimentary rocks and the upheaval of those rocks into mountains; for the erosional destruction of those mountains. Did these processes take millions, tens or hundreds of millions, or billions of years?

The Geologic Time Scale

The product of nineteenth-century geologic thought was the geologic time scale (Fig. 11), a kind of geologic calendar that reflected the vast amounts of time in the Earth's history. It was the first revolution in the science of geology. Philosophically, the concept of geologic time has probably had as big an impact on science as astronomers' discovery of the vastness of the universe and physicists' discovery of the connection between matter and energy.

The geologic time scale is divided into Eras, Periods, and Epochs on the basis of the sequential appearance of fossils and using the fundamental laws of *stratigraphy* to establish the age of one rock unit relative to another (relative age). (Geologists who study deposits of the Quaternary Period commonly use the analysis of soil development to estimate relative age.) In this guide, we will be using time terms from the Cenozoic Era because all of the rocks accessible via this road guide are of Eocene age or younger.

Radiometric Age Determination

Radiometric age determination or *radiometric dating*, developed in the early 1900s, soon became the most reliable method of establishing the absolute (as opposed to relative) age of a rock and led to the refinement of the geologic time scale. Radiometric age determination uses the nuclear decay of naturally occurring *isotopes* in geologic materials to calculate the age of the rock or crystal in years. *Potassium-argon dating*, *fission-track dating*, and *radiocarbon dating* are radiometric methods used in the Mount St. Helens area.

Potassium-Argon Dating. Potassium-argon (K-Ar) dating uses the fact that 11 percent of the potassium isotope ^{40}K in rocks disintegrates to the stable argon isotope ^{40}Ar at a constant rate (the remaining 89 percent of the ^{40}K atoms decay to ^{40}Ca). The *half-life* of ^{40}K is 142 million years, so half of the original ^{40}K will be gone in that amount of time. If the amounts of those respective isotopes in the rock are determined, the age of the rock can be estimated. However, this method does not work well for rocks younger than about 400,000 years.

Fission-Track Dating. The fission-track method estimates the age of a rock by counting the density of fission tracks, scars left by the spontaneous nuclear



Figure 58. Segment of a sanded and polished tree core showing the sequence of narrow tree rings that followed the eruption of 1800. Heavy tephra fall from this eruption (T tephra layer) traumatized the tree, causing slow growth (narrow rings) and missing rings (1801–1803?). By cross dating the ring pattern that precedes the narrow rings with that of nearby old-growth trees, dendrochronologist David Yamaguchi was able to precisely date this eruption to the period between the end of the 1799 growing season and the beginning of the 1800 growing season (marked with three dots). Photo by David Yamaguchi, University of Washington.

breakdown of uranium isotopes in a crystal. This method can be used on rocks of nearly all ages.

Radiocarbon Dating. Radiocarbon (^{14}C) dating relies on the disintegration of the carbon isotope ^{14}C to determine the age of an organic sample on the basis of an assumed natural abundance of that isotope. This method is useful for determining the age of a deposit between 35,000 and 200 years old when wood or another contemporaneous organic material can be found in the deposit.

Tree-Ring Dating. Tree-ring dating (*dendrochronology*) has been used to precisely date prehistoric lahars, eruptions, and lava flows at Mount St. Helens. This technique not only provides a detailed chronology of relatively recent events for individual volcanoes, but the greater precision also allows a better characterization of chemical trends at a volcano.

By comparing (*cross dating*) the ring patterns of trees injured by tephra falls, lahars, and lava flows (Fig. 58) with those of uninjured old-growth trees in the area, David Yamaguchi (1983) has been able to date numerous eruptive events of the past 500+ years.

PLATE TECTONICS: THE SECOND REVOLUTION IN GEOLOGY

A second revolution in the science of geology began in the early 1960s, brought about by the general acceptance of the theory of plate tectonics. This theory states that the Earth's crust is made up of rigid plates that move slowly across the surface. The plate-tectonic theory helps to explain (albeit with many unanswered questions!) the causes of volcanoes and magma; the origin of mountain ranges, *faults*, *folds*, and uplift; the origin of deep basins of sedimentary rocks; and even the origin of the Earth's magnetic field.

The notion of moving continents was first put forth by Francis Bacon in about 1620. However, the idea first became a serious scientific issue when it was postulated by a German meteorologist named Alfred Wegener in 1912. Wegener's theory of "continental drift" was widely criticized, although he had much geologic evidence in support of the idea. The theory had fallen out of favor by the time Wegener died in 1940 because he had failed to come up with a plausible explanation of what caused the continents to move. Continental drift was revived after World War II because of new evidence uncovered by the study of paleomagnetism in the rocks of the ocean floor.

Paleomagnetism: Volcanoes as Tape Recorders

Geophysicists study paleomagnetism, the natural magnetization in rocks, to determine the history of the Earth's magnetic field. Atoms in magnetite or other iron-rich minerals crystallizing from molten magma or lava orient themselves with the Earth's magnetic field just like a compass needle. As the rock solidifies, this magnetic orientation is preserved and can be detected with a sensitive instrument called a magnetometer. Under the right conditions, this magnetic alignment can also occur in sediments. Changes in the Earth's magnetic field can, therefore, be interpreted from the magnetic orientations recorded in rocks and compared with the orientation of the present magnetic field.

In 1929, a Japanese geophysicist named Motonari Matuyama published the results of his research on changes in the magnetic field. He had noticed that the magnetism of rocks generally pointed either north (like today's magnetic field) or south. He deduced that the Earth's magnetic field reverses about every few hundred thousand years. Although his theory was controversial and not accepted for many years, eventually a history of the Earth's magnetic reversals was compiled with the help of advances in the radiometric dating of rocks.

During the 1950s, technological advances made during World War II became available for more detailed studies of the ocean floor (including topography, gravity, seismic studies, heat flow, and paleomagnetism). Geophysicists on research ships towing magnetometers discovered a pattern of multiple magnetic stripes, each 12 to 18 mi (20–30 km) wide, across the sea floor. (In Figure 59, these stripes are shown in cross section.) The stripes seemed to be parallel to and symmetric across mid-ocean ridges. Meanwhile, other geophysicists were compiling data about apparently anomalous magnetic orientations in rocks worldwide. These deviations made it appear that the Earth's magnetic poles had gradually changed position. Plots of these pole positions that show this apparent movement of the magnetic poles are called "polar wandering curves".

