Cenozoic Volcanism in the Cascade Range and Columbia Plateau, Southern Washington and Northernmost Oregon

Seattle, Washington to Portland, Oregon
July 3–8, 1989

Field Trip Guidebook T106

Leader: *Donald A. Swanson*

Associate Leaders:
Joseph A. Vance *Geoffrey A. Clayton* *Russell C. Evarts*

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COVER Mount St. Helens from Harry's Ridge, showing 1980 crater, dome, north flank, and pumice plain. Dome is 750 m wide. Photo by Lyn Topinka on May 20, 1988. Optional hiking trip to crater starts on pumice plain at left side of photo, traverses west, climbs to crater along west side of deep canyon, and leaves east part of crater before traversing east to vehicles.

Leader:

Donald A. Swanson
U.S. Geological Survey
Cascades Volcano Observatory
5400 MacArthur Blvd.
Vancouver, WA 98661

Associate Leaders:

Joseph A. Vance and Geoffrey A. Clayton
Department of Geological Sciences, AJ-20
University of Washington
Seattle, WA 98195

Russell C. Evarts
U.S. Geological Survey, MS 901
345 Middlefield Road
Menlo Park, CA 94025

IGC FIELD TRIP T106: CENOZOIC VOLCANISM IN THE CASCADE RANGE AND COLUMBIA PLATEAU, SOUTHERN WASHINGTON AND NORTHERNMOST OREGON

Donald A. Swanson[1], Kenneth A. Cameron[1], Russell C. Evarts[2], Patrick T. Pringle[1], and Joseph A. Vance[3]

INTRODUCTION

This guidebook is for a six-day excursion between Issaquah, Washington (east of Seattle), and Portland, Oregon, that emphasizes the Tertiary and Quaternary volcanic geology of the western Columbia Plateau and the Cascade Range of southern Washington and northern Oregon (Figures 1 and 2). The guidebook summarizes the geology of selected areas along the route and provides a brief introduction to the general volcanic history of the Columbia River Basalt Group and the southern Washington Cascades. An extensive but not exhaustive bibliography accompanies the guidebook. The road logs are designed to be self-guiding; as such, they are more complete than necessary for guided bus excursions.

TECTONIC AND GEOPHYSICAL SETTING OF THE CASCADE RANGE IN SOUTHERN WASHINGTON

The Cascade Range has been an active arc for about 36 m.y. as a result of plate convergence [*Atwater*, 1970]. Volcanic rocks between 55 and 42 Ma occur in the Cascades [*Vance et al*, 1987] but are probably related to a rather diffuse volcanic episode that created the Challis arc extending southeastward from northern Washington to northwest Wyoming [*Armstrong*, 1978; *Vance*, 1979]. Convergence between the North American and Juan de Fuca plates continues at about 4 cm/yr in the direction of N50°E, a slowing of 2-3 cm/yr since 7 Ma [*Riddihough*, 1984]. According to most interpretations, volcanism in the Cascades has been discontinuous in time and space [*McBirney*, 1978; *Luedke and Smith*, 1982; *Guffanti and Weaver*, 1988], with the most recent episode of activity beginning about 5 Ma and resulting in more than 3000 vents [*Guffanti and Weaver*, 1988]. In Oregon, the young terrane is commonly called the High Cascades and the old terrane the Western Cascades, terms that reflect present physiography and geography. The terms are not useful in Washington, where young vents are scattered across the dominantly middle Miocene and older terrane.

Oligocene and Miocene rocks in the southern Washington Cascades and adjacent western Washington and Oregon are tectonically rotated in a clockwise sense according to paleomagnetic data [*Simpson and Cox*, 1977; *Beck and Burr*, 1979; *Bates et al.*, 1981; *Wells and Coe*, 1985]. The amount of rotation in general increases with increasing age. Rocks probably about 30-35 Ma in the southern Washington Cascades are rotated about 34° [*Bates et al.*, 1981], whereas the 12-Ma Pomona Member of the Saddle Mountains Basalt is rotated only 8-10° at the western end of the Columbia Gorge [*Wells and England*, in press; *Wells et al.*, in press]. Middle Eocene rocks in the Oregon Coast Range are rotated from 20° to as much as 65° [*Wells and Coe*, 1985], and Eocene rocks in central Oregon (Clarno Formation), more than 300 km inboard of the continental margin, an average of 16° [*Grommé et al.*, 1986]. In some models, the rotation pattern implies that the Paleogene trend of the Cascades was northwestward rather than northward as at present [*Magill et al.*, 1981]. In other models, the rotation is confined to domains tens of meters to as much as 30 km across and is related to shear along dextral northwest-trending faults or Riedel shears rather than to wholesale regional block rotation of microplates [*Beck*, 1980; *Wells and Coe*, 1985]. The continuum model of *Wells and England* [in press] suggests that the average rate of rotational shear is about 1.3° per million years near the southwest margin of the southern Washington Cascades. The origin of the rotations remains unresolved, but appropriate strike-slip faults in the region make the dextral-shear model attractive. No evidence for significant rotation younger than 12 Ma has been recognized, owing in large measure to the paucity of upper Miocene rocks in southern Washington and northern Oregon.

In Washington and Oregon, a striking contrast has existed for the past 5 m.y. in the style of volcanism in the Cascades relative to geography [*Weaver and Malone*, 1987; *Guffanti and Weaver*, 1988]. North of Mount Rainier, young volcanism is concentrated in only a few isolated andesitic and dacitic composite cones (notably Glacier Peak, Mount Baker, and the volcanoes of the Garibaldi belt in British Columbia), whereas south of Mount Hood moderate-sized andesitic and dacitic composite cones are relatively unimportant features of a landscape dominated by small andesite and basalt vents (Figure 1) [*Guffanti and Weaver*, 1988]. The area between Mounts Rainier and Hood is transitional; large andesite and dacite composite cones (Rainier, Adams, St.

[1]U.S. Geological Survey, Cascades Volcano Observatory, Vancouver, Washington.

[2]U.S. Geological Survey, Menlo Park, California.

[3]Department of Geological Sciences, University of Washington, Seattle, Washington.

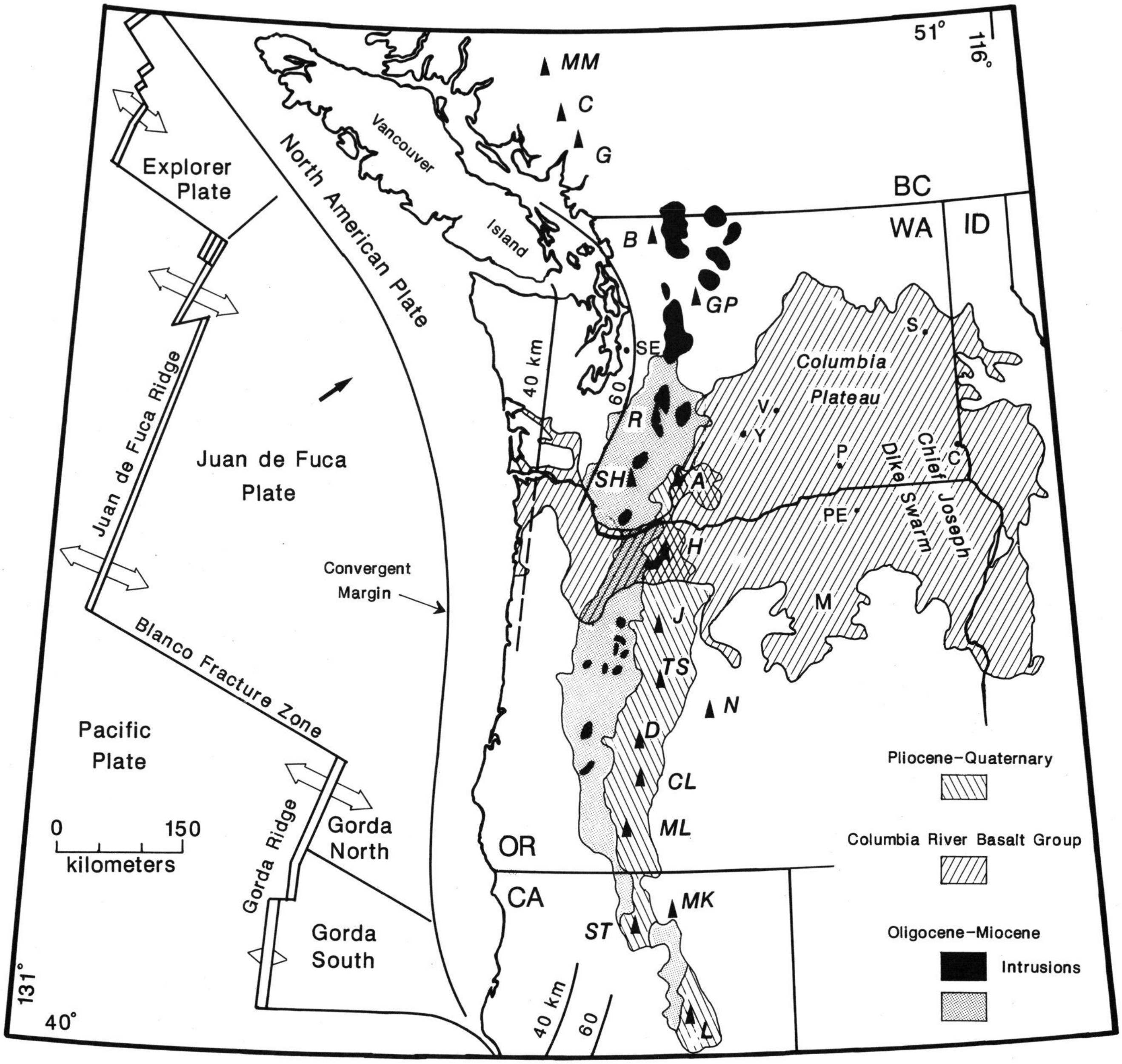
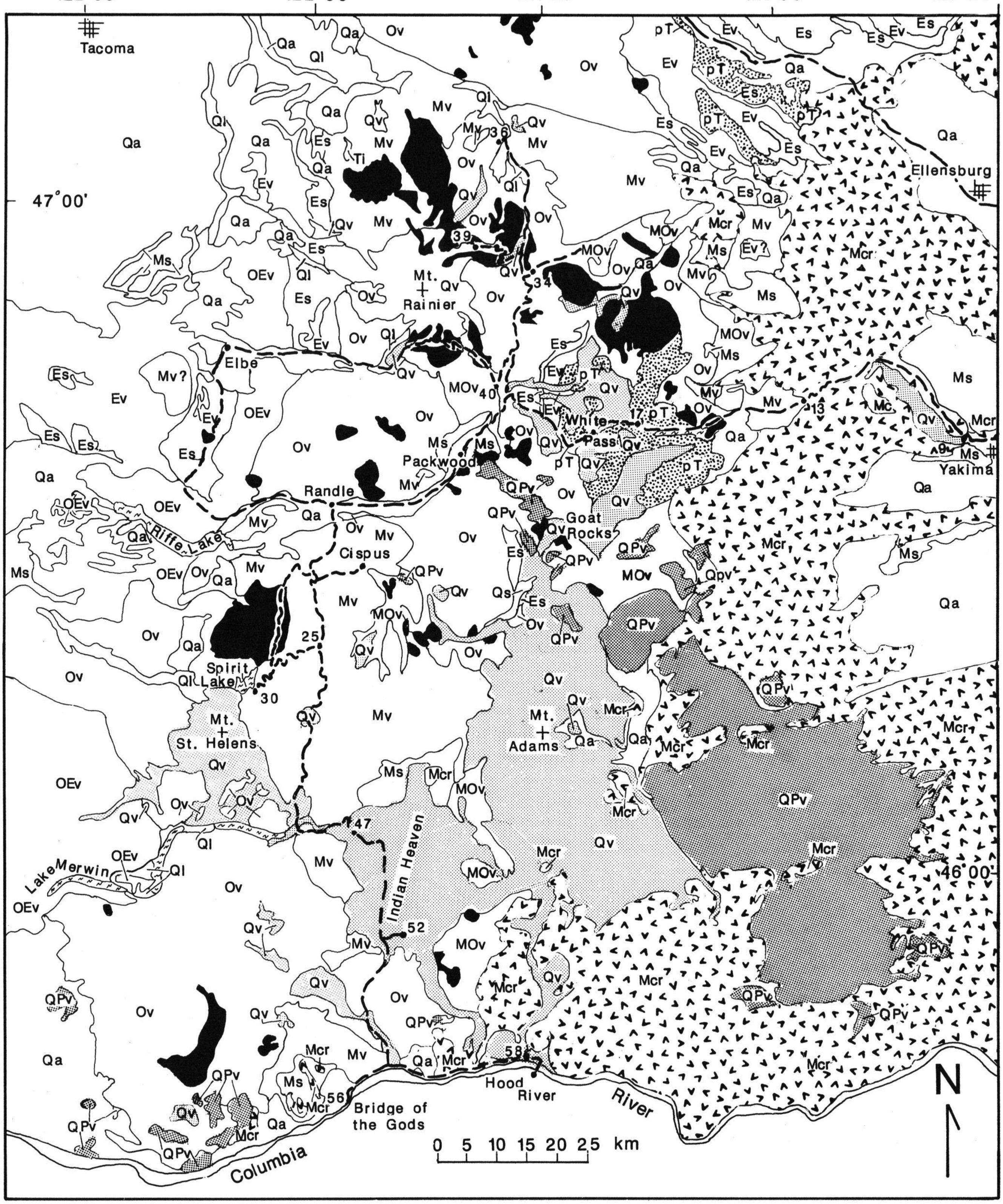


FIGURE 1. Features of Juan de Fuca-North American subduction system [*Riddihough*, 1984] relative to Cascade Range and Columbia Plateau. Open arrows, ridge-spreading directions; solid arrow, convergence direction. The 40- and 60-km contours show depth of seismicity in upper part of downgoing slab [*Weaver and Baker*, 1988]. Generalized subdivision of Cascade Range from *Hammond* [1979]. Distribution of Columbia River Basalt Group from *Tolan et al.* [in press]. Solid triangles, major Quaternary volcanoes: MM, Meager Mountain; C, Mount Cayley; G, Mount Garibaldi; B, Mount Baker; GP, Glacier Peak; R, Mount Rainier; SH, Mount St. Helens; A, Mount Adams, H, Mount Hood; J, Mount Jefferson; TS, Three Sisters; N, Newberry; D, Diamond Peak; CL, Crater Lake (Mount Mazama); ML, Mount McLoughlin; MK, Medicine Lake; ST, Mount Shasta; L, Lassen Peak. M, Monument dike swarm; SE, Seattle; V, Vantage; Y, Yakima; P, Pasco; PE, Pendleton.

FIGURE 2 (facing page). Geologic map (faults not shown) for southern Washington Cascades and adjacent Columbia Plateau, simplified from *Walsh et al.* [1987]. Units in order of descending age: Qa, basin fill, alluvium, drift, and landslide deposits; Ql, lahars, including 1980 debris avalanche at Mount St. Helens; Qv, Quaternary volcanic rocks; QPv, Quaternary and Pliocene volcanic rocks; Ms, Miocene sedimentary rocks, mostly younger than bulk of Yakima Basalt Subgroup; Mcr, Yakima Basalt Subgroup; Mv, lower and middle Miocene volcanic rocks; MOv, Miocene and Oligocene volcanic rocks; Ov, Oligocene volcanic rocks; OEv, Oligocene and Eocene volcanic rocks; Ev, Eocene volcanic rocks; Es, Eocene sedimentary rocks; pT, pre-Tertiary rocks; solid, intrusions, mostly of early and middle Miocene age. Dashed line, route of field trip, with selected stops numbered.



Helens, Hood, and the extinct Goat Rocks volcano) occur together with fields and scattered vents of olivine basalt (Indian Heaven, Simcoe Mountains, and the King Mountain fissure zone south of Mount Adams).

Weaver and Malone [1987] point out that the southern Washington Cascades are also transitional geophysically (Figure 3). An east-west saddle in an otherwise west to east Bouguer gravity gradient occurs along the

Columbia River between Oregon and Washington [*Thiruvathukal et al.*, 1970; *Couch and Baker*, 1979). North of Mount Adams a broad gravity low follows the Cascade crest, whereas south of Mount Hood the Cascade gravity low merges eastward into a low related to extension of southeast Oregon [*Weaver and Malone*, 1987].

Magnetotelluric profiles south of Mount Hood reveal a flat-lying, relatively simple conductivity structure [*Stanley*, 1984], whereas profiles in the southern Washington Cascades show a high-conductivity anomaly that dips eastward and may reflect accreted marine sedimentary rocks in a compressed forearc basin [*Stanley et al.*, 1987] (Figure 3; see following section).

Heat flow in the southern Washington Cascades is between 70 and 90 mWm^{-2} [*Blackwell and Steele*, 1983], whereas that south of Mount Hood averages about 100 mWm^{-2} [*Blackwell et al.*, 1982] and that north of Mount Rainier a relatively low 40-60 mWm^{-2}. A rapid transition occurs from low heat flow west of the Cascades to high heat flow in the range in both Oregon and southern Washington [*Blackwell and Steele*, 1983].

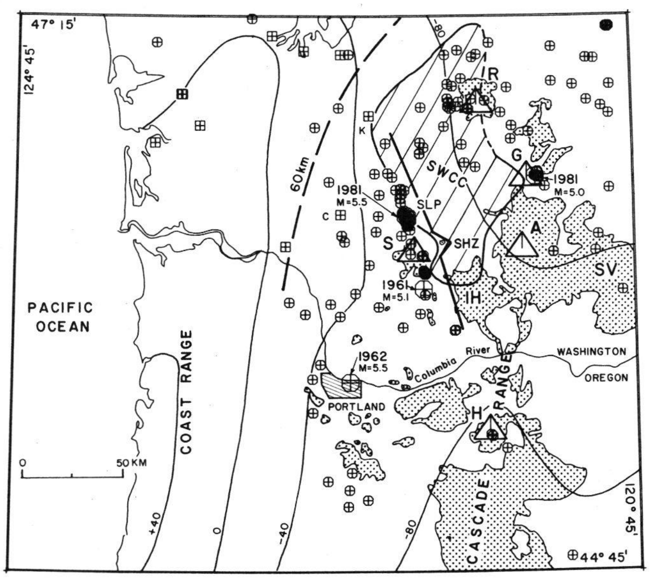


FIGURE 3. Map from *Weaver and Malone* [1987] showing selected geophysical and geologic elements of southern Washington and northern Oregon Cascades. Stippled, late Cenozoic volcanic rocks [*Luedke and Smith*, 1982]. Large letters, volcanic centers: R, Rainier; G, Goat Rocks; A, Adams; S, St. Helens; IH, Indian Heaven; SV, Simcoe volcanics; H, Hood. Ruled area, southern Washington Cascades conductor (SWCC) [*Stanley et al.*, 1987]. Earthquakes: circles, depth <30 km; squares, depth >30 km; date and magnitude given for magnitudes >5; small symbols for magnitudes between 2.5 and 4.9. Bold bracket (SHZ), St. Helens seismic zone. Bold dashed line, top of Juan de Fuca plate at 60 km depth. Light lines, Bouguer gravity contours in milligals, filtered to pass wavelengths >100 km at reduction density of 2.43 g/cm^3. SLP, Spirit Lake pluton.

The southern Washington Cascades are seismically active (Figure 3). Most earthquakes occur along the 100-km-long, north-northwest trending St. Helens seismic zone [*Weaver and Smith*, 1983], where most focal mechanisms show dextral slip parallel to the trend of the zone and consistent with the direction of plate convergence [*Grant et al.*, 1984; *Weaver et al.*, 1987]. Other crustal earthquakes concentrate just west of Mount Rainier and in the Portland area [*Weaver and Malone*, 1987]. Few earthquakes occur north of Mount Rainier or south of Mount Hood [*Weaver and Michaelson*, 1985].

From tomography, *Rasmussen and Humphreys* [1988] interpret the subducted Juan de Fuca plate as a quasi-planar feature dipping about 65° to about 300 km under the southern Washington Cascades. The plate is poorly defined seismically, however, owing to a lack of earthquakes within it [*Weaver and Baker*, 1988]. *Guffanti and Weaver* [1988] show that the present volcanic front of the Washington Cascades, defined by the westernmost young vents, parallels the curved trend of the subducting plate reflected by the 60 km-depth contour (Figure 1). The front trends northwest in northern Washington—where Glacier Peak, Mount Baker, and the volcanoes of southern British Columbia occur along a virtually straight line—and northeast in southern Washington. A 90-km gap free of young volcanoes between Mount Rainier and Glacier Peak is landward of that part of the subducting plate with the least average dip to a depth of 60 km [*Guffanti and Weaver*, 1988]. South of Portland, the volcanic front is offset 50 km eastward and extends southward into California, probably still parallel to the trend of the convergent margin [*Guffanti and Weaver*, 1988].

The Southern Washington Cascades Conductor

A recent magnetotelluric survey of the southern Washington Cascades, combined with geomagnetic variation data [*Law et al.*, 1980], defines a broad, high-conductivity anomaly with a resistivity of 1-4 ohm m and a thickness possibly more than 15 km, whose top is 2-8 km below less conductive volcanic and sedimentary rocks at the surface [*Stanley et al.*, 1987]. This anomaly, the "southern Washington Cascades conductor" (SWCC) of *Stanley et al.*, is roughly within the area bounded by Mounts Rainier, St. Helens, and Adams but extends somewhat farther north than Mount Rainier (Figure 3). Three aeromagnetic lows approximately enclose the SWCC. One of the lows coincides with the western margin of the SWCC and with the St. Helens seismic zone [*Weaver and Smith*, 1983], in which clusters of 5-15-km deep earthquakes occur in an apparent dextral shear zone. Another aeromagnetic low occurs within the SWCC west and south of Mount Rainier and correlates with a zone of folds mapped by *Hammond* [1980] and *Fiske et al.* [1963]; the north end of the low coincides with an elongate belt of seismicity just west of Mount Rainier. The third low coincides with the southern end of the SWCC but extends farther south into Oregon.

Stanley et al. [1987] interpret the SWCC as caused by "marine sedimentary rocks of early Jurassic to Eocene age, containing hypersaline fluids and posssibly dominated by shale facies" that form an accreted seamount complex in a compressed forearc basin. Mount Rainier lies on the eastern edge of the SWCC [*Stanley et al.*, 1987], and Mount St. Helens is on the western edge as well as on the St. Helens seismic zone (Figure 3). Tectonic controls on the locations of these volcanoes may reflect the accretionary history of the region.

TRAVERSE ACROSS THE CASCADES ON INTERSTATE 90

The rocks along and south of this route are largely Cenozoic, but Mesozoic basement is locally exposed in inliers and fault blocks. The route follows a transition from dominantly Tertiary volcanic rocks south of I-90 to the largely pre-Tertiary North Cascades. Four major groupings of rocks are present:

Mesozoic—Jurassic ophiolite and island-arc rocks and their associated Jurassic and Cretaceous sedimentary cover; Early Cretaceous high P-T metamorphic rocks, largely blueschist, greenschist, and phyllite; and Cretaceous plutonic rocks.

Eocene strata—Thick sections of nonmarine arkose and interbedded volcanic rocks.

Rocks of the Cascade magmatic arc—Lava flows and volcaniclastic rocks of the Oligocene Ohanapecosh Formation and the overlying upper Oligocene and lower Miocene Fifes Peak Formation, and the shallow granitoid plutonic rocks of the Miocene Snoqualmie batholith.

Columbia River Basalt Group—Miocene flood basalt erupted from vents far east of the Cascade Range.

Smith [1904] and *Smith and Calkins* [1906] worked out much the basic geology of this area. *Porter* [1976] described the Quaternary deposits along I-90.

Interstate 90 crosses the southern end of the Straight Creek fault, a major Tertiary structure. This fault, more than 500 km long, extends southward down the Fraser River in British Columbia into the Washington Cascades to I-90, where it splits into a series of southeast-trending splays that disappear beneath the Columbia River Basalt Group. About 90-110 km of dextral strike slip occurred on the fault [*Vance*, 1985; *Kleinspehn*, 1985]. Marked lithologic differences distinguish the Mesozoic and Eocene units on either side of the Straight Creek fault.

Mesozoic Rocks

A wide variety of units, mostly of Jurassic or Cretaceous age, represent several exotic terranes that accreted to western North America certainly before the Eocene and probably before the end of the Mesozoic.

The Mesozoic section west of the Straight Creek fault consists of graywacke and argillite with local chert and limestone. These sedimentary rocks are associated with greenstone, gabbro, and minor tonalite; all rocks are highly folded, faulted, and sheared. Contacts between units are commonly tectonic. *Frizzell et al.* [1987] mapped the suite as two tectonic-melange belts distinguished by differences in relative abundance of sedimentary and igneous rocks. The western melange belt, consisting largely of Jurassic marine turbidites, is widely exposed along the western front of the Cascades north of North Bend. The eastern melange belt, distinguished by more abundant greenstone, chert, and limestone, occurs in scattered outcrops north of Snoqualmie Pass. U-Pb ages for tonalite and gabbro in the melanges are Jurassic, and fossils from the chert and clastic sedimentary rocks have mostly Late Jurassic and Early Cretaceous ages. The lithology and age of the melanges led *Frizzell et al.* [1987] to conclude that the igneous rocks are an oceanic suite (root of an island arc?) that were intruded into the sedimentary rocks prior to the deformation that formed the melange.

Several Mesozoic units lie just east of the Straight Creek fault and between its southeasterly splays. The most widespread is the high P-T Easton Metamorphic Suite consisting of blueschist, greenschist, and phyllite. Farther north, lithologically equivalent rocks of the Shuksan Metamorphic Suite [*Misch*, 1966] occur extensively west of the Straight Creek fault and have been offset about 90 km from the Easton by dextral slip [*Vance*, 1985]. Most workers interpret the Easton and related rocks as metamorphosed oceanic basalt of MORB affinity and its sedimentary cover [*Brown*, 1986; *Dungan et al.*, 1983]. Radiometric dating suggests a Late Jurassic age for the Easton protolith and an Early Cretaceous age for its metamorphism [*Brown et al.*, 1982]. Other Mesozoic units between the Straight Creek splays include medium-grade pelitic schist [*Stout*, 1964] and gneissic tonalite of Jurassic age [*Frizzell et al.*, 1984].

Two other Mesozoic units are visible from I-90 in the Stuart Range 30 km north of Cle Elum. The older, the upper Jurassic and lower Cretaceous Ingalls Tectonic Complex, consists of a faulted sequence of ultramafic rocks, gabbro, diabase, pillow basalt, and associated sedimentary rocks generally interpreted as an ophiolite [*Southwick*, 1974; *Tabor et al.*, 1982b, 1987; *Miller*, 1985a]. The younger unit (95-88 Ma) consists of tonalite, diorite, and granodiorite of the upper Cretaceous Mount Stuart batholith, which intrudes the Ingalls.

Eocene Sedimentary and Volcanic Rocks

Eocene strata dominate the bedrock along I-90 between Issaquah and Cle Elum. They include volcanic and fluvial arkosic rocks, in places interbedded. The sedimentary units are quartzose to arkosic micaceous sandstone, shale, and conglomerate derived from a plutonic and metamorphic terrane farther east or northeast. They are locally marine but mostly fluvial and deltaic. Major coal production came from the Puget Group and the Roslyn Formation. The Eocene units are thick (2-4 km) and were deposited in rapidly subsiding, fault-bounded extensional basins [*Tabor et al.*, 1984; *Johnson*, 1985]. Many of the Eocene volcanic assemblages are bimodal, composed of basalt (or andesite) and high-silica rhyolite. Radiometric ages of the volcanic rocks are 51-42 Ma, mostly middle Eocene [*Tabor et al.*, 1984; *Turner et al.*, 1983; *Frizzell et al.*, 1984]. Invertebrate faunas in the rare marine sedimentary units are middle to late Eocene. The volcanic rocks do *not* belong to the Cascade arc but instead to the older and much broader field Challis arc [*Armstrong*, 1978], which encompasses large areas of Eocene volcanic and shallow plutonic rocks in the Pacific Northwest. *Ewing* [1980] and *Heller et al.* [1987] discussed the regional tectonics and paleogeography during the Eocene.

Figure 4 is a simplified correlation chart for some of the Eocene units along the field-trip route. These units pose several stratigraphic and tectonic problems. Obvious contrasts exist between Eocene rocks east and west of the Straight Creek fault. The extent to which the fault merely separated adjacent basins with different histories or juxtaposed the basinal sequences by major dextral movement is unresolved. Stratigraphic relations are not fully understood for the Eocene units separated by the southeastern splays of the Straight Creek fault.

Some Eocene volcanic units exhibit clear structural control. For example, eruption of basalt in the Teanaway Formation was localized in the southeastern bend of the Straight Creek fault. However, no structural control has been identified for other thick volcanic units, such as the Tukwila Formation interbedded in the Puget Group between North Bend and Seattle.

The Puget Group is widely exposed in the eastern Puget Sound basin and in the western Cascade foothills, where it is at least 2.7 km thick [*Buckovic*, 1979]. East of Seattle the Puget is underlain by the Raging River Formation and is subdivided into three formations [*Vine*, 1962, 1969]. From the base upward the four units are:

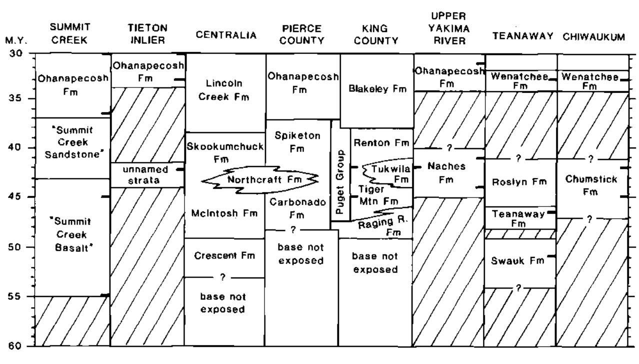


FIGURE 4. Correlation of Eocene rocks of central Washington Cascades and vicinity. Diagram and sources of data from *Vance et al.* [1987].

1) Raging River Formation, fossiliferous and tuffaceous marine sedimentary rocks of middle Eocene age;

2) Tiger Mountain Formation, nonmarine arkosic sedimentary rocks;

3) Tukwila Formation, largely coarse andesitic pyroclastic and volcaniclastic rocks with arkosic interbeds;

4) Renton Formation, nonmarine arkose.

Abrupt facies changes characterize the Puget Group. The volcanic rocks of Mount Persis [*Tabor et al.*, 1982a], probably correlative with the Tukwila Formation, make up the entire Eocene section in the western Cascade foothills of southern Snohomish County but are absent in the thick Puget section of southern King County.

Interbedded volcanic and arkosic sandstones of the Naches Formation occur along I-90 between Snoqualmie Pass and Easton west of the Straight Creek fault. The Naches is as thick as 3 km and is mostly coeval with and lithologically similar to the Puget Group. Silicic lava flows and ash-flow tuffs are abundant in the Naches; one prominent silicic welded tuff, the Mount Catherine Rhyolite Member [*Foster*, 1960; *Hammond*, 1977; *Tabor et al.*, 1984], has been mapped separately.

The Puget over most of its extent is deformed into tight plunging folds. The Oligocene marine Blakeley formation (informal), which conformably overlies the Puget, is likewise folded, but farther north the volcanic rocks of Mount Persis, coeval with the Blakeley, are not.

The Naches Formation is modestly to strongly deformed, particularly near the Straight Creek fault, where tight overturned folds occur. The Naches was folded in at least two episodes. The first predates the Oligocene Ohanapecosh Formation, which overlies the Naches with marked angular unconformity near the Straight Creek fault. This unconformity is absent above the Puget farther west. The second, weaker eposide of folding warped both the Ohanapecosh and Naches.

The Eocene section near the bend of the Straight Creek fault (Figure 5) was described and named by *Smith* [1904] and *Smith and Calkins* [1906] and further studied by *Foster* [1960], *Stout* [1964], and *Tabor et al.* [1982b, 1984]. Field-trip guides [*Hammond*, 1977; *Gresens et al.*, 1977] provide additional data. The Eocene section in this area is quite different from that west of the Straight Creek fault. The oldest unit, the Swauk Formation, is a thick nonmarine arkosic unit that unconformably overlies the Ingalls Tectonic Complex. Silicic volcanic rocks (Silver Pass Volcanic Member) interbedded in the Swauk Formation are dated at about 50 Ma. Consequently the Swauk is older than the Eocene rocks west of the Straight Creek. The Swauk was moderately folded about 48 Ma. Basalt flows of the Teanaway Formation (about 47 Ma) and overlying sandstone of the Roslyn Formation were deposited unconformably on the eroded Swauk. The Swauk-Teanaway unconformity is the earliest clear evidence of movement on the Straight Creek fault. A swarm of north-northeast-trending feeder dikes for the Teanaway reflects continued dextral shear on the Straight Creek fault during Teanaway time. The Teanaway and Roslyn were then deformed into a broad syncline, probably in response to late movement on the Straight Creek fault.

Cascade Arc

The Cascade magmatic arc in Washington is defined by a narrow north-south belt of Oligocene and Miocene shallow plutons and coeval volcanic rocks. This belt coincides closely with the zone of large Quaternary stratovolcanoes that dominate the present landscape. In Washington, the Cascade arc is superposed on the older, unrelated Eocene rocks of the much broader and more diffuse Challis magmatic field [*Vance*, 1982]. Inception of the Cascade arc occurred about 36 Ma and is marked by the outbreak of volcanism (Ohanapecosh Formation) and emplacement of the earliest Cascade plutons in the Index and Chilliwack batholiths [*Vance et al.*, 1986].

Rocks of the Cascade arc are widely exposed south of I-90. The two major units are the Ohanapecosh and the uppermost Oligocene and lower Miocene Fifes Peak Formations [*Fiske et al.*, 1963; *Vance et al.*, 1987]. The Ohanapecosh includes thick sequences of well-bedded volcaniclastic rocks of intermediate composition and debatable depositional enivronment [*Fiske*, 1963; *Vance et al.*, 1987], as well as andesitic and local silicic lava flows and silicic ash-flow tuffs. *Hammond* [1977] described thick, near-vent rhyodacitic ash-flow tuff along the shore of Lake Keechelus that correlates with the Ohanaceposh on the basis of field relations and radiometric ages [*Tabor et al.*, 1984]. The volcaniclastic rocks of Wildcat Creek [*Swanson*, 1978] in the Tieton River area on the east flank of the Cascades are a distal facies of the Ohanapecosh [*Vance et al.*, 1987]. Oligocene forearc-basin deposits west of the Cascades (Blakeley formation of the Puget Sound basin and Lincoln Creek Formation of southwest Washington) consist largely of volcaniclastic debris reworked from the Ohanapecosh.

The Ohanapecosh Formation is overlain, commonly unconformably, by the Fifes Peak Formation, which consists mostly of andesitic to basaltic lava flows, pyroclastic rocks, and lahars, as well as several thick silicic ash-flow tuffs. Vents for the Fifes Peak are known in the Fifes Peaks themselves [*Carkin*, 1985] and in the Tieton River area [*Swanson*, 1978]. *Fiske et al.* [1963] defined the Stevens Ridge Formation to include silicic ash-flow tuffs between the Ohanapecosh and Fifes Peak Formations in Mount Rainier National Park. Recent work shows that such tuffs are common throughout the section and are not useful for regional stratigraphic subdivision. Therefore, *Vance et al.* [1987] referred the Stevens Ridge to member status within the Fifes Peak Formation.

Volcanic rocks in the range 18-5 Ma are sparsely represented in the Cascade arc in Washington. However, scattered plutons in this interval are present, and recent sedimentological studies and radiometric dating [*Smith et al.*, 1988] confirm that the dacitic volcaniclastic detritus in the Ellensburg Formation, which overlies and interleaves with the Columbia River Basalt Group, is the distal volcanic debris from eruptions of this time.