Sea-Floor Spreading

The magnetic stripes in lavas on the ocean floor were explained in 1963 by two British scientists, Fred Vine and Drummond Matthews. They reasoned that new ocean floor was being created where lava comes up along a mid-ocean ridge (Fig. 59). As it cools, the lava records the current orientation of the Earth's magnetic field. This cooled lava breaks apart to allow new lava to erupt (and hence new sea floor to be produced). The new lava records the magnetic orientation that exists when it cools. Every several hundred thousand years, when a reversal of the magnetic field takes place, this ocean floor "tape recorder" makes a record of the

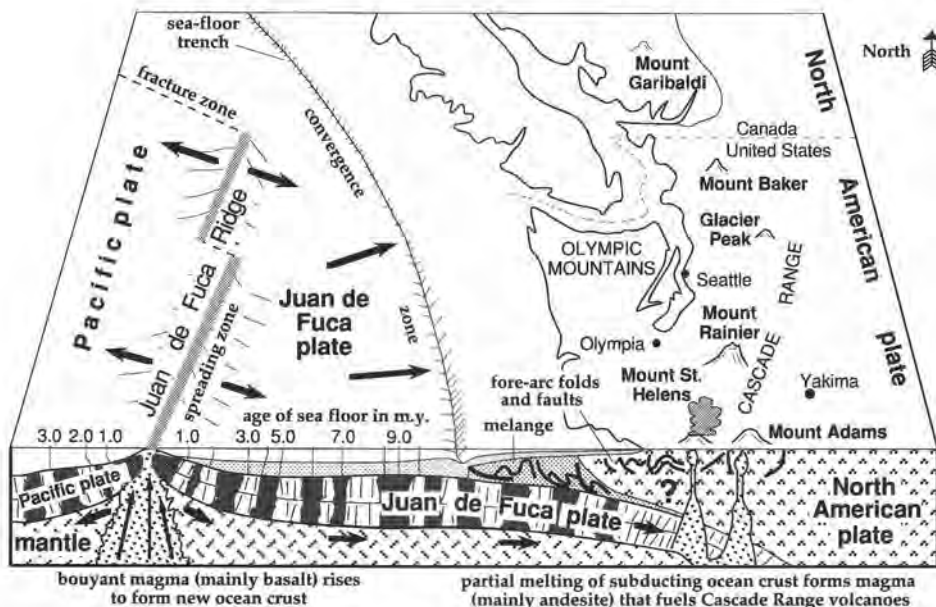


Figure 59. A diagrammatic cross section through the Juan de Fuca spreading ridge and the Cascadia subduction zone (the area from the trench east to where the Juan de Fuca plate sinks beneath the North American plate) showing the magnetic orientations of the sea floor recorded at the Juan de Fuca spreading ridge. Darker shaded areas shown 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. Melange 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) and Uyeda (1978).

change. The lava from subaerial volcanoes records magnetism in the same way. The age of the magnetized rock is determined by radiometric methods.

Although scientists do not understand why magnetic reversals take place, the dramatic movement of ocean floors, called "sea-floor spreading", could now be demonstrated by paleomagnetism. Polar wandering curves could be explained too: the mantle-ocean floor "conveyor belt" system was moving continental land masses around, changing the apparent location of the recorded ancient pole position.

Sea-floor spreading hypothesizes that ocean crust is created by upwelling magma at mid-ocean ridges like the Juan de Fuca Ridge (Fig. 59). The new crust cools and then moves away from the rift (ridge) at a rate of about an inch (several centimeters) per year. The mechanism driving the process is convection of the hot material in the Earth's mantle.

When older, cooled ocean crust (averaging 5 mi or 8 km thick) finally collides with lighter, "floating" continental crust (averaging 28 mi or 45 km thick), the ocean crust tends to sink (subduct) beneath the continental crust, carrying incor-

porated ocean sediments and water toward the mantle. *Composite volcanoes* commonly occur in regions where subduction takes place; the sinking slab of ocean-floor *basalt* and water-rich sediment melts as it sinks down into the mantle. The melted, lighter rock finds its way up through the crust along weak zones as igneous intrusions, which may fuel volcanic eruptions like those at Mount St. Helens.

The theory of sea-floor spreading gave rise to the theory of plate tectonics, which states that the Earth consists of about 10 major plates that float on the underlying mantle. The mantle acts as a conveyor belt. The conveyed oceanic crust moves the continents apart or together, slides by them, or sinks under them.

Plate tectonics solves the mystery of the youth of the ocean basins. No sea-floor material older than about 170 Ma has been found in these basins, for in that time or less the oldest ocean floor has moved across an ocean basin and been subducted under a continent.

THE ROCK CYCLE

The rock cycle is a sequence of events involving the formation, alteration, destruction, and re-formation of rocks as the result of processes such as *magmatism*, erosion, transportation, deposition, *lithification*, and metamorphism. Figure 60 diagrammatically shows changes that may occur in a rock over time in response to various geologic processes. It is easy to see that the path can be complex. Weathering and erosion can break a rock into particles and carry them away to be deposited and lithified into sedimentary rock. Or rock can be baked or squeezed to become metamorphic rock. Or totally remelted into igneous rock. Or any combination of the above!

Weathering

Weathering is any process by which rocks exposed to the atmosphere are broken down and decomposed. The two types of weathering, mechanical and chemical, work harmoniously.

Mechanical weathering comprises the physical processes that cause a rock to disintegrate, such as daily or seasonal heating and cooling, differential thermal expansion, frost action, or abrasion as rocks grind against one another.

Chemical weathering or decomposition is more complicated and includes processes in which the original rock breaks down into different chemical products. The rate of chemical weathering depends on the composition of the rock, the climate of the area, and the chemicals available. Moist climates tend to accelerate chemical weathering processes, as do volcanic *hydrothermal* systems with their corrosive fluids. The yellowish or reddish stain visible on rocks and on layers of fragmental rock in a soil is evidence of oxidation associated with chemical weathering. The weathering of geologic materials makes them more readily transportable by mechanical processes, such as erosion. Soil formation is primarily controlled by the weathering of geologic material.

Erosion and Deposition

The Cascades landscape, or any landscape for that matter, is constantly being modified by erosion and deposition. These processes, although at work everywhere, operate at different rates and with different styles depending on the local

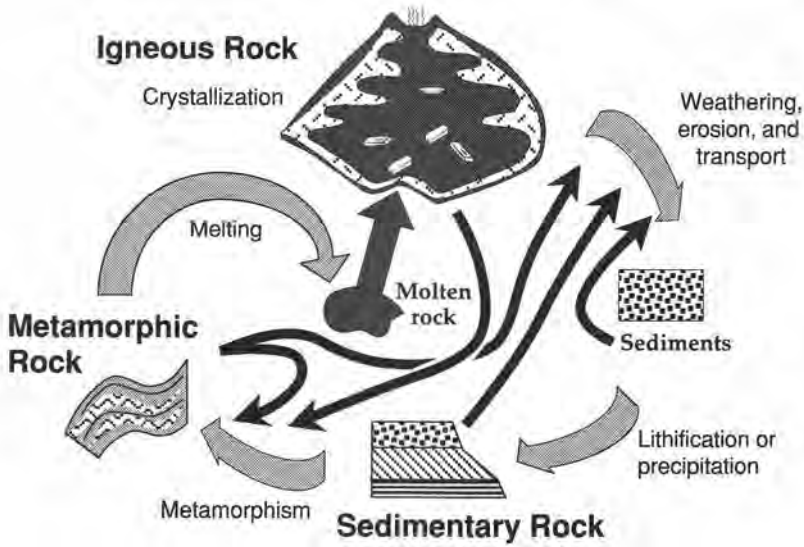


Figure 60. The rock cycle. Earth materials are continually being eroded, transported, and (or) recycled to become rock again. Redrawn from Robbins (1990).

climate and geologic material. Events that upset the equilibrium of a landscape, such as the devastating eruption of Mount St. Helens in 1980, can trigger tremendous accelerations in the rates of some natural processes. Sometimes these secondary effects, such as accelerated erosion and downstream deposition, are nearly as costly to recover from as the primary effects of an eruption.

Running water is the most significant agent of landscape change in a humid climate. Most of the precipitation that falls in the Mount St. Helens area becomes runoff, which includes sheets of water (slope wash), rills (small streams), and ultimately rivers. All forms of runoff are agents of erosion as they wear away and transport materials. They further transform the landscape by deposition of the transported debris.

River processes operate in a state of dynamic equilibrium; the interrelation of a variety of factors affects a river's form. Stream gradient or slope is the amount of drop in a given channel length. As the locations and gradients of stream channels shift through time, their overall geometry adjusts to maintain equilibrium along the entire extent of the river. The eruption of Mount St. Helens drastically upset the equilibrium of the rivers draining the area.

Pyroclastic flows and *lahars* left deposits in river valleys close to the volcano throughout their length. The *debris avalanche* filled the upper North Fork Toutle River valley with as much as 670 ft (200 m) of material, and the *blast*, *pyroclastic flows*, and *ash cloud* covered much of the area with highly erodible tephra deposits. These deposits changed the stream gradients, resulting in much erosion and incision on and near the volcano.

Rain and snowmelt carried the newly deposited sediments off slopes at high rates for about the first 3 years. Erosion, both downcutting and sidecutting, occurred at tremendous rates (Fig. 23) during the first 6 years following the eruption as running water carved into the thick debris avalanche and other deposits in the

North Fork Toutle River valley. This erosion choked rivers with sediment that was transported both in a state of suspension (*suspended load*) and as moving bed material (*bed load*). (See p. 43.)

Alternating episodes of erosion and deposition create alluvial *terraces*. These form where a stream cuts into sediments previously deposited in its valley. The complex array of terraces visible in the upper reaches of the North Fork Toutle valley attests to that river's struggle to re-establish equilibrium following the influx of sediments after eruptions.

Mass Movement

The movement of geologic materials under the influence of gravity is called *mass movement* or mass wasting. *Slump, creep, lahars* (volcanic debris flows and mudflows), *debris slides*, rockfalls, debris avalanches, and combinations of flow types are all forms of mass movement that have been particularly active in the Mount St. Helens area because of the effects of the May 18, 1980, eruption (Table 8).

Falls. Falls travel most of the distance through the air. Movement is extremely rapid and includes free fall and movement by tumbling and rolling of fragments of bedrock or soil. Rockfalls are common in Mount St. Helens crater.

Slides. Slides move by shear displacement as a unit along one or more zones of weakness, often because of the higher pore pressure of fluids with those zones. Movement along the surface may be rotational, as in a slump, or translational along a more or less planar surface. Scars from debris slides (shallow soil *slips*) commonly appear on steep slopes that have been stripped of vegetation. Numerous studies have shown that live tree roots contribute to holding the soil together and help tie the upper soil horizon to the subsoil. The 1980 tephra deposits increased runoff and surface erosion on hillslopes. This runoff and surface erosion, when combined with the decrease in tree-root tensile strength caused by

Table 8. Types of mass movement in the Mount St. Helens area. Adapted from Keller (1979)

TYPE OF MOVEMENT	TYPE OF MATERIAL		RATE OF MOVEMENT
	ROCK	SOIL	
Falls	rock falls	collapse	rapid
Slides (varied water content)	slump blocks wedge failures translational slides	slump blocks rotational slides shallow slips	varied
Flows	rock creep	soil creep	slow
	UNCONSOLIDATED MATERIALS		slow to rapid
	Saturated	Dry to mostly dry	
	plastic flows mudflows debris flows	debris avalanche	
Complex	combinations (earthflows)		

the stripping of vegetation and soil by the blast, has contributed to many shallow landslides in the devastated area.

Slumps. A slump is a type of slide where the movement is rotational, producing a rupture that is concave upward. Slumps and slump earthflows (Fig. 61) are common in the thick deposits of the 1980 debris avalanche and pyroclastic flows. Rapid incision into these deposits by streams has resulted in steep valley walls that are unstable. Clay-rich, *hydrothermally altered* zones within the debris avalanche deposit are especially vulnerable to *plastic flow* when saturated. If enough water is present, the material can "liquefy" and flow as a mudflow. During one such mudflow, which was triggered by a rainstorm in January 1990, a saturated mass of the 1980 debris-avalanche deposit flowed from the area of the Pumice Plain down along the North Fork Toutle River to its confluence with Coldwater Creek (6 mi or 10 km). When slumps and slump earthflows occur, they typically leave behind a steep scarp that is itself vulnerable to further slumping. Slumps also commonly occur in areas underlain by *till* and (or) glacial lake deposits (p. 21), both of which are vulnerable to plastic flow when they are saturated. Slumping commonly occurs in conjunction with the plastic flow of sediments underneath the slumping unit.

Flows. Flows move as if they were viscous fluids. Properties of flows vary according to their sediment concentration, amount and nature of clay minerals, and energy. Creep is a flow that moves at an almost imperceptible rate.

Complex movements. Complex movements are combinations of two or more of the five principal types of movements shown in Table 8, such as the slump earthflow.

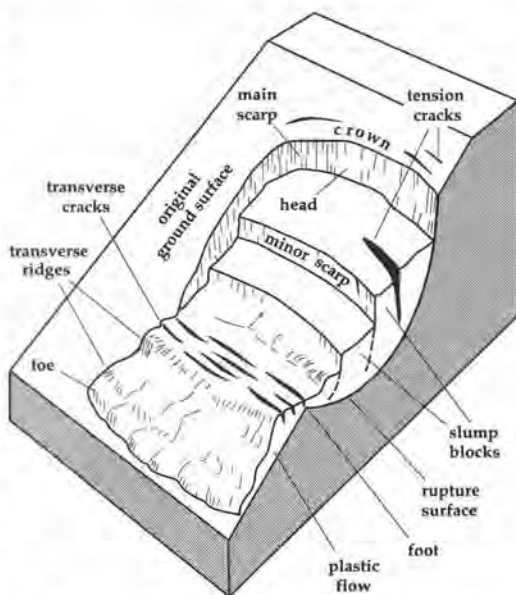


Figure 61. Sketch showing a typical slump earthflow, a complex movement involving both slump and plastic flow. Tension cracks and ridges form in response to the shape of the surface on which the flow is moving. Redrawn from Varnes (1978).

VOLCANOES AND VOLCANIC PROCESSES

A volcano is a vent in the surface of the Earth (or other planet) through which magma (molten rock, called lava when it reaches the surface) and associated gases erupt. Volcano is also the term used to describe the structure produced by the material ejected through the vent. Tephra is a general term for ejected fragmental material of any size, whereas ash is defined as ejected volcanic debris that is less than 2 mm in diameter (sand size or smaller).

There are at least five types of volcanoes near Mount St. Helens. The first, typified by Mount St. Helens, is a composite volcano (also known as a stratovolcano). Composite cones are commonly associated with subduction zones. Mount St. Helens is situated on the Circum-Pacific Rim ("Ring of Fire") where subducting ocean floor sinks beneath the edges of continents and is remelted at depth (Fig. 59). Some composite volcanoes are also found in the Mediterranean–Himalayan Belt where collisions between continental plates are occurring.