The Snoqualmie batholith, a typical shallow plutonic complex of the Cascade arc, is exposed in many places along I-90 for about 15 km west of Snoqualmie Pass. This composite intrusive body ranges from gabbro to granite but is dominantly hornblende-biotite tonalite and granodiorite [*Erikson*, 1969; *Tabor et al.*, 1982a; *Frizzell et al.*, 1984]. Radiometric dating indicates that the batholith consists of two major phases, each with a wide compositional range. A northeastern phase is about 25 Ma and correlates with the Grotto batholith and related smaller plutons farther north. This phase intruded and postdates movement on the Straight Creek fault. The southern part of the batholith, including the exposures along I-90, is in the range 20-17 Ma.

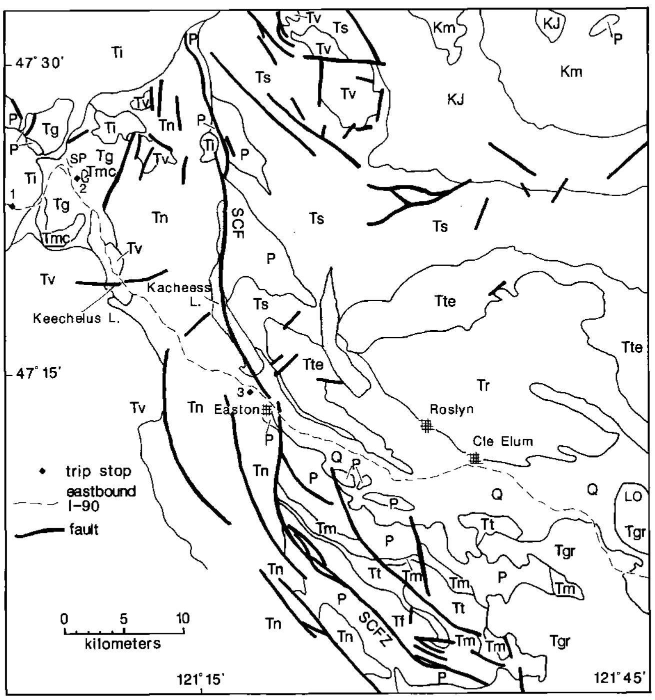


FIGURE 5. Generalized geologic map of central Cascades in Washington, simplified from *Tabor et al.* [1984]. SP, Snoqualmie Pass; LO, Lookout Mountain; SCF, Straight Creek fault. Geologic units, in order of increasing age: Q, Quaternary deposits; Tgr, Grande Ronde Basalt; Ti, Snoqualmie batholith; Tv, Miocene and Oligocene volcanic rocks; Tn, Naches Formation, undivided; Tmc, Mount Cathrine Rhyolite Member of Naches Formation; Tg, Guye Sedimentary Member of Naches Formation; Tr, Roslyn Formation; Tf, basalt of Frost Mountain; Tte, Teanaway Formation; Tt, Taneum Formation; Tm, Manastash Formation; Ts, Swauk Formation; P, pre-Tertiary rocks, undivided. Stops 1-3 labeled.

MOUNT RAINIER

Mount Rainier, highest (4392 m) and third-most voluminous volcano in the Cascades after Mounts Shasta and Adams, dominates the Seattle-Tacoma area, where more than 1.5 million know it fondly as *The Mountain*. The Mountain is, however, the most dangerous volcano in the range, owing to the large population and to the huge area and volume (92×10^6 m^2 and 4.4×10^9 m^3, respectively [*Driedger and Kennard*, 1986]) of ice and snow on its flanks that could theoretically melt to generate debris flows during cataclysmic eruptions. In addition, sector collapses of clay-rich, hydrothermally altered debris have generated at least three huge ($>2 \times 10^8$ m^3) debris flows in the last 5000 years. Yet surprisingly little is known of Mount Rainier's eruptive history, composition, or age. For example, probably fewer than two dozen chemical analyses of Rainier's products have been published. Probably the dominantly nonexplosive nature of past eruptions and the challenging logistics of studying the cone contribute to the relatively limited knowledge. Outstanding work, however, has been completed on its fragmental deposits, and most of what is known about the volcano derives from this work.

Underpinnings

Mount Rainier is underlain by middle Tertiary volcanic rocks of the Ohanapecosh, Stevens Ridge, and Fifes Peaks Formations [*Fiske et al.*, 1963; *Vance et al.*, 1987], described elsewhere in this guide. These rocks were gently warped along a northwest-trending system of folds and intruded by the Tatoosh pluton, chiefly granodiorite and quartz monzonite. The main body of the Tatoosh is 17.5-14.1 Ma, but dikes, sills, and various volcanic deposits interpreted as forerunners to the emplacement of the pluton to its final level are as old as 26 Ma, judging from U-Pb dating of zircons [*Mattinson*, 1977]. *Fiske et al.* [1963] interpreted the Tatoosh to have "broken through to the surface" several times, giving rise to eruptions such as that which created The Palisades, a 250-m-high cliff of 25-Ma silicic welded tuff 5 km northeast of Yakima Park [*Mattinson*, 1977].

Forerunner to Mount Rainier

No evidence has been found for magmatism near Mount Rainier between about 14 and 3 Ma. The Lily Creek Formation, a thick sequence of debris flows and related volcanic deposits [*Crandell*, 1963a], crops out just west of the volcano and was hypothesized by *Fiske et al.* [1963] to have been erupted from the Tatoosh. However, *Mattinson* [1977] dated the Lily Creek as no older than 2.9 Ma and therefore agreed with *Crandell* [1963a] that it likely was formed during the earliest activity of Mount Rainier or from a center that just preceded the cone. Stratigraphic relations with glacial deposits suggest that Lily Creek volcanism began before 0.84 Ma [*Easterbrook et al.*, 1981; *Smith*, 1987]. Hornblende occurs in juvenile clasts of the Lily Creek but not in rocks from Mount Rainier [*Fiske et al.*, 1963]. No chemical analyses have been published for the Lily Creek.

The Main Cone

Mount Rainier was built on a rugged surface with more than 700 m of relief eroded mainly into the Tatoosh pluton and the Stevens Ridge Formation [*Fiske et al.*, 1963]. Early andesite flows from the volcano, undated but presumably several hundred thousand years old, were channelled along deep canyons, some of which were oblique to the present radial drainage pattern. The eruptions were apparently frequent, because in places one flow rests on the undissected surface of its predecessor [*Fiske et al.*, 1963]. Laharic deposits and till locally occur between the early flows. Eventually the flows stacked up to form a mound near the main vent that became the foundation of the present cone.

Most of Mount Rainier's cone was built by hundreds of thin lava flows interbedded with breccia and minor tephra. The flows are rarely more than 15 m thick high on the cone, where they drained down the steep slopes. They thicken near the base, and flows more than 60 m thick occur on the apron around the cone [*Fiske et al.*, 1963]. Some flows entered canyons radial to the volcano. Much breccia on the cone was probably derived from moving flows, but some probably reflects explosions and lahars. Radial dikes are prominent in places [*Smith*, 1897; *Coombs*, 1936; *Fiske et al.*, 1963]; possibly they fed some of the flows. The flows and dikes are petrographically uniform two-pyroxene andesite; the few chemical analyses available (Figures 6 and 7) are medium-K silicic andesite, with three analyses marginally dacitic. The flows and breccia eventually built a cone standing 2100-2400 m above its surroundings before the end of the latest major glaciation about 10 ka.

A thick pumice layer northeast, east, and southeast of the volcano may have been erupted from Mount Rainier between 70 and 30 ka. Estimates from limited outcrops suggest it is an order of magnitude more voluminous than any of the volcano's Holocene tephra layers.

Two late Pleistocene vents, Echo Rock and Observation Rock, erupted olivine-phyric basaltic andesite near the northwest base of the cone after Mount Rainier was almost fully grown [*Fiske et al.*, 1963]. The basaltic andesite is more mafic than the cone-building flows [*Condie and Swenson*, 1973] (Figures 6 and 7).

Smith [1987] estimates that about 270 km^3 of lava was erupted from Mount Rainier in the last 1 Ma.

Postglacial Eruptive History

Eleven tephra layers record evidence of Holocene explosive volcanism at Mount Rainier [*Mullineaux*, 1974].

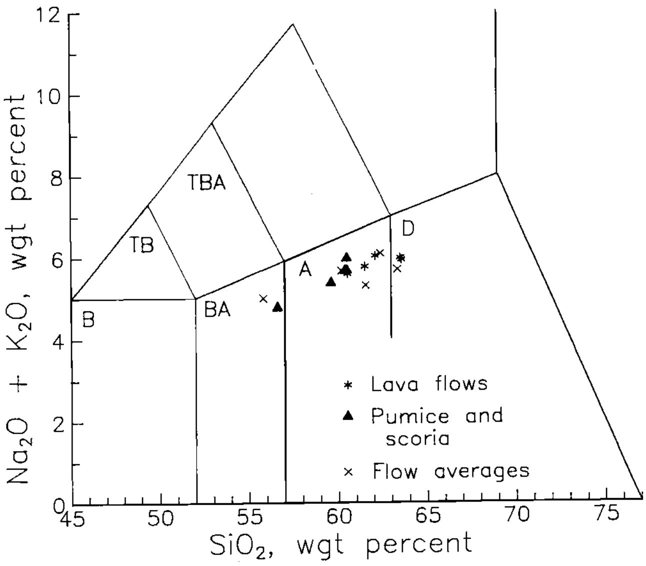


FIGURE 6. Total alkali-silica diagram for Mount Rainier. Analyses from *Coombs* [1936] (lava flows), *Condie and Swenson* [1973] (flow averages), and *Mullineaux* [1974] (pumice and scoria), calculated water-free to 100%. See Figure 17 for field names.

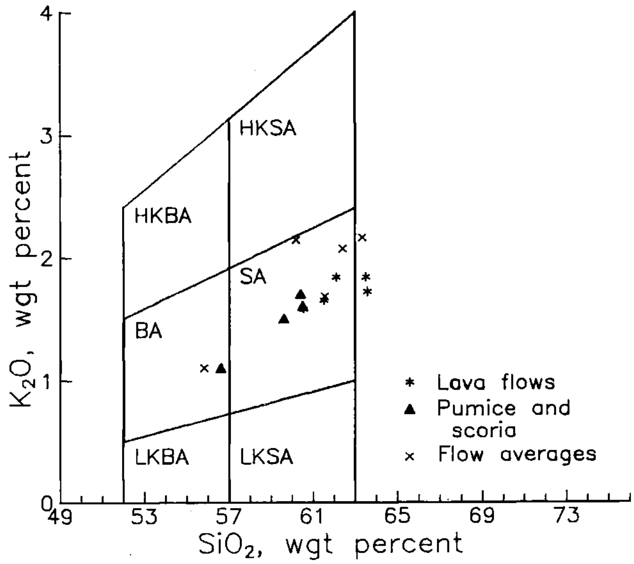


FIGURE 7. Andesite classification for Mount Rainier, from *Gill* [1981] except that basalt-andesite division is 52%. Data sources in Figure 6. HKBA, high-K basaltic andesite; BA, basaltic andesite, LKBA, low-K basaltic andesite; HKSA, high-K silicic andesite; SA, silicic andesite; LKSA, low-K silicic andesite.

Eight of the tephras fell between 6500 and 4000 ^{14}C years B.P. (Table 1). Only one tephra-producing eruption, between about 1820 and 1854 A.D., is known from the last 2200 years [*Mullineaux*, 1974]; it was very small and left a scanty deposit that could easily be overlooked if it were older. Chemical analyses indicate that layer D is basaltic andesite and layers L and C are silicic andesite (Figure 7) [*Mullineaux*, 1974].

The tephra layers rich in lithic fragments are probably products of phreatic or phreatomagmatic eruptions. Layer F contains 5 to 25% clay-sized material, as much as 80 percent of which locally consists of clay minerals, chiefly montmorillonite, that was derived from altered rocks within Mount Rainier [*Mullineaux*, 1974]. Layer F and the Osceola debris flow [*Crandell*, 1971] have similar clay contents and ages, and are likely correlative. However, layer F has not been found on the Osceola and so could be slightly older.

Layer C, the most widespread and voluminous of the Mount Rainier tephras, covers the east half of the National Park with 2-30 cm of lapilli, blocks, and bombs. Overall it is the coarsest of the tephras, with 25-30-cm bombs 8 km from the summit. A block-and-ash flow in the South Puyallup valley west of the volcano contains blocks emplaced above the Curie isotherm and charcoal dated at 2350 ± 250 ^{14}C years [*Crandell*, 1971]. Its age and lithologic similarity suggest correlation with layer C.

Isopachs and isopleths for layer C indicate an origin at the summit of Mount Rainier, yet the layer does not occur on snow-free parts of Columbia Crest cone, a young andesite cone standing 250 m above the former summit of the volcano [*Mullineaux*, 1974]. Columbia Crest cone is therefore younger than about 2200 years.

TABLE 1. Holocene tephras from Mount Rainier

Layer	Age	Predominant materials	Volume
X	±150	Pumice	1
C	2200	Pumice, scoria, lithic frags.	300
B	>4000	Scoria, lithic fragments	5
H	>5000	Pumice, lithic fragments	1
F	5000	Lithic frags, pumice, crystals, clay	25
S	5200	Lithic fragments	20
N	5500	Lithic fragments, pumice	2
D	6000	Scoria, lithic fragments	75
L	6400	Pumice	50
A	6500	Pumice, lithic fragments	5
R	>8750	Pumice, lithic fragments	25

From *Mullineaux* [1974]. Age of X from tree rings; all others in radiocarbon years B.P. Volume in millions of m^3.

Crandell [1971] found numerous lahars and flood deposits in valleys surrounding the mountain that postdate layer C but predate layer Wn (1480 A.D.) from Mount St. Helens; some of the flowage deposits have ^{14}C ages older than 1000 years B.P. The eruptions that formed Columbia Crest cone likely produced some of those deposits. If so, the layer-C explosions might have initiated activity that formed Columbia Crest, and the cone would be about 2000 years old [*Mullineaux*, 1974].

Crandell [1971] identified more than 55 lahars and debris flows of Holocene age from Mount Rainier. At least some were probably associated with eruptions, most notably the Paradise lahar [*Crandell*, 1963b, 1971] (possibly associated with tephra layers A, L, or D) and the Osceola debris flow (layer F). The Osceola is described in the road log for Mount Rainier. In general, *Crandell* [1971] associates lahars that lack much clay at Mount Rainier with magmatic eruptions, and those that contain much clay with phreatic or phreatomagmatic eruptions or with collapses of the hydrothermally altered edifice. Glacier-outburst floods from Little Tahoma Glacier, typically in late afternoon of warm days or after heavy rain, repeatedly scoured Tahoma Creek in the late 1960s and the middle and late 1980s. Outburst floods frequently modified many other drainages, most notably Kautz Creek and Nisqually River, during historical time.

About 20 small earthquakes occur yearly at Mount Rainier, more than at other composite cones in the Cascades except Mount St. Helens [*Malone and Swanson*, 1986]. Trilateration and tilt networks established in 1982 indicate no definite deformation. Seven significant thermal areas above 3350 m on the volcano, including one at the summit, reflect "a narrow, central hydrothermal system...forming steam-heated snowmelt at the summit craters and localized leakage of steam-heated fluids within 2 km of the summit" [*Frank*, 1985].

SUMMARY OF THE GEOLOGY OF THE MOUNT ST. HELENS AREA

Mount St. Helens rests on the deeply-dissected remains of the mid-Tertiary Cascade magmatic arc, represented by a diverse assemblage of variably altered subaerial volcanic and plutonic rocks (Figure 8). Near the volcano, 5-7 km of Tertiary rocks crop out in the east-dipping limb of a broad, south-trending and plunging anticline. Exceptional exposures occur near Spirit Lake, where vegetation and surficial deposits were removed by the May 1980 eruption and subsequent erosion.

Many age determinations show that volcanic and plutonic activity that constructed the Tertiary arc in southern Washington occurred largely between 36 and approximately 17 Ma [*Frizzell et al.*, 1984; *Phillips et al.*, 1986; *Evarts et al.*, 1987; *Vance et al.*, 1987]. Volcanism was more or less continuous during this period. Although unconformities are widespread in the section in southern Washington [*Fiske et al.*, 1963; *Evarts et al.*, 1987; *Vance et al.*, 1987], none has regional extent. K-Ar and ^{40}Ar-^{39}Ar ages from just north of Mount St. Helens indicate a deposition rate of about 360 m/m.y, similar to those compiled by *Smith* [in press a] for other well-mapped and dated mid-Tertiary sequences in the Washington Cascades. Radiometric ages suggest that the rate of volcanism in southern Washington declined between 20 and 17 Ma, and that a subsequent further downturn coincided with eruption of the Grande Ronde Basalt on the Columbia Plateau. Beds of Cascade-derived tephra between flows of Grande Ronde Basalt indicate that explosive volcanism did not stop entirely, but reliable age determinations from the Cascades in the 17-5-Ma range are rare [*Smith et al.*, 1988; *Smith*, in press a].

The rate of volcanism in southern Washington increased in the early Pliocene, after regional folding, uplift, and extensive erosion. The volcanism continues but is localized and sporadic relative to that of the mid-Tertiary. Products of this period include basalt fields such as Indian Heaven as well as the prominent composite cones of Mounts Rainier, Adams, and St. Helens.

Mid-Tertiary Volcanic Rocks

The Tertiary section near Mount St. Helens contains rocks typical of near-vent depositional environments, such as abundant lava flows and domes, coarsely pumiceous pyroclastic rocks, coarse lithic tuff-breccia and lapilli tuff, fine-to medium-grained intrusive rocks, and widespread, locally intense, hydrothermal alteration. The units are mostly discontinuous and lenticular. Well-bedded, finer-grained volcaniclastic rocks of more distal character, such as those in the Ohanapecosh Formation near Mount Rainier [*Fiske et al.*, 1963], are common only near Cougar south of Mount St. Helens (Figure 8).

The eruptive products range from olivine-phyric basalt to pyroxene rhyodacite. The distribution of these chem-

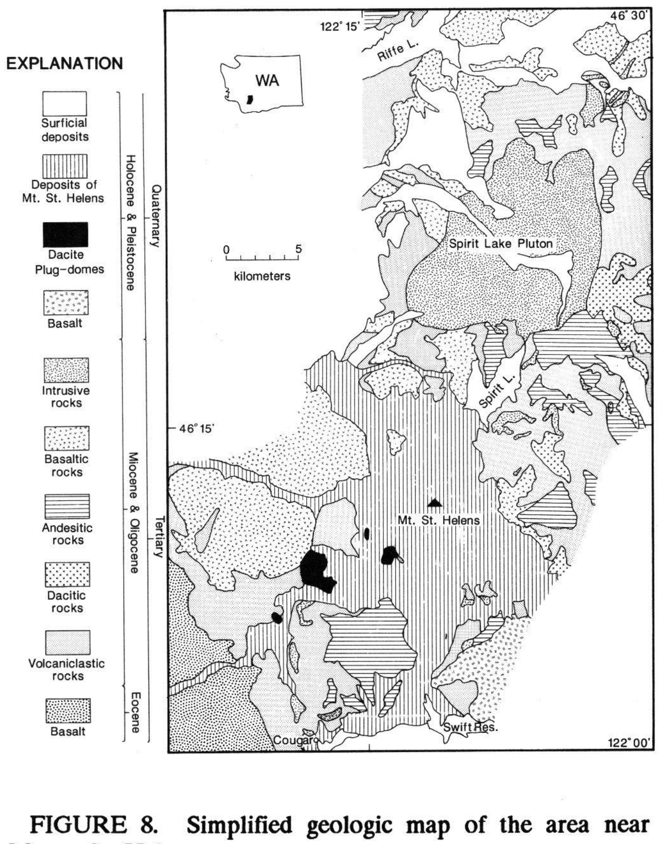


FIGURE 8. Simplified geologic map of the area near Mount St. Helens.

ically diverse rocks is complex but not random. The upper Eocene and lower Oligocene section west of Mount St. Helens is almost entirely basalt and basaltic andesite, whereas lower Miocene rocks farther east are mostly pyroxene andesite and dacite. The relative volume of pyroclastic rocks increases upsection. Vent areas of several kinds have been recognized, including a swarm of mafic dikes west of Spirit Lake, a silicic dome field on the east flank of Strawberry Mountain north of Bear Meadow, and an inferred caldera along Quartz Creek.

Most rocks are phyric, but sparsely phyric to aphyric andesite and dacite are common. Phenocrysts in basalt are plagioclase, olivine, and in some samples augite; andesite and dacite typically contain plagioclase, augite, and hypersthene. Rhyodacite and silicic tuff rarely contain quartz phenocrysts. Notably absent from the Tertiary volcanic rocks are hornblende and biotite, although hornblende occurs rarely in a few subvolcanic intrusions.

Chemical analyses of the least altered samples have subalkaline tholeiitic to calc-alkaline compositions typical of volcanic arcs [*Ewart*, 1982]. The ratio of calc-alkaline to tholeiitic rocks increased with time. The most notable chemical feature is relatively low K_2O (Figure 9); in this respect the rocks resemble those of evolved ensimatic arcs such as the Aleutians more than those of the Quaternary Cascades [*Evarts et al.*, 1987].

Plutonic Rocks

Intrusive rocks are widespread near Mount St. Helens and elsewhere in southern Washington [*Hammond*, 1980]. They range from shallow subvolcanic dikes and plugs to medium- to coarse-grained epizonal granitic bodies typified by the Spirit Lake pluton [*Evarts et al.*, 1987]. Compositions of the intrusive and volcanic rocks span the same range, from olivine gabbro to granite, and many probably fill synvolcanic conduits. Most of the smaller bodies are undated. A composite sill complex along Windy Ridge east of Spirit Lake has a K-Ar age (plagioclase) of about 24 Ma (roughly 2 Ma younger than its host rocks), and several K-Ar and fission-track ages on the Spirit Lake pluton are about 21 Ma. Most of the intrusive bodies are probably only slightly younger than their volcanic country rock, late Oligocene to early Miocene. Intrusions elsewhere in the Cascades generally have similar ages [*Tabor and Crowder*, 1969; *Engels et al.*, 1976; *Mattinson*, 1977; *Power et al.*, 1981; *Tabor et al.*, 1982a; *Frizzell et al.*, 1984; *Vance et al.*, 1987].

The Spirit Lake pluton consists of three major phases, each containing many smaller units. The earliest phase comprises phyric quartz diorite and granodiorite that occur as relatively fine-grained dikes with hornfels screens in the northwest part of the pluton and as isolated bodies in the main phase. Most of these rocks display intense deuteric alteration and are intruded by rocks resembling those of the main phase. The pluton consists mainly of the main and granite phases, which are coarser and more massive than the quartz diorite. The pluton has a configuration of a flat-roofed cylinder tilted eastward with its country rock. Its contact sharply truncates wall rock and is generally simple, but complex to gradational contacts are common internally. Stratigraphic evidence suggests a emplacement less than 3 km deep.

Chemical and petrographic attributes of the Spirit Lake pluton are those of I-type granitic rocks found in most arc environments [*Brown et al.*, 1982]. Plagioclase, augite, and hypersthene generally form euhedral to subhedral crystals in a matrix of coarse anhedral to micrographic quartz and K-feldspar. Minor late hornblende and biotite occur sparingly, mainly in the deeper western half of the pluton. The magma was probably relatively dry. SiO_2 contents vary from 56 to 75%.

Metamorphism and Hydrothermal Alteration

The Tertiary rocks were affected by very low-grade, zeolite-facies burial metamorphism. Some massive flows and densely welded ash-flow tuffs still contain glass (albeit hydrated), but generally the glass was replaced by iron-rich smectitic clay minerals that provide the green colors characteristic of the Tertiary units. More intense recrystallization took place around plutonic bodies. The Spirit Lake pluton produced a well-developed contact metamorphic aureole consisting of an inner zone of fine-grained black amphibole hornfels and an outer zone of green albite-epidote hornfels. Broad zones of epidote-bearing hornfels commonly surround even small phaneritic intrusive bodies, which may therefore be cupolas extending from a much larger pluton at shallow depth.

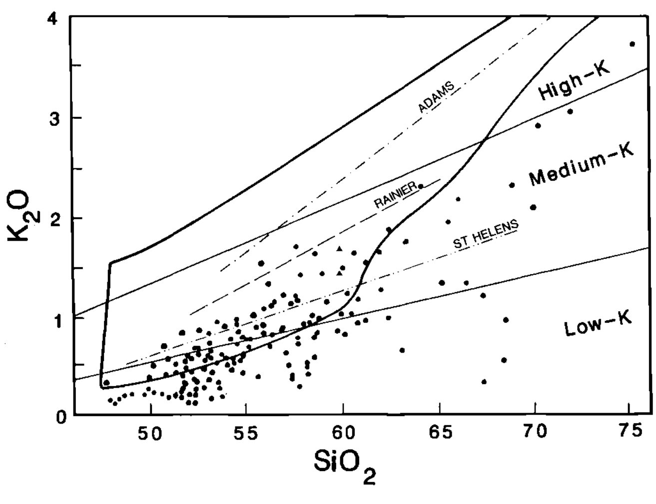


FIGURE 9. K_2O-SiO_2 variation for Tertiary volcanic rocks near Mount St. Helens. Heavy line encircles field of Quaternary volcanic rocks in southern Washington Cascades [*Hammond and Korosec*, 1983]. Generalized trends for Quaternary rocks at Mounts St. Helens, Rainier, and Adams from *Greeley and Hyde* [1972], *Condie and Swenson* [1973], *Hoblitt et al.* [1980], and *Hildreth and Fierstein* [1985]. Modified from *Evarts et al.* [1987].

Intense metasomatic alteration of several types has been recognized in the area [*Evarts et al.*, 1987]. Widespread localized low-temperature alteration to carbonate and clay is particularly common near abundant dikes and along minor faults, as on Johnston Ridge. Higher temperature argillic to advanced argillic assemblages occur in three areas near the north end of the Spirit Lake pluton. A few kilometers farther south is the Earl porphyry copper-molybdenum deposit, the largest of many such occurrences in the Washington Cascades. The Earl is within the Spirit Lake pluton, yet multiple age determinations indicate that it is about 4 m.y. younger and thus not genetically related to the pluton.

Quaternary Volcanism Exclusive of Mount St. Helens

Quaternary rocks near Mount St. Helens are restricted to isolated vents south and southwest of the volcano. Basalt and basaltic andesite dominate, but a few silicic domes and plugs follow an east-northeast trend southwest of the volcano [*Evarts et al.*, 1987].

In contrast to the Tertiary rocks, many of the younger intermediate to silicic rocks contain hornblende and biotite phenocrysts. They are typically more phyric (especially the dacite) and richer in K_2O at equivalent silica contents than the Tertiary rocks [*Evarts et al.*, 1987].

Structural Elements

Broad open folds with north- to northwest-trending axes dominate the structure of the southern Washington Cascades [*Hammond*, 1980; *Walsh et al.*, 1987]. The age of folding is poorly constrained, but much probably occurred in the middle to late Miocene, for all Tertiary rocks are affected whereas Pliocene rocks apparently are not. A few low-angle unconformities within the mid-Tertiary section suggest that minor folding took place as the rocks were accumulating [*Evarts et al.*, 1987; *Vance et al.*, 1987], although such unconformities are easily confused with those caused by primary dips at volcanoes.

Few faults of regional significance have been documented in the southern Washington Cascades [*Walsh et al.*, 1987]. Rapid facies changes within the volcanic pile make faults hard to find. However, even mapped faults in the well-exposed area north of Mount St. Helens are clearly minor features that may reflect local stress near volcanoes rather than regional tectonic stress. Many of these faults are associated with hydrothermal alteration or are occupied or cut by Tertiary dikes. The only demonstrably young faulting was related to emplacement of the Goat Mountain dacite plug west of Mount St. Helens. No surface offset along the north-northwest-trending St. Helens seismic zone [*Weaver and Smith*, 1983] is apparent; this zone connects several clusters of shallow earthquakes, including those beneath Mount St. Helens, whose preferred focal mechanisms suggest dextral displacement parallel to the trace of the zone.

Minor but pervasive north- and northwest-trending dextral shear zones, and northeast-trending sinistral shear zones, occur in the area east of Mount St. Helens. Subhorizontal slickensides on stepped fault surfaces allow the sense of displacement to be determined, but offsets are less than a few centimeters. These shear zones are part of a regional system of similar structures, chiefly dextral, recognized on the western Columbia Plateau in Washington and northern Oregon; in places they are simply shear zones with little displacement and in other places faults with offsets of hundreds of meters or more [*Bentley and Anderson*, 1980; *Anderson et al.*, 1987].

Evarts et al. [1987] and *Weaver et al.* [1987] discuss linear trends of geologic features that may reflect deep crustal structures in the Mount St. Helens area (see also Stop 45). Mount St. Helens, Mount Rainier, and Glacier Peak define a north-northeast-trending segment of the modern arc. This trend coincides with that of the major epizonal Miocene intrusions of the region, such as the Silver Star (east of Vancouver [*Felts*, 1939]), Snoqualmie, Tatoosh, and Spirit Lake bodies, which define the core of the Tertiary arc. Thus the position of the volcanic front in southern Washington has been more or less fixed for 25 Ma. The position of Mount St. Helens may be determined by the intersection of this broad trend with younger crustal flaws manifested in a line of Quaternary silicic vents and the St. Helens seismic zone.

Geophysics

Williams et al. [1987] inferred a large, shallow "intrusive complex" under Mount St. Helens on the basis of gravity data. The inferred complex is interpreted to be 5-6 km thick and to intrude the putative compressed forearc marine basin in the southern Washington Cascades conductor [*Stanley et al.*, 1987]. Conceivably this complex could be the source of gabbroic inclusions [*Heliker*, 1984] in the dacite of Mount St. Helens, although its size (10 by 20 km to as large as 18 by 22 km) is much larger than the inferred current magma reservoir.

Finn and Williams [1987] found a residual magnetic high over Mount St. Helens after correcting pre- and post-1980 aeromagnetic data for terrane effects. The anomaly is shallow, probably near or at the base of the volcano. They suggest that the high, which is not reflected by the gravity data, results from terrain that predates Mount St. Helens, such as a buried andesitic or basaltic cone or a valley filled with lava flows. These two possibilities cannot be distinguished, although the presence of an eroded and buried cone, perhaps fed by the inferred intrusive complex, is appealing. Such a cone would probably be older than 50 ka, the approximate age of the oldest dacite from Mount St. Helens.

MOUNT ST. HELENS

Mount St. Helens is young. Its oldest known deposits were erupted about 50-40 ka, and the cone that partly collapsed in 1980 is only 2200 years old. Since its birth it has produced more than 60 tephra layers [*Mullineaux*, 1986], several tens of volcanically-induced debris flows (at least six of which entered the Columbia River 100 km downstream [*Scott*, 1988]), and the equivalent of 60 km^3 of dacitic lava [*Smith*, 1987]. It has been the most active volcano in the Cascades during the Holocene, and for that reason its eruption in 1980 came as no surprise. The volcano has been studied intensively, and its eruptive history is known with greater clarity than that of any other Cascade volcano.

Eruptive History

Crandell [1987] divides the history of the volcano into "four extended stages of intermittent activity, each lasting two thousand years or longer. The volcano is now in such a stage that began about 4,000 radiocarbon years ago" (Table 2). The stages are separated by dormant intervals of thousands of years. Each stage contains eruptive periods with durations of decades to centuries; those periods for the current stage are named, but those for past stages are not. Many ^{14}C and dendrochronologic ages [*Crandell et al.*, 1981; *Mullineaux*, 1986; *Yamaguchi*, 1983, 1985] provide a well-constrained context within which to interpret the volcanic history.

Mullineaux [1986] recognized at least one tephra set, comprising several layers of tephra, in each eruptive stage and period except the Sugar Bowl and Goat Rocks periods, each of which has only one layer. The tephra sets and some single tephra layers form distinctive markers, recognizable by the assemblage and relative proportions of ferromagnesian phenocrysts (hypersthene, hornblende, biotite, cummingtonite, olivine, and augite). The tephra sets and some layers can be correctly identified in the field with a mortar, pestal, and binocular microscope using methods developed by D. R. Mullineaux.

The tephras are the most useful means of placing deposits of Mount St. Helens in proper stratigraphic context. They are also used to date events far from the volcano. For example, set S, about 13 ka, is interbedded with deposits of the Missoula floods on the Columbia Plateau and provides one of the best ages for the floods [*Mullineaux et al.*, 1978; *Waitt*, 1985]. Tephra layer Cs, about 37 ka, spread southward into the Lake Lahontan basin of Nevada, where it is probably equivalent to the Marble Bluff Bed [*Davis*, 1978; *Mullineaux*, 1986]. Layer Yn, about 4 ka, occurs near Entwhistle, Alberta, 900 km north-northeast of Mount St. Helens [*Westgate et al.*, 1970; *Mullineaux*, 1986]. Layer Ye occurs in northeast Oregon, 300 km from the volcano [*Borchardt et al.*, 1973]. Layers Wn (1480 A.D.) and We (1482 A.D.) [*Yamaguchi*, 1983, 1985] are known 400 km northeast and east of the volcano, respectively [*Smith et al.*, 1977]. Layer T (1800 A.D.) occurs in northwestern Montana, 375 km away [*Okazaki et al.*, 1972].

Pyroclastic flows and lahars formed in each eruptive stage and period [*Mullineaux and Crandell*, 1981; *Crandell*, 1987]. Many pyroclastic flows carry lithic fragments probably derived from coeval domes. Lava flows are known with certainty from only the Cougar stage and Castle Creek and Kalama periods, although the "floating island" lava flow [*Lawrence*, 1941; *Hoblitt et al.*, 1980] probably erupted in the 19th century [*Crandell*, 1987].

All chemical analyses reported by *Smith and Leeman* [1987; see also *Smith*, 1984] and *Crandell* [1987] from pre-Castle Creek tephras are silicic andesite or dacite (Figure 10), mostly with water-free SiO_2 contents of 61-68% but rarely as low as 57%.

The lack of mafic tephra suggests that no basaltic andesite or basalt was erupted before Castle Creek time. Proximal exposures are needed to test this suggestion, however, because such flows can be erupted with little tephra. Large dacite or silicic andesite domes of Pine Creek age, but no mafic flows, occur in the lower half

TABLE 2. Eruptive History of Mount St. Helens

Eruptive Stage or Period[1]	Age[2]	Tephra Set	Nature of Volcanism[3]
Present	1980-	1980	Phreatic explosions, cryptodome, landslide, blast; dacite t., p.f., and dome.
Goat Rocks	180-123[4]	T[6]	Dacite t. and dome; andesite flow
Kalama	500-350[5]	X W	Dacite t., p.f., and dome; andesite t.
Sugar Bowl	1150[5]	D[6]	Dacite dome, blast, t., and p.f.
Castle Creek	2200-1700[5]	B	Andesite, dacite, and basalt t.; andesite and basalt flows; andesite and dacite p.f.
Pine Creek	3000-2500[5]	P	Dacite t., dome, p.f.
Smith Creek	4000-3300[5,7]	Y	Dacite t., dome, p.f.
SWIFT CREEK	13-10 ka[7]	J S	Dacite t., dome, p.f.
COUGAR	21-18? ka[7]	K M	Dacite t., dome, p.f. and lava flows.
APE CANYON	<50-36? ka	C	Dacite t. and p.f.

Simplified from *Crandell* [1987]. [1]Stages are capitalized; periods are in Spirit Lake eruptive stage. [2]Approximate ^{14}C age in years before 1950. [3]t., tephra; p.f., pyroclastic flow; lahars formed in each stage. [4]Years before 1980, from tree-ring ages and historical records. [5]Years before 1980, from tree-ring and ^{14}C ages. [6]One tephra layer only. [7]Probably includes dormant intervals of at least a few centuries.

of the present crater wall, so it is unlikely that mafic flows were produced during Pine Creek time. Three dacite or silicic andesite domes of possible Smith Creek age or older crop out in the northern part of the crater; their age assignment is based on the presence of cummingtonite, which is absent in younger deposits. However, domes and tephras of a given period need not have the same phenocryst assemblage. Aside from these questionably older domes, no pre-Pine Creek deposits occur in the crater. Near-vent mafic flows, perhaps in a small cone [*Finn and Williams*, 1987], *could* underlie the Pine Creek domes. No direct evidence exists for such flows, but gabbro inclusions resembling those in the present dome [*Heliker*, 1983, 1984] occur in Cougar and Pine Creek deposits (J.S. Pallister, written commun., 1988) and suggest that mafic magma was in the reservoir system during much of Mount St. Helens history, possibly even before 50 ka [*Williams et al.*, 1987]. Nonetheless, the volcano has surely been *dominated* by silicic domes throughout most of its history.