Composite volcanoes can have their own individual eruptive personalities; however, they are typically characterized by the following traits:

- Their lava has an intermediate *viscosity*, which causes it to pile up and form steep slopes around the vent and to form *domes*. The lava contains about 55 to 65 percent silica, which defines it as *andesite* and *dacite*. (See Table 6, p. 94.)
- They have a moderate to high potential for violent explosions compared to volcanoes with lavas that contain less silica. (The higher the silica content of the magma, the higher the viscosity and the potential for explosive eruptions.)
- They consist of interbedded pyroclastic debris and lava flows. The ratio is generally about 50:50, but, for example, at Mount Rainier and Mount Baker the ratio is about 10:90.
- Lava flows tend to be thick: 65 to 330 ft (20–100 m).
- They generate lahars (volcanic debris flows) and debris avalanches because of the large amount of fragmental material and their steep slopes. Lahars are caused mainly by the interaction of pyroclastic debris with snow and ice, by collapse of weakened parts of the volcano, and by erosion of fragmental debris.

Glacier Peak and Mounts Adams, St. Helens, Rainier, and Baker are Washington's modern composite volcanoes. Other types of volcanoes found in the region are *calderas*, *shield volcanoes*, *cinder cones*, and *maar volcanoes*. The nearest postglacial shield volcanoes and cinder cones can be found at the Indian Heaven volcanic field about 18 mi (30 km) southeast of Mount St. Helens. These features are generally formed by eruptions of fluid basaltic lava. The nearest maar volcano is at Battleground Lake, about 30 mi (50 km) south-southwest of Mount St. Helens. Maars are formed by explosion of shallow superheated ground water in contact with magma: in a sense, they are larger versions of the *phreatic explosion* pits. Calderas are large, roughly circular volcanic depressions whose diameter is many times larger than the volcanic vent itself. They are typically formed by eruptions in which such a large part of the magma chamber is emptied that the volcano collapses on itself. Crater Lake, in Oregon, is the nearest postglacial caldera. Nearby relics of ancient calderas are the Fives Peaks caldera east of Mount Rainier (not recognized as a caldera until 1991) and a possible caldera associated with the Spirit Lake pluton. Yellowstone (Wyoming) and Newberry (Oregon) calderas are the other Quaternary calderas in the Northwest.

Lava Flows and Domes

Viscous lava tends to pile up and form domes because it does not flow very readily. Lava that has a lower viscosity, such as Hawaiian basaltic lava, can flow for many miles. The main hazard from the more fluid lava flows is damage or total destruction by burying or burning everything in their path—and they can cover

Table 9. Types and characteristics of volcanic mass movements. Modified from Eisbacher and Clague (1984)

Type of movement		Temp. (°C)	Water content	Gas content	Clay content	Solid constituents	Relation to eruption
pyroclastic density current		>100 <850	low	high	low	pyroclastics	during
lahars	hot debris flow (noncohesive)	30-100	high	low	low	pyroclastics; crystalline volcanic rocks ¹	during
	cold debris flow (noncohesive)	<30	high	low	low	pyroclastics, crystalline volcanic rocks ¹	during or unrelated
	cold mudflow (cohesive)	<30	high	low	high	crystalline volcanic rocks; clay from hydrothermal alteration ¹	during or unrelated
rock avalanche		<30	low	low	low	crystalline volcanic rocks	during or unrelated
debris avalanche		<30	low	low	low to high	pyroclastics	during or unrelated
rockfall		<30	low	low	low	crystalline volcanic rocks	during or unrelated

¹ The solid constituents of mudflows (cohesive lahars) are mainly dust (clay and silt size), ash, and lapilli; in contrast, debris flows (noncohesive lahars) consist of both fine and coarse pyroclastic material or a mixture of such material and fragments of lava flows, domes, plugs, dikes, or sills.

very large areas. Lava flows of higher viscosity, such as the andesitic Worm Flows at Mount St. Helens, generally do not flow great distances from the volcano. Dome collapses, however, can produce hazardous pyroclastic flows and surges when the lava is still fairly hot, because of the greater tendency of their more viscous lava to fragment and turbulently interact with snow and ice.

Pyroclastic Density Currents: Flows, Surges, and Blasts

The word pyroclastic literally means "broken by fire". The general name for several different kinds of pyroclastic phenomena is *pyroclastic density currents* (Table 9). These include pyroclastic flows, surges (hot and cold), and explosive blasts (Tilling, 1989).

As the silica content of a volcano's products increases, so does the viscosity. The higher viscosity (greater resistance to flow) of magmas having a high silica content makes it more difficult for the gases driving the eruption to escape. To relieve gas pressure and move, the magma tends to blow apart to form pyroclastic flows instead of flowing cohesively as a lava flow. Typically, pyroclastic density currents have two components: a ground-hugging, basal portion (pyroclastic



Figure 62. The August 7, 1980, pyroclastic density current at Mount St. Helens, showing a convecting cloud of ash and gas. View is to the south from Coldwater Peak, about 6.5 mi (11 km) from the crater. The photo was taken about 8 minutes after the start of the eruption, about 2.5 minutes after the main flow front exited The Breach, and about 18 seconds after it flowed onto the apex of the Pumice Plain at the base of the mountain. The average velocity of the flow for this interval was about 55 mi/hr (25 m/s). Photo by Richard Hoblitt, U.S. Geological Survey.

flow) and a turbulent *pyroclastic surge* of finer particles that rides above the flow (Fig. 62).

Pyroclastic Flows

Pyroclastic flows are masses of hot (about 570°–1470°F or 300°–850°C), fairly dry pyroclastic debris (large rock fragments) and gases that move rapidly along the ground at velocities ranging from 8 to 140 mi/hr (3.5–60 m/s) (Fisher and Schmincke, 1984). Direct hazards of pyroclastic flows are incineration, asphyxiation, impact, and burial. Pyroclastic flows can also generate lahars and floods by quickly melting snow and ice. At some volcanoes, these flows have dammed tributary valleys to form lakes or have started fires. Pyroclastic flows are strongly controlled by topography and are usually restricted to valley floors. Most pyroclastic flows from composite volcanoes travel less than 15 mi (25 km) from the vent.

Pyroclastic Surges

Pyroclastic surges are hot, turbulent clouds of finer particles that ride above, and develop from, a pyroclastic flow. Surges are driven by gases and heat escaping a flow. They have a lower concentration of particles than flows and can affect larger areas. Pyroclastic surges can travel many tens of miles or kilometers from the

volcano and are not necessarily confined to the valleys. Hot pyroclastic surges can generate secondary pyroclastic flows like the one down the valley of South Cold-water Creek during the 1980 eruption. (See p. 59.) Surges are responsible for many catastrophes, including 30,000 deaths at Mount Pelée in Martinique, West Indies (1902), and 2,000 at El Chichón in Mexico (1982).

Blasts (Blast Density Flows)

Blasts or blast density flows are very powerful laterally directed explosions such as those at Mount St. Helens in 1980 and at Bezymianny, Kamchatka, in 1956. As demonstrated at Mount St. Helens, this type of explosion can affect a large area (216 mi² or 600 km²). Debris carried by the blast (the "stone wind") can flatten trees and plane off nearly everything in its path.

Lahars: Volcanic Debris Flows and Mudflows

Lahars are debris flows or mudflows, rapidly flowing mixtures of rock debris and water that originate on the slopes of a volcano. They can be cold or carry hot pyroclastic material. Lahars are one of the greatest hazards at composite volcanoes because they can travel great distances from the volcano, placing people living in valleys draining the volcano at risk.

Composite volcanoes have all the necessary ingredients for lahars. Their average silica composition (andesite-dacite range) yields a moderately explosive magma of relatively high viscosity that produces a significant amount of fragmental debris. The resulting steep-sided volcanic pile is extremely vulnerable to slope failures and collapse, especially where rocks have been weakened by hydrothermal activity. In hydrothermal action, a combination of heat and acids and salts in solution alters volcanic deposits to clay minerals. Clay minerals act as a lubricant and lower the stability of the volcano's slopes. Volcanoes at which hydrothermal alteration occurs are typically those with large amounts of snowpack and glacial ice, a source of water ready to be melted during an eruption.

The driving force in a lahar is gravity. In a normal river flood, the water is carrying individual rock particles along. In a lahar, the particles are so concentrated that they flow downslope en masse carrying the water. Lahars are restricted to stream valleys, although some lahars that have very large volumes can pass over topographic barriers under rare circumstances.

Noncohesive Lahars

Lahars with a low clay content (less than 4 percent) typically begin as a flood surge that incorporates enough sediment to become a debris flow. They can transform downstream to more diluted flow types such as *lahar-runout* flows and floods. These flows are sometimes called noncohesive lahars. The South Fork Toutle and Muddy River lahars of 1980 (Fig. 63) were formed when hot pyroclastic material melted snow and ice. The causes of noncohesive lahars can include:

- Interaction of a pyroclastic density current with snow and ice
- Severe rainstorms and (or) rapid snowmelt that causes erosion of tephra (or other fragmental debris) or landslides from the slopes of a volcano
- Flood caused by failure of a landslide-dammed lake on a volcano's flank
- Glacial *outburst flood* (jökulhlaup) on a volcano's flank



Figure 63. Coatings of mud, sand, and fine gravel left on tree trunks and rocks by the May 18, 1980, Muddy River lahar show its depth (about 40 ft or 12 m). Person on the bank (arrow) for scale. Arrow also shows direction of flow. Photo taken in 1980 by Lyn Topinka, U.S. Geological Survey.

Cohesive Lahars

Lahars rich in clay-sized particles (more than 4 percent) are sometimes called mudflows or cohesive lahars. *Cohesive lahars* can originate when an entire sector or sizeable mass of a volcano collapses or slides away. This might be triggered by regional or *volcanic earthquakes*, steam explosions, or by means other than eruptions. Cohesive lahars can have huge volumes and flow great distances without undergoing significant dilution. The Electron and Osceola Mudflows at Mount Rainier and the Middle Fork Nooksack flow at Mount Baker are examples of fairly clay-rich lahars. The Osceola Mudflow had a volume of at least 0.6 mi^3 (3 km^3) and flowed more than 60 mi (100 km) from Mount Rainier. An ancient cohesive lahar from Mount Hood crossed the Columbia River. The 1980 North Fork Toutle mudflow was a cohesive lahar. (See p. 30.)

GLACIERS AND GLACIAL DEPOSITS

A glacier is a large mass of ice that moves slowly downslope and spreads (where not constrained) under the force of its own weight. Glaciers are formed by the compaction and recrystallization of snow (Fig. 64). When an ice mass develops enough depth and weight, it deforms (becomes plastic) and can begin to move. Two signs of glacier movement are *crevasses* and *rock flour*. A crevasse is a deep fissure or crack in the ice caused by the glacier's movement over an uneven surface.

GEOLOGIC STRUCTURES IN THE MOUNT ST. HELENS AREA

About 18 million years ago, localized compression of the Earth's crust began to fold and fault the rocks of the Cascades. That process may still be going on today.

Folds

Folds are curves or bends in the rock strata. Folds that arch upward in the middle are called *anticlines* and those that are bowed downward, *synclines* (Fig. 65). While driving through the Mount St. Helens National Monument and adjacent areas, you will pass along or across the axes of several broad anticlines and synclines. West of Mount St. Helens these structures trend northwest, whereas east of the volcano they trend nearly north. The Lakeview Peak anticline, west of Mount St. Helens, plunges downward at both its northwest and southeast ends, giving the anticline a sort of whaleback look. This configuration suggests a minor component of crustal compression has, at some time, been parallel with the fold as well as perpendicular to it.

Faults

Faults are fractures in rock along which movement has occurred (Fig. 66). They are the result of brittle failure of rock. No major faults are visible in outcrop within the monument. However, offsets along small faults can be seen in several roadside outcrops and in the back country. (See mile 25.0, p. 45.) Generally, these have displacements of only a few meters at most. Smoothly polished and grooved surfaces called *slickensides* are visible in some zones of faulting.

Normal fault. A *normal fault* is a steeply dipping fault in which the hanging wall has moved downward relative to the footwall. The dip of the fault plane is usually between 45° and 90° .

Reverse fault. A *reverse fault* is a steeply dipping fault in which the hanging wall appears to have moved upward relative to the footwall. The dip is usually greater than 90° .

Thrust fault. A *thrust fault* is a low-angle fault (less than 45°),

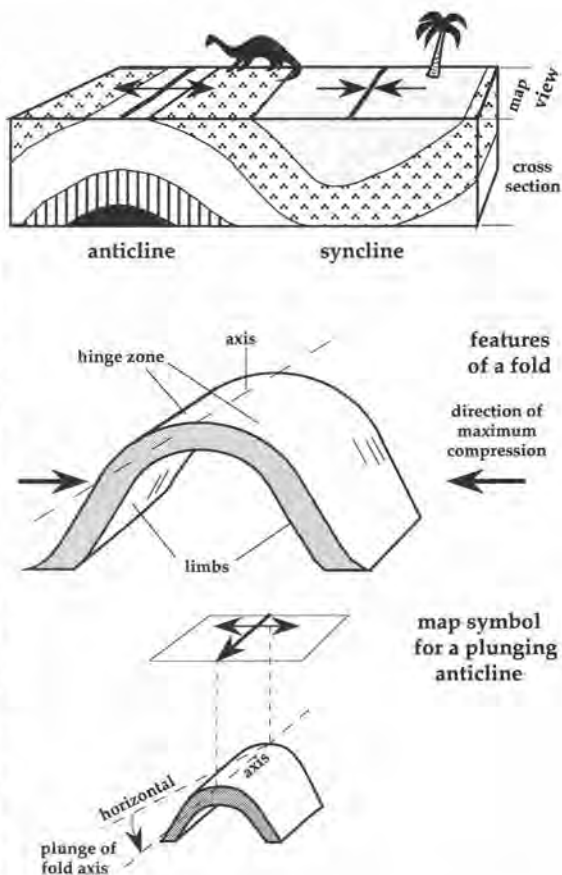


Figure 65. Sketch showing the features of synclines and anticlines and the map symbols for each.