A major compositional change occurred at the onset of Castle Creek time about 2200 years B.P. The period began, was dominated by, and ended with basalt, basaltic andesite, and lesser andesite, although dacite tephras, pyroclastic flows, and possibly a dome also formed (Figure 10) [*Mullineaux and Crandell*, 1981; *Smith and Leeman*, 1987; Crandell, 1987]. Numerous mafic lava flows, mostly borderline trachybasalt and trachybasaltic andesite [*Le Bas et al.*, 1986] (Figure 10) although more often called olivine basalt and two-pyroxene basaltic andesite, were erupted on all sides of the volcano, especially the southwest and north. The Cave Basalt (the one basalt plotted in Figure 10) issued from a vent probably near the southwest base of the cone about 1700 ^{14}C years B.P.; it contains 3.4-km-long Ape Cave, the longest known uncollapsed segment of a lava-tube, as part of its 8.3-km-long tube system [*Greeley and Hyde*, 1972].

Sugar Bowl dome on the north flank of the cone formed about 1200 ^{14}C years B.P. Two lateral blasts, the largest of which threw lithic lapilli 10 km northeast of the vent, probably accompanied dome growth [*Crandell and Hoblitt*, 1986]. East dome, at the east foot of the volcano, chemically resembles Sugar Bowl; it is undated, but bracketing ages allow it to be of Sugar Bowl age. The rhyodacitic compositions of both domes (Figure 10) are the most silicic (69-70%) yet found at Mount St. Helens [*Smith and Leeman*, 1987].

The Kalama eruptive period began in winter or early spring of 1479-1480, as deduced from dendrochronologic dating of the dacitic Wn tephra [*Yamaguchi*, 1983, 1985], the most voluminous tephra from Mount St. Helens since the Y tephras about 4000 years B.P. Another widespread tephra, We, fell in winter or early spring of 1481-1482. Episodic activity thereafter produced voluminous silicic andesite lava flows. The symmetric pre-1980 cone, known as North America's Fuji, was built by these and the older Castle Creek flows. A dacite dome formed at the summit during Kalama time, and lahars and pyroclastic flows were frequently produced.

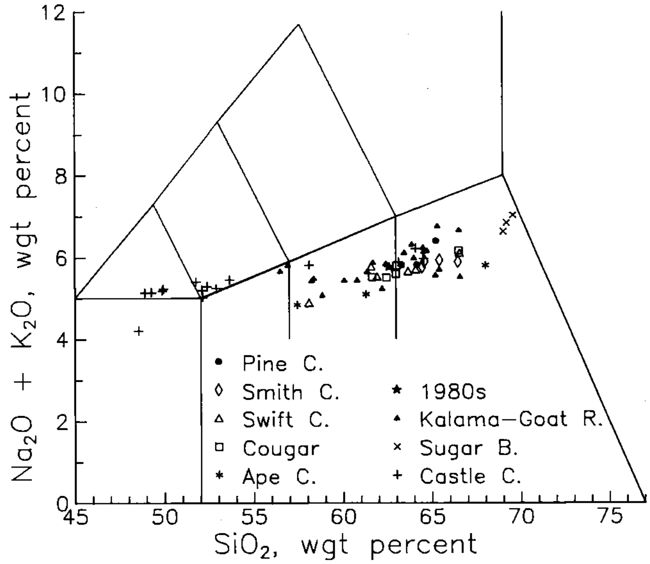


FIGURE 10. Total alkali-silica diagram for Mount St. Helens. Analyses from *Smith* [1984], *Smith and Leeman* [1987], and *Crandell* [1987], calculated water-free to 100%. Symbols indicate age (see text). Figure 17 gives field names.

The Goat Rocks eruptive period began in 1800 A.D. with the dacitic tephra layer T and ended in 1857 [*Crandell*, 1987]. The "floating island" silicic andesite flow was erupted before 1838, and an explosion sent lithic ash 100 km downwind in 1842. The Goat Rocks dome was extruded on the northwest flank of the volcano 600-700 m below the summit within several years after the 1842 explosion, possibly during or before 1847, when Paul Kane, a Canadian artist, painted a famous canvas of its growth. A large fan of debris spread downslope from the Goat Rocks dome; prismatic jointing is common in blocks of the fan, and paleomagnetic measurements indicate that some of the blocks were deposited above the Curie point and others below (R. P. Hoblitt in *Crandell* [1987]). Contemporary accounts indicate activity several times during the 1840s and 1850s but are non-specific and even contradictory. The last significant activity before 1980 was "dense smoke and fire" in 1857, although minor, unconfirmed eruptions were reported in 1898, 1903, and 1921 [*Majors*, 1980].

Volcanic Activity, 1980-1988

This activity has been thoroughly documented and is familiar to most volcanologists. See especially papers in *Lipman and Mullineaux* [1981], a series of nine papers in Science (v. 221, no. 4618, 1983), and *Swanson et al.* [1987] for general summaries. Only a synopsis is given here; other specifics are mentioned in the road log.

Seismicity began several days before March 20, 1980, when an earthquake (M=4.2) centered under the volcano commanded wide attention. The first of a series of small phreatic explosions occurred on March 27, accompanying the opening of a crater within a horseshoe-shaped graben concave northward at the summit of the cone. Strong seismicity continued, at times with bursts of volcanic tremor [*Endo et al.*, 1981; *Qamar et al.*, 1983]; deep tremor was felt state-wide in early April but died away without returning. By mid-April a bulge was obvious on the north flank of the volcano; geodetic measurements began shortly thereafter and documented horizontal growth of the bulge at a steady maximum rate of >1.5 m/day [*Lipman et al.*, 1981a]. The bulge was surface evidence of a cryptodome intruding the volcano. Seismicity continued into May, with fewer but larger earthquakes, and phreatic activity was intermittent. No magmatic gas was detected, although new fumaroles appeared in the crater and at the head of the bulge.

At 0832 on May 18, a complex earthquake (M=5.1) shook the volcano, probably causing (but possibly caused by) a huge, 2.7-km^3-landslide that in three different blocks successively removed the bulge and upper 400 m of the volcano [*Voight et al.*, 1981, 1983], leaving a 600-m-deep crater 2 km wide rim-to-rim. The landslide quickly developed into a debris avalanche that sped at 110-240 km/hr for 24 km down the North Fork Toutle River; arms of the avalanche entered Spirit Lake, 8 km from the summit, and overtopped 300-380-m high Johnston Ridge north of the Toutle. The avalanche buried the Toutle valley to a depth of nearly 50 m. Its hummocky deposit is distinctive; similar morphology at other volcanoes has been reinterpreted in light of its observed origin [*Siebert et al.*, 1987].

The landslide removed confining pressure on the cryptodome and its surrounding hydrothermal system. Juvenile gas was rapidly released from the cryptodome and superheated groundwater flashed to steam, causing a blast that exploded laterally from the collapsing north flank. The blast, called a "stone wind" by local journalists, knocked down most trees (the equivalent of about 150,000 houses) in a 600-km^2 area. Its maximum velocity may have been supersonic [*Kieffer*, 1981b]. The degree to which juvenile gas or flashed groundwater drove the blast is debated [*Eichelberger and Hayes*, 1982; *Kieffer*, 1981a, b; see also *Brugman*, 1988], as is the question of whether the blast was, in volcanologic terms, a low-aspect-ratio ignimbrite [*Walker and McBroome*, 1983] or a surge [*Hoblitt and Miller*, 1984; *Waitt*, 1984b].

Soon after the blast, a lahar rushed down the South Fork Toutle River and several streams draining the south and east flanks of the volcano. Whether water for these lahars came from snowmelt or from groundwater ejected by the eruption is hotly argued. The largest lahar, down the North Fork Toutle, did not start until early afternoon; it was fed as the debris avalanche dewatered [*Janda et al.*, 1981]. In addition to causing havoc along the rivers themselves, the lahars fed so much debris into the Columbia River that 31 ships were stranded in upstream ports until the 4-m-deep channel was dredged to its pre-eruption depth of 12 m—the first in a series of similar dredgings to maintain Portland as a seaport.

Juvenile dacite pumice and ash mixed with lithic debris began erupting soon after the blast [*Criswell*, 1987], perhaps from the shallow root of the cryptodome. The flux increased about noon, apparently with arrival of pumice from a 7-10-km-deep reservoir [*Rutherford et al.*, 1985; *Carey and Sigurdsson*, 1985; *Scandone and Malone*, 1985]. Experimental work suggests that just before eruption this reservoir was at a pressure of 220 ± 30 MPO, P_{water} was 0.5-0.7 P_{total}, and the temperature was 930° ± 10°C [*Rutherford et al.*, 1985]. Pyroclastic flows fed by the eruption column covered the debris avalanche in the upper North Fork Toutle basin, forming the pumice plain. Hydroexplosions created phreatic pits on the pumice plain, possibly as the pyroclastic flows covered the dewatering debris avalanche [*Moyer and Swanson*, 1987].

Plinian to subplinian explosions took place on May 25, June 12, July 22, August 7, and October 16-18, 1980. Products of the explosions decreased in SiO_2 content with time from 65 to 63% or less, possibly because they tapped a magma body zoned chemically [*Lipman et al.*, 1981b], mineralogically [*Kuntz et al.*, 1981], and in gas content [*Melson*, 1983; *Scandone and Malone*, 1985].

Small domes grew in June and August but were destroyed by the next explosion. The current dome began growing after the last major explosion on October 18. As of December 1988, 17 episodes of dome growth have taken place, each lasting several days to 1 year (1983-1984); the latest was in October 1986. The dome stands 267 m above its vent and 350 m above its north base, is 860 m by 1060 m across, and contains 74 x 10^6 m^3. The dome is highly phyric (30-35% plagioclase, 5% hypersthene, 1-2% hornblende, 1-2% Fe-Ti oxides, and <0.5% clinopyroxene [*Cashman*, 1988]), about 50% crystalline, and has about 63% SiO_2. Geodetic and seismic precursors enabled prediction of growth events [*Swanson et al.*, 1983, 1985; *Chadwick et al.*, 1988]. The geometry and volumetric rate of growth of the dome followed consistent patterns with time [*Swanson and Holcomb*, in press]. Several hundred small explosions occurred from the dome between 1980 and 1986, and a few large rockfalls spawned minor lithic pyroclastic flows and surges, none of which had sufficient volume to leave the crater [*Mellors et al.*, 1988]. Several small lahars formed when snow melted during explosions and rockfalls [*Waitt et al.*, 1983; *Waitt and MacLeod*, 1987].

Petrologic interpretation

Smith and Leeman [1987] found that the St. Helens dacite has similar or even lower contents of many incompatible elements than to basalt and andesite from the volcano but is relatively enriched in Ba, Rb, K, Cs, and Sr. The unusual depleted nature of the dacite, and low bulk distribution coefficients for numerous trace elements, preclude an origin by fractionation of the basalt or andesite. *Smith and Leeman* [1987] favor an interpretation involving melting of metabasaltic crustal rocks enriched in Ba, Rb, Cs, and Sr owing to interbedded sedimentary rocks or metasomatic enrichment of the source region. They consider mantle-derived basaltic magma to be the heat source for crustal melting.

WHITE PASS-GOAT ROCKS NEOGENE VOLCANISM

The White Pass-Goat Rocks area (Figure 2) has been host to volcanism since 4 Ma, producing at least 25 volcanoes and >175 km^3 of material [*Clayton*, 1983]. Geoff Clayton has been working in this area for many years, and the following is excerpted from his M.S. thesis [*Clayton*, 1983] and a USGS open-file report on the Goat Rocks Wilderness [*Swanson and Clayton*, 1983].

Pliocene volcanism (4-2.8 Ma) resulted in domes, tuff, and shallow intrusions of hornblende dacite north of White Pass. South of the pass, high-silica rhyolite tuff, many layers of which are welded, form a 650-m-thick section on the east flank of the present Goat Rocks area. Flow-layered rhyolite and autobreccia probably belong to one or more domes and have a zircon fission-track age of 3.2 Ma. *Smith* [in press b] mapped part of a caldera margin enclosing the rhyolitic deposits.

Silicic volcanism ended about 3 Ma, and undated olivine basalt was locally erupted onto the rhyolitic rocks. Soon thereafter lava flows of high-K_2O andesite, dominantly pyroxene-phyric but including some flows with abundant hornblende, began to form the large composite Goat Rocks volcano. Eruptions probably took place between about 2.5 Ma and 0.6 Ma, as judged from zircon fission-track ages and magnetic polarity. Some large-volume lava flows entered paleovalleys and advanced many kilometers from their source. The most notable of these flows is 2-km^3-Tieton Andesite, which moved about 80 km eastward down the valleys of the ancestral Tieton and Naches Rivers. Thick sections of lava flows with radial dips of 10-20° surround the hydrothermally altered core of the volcano; dikes cut the flows and define several sectors of a radial swarm. The Cispus Pass pluton occupies the southern part of the altered core and may be as young as 1 Ma (based on one fission-track age).

After a period of erosion, hornblende andesite erupted from vents near the core of Goat Rocks volcano. The highest point in the Goat Rocks area, Gilbert Peak (2476 m), is capped with hornblende andesite. Old Snowy Mountain along the Cascade crest erupted lava flows of hornblende andesite that poured westward into the glaciated Cispus River valley. The hornblende andesite is glaciated and at least as old as late Pleistocene. Whether it represents rejuvenation of the Goat Rocks volcano or independent volcanism is unclear.

More than 200 olivine basalt and basaltic andesite lava flows formed the 700-m-high Hogback Mountain shield volcano just south of White Pass during the late Pliocene and early Pleistocene. The flows intertongue with those from Goat Rocks. A magnetic reversal high in the shield may mark the base of the Olduvai event (1.7-1.9 Ma [*Mankinen and Dalrymple*, 1979]).

As volcanism at Goat Rocks and Hogback Mountain waned in the early Pleistocene, activity shifted to the Tumac Plateau north of White Pass. Most of the plateau is composed of hornblende andesite and olivine-bearing basaltic andesite. At least five volcanoes on the plateau are of late Pleistocene age. The youngest, Tumac Mountain, is a basaltic shield that last erupted 20-30 ka according to tephra studies [*Clayton*, 1983].

Many Pliocene and Quaternary lava flows of olivine basalt erupted in a zone extending 25 km south from the Goat Rocks to Mount Adams [*Hildreth and Fierstein*, 1985]. One vent, the subglacial Walupt Lake volcano, may date from the Evans Creek maximum *ca.* 18-15 ka [*Hammond*, 1980; *Swanson and Clayton*, 1983].

INDIAN HEAVEN VOLCANIC FIELD

The Indian Heaven volcanic field (Figure 2), midway between Mount St. Helens and Mount Adams, is a Quaternary center, chiefly of basalt. Paul Hammond has worked here for many years but has published few detailed results [*Hammond et al.*, 1976; *Hammond and Korosec*, 1983; *Hammond*, 1984, 1987]. He graciously allowed some of his work to be summarized, mainly from an informal field guide he wrote in 1985.

About 60 eruptive centers lie on the 30-km-long, N10°E-trending, Indian Heaven fissure zone [*Hammond*, 1984; *Hammond et al.*, 1976]. The 600-km^2 field has a volume of about 100 km^3 and forms the western part of a 2000-km^2 Quaternary basalt field in the southern Washington Cascades, including the King Mountain fissure zone along which Mount Adams was built [*Hammond et al.*, 1976; *Hildreth et al.*, 1983].

All lava flows at Indian Heaven have normal magnetic polarity [*Hammond et al.*, 1976] and so are assumed to be younger than about 0.73 Ma, consistent with their morphology and geomorphic relations. Two K-Ar ages [*Hammond and Korosec*, 1983; *Hammond*, 1987] suggesting ages between 3 and 4 Ma are probably too old [*Korosec*, 1987a, b]; they are based on trace contents of radiogenic argon, and no evidence exists for a long hiatus or marked erosion to explain the lack of reversely magnetized flows in the section. The youngest eruption produced Big Lava Bed about 8200 ^{14}C years B.P.

The field is dominated by small shield volcanoes surmounted by cinder and spatter cones. Subglacial vents occur on the northwest flank of the field [*Hammond*, 1987]. The overall shape of the field is that of a north-south elongate shield, with basal diameters of 30 km and 10-15 km, whose center rises about 1 km above its base. *Hammond* [1984] noted that most of the flows erupted from the center of the field. Hence Indian Heaven can be interpreted as a large, complex shield volcano, fed by a central reservoir, that supports numerous flank vents.

Pahoehoe and a'a typify the basalt flows; some of the andesite is block lava. Tephra production was minimal, although the basaltic tephra accompanying extrusion of the Big Lava Bed flow has a volume of about 10^5 m^3. Big Lava Bed is known for its tubes and for the remarkable microtopography on its surface, which mostly results from inflation of the flow when its feeder tubes clogged.

The field is dominantly basaltic (Figure 11) [*Smith*, 1984; *Hammond*, 1984], but basaltic andesite and andesite also occur. Mann Butte, a rhyolite dome or plug east of the field, was once considered to be Pleistocene [*Hammond et al.*, 1976] but now is interpreted as Tertiary (P.E. Hammond, oral commun., 1986). About half of the basaltic andesite and andesite was erupted on the flank of the field, possibly from fractionated stranded magma bodies, and the rest in the central part of the field [*Hammond*, 1984]. Both low-K, olivine-normative tholeiitic basalt and high-Al, hypersthene-normative calc-alkaline basalt occur [*Smith*, 1984; *Hammond*, 1984], as well as transitional types. In this regard the basalt at Indian Heaven is representative of basalt elsewhere in the southern Washington Quaternary field [*Smith*, 1984].

The field occupies a 100-mgal gravity low [*Hammond et al.*, 1976; *Williams et al.*, 1988] that may reflect light Tertiary rocks below the field, a hydrothermally altered or fractured zone, or a shallow magma reservoir as yet undetected by other means.

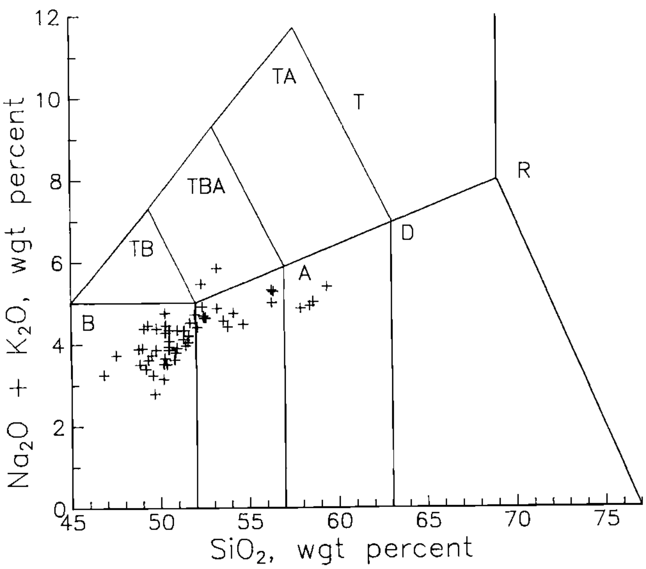


FIGURE 11. Total alkali-silica diagram for Indian Heaven. Unpublished analyses courtesy of P. E. Hammond; published analyses from *Smith* [1984]. Field names as in Figure 17; R, rhyolite; T, trachyte.

The elongate field follows the direction of regional extension and faulting as well as overall volcanism in the Cascades. A few north-trending normal faults are mapped just northeast and southwest of the field [*Walsh et al.*, 1987], chiefly on the basis of relations within the Tertiary section. Little is known of their ages, not surprising in view of the overall lack of detailed knowledge of the Tertiary rocks in the southern Washington Cascades.

MOUNT HOOD

Mount Hood (Figure 12), 3428 m high, is the fourth highest peak in the Cascades and the highest in Oregon. It was named after a British admiral and first described in 1792 by William Broughton, member of an expedition under command of Captain George Vancouver [*Broughton*, 1929]. The first geologic reconnaissance primarily described the existing glaciers [*Hague*, 1871]. A complete geologic study of Mount Hood is still wanting; no detailed geologic map exists, and few ages have been obtained on lava flows that form most of the cone.

Early History

The Mount Hood area has hosted volcanic activity since at least the middle Miocene. More than 400 m of locally derived intermediate and silicic volcaniclastic rocks (14-11-Ma Rhododendron Formation) interfinger with and overlie the Wanapum Basalt of the Columbia River Basalt Group [*Wise*, 1968, 1969; *Priest et al.*, 1982; *Keith et al.*, 1982, 1985]. The Rhododendron underlies flows of the 10.5-Ma Last Chance andesite of *Priest et al.* [1982]. Both units are cut by the Laurel Hill and Still Creek quartz diorite plutons and related offshoots, with K-Ar ages of *ca.* 9.3-8.5 Ma [*Bikerman*, 1970; *Priest et al.*, 1982; *Keith et al.*, 1985]. In the Pliocene local vents erupted thick flows of andesite and minor basalt that cap many ridges surrounding Mount Hood (Zigzag Mountain, Tom Dick and Harry Mountain) [*Wise*, 1969].

The late Pliocene Sandy Glacier volcano (Figure 12) produced basalt, basaltic andesite, and minor andesite near the site of Mount Hood [*Wise*, 1968, 1969]. More than 900 m of this composite cone are exposed on the west flank of Mount Hood under Sandy and Reid Glaciers and contain the most mafic rocks known on Mount Hood (Figures 13 and 14). The youngest exposed flows of the Sandy Glacier volcano have a K-Ar whole-rock age of about 1.3 Ma [*Keith et al.*, 1985]. Reversely magnetized andesite flows of approximately the same age [*Keith et al.*, 1985] occur in inverted topography on Vista Ridge and apparently came from a vent now buried under the north flank of Mount Hood. Aeromagnetic data indicate a reversely magnetized body, perhaps the source of the flows, beneath the northern flank [*Flanagan and Williams*, 1982; *Williams and Keith*, 1982].

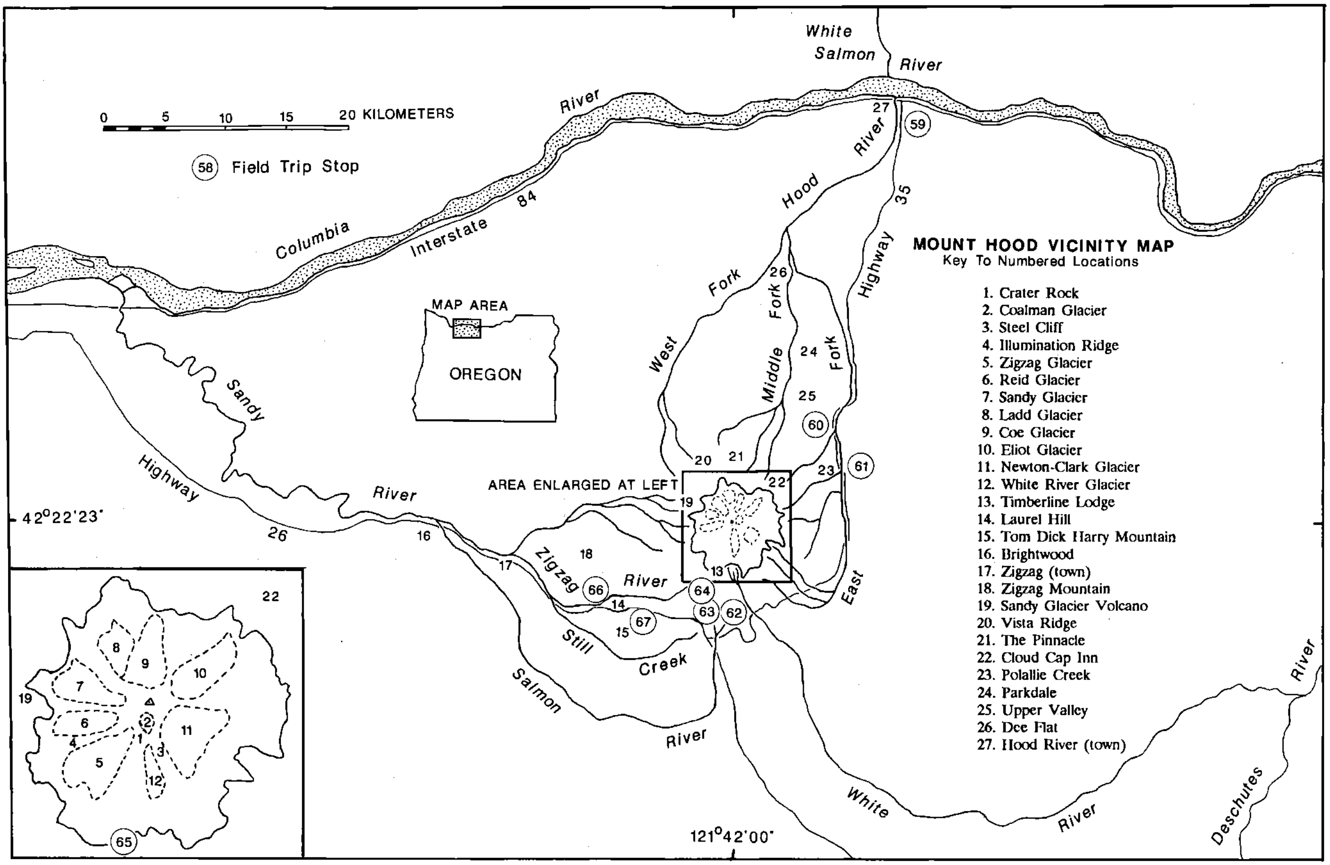


FIGURE 12. Map of Mount Hood area, showing localities mentioned in text and locations of stops.

Construction of the Cone

The age of the main edifice of Mount Hood is poorly known. All tested lava flows have normal magnetic polarity, so the cone is probably younger than 0.73 Ma. Whole-rock K-Ar ages for two flows and one dike of the main cone range from 0.6 to 0.3 Ma [*Keith et al.*, 1985]; the dated flows are from stratigraphically low parts of the section in the upper Zigzag River canyon.

The volcano comprises approximately 70% andesite flows and 30 percent clastic material (mostly concentrated high on the cone) [*Wise*, 1969]. Flows near the summit dip away from a source higher than, and north of, the present summit. Most of the flows are less than 3 m thick, but notable exceptions occur in Steele Cliff and Illumination Ridge, where lava apparently ponded to depths of over 100 m. Eruptions were relatively nonexplosive, and significant tephra deposits were limited to the flanks and a small area east of the mountain, where they rarely total more than 1 m thick.

Most of the cone-building flows are medium-K silicic andesites (Figure 14); a few others are mafic dacite. The cone-building flows include no basaltic andesite or basalt, in contrast to the older Sandy Glacier volcano. The cone-building flows are phyric, chiefly two-pyroxene andesite with lesser olivine andesite; hornblende is a disequilibrium phase in about half of the flows. Neither *Wise* [1969] nor *White* [1980] recognized an overall change with time in major-or trace-element compositions.

After construction of most of the cone, relatively small flows erupted from satellite vents on Vista Ridge and The Pinnacle (Figure 12). A flow from The Pinnacle has a K-Ar whole-rock age of 0.15 ± 0.02 Ma [*Keith et al.*, 1985]. *Wise* [1969 interpreted flows erupted near Cloud Cap Inn to be young, but one sample yielded whole-rock K-Ar ages of 0.49 to 0.65 Ma, similar to or even older than the age of the main cone [*Keith et al.*, 1985]. The satellite flows including Cloud Cap are more mafic than the andesite forming the main cone [*Wise*, 1969; *White*, 1980], comprising medium-K mafic andesites or basaltic andesites (Figures 13 and 14).

Between about 0.05 and 0.1 Ma (based on profiles of soil development), a sector collapse on the north or northeast side of the volcano formed a debris avalanche that traveled the length of Hood River, crossed the Columbia River, and moved 5 km up the White Salmon River—a distance of at least 40 km (Figure 12) [*Vallance*, 1986]. The avalanche deposits locally are more than 40 m thick; much of Hood River town is built on them. No source for the avalanche is evident, and no avalanche deposits crop out within 10 km of the volcano, because of a blanket of glacial outwash. This leaves as a mystery the exact point of origin of what is probably the largest single event to occur on Mount Hood.

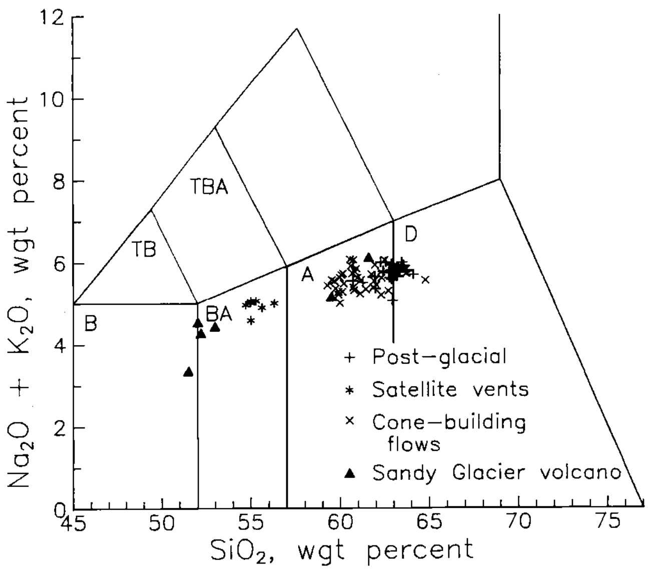


FIGURE 13. Total alkali-silica diagram for Mount Hood. Representative analyses from *Wise* [1969] and *White* [1980], recalculated water-free to 100%. Figure 17 gives field names.

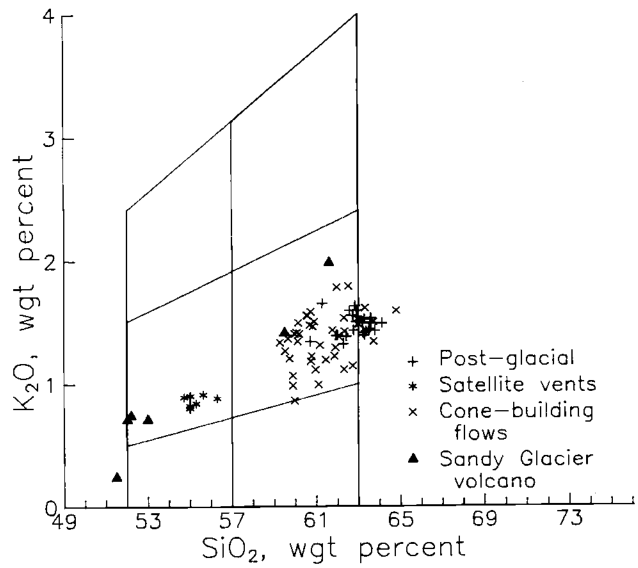


FIGURE 14. Andesite classification for Mount Hood, from *Gill* [1981] except that basalt-andesite division is 52%. Data sources as in Figure 13; fields as in Figure 7.

The 5-km-long Parkdale flow erupted in Upper Hood River Valley about 6 ka. It chemically resembles the basaltic andesite from The Pinnacles [*Wise*, 1969].

The latest addition to the cone was a composite hornblende dacite dome, Crater Rock, just south of the summit. *Wise* [1969] considered the dome as coeval with the main stage of cone building, but *Crandell* [1980] and *Cameron and Pringle* [1986] interpreted it to have formed 200-300 years ago.

The summit of Mount Hood is about 1 km south of the apex of a gravity high of at least 8 mGals. *Williams and Keith* [1982] interpret the high to reflect a dense intrusive body that fed Mount Hood and its forerunners.

Glaciation

Twelve glaciers and named snowfields cover approximately 80% of the cone above the 2100-m level and contain about 0.35 km^3 of ice [*Driedger and Kennard*, 1986]. Most of the glaciers have remained roughly constant in size over the last few decades, after retreating from a neo-glacial maximum early in the 18th century [*Lawrence*, 1948].

Modern glacier termini are at about 2100 m, but in the last major alpine glaciation (Fraser, about 29-10 ka) glaciers reached the 700-800 m level. During this time, ice spread 15 km from the summit area [*Crandell*, 1980].

Lacustrine siltstone from near-terminus periglacial lakes plaster valley walls just upstream from the mouth of Polallie Creek on the east side of the mountain. Highway 35 crosses White River near the maximum extent of Fraser ice, and the left-lateral moraine is prominent just upstream from the bridge. The full extent of the Fraser-age glaciers has not been accurately mapped.

Glacier retreat released large volumes of outwash, some of which filled the ancestral Hood River Valley near Parkdale, forming the flat surfaces of Upper Hood River Valley and Dee Flat. Outwash also formed a debris fan in the upper East Fork Hood River.

Evidence of older glaciation is seen in roadcuts on the southeast side of the volcano and in rolling morainal landscape near Brightwood west of the volcano. The deposits are not dated but may be coeval with the Hayden Creek Drift near Mount Rainier [*Crandell*, 1980], probably about 0.14 Ma [*Colman and Pierce*, 1981].

Postglacial Eruptive History

Mount Hood has had at least four eruptive periods in and after late Fraser time, in order of decreasing age: 1) Polallie (15-12 ka [*Crandell*, 1980]), 2) Timberline (1400 to 1800 years B.P. [*Crandell*, 1980; *Cameron and Pringle*, 1986]), 3) Zigzag (400 to 600 years B.P. [*Cameron and Pringle*, 1986]), and 4) Old Maid (170 to 220 years B.P. [*Cameron and Pringle*, 1987]). Work in progress will determine the details of these episodes in order to assess hazards of a future eruption.

The Polallie eruptive period occurred during the final stage of the Fraser Glaciation [*Crandell*, 1980]. Lahars, thin tephras, and pyroclastic flows intertongue with late Fraser-age outwash in Upper Hood River Valley. Elsewhere, Polallie deposits mantle ridge crests and valley walls but not valley floors. Probably glacial ice still occupied valley floors at the time of the eruptions. No radiometric ages have been obtained for the Polallie.

The Timberline eruptive period broke the apparent 10-ka-long post-Polallie quiescence. The vent shifted from its summit location during Polallie time to the high southwest flank. Erupted material except airfall tephra was consequently confined to the Sandy, Salmon, and

Zigzag River drainages, where it formed the broad, gently-sloping debris fan that dominates the southwest flank of the volcano. Pyroclastic flows dated at 1440 ± 155 years B.P. [*Cameron and Pringle*, 1986] moved at least 8 km down the Zigzag River, and lahars reached the mouth of the Sandy River more than 80 km from the volcano. Small debris fans formed in the canyons of the upper Salmon and Sandy Rivers. An upper age for the Timberline of 1830 ± 50 years B.P. was obtained from a pyroclastic-flow deposit near Zigzag (K. A. Cameron and P. T. Pringle, unpub. data).

The Zigzag eruptive period was apparently minor, feeding several lahars and related floods into the Zigzag River and one pyroclastic flow into the Sandy River. The pyroclastic flow has an age of 455 ± 135 years B.P., and trees buried by the first lahars are 550 ± 130 years old [*Cameron and Pringle*, 1986].