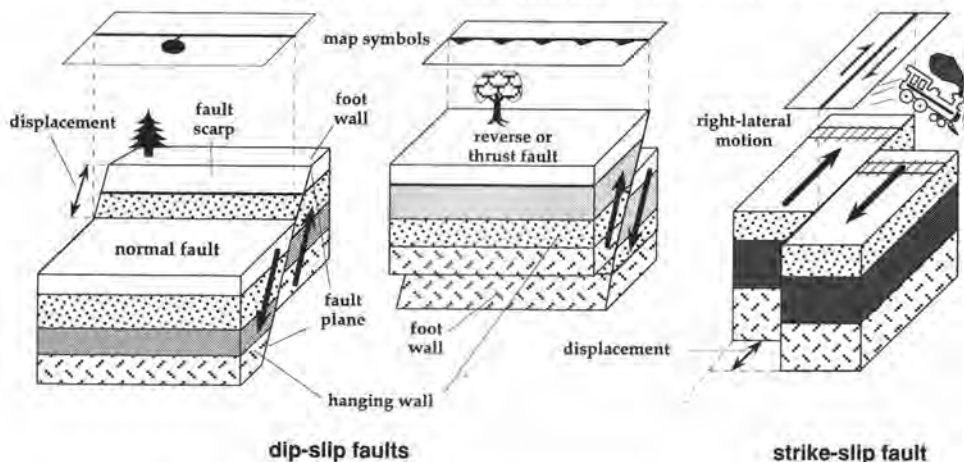


Figure 66. Types of faults in the Mount St. Helens area.

typically caused by horizontal compression, in which the hanging wall has moved upward relative to the footwall. Small thrust faults in the crater floor were used in the early 1980s to monitor the deformation that preceded extrusion of lava from the dome. (See Fig. 20 and discussion on p. 33.) Slickensides on lava dome rocks indicate that similar brittle failure takes place within, or immediately under the dome.

Strike-slip fault. A *strike-slip fault* is a fault in which displacement occurred parallel to the strike of the fault plane, that is, sideways instead of up and down.

Fault Zones

The Chelatchie Prairie fault zone is an east-northeast-trending *normal fault* system a few kilometers south of, and generally parallel to the Lewis River. Tumtum Mountain is situated on this fault zone. Rocks north of faults in the zone have dropped downward with respect to the rocks on the south side. Geologists have not noted any recent activity on this fault zone.

The *St. Helens zone* is a north-northwest-trending zone of active seismicity that extends for about 80 mi (130 km) and passes through Mount St. Helens. (See the various road-guide maps.) This seismic zone is apparently a series of strike-slip faults that are related to the collision between the North American plate and the Juan de Fuca plate. The St. Helens zone and nearby faults create a zone of weakness in the crust that probably controls the location of the vent that feeds Mount St. Helens as well as the vents of the Marble Mountain–Trout Creek Hill volcanic zone to the south.

A strong (*magnitude* 5.1) earthquake occurred along the St. Helens zone in 1981. The epicenter was near Elk Lake, about 10 mi (15 km) north-northwest of the Mount St. Helens crater. Seismologists have estimated that this fault zone could generate an earthquake as large as magnitude 6.2 to 6.8—depending on the length of the fault segment that ruptured.

PART IV: REFERENCES, GLOSSARY, AND UPDATE

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GLOSSARY

ablation – the loss of snow and ice from a glacier due to melting, erosion, evaporation, or sublimation.

accretion – that process by which one terrane, a fault-bounded body of rock of regional size, is attached to another having a different history. Typically accretion occurs during tectonic collision.

accretionary lapilli – a mass of cemented ash 1-10 mm in size.

alluvium – a general term for stream deposits.

amphibole – a group of dark, rock-forming ferromagnesian silicate minerals; for example, hornblende.

andesite – a fine-grained extrusive igneous rock generally containing abundant plagioclase, lesser amounts of hornblende and biotite, little or no quartz; 54 to 62 percent silica.

anticline – a convex-upward fold having stratigraphically older rocks in its core.

ash – see *volcanic ash*.

ash cloud – an eruption cloud of volcanic gas and fine particles.

basalt – a fine-grained volcanic rock, typically dark, that contains 45 to 54 percent silica.

bed load – sediment, such as cobbles, pebbles, and granules, that is transported along the bed of a river but is not in suspension.

biotite – “black mica”; a common mafic mineral.

blast – the enormous volcanic explosion and pyroclastic density current on May 18, 1980.

blast dacite – the bluish-gray to gray rocks, chilled pieces of the cryptodome, that were erupted in the blast on May 18, 1980.

blast density flow – see *blast*.

blast zone – see *devastated area*.

breadcrust bombs – volcanic bombs that have a breadcrust-like (open cracks) texture on their outer surface caused by contraction during sudden cooling.

breccia – a rock composed of coarse, angular fragments in a matrix of finer particles.

calcite – a common mineral composed of calcium carbonate (CaCO_3).

caldera – a large, typically steep-sided, volcanic basin produced by collapse of an underlying magma chamber.

cinder cone – a fairly small, cone-shaped volcanic vent consisting mainly of accumulated cinders and other pyroclastic fragments.

cirque – a glacially carved, horseshoe-shaped hollow at the head of a valley.

clast – general term for any fragment or individual piece of rock.

coal – a black, combustible sedimentary rock formed by compaction of plant matter.

cohesive lahar – a volcanic debris flow or mudflow that contains more than 4 percent clay minerals in its matrix.

composite volcano – a steep-sided volcano consisting of alternating layers of lava and pyroclastic debris. A stratovolcano.

conglomerate – a coarse-grained sedimentary rock consisting of rounded rocks cemented together in a finer matrix.

contact metamorphism – a type of recrystallization or change in rocks that takes place adjacent to a magma body; also known as “thermal metamorphism”.

creep – slow downhill movement of surficial materials (such as soil).

crevasse – a deep fissure in the surface of a glacier.

cross dating – a method of matching tree rings that uses the known patterns or characteristics of tree rings in an area to precisely date wood or trees such as those buried in volcanic deposits or injured by volcanic activity.

cryptodome – the near-surface intrusion of magma that produced the pre-May 18, 1980, bulge in the north flank of Mount St. Helens.

dacite – a fine-grained extrusive igneous rock typically having 62 to 69 percent silica.

debris avalanche – a granular flow of unsorted rock debris that typically moves at high velocity.

debris flow – a moving mass of debris, typically saturated.

debris slide – a shallow mass movement of the soil layer or other geologic material.

dendrochronology – the scientific study of tree rings.

devastated area – the area of downed and singed vegetation created by the volcanic events at Mount St. Helens on May 18, 1980.

dike – a tabular intrusive rock body that forms where magma cuts across the bedding planes of other rock bodies.

diorite – a coarse-grained intrusive igneous rock having roughly the same chemical composition as andesite (54 to 62 percent silica).

discharge – the rate of stream flow at a given time in units of volume per unit of time (ft^3/s or m^3/s).

dome – see *volcanic dome*.

drift – a general term for any glacial deposit.

earthflow – a type of mass movement that typically takes place along well-defined failure planes and may involve more than one failure process, such as slumping and plastic flow.

faceted spur – the end of a ridge that has been ground down by the action of ice or water.

fault – a fracture along which a rock mass has been displaced.

feldspar – a common rock-forming mineral group consisting of silicates of aluminum, sodium, potassium, and calcium.

ferromagnesian minerals – silicate minerals such as olivine, pyroxenes, and amphiboles, that contain considerable amounts of iron and magnesium.

firn – a material that is transitional between snow and glacier ice.

fission-track dating – a method of determining the age of a rock based on the number of tracks

recording emission of subatomic particles during radioactive deterioration.

flood basalt – plateau basalt; the lava produced by enormous fissure eruptions, such as the Columbia River basalt flows.

flow breccia – a deposit of angular rock fragments, some of which are welded together, that is produced in association with a lava flow.

fold – a bend in a rock stratum or layer.

fumarole – a volcanic vent that emits gases.

gabbro – a coarse-grained intrusive igneous rock consisting mainly of calcium-bearing plagioclase and pyroxene minerals and having roughly the same chemical composition as basalt (45 to 54 percent silica).

glacier – a mass of ice, mainly recrystallized snow, that is heavy enough to move under its own weight.

granite – a coarse-grained intrusive igneous rock composed of potassium feldspar, plagioclase, quartz, and some mafic minerals; more than 69 percent silica.

granodiorite – a coarse-grained intrusive rock, similar to a granite, in which plagioclase minerals are more common than potassium feldspar; 62 to 69 percent silica.

groundmass – the fine-grained matrix of a porphyritic igneous rock.

half-life – the time required for half of the atoms in a sample of a radioactive isotope to decay.

heavy mineral – slang for ferromagnesian or mafic minerals.

hornblende – a mafic mineral of the amphibole group.

hornfels – a fine-grained metamorphic rock formed by recrystallization.

hydrothermal activity – the migration of hot, typically mineral-rich fluids produced by magma or by reactions of magma with adjacent rocks and (or) ground water.

hydrothermal alteration – the alteration of rocks or minerals owing to contact with hydrothermal waters.

igneous rock – a rock formed by the cooling of magma.

intrusive rock – an igneous rock that solidifies under the surface of the Earth.

isotope – one of two or more forms of an element having different atomic weights.

joint – a fracture in a rock along which movement has not occurred.

juvenile material – volcanic rocks derived directly from magma that has reached the surface.

K-Ar dating – see *Potassium-Argon dating*.

lahar – general term for a volcanic debris flow, a moving mixture of pyroclastic material and water that originates at a volcano.

lahar runoff – the muddy flood caused by dilution of a lahar as it mixes with streamwater. The deposits are typically very sandy and have fewer large rocks than lahar deposits.

lapilli – volcanic particles in the range of 2 to 64 mm.

lateral blast – see *blast*.

lateral moraine – an accumulation of till along the sides of a glacier where it meets the valley wall.

lava – magma that reaches the Earth's surface.

levee – an area of deposits marginal to a flow that roughly records the maximum height of the flow.

lithic pyroclastic flow – a pyroclastic flow that contains a significant percentage of previously formed rock fragments mixed in with the juvenile rocks.

lithification – the process by which sediment is converted into solid rock.

mafic rock – a rock that contains more than 50 percent ferromagnesian minerals.

magma – molten rock; can contain liquids, gases, and crystals.

magmatism – the formation and movement of magma.

magnitude – a scale for measuring the energy released by an earthquake.

mass movement – the movement of geologic materials downslope under the influence of gravity.

mass wasting – see *mass movement*.

metamorphic rock – a rock whose composition and (or) texture has changed because of heat and (or) pressure.

mineral – a naturally formed solid chemical substance having a fixed crystal structure and range of chemical compositions.

moraine – a landform composed of till or drift.

mudline – the maximum level of inundation by a lahar or flood based on the height of mudmarks on trees or rocks. See Fig. 63.

normal fault – a steeply dipping fault in which the hanging wall has moved downward relative to the footwall. See Fig. 66.

outburst floods – jökulhlaups; sudden releases of water stored in or adjacent to a glacier or in a glacial lake.

outcrop – an exposure of rock or a deposit.

outwash – stratified deposits produced by glacial meltwater.

pahoehoe – [pä.hoy'.hoy] a Hawaiian term for basaltic lava flows having a smooth or ropy surface.

phenocryst – a large individual crystal in a porphyritic igneous rock.

phreatic explosion or eruption – an explosive mixture of steam and fine rock debris produced when water contacts hot rock.

plastic flow – change in shape of a solid that takes place without rupture.

Plinian column – a strong, turbulent, and sustained vertical eruption column.

pluton – the cooled body of a large intrusive igneous rock mass.

porphyritic – a texture of igneous rock in which coarse mineral crystals are scattered among finer grains and (or) glass.

porphyry copper deposit – a type of hydrothermal mineral deposit associated with plutons that contains associated copper minerals.

potassium-argon dating – the radiometric determination of the age of a rock sample based on the ratio of argon-40 to potassium-40.

proglacial – immediately in front of or just beyond the limits of the glacier.

pumice – solidified rock froth; a porous volcanic rock that floats.

pyroclastic density current – a general name for any of the mixtures of volcanic gas and particles (including surges and flows) that move downslope on the flanks of a volcano under the influence of gravity. See Table 9.

pyroclastic flow – a mass of hot, dry, pyroclastic debris and gases that move rapidly along the ground surface. They can be caused by an eruption or collapse of a dome.

pyroclastic surge – a turbulent, mixture of gases and particles that flows above the ground surface at high velocities. It can develop from a pyroclastic flow and is highly mobile.

pyroxene – a group of mafic silicate minerals.

Quaternary – the geologic period lasting from about 1.7 Ma to the present. It consists of the Pleistocene Epoch (ending about 10 ka) and the Holocene (10 ka to present).

radiocarbon dating – the calculation of the age of geologic material by any of the methods based on nuclear decay of natural radioactive elements in carbonaceous material.

radiocarbon years – years before 1950 (by convention) based on the proportion of the ^{14}C isotope to normal carbon atoms. Typically radiocarbon years differ from "calendar years" because of variations of the carbon isotope content of atmospheric carbon dioxide through time. A calibration to adjust these ages on the

basis of tree rings (for about the last 8,000 years) has been devised; however, for simplicity, only the raw radiocarbon ages are presented in this guidebook. For the most part, these ages do not differ radically from actual calendar years. Tree-ring dates for Mount St. Helens deposits laid down since A.D. 1480, however, are given in calendar years.

radiometric age – see radiometric dating.

radiometric dating – a method of estimating the age of a rock or mineral by measuring the proportion of radioactive elements to their decay products in a rock sample.

raveling – erosion involving the movement of individual rocks and grains down a slope.

rock flour – fine rock particles produced by glacial pulverization.

roofless explosion crater – small, shallow craters produced by phreatic explosions.

St. Helens zone – a linear zone of earthquake activity that extends from north of Mount St. Helens through the volcano almost to the Columbia River.

scoria – an igneous rock containing abundant cavities (vesicles) but which does not float.

shield volcano – a large, broad volcano having fairly shallow slopes formed by the eruption of highly fluid basalt lava.

sill – a tabular intrusive rock body that forms where magma is injected between two layers of rock.

singe zone – the zone at the periphery of the devastated area in which trees were scorched or damaged but not blown down.

slickensides – striated or polished surface of a rock produced by abrasion along a fault.

slips – debris slides.

slosh line – see *trimline*.

slump – a type of mass wasting in which blocks of material fail with a backward rotational motion.

snag – the trunk of a dead tree.

stratigraphy – the study of strata, its succession and composition, fossils and other characteristics.

striation – a scratch or groove on a rock produced by the passage of a glacier or other geologic agent.

strike – the bearing or azimuth along which a fault or fold or other planar feature is oriented.

strike-slip fault – a fault in which displacement has been parallel to the strike of the fault. See Fig. 66.

suspended load – fine sediment carried in suspension by a river.

syncline – a fold that is concave upward, like a trough.

talus – rock debris, typically coarse, that accumulates at the base of a cliff or slope.

tarn – a small mountain lake that occupies a cirque.

tephra – a general term for all sizes of rock and lava that are ejected into the air during an eruption.

terrace – a long, narrow, nearly flat surface that forms a step-like bench in a slope.

terrane – a large block of the Earth's crust, bounded by faults, that can be distinguished from other blocks by its geologic character.