The Old Maid eruptive period apparently began with emplacement of the Crater Rock hornblende dacite dome high on the north flank of the cone. Reconnaissance work shows that the dome comprises three lobes of markedly differing internal structure [*Cameron and Pringle*, 1986] but does not clarify how each lobe relates to the others. Numerous lahars probably fed by avalanches from the dome and accompanying snowmelt entered the Sandy, Zigzag, Salmon, and White Rivers; a pyroclastic flow traveled from the Crater Rock area at least 9 km along the White River. One lahar extends 65 km along the White River, and the sandy run-out deposit from another is identifiable 80 km from the mountain. At least 60 m of lahar and fluvial deposits partly fill the upper White River canyon near Timberline Lodge. A terrace made of a lahar overlain by reworked eruptive debris is more than 13 m thick on the lower Sandy River, 60 km from the mountain. Dendrochronologic dating of some of these events [*Cameron and Pringle*, 1987] indicates that the Sandy River lahar occurred in the mid-1790s, the pyroclastic flow in the upper White River about 1800, and the lahar that traveled 80 km down the White River between 1800 and 1810.

The post-glacial products are dominantly mafic dacite and silicic medium-K andesite [*Wise*, 1969; *White*, 1980; *Crandell*, 1980], generally more silicic than the cone-building flows. *White* [1980, p. 5] claims that, within the post-glacial sequence, "a general trend can be seen in which rocks from the younger units are slightly richer in SiO_2 and poorer in MgO, CaO, and Fe_2O_3."

Historical Activity

No major eruptive events have occurred at Mount Hood since systematic records began in the 1820s. Reports of steam and tephra emissions accompanied by red glows or "flames" from the area of the post-glacial vent are known from 1859, 1865 (twice) and 1903 A.D. No tephra deposits have been correlated with these events, though the summit area is capped by stratified tephra and scattered pumice blocks and breadcrust bombs.

Present thermal activity is in fumarole fields near Crater Rock, at the apex of a semi-circular zone of fumaroles and hydrothermally-altered, heated ground. In summer 1987, maximum ground temperatures were near 85°C and maximum fumarole temperatures were about 92°C [*Cameron*, 1988], slightly above the boiling point of water at 3100 m. Many of the fumaroles are actively precipitating crystalline sulfur. Comparison of modern and historical photographs shows that the amount of perpetually snow-free ground surrounding the fumarole fields has been increasing since last century. Until the 1980 eruption of Mount St. Helens, the only volcanically related human fatality in the Cascades occurred in the thermal area at Mount Hood in 1934, when a climber exploring ice caves in Coalman Glacier melted by fumaroles suffocated in the oxygen-poor gas.

Jökulhlaups (glacial-outburst floods) have been recorded from the Zigzag, Ladd, Coe, and White River Glaciers. In 1922, a dark debris flow issued from a crevasse high on Zigzag Glacier and moved 650 m over the ice before entering another crevasse; this event initiated a scare that Mount Hood was erupting [*Conway*, 1921]. The Ladd Glacier jökulhlaup in 1961 destroyed sections of the road around the west side of the mountain and partly undermined a tower of a major powerline [*Birch*, 1961]. The Coe Glacier outburst occurred around 1963, causing a section of trail to be abandoned and the "round-the-mountain" trail to be rerouted farther from the glacier. Jökulhlaups from White River Glacier were reported in 1926, 1931, 1946, 1949, 1959, and 1968; the Highway 35 bridge over the White River was destroyed during each episode. The more frequent outbursts from White River Glacier may be due in part to an increase in size of the fumarole field at the head of the glacier at Crater Rock [*Cameron*, 1988].

A rainfall-induced debris flow on Polallie Creek on Christmas 1980 killed one and destroyed an 8-km section of Highway 35. The flow started as a moderate slope failure of only 3800 m^3 but rapidly bulked up and deposited over 76,000 m^3 of debris at the mouth of Polallie Creek [*Gallino and Pierson*, 1984]. The debris dammed the East Fork Hood River, creating a temporary lake; the dam breached, and flooding destroyed the highway.

Felt earthquakes occur on Mount Hood occur every 2 years on average. Seismic monitoring, in effect since 1977 [*Weaver et al.*, 1982], indicates a generalized concentration of earthquakes just south of the summit area and 2-7 km below sea level. A seismic swarm in July 1980, during which nearly 60 earthquakes (mostly 5-6 km deep with a maximum bodywave magnitude of 2.8) recorded in a 5-day period [*Rite and Iyer*, 1981], prompted development of an emergency response plan to coordinate local authorities in the event of future eruption.

Geodetic surveillance of the volcano was initiated in 1980, and 30 EDM lines and several tilt stations were resurveyed in 1983 and 1984 [*Chadwick et al.*, 1985;

Cascades Volcano Observatory, unpub. data]. Observed changes are within the range of expected error.

COLUMBIA RIVER BASALT GROUP

The Columbia River Basalt Group (CRBG) is the youngest and most studied flood basalt. The province underlain by the basalt is loosely termed the Columbia Plateau (Figure 1). Such an overall designation is a misnomer, however, for the basalt has been sharply folded and broadly warped, so that its top varies in elevation from slightly below sea level in the Pasco Basin to more than 2.5 km above sea level in the Wallowa Mountains of northeast Oregon. On this trip we see a small part of the western section of the plateau, as well as part of the route taken by flows as they followed the ancestral Columbia River across the Cascades.

Stratigraphy and age

The group is formally divided into five formations (Figure 15), which in turn are broken into formal and informal members [*Swanson and others*, 1979a; *Camp*, 1981; *Beeson et al.*, 1985; *Reidel et al.*, in press; *Bailey*, in press]. On this trip we will visit flows in the Grande Ronde and Wanapum Basalts only.

The group has a volume of about 174,000 km^3 and covers about 164,000 km^2 [*Tolan et al.*, in press]. These figures have been revised downward from previous estimates. It was erupted between 17.5 and 6 Ma, as measured by K-Ar and ^{40}Ar-^{39}Ar ages [*Long and Duncan*, 1983; *McKee et al.*, 1977, 1981; *Swanson et al.*, 1979a]. Early eruptions (17.5-17 Ma) fed the Imnaha Basalt, which is confined to the southeast part of the province [*Hooper et al.*, 1984]. Most of the group was formed during a 1.5-m.y. period between about 17 and 15.5 Ma (Figure 16), resulting in the Grande Ronde Basalt [*Mangan et al.*, 1986; *Reidel et al.*, in press] and the greatly subordinate and geographically limited Picture Gorge Basalt [*Waters*, 1961; *Bailey*, 1986]. Later eruptions formed the Wanapum Basalt (about 15.5-14.5 Ma) and the Saddle Mountains Basalt (about 14-6 Ma) [*Swanson et al.*, 1979a; *Camp*, 1981; *Beeson et al.*, 1985]. Relatively little erosion took place between flows, owing to the rapid rate of accumulation, except during Saddle Mountains time. However, a regionally extensive saprolite (fossil soil) or a sedimentary interbed separates the Grande Ronde and Wanapum in most places; flows just below and above the contact typically are normally magnetized, so that the time represented by the break is probably less than a few hundred thousand years, most likely less than 100,000 years. In Saddle Mountains time, however, interflow erosion was significant, and most contacts are erosional unconformities.

series	group	sub-group	formation	member	mag polarity
Miocene	Columbia River Basalt Group	Yakima Basalt Subgroup	Saddle Mountains Basalt	Lower Monumental Member	N
				Ice Harbor Member	N,R
				Buford Member	R
				Elephant Mountain Member	R,T
				Pomona Member	R
				Esquatzel Member	N
				Weissenfels Ridge Member	N
				Asotin Member	N
				Wilbur Creek Member	N
				Umatilla Member	N
			Wanapum Basalt	Priest Rapids Member	R3
				Roza Member	T,R
				Frenchman Springs Member	N2
				Eckler Mountain Member	N2
			Grande Ronde Basalt		N2
					R2
			Picture Gorge Basalt		N1
					R1
			Imnaha Basalt		R1
					T
					N0
					R0

FIGURE 15. Stratigraphic subdivision of Columbia River Basalt Group. N, normal magnetic polarity; R, reversed polarity; T, transitional polarity. Subscripts denote magnetostratigraphic units.

Chemical composition

All major flows within the Yakima Basalt Subgroup (focus of this trip) are tholeiitic, with MgO contents from 2.75 to 8.25% (Table 3; Figure 17). Specific chemical compositions characterize each formation (*Wright et al.*, in press]. Flows of the Grande Ronde Basalt are aphyric and have low MgO (3-6%), high SiO_2 (52-58%), relatively low TiO_2 (1.5-2.5%) and FeO (9-13%), and a

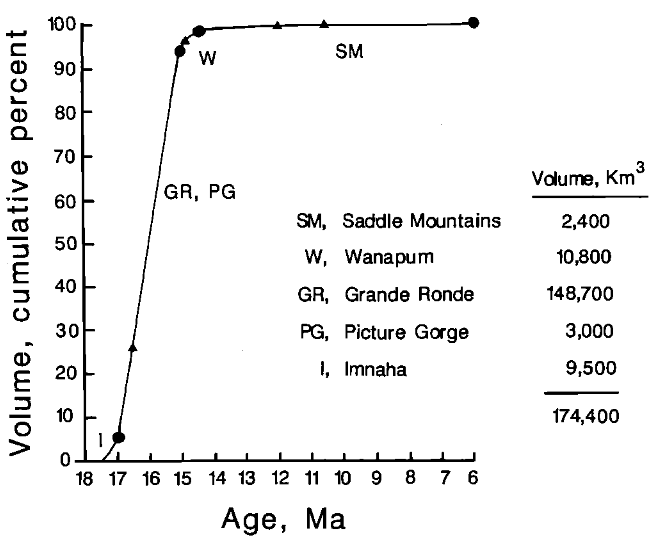


FIGURE 16. Cumulative volume erupted vs. age for units of Columbia River Basalt Group. Dots separate formations; solid triangles are selected radiometric dates. Data from *Tolan et al.* [in press].

TABLE 3. Representative Major-Oxide (%) and Trace-Element (ppm) Analyses of Grande Ronde, Wanapum, and Saddle Mountains Basalts [*Wright et al.*, in press]

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
SiO_2	53.84	55.69	49.90	52.37	51.70	50.94	49.95	50.12	54.76	54.34	50.87	54.26	52.00	51.27	47.51	50.20
Al_2O_3	14.37	13.78	16.82	15.47	13.48	14.27	13.44	14.17	14.24	14.49	16.05	13.85	15.04	13.28	13.79	14.17
"FeO"	11.37	11.85	10.16	10.78	14.35	13.50	14.78	13.93	12.29	11.18	9.54	12.65	10.45	14.79	15.03	14.21
MgO	5.25	3.51	8.21	5.91	4.44	4.57	4.50	5.16	2.75	4.51	8.25	3.98	7.19	4.18	6.05	4.89
CaO	8.97	7.11	10.83	9.90	8.08	8.56	8.67	8.82	6.21	8.42	10.79	7.40	10.39	8.35	9.75	8.63
Na_2O	2.92	3.20	2.43	2.91	2.74	2.85	2.80	2.59	3.39	2.65	2.29	2.58	2.23	2.44	2.28	2.69
K_2O	1.10	2.01	0.37	0.68	1.36	1.25	1.21	1.05	2.56	1.76	0.39	1.71	0.65	1.25	0.78	1.44
TiO_2	1.75	2.23	0.97	1.46	3.02	3.12	3.60	3.23	2.79	1.90	1.48	2.92	1.62	3.61	3.70	2.93
P_2O_5	0.23	0.43	0.17	0.36	0.61	0.68	0.84	0.73	0.82	0.51	0.19	0.44	0.24	0.60	0.87	0.64
MnO	0.19	0.20	0.14	0.15	0.22	0.25	0.20	0.19	0.19	0.23	0.14	0.22	0.18	0.23	0.24	0.20
Ba	472	730	175	348	549	556	600	539	3313	876	303	592	243	485	611	541
Ce	38.0	54.2	16.3	32.3	51.0	54.2	62.7	57.4	88.2	80.5	31.5	73.8	35.3	68.7	85.6	67.8
Cr	54.9	12.5	151.4	159.7	39.5	44.3	13.6	82.0	3.6	36.6	283.7	18.9	109.0	18.5	148.8	24.0
La	19.5	27.6	7.6	15.2	25.4	27.0	31.1	28.0	46.7	43.7	15.7	38.2	17.0	33.7	42.9	35.3
Nb	11.5	13.0	6.0	8.7	13.0	17.0	17.0	15.8	21.3	16.7	13.0	21.8	13.0	24.5	23.7	25.7
Ni	15.5	--	117.0	42.7	39.3	33.6	27.0	35.0	2.7	47.0	203.3	16.0	51.3	30.7	42.0	28.5
Rb	30.5	45.4	--	15.8	35.4	31.4	34.6	26.6	47.0	38.2	10.0	47.3	10.0	27.6	19.8	18.0
Sm	5.6	7.3	2.7	4.2	6.1	6.9	7.6	7.9	9.8	7.8	4.3	8.4	4.7	9.4	10.7	7.1
Sr	335	359	353	397	317	313	286	302	276	277	252	257	227	213	227	350
Th	3.4	6.38	0.37	1.16	3.88	3.98	4.04	3.56	7.25	6.65	2.05	8.67	2.55	5.91	2.19	4.98
Yb	3.25	3.13	2.10	3.08	3.52	3.89	4.62	3.92	4.52	4.23	2.37	3.65	2.73	4.58	5.64	3.13
Zr	135	178	96	136	196	223	238	223	520	282	--	240	--	316	293	350

Grande Ronde Basalt:
1, High MgO
2, Low MgO
Wanapum Basalt:
3, Eckler Mountain Member, Robinette Mountain flow
4, Eckler Mountain Member, Dodge flow
5, Frenchman Springs Member
6, Roza Member
7, Priest Rapids Member, Rosalia type
8, Priest Rapids Member, Lolo type

Saddle Mountains Basalt:
9, Umatilla Member
10, Wilbur Creek Member
11, Asotin Member
12, Esquatzel Member
13, Pomona Member
14, Elephant Mountain Member
15, Ice Harbor Member, Basin City flow
16, Lower Monumental Member

relatively low initial $^{87}Sr/^{86}Sr$ isotopic ratio (0.703-0.705). Most flows of the Wanapum Basalt have lower SiO_2 (49-52%) for the same range of MgO, much higher contents of TiO_2 (>3%) and FeO (13-15%), and slightly higher initial $^{87}Sr/^{86}Sr$ (0.704-0.7055). Both formations have similar trace-element contents despite the contrasts in major-oxide composition. Chondrite-normalized rare-earth patterns for both formations are enriched in light rare earths, slightly concave upward with small or no negative europium anomalies, and parallel or slightly convergent toward the heavy rare earths at differing degrees of absolute rare-earth content.

Flows of the Saddle Mountains Basalt span a wide range of major oxide compositions, some of which resemble those of older units. With few exceptions, incompatible trace elements are enriched and compatible elements (particularly Sr and Sc) depleted relative to older units, and $^{87}Sr/^{86}Sr$ ratios are higher (>0.707). Chondrite-normalized rare-earth patterns for many units are steeper, with a more marked negative europium anomaly, than are those of the older formations. The Umatilla is the only member in the Saddle Mountains with a large positive europium anomaly.

Vent Systems

Linear vent systems occur only in the eastern half of the province, except for feeders of the Picture Gorge (the Monument dike swarm) near the southern limit of the province (Figure 1) [*Waters*, 1961; *Swanson et al.*, 1975, 1979a; *Tolan et al.*, in press]. Some vent systems are longer than 150 km, and all trend within a few degrees of due north, mostly north-northwest. The systems are correlated with specific stratigraphic units chiefly by the presence of dikes of appropriate chemical composition, petrography, magnetic polarity, and stratigraphic position. Hundreds of dikes have been identified, although many probably represent *en echelon* segments of one vent system [*Waters*, 1961; *Taubeneck*, 1970]. Most dikes are known from Chief Joseph dike swarm in the tri-state area of Washington, Oregon and Idaho [*Taubeneck*, 1970]. Distribution patterns for some flows of the Grande Ronde Basalt suggest that their feeder dikes are hidden beneath younger flows north of the Chief Joseph swarm [*Reidel et al.*, in press]. The dikes typically are a few meters wide, but some are wider than 20 m. Composite dikes, consisting of basalt of two or more different compositions and hence ages, have not been found, but multiple dikes, with internal jointing patterns suggestive of two or more pulses during the same intrusive event, are common. Remnants of spatter cones and other near-vent features, similar to those of modern Kilauea, occur locally [*Swanson et al.*, 1975]. The degree of vesicularity and breakage of pyroclasts in these deposits resembles that of modern basaltic tephra, so it is unlikely that the magma was unusually rich in gas.

Volumes and Eruption Rates

Flood-basalt provinces by definition contain flows of huge volume, on the order of 5-10 km^3 or more; this is the major distinction between flood-basalt and plains-basalt provinces [*Greeley*, 1977], such as the Snake River Plain and Iceland, in which flows are generally much less than 1 km^3. Recent work by *Tolan et al.* [1987, in press] suggests that about 300 *great* flows were erupted on the Columbia Plateau, with an average volume per flow of about 580 km^3. Numerous low-volume flows are probably present near vents, but the great flows form most of the province. Flows with volumes more than 100 km^3 occur in all of the formations, but most such flows were erupted during Grande Ronde time, when at least 110 major flows with volumes of 90 km^3 to more than 5000 km^3 were produced [*Reidel et al.*, in press; *Tolan et al.*, 1987, in press]. Such a huge eruption, if from a shallow crustal source, would probably have resulted in recognizable subsidence along the trace of its fissure system. No such evidence has been found, so the inference on geologic grounds alone is that the eruptions tapped a deep reservoir. Viewed regionally, the overall saucer-like subsidence of the province might reflect withdrawal of magma, but its amplitude and diameter would demand a deep source. Petrologic evidence [*Helz*, 1978; *Hooper*, 1984; *Wright et al.*, in press] supports a deep storage reservoir, perhaps at the base of the lithosphere.

Model calculations [*Shaw and Swanson*, 1970], based on evidence that little cooling occurred during flowage of hundreds of kilometers, suggest that eruption and emplacement spanned only a few days for these huge outpourings. The flows evidently moved 5-15 km/hour or faster [*Shaw and Swanson*, 1970] and advanced as sheet floods; no lava tubes have been found. The evidence for little cooling during transport is that flows quenched to glass when they entered water after traveling several hundred kilometers; the crystal content of the glass is no higher than that of chilled margins of feeder dikes. The effective viscosity of the lava was *not* unusually low; in

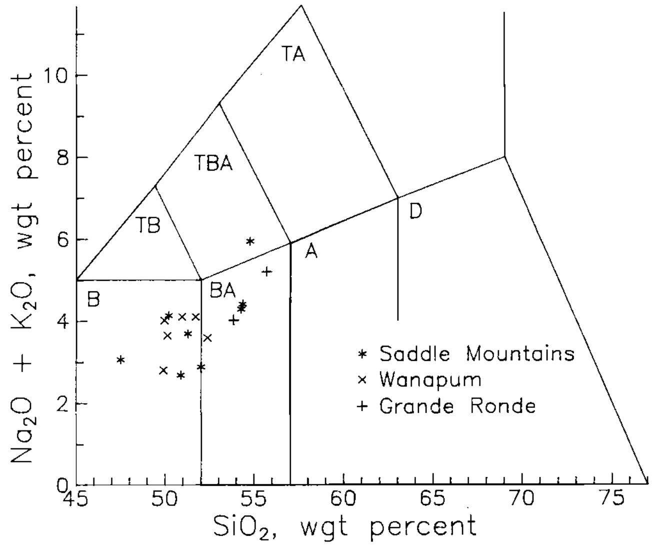


FIGURE 17. Total alkali-silica diagram for Yakima Basalt Subgroup. Selected analyses from *Wright et al.* [in press]. Rock types and fields from *Le Bas et al.* [1986]. B, basalt; BA, basaltic andesite; A, andesite; D, dacite; TB, trachybasalt; TBA, trachybasaltic andesite; TA, trachyandesite.

fact, calculations of the viscosity based on the chemical composition for a range of reasonable water contents indicate that the lava was somewhat more viscous than modern Kilauea lava. According to *Shaw and Swanson* [1970], the high rate of eruption (about 1 km^3/day/linear kilometer of fissure or higher, 3-4 orders of magnitude faster than rates of Hawaiian and Iceland eruptions [*Swanson et al.*, 1975]) combined with the huge volume of available magma enabled the flows to travel so far, a relation that *Walker* [1973] found on empirical grounds (Figure 18). Regional mapping [*Swanson et al.*, 1979b, 1980, 1981] indicates that the flows ponded against opposed slopes, including locally recognizable natural levees, and formed low-aspect-ratio (0.0002-0.0001) lava lakes generally 30-40 m thick and 200-400 km in diame-

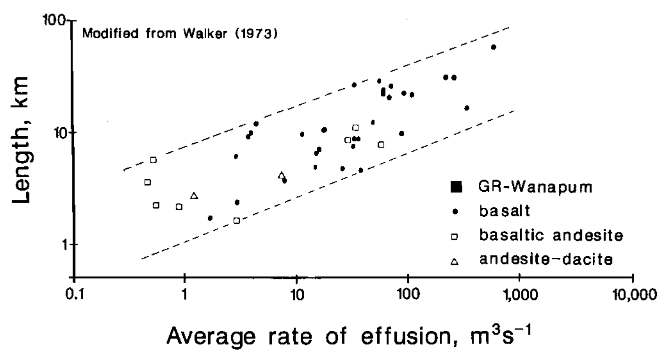


FIGURE 18. Relation of length and rate of effusion for representative lava flows of Grande Ronde and Wanapum Basalts and for historical flows throughout world. Modified from *Walker* [1973]. Rates were observed except those for Grande Ronde and Wanapum, which were calculated using model of *Shaw and Swanson* [1970].

ter. The lakes cooled to ambient temperatures within a few years to a few tens of years [*Long and Wood*, 1986].

Average Magma Supply Rate

About 5.5% of the group was erupted during the first 0.5 m.y. of volcanism to form the Imnaha Basalt [*Tolan et al.*, in press]. Activity peaked during 1.5-m.y. Grande Ronde time, when 87% of the group was erupted, 85% as the Grande Ronde Basalt and 2% as the Picture Gorge Basalt and other units. Activity waned thereafter, accounting for 6% of the group during Wanapum time, which lasted about 1 m.y., and 1.5% during prolonged Saddle Mountains time from about 14 to 6 Ma.

During peak activity the average interval between major eruptions was about 13,500 years, the average volume per major flow was about 1350 km^3, and the average magma supply rate was 0.1 km^3/year. The average supply rate is identical to that calculated for historical time at Kilauea [*Swanson*, 1972; *Dzurisin et al.*, 1984]. On this basis, a larger heat source for Grande Ronde Basalt than for modern Kilauea is unnecessary. An important distinction between the two provinces is that magma "leaks" from Kilauea almost continuously, whereas magma for the CRBG, if produced at the Kilauea rate, must have been stored for thousands of years before eruption in order to account for the huge volumes of single flows. (*Baksi* [1988] believes the maximum rate of supply, in late Grande Ronde time, was 2-3 times that at Kilauea; this interpretation is based on his revision of the geomagnetic time scale and seems overly dependent on his model for the time scale.)

The difference in eruption style between the CRBG and Kilauea may result from the 40-km-thick continental crust [*Catchings and Mooney*, 1988; *Michaelson and Weaver*, 1986] above the melting zone for the CRBG compared to the 12-km-thick oceanic crust above the melting zone for Kilauea. The continental crust may have provided a density trap keeping magma from rising until the trap was broken tectonically. Petrologic evidence suggests that the basalt was derived from a complex, multisource zone in the mantle with little crystal fractionation or crustal contamination during rise to the surface [*Hooper*, 1982, 1984; *Wright et al.*, in press; *Carlson*, 1984; *Carlson and Hart*, in press; *Hart and Carlson*, 1987]. This interpretation implies that the rise was rapid, consistent with the idea that fracturing, not a rising diapir, caused the magma to move to the surface.

Coeval Deformation

The basalt was erupted into a subsiding basin centered north of Pasco, Washington, in which sediment was accumulating [*Reidel*, 1984; *Reidel et al.*, in press]. How much of the subsidence owes itself to isostatic response caused by magma withdrawal, to weighting of the crust, and to tectonism is unclear [*Waitt and Swanson*, in press; *Catchings and Mooney*, 1988]. Seismic-refraction data, in concert with other geophysical data, suggest that rifting beneath the central part of the province occurred in the Eocene and possibly later [*Catchings and Mooney*, 1988]. If part of the Miocene subsidence was caused by magma withdrawal, significant lateral transport of magma from beneath the center of the province to its eastern flank—the locus of venting—is required.

Tectonic deformation was clearly taking place as the basalt accumulated, because single flows change thickness in anticlines and synclines [*Reidel*, 1984; *Reidel et al.*, in press]. The fold pattern is complex, and no fully satisfactory model for its development exists [*Laubscher*, 1981; *Davis*, 1981; *Barrash et al.*, 1983; *Hart and Carlson*, 1987]. Most folds trend within 20° of east, but some of the largest structures, such as the Pasco Basin and the Naneum Ridge anticline-Hog Ranch uplift, trend nearly north, as does the Cascade Range, whose uplift raised the basalt as much as 2 km. Most of the folds are confined to the western half of the province, but the longest structure, the Blue Mountains uplift, bounds the Columbia Plateau along most of its southern margin.

Ongoing folding, coupled with Cascade uplift and broad subsidence centered on the Pasco Basin, markedly influenced drainage patterns, particularly during Saddle Mountains time when quiet periods were long and canyons had time to form [*Swanson and Wright*, 1979; *Fecht et al.*, 1987; *Waitt and Swanson*, 1987, in press]. This topography in turn controlled the distribution of many flows of the Saddle Mountains Basalt. The most notable example is the Pomona Member, which erupted east of Lewiston, Idaho, flowed down the ancestral Clearwater and lower Snake Rivers, spread across the sagging central plateau, and left the plateau via structurally controlled channels that led through the Cascade Range and finally to the Pacific Ocean [*Swanson et al.*, 1979a; *Anderson*, 1980; *Camp*, 1981; *Tolan and Beeson*, 1984c; *Anderson and Vogt*, 1987; *Wells and Simpson*, 1987].

Invasive Flows and Sedimentary Interbeds

Sediment deposited between eruptions was commonly invaded by the next basalt flow that entered the area [*Schmincke*, 1967c; *Byerly and Swanson*, 1978, 1987; *Swanson et al.*, 1979a; *Niem and Niem*, 1985; *Wells and Niem*, 1987], producing pépérites and sill-like bodies called *invasive flows* that closely resemble classic intrusions. The only way to distinguish invasive flows from intrusions in such a setting is to know the stratigraphy and map the relations between subaerial and invasive components of the flow.

The sediment between the basalt flows has four general sources: erosion of highlands along the margin of the province, erosion of basalt within the province, deposition of diatomite in lakes within the province, and explosive volcanism in the adjacent Cascade Range.

Evidence for coeval Cascade volcanism is clear. Primary pyroclasts, generally mixed with epiclastic detritus but forming pure tuff in places, occur in interbeds in the section of basalt [*Schmincke*, 1964, 1967d; *Swanson*, 1967; *Priest et al.*, 1982]. However, no lava flows from the Cascades have been shown to be interbedded with the Grande Ronde or Wanapum Basalt; drilling in these formations just west of Mount Hood, Oregon, encountered andesite once thought to be flows [*Priest et al.*, 1982] but now interpreted by some as intrusions [D. R. Sherrod and T. L. Tolan, oral commun., 1988]. Apparently active vents in the Cascades were beyond the limit of the basalt flows, so that only tephra and laharic debris reached them. Cascade-derived debris in interbeds of Grande Ronde and Wanapum age is so sparse relative to that in beds of Saddle Mountains age and younger [*Schmincke*, 1964, 1967d; *Smith*, 1988; *Smith et al.*, 1988] that some workers [e.g. *Smith*, in press a; *Sherrod and Smith*, in press] suggest a downturn in Cascade activity followed by an upsurge during Saddle Mountains time. This idea is reasonable, although the short span of Grande Ronde and Wanapum time would by itself have resulted in minimal interbedding, all else being equal.

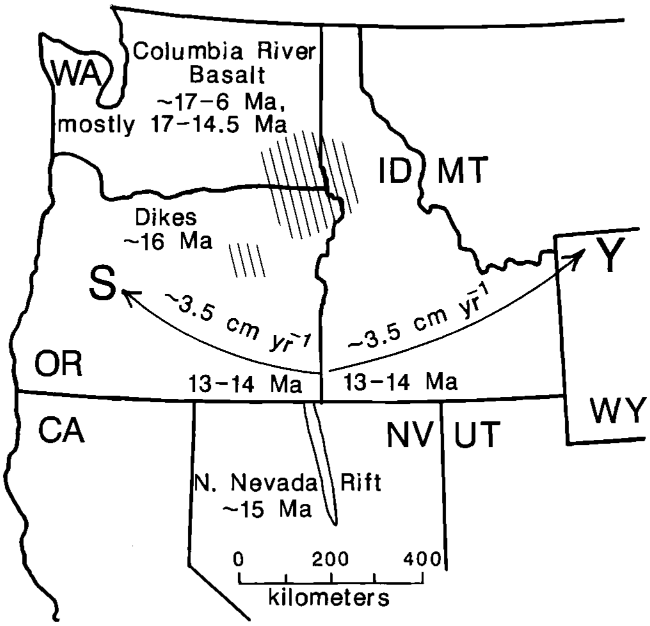


FIGURE 19. Map showing spatial and temporal relations of dikes of Columbia River Basalt Group, Northern Nevada Rift, and direction, onset time, and rates of migrating silicic volcanism toward Quaternary vents at South Sister, Oregon (S) and Yellowstone (Y). See text for discussion.

Speculations on Origin

Rampino and Stothers [1988] and *Alt et al.* [1988] recently suggested that flood-basalt provinces are generated by boloid impacts. The CRBG was probably not so generated. Geophysical work and deep drilling show no evidence of such an impact; in fact, the rift-like topography indicated by seismic refraction [*Catchings and Mooney*, 1988] beneath the center of the plateau would be nearly impossible to duplicate by impact. Moreover, calc-alkaline volcanism in the Cascades continued during flood-basalt volcanism but did not upsurge when basaltic eruptions began. One might expect that activity in the nearby Cascades would have followed suit if impact had triggered the basalt. Apparently the flood-basalt volcanism was independent of calc-alkaline volcanism, and neither was caused by impact.

Morgan [1981, 1988] suggested that new hot spots (mantle plumes) give rise to flood basalts, and *Duncan* [1982] argued that the CRBG is the product of the Yellowstone hot spot. At least two major problems exist with this idea. First, no fossil hot-spot track is preserved in the province, despite 11 m.y. of volcanism (17-6 Ma). Instead, feeder dikes are distributed randomly across the eastern half of the province; for example, the 8.5-Ma feeders for the Ice Harbor Member are on the east flank of the Pasco Basin [*Swanson et al.*, 1979a], the 12-Ma feeder for the Pomona Member is more than 210 km *east* of there (in the opposite direction from that expected of a hot-spot trace) [*Camp*, 1981], and the other dikes lie between. Second, the feeder system is only the northernmost part of a complex zone of basaltic dikes extending onto the Columbia Plateau from the [*Zoback and Thompson*, 1978; *Christiansen and McKee*, 1978]. This zone is not only a locus of basaltic magmatism but also a "plane of symmetry" separating traces of silicic volcanism migrating west-northwest across eastern Oregon and east-northeast across Idaho [*Armstrong et al.*, 1975; *MacLeod et al.*, 1975; *Eaton et al.*, 1978]. The basaltic activity along the zone began about 17 Ma, and the initiation of the migrating silicic volcanism about 13-14 Ma. The Yellowstone hot spot cannot easily explain these observations.

Lachenbruch and Sass [1977] and *Christiansen and McKee* [1978] pointed out that the high heat flow of the Basin and Range province requires the presence of a huge volume of Neogene basaltic magma, possibly equivalent to that produced on the Columbia Plateau, in the form of cooling intrusions in or underplated [*Furlong and Fountain*, 1986] on the base of the crust. In this context, *Christiansen and McKee* [1978] (R.L. Christiansen, numerous oral communications) suggested that stress relief at the base of the lithosphere, in response to crustal extension resulting from plate interactions, generated the voluminous basaltic magma. In this hypothesis, extension was greatest in the Basin and Range, so that magma could be stored in crustal reservoirs that developed in response to the extension, and least on the Columbia Plateau, so that crustal reservoirs were not formed and most of the magma that intruded the crust continued through it to the surface and fed the flood-basalt eruptions. This idea does not explain the bilaterally symmetrical nature of migrating silicic volcanism (no published hypothesis does, although the traction concept of *Eaton et al.* [1978] is stimulating) but does link the middle Miocene basaltic magmatism throughout the zone to plate interaction and as such is more appealing than either the hot spot or boloid-impact models.

Wright et al. [in press], building on work of *Carlson* [1984], conclude that the source for the basalt is a mixed oceanic-continental mantle that includes depleted oceanic mantle, subducted oceanic crust, original continental mantle, and old continental crust. They postulate that large bodies of magma generated from this material were underplated as sill-like bodies at the base of the continental crust and then tapped during deep continental extension or rifting. All of the magmas are inferred to have equilibrated with clinopyroxene during either melting or storage, but little evidence exists for fractionation of olivine, augite, and plagioclase as the petrogenetic models of *Cox* [1980] and *Hooper* [1984] demand. *Wright et al.* [in press] interpret the Grande Ronde as derived from relatively young oceanic mantle contaminated with subducted oceanic sediment, possibly with minor interaction with lower crustal rocks prior to or during ascent. They interpret the Wanapum to have much the same origin, except from a part of the oceanic mantle that had undergone Fe-Ti-P metasomatism. They interpret the Saddle Mountains to have a source related in some way to those for the Grande Ronde and Wanapum, owing to the similarity in major-element chemistry. However, the different trace-element abundances and ratios require additional complexity such as a second metasomatic event or melting of 2.5-Ga continental mantle with relatively high incompatible element contents.

ROAD LOGS

These logs are planned for use with a large bus, but we designed optional stops and routes for use by vans and automobiles. We list too many stops (Figure 20) for a bus load each day, but vans and passenger vehicles should have little trouble in visiting all of them.

Each day has a specific emphasis. The first stresses the Columbia River Basalt Group but also introduces the middle Tertiary geology of the Cascades. This day involves considerable driving on high-speed roads and ends in Yakima. The second day crosses a section of Oligocene to Quaternary volcanic rocks on the east flank of the range west of Yakima, ending in Packwood. Two options exist for the third day, each starting in Packwood and ending at Cispus Center. The first takes in the Tertiary and Quaternary volcanic geology of Mount Rainier National Park. Snow is a likely problem through July 4 for this trip. If so, the third day will involve a trip to the Mount St. Helens area, stressing the Tertiary geology as well as the May 18, 1980, eruption. The fourth day has two options dependent on the third day, both again ending at Cispus Center. If we visit Mount Rainier on the third day, the fourth day will be the trip to the Mount St. Helens area. Otherwise the fourth day will be devoted to hiking trips around Mount St. Helens, including an arduous trip into the crater and a less strenuous excursion onto the Pumice Plain. No guide has been written for this trip, because the area is not open to the public and we do not want to encourage self-guided tours, but we will supply handouts. The fifth day involves a long drive on back-country roads to see Quaternary basalt of the Indian Heaven area, including subglacial basalt, and some of the geology of the Columbia Gorge, ending in Hood River, Oregon. The sixth day emphasizes the Quaternary volcanic geology of Mount Hood and ends in Portland.

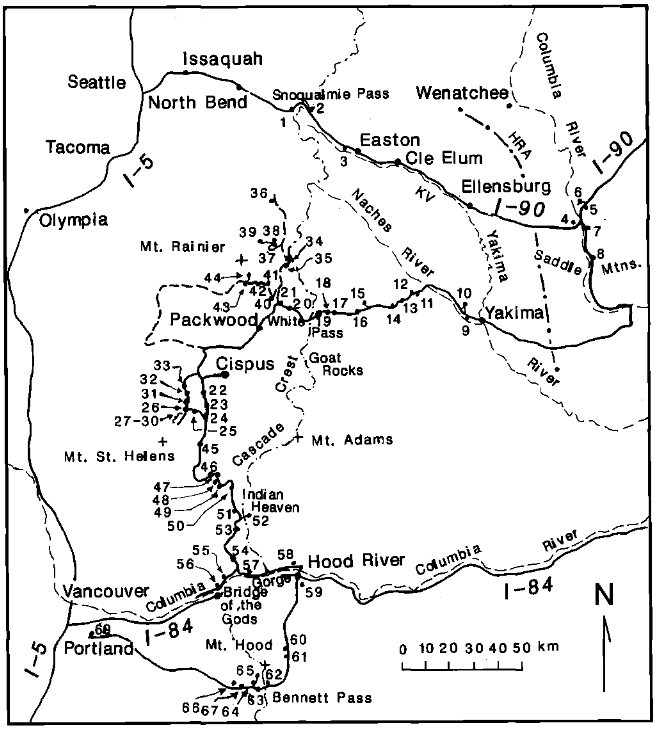


FIGURE 20. Map showing route of field trip between Issaquah, Washington, and Portland, Oregon. Numbers are stops. KV, Kittitas Valley; HRA, Hog Ranch Axis.

Cumulative mileage is listed for each day of the trip, and interval mileages are given in bold face at the end of each entry. Numerous mileage check points are available. I indicates Interstate Highway, as I-90.

Log for Day 1, Issaquah to Yakima via Vantage

Drive east on Interstate 90 from Seattle to Issaquah.

0.0 Continue on I-90 at Exit 17 to Issaquah.

0.7 Climb onto kame terrace formed about 12 ka by the Puget Lobe during the Vashon stade of the Fraser glaciation. Large gravel pit visible to left just before start of log is in this terrace. **0.7**

1.7 Hills are underlain by the Puget Group. **1.0**

3.1 High Point off-ramp. Tukwila Formation, andesitic mudflow breccias of middle Eocene age, in cuts to left. The Tukwila is probably correlative with the Naches Formation, about 44-40 Ma [*Tabor et al.*, 1984]. **1.4**

4.6 Tukwila Formation in roadcut to left. **1.5**

9.5 Exposures of steeply dipping arkose and volcaniclastic rocks of the Eocene Puget Group. The Puget is moderately folded in most places. It crops out discontinuously from here to North Bend. **4.9**

11.6 Craggy peak to left is Mount Si, underlain by Jurassic gabbroic and diabasic greenstone, possibly a dismembered ophiolite, and its sedimentary cover in the western melange belt of *Frizzell et al.* [1984]. The belt contains mostly Jurassic and Lower Cretaceous rocks and forms the west flank of the Cascades north of here. **2.1**

16.6 Rugged ridge crest at 11 o'clock is underlain by the Snoqualmie batholith. **5.0**

17.6 Low ridge ahead is a kame terrace formed by the Puget Lobe about 12 ka. Such features were built as deltas formed in lakes when the Puget Lobe blocked drainage from the Cascades. **1.0**

19.6 Range front of the Cascades, here mostly underlain by the volcanic rocks of Huckleberry Mountain [*Frizzell et al.*, 1984], correlative with the Ohanapecosh Formation seen later in the trip. **2.0**

23.1 Gabbro related to Snoqualmie batholith in roadcut on left. From here road stays in the batholith for 9-10 miles and enters the area of Figure 5 near Stop 1. **3.5**

31.8 STOP 1. Pull off on shoulder of freeway. If this is deemed too dangerous, vehicle can continue for 0.4 miles to a small road where parking is available, and geologists can walk back to stop. In roadcut view granodiorite of the Snoqualmie batholith, cut by aplite veins and containing mafic enclaves. The Snoqualmie is a large composite intrusive body and one of a series of shallow mid-Tertiary plutons in a narrow north-south belt in the Cascades. Radiometric ages are consistently between 20 Ma and 17 Ma [*Frizzell et al.*, 1984], mostly about 19 Ma, in this area, which is the main outcrop area of the batholith. The eastern part of the batholith, where individual plutons such as the Grotto have been delineated, is older, about 25 Ma. The batholith consists mainly of hornblende-biotite granodiorite and tonalite but includes gabbro, diorite, monzonite, and granite.

Sandstone float from the Naches Formation occurs along the road. **8.7**

32.8 Bare Snoqualmie Mountain in distance, 1890 m elevation. Contact with hornfelsed basalt of the Naches Formation in roadcut nearby. **1.0**

34.9 Roadcuts in argillite and sandstone of the Guye Sedimentary Member of the Naches Formation [*Tabor et al.*, 1984], metamorphosed by the batholith. **2.1**

35.5 Summit of Snoqualmie Pass, 921 m, the lowest pass across the Washington Cascades owing to the presence of non-resistent argillite in the Guye. **0.6**

37.6 Leave freeway at Hyak-Rocky Run exit. **2.1**

37.8 Turn left at stop sign and go under freeway. **0.2**

38.1 Turn right on pavement toward Rocky Run. **0.3**

38.5 STOP 2. Bus can stop on road, which has little traffic. View the Mount Catherine Rhyolite Member of the Naches Formation [*Tabor et al.*, 1984], a welded ash-flow tuff. Two fission-track ages of about 35 Ma for the Mount Catherine have probably been reset by the Snoqualmie batholith from true ages of about 44-40 Ma [*Tabor et al.*, 1984]. Note steeply dipping (about 65° SE), vague foliation in the welded tuff. **0.4**

38.7 Bus turnaround. High country to left up Gold Creek is underlain chiefly by basalt and feldspathic sandstone of the Naches Formation. **0.2**

Return to freeway and turn east toward Spokane.

39.9 Lake Keechelus on right is a natural lake further dammed for irrigation use. Roadcuts expose sandstone of the Naches Formation to mileage 42.6. **1.2**

42.6 Start of series of cuts in massive dacitic ash-flow tuff of Lake Keechelus [*Frizzell et al.*, 1984]. Zircon fission-track ages are 32-30 Ma, equivalent to the age of the Ohanapecosh Formation farther south, where similar tuff is interbedded with the Ohanapecosh. The tuff is quartz phyric and contains numerous large pumice lapilli and lithic inclusions. Columnar jointed in places, and commonly thoroughly welded and lithophysal. The tuff has a relatively gentle dip and rests on the eroded surface of the steeply dipping Naches Formation. Forms both north and south shores of Lake Keechelus. **2.7**

44.4 Last roadcut in the tuff of Lake Keechelus. **1.8**

45.9 Roadcuts in an ash-flow tuff in the Naches Formation dipping about 45 degrees. The freeway stays in the Naches Formation until it crosses the Straight Creek fault. The Naches consists chiefly of interbedded sandstone and a variety of volcanic rocks, chiefly basalt, basaltic andesite, and rhyolite, forming a more or less bimodal suite. It is about 4 km thick, comparable to the Puget Group farther west, and was apparently deposited in a subsiding extensional basin. The Naches is highly deformed; near-vertical dips are common in this area. It comprises most of the Cabin Creek block of *Tabor et al.* [1984] and *Frizzell et al.* [1984], a structural block west of the Straight Creek fault. The freeway follows the southeast strike of the formation. **1.5**

54.7 Basalt flows of the 48 to 47- Ma Teanaway Formation [*Tabor et al.*, 1984] occur at 10 o'clock on a ridge in the Teanaway River structural block east of the Straight Creek fault [*Frizzell et al.*, 1984]. **8.8**

55.2 Leave I-90 at Exit 70. At stop sign follow road toward Easton. **0.5**

55.6 STOP 3. Look up Lake Kachess valley, which is the trace of the Straight Creek Fault (Figure 5), to see the Teanaway overlying the steeply dipping Silver Pass Volcanic Member of the Swauk Formation [*Tabor et al.*, 1984] in the Teanaway River block. The Silver Pass, chiefly andesitic to dacitic flows and pyroclastic rocks, is about 1.8 km thick and is interbedded with fluvial subquartzose sandstone of the Swauk. The Silver Pass is 52-50 Ma on the basis of zircon fission-track ages [*Vance and Naeser*, 1977; *Tabor et al.*, 1984].

The Straight Creek fault is a major dextral strike-slip structure extending from central Washington into Canada [*Misch*, 1977; *Davis et al.*, 1978]. The northern segment of the fault in Washington separates low-grade metamorphosed rocks on the west from plutonic and high-grade metamorphic rocks of the North Cascades on the east. The southern segment separates lower Eocene sedimentary and volcanic rocks on the east (Teanaway River block) from upper Eocene to Oligocene(?) rocks on the west (Cabin Creek block) [*Tabor et al.*, 1984]. Movement of the southern part of the fault began at or before 48-47 Ma, as reflected by the angular unconformity separating the Silver Pass from the overlying Teanaway. Movement continued until at least 42 Ma, because the Naches Formation is cut by fault splays. The 25-Ma eastern part of the Snoqualmie batholith is not offset by the fault [*Vance and Miller*, 1981]. **0.4**

Bus can continue along road, turn around, and come back to the site. Return to freeway.

56.0 Reenter east-bound freeway. Just to south the Straight Creek fault bends southeast and splits into splays covered by the Grande Ronde Basalt. **0.4**

61.4 Tenaway Formation underlies ridge to left. The light gray exposures on the ridge behind Cle Elum are sandstones of the Roslyn Formation. **5.4**

68.7 At 12 o'clock is Lookout Mountain (Figure 5), underlain by N_2 and R_2 flows of the Grande Ronde Basalt near the western limit of the area underlain by the Columbia River Basalt Group. The basalt dips about 5° SE and defines the plunging trough of the Kittitas Valley syncline. Grande Ronde Basalt also forms most of Cle Elum Ridge south of the valley, where it rests on the Teanaway Formation [*Tabor et al.*, 1982b]. **7.3**

As we drive, observe the Stuart Range northwest of here. The brown rocks are ophiolite of the upper Jurassic and lower Cretaceous Ingalls Tectonic Complex [*Miller*, 1985a; *Tabor et al.*, 1987]. The gray peaks are tonalite of the upper Cretaceous Mount Stuart batholith.

77.8 Elk Heights pass. From here the route is within the Kittitas Valley syncline, developed principally in the Grande Ronde Basalt. The basalt is overlain in most places by the Pliocene Thorp Gravel capped by modern stream alluvium and glacial drift. **9.1**

83.2 White bluffs to north are in volcaniclastic rocks of the Ellensburg Formation interbedded with flows of the Grande Ronde Basalt. The Ellensburg here is pumiceous diamict and sandstone that indicates contemporaneous dacitic volcanic activity in the Cascades as the Grande Ronde Basalt was being erupted. **5.4**

85.0 Dark exposures north of road are type locality of Thorp Gravel, deposited by the ancestral Yakima River and its tributaries. The gravel contains two facies: mainstream alluvium dominated by durable silicic volcanic rocks derived from the Naches and Ohanapecosh Formations, and sidestream alluvium eroded from the Grande Ronde Basalt in the limbs of the syncline [*Waitt*, 1979; *Tabor et al.*, 1982b]. *Waitt* [1979] recognized three east-trending faults cutting the Thorp, which is about 4 Ma on the basis of fission-track ages on interbedded tuff and is the youngest deformed unit in the area. **1.8**

87.3 To south is Manastash Ridge, a complex thrusted anticline. Manastash is one of the most northern uplifts in the Yakima fold belt [*Bentley*, 1977]. **2.3**

94.7 Continue past Exit 109 to Canyon Road, which follows Yakima Canyon across several well-exposed, ESE-trending anticlines and synclines. The river follows structural sags in the anticlines and thus is considered consequent [*Waitt and Swanson*, 1987]. Continued folding caused the river to incise the anticlines within the broad N-S sag between the Hog Ranch and Cascade uplifts [*Schmincke*, 1964; *Waitt and Swanson*, 1987]. **7.4**

95.5 Continue past junction with I-82. Cuts along I-82 show deformed Wanapum Basalt and interbedded Ellensburg Formation [*Bentley*, 1977] but are hard to visit owing to laws against walking along the freeway. **0.8**

98.1 Kittitas Valley gradually ends to the east, where a low south-trending ridge system, the Hog Ranch uplift [*Mackin*, 1961], cuts off the southeast-trending Kittitas Valley syncline. The uplift, largely defined by the culminations of transverse anticlines, is a southward extension of the Naneum Ridge anticline [*Tabor et al.*, 1982b]. Major east-trending folds cross the uplift. **2.6**

105.5 Cuts in coulee left of freeway show pillowed flow in Frenchman Springs Member, which in this area is separated from the Grande Ronde Basalt by tuffaceous sandstone in the Vantage Member of the Ellensburg Formation. Exposures of the Frenchman Springs (in places pillowed), the Vantage, and the upper flow of the Grande Ronde occur for many miles as the highway crosses the Hog Ranch uplift. **7.4**

110.9 Ryegrass Crest, 773 m elevation. From here highway descends from Hog Ranch uplift to Columbia River. White tuffaceous sandstone of the Vantage crops out in places between the Frenchman Springs and underlying Grande Ronde Basalt. **5.4**

121.2 Exit 136. Leave I-90 toward Vantage. **10.3**

121.5 Stop, turn left, and drive through Vantage. **0.3**

122.2 Turn right to Ginkgo museum. **0.7**

122.7 **STOP 4.** Visit the museum, which displays petrified wood from the Vantage Member. The trees and logs were engulfed by and mixed with pillows and hyaloclastic debris when the basal flow of the Frenchman Springs crossed a swamp. The wood, chiefly cypress and ginkgo, indicates a warm, humid to wet setting, quite different from today's aridity.

Across the Columbia River, I-90 follows a prominent bench eroded along the Vantage Member. The bench rises northward toward the crest of the Frenchman Hills anticline. Flows in the Grande Ronde below the Vantage have been given informal names. The two best known are the Museum, the thin upper flow just below the east bridge abutment and the museum, and the underlying Rocky Coulee, a thick, complex flow that forms most of the cliff near the east end of the bridge.

Flows of Wanapum Basalt above the Vantage likewise have only informal names but belong to formal members (Figure 15). The lowest, named the Ginkgo flow by *Mackin* [1961], is mostly covered by talus above the east end of the bridge; it is the flow beneath which the petrified forest occurs. The overlying flow, the Sand Hollow, has a "double-barrelled" jointing aspect [*Mackin*, 1961] that suggests a compound cooling unit. The highest flow is the Sentinel Gap, here consisting of foreset-bedded pillows and hyaloclastite near the flow terminus. All three flows belong to the Frenchman Springs Member. On the skyline is the Roza Member, and still farther back from the river is the Priest Rapids Member. These three members can be traced across much of the Columbia Plateau and form marker units whose distributions, vent areas, and chemical compositions are among the best known of the province. **0.5**

Return to eastbound I-90.

125.1 Straight ahead note foreset-bedded pillows in Sentinel Gap flow on top of cliff. North dip of foresets indicates direction of flow. **2.4**

126.9 West of river, note museum and bench formed on top of Grande Ronde by stripping of the Vantage. **1.8**

131.4 Exit 143. Turn right on Champs deBrionne Winery road. **4.5**

131.7 STOP 5 just before intersection with the winery road. Plagioclase-phyric Roza Member invades diatomite to form a pépérite, which is overlain by silicic tuff capped by very sparsely plagioclase-phyric Priest Rapids Member (Figure 21). Note the stringers and dikelets of Roza mixed with diatomite. Note the sharp contact between the pépérite and the younger tuff.

Observe the sparsely phyric Priest Rapids and contrast it with the highly plagioclase-phyric Roza. Note that the vesicular top of the Roza is relatively less phyric than the rest of the flow. **0.3**

131.8 Turn left on Champs deBrionne Winery road. **0.1**

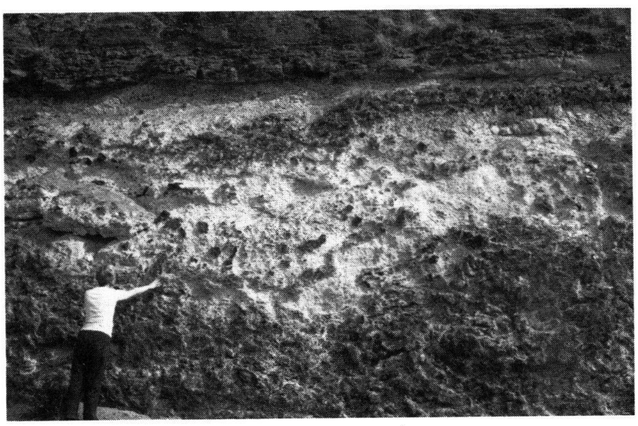


FIGURE 21. Person points to Roza Member of Wanapum Basalt invading and mixed with diatomite to form pépérite at Stop 5. Priest Rapids Member (top of photo) overlies thin silicic tuff (massive unit above lithic-rich pépérite near upper right edge of photo) deposited on pépérite.

132.5 Turn left at stop sign. **0.7**

132.7 Roza Member in roadcut. **0.2**

133.1 Bench on top of Frenchman Springs Member. Farther along, roadcuts show the vesicular top on this flow, the Sand Hollow. **0.4**

133.7 STOP 6. Spiracle at base of Roza Member. Spiracles presumably form as steam blasts through a flow from a wet substrate. A natural "Stonehenge" of platy columns has been eroded from the Roza Member just beyond the stop. Platy jointing is common in relatively coarse flows; the joints do not cross column boundaries and probably form during cooling. Frenchman Coulee below is a flood-carved coulee eroded as waters poured from the Quincy basin to the northeast and descended to the Columbia. The coulee is dry except for excess irrigation water. White mounds on the Roza north of the coulee are spoil from diatomite mines in the Squaw Creek Member of the Ellensburg, the deposit invaded by the Roza. Note the varied jointing patterns of the flows in the coulee wall, which illustrate the problems in using jointing habits for flow correlation. **0.6**

133.8 Good bus turnaround. Return to I-90. **0.1**

135.7 Turn right onto I-90. **1.9**

136.9 At 1200 is good view of high sharp peak in distance, Whiskey Dick Mountain. Shell Oil drilled an exploration hole near Whiskey Dick, as well as in several other areas in the western plateau, during the 1980s. The Whiskey Dick hole penetrated about 1.5 km of basalt, and a hole in the Saddle Mountains south of here went through more than 3.5 km of basalt, about 3.2 km of which was Grande Ronde only. No oil was found in the target beneath the basalt, presumably Eocene sandstone. Few data are publicly available for these holes. Drilling was continuing in summer 1988. **1.2**

140.7 Roadcut in Museum and underlying hackly jointed Rocky Coulee flows of the Grande Ronde Basalt. **3.8**

141.4 Take Highway 26 at Exit 137. **0.7**

142.1 Good exposure in cliff at 9 o'clock of "double-barrelled" Sand Hollow flow. **0.7**

142.8 Keep left at junction with Highway 243. **0.7**

143.0 STOP 7. Mouth of Sand Hollow. Walk 100 m to next roadcut. Pillows and palagonite in Ginko flow of Frenchman Springs Member. Note the dipping foresets in a lava delta that indicates local movement toward the west or northwest. **0.2**

145.2 Bus turnaround at road junction. **2.2**

147.6 Return to Highway 243 and turn left. **2.4**

147.9 Start up grade across Frenchman Springs and overlying Roza Members. Type locality for the Wanapum Basalt, named from nearby Wanapum Dam. **0.3**

152.2 View at 12 o'clock of Sentinel Gap, eroded across the Saddle Mountains anticline [*Reidel*, 1984]. **4.3**

154.9 White layer high on west wall of Sentinel Gap is sandstone of Vantage Member. **2.7**

157.8 STOP 8 at turnout along right side of highway in Sentinel Gap. The Sentinel Bluff section here has been closely studied by geologists formerly of Rockwell Hanford Operations, in particular Steve Reidel [*Reidel*, 1984] and Phil Long [*Long and Wood*, 1986; *McMillan et al.*, 1987], during investigation for a potential nuclear-waste repository within the basalt on the Hanford Reservation. The four oldest exposed flows are in the Grande Ronde Basalt, have a relatively low-MgO composition [*Myers and Price*, 1979], and are assigned to the Schwana unit. The oldest Schwana flow, not exposed here but cropping out just to north, has reversed magnetic polarity. The youngest Schwana flow, the Umtanum, is approximately 60 m thick divided equally between a lower colonnade and an upper entablature. The Umtanum was the main candidate flow for the nuclear-waste repository at Hanford. Overlying the low-MgO flows are eight relatively high-MgO flows in the Sentinel Bluffs unit of the Grande Ronde [*Myers and Price*, 1979], the uppermost of which is the Museum flow. A prominent bench, eroded back along the Vantage, separates the Sentinel Bluffs from the overlying Frenchman Springs. Work based on jointing in this section and elsewhere led *Long and Wood* [1986] and *DeGraff and Aydin* [1987] to conclude that entablatures are produced by rapid cooling as water percolates downward into opening joints.

A prominent tongue of basalt southwest of the gap (the Huntzinger flow of *Mackin* [1961]) belongs to the Asotin Member of the Saddle Mountains Basalt; it partly fills a paleovalley cut into the Priest Rapids along the course of the ancestral Columbia River about 13 Ma.

The Saddle Mountains anticline is asymmetric with a faulted north limb. The fold axis on the east side of the river is 2.5 km south of that on the west side, perhaps because of a tear fault [*Reidel*, 1984]. The Saddle Mountains reverse fault is best exposed across the river on the north limb of the fold. Some flows thin and even pinch out against the uplift, as does the Vantage Member [*Reidel*, 1984]. Apparently the fold was growing during deposition of the basalt and interbeds.

Ash erupted about 7 ka from Mount Mazama (Crater Lake, Oregon) 475 km to the south occurs in colluvium. Evidence of the Missoula floods are obvious. **2.9**

159.0 High on ridge at 8 o'clock is an abandoned quarry exposing two layers of vitric rhyolite tuff between the Wanapum and Saddle Mountains Basalts. The lower tuff, as thick as 15 m, contains prominent layers rich in accretionary lapilli [*Schmincke*, 1967a, 1967c]. The Pomona Member of the Saddle Mountains Basalt invades the tuff just above the lapilli layers. This duo—Pomona lying above accretionary lapilli in a vitric tuff (commonly welded) [*Schmincke*, 1967c]—occurs in many places on the Columbia Plateau as far east as Clarkston, Washington. The ash and far-flung accretionary lapilli testify to a powerful explosion in the Cascades just before eruption of the Pomona in northern Idaho about 12 Ma. **1.2**

164.2 Ahead is Umtanum Ridge, one of the larger and most studied anticlines on the Plateau [*Price*, 1982]. **5.2**

169.7 At 12 o'clock is view of rollover in Umtanum Ridge anticline. The north limb is locally overturned. The fold is cut by thrust faults [*Price*, 1982]. **5.5**

170.8 Steeply overturned flow at 3 o'clock. **1.1**

172.5 Road travels along the 82-km *Hanford Reach*, the only free-flowing stretch of the Columbia River from the Canadian border to Bonneville Dam near Portland. **1.7**

175.7 Stay right at junction to Vernita Bridge. **3.2**

178.2 Pomona Member overlies Umatilla Member of Saddle Mountains Basalt on hillslope along grade up from Vernita Bridge. Ridges in distance, Gable Mountain and Gable Butte, are local culminations of largely buried Umtanum Ridge anticline. **2.5**

182.0 Turn right on Highway 24 toward Yakima. Road goes up Cold Creek Syncline, whose lower, broader part was the favored site of a planned storage repository for high-level nuclear waste. The site was abandoned in 1988 in favor of one in Nevada, owing to a complex decision involving hydrologic questions and politics. **3.8**

186.9 Ridge at 10 o'clock is Rattlesnake Hills. Near its crest the first deep hole was drilled on the Columbia Plateau in 1957-58, a wildcat owned by Standard of California. The hole bottomed at 3248.6 m in Grande Ronde Basalt, as interpreted from the chemical compositions of the cuttings [*Reidel et al.*, 1982]. Drilling by Shell in the 1980s confirmed the great thickness of the basalt, particularly the Grande Ronde.

Scattered outcrops for the next several miles expose the Pomona and Elephant Mountain Members of the Saddle Mountains Basalt. **4.9**

189.2 Keep right at junction with road to Sunnyside, and follow the axis of the Black Rock syncline. **2.3**

191.7 Ridge to left is continuation of Rattlesnake Hills, which extends from 50 km west of Yakima to 23 km southeast of Pasco, a total length of about 175 km—the longest anticlinal structure on the Columbia Plateau. **2.5**

206.2 Rounded hill at 11 o'clock is Elephant Mountain, local high point on the Rattlesnake Ridge anticline and the type locality of the Elephant Mountain Member of the Saddle Mountains Basalt [*Waters*, 1955; *Schmincke*, 1967a]. The Elephant Mountain erupted in northeast Oregon about 10.5 Ma and flowed via a canyon system to the western plateau [*Swanson et al.*, 1979a]. **14.5**

215.3 At 9 o'clock is Union Gap, a water gap exposing Wanapum and Saddle Mountains Basalt cut by the Yakima River through the Rattlesnake Hills anticline. **9.1**

219.1 Turn north on I-82. **3.8**

222.2 Exit 31 to North First Street in Yakima. End of a long first day. **3.1**

Log for Day 2, Yakima to Packwood

0.0 Entrance to freeway bypass at north end of North First Street in Yakima.

0.1 Selah Gap in Yakima Ridge anticline exposes flows of Frenchman Springs and Priest Rapids Members. **0.1**

2.8 At 11 o'clock is bluff of Tieton Andesite. **2.7**

3.5 Turn left on Ackley Road. **0.7**

3.6 At stop sign turn left and park. **STOP 9.** Walk

100 m west and climb stairs to view the reversely magnetized, 1.0 Ma Tieton Andesite. This is an archaeological site (Indian paintings); **do not sample here** (a sampling opportunity may be possible at Stop 11). This is the most voluminous of several flows erupted from the Goat Rocks volcano, a Pliocene and Pleistocene andesitic cone on the crest of the Cascades 80 km west of here. The flow poured down the ancestral canyon of the Tieton River until debouching into the lower-gradient Naches Valley, where it spread out, developed pressure ridges and tumuli, and terminated at this site [*Warren*, 1941; *Becraft*, 1950; *Swanson*, 1964, 1978; *Clayton*, 1983]. The flow has about 60% SiO_2 and 2.8% K_2O and is a high-potassium andesite. It contains 30-35% phenocrysts of plagioclase (greatly dominant), clinopyroxene, hypersthene, and magnetite. These characteristics suggest rather low fluidity, yet the flow is the longest known andesite, longer than any in *Walker's* [1973] compilation. Apparently the flow advanced so far because of its large volume (conservatively estimated as 2 km^3), possibly high eruption rate, and confined course in the canyon. Note the complicated columnar joints, which probably record cooling against a vertical channel wall eroded into volcaniclastic rocks of the Ellensburg Formation (since removed). Note the glassy texture, typical of its entire length. **0.1**

3.7 Return to highway and turn left. **0.1**

4.5 Turn right on Old Naches Highway and stay left at Y-junction immediately after turn. **0.8**

5.3 Turn right on Mapleway Road. Bluffs ahead and to left are considered by many workers as the "type" locality of the Ellensburg Formation, although Ellensburg itself is more than 30 km farther north. **0.8**

5.9 Roadcut exposes tuffaceous sandstone and dacite-rich conglomerate representative of the volcaniclastic upper part of the Ellensburg Formation in this area. The dacite was produced by explosive activity in the Cascades mostly between 12 and 8 Ma [*Smith et al.*, 1988]. Specific sources have not been identified, but a dacite-porphyry intrusion near Bumping Lake 60 km west-northwest of here has a K-Ar age of 8.8 ± 0.2 Ma and could be an Ellensburg feeder [*Smith et al.*, 1988]. The Ellensburg here is overlain by dacite-poor conglomerate that contains reworked tephra with a K-Ar age of 7.4 ± 0.4 Ma [*Smith*, 1988]. *Smith* [1988] interprets the dacite-poor conglomerate, forming part of his Pleasant Hill conglomerate unit, as partly filling a paleovalley eroded into the volcaniclastic Ellensburg. **0.6**

6.2 STOP 10. Examine pumiceous debris flow with fine-grained base in Pleasant Hill conglomerate (Figure 22). The origin of the fine-grained base, a photo of which appears in *Schmincke* [1967b], is debatable. The debris flow contains scattered prismatically jointed blocks of dacite, rests on dacite-poor conglomerate, and underlies dacite-rich conglomerate. Apparently the debris flow formed during a period of renewed dacitic volcanism in the ancestral Naches River basin [*Smith et al.*, 1988]. Walk to bottom of grade from here to examine deposits described at mileage 5.9. Bus continues up hill. **0.3**

6.5 Bus turns around at top of hill, returns to bottom of hill, and waits for group. **0.3**

7.6 Stop at Old Naches Highway and continue straight on Mapleway Road. **1.1**

8.7 Turn left on McCormick Road and then right on Highway 12. **1.1**

8.9 At 9 o'clock is bluff of Tieton Andesite. The present flow margin probably approximates its original margin, a conclusion consistent with its overall jointing characteristics. If so, the Naches Valley has widened about 2 km to its present position in the last 1 m.y., presumably when high discharge during glacial periods eroded the relatively nonresistant deposits of the Ellensburg. Wells drilled on the bluff tap water from river gravel below the Tieton Andesite, good evidence that the flow advanced down the main channel of the ancestral Naches. Presumably the Naches then re-established itself along the margin of the flow and commenced widening its valley asymmetrically northward. **0.2**

11.4 At 3 o'clock the Pomona Member rests on white tuffaceous rocks of Ellensburg Formation. **2.5**

12.2 Roadcut in Frenchman Springs Member just before substation. This is the farthest west the Frenchman Springs and Pomona can be traced in this area. **0.8**

12.9 Bluffs to north show Ellensburg Formation stratigraphically higher than the Pomona Member. **0.7**

13.8 Ahead is Cleman Mountain, one of the highest anticlines on the Columbia Plateau. It stood high enough to trap most coarse Ellensburg detritus in the Nile basin just west of the mountain, keeping it from reaching the Naches Valley (R.S. Fiske, oral commun., 1962; [*Smith*, 1988]). The anticline continued to grow after Ellensburg time to its present elevation. **0.9**

16.3 Good views of Tieton Andesite left of road. Note the hummocky nature of its surface, caused by large pressure ridges. Cleman Mountain looms at 1 o'clock.

FIGURE 22. Fine-grained base of pumiceous debris flow containing rare "hot" dacite blocks. Stop 10.

The south limb of the anticline is locally overturned. The structure of the anticline is poorly known, owing to the absence of marker flows younger than Grande Ronde and to the complexity of the structure itself. **2.5**
19.8 Turn left toward White Pass on Highway 12. **3.5**
20.0 Cross Naches River just upstream from mouth of Tieton River. View to left of Tieton Andesite, which flowed down the Tieton River canyon. Note the angular discordance with the underlying northeast-dipping Grande Ronde Basalt. Remnants of Tieton Andesite hang on the walls of the canyon, carved in Grande Ronde Basalt and the Fifes Peak Formation, for the next 30 km into Tieton basin. Tieton Andesite can generally be recognized in the canyon by its unconformable contact and notable columnar jointing, commonly with an entablature above long subvertical columns. **0.2**
21.9 Entrance to Oak Creek Wildlife Recreation Area. Exposures at 2 o'clock show Tieton Andesite only a few meters above river level. Apparently base level did not change much during the last 1 m.y., so that no downcutting took place except through the lava flow. **1.9**
22.6 STOP 11. Dangerous curve. Pull bus to left of road if traffic is light. Tieton Andesite rests on imbricated boulder gravel of ancestral Tieton River (Figure 23). East of river, erosional unconformity between Grande Ronde and Tieton Andesite is well exposed. **0.7**
23.9 STOP 12. Micaceous sandstone and siltstone between two N_2 flows of Grande Ronde Basalt (Figure 24; locality 2 in table 10 of *Swanson* [1967]). The lower flow is invasive into wood-bearing subarkose, probably unconsolidated at the time of invasion; note the dense glassy top on the flow and the disruption and tilting of the sediment. Mica-bearing sediment and the accompanying metamorphic and plutonic heavy-mineral suite [*Swanson*, 1967] indicate a northern provenance and therefore imply a south-flowing river during Grande Ronde time, which is interpreted from regional evidence to be the ancestral Columbia or a major tributary. During Grande Ronde time, no ancestral Columbia is known from within the Columbia Plateau itself. A reasonable interpretation is that the river had been diverted to the margin of the province by the basalt flows [*Fecht et al.*, 1987; *Waitt and Swanson*, 1987]. Mixed with the metamorphic and plutonic suite is a pyroclastic suite, including euhedral oxyhornblende, glass shards, and glass-rimmed plagioclase and mafic minerals. This suite provides clear evidence of explosive activity from Cascade volcanoes during Grande Ronde N_2 time, 17-16 Ma. Pyroclastic debris in older interbeds shows that Cascade activity also occurred in N_1 and R_2 time. **1.3**
24.7 Nearly vertical contact between Tieton Andesite and Grande Ronde Basalt at 11:30 o'clock. **0.8**
26.2 Roadcut shows flow of Grande Ronde Basalt that invaded unconsolidated micaceous sand (locality 1, table 10 of *Swanson* [1967]). **1.5**
27.9 Windy Point measured section of Grande Ronde Basalt ahead. Lower 3 flows are in magnetostratigraphic unit R_2, and the upper 9 in N_2 [*Swanson*, 1978]. **1.7**
28.5 Polished fault plane cutting pillows of Grande Ronde. The fault cannot be traced from the cut. **0.6**
28.8 Pillowed Grande Ronde Basalt west of bridge. **0.3**
29.0 STOP 13. Local margin of Grande Ronde Basalt, where it lapped onto the eroded remnant of Tieton volcano [*Swanson*, 1966, 1978], a large stratocone in the Fifes Peak Formation (Figure 25). The contact is obscured by landsliding. Note the foreset-bedded lava delta in one of the lower R_2 flows of the Grande Ronde that indicates westward advance of the basalt.

The base of Tieton volcano consists of gently dipping two-pyroxene basaltic andesite flows that lap against the deformed flanks of an older cone and form a shield about 200 m thick (Figure 26). More than 1500 m of bedded tuff, lithic-lapilli tuff, and breccia overlie the shield (Figure 27); the steep radial dips of the fragmental rocks define a volcaniclastic cone. The reconstructed volcano had a basal diameter of at least 1.5 km and probably rose 2400-3000 m above its base before erosion and partial inundation by the Grande Ronde Basalt.

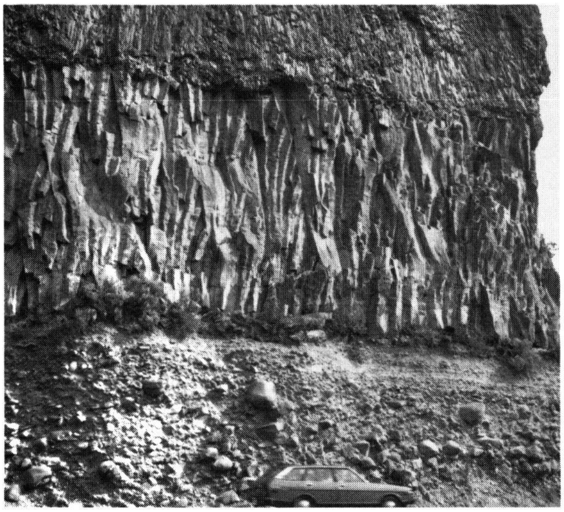


FIGURE 23. Base of columnar Tieton Andesite resting on gravel of ancestral Tieton River, Stop 11.

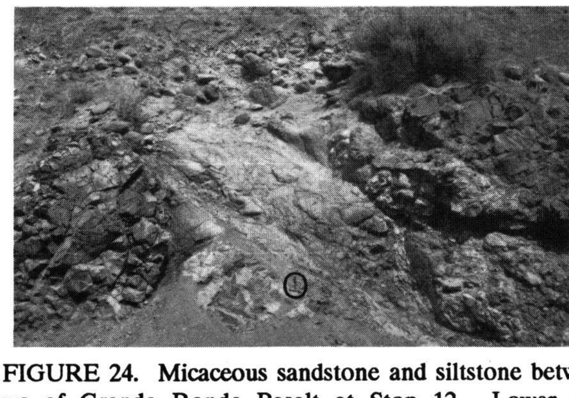


FIGURE 24. Micaceous sandstone and siltstone between flows of Grande Ronde Basalt at Stop 12. Lower flow invades sandstone. Hammer at contact.