Tertiary – the geologic period lasting from about 67 Ma to 1.7 Ma.

thrust fault – low-angle fault (less than 45°) in which the hanging wall has moved upward relative to the footwall; typically caused by horizontal compression.

till – an unsorted glacial deposit produced directly under, within, or on top of a glacier.

transform fault – strike-slip faults that separate major geologic plates or plate segments.

trimline – boundary between the area affected by scour or scrape and undisturbed terrain that denotes the maximum height of runoff or inundation by an avalanche, debris flow, flood, wave, or glacier.

tuff – a fine-grained rock composed mostly of volcanic ash.

valley glacier – a glacier that heads at a cirque or cirques and then flows into, and is confined by, a valley; an alpine glacier.

viscosity – resistance to internal flow.

volcanic arc – a curved belt of volcanoes and volcanic rocks associated with a subduction zone.

volcanic ash – fine-grained pyroclastic particles (less than 2 mm in diameter).

volcanic dome – a steep-sided bulbous mass of lava, such as the Lava Dome, that is commonly formed by eruptions of highly viscous dacite or rhyolite lava.

volcanic earthquakes – the sudden release of strain energy under or in a volcano as magma or volcanic gas pushes its way to the surface.

volcaniclastics – a general name for all fragmental material produced by a volcano.

vug – a cavity in a vein or rock. Some vugs are lined with crystals. ■

UPDATE 1993-2001

Since the second printing of this book (1993), the Spirit Lake Highway (SR 504) has been completed to the new Johnston Ridge Observatory (JRO). Along SR 504 several other new facilities are available for visitors and new hiking trails have opened, such as the Hummocks Trail and Winds of Change Trail. These trails allow the visitor to observe the deposits and effects of the 1980 eruption and to witness the ecosystem recovery and post-disturbance landscape adjustments.

This update describes or lists: post-1993 road changes and new trails, volcanic and geomorphic activity at the volcano since 1993, a growing glacier in the crater, results of selected new geological research at the mountain, as well as citations and books that may help visitors, new references and further reading, selected internet resources.

Road Changes and New Trails

SR 504 now extends 8 mi (13 km) past Coldwater Creek to the top of Johnston Ridge and the spectacular Johnston Ridge Observatory (JRO). JRO hosts interpretive programs and exhibits and an unparalleled view of Mount St. Helens, the effects of the 1980 and subsequent eruptions, and ecosystem recovery (Fig. 34, p. 57). Along the new Hummocks Trail (p. 52), visitors can hike among the gigantic chunks of the debris avalanche, the world's largest historic landslide deposit. Those who revisit the Hummocks Trail periodically will see geomorphic changes, such as slumping and erosion of the debris avalanche, and channel changes of the North Fork Toutle River. The hummocks and the ponds among them are also of interest because of the nature of the vegetation and ecosystem recovery taking place there.

Volcanic and Geomorphic Activity Since 1993

Mild background seismic activity has continued since 1993, with noteworthy episodes of increased activity in the spring and summer of 1998 and the fall of 2001. The level of earthquake activity at Mount St. Helens had been gradually increasing in early 1998 and accelerated during May, June, and early July 1998. Rates of activity increased from an average of about 60 well-located events per month in January 1998 to 318 in June and 445 in July. Most of these earthquakes were very small, with only three events exceeding magnitude 2. The largest earthquake was on 1 May, at magnitude 2.2. These earthquakes occurred in two clusters directly beneath the lava dome in the crater. One cluster was at 1.2 to 3.1 mi (2-5 km) depth and the other 4.4 to 5.6 mi (7-9 km) below the dome. Airborne surveys of volcanic gases have revealed the discharge of magmatic carbon dioxide at a rate of about 2000 tons/day. Under high pressure deep within Earth's crust, carbon dioxide is dissolved in magma.

The 1998 seismic activity seems to be similar to that which occurred in 1995, although the activity of May 1998 was more energetic. The 1995 activity lasted for several months, had a maximum earthquake rate of 95 events per month, and resulted in no volcanic activity. Earthquakes returned to background levels by August 1998. A similar increase in earthquake activity in the St. Helens system occurred from 1989 to 1991. However, at that time there were also a number of very



Figure 67. Aerial-oblique photograph of the Lava Dome and growing glacier in the Mount St. Helens crater. View is to the southwest. Note the crevasses visible on the far right side of the photograph. This snow, ice, and rock glacier is now more than 500 ft (~150 m) thick, which is more than half the height of the 876-ft-tall (267 m) Lava Dome. Photo courtesy of Jon Major (USGS), 2001.

shallow earthquakes accompanied by a series of sudden steam explosions. These explosions ejected rocks and ash from cracks in the dome. Rocks were thrown as far as 0.6 mi (1 km) from the dome, ash clouds reached altitudes of 3.7 mi (6 km), and a dusting of ash was deposited locally downwind. By the end of 1998, earthquake activity had subsided to background levels of less than five events per day, but future earthquake episodes could lead to steam emissions or another eruption of the volcano.

A Growing Glacier in the Crater

In the 1993 edition of this book, I mentioned that a small glacier was growing in the crater south of the Lava Dome (Fig. 15). That body of rock, ice, and snow has continued to grow throughout the 1990s and is now more than 500 ft (~150 m) thick (Fig. 67) and has a volume greater than 100 million yds³ (76 million m³) (Hill, 2001; Schilling and others, 2002). Mills and Keating (1992) suggested that rock debris made up a significant fraction of the material accumulating on the crater floor. U.S. Geological Survey scientists estimate that rock may account for about one-third of the volume of the new glacier. The new glacier is a source of perennial water that will contribute to the ground water in the volcano and also be available for incorporation into future lahars.

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Selected Internet Resources (as of April 2002)

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| Cascade Volcano Observatory | http://vulcan.wr.usgs.gov/ |
| DNR Division of Geology and Earth Resources | http://www.wa.gov/dnr/htdocs/ger/ |
| Mount St. Helens National Volcanic Monument | http://www.fs.fed.us/gpni/mshnvm/ |
| Mount St. Helens Institute | http://www.mshinstitute.org/ |
| Mount St. Helens seismicity | http://spike.geophys.washington.edu/SEIS/PNSN/HELENS/ |



First walk on the Mount St. Helens crater rim after the 1980 eruption. The crater rim can now be reached by several popular climbing routes (Beckey, 1987; Phillips, 1987). Climber is the late Dick Janda, to whom this book is dedicated. Photo taken in the fall of 1983 by Barry Voight, Pennsylvania State University.



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