Holocene	Alluvium and colluvium
Pleistocene	Intracanyon flows of hypersthene-augite Tieton Andesite (1 Ma) and olivine basalt erupted from vents near Goat Rocks and the White Pass area. Overlain and underlain by till.
Pleistocene and Pliocene	Small plugs of olivine basalt and andesite.
	UPLIFT
Pliocene(?)	Gravel on top of Grande Ronde Basalt
	EROSIONAL AND ANGULAR UNCONFORMITY
Middle Miocene	Grande Ronde Basalt (approx. 17-15 Ma). As much as 520 m of gently eastward-tilted flows. Local discontinuous interbeds of clastic sediment, tuff, and palagonite.
	EROSIONAL AND POSSIBLE ANGULAR UNCONFORMITY
Early Miocene	Fifes Peak Formation (approx. 23 Ma in this area). More than 1 km-thick section of andesite and basaltic andesite lava flows and breccia, and dacite-rhyolite pyroclastic flows, erupted from at least two large composite cones. Prominent radial dike swarm. Cut by andesitic and microdioritic intrusions in western part of area.
	ANGULAR UNCONFORMITY
Oligocene	Volcaniclastic rocks of Wildcat Creek, probable correlatives with Ohanapecosh Formation (about 32-33 Ma in this area). More than 300 m of volcaniclastic rocks, many of which are graded, have continuous bedding across outcrops, generally lack current structures, and have poorly developed sole marks. Vertebrate fossils. Zeolitized. Probably deposited either by subqueous turbidity currents or subaerial debris flows.
	EROSIONAL AND POSSIBLE ANGULAR UNCONFORMITY
Eocene	Welded tuff of Spencer Creek (about 42 Ma) and associated epiclastic sandstone and conglomerate.
	ANGULAR UNCONFORMITY
Cretaceous and Jurassic	Russell Ranch Formation, graywacke and argillite with lesser pillow basalt (greenstone) and chert. Also includes Indian Creek unit, mainly sheared orthogneiss of tonalitic composition but varying from gabbro to trondhjemite. Together comprise the "Tieton inlier" of pre-Tertiary rocks.

FIGURE 25. Stratigraphy of Tieton River area, simplified from *Swanson* [1967]. Ages for rocks older than Grande Ronde Basalt from *Vance et al.* [1987]. Data for Indian Creek unit from *Miller* [1985].

On Bethel Ridge, 6-10 km west of the center of the volcano, at least 300 m of gently dipping debris-flow deposits (mainly lahars), lava flows, and low-silica rhyolitic pyroclastic flows can be traced nearly continuously into the cone. Some breccias thin and pinch out to the west, and one andesite flow ends with westward-inclined foreset lenses of breccia and lava at its snout. The Bethel Ridge rocks probably formed part of a lowland apron at the foot of Tieton volcano.

The volcano erupted block-lava flows, coarse- to fine-grained bedded tuff, and chaotic breccia of multiple origins. Intruding them are more than 200 dikes that form the southern half of a radial swarm centered on the volcano. Single dikes are 1.5-6 m wide and dip 70-90°. They decrease in abundance upward in the volcano and were injected subvertically, not laterally, as indicated by lineations on the dike margins. The dikes and lava flows are medium-K mafic and slightly silicic andesite (or basaltic andesite and lesser andesite.

A lava flow in the apron of Tieton volcano yielded a fission-track age of 23.3 ± 2.0 Ma [*Vance et al.*, 1987, sample JV 140]. Other isotopic ages for the Fifes Peak Formation range from 20.0 ± 2.0 to 27.3 ± 2.9 Ma [*Vance et al.*, 1987]. Centers similar to those in the Tieton River area occur at the type locality in the Fifes Peaks themselves, 40 km northwest of Tieton volcano.

Tieton volcano cannot be seen well from the highway, because the canyon is so narrow, but it is splendidly displayed from a high ridge road, inaccessible to buses, that turns off at mileage 28.3. Many of the radial dikes are visible from the highway, however. Keep track of their trends as we drive through the canyon to convince yourself that they radiate from a common center. **0.2**

29.2 Dike in roadcut, with strike of about 295°. Wall-rock is andesite flow and breccia of Tieton volcano. **0.2**

30.0 Slope above road shows rocks of older Fifes Peak volcano cut by radial dikes of Tieton volcano. **0.8**

30.6 STOP 14. Bus stops here. Group walks 100 m ahead to examine roadcut exposing at least 11 basaltic andesite dikes belonging to the radial dike swarm cutting rocks of the older volcano. **0.6**

31.8 Prominent knob to left is Sentinel Rock, capped by Tieton Andesite. **1.2**

34.0 Radial dikes at 3 o'clock. Remnant of Tieton Andesite high on ridge. **2.2**

35.7 Breccia and platy basaltic andesite of the older Fifes Peak volcano. The units resemble those of Tieton volcano but can be distinguished by map relations. **1.7**

36.2 Enter Tieton basin, chiefly underlain by landslide debris. **0.5**

37.0 Goose Egg Mountain microdiorite ahead. **0.8**

37.9 Start series of roadcuts in bedded volcaniclastic rocks of Wildcat Creek, age and possibly stratigraphic correlatives of the Ohanapecosh Formation. A fission-track age of 32.2 ± 3.3 Ma was obtained on a pumiceous ash-flow tuff near the west end of these cuts [*Vance et al.*, 1987, sample JV 139]. **0.9**

38.7 Straight ahead is Westfall Rocks, a microdiorite twin of Goose Egg Mountain. **0.8**

39.0 Turn right on Wildcat Road 1306. **0.3**

39.6 Cattle guard. **0.6**

39.8 STOP 15. Climb steep slope to examine deposits typical of the upper part of Wildcat Creek unit (Figure 28), which consists dominantly of laterally extensive, graded beds 1-6 m thick separated by thinly bedded tuff. The lower several centimeters of each thick bed is typically framework-supported, zeolite-cemented lapillistone, which locally has sole marks on its base (Figure 29). The lapillistone grades abruptly upward into poorly sorted lapilli tuff, which grades gradually upward into well-sorted tuff. The thin beds are commonly graded, and some beds are crudely laminated; small-scale cross

FIGURE 26. Nearly horizontal andesite flows in basal shield of Tieton volcano, overlain by volcaniclastic cone. Base of shield (dashed line) overlies tilted flows and breccia of older volcano. Between Stops 13 and 14 on north side of canyon.

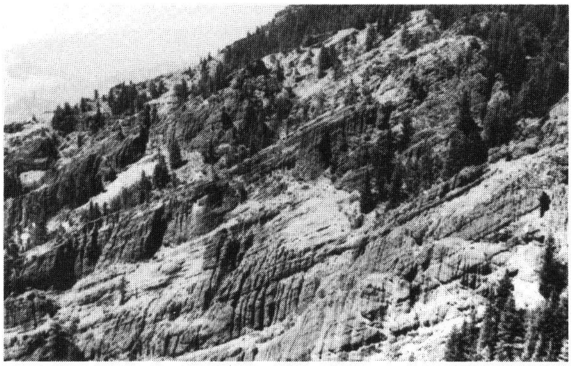


FIGURE 27. Bedded volcaniclastic rocks forming cone of Tieton volcano on north side of canyon between Stops 13 and 14. Note concave-upward attitude.

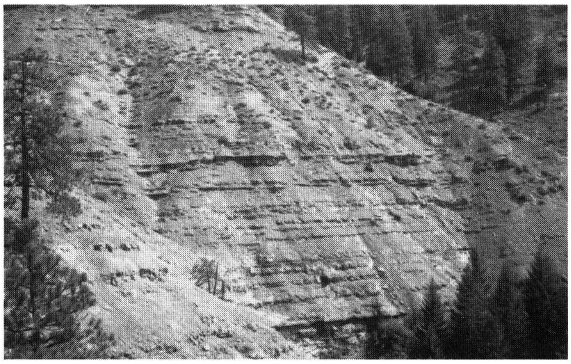


FIGURE 28. Continuous bedding in the volcaniclastic rocks of Wildcat Creek, Stop 15.

bedding and channelling occur in some thin beds.

Clasts are freshly erupted crystals (commonly exhibiting bubble-wall texture), dense lithic fragments (chiefly andesite and dacite), pumice (mostly of the long-tube

FIGURE 29. Lapillistone base of graded lapilli tuff at Stop 15. Note possible load casts at base of bed.

type), and ash. Accretionary lapilli, both broken and whole, occur in the lapilli tuff and tuff, and fragmentary vertebrate fossils have been found [*Grant*, 1941; *Swanson*, 1964; *Lander*, 1977]. All glass is entirely altered to, in order of formation, opal or chalcedony, clay and celadonite, heulandite, mordenite, and calcite.

At the base of the outcrop is a poorly exposed pumice-lapilli tuff, probably an ash flow; it is better exposed in roadcuts along Highway 12 and is the one dated by *Vance et al.* [1987] (see mileage 37.9). Farther down section, obvious fluvial deposits occur; current directions indicate southeast-directed transport.

The origin of these beds is debatable. *Swanson* [1964; 1978] interpreted the thick graded units as products of subaqueous turbidity currents carrying a mixture of freshly erupted and older detritus. Recent work on lahars and hyperconcentrated streamflows [*Scott*, 1988; *Pierson and Scott*, 1985; *Pierson*, 1985; *Smith*, 1986] raises the possibility of such subaerial origins for these rocks. The volcaniclastic rocks of

Wildcat Creek are interpreted as a distal facies of the Ohanapecosh Formation in Mount Rainier National Park, where lava flows and coarser, thicker graded beds occur [*Vance et al.*, 1987]. **0.2**

40.2 Bus turnaround. Return to Highway 12. **0.4**

41.3 Junction with Highway 12. Turn right. **1.1**

41.5 Cross Wildcat Creek. At 5 o'clock is remnant of a Pleistocene olivine basalt flow that elsewhere fills a channel eroded into Tieton Andesite. **0.2**

41.8 Westfall Rocks microdiorite unit. **0.3**

42.9 STOP 16. Margin of Westfall Rocks microdiorite unit, with dark hornfelsed Wildcat Creek lapilli tuff hanging on margin (Figure 30). This intrusion, as well as Goose Egg Mountain and two other dikelike bodies of similar lithology, Kloochman Rock and Chimney Peaks, are of mid-Tertiary age but have not been dated. Whether they are feeders for andesite in the Fifes Peak Formation is problematic. The Westfall Rocks and Goose Egg intrusions are probably connected at depth but have joint patterns that suggest they are separate bodies at the present level of exposure. Both bodies were intruded along the contact between the volcaniclastic rocks of Wildcat Creek and pre-Tertiary rocks of the Rimrock Lake inlier [*Miller*, 1985b] that underlie Rimrock Lake. The nature of this contact is not clear, but *Miller* [1985b] believes that contacts of the Rimrock Lake inlier and the Cenozoic rocks "are generally pronounced angular unconformities that only locally show minor modification by faulting."

Cliffs on the southern skyline expose the Divide Ridge section of Grande Ronde Basalt, about 500 m of basalt and interbedded micaceous sandstone [*Swanson*, 1967]. Twelve to 15 flows are present; the lower 3 or 4 are in the N_1 magnetostratigraphic unit, the middle 6 or 7 in the R_2 unit, and the upper 3 or 4 in the N_2 unit. At least 3 sill-like invasive flows occur in the section.

The Grande Ronde dips gently eastward on the flank of the Cascade uplift. The uppermost flow, which correlates with the upper part of the Sentinel Bluffs sequence at Sentinel Gap [*Mangan et al.*, 1986], is at a maximum elevation of about 2100 m at the west end of the ridge [*Swanson*, 1967, 1978]. A similar stratigraphic position below the museum at Vantage is at an elevation of less than 150 m and in the Pasco Basin is as low as 600 m below sea level [*Myers and Price*, 1979]. Structural relief of more than 2700 m is therefore indicated. East of Pasco Basin, a general elevation for the top of the Grande Ronde is about 730 m near the northern and northeastern periphery of the province, where the basalt has not been markedly deformed [*Swanson et al.*, 1979c]. If this reflects a "stable" datum, then the Divide Ridge area has been uplifted about 1370 m absolutely.

Whether the uplift is tsuly absolute is uncertain, but the calculation emphasizes the general observation that the Cascade Range at this latitude has been significantly uplifted in the last 15 m.y. About 75% of this uplift is confined to the western 16 km of the present Columbia

FIGURE 30. Hornfelsed lapilli tuff along margin of Westfall Rocks microdiorite unit at Stop 16.

Plateau, for the top of the Grande Ronde is lower than 580 m near Tampico, about 19 km southeast of here, whereas it is higher than 2100 m only 16 km farther west [*Swanson*, 1967]. West of Divide Ridge the basalt projects into a younger volcanic center (Goat Rocks volcano) built on an uplifted platform of lower Tertiary rocks [*Swanson and Clayton*, 1983], and the basalt does not occur farther west at this latitude on the western flank of the Cascades.

The gently sloping, flat-topped ridge south of Rimrock Lake is Pinegrass Ridge, underlain by Tieton Andesite and several other Pleistocene lava flows. This marks the pathway by which the long flow of Tieton Andesite moved from Goat Rocks volcano into Tieton basin. **1.1**

43.5 Sheared trondhjemitic phase of the Jurassic Indian Creek unit [*Miller*, 1985b; *Swanson*, 1964]. **0.6**

43.6 Fault contact of trondhjemite with the "eastern greenstone belt" [*Miller*, 1985b] of the Russell Ranch Formation. **0.1**

44.8 Roadcuts of Jurassic and Cretaceous Russell Ranch Formation [*Miller*, 1985b] to Indian Creek. This assemblage (dominantly graywacke and argillite, with lesser pillow basalt, radiolarian chert, green tuffs, and red shale) dominates the pre-Tertiary Rimrock Lake inlier, which is the southernmost occurrence of pre-Tertiary rocks in the Washington Cascades. *Miller* [1985b] believes that "the various rock types originally formed at a considerable distance from each other" and were juxtaposed by faulting and major lateral transport. **1.2**

48.8 Cut along highway at junction is olivine basalt of Tumac Mountain, a late Pleistocene cone on the Cascade crest 10 km to the northwest [*Clayton*, 1983]. **4.0**

50.8 STOP 17. Sheared Indian Creek unit, a weakly foliated orthogneiss that *Hopson and Mattinson* [1973] suggested was part of a dismembered ophiolite. **2.0**

50.9 Upper Pleistocene hornblende andesite in roadcut. Cuts for next 3 km expose this andesite. **0.1**

51.5 STOP 18. Park just **before** "No Parking" sign. Platy upper Pleistocene hornblende andesite flow erupted from Tumac Plateau north of road. Its vent is not known, but similar flows issued from vents now filled by small domes [*Clayton*, 1983]. Chemical analyses from farther west in the roadcuts indicate silicic andesite (about 62.8% silica) [*Clayton*, 1983]. **0.6**

53.0 Spiral Butte at 12 o'clock is a hornblende dacite (64-66% silica) dome that merges outward into a 4-5 km long flow [*Clayton*, 1983]. *Clayton* [1983] suggests that Spiral Butte is the youngest hornblende andesite or dacite vent in the area and is no more than 45 ka, judged from sedimentation rates on the butte below Mount St. Helens tephra layer C (about 36 ka). **1.5**

53.8 STOP 19. Clear Creek Falls Overlook. Restrooms. The hornblende silicic andesite of Deer Lake Mountain [*Clayton*, 1983] forms the falls. It was erupted from a vent about 5 km farther west (now occupied by a 250-m-high dome 250) and advanced into the glaciated North Fork Clear Creek valley. The flow is more than 100 m thick, overlies a basalt dated at 0.65 ± 0.08 Ma, and is normally magnetized [*Clayton*, 1983]. **0.8**

54.0 Outlet for Dog Lake, with Spiral Butte towering above. Growth of Spiral Butte dome impounded Dog Lake, according to *Clayton* [1983]. **0.2**

54.9 Roadcuts in Deer Lake Mountain flow. **0.9**

56.2 Summit of White Pass (1362 m), with Deer Lake Mountain flow to north dipping from its dome-like vent. The pass is eroded into relatively nonresistant graywacke and argillite of the Russell Ranch Formation. Chair lift crosses gentle slopes of Russell Ranch capped by more resistant olivine basalt and basaltic andesite erupted in the late Pliocene or early Pleistocene from Hogback Mountain 5 km south of White Pass. **1.3**

57.3 Russell Ranch in roadcuts here and following. **1.1**

58.5 Ridge ahead of Ohanapecosh Formation, in places overlain by quartz-phyric ash-flow tuff of the Stevens Ridge Formation (*Swanson and Clayton*, 1983). **1.2**

60.1 Roadcuts still in Russell Ranch Formation. **1.6**

61.0 Bench to left across canyon is on top of Clear Fork andesite flow (see Stop 20) [*Ellingson*, 1972; *Clayton*, 1983; *Swanson and Clayton*, 1983]. **0.9**

61.4 Cortright Creek [*Hammond*, 1980] fault zone between Russell Ranch and Ohanapecosh Formations. *Miller* [1985b] found that the "straightness of the map pattern for much of this contact is compatible with a steep fault" but saw "little evidence to indicate that there has been anything more than minor movement along this contact." Extensive landslides obscure the contact south of here [*Swanson and Clayton*, 1983]. **0.4**

61.7 Cuts in Ohanapecosh Formation, riddled by fine-grained plagioclase-phyric andesitic sills. The sills resemble those in nearby Mount Rainier National Park that *Fiske et al.* [1963] and *Mattinson* [1977] ascribe to an early hypabyssal stage of the Tatoosh pluton, a Miocene granodiorite and quartz monzonite body. **0.3**

63.7 Start of cuts in the Pliocene or Pleistocene olivine basalt of Hogback Mountain. **2.0**

65.0 Prominent columnar-jointed sill cutting Ohanapecosh Formation in cut. Near base of measured section of the Ohanapecosh [*Fiske et al.*, 1963]. Lower part of formation is exposed farther north, where it intertongues with arkosic sandstone [*Vance et al.*, 1987]. **1.3**

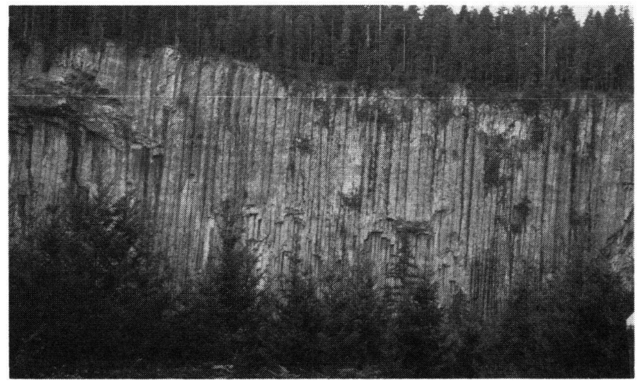


FIGURE 31. Columnar-jointed hornblende andesite of Clear Fork at Stop 20. Trees on flow about 25 m high.

66.2 Turn left into Palisades viewpoint. **1.2**

66.3 STOP 20. Restrooms. View the remarkably columnar hornblende andesite of Clear Fork (Figure 31) [*Ellingson*, 1972; *Hammond*, 1980; *Clayton*, 1983]. The flow has 59-62% SiO_2 [*Clayton*, 1983], slightly lower than other hornblende andesites in the White Pass area. The flow was erupted near Coyote Lake, 9 km to the southeast [*Swanson and Clayton*, 1983], and moved down the canyon in the late Pleistocene. It partly fills a glaciated canyon but is overlain by Evans Creek Drift (*ca.* 18-15 ka). *Hammond* [1980] suggests, because of the abrupt termination and vertical columns indicative of ponding, that the flow was blocked by the Cowlitz glacier during the Hayden Creek stade (*ca.* 140 ka). **0.1**

66.4 Leave viewpoint and turn left on highway. **0.1**

66.9 Ohanapecosh Formation along road. **0.5**

68.8 Junction of Highways 12 and 123. Turn right and then immediately left into parking area. **1.9**

68.9 STOP 21. Restrooms. Roadcut in Ohanapecosh Formation shows wood-bearing, well-bedded volcanic siltstone, lapillistone, and lithic-lapilli tuff above an ash-flow tuff. Thin sill cuts the ash-flow tuff. **0.1**

69.0 Return to Highway 12 heading west. **0.1**

70.6 Roadcut in bedded volcaniclastic rocks of the Ohanapecosh Formation. **1.6**

70.8 Quartz-phyric ash-flow tuff above bedded volcaniclastic rocks. This tuff, formerly considered the basal unit of the Stevens Ridge Formation, has been fission-track dated as 36.4 ± 3.6 Ma [*Vance et al.*, 1987, sample JV 126]. This age is consistent with assignment to the lower part of the Ohanapecosh [*Vance et al.*, 1987]. Several roadcuts from here to Packwood expose ash-flow tuff and volcaniclastic rocks of the Ohanapecosh. **0.2**

75.9 Quarry to right in volcanic siltstone under sill. **5.1**

76.2 Forest Service station on left in Packwood, opposite junction with Forest Road 52. End of log. **0.3**

Log for Day 3 or Day 4, Packwood to Cispus Center via Windy Ridge

0.0 Leave Forest Service station in Packwood.
1.0 Hills to left and ahead have not yet been mapped in detail. Reconnaissance suggests a middle Tertiary terrane intruded by dikes and sills. **1.0**
8.4 Cowlitz River, which heads on Cowlitz Glacier at Mount Rainier. The river flows across a terraced flood plain on Evans Creek Drift (about 18-15 ka) of the Fraser glaciation [*Crandell and Miller*, 1974]. **7.4**
16.2 Turn left at light in Randle onto Cispus Road. **7.8**
17.1 Keep right on Road 25 at junction. **0.9**
17.5 At 2 o'clock is basalt and basaltic-andesite center of Huffaker Mountain, about 23.5 Ma [*Evarts et al.*, 1987], with east dip of 20° toward synclinal trough. **0.4**
24.8 Turn left on Road 25 at junction just after bridge across Cispus River. **7.3**
25.0 Bedded volcaniclastic rocks, chiefly sandstone. **0.2**
25.9 Continue on Road 25 at junction. Landslide. **0.9**
30.2 Active landslide disrupts road. Volcaniclastic rocks dip east parallel to the slope, facilitating sliding. **4.3**
30.3 Lithic-lapilli tuff in cuts near Benham Creek, about 23 Ma as judged by field relations between here and junction of Roads 25 and 99. **0.1**
30.5 STOP 22. Warped volcanic sandstone and siltstone, probably deformed during landsliding or soft-sediment deformation. Similar small outcrops of disturbed fine-grained volcaniclastic rocks occur throughout the area, with no consistency of attitudes. **0.2**
31.4 Lapilli tuff and sandstone at Fourmile Creek. **0.9**
33.5 STOP 23. Basaltic andesite with phenocrysts of plagioclase and two pyroxenes, representative of the middle Tertiary section in this area. Not hornfelsed, as are other flows seen later today. **2.1**
35.6 Basaltic andesite in roadcut. This flow caps the dominantly volcaniclastic section since last stop. **2.1**
36.0 Turn right on Road 99 toward Windy Ridge. **0.4**
36.1 STOP 24. Vitrophyre at base of dacitic ash-flow tuff. Contact with underlying fine-grained tuffaceous siltstone exposed. Columnar, with columns indicating east dip. Vitrophyre grades up into lithic-lapilli tuff. Dated as 23.3 ± 1.8 Ma by Ar-Ar on plagioclase (R. C. Evarts and J. G. Smith, unpub. data, 1987]. **0.1**
37.0 Road traverses through ash-flow tuff, with andesite flows visible on hillslope to north (right). **0.9**
39.4 Thin andesite in a mainly tuffaceous section. **2.4**
40.1 Altered, fine-grained, phyric granodiorite in cut. Sill-like body underlies hill south of Bear Meadow. **0.7**
40.5 STOP 25. Bear Meadow parking area. Restrooms. This is the site from which the two most famous series of photographs of the May 18, 1980, landslide and blast from Mount St. Helens were taken by Gary Rosenquist and Keith Ronholm. The following description, abstracted from *Rosenbaum and Waitt* [1981], is from accounts of eyewitnesses at Bear Meadow:

One observer watching with binoculars saw the north side of the volcano get "fuzzy, like there was dust being thrown down the side." Several seconds later the north face began to slide. The "bulge was moving...the whole north side was sliding down." The first cloud appeared to form at the base of a "cirque-like" wall from which the bulge had moved. In about 20 sec the landslide was out of view behind a ridge. At this time, two distinct clouds seemed to issue from separate vents. An extremely dark cloud grew vertically from the summit. A lighter cloud (the blast cloud), which seemed to come from the area vacated by the landslide, expanded uniformly except for a large "arm" that shot out to the north in the direction of the avalanche. As the blast cloud grew, what appeared to be a shock wave similar to that associated with a nuclear explosion moved ahead of it. About 1-1/2 min after the blast, a noise resembling a thunder clap was heard at Bear Meadow, accompanying a sudden pressure change. This noise was followed by continuous rumbling "like a freight train." The blast cloud moved toward Bear Meadow, reaching the ridge nearest the mountain 25-30 sec after the start of the landslide. When the cloud hit the ridge, it rose and "boiled" upward. Just before the top of the mountain became obscured, observers saw the south side of the summit crumble into the hole formed by the landslide. Seven or eight minutes after the eruption's start, rocks began falling on one of the witnesses 3-5 km northeast of Bear Meadow. He collected two "golfball-sized" rocks (determined later to be cryptodome dacite) from the fall, which continued for roughly 30 sec. As he drove, this material was replaced by "mud drops" that flattened on impact. The largest observed flattened mud drop was 19 mm across. Gradually mudfall abated, but fine ash fell more heavily until the witness could no longer see to drive. Ashfall then abated slowly.

Note that the blast stopped little more than 3 km from Bear Meadow. An anecdote illustrates the serendipity of the remarkable Rosenquist photographs. His camera was mounted on a tripod and centered on the volcano. When the eruption began, Rosenquist was looking away from the volcano. As he quickly turned, he hit the tripod, rotating the camera slightly clockwise so that the mountain was no longer centered but instead was far to the left side of the image. This accident improved coverage of the north flank of the volcano, thereby enabling the sequence of events to be captured in the series of photographs that was later made into a kind of time-lapse video.

Examine the altered, flow-layered dacite, typical of the Strawberry Mountain dacite dome and flow field, in roadcuts 100 m beyond Bear Meadow. North of here, the dacite generally dips eastward and interfingers with the section of ash-flow tuff that we traversed beginning at Stop 24. Thus the dome and flow field may be the

source area for the tuffs. **0.4**
40.7 Volcaniclastic rocks beneath the dacite flow. **0.2**
40.8 Flow-layered dacite; breccia just beyond. **0.1**
41.1 Andesite flow in roadcut. **0.3**
41.7 Epidote-bearing andesite in the outer part of the hornfels zone around the Spirit Lake pluton. From this point, the road roughly parallels the margin of the pluton, and most of the rocks are recrystallized to assemblages of the albite-epidote hornfels facies. **0.6**
42.0 Margin of 1980 devastated zone just above to right. Standing dead trees typify the outer few hundred meters of the devastated area. The *standing dead* were killed by the heat of the blast cloud, which had lost so much lithic debris at its margins that it became lighter than air and lifted off the ground. **0.3**
42.5 Enter the devastated area. Still in andesite. **0.5**
43.9 Lithic-lapilli tuff interbedded in the dominantly andesitic section. **1.4**
44.9 STOP 26. Junction with Road 26. Park just beyond junction and walk back to roadcut exposing Mount St. Helens tephra deposits: 1980 pumice and blast, layer T (early 1800) [*Yamaguchi*, 1983], set X (16th century?), layers Wn and We (early 1480 A.D. and early 1482 A.D., respectively) [*Yamaguchi*, 1985], and sets B (2.2-1.6 ka), P (2.5 ka), Y (3.5-3.0 ka), and J (11 ka) [*Mullineaux*, 1986]. All the tephras are dacitic except for T (andesitic) and part of B (basaltic and andesitic). Yamaguchi's tree-ring ages recognize that the 1800, 1480, and 1482 eruptions could have occurred in the last 3-4 months of the preceding year—remarkable precision for geologic events of prehistorical vintage! **1.0**

Continue straight on Road 99.

45.0 Miner's car, destroyed in blast and preserved here as a much-vandalized relic. Interbedded andesite flows and volcaniclastic rocks on skyline to west are in albite-epidote hornfelsed zone. **0.1**
45.1 Trailhead to Meta lake, which was covered by ice on May 18, 1980, and so retained abundant aquatic life, including trout. Young evergreens around the lake survived the blast because of snow cover. **0.1**
45.6 Nice example of blowdown on hill to right. **0.5**
46.1 Pyroxene diorite dikes, nearly parallel to road, cut hornfelsed volcaniclastic rocks in roadcut. Minor intrusions ranging from pyroxene diorite to monzogranite are common in the Tertiary rocks of the area. Few have been dated directly, but most are believed to be of early Miocene age (25-17 Ma). **0.5**
46.4 STOP 27. Cascade Peaks Viewpoint and Crater House Restaurant and Gift House. Restrooms. Views of Mounts St. Helens, Adams, and Hood (in Oregon). Roadcut opposite restaurant exposes Mount St. Helens tephra deposits, including layer D (1200 B.P.), a thin dacitic blast deposit formed during emplacement of the Sugar Bowl dome [*Crandell and Hoblitt*, 1986], between sets W and B. The tephra overlies hornfelsed pumice-lapilli tuff, probably ash-flow tuff. **0.3**
46.7 Dacite plug visible in hill west of road. **0.3**
47.3 Up creek to right is relatively fresh hornblende andesite dike cutting hornfelsed dacite breccia. Hornblende dated as 19.9 ± 0.7 Ma [*Evarts et al.*, 1987]. **0.6**
47.4 Diorite in roadcut. **0.1**
47.9 STOP 28. Trail to Independence Pass. Hike 200 m to small bench on crest of low hill. The blast deposit is easily recognized by its gray color, poor sorting, and content of shredded wood. Note the tack driven in the sawn end of log at switchback; it marks a period of stressed growth (narrow tree rings) in 1801-1805 A.D. caused by fall of the dacitic T tephra in 1800. From the bench are good views of Spirit Lake, tree blowdown, and the northwest corner of the dacite dome in the crater. Standing tree trunks on and behind ridge to north indicate that the blast lofted but snapped off their crowns. Note zone of tree removal on Harry's Ridge west of the lake; trees were removed as the debris avalanche scoured the lower part of the ridge. Below is Harmony Falls basin, through which a trail leads to the shore of Spirit Lake, whose high level drowns most of the falls. Hill between here and Mount St. Helens is underlain by an andesite flow (cliffs along Harmony Falls trail) capped by the dacite dome seen at Stop 29.

The Tertiary rocks visible across the lake are east-dipping andesite flows and volcaniclastic rocks similar to those already seen. North of the lake, the rocks are progressively more thoroughly recrystallized as the southern contact of the Spirit Lake pluton is approached. The ridge on the skyline is made of hard flinty hornblende hornfels adjacent to the contact, which is just north of the ridgeline. **0.5**

48.0 Coarse lithic-lapilli tuff, containing clasts of dacite seen at next stop, cut by a northwest-trending (335°) shear with horizontal slickensides and steps indicating dextral slip. The southern Washington Cascades and adjacent Columbia Plateau are host to hundreds of such northwest-trending dextral shears, in most places with little demonstrated displacement. **0.1**
48.6 On inside of curve, brecciated andesite flow fills a vertically walled channel eroded into wood-bearing lithic-pumice lapilli tuff cut by zeolite veins. **0.6**
49.2 Trail to Harmony Falls. Enjoyable walk to shore of Spirit Lake, with well-exposed volcaniclastic rocks near water's edge. Harmony basin was site of floods fed by water displaced from Spirit Lake by the debris avalanche [*Waitt*, 1984a; *Doukas and Swanson*, 1987]. **0.6**
49.5 STOP 29. Cedar Creek Viewpoint. Excellent view of Spirit Lake. Walk back along road 150 m to quarry in dacite flow. The dacite, probably a dome or small intrusion, is very fine grained, essentially aphyric, and has numerous limonitic stains along flow layers that probably represent oxidized pyrite. **0.3**
50.4 Donnybrook Viewpoint. Complex of granodiorite sills at 2 o'clock. Good exposure of Mount St. Helens tephra deposits in roadcut opposite viewpoint. **0.9**
50.9 Smith Creek Viewpoint. Good views into the Smith Creek drainage, devastated by the blast and later

lahars [*Brantley and Waitt*, 1988], and, farther east, the shield-like Indian Heaven Wilderness, made of Quaternary olivine basalt. The huge andesitic cone of Mount Adams, the second-most voluminous Cascade volcano after Mount Shasta, dominates the eastern skyline. Tertiary rocks underlying Mount St. Helens below Plains of Abraham include many small intrusions, like those seen along this road, cutting andesite flows and volcaniclastic rocks. Much of the host rock is hornfelsed even between the small intrusions, perhaps because a master intrusion is at shallow depth. **0.5**

51.0 Roadcuts in multiphase granodiorite intrusive complex of Windy Ridge. Some phases contain hornblende, a sample of which was K-Ar dated at 24.3 ± 1.3 Ma [*Evarts et al.*, 1987]. **0.1**

51.9 STOP 30. Windy Ridge Viewpoint. Restrooms. Ascend steps for best views of Spirit Lake, Harry's Ridge, hummocky debris avalanche that dams Spirit Lake, the Pumice Plain, and lahar fan directly north of crater. The Pumice Plain was at one time entirely covered by 1980 pyroclastic flows, but lahars generated by eruption-induced snow melt in the crater have swept away or covered most of the flows due north of the crater. Part of the Pumice Plain west of the lahar fan still has an intact, though deeply gullied, primary surface.

The debris avalanche dammed and partly filled Spirit Lake, displacing water so that the surface of the new lake was about 61.5 m higher than before (1036.3 m *vs.* 974.8 m). Harry Truman, who stubbornly refused to vacate his lodge on the shore of Spirit Lake, was buried beneath about 45 m of debris and 25 m of water in the southwest corner of the lake. The avalanche formed an unstable debris dam that threatened to fail catastrophically when lake level rose to the approximate height of the low point on the dam. The Army Corps of Engineers began pumping the lake in November 1982 to stabilize water level at an acceptable elevation (1055.2 m). This costly venture was ended in April 1985 when a 2.6-km, 14-million-dollar, tunnel was opened through Harry's Ridge and began to serve as a gravity-fed controlled outlet for the lake [*Sager and Chambers*, 1986]. The tunnel is 3.4 m in diameter, has a grade of 1%, and was constructed with a tunnel-boring machine advancing at an average rate of 20 m per day for 5.5 months. The portal to the tunnel, which crosses the St. Helens seismic zone with a capability of a M=7 earthquake [*Weaver and Smith*, 1983], is visible about halfway along the western shore in basaltic andesite and breccia. Opening the tunnel caused lake level to drop about 6.7 m to the elevation of the portal, resulting in the prominent shoreline with stranded logs. Water from the tunnel eventually enters the Toutle River after flowing through South Coldwater Creek and Coldwater Lake.

The northwest corner of the 1980-86 dacite dome can be seen from the hilltop [*Swanson et al.*, 1987; *Swanson and Holcomb*, in press]. At the time of writing (December 1988) the dome had last grown in October 1986 and was about 267 m high, 1,060 m long, 860 m wide, and had a volume of 74.1 x 10^6 m^3. Its volumetric rate of growth and geometry were notably regular [*Swanson and Holcomb*, in press], and each period of growth was easily predicted on the basis of precursory ground deformation and seismicity [*Swanson et al.*, 1983; 1985].

A small shed on top of Harry's Ridge houses surveying and radio equipment used by volcanologists of the U.S. Geological Survey's Cascades Volcano Observatory (CVO) to monitor volcanic activity. Most monitoring is now conducted within the crater and on the dome. CVO notifies the U.S. Forest Service and other governmental agencies when monitoring indicates significant changes in activity. All decisions regarding access and land use in Mount St. Helens National Volcanic Monument are made by the Forest Service. **0.9**

59.1 Return to Road 26 and turn left (north). **7.2**

59.7 The family of three who owned the car on display were killed in a small cabin near the portal to their prospect high on the hillside at 9 o'clock. They had reopened an adit originally excavated during a period of mining in the southern Washington Cascades around the turn of the century. The adit was driven along a polymetallic sulfide (pyrite, chalcopyrite, sphalerite) vein, one of a set of northwest-trending veins peripheral to the Earl porphyry copper deposit. The only known production from the St. Helens district was a few hundred kilograms of copper from the Sweden Mine, now under 30 m of water at the northeast end of Spirit Lake. All the copper reportedly found its way into a statue of Sacajewea, the guide for the Lewis and Clark expedition, that stands in a park in Portland [*Moen*, 1977]. **0.6**

60.0 Trailhead to Norway Pass, which affords excellent views of Spirit Lake and the crater. From Norway Pass, trails connect to Independence Pass and continue into the high country north of Spirit Lake. **0.3**

60.4 Cross from hornfelsed wallrock into Spirit Lake pluton. No place to stop. The pluton underlies the Green River basin and tree-covered hillside ahead, beneath which most of the 17-Ma Earl porphyry-copper deposit resides. This large-tonnage, low-grade deposit would probably have been open-pit mined if it were in Arizona, but mining wasn't done here, owing to 1) the eruption and presumed hazards therefrom, 2) the steep decline in copper prices in the early 1980s, and 3) environmental concerns about acid waste. Molybdenum would have been a byproduct of the copper mining. **0.4**

61.9 Looking west down Green River at 9 o'clock, all exposures are of the Spirit Lake pluton. **1.5**

62.6 Note margin of tree-blowdown area. Much of this area had been logged before 1980, as seen by the sawn stumps, but the standing dead that fringe some clearcuts provide evidence of the waning blast. **0.7**

62.8 Turn left on Road 2612 beyond Ryan Lake. **0.2**

62.9 STOP 31. Granodiorite porphyry, representative of the main phase of the Spirit Lake pluton, occurs in a nearby roadcut. The pluton consists of three phases, each displaying substantial internal compositional and textural variation [*Evarts et al.*, 1987]. The main phase, constituting most of the intrusion, ranges from diorite to granodiorite and is well dated at 21 Ma. The porphyritic texture here is typical of the main phase in the eastern half of the pluton. To the west, coarser-grained, more equigranular textures predominate. This pattern suggests that the pluton and its host rocks have been tilted eastward and eroded more deeply in the west.

Ryan Lake was once nestled in old growth forest out of sight (and mind) of Mount St. Helens. The campground was in use on May 18, 1980. Imagine the terrifying sensation when the blast cloud appeared over the hill with little if any warning. A body buried by ash alongside the outhouse was found a month after the explosion, and others were killed in the Green River basin. One miner managed to walk from his work site farther west to his pickup parked here, to drink a bottle or two of beer to try to clear his throat of the choking ash, and then to walk (downed trees kept him from driving) several kilometers down Road 26 before collapsing. An autopsy showed his lungs coated with ash.

Bus can go 0.3 miles farther to Goat Mountain trailhead to turn around and return to stop. **0.1**

63.0 Return to Road 26 and continue north. **0.1**

63.7 Note standing and fallen dead trees on east side of Quartz Creek basin. The prominent scars on the hillside record pumiceous debris flows of the last several winters. Such flows were a problem before 1980 that has been exacerbated by the May 18 deforestation. **0.7**

65.8 Cross contact from main phase, seen at Ryan Lake, into granite phase of Spirit Lake pluton. The contact is hard to define here owing to an overprint of intense deuteric alteration, but it appears gradational. Elsewhere, sharp contacts locally marked by intrusion breccia indicate that the granite phase is younger. **2.1**

66.1 STOP 32. Examine the granite phase of the Spirit Lake pluton in roadcut. Rocks of the granite phase are distinctly lighter in color, finer-grained, and more felsic than those of the main phase. Outcrops of the granite phase are concentrated along the eastern margin (top) of the exposed part of the pluton. **0.3**

66.4 At 9 o'clock, note standing dead along road. **0.3**

66.7 Leave devastated area. Green trees again! **0.3**

67.2 Roadcut in main phase of pluton. **0.5**

67.8 Back in granite phase of pluton. **0.6**

68.6 Series of roadcuts in granite phase of pluton. **0.8**

69.7 STOP 33. Screens of hornfelsed host rock, originally lithic- and pumice-lapilli tuff, cut by several aplite dikes and at least one granite dike. Contact with Spirit Lake pluton is obscured by forest just up road from here. The wallrock outside of the hornfelsed zone is coarse breccia and dacite flows, whose attitudes suggest the site of a Miocene caldera [*Evarts et al.*, 1987]. **1.1**

70.1 Hornfelsed dacite, in places with relict flow layering, and dacite breccia. **0.4**

70.7 Clastic dacite and andesite, possibly caldera fill, cut by two andesite dikes. Entire assemblage is recrystallized to albite-epidote hornfels. Similar rocks occur in discontinuous roadcuts for next 3 miles. **0.6**

71.1 At 9 o'clock, dacite flow in quarry dips east. **0.4**

72.8 Bedded volcaniclastic rocks, chiefly sandstone and siltstone, with Cispus River to right. Some of the sandstone is normally graded. **1.7**

73.1 Turn right at junction with Road 25. **0.3**

73.3 Same unit as at mileage 72.8. **0.2**

74.2 Turn left onto road 76 to Cispus Center. **0.9**

74.3 Bridge across Iron Creek. Bedded sandstone in stream cut. **0.1**

77.1 Columnar ash-flow tuff over tuffaceous sandstone, siltstone, and lithic lapilli tuff. **2.8**

79.7 Keep right at intersection. At 2 o'clock is Tower Rock monolith, an intrusion whose face was greatly steepened by glaciation in Cispus valley. **2.6**

81.2 Turn left into Cispus Center. End of log. **1.5**

Log for Optional Day 3, Packwood to Cispus Center via Mount Rainier

0.0 Depart Forest Service station in Packwood and retrace route of Day 2 on Highway 12 to Highway 123.

7.2 Turn left on Highway 123. **7.2**

7.8 Bridge across Carlton Creek, on either side of which are roadcuts in bedded Ohanapecosh Formation on east limb of Unicorn Peak syncline. Cuts for next several miles are in Ohanapecosh cut by sills. **0.6**

12.5 Stevens Canyon Road. Stay right. **4.7**

15.4 View straight ahead of Ohanapecosh Formation on Double Peak. **2.9**

17.4 Roadcuts of lapilli tuff in the Ohanapecosh cut by sills emplaced during the early stage of the Tatoosh pluton [*Fiske et al.*, 1963; *Mattinson*, 1977]. **2.0**

21.9 Good roadcuts in Ohanapecosh Formation. **4.5**

23.4 Junction with Highway 410 at Cayuse Pass (1431 m). Turn right toward Chinook Pass. **1.5**

23.6 All roadcuts from here to Chinook Pass are in Ohanapecosh Formation cut by sills. **0.2**

23.7 Good exposure of thin-bedded Ohanapecosh. **0.1**

25.1 Roadcuts at Stop 35 after bus turns around. **1.4**

26.9 Summit of Chinook Pass, 1899 m. **1.8**

27.0 STOP 34. Turn right into parking area. Restrooms across highway at lower parking lot. Scenic view down American River. Retrace route to next stop. **0.1**

28.9 STOP 35. Bus park on right side of road at curve. View of Governor's Ridge toward west, underlain by bedded Ohanapecosh. Craggy higher ridge behind Governor's Ridge is Cowlitz Chimneys and Sarvent Glaciers area, both in an Ohanapecosh lava-flow complex interpreted as a vent area that fed pyroclastic detritus into the Ohanapecosh [*Fiske et al.*, 1963].

Walk down road to observe 27-m-thick bed of pumice-lithic-lapilli tuff (probably a pyroclastic flow) and underlying thin beds of volcaniclastic rocks figured by *Fiske* [1963, Plate 4]. Fiske interpreted the thick deposit as a subaqueous pyroclastic flow, but *Vance et al.* [1987] believe it was deposited subaerially. *Fiske* [1963] interpreted the thin beds as products of turbidity currents, whereas *Vance et al.* [1987] think they were deposited by airfall or surges on land. Many sedimentologists have argued at this outcrop with no clear concensus. **1.9**

Return to Cayuse Pass.

30.8 Cayuse Pass. Turn right on Highway 410. **1.9**

33.0 Road goes down canyon of Klickitat Creek. Good view of Mount Rainier and source (Fryingpan, Emmons, and Inter Glaciers) of White River to left. **2.2**

34.0 Hidden contact of Tatoosh pluton cutting Ohanapecosh Formation [*Fiske et al.*, 1963]. **1.0**

34.3 Turn left at junction with road to Sunrise. **0.3**

Optional Trip to See Osceola Debris Flow

(0.0) Continue straight on Highway 410 at Sunrise junction. All roadcuts for next 5 km are in Tatoosh pluton, but exposure is poor because of till.

(2.4) Approximate contact of Tatoosh with volcaniclastic rocks of the Ohanapecosh [*Fiske et al.*, 1963]. **2.4**

(11.8) Pass entrance to Dalles Campground. **9.4**

(12.8) Turn left on Road 73 and at all junctions. **1.0**

(13.4) Keep left on Road 120; follow power line. **0.6**

(13.9) STOP 36. Gravel pit. Observe a cross section of the Osceola debris flow (see Stop 39 for discussion). The Osceola has a high clay content, presumably from hydrothermally altered rocks on the volcano, but here 50-60% of the clasts were derived from stream gravel and till, not the volcano. Here the upper 1-3 m of the Osceola is yellow, and the lower 2-4 m pinkish gray; this reflects ground-water oxidation in the aereated zone and is **not** a contact. The Osceola here overlies iron-oxide-coated hardpan on outwash gravel of probable Evans Creek age (*ca.* 18-15 ka). The hummocky terrain 200 m northwest of the gravel pit was once thought to be a separate lahar (the Greenwater lahar [*Crandell*, 1971]) but is now considered a marginal facies of the Osceola (J. W. Vallance, oral commun., 1988). **0.5**

Retrace route to Sunrise junction.

End of optional trip. **13.9**

39.4 White River bridge. Road starts up ridge, underlain by Tatoosh pluton, zircon-dated here as 14.1 Ma [*Mattinson*, 1977]. Till mantles much of slope. **5.1**

41.6 Start across intracanyon lava flow. **2.2**

41.8 STOP 37. Bus pullover along right side of road. View highly plagioclase-clinopyroxene-hypersthene-phyric andesite flow from Mount Rainier that partly filled the ancestral canyon of White River [*Fiske et al.*, 1963]. This site is near the terminus of the flow, and its columns are nearly horizontal where the flow cooled against canyon walls. Walk back 100 m, staying outside rock wall, to view the cross-sectional shapes of the columns and the transition to steeply platy andesite (Figure 32). The flow is one of the earliest intracanyon flows from the volcano and extends from Burroughs Mountain through Yakima Park to here [*Fiske et al.*, 1963]. It is 240 m thick at Burroughs Mountain. Opposite Yakima Park, White River has entrenched 400 m since the andesite was erupted [*Fiske et al.*, 1963]. **0.2**

42.2 Switchback at margin of the intracanyon andesite flow. Till obscures the contact. Tatoosh pluton along road to top of ridge. **0.4**

46.3 Bench on hillside below road at 3 o'clock is developed along top of intracanyon andesite flow. **4.1**

46.8 STOP 38. Parking area for viewpoint at switchback on crest of Sunrise Ridge, 1860 m. View of ridge-like Sourdough Mountains to northwest, capped mostly by lapilli tuff of the Ohanapecosh Formation intruded by the Tatoosh. Good view to south of Cowlitz Chimneys and Sarvent lava complex in the Ohanapecosh.

Examine calc-alkalic granodiorite and quartz monzonite of the Tatoosh pluton in roadcut and stone wall. Granodiorite is the dominant lithology of the pluton, but quartz monzonite is common in the roof areas, and quartz diorite and granophyre are common locally. Isotopic zircon ages suggest that the plutonic complex "was emplaced in a series of intrusive and extrusive events over a span of about 12 m.y." [*Mattinson*, 1977]. According to *Mattinson* [1977], the initial activity was intrusion of a dike and sill swarm about 26 Ma. Eruptions from the plutonic complex formed thick welded tuffs about 25 Ma and 22 Ma. The core of the pluton rose and intruded its earlier volcanic and hypabyssal cover in two stages, 17.5 and 14.1 Ma. This locality is interpreted as in the roof zone of the main pluton [*Fiske et al.*, 1963], and *Mattinson* [1977] dated this rock as 24.1 Ma. The Palisades, visible north of here, is underlain by welded tuff thought to grade downward into the pluton and has been dated as 25.1 Ma [*Mattinson*, 1977]. **0.5**

49.0 Approximate contact between Tatoosh pluton and intracanyon flow we saw earlier. This flow underlies Yakima Park and the Sunrise Lodge area. **2.2**

FIGURE 32. Columnar intracanyon andesite flow from Mount Rainier at Stop 37.

49.6 STOP 39. Flag pole at Sunrise, 1950 m elevation. The 10-12 cm-thick layer of crunchy brown pumice belongs to tephra layer C, erupted from Mount Rainier 2200-2300 years B.P. [*Mullineaux*, 1974]. Walk to Emmons Nature Trail Overlook above White River for view of the source area of the Osceola debris flow (2 km^3) that poured down the White River and West Fork White River and spread across more than 260 km^2, mostly in the Puget Sound lowland 40-70 km from the volcano [*Crandell and Waldron*, 1956; *Crandell*, 1971]. Logs in the Osceola give a bristlecone-corrected ^{14}C age of about 5700 years B.P. [*Crandell*, 1969, 1971].

The Osceola everywhere has a high content of clay (6-12% [*Crandell*, 1971]), presumably derived from hydrothermally altered rocks high on the volcano. The source area is now hidden beneath the broad upper part of the Emmons and Winthrop Glaciers and possibly includes material removed from a former summit region above 4250 m [*Crandell*, 1963b; *Crandell*, 1971]. As *Crandell and Waldron* [1956] pointed out, "The very existence of this broad expanse of ice suggests the possibility that the ice occupies a depression that resulted from the explosive destruction of part of the volcano, or from eruptive action followed by partial collapse of this area." The Osceola occurs on ridgetops above Glacier Basin and on top of Steamboat Prow (2957 m), so clearly it originated even higher on the volcano [*Crandell and Waldron*, 1956; *Crandell*, 1971]. A remnant of the debris flow is visible from here as a terrace along Inter Creek just upstream from the White River. Conceivably the debris flow could have been generated by collapse of the altered flank of the cone without accompanying eruptive activity. Whether an eruption occurred is uncertain. Tephra layer F [*Mullineaux*, 1974] from Mount Rainier is clay-rich like the Osceola and has a corrected ^{14}C age of 5.7-5.8 ka; it has been found neither above nor below the Osceola, however, perhaps owing to unfavorable wind directions. A reasonable supposition is that layer F records phreatic activity preceding or accompanying generation of the avalanche and resulting debris flow. The Osceola is 2-7 m thick along its margins but presumably much thicker in its center. Remnants of the debris flow on the sides of the White River and West Fork White River valleys show that the thickness was locally at least as much as 150 m while the debris flow was moving. A three-dimensional model in the visitor center helps to visualize the geometry and enormity of the Osceola. A measure of its size is the profound effect it had on Puget Sound more than 100 km from the volcano; the shoreline was displaced seaward 27-50 km as more than 460 km^2 of new land was created! **0.6**

Return to Highway 410 and thence southward past Cayuse Pass to junction with Stevens Canyon road.

79.3 Stevens Canyon road. Turn right toward Paradise. Road traverses through volcaniclastic rocks of the Ohanapecosh for next 8.5 km. **29.7**

84.4 Start of roadcuts on Backbone Ridge in upper part of Ohanapecosh Formation, according to *Fiske et al.* [1963]. Note the abundance of wood and presence of what *Fiske et al.* called a saprolite (fossil soil). **5.1**

84.7 Basal zone of Stevens Ridge Formation above the Ohanapecosh. **0.3**

84.8 STOP 40. Bus can let group off at narrow paved area on right side of road and park at trailhead 0.1 mile farther. Walk back 180 m to view basal zone in quartz-plagioclase-phyric welded ash-flow tuff of Stevens Ridge Formation. The ash flow plowed into loose "soil" atop the Ohanapecosh and incorporated blocks of the soil into its base (Figure 33) [*Fiske et al.*, 1963]. Note the intimate mixture of soil with the ash-flow tuff, as well as larger discrete pieces of soil within the tuff. Same site as that photographed in *Fiske et al.* [1963, figure 22]. Rock hammers can be used here; we are just outside the National Park! The ash-flow tuff here has been dated at 27.3 ± 2.9 Ma by *Vance et al.* [1987, sample JV 32].

Quartz-phyric ash-flow tuffs are abundant in the Stevens Ridge Formation, but according to *Vance et al.* [1987] they also occur in the underlying Ohanapecosh and hence are not useful in discriminating the two units. The tuff of Lake Keechelus (Day 1) is an example. *Vance et al.* [1987] therefore propose to demote the Stevens Ridge as defined by *Fiske et al.* [1963] to member status and assign it to the Fifes Peak Formation. **0.1**

87.0 Base of Stevens Ridge Formation hidden in forest. Road re-enters Ohanapecosh. **2.2**

89.6 STOP 41. Restrooms. Box Canyon of the Cowlitz River, a narrow gorge cut into glacially smoothed and polished diorite. Roadcut exposes the diorite, a minor but ubiquitous component of the Tatoosh pluton. **2.6**

Roadcuts for next 1.2 miles show diorite and granodiorite of Tatoosh pluton.

91.5 Prominent roadcuts in welded ash-flow tuff of Stevens Ridge Formation. **1.9**

91.8 Good view across Stevens Canyon to young intra-canyon andesite flow just above creek. Note the complex columnar joints, which *Fiske et al.* [1963] suggest result from flowage along the side of a glacier. **0.3**

92.3 Granodiorite of the Tatoosh pluton in roadcuts. This unit continues for about 1 km. **0.5**

FIGURE 33. Dark pods of "soil" mixed in base of ash-flow tuff in Stevens Ridge Formation, Stop 40.

92.7 STOP 42. View granodiorite of the Tatoosh pluton here, if the Sunrise road is snowed in. See comments about the Tatoosh under description of Stop 38. The roadcuts are some of those used by *Dunn et al.* [1971] to document a magnetic field reversal (reversed to normal) during cooling of the pluton. **0.4**
93.5 Bridge across Stevens Creek. Cross a narrow intracanyon flow of andesite, then quickly return to granodiorite and in turn back into andesite. **0.8**
94.4 Intracanyon andesite visible high at 3 o'clock. **0.9**
94.7 Same andesite in roadcut at switchback. **0.3**
95.6 A narrow tongue of granodiorite in roadcut, with andesite around next curve. **0.9**
95.9 Louise Lake to right. Road from here to Reflection Lakes is along contact of Mount Rainier andesite flow and granodiorite. **0.3**
96.8 Reflection Lakes. Continue in granodiorite. **0.9**
97.8 STOP 43. Panoramic view of Mount Rainier from turnout on left: from east to west, top of Little Tahoma Peak, Gibraltar Rock, Nisqually Glacier, Wapowety Cleaver, and Success Cleaver. Note columnar Mount Rainier andesite above road. **1.0**
98.1 Keep left at junction. **0.3**
98.3 Turn right. Roadcut in granodiorite. **0.2**
98.9 Roadcut in andesite flow from Mount Rainier. Similar cuts continue sporadically to Paradise. **0.6**
99.7 Stay left at junction. **0.8**
100.2 STOP 44. Paradise visitor center. Restrooms, cafeteria, gift shop, and museum. General views, especially of the mountain and the Tatoosh Range.
Leave Paradise on Longmire road. **0.5**
102.1 Keep right toward Longmire at junction. Next roadcuts are in andesite. **1.9**
103.3 Platy andesite in roadcut. **1.2**
105.0 Continue right at junction. Road passes from andesite into the Tatoosh pluton as it descends into Nisqually River valley. Note snout of Nisqually Glacier covered by moraine. In early 20th century, the glacier extended nearly to the bridge. **1.7**
106.9 Roadcuts in granodiorite. **1.9**
108.2 View through trees across canyon of thick, complexly columnar intracanyon andesite flow. This is the flow that we were driving on near Paradise. **1.3**
109.0 View ahead of granodiorite on Cougar Rock. **0.8**
109.3 Roadcuts and natural exposures in volcaniclastic rocks of the Ohanapecosh Formation. **0.3**
114.2 Kautz Creek, scene of a series of lahars on October 2-3, 1947, induced by a cloudburst possibly enhanced by a glacier-outburst flood [*Crandell*, 1971]. **3.1**
116.4 Tahoma Creek, site of numerous debris flows in the middle and late 1980s fed by glacier-outburst floods from South Tahoma Glacier. The floods typically occurred in late afternoon of warm days. Water was photographed leaving the glacier well above its terminus. The debris flows repeatedly covered the Westside Road, which was closed to public travel in summer 1988. **2.2**
117.6 Leave Mount Rainier National Park. **1.2**

End of geologic log. To drive to Cispus Center, continue on Highway 706 from National Park to Elbe (10 miles), turn left on Highway 7 to Morton (16 miles), and then turn left on Highway 12 to Randle (17 miles). Thence follow log from Randle to Cispus Center.

Alternatively, turn left 3.3 miles outside National Park on Road 52 toward Packwood. After 1.8 miles turn left on Road 52 (here called Osborn Road) and follow it to the Forest Service Station in Packwood, 21.4 miles farther. (Most of this road was gravel in fall 1988 but was being readied for paving.) Thence follow log from Packwood to Cispus Center.

Total mileage to Cispus Center by either route is 177 miles (205 miles with the optional trip to see the Osceola debris flow.)

Log for Day 5, Cispus Center to Hood River via Indian Heaven

Retrace route back to Road 25 and then to junction with Road 99, where log starts.
0.0 Continue south on Road 25.
0.6 Andesite flow in roadcut. **0.6**
2.8 Pumice-lithic-lapilli tuff, probably ash-flow tuff. **2.2**
4.9 Basaltic andesite flow cut by narrow, petrographically similar dike trending 280°. This trend typifies that of a major dike swarm in this area. **2.1**
5.7 Basaltic andesite, with complex platy jointing. **0.8**
6.1 Lithic-pumice-lapilli tuff, probably an ash flow, that slides easily because of clay alteration. Underlies andesite flow seen in previous roadcut. **0.4**
6.8 At 2 o'clock is stack of thin near-vent basaltic andesite flows, slightly older than flows in roadcuts. **0.7**
6.9 Start cuts in mafic intrusion. Probably subvolcanic, but overall shape is unknown. **0.1**
8.8 Continue straight on Road 25 at junction. *Note: Major road work was underway when the trip was logged from here to Road 2573. Exposures and mileages may differ significantly from those given below.* **1.9**
9.0 Clearwater Overlook. Cut in finely hornblende-phyric fragmental dacite flow or ash-flow tuff. **0.2**
9.4 This unit cut by 5-m-thick columnar sill of plagioclase-phyric andesite. Similar exposures occur for next 0.4 miles. **0.4**
10.2 Andesite flow(?) in roadcut. **0.8**
10.4 STOP 45. Start of 0.6 miles of roadcuts in Quaternary olivine basalt of Paradise Falls [*Korosec*, 1987a], which erupted on the ridge crest just east of the road and poured into the valley of Clearwater Creek. It contains large phenocrysts of olivine (rimmed by iddingsite in oxidized samples) but none of plagioclase.

The vent for this flow lies midway along a N35°E line of Quaternary vents extending for about 50 km from Tumtum Mountain south of the Lewis River to Badger Ridge south of Cispus Center (Figure 34). Six vents lie along the Tumtum-Badger Ridge line, and only a few other Quaternary vents occur near it, except for a cluster around Mount St. Helens. The line can be extended with only slight bends to include a vent east of Cispus Center and the Battle Ground Lake maar [*Mundorff*, 1964] and adjacent vent [*Walsh et al.*, 1987], a total length of about 87 km (Figure 34). K-Ar whole-rock ages are available for the basalt of Paradise Falls (0.04 ± 0.03 Ma [*Hammond and Korosec*, 1983]), a flow on Marble Mountain (0.16 ± 0.01 Ma [*Hammond and Korosec*, 1983]), and the olivine basaltic andesite of Badger Ridge (0.65 ± 0.02 Ma; J. G. Smith, written commun., 1986). *Mundorff and Eggers* [1988] interpret Tumtum Mountain as slightly younger than the Amboy drift (a likely correlative [*Walsh et al.*, 1987] to the *ca.* 0.14-Ma Hayden Creek Drift). Battle Ground Lake maar is older than 20.2 ± 0.4 ka (the age of the oldest dated sediment in the lake [*Barnosky*, 1985]. The undated vents have normal magnetic polarity (except for that east of Cispus Center) and so are younger than about 0.73 Ma. Seven vents produced olivine basalt or basaltic andesite, but Tumtum Mountain erupted hornblende dacite (68% SiO_2) [*Mundorff and Eggers*, 1988]. Marble Mountain, the largest Quaternary vent area in southern Washington west of Indian Heaven (except for Mount St. Helens), grew where the line crosses the St. Helens seismic zone [*Weaver and Smith*, 1983].

Whether the Tumtum-Badger Ridge line reflects tectonic control is unclear. Relatively few Tertiary dikes in the area parallel the line, which is slightly oblique to the plate-convergence direction of N50°E [*Riddihough* [1984]; minor sinistral shears have northeast trends. The line does not extend northeast of the Cispus-Lewis fault zone mapped by *Hammond* [1980] or southwest of the Lacamas Lake fault and associated lineament *Walsh et al.* [1987]. The line is not directly reflected by the southern Washington Cascades conductor (SWCC) or other anomalies [*Stanley et al.*, 1987], although its projected trend merges into and parallels that of conductance contours in the south part of the SWCC. **0.2**

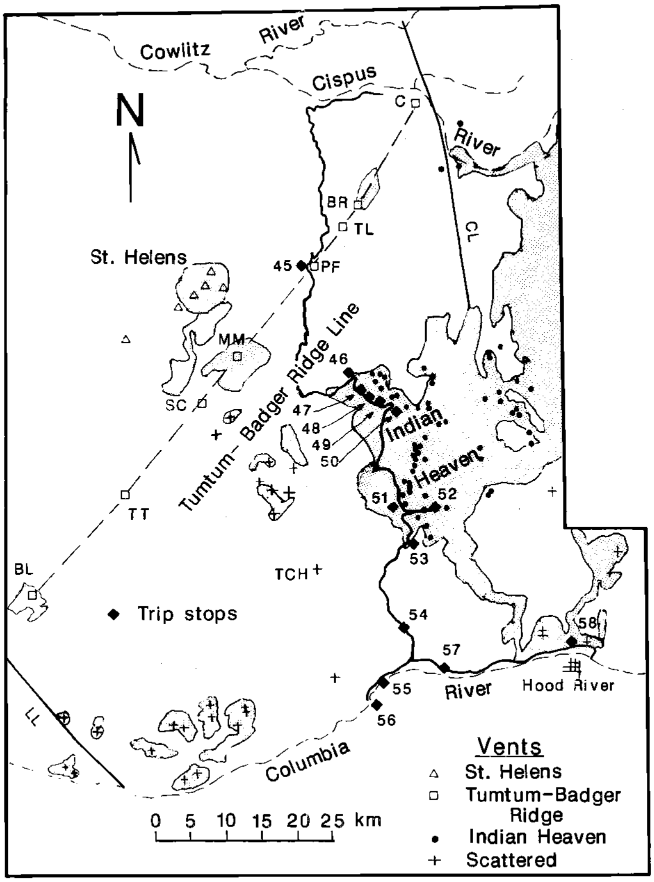


FIGURE 34. Map showing Pliocene and Quaternary vents (keyed to location) and major flow fields (shaded) near field-trip route between Cispus Center and Hood River. Tumtum-Badger Ridge line connects isolated vents. BL, Battle Ground Lake; TT, Tumtum Mountain; SC, vent south of Swift Dam; MM, Marble Mountain; PF, basalt of Paradise Falls; TL, The Loaf; BR, Badger Ridge; C, basalt east of Cispus Center; TCH, Trout Creek Hill; LL, Lacamas Lake lineament; CL, Cispus-Lewis fault zone. See text for discussion.

11.6 Plagioclase-phyric, oxidized, Tertiary andesite. Similar cuts occur sporadically for next 5 miles. **1.2**
17.0 Pumice-lapilli tuff, probably an ash flow. **5.4**
19.3 Section of Mount St. Helens tephra deposits in roadcut above oxidized Tertiary ash-flow tuff. **2.3**
20.0 Small roadcut of ash-flow tuff, with andesite flow just beyond. **0.7**
20.4 Alder-covered surface of lahar of May 18, 1980, which was generated on the southeast flank of Mount St. Helens by rapid melting of eroded snow incorporated into the blast surge and possibly enhanced by water ejected from the volcano [*Pierson*, 1985]. Mudlines 4-6 m above this surface (still evident on some trees in 1988) indicate maximum thickness of flowing lahar. The lahar reached a peak velocity of 30-40 m/s near the base of the volcano but had slowed to an approximately constant 3-6 m/s by the time it reached here [*Pierson*, 1985]. The lahar was generated soon after the start of eruption at 0832 and reached the site of the bridge (destroyed by the lahar) at about 0856. A smaller, pumiceous lahar, generated by a pyroclastic flow on the volcano's southeastern slope between 1530 and 1610, probably reached the site of the bridge at about 1625 [*Pierson*, 1985]. **0.4**
20.7 Bridge across Muddy River. From here to Pine Creek the road crosses pyroclastic-flow and laharic deposits older than 2200 years B.P. [*Phillips*, 1987]. **0.3**
24.3 Pine Creek. Another branch of the first May 18 lahar roared down Pine Creek at a peak discharge of about 29,000 m^3/s [*Pierson*, 1985]. Here erosion on one side of the channel was balanced by deposition on the other [*Pierson*, 1985]. The Muddy River and Pine Creek lahars destroyed 16 bridges, buried several kilometers of road, and raised the level of Swift Reservoir 0.8 m by depositing 13.4 million m^3 of slurry [*Cassidy et al.*, 1980 (quoted in *Pierson*, [1985]); *Schuster*, 1981]. **3.6**
25.1 Turn left at junction with Road 90. **0.8**
25.5 Cross Lewis River at east end of Swift Reservoir. Most logs along river were carried by lahars on May 18,

1980. Eagles Cliff to left is columnar welded ash-flow tuff, probably of early Miocene age [*Phillips*, 1987], overlain by Quaternary(?) basalt of Thomas Lake [*Hammond*, 1987; *Korosec*, 1987a; *Walsh et al.*, 1987]. **0.4**
26.1 Roadcuts on left are in lahar deposit that predates the Castle Creek eruptive period [*Phillips*, 1987]. **0.6**
26.4 Start long roadcut in highly plagioclase-phyric, densely welded ash-flow tuff of Eagles Cliff. The tuff underlies ridge left of road for next 2 km. **0.3**
28.0 Roadcuts of bedded lapillistone, tuff, and wood-bearing mudstone. Andesite dike 3 m wide cuts section. Similar roadcuts occur for next 600 m. **1.6**
30.2 Landslide blocks of the basalt of Thomas Lake [*Korosec*, 1987a]. **2.2**
30.6 Stay on Road 90 at junction with Road 51. **0.4**
31.5 Lithic-pumice lapilli tuff at Rush Creek. Cliff of basalt of Thomas Lake high ahead. **0.9**
32.3 Roadcuts of augite-plagioclase-olivine-phyric, vesicular Quaternary(?) basalt of Thomas Lake. A whole-rock K-Ar age of 3.8 ± 0.5 Ma was obtained for this flow from next series of cuts [*Hammond and Korosec*, 1983]; however, this age is analytically questionable (only 2.7% radiogenic argon), and the normally magnetized basalt is mapped as Quaternary on the basis of field relations and general appearance [*Korosec*, 1987a]. Nonetheless, the basalt is one of the oldest units of the Indian Heaven volcanic field [*Korosec*, 1987a; *Hammond*, 1987]. It was erupted just south of East Crater (15 km southeast of here) and flowed northwest into the ancestral Lewis River. The unit has a volume of about 4 km^3 [*Korosec*, 1987a] and is locally as thick as 150 m in the ancestral Lewis River valley [*Hammond*, 1987]. **0.8**
32.5 Basalt of Thomas Lake in discontinuous roadcuts for next mile. **0.2**
33.5 STOP 46. Possible bus parking at last chance to observe basalt of Thomas Lake. **1.0**
33.9 Turn right on obscure gravel road (3211) in middle of straight segment of Road 90. **0.4**
36.1 Intraglacial basalt of Burnt Peak in roadcut (Stop 14 of *Hammond* [1987]). Radially jointed olivine basalt is partly enclosed in pillow lava. **2.2**
36.6 Pillowed basalt of Burnt Peak, with minor palagonitized hyaloclastite. **0.5**
37.0 STOP 47. Stop 13 of *Hammond* [1987]. Pillows in the basalt of Burnt Peak dominate the outcrop. They invade thinly bedded lacustrine and fluvial or turbidite "black sand" hyaloclastite (Figure 35). The sediments terminate against a nearly vertical invasive or intrusive contact near the left side of the cut. The interstices between the pillows are filled by bedded sediment, which is locally distorted, has truncated bedding, and forms a pépérite with glassy basalt. A lower layer of pillows has similar interstitial fillings and clearly invades white laminated lacustrine(?) siltstone. The siltstone is overlain by bedded sand possibly deposited on top of the basalt; the bedded sand contains a few large blocks of glassy basalt that lack pillow forms and may have broken off a pillow complex. Overlying the pillow basalt and sediment is lithic-rich hyaloclastite in erosional contact with the bedded sand. The hyaloclastite is crudely layered and has west-dipping foreset bedding. A small fault offsets the diamict-basalt contact near the left end of the cut. **0.4**
37.2 Narrow basalt dike intrudes pillows and hyaloclastite. Similar exposures continue for 200 m. **0.2**
37.5 Broken pillow breccia and hyaloclastite. **0.3**
37.8 STOP 48. Stop 12 in *Hammond* [1987]. Well-bedded, reworked hyaloclastite, white because of opal cement, grades laterally into primary hyaloclastite cored by jointed and quenched basalt. Exposure extends about 100 m in roadcut. Bus park at start of cut. **0.3**
38.0 Top of plateau in Crazy Hills, so named by early surveyors who were puzzled by the morphology, which is dominated by erosionally modified moberg hills (hills consisting of palagonitized hyaloclastite and pillows) [*Kjartansson*, 1959]. The Crazy Hills moberg field covers about 21 km^2, has a volume of about 1.7 km^3, and contains hills and ridges 122 to 366 m high [*Hammond*, 1987]. According to Hammond, the hills are composed chiefly of palagonitized hyaloclastite in massive, thick to thin beds containing clasts of silt to boulder size. The basal parts of the hills are thought to consist of pillow lava, and the entire complex is interpreted to overlie subglacial and intraglacial lava flows and pillow lavas. The higher hills are held up by dikes, sills, and lava flows. View straight ahead of Lone Butte [*Hammond*, 1987], a tuya (volcano that erupts initially beneath a glacier, melts through the ice, and develops an upper, subaerial, commonly flat top [*Jones*, 1969]).

Lone Butte and the Crazy Hills apparently formed during the Hayden Creek Stade of the Salmon Springs glaciation, probably about 0.14 Ma [*Hammond*, 1987; *Crandell and Miller*, 1974; *Coleman and Pierce*, 1981]. The glacier filled the Lewis River valley, spilled onto the site of the Crazy Hills, and merged with a local glacier from the northern end of Indian Heaven. The hills and tuya have been modified by the later Evans Creek glaciation, which climaxed about 18-15 ka. **0.2**
38.1 Hyaloclastite in cut on curve. After rounding

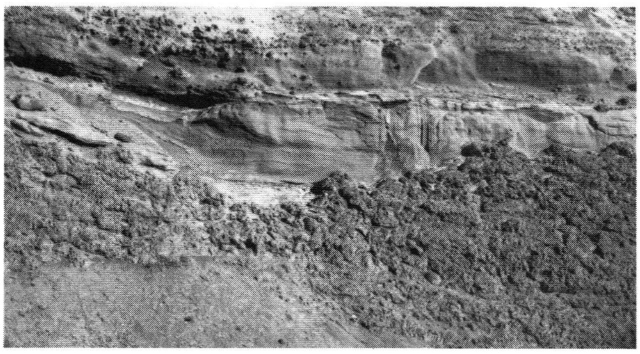


FIGURE 35. Subglacial pillowed basalt invading lacustrine silt (light unit in floor of depression) overlain by sand at Stop 47. Crudely layered hyaloclastite overlies the sand. Height of exposure about 10 m.

curve, Burnt Peak is straight ahead. **0.1**
38.5 Keep right on Road 3211 at junction. **0.4**
38.9 Broken pillow hyaloclastite. **0.4**
39.1 Crudely bedded palagonitized hyaloclastite, possibly reworked. Stop 5 in *Hammond* [1987]. **0.2**
40.2 STOP 49. Stop 4 in *Hammond* [1987]. Small quarry shows pillowed basalt of Burnt Peak invasive into crudely bedded hyaloclastite. Pépérite halos surround sediment clasts between pillows. At west end of exposure, steeply dipping dikes of hyaloclastite cut bedded hyaloclastite, as if squeezed up from below by weight of pillow complex. In middle of cut above the pillow zone is a possible pipe of explosion breccia containing abundant angular lithic clasts of basalt with differing degrees of vesicularity. The pipe is cut off by the pillows. The explosion pipe dies out upward, but traces of it continue to top of second cut not visible from road. Other narrow sediment dikes cut the hyaloclastite in the second cut; walk above the exposure to see this. Small faults cut tilted hyaloclastite at east end of cut. **1.1**
40.4 Turn right at junction with Road 32. **0.2**
40.6 Turn left at junction with Road 30. **0.2**
40.7 View ahead of 430-m-high, 0.3-km^3 Lone Butte tuya [*Hammond*, 1987]. According to Hammond, the lower 230 m of the tuya is palagonitized hyaloclastite, overlain by 40 m of hyaloclastic surge deposits at the eastern end of the tuya and 40 m of foreset-bedded pillow breccia at the western end (exposed in the quarry visible from here). These subaqueous deposits are capped by a 145-m-thick remnant of a subaerial scoria cone, whose western flank is overlain by 65 m of subaerial basalt flows. Four dikes cut the hyaloclastite. At least 3 hours hiking time are needed to see these relations. **0.1**
41.9 At 10 o'clock is subaerial cap on Lone Butte. **1.2**
42.3 Turn right on Road 65. **0.4**
43.6 STOP 50. Bus can stop just before bridge over Rush Creek. Basalt of Outlaw Creek, a fine-grained, olivine-phyric diktytaxitic basalt with about 51.6% SiO_2 and 0.96% K_2O (P. E. Hammond, unpub. data), crops out along the creek. This flow is stratigraphically the oldest in the Indian Heaven field. **1.3**
47.9 Roadcut in basalt of Indian Heaven, diktytaxitic and highly plagioclase- and olivine-phyric [*Hammond*, 1987]. Flow was erupted from west vent of 120-m-high East Crater in the Indian Heaven Wilderness between 29 ka and Evans Creek time [*Hammond*, 1987]. The basalt has about 50.2% SiO_2 and 0.45% K_2O (P. E. Hammond, unpub. data, 1985). **4.3**
48.4 Roadcut in basalt of Indian Heaven. **0.5**
52.1 Continue straight at junction, crossing drift-covered andesite of Black Creek [*Korosec*, 1987b]. **3.7**
53.3 At 9 o'clock is The Wart, a 145-m-high cinder cone that erupted a small basaltic andesite flow just prior to Evans Creek time. Also visible is top of 1514-m-high Red Mountain (with lookout tower), a vent complex that erupted andesite, basaltic andesite, and olivine basalt several times, most recently between the Hayden Creek and Evans Creek stades (P. E. Hammond, written commun., 1983; [*Wise*, 1970]). **1.2**
53.8 STOP 51. Roadcut in basaltic andesite of The Wart (P. E. Hammond, written commun., 1983), included with andesite of Black Creek by *Korosec* [1987b]. Fine-grained and finely plagioclase-olivine-phyric. Contains about 53.8% SiO_2 and 0.8% K_2O (P. E. Hammond, unpub. data, 1985). **0.5**
54.0 Turn left toward Trout Lake on Road 60 and stay on this road to Stop 52. **0.2**
54.9 Small cut in basalt of Sheep Lakes, erupted from east base of Red Mountain just before eruption at The Wart (P. E. Hammond, written commun., 1983). **0.9**
55.3 Basalt of Big Lava Bed visible right of road. **0.4**
56.3 Cross west margin of Big Lava Bed tephra. **1.0**
56.7 STOP 52. Glaciated cinder cone covered by 3 m of Big Lava Bed tephra deposit along edge of Big Lava Bed flow. The cinder cone is oxidized, weathered, and clay-rich. It is locally overlain by 5 m of Evans Creek Drift (P. E. Hammond, written commun., 1983).

The Big Lava Bed tephra deposit was erupted from a 295-m-high cone about 3.5 km east of here. This cone is the source of the tube-fed basalt flow that forms Big Lava Bed itself. The tephra blanket is oval, extends northeastward toward Trout Lake, covers about 200 km^2, and contains about 10^5 m^3 (P. E. Hammond, written commun., 1985). The Big Lava Bed flow moved west from the cone before turning south, eventually reaching the Little White Salmon River nearly 17 km from its source [*Korosec*, 1987b]. It consists of many thin flow units fed by lava tubes. Pressure ridges and plateaus testify to inflation of the flow when lava poured into blocked tubes. A platform at the west base of the source cone was apparently uplifted about 60 m during the eruption (P. E. Hammond, written commun., 1985). The Big Lava Bed flow contains about 0.9 km^3, covers 59 km^2 [*Korosec*, 1987b], and is 8200 ± 100 years ^{14}C years B.P. [*Hammond and Korosec*, 1983]. **0.4**

Return to Road 65.

59.3 Turn left on Road 65. Andesite of Black Creek underlies Evans Creek Drift. A K-Ar whole-rock age of 3.3 ± 0.25 Ma was obtained on the andesite about 1 km south of here [*Hammond and Korosec*, 1983]; *Korosec* [1987b] considers this is too old, partly because no reversely magnetized flows overlie the andesite (or occur anywhere in the Indian Heaven area). **2.6**
62.2 Road winds into canyon of Panther Creek, which is eroded into middle Tertiary volcaniclastic rocks unconformably capped by the andesite of Black Creek [*Wise*, 1970; *Korosec*, 1987b]. **2.9**
62.6 Roadcuts in bedded volcaniclastic rocks. *Korosec* [1987b] considers these and other Tertiary rocks along Panther Creek to be of late Oligocene age. *Wise* [1970] tentatively correlated them with the Ohanapecosh Formation on the basis of lithology and reconnaissance tracing of the Ohanapecosh southward from Mount Rainier by R. S. Fiske and A. C. Waters in the early

1960s. A firm basis for this correlation is lacking. **0.4**
62.8 STOP 53. Quarry in columnar intracanyon flow of olivine-phyric andesite of Black Creek. This flow came down the valley of ancestral Panther Creek from an unknown vent near Red Mountain. A similar remnant occurs in 0.9 miles. **0.2**
64.1 Start series of cuts in middle Tertiary rocks. **1.3**
70.2 Turn right at junction with Old State Highway. **6.1**
70.3 Turn left at T-intersection. For next 8 km the road follows the Wind River valley on the surface of a basalt flow erupted from Trout Creek Hill 12 km northwest of here [*Wise*, 1970; *Korosec*, 1987b]. **0.1**
71.3 Skyline hill with tall antenna at 12 o'clock is Mount Defiance, Oregon, a middle or late Pleistocene shield volcano of basaltic andesite and andesite on the rim of the Columbia Gorge (D. R. Sherrod, written commun., 1988; [*Hammond*, 1980]). **1.0**
72.0 Small hill of Tertiary lapilli tuff surrounded by basalt of Trout Creek Hill. **0.7**
72.2 STOP 54. Bus parking just before roadcut in basalt of Trout Creek Hill. Coarsely olivine-phyric (clots to 5 mm or more) diktytaxitic basalt. Several flows were erupted from Trout Creek Hill about 0.34 ± 0.075 Ma (whole-rock K-Ar age) [*Hammond and Korosec*, 1983; *Korosec*, 1987b]. The cumulative thickness of flows in the Wind River valley is at least 70 m, measured below the bridge 500 m southeast of here [*Wise*, 1970; *Korosec*, 1987b]. The flows moved down valley to the Columbia River and built a hyaloclastite dam across the Columbia [*Waters*, 1973]. The Wind River formed a delta 45 m thick into the temporary lake [*Waters*, 1973] before the Columbia breached the dam and drained the lake. **0.2**
72.5 Bridge across Wind River, where the river crosses the 70-m-thick basalt fill just upstream from the mouth of Panther Creek. Before basalt flooded the ancestral drainage, Panther Creek and Wind River must have joined near the spot where we first met the Wind River Road. The flows diverted Panther Creek along the northeast margin of the valley fill and Wind River along the southwest margin. Enter Carson. **0.3**
72.9 Roadcut in basalt of Trout Creek Hill. **0.4**
74.6 Conical hill between 9 and 10 o'clock is Wind Mountain, a quartz diorite intrusion (see Stop 57). **1.7**
75.3 Roadcut in columnar andesite flow in the lower Miocene volcanic rocks of Stevenson Ridge [*Korosec*, 1987b]. Roadcuts from here to the outskirts of Stevenson are in this unit, which *Korosec* [1987b] estimates from K-Ar ages and geology to be 24-21 Ma. **0.7**
76.1 Turn right on Highway 14 and drive west along the Columbia River, ponded behind Bonneville Dam. **0.8**
76.5 Start prominent series of roadcuts in andesite flows and minor volcaniclastic rocks of Stevenson Ridge. **0.4**
78.9 Enter Stevenson, on volcaniclastic rocks of the 22-17-Ma Eagle Creek Formation [*Korosec*, 1987b]. **2.4**
79.2 Turn left on Russell Avenue at flashing caution light in front of Court House. **0.3**
79.3 Cross railroad tracks, turn right, and park opposite Waterfront Park. Walk to viewing area. **STOP 55.** (Stop 18 in *Tolan and Beeson* [1984b]). A thick red hyaloclastite of Pliocene or Pleistocene high-alumina basalt is exposed 500-600 m above the river. The hyaloclastite must have formed in water, yet the deposit is too low to have formed subglacially. *Tolan and Beeson* [1984b] reason that the most likely source of water was from the Columbia River and "think that the complex probably formed near present river level when the river was invaded by high-alumina basalt lava flows and was later elevated by Cascade upwarping while the river incised the Columbia River Gorge" (p. 112). They feel that the incision would have occurred in the last 2 m.y., the approximate age of the youngest alluvial deposits of the ancestral Columbia (the Troutdale Formation) that were incised during uplift [*Tolan and Beeson*, 1984a, c; *Lowry and Baldwin*, 1952; *Trimble*, 1963]. Their conclusion is rather controversial, but the main point is that Cascade uplift in this area is of late Neogene age, whatever the exact age might be.

Back bus up and return across tracks. **0.1**
79.6 Turn left on First Street, right at stop sign, and left on Highway 14. **0.3**
79.7 View ahead of part of the Columbia Gorge. On north side, dark, nearly shear cliffs of Grande Ronde Basalt overlie light-colored bedded volcaniclastic rocks of the Eagle Creek Formation that dip south, are rich in clay, and slide easily. The area south of the cliffs is the giant Bonneville landslide complex, parts of which are still active and on which the northern end of Bonneville Dam, the first dam constructed across the Columbia, is based. On the Oregon side of the gorge, the cliffs are mainly Grande Ronde Basalt capped in places by Pliocene and Pleistocene basalt and andesite flows. Locally, the Priest Rapids and Pomona Members partly fill channels carved in the Grande Ronde [*Tolan and Beeson*, 1984c]. From here to Bridge of the Gods, Highway 14 crosses three of the four units that form the Bonneville landslide complex: the Red Bluff, Mosley Lakes, and Bonneville slides [*Wise*, 1961; *Minor*, 1984]. **0.1**
82.1 Turn left at Historical Marker sign and stop in parking lot. **STOP 56.** View of Bridge of the Gods at the site of the original "Bridge of the Gods" of Native American legend, which formed in about 1100 A.D. [*Minor*, 1984] when the Bonneville landslide temporarily dammed the Columbia. The legend tells of crossing the river on dry land. The river was about 1.5 km wide and relatively straight before the slide displaced it at least 1 km southward. The resulting dam impounded a lake whose surface elevation reached 60-90 m above sea level and whose water drowned forests for 60 km upstream. After a few weeks the dam broke and generated a major flood [*Minor*, 1984]. The breaching resulted in the narrowest constriction in the Columbia Gorge and produced four main rapids with a total fall of 11 m [*Hodge*, 1938]. Native Americans established villages and seasonal camps, now important archaeologic sites, along the

rapids for fishing and trade control. **2.4**

Return to road to Carson (mileage 76.1).

87.9 Continue east at junction with road to Carson. **5.8**

88.4 Start series of cuts in flow and talus of basalt of Trout Creek Hill. **0.5**

90.5 Wind Mountain intrusion at 11 o'clock. **2.1**

91.8 STOP 57. Wind Mountain intrusion, a fine-grained plagioclase-phyric quartz diorite, in places with hypersthene and hornblende phenocrysts. The intrusion contains inclusions of Grande Ronde Basalt, and basalt on the west side of Dog Mountain, 3 km farther east, was hornfelsed by the intrusion. A similar quartz diorite occurs south of the river at Shellrock Mountain. These shallow bodies, and several others in the area, presumably were related to volcanic activity. K-Ar whole-rock ages of 4.9 ± 0.1 Ma [*Korosec*, 1987b] and 6.6 ± 0.7 Ma (T. L. Tolan in *Korosec* [1987b]) have been obtained for the Wind Mountain intrusion, and one of 5.7 ± 0.6 Ma (T. L. Tolan in *Korosec* [1987b]) exists for Shellrock Mountain. No clasts of these quartz diorite bodies have been identified in the coeval Troutdale Formation [*Tolan and Beeson*, 1984b]. If the intrusions fed volcanoes, where is the eruptive debris? **1.3**

93.8 Start of long series of roadcuts in tectonically fractured and faulted flows of Grande Ronde Basalt in the Dog Mountain section, the thickest (more than 1.3 km) unrepeated section of Grande Ronde Basalt (almost entirely the R_2 magnetostratigraphic unit) exposed west of the Columbia Plateau. **2.0**

95.9 At 12 o'clock is narrow dike-like fault breccia 10-20 m above road. **2.1**

97.3 Bridge across the Little White Salmon River. Thin flows of Quaternary olivine basalt from Underwood shield volcano, about 7 km northeast of here, cap tilted flows of Grande Ronde Basalt at 10 o'clock. Start series of five tunnels through tilted Grande Ronde. **1.4**

99.5 Good exposure of olivine basalt flows of Underwood volcano at 12 o'clock. One of these flows has a K-Ar age of 0.85 ± 0.02 Ma [*Korosec*, 1987b], although at least some flows from the volcano are normally magnetized, not reversely as would be expected for this age. From here to sawmill at Hood these flows cap Grande Ronde and are pillowed where they poured into the ancestral Columbia. **2.2**

103.5 Quartzite-bearing gravel and sand of the ancestral Columbia River. The deposit is younger than the 12-Ma Pomona Member of the Saddle Mountains Basalt and correlates with part of the Troutdale Formation farther west and the Snipes Mountain conglomerate on the Columbia Plateau [*Tolan and Beeson*, 1984b]. **4.0**

103.8 Turn left on Cook Underwood Road at mouth of White Salmon River. **0.3**

104.4 STOP 58. Deposit of a huge debris avalanche probably formed by collapse of the north or northeast flank of an ancestral Mount Hood 0.05-0.1 Ma. The avalanche traveled down Hood River, crossed the Columbia, and back-filled 5 km up the White Salmon River, a distance of 40 km [*Vallance*, 1986]. Here the deposit overlies gravel of the ancestral White Salmon River and underlies sand and gravel of the Late Pleistocene Missoula floods. The base of the avalanche deposit is 30 m above present lake level and 30 m thick. The deposit is about 80 m thick across the Columbia in Hood River, where its top is at about 105 m elevation and its base only slightly above river level (22 m). **0.6**

105.2 Turn left at fire-station sign. **0.8**

105.3 Turn around at Underwood Comunity Center and return to Highway 14. **0.1**

106.8 Turn left on Highway 14. **1.5**

107.0 Stratified hyaloclastite and pillowed olivine basalt erupted from White Salmon volcano about 2 km farther east. Its age is unknown, but *Korosec* [1987b] suggests it is coeval with the basalt of Underwood Mountain. The basal flows have normal magnetic polarity and are probably younger than 0.73 Ma. Similar exposures continue to White Salmon. **0.2**

108.6 Turn right across Hood River Toll Bridge. **1.6**

109.7 Intersection south of toll booth. End of log. **1.1**

Log for Day 6, Hood River to Portland via Mount Hood

0.0 First 4-way stop south of toll bridge in Hood River. Follow Highway 35 south over railroad tracks.

0.4 Stop and continue south on Highway 35, which climbs up Hood River Valley. Roadcuts in Frenchman Springs Member of Wanapum Basalt [*Swanson et al.*, 1981; *Korosec*, 1987b]. **0.4**

1.8 Roadcut in olivine basalt underlying much of Hood River Valley. Pliocene or Pleistocene in age [*Korosec*, 1987b]. **1.4**

2.1 Roadside quarry in this olivine basalt. **0.3**

2.2 Start of cuts in debris flow from Mount Hood (see Stop 58). **0.1**

2.4 Turn left at junction to Panorama Point. **0.2**

2.9 Turn left at T-intersection. **0.5**

3.5 Turn left into Panorama Park. **0.6**

3.7 STOP 59. Panorama Point. From right to left: Underwood Mountain volcano on west side of White Salmon River; Columbia Gorge, with Hood River Valley in foreground capped near shopping center by deposits of Missoula floods; Pleistocene Mount Defiance volcano across terraced Hood River Valley; main part of Hood River Valley; Middle Mountain separating Upper Valley from the main valley; Mount Hood; and Hood River fault zone bounding the east side of the valley. Several cones of olivine basalt occur in Hood River Valley south of here. The orchards grow on the Parkdale soils [*Harris*, 1973], probably ash-cloud deposits (perhaps rain-flushed as suggested by accretionary lapilli) associated with pyroclastic flows erupted from Mount Hood during late Polallie time about 12 ka [*Crandell and Rubin*, 1977; *Crandell*, 1980]. **0.2**

Retrace route toward Highway 35.

4.4 Turn right on Whiskey Creek Road and then left on Highway 35. **0.7**

5.1 Cuts in olivine basalt. **0.7**

9.3 Parkdale soils on basalt opposite Odell road. **4.2**

9.9 Road gradually climbs to saddle east of Middle Mountain, underlain by faulted N_2 flows of the Grande Ronde Basalt and Frenchman Springs Member [*Swanson et al.*, 1981; *Korosec*, 1987b]. Pliocene or Pleistocene olivine basalt occurs in and east of saddle. **0.6**

10.5 Hills ahead are eroded vents for the Pliocene or Pleistocene olivine basalt. **0.6**

12.3 At 10 o'clock is ridge in R_2 and N_2 flows of Grande Ronde Basalt and Frenchman Springs Member in Hood River fault zone [*Swanson et al.*, 1981]. **1.8**

18.7 Roadcut in Frenchman Springs cut by fault of Hood River fault zone [*Swanson et al.*, 1981]. **6.4**

20.3 Cuts in faulted N_2 Grande Ronde and Frenchman Springs in Hood River fault zone. **1.6**

20.5 Overbank deposits from Christmas 1980 flood down Polallie Creek and East Fork Hood River [*Gallino and Pierson*, 1984]. **0.2**

21.6 STOP 60. Be alert for rockfalls! Cliff face exposes intracanyon flows of normally magnetized olivine andesite of Cloud Cap [*Keith et al.*, 1982; *Wise*, 1969], erupted from a vent on the northeast flank of Mount Hood 10 km southwest of here. Five flows or more totalling about 150 m thick were produced from this vent [*Wise*, 1969]. The eruptions supposedly occurred after the main cone-building stage of Mount Hood but before the Fraser glaciation about 29 ka [*Wise*, 1969; *Crandell*, 1980]. However, three K-Ar whole-rock ages from one sample near the Cloud Cap vent are about 0.49, 0.63, and 0.65 Ma [*Keith et al.*, 1985], coeval or even older than the main cone. *Wise* [1969] believes that the flows are not genetically related to those forming the Mount Hood edifice. Glaciofluvial deposits and Polallie-age lahars abut and overlie the andesite flows here. **1.1**

22.6 To left on ridge is white pumiceous ash-flow tuff interleaved with hornblende dacite flows partly filling old valley [*Wise*, 1969]. Erupted from dacite domes at Mill Creek Buttes, with a K-Ar (hornblende) age of 6.2 ± 1.3 Ma [*Fiebelkorn et al.*, 1983]. Rugged point at 12 o'clock is olivine andesite of Cloud Cap. **1.0**

23.2 Cut in upper Miocene pyroxene andesite [*Wise*, 1969; *Keith et al.*, 1982]. *Keith et al.* [1985] obtained a K-Ar whole-rock age of 8.18 ± 0.06 Ma near here. **0.6**

23.6 Fault zone in upper Miocene andesite flow. **0.4**

24.5 Deposits of Christmas 1980 Polallie Creek flood along river, in places reworked by man. **0.9**

24.9 Good exposures east of river of upper Miocene andesite K-Ar dated as 7.0 ± 0.8 Ma [*Wise*, 1969]. The andesite is overlain by Quaternary olivine basalt and basaltic andesite [*Wise*, 1969]. **0.4**

25.2 STOP 61. Mouth of Polallie Creek. Observe deposits and effects of the Christmas 1980 debris flow, whose volume is more than 20 times that of the initial slumped material owint to sediment-bulking during transport [*Gallino and Pierson*, 1984]. The debris flow, generated by intense rainfall, rushed down Polallie Creek, which cut into volcaniclastic deposits of Polallie age that contributed to the bulking. The debris flow dammed the river for 12-18 minutes; once the dam breached, a flood surged downstream, destroying 13 km of road and causing $13-million of damage. **0.3**

25.4 Upper Miocene andesite in roadcuts. **0.2**

26.6 Roadcut exposing interbedded lake and lahar deposits of Polallie age [*Crandell*, 1980]. Several cuts farther along show similar deposits. Polallie deposits, mainly pyroclastic flows near the volcano and lahars farther away, formed on all sides of the volcano. Here on the northeast side, the deposits form a broad triangular apron converging on Cooper Spur, 825 m below the present summit [*Crandell*, 1980]. The deposits flank both sides of Polallie Creek and form a fill (mostly eroded) in the valley of East Fork Hood River downstream from the mouth of the creek [*Crandell*, 1980]. The deposits created temporary dams and lakes upstream from Polallie Creek; the thinly bedded fine sand and silt in the cuts record these lakes [*Crandell*, 1980]. **1.2**

26.9 Good exposure of interbedded lake and lahar deposits in cut opposite Sherwood Campground. **0.3**

28.6 Smooth topography is caused by huge fan of Fraser-age outwash that fills valley and extends down from Newton Clark Glacier. **1.7**

34.3 Roadcut in Quaternary andesite flow of the cone-building stage [*Wise*, 1969] (called Main Stage by *White* [1980]) of Mount Hood, with outwash beyond. **5.7**

35.2 Bennett Pass. Roadcuts expose three tills, the youngest of which is of Fraser age [*Crandell*, 1980]. The ages of the older tills are not known. **0.9**

35.5 Next few cuts are in Miocene andesite flows. **0.3**

36.8 Cone-building andesite flow of Mount Hood. **1.3**

37.2 Cross White River. Terrace upstream is of Old Maid age [*Crandell*, 1980], about 1760-1810 A.D. [*Cameron and Pringle*, 1987]. Outburst floods from White River Glacier destroyed bridges here 5 times in this century, most recently in 1959 and 1968. **0.4**

37.3 Turn right into parking area and then right on gravel road. **0.1**

37.8 Turn right onto top of levee. If road is bad, continue straight and park wherever possible. **0.5**

38.0 STOP 62. Walk to stream cuts exposing dacitic lithic pyroclastic flow (as thick as 10 m) of Old Maid age capped locally by at least two thin lahars [*Crandell*, 1980; *Cameron and Pringle*, 1987]. The pyroclastic flow contains thoroughly charred wood and radially-jointed blocks that magnetic measurements indicate were above the Curie point when deposited [*Crandell*, 1980]. The charred wood has a ^{14}C age of 260 ± 150 years [*Crandell*, 1980]. The pyroclastic flow traveled down the easternmost drainage of the White River, probably from near Crater Rock, and entered the main drainage at a high angle, running about 75 m up the west valley wall; *Cameron and Pringle* [1987] calculated a minimum velocity of 135 km/hr from this relation. A Fraser-age lateral moraine stands above the left bank of the river. **0.2**

Return to Highway 35 and turn right.

39.1 Next several roadcuts are in Miocene andesite. **1.1**

41.6 Roadcut in Miocene platy andesite. **2.5**

42.5 Keep right toward Government Camp, merging onto Highway 26. Cross Salmon River drainage. **0.9**

43.8 Cuts in platy andesite of cone-building stage. **1.3**

44.0 STOP 63. Quarry on right in platy, plagioclase-hypersthene andesite flow from cone-building stage of Mount Hood. Hypersthene is visible as light brown phenocrysts. Flow contains abundant rounded inclusions of fresh holocrystalline microdiorite. More than 90% of the cone consists of preglacial (older than 29 ka) lava flows, breccia, and pyroclastic rocks, most of which are andesitic and about 70 percent of which are lava flows [*Wise*, 1969; *White*, 1980. No rocks with reversed magnetic polarity have been found, so the cone is assumed to postdate 0.73 Ma [*White*, 1980; *Mankinen and Dalrymple*, 1979]. *Keith et al.* [1985] present K-Ar whole-rock ages ranging from 0.57 to 0.35 Ma for two cone-building lava flows in Zigzag Canyon. **0.2**

45.0 Turn right toward Timberline Lodge. For the next 2.6 miles the road passes through small cuts of Fraser-age till and cone-building andesite. **1.0**

47.6 Andesite flow overlying andesitic breccia. **2.6**

49.1 STOP 64. Cut in interlayered fine pink ash and coarse grayish-pink diamict. A few clasts are radially jointed. Possibly the diamict was a lahar generated by collapse of a hot dome onto snow. The age is unknown but probably Polallie. **1.5**

49.6 Roadcut exposes diamict with scattered hot blocks capped by ash or wind-blown sand. Diamict overlies a cone-building andesite flow. **0.5**

50.2 Andesite flow capped by thin tephra layers. **0.6**

50.5 Turn left into **bus** parking lot just before Timberline Lodge. **STOP 65.** Restrooms in building nearest the lot. Walk back down road 100 m to overflow parking lot and then up dirt road and cross country to Timberline (Skyline) trail contouring on hill slope. Follow trail east across small creek (headwaters of Salmon River). Stop on crest of next ridge at Ghost Forest Overlook. From here one can look down White River and see a buried forest engulfed by fluvial and cold-lahar deposits of Old Maid age that form a flat-topped terrace. A ^{14}C age of 250 ± 150 years B.P. dates one of the buried stumps [*Crandell*, 1980]. The Old Maid deposits formed a fill whose surface is about 100 m above the White River. Upstream is White River Glacier, source of outburst floods that periodically destroy the bridge on Highway 35. The main thermal area of the volcano (Devil's Kitchen) can be seen between the head of White River Glacier and the summit ridge; temperatures as high as 92°C, which is above boiling at 3171 m, have been measured [*Nehring et al.*, 1981; *Cameron*, 1988]. Crater Rock, remnant of a three-lobed hornblende dacite dome [*Cameron and Pringle*, 1986], can be seen left (west) of Devil's Kitchen. Crater Rock was probably emplaced at least in part in Old Maid time [*Crandell*, 1980; *Cameron and Pringle*, 1986], although *Wise* [1968, 1969] ascribed it to what today is called the Timberline eruptive period. Trim lines from the neoglacial maximum (about 1740 A.D.) can be seen below Steel Cliff, to right of White River Glacier.

Many trees near Timberline Lodge, including those at this locality (the *ghost forest*), were killed around 1795-1810, probably near 1800 A.D. [*Lawrence*, 1948]. The trees were killed neither by beetles (no galleries exist below the remaining bark) nor by forest fire (no charring can be found on the dead trees). The ghost forest occurs only within about 500 m of the west side of White River canyon and within 2 km of the east side [*Cameron and Pringle*, 1987]. The trees were probably killed by a hot ash cloud from the dacitic lithic pyroclastic flow at Stop 62 [*Cameron and Pringle*, 1987].

Walk to south end of lower paved parking area near bus parking lot. Several layers of Timberline-age tephra in a 35-cm-thick section overlie the weathered top of a Polallie-age lahar and underlie young soil and possibly an Old Maid-age tephra. The Timberline-age tephra here comprise two or three light-colored ash layers sandwiched in dark andesitic or muddy ash. Note the surrounding ghost forest, near its western limit. **0.3**

Return to Highway 26.

55.7 Junction with Highway 26. Turn right. **5.2**

58.0 Polallie lahars in roadcuts [*Crandell*, 1980]. **2.3**

58.2 Roadcut in quartz diorite of Laurel Hill. **0.2**

58.6 Fractured margin of Laurel Hill pluton. **0.4**

58.9 At 3 o'clock across Little Zigzag Canyon is cliff of Mount Hood andesite flows. **0.3**

59.0 Roadcut in Laurel Hill pluton. Many cuts in next mile expose this pluton. **0.1**

60.2 Two dikes cut the Laurel Hill pluton. We will stop here later in the day. Roadcuts expose the Laurel Hill for next mile. **1.2**

61.4 Turn right from Highway 26 onto road toward Mount Hood Kiwanis Camp. **1.2**

63.3 STOP 66. Bus can turn around 0.2 mi farther. Small quarry in three lithic pyroclastic flows of Timberline age. Wood is entirely charred in uppermost thick, gray deposit and partly charred in the underlying two flows. Prismatically jointed blocks are scarce. Below the thickest gray flow is a poorly exposed thin unit with noncharred wood that may record high energy, surgelike emplacement. Radiocarbon ages on wood in the deposits indicate that the thick gray flow is 1440 ± 155 years B.P. [*Cameron and Pringle*, 1986] and the second unit below it is 1830 ± 50 years B.P. (K. A. Cameron and P. T. Pringle, unpub. data). Tan unit on top of gray pyroclastic flow is cold lahar that is also likely of Timberline age, for no recognizable weathering zone separates it from the pyroclastic flows. **1.9**

63.5 Bus turnaround. Return to quarry. **0.2**

65.5 Highway 26. Turn left and retrace route to Laurel Hill pluton. **2.0**

66.7 STOP 67. Stop on outside of curve. The Laurel Hill pluton is plagioclase-hornblende-phyric quartz diorite with lesser quartz monzonite and patches of granophyre [*Wise*, 1969]. Its groundmass is pervasively propylitized. Similar bodies crop out 4 km to the south along Still Creek and 2 km to the west along Zigzag River. Drilling on the south side of Zigzag Mountain and in the Old Maid Flat area, 4 km and 10 km respectively northwest of here, penetrated similar quartz diorite. These bodies are likely connected at depth [*Wise*, 1969]. The quartz diorite intrudes the Grande Ronde and Wanapum Basalts, the Rhododendron Formation (about 14-11 Ma; D. R. Sherrod, written commun., 1988), and the Last Chance andesite (K-Ar whole-rock ages of 10.7 ± 0.5 and 10.5 ± 0.5 Ma) [*Priest et al.*, 1982].

For the Laurel Hill, *Bikerman* [1970] obtained K-Ar hornblende ages of 8.4 ± 0.6 and 8.0 ± 0.6 Ma, and *Keith et al.* [1985] determined K-Ar whole-rock ages of 8.6 ± 0.14 and 8.75 ± 0.18 Ma on a single sample. *Priest et al.* [1982] reported a K-Ar hornblende age of 9.3 ± 0.9 for biotite-bearing hornblende microquartz diorite in a drill hole near Old Maid Flat. *Wise* [1969] noted that a K-Ar age of 11.6 ± 1.2 Ma for the Laurel Hill was too old, for the pluton intrudes definitely younger rocks. The Laurel Hill, just as the Tatoosh pluton at Mount Rainier, cooled during a field reversal (from reverse to normal) [*Dunn et al.*, 1971].

Walk up road 200 m to see two slightly vesicular andesite dikes cutting the quartz diorite. *Bikerman* [1970] apparently dated one of these dikes as about 5 Ma (K-Ar whole-rock). **1.2**

67.2 Tom Dick and Harry Mountain at 3 o'clock, composed of upper Miocene and Pliocene andesite. **0.5**

69.9 Turn right into parking area, turn around, and continue west. **2.7**

75.6 Road is on lahar surface of post-Fraser age. Valley walls in Rhododendron Formation. **5.7**

80.0 Forest Service Station in Zigzag. Continue west on Highway 26 toward Portland or turn right on East Lolo Pass Road for optional side trip. **4.4**

82.5 Signal light in Welches, built on a Timberline lahar surface. **2.5**

End of geologic guide. To reach I-84, continue on Highway 26 to east side of Gresham. Then,

127.0 Continue straight on Burnside rather than turning left on Highway 26 toward Portland. **44.5**

127.7 Turn right at signal on SE 242nd. Drive toward I-84 and follow signs; stay on same road all the way. **0.7**

130.5 Wood Village-Gresham interchange at I-84. 2.8

Optional Trip to Mount Tabor and Boring Lava

(0.0) At mileage 127.7, continue straight on Burnside.

(0.3) At signal light, turn left onto Division. Follow Division to mile 8.9. **0.3**

(2.4) At 9 o'clock is a cone-shaped hill of Pliocene and early Pleistocene Walters Hill Formation (conglomerate, sandstone, and mudflows) [*Trimble*, 1963]. **2.1**

(6.4) At 9 o'clock is Kelly Butte, a cinder cone of the Boring Lava [*Treasher*, 1942; *Trimble*, 1963; *Allen*, 1975; *Tolan and Beeson*, 1984], which contains Pliocene and Pleistocene olivine basalt and basaltic andesite flows with vents throughout the Portland metropolitan area. **4.0**

(7.1) Pass beneath I-205. **0.7**

(7.9) Mount Tabor, another Boring cone, to right. **0.8**

(8.9) Turn right on S.E. 60th Avenue. **1.0**

(9.4) Turn right on S.E. Salmon for Mount Tabor. **0.5**

(9.7) Sharp turn to left. Parking lot here affords view of city center and the Portland Hills, which are a faulted anticline of Grande Ronde and Wanapum (Frenchman Springs) Basalts overlain in places by Boring Lava. **0.3**

(10.0) Turn into parking lot. **STOP 68.** A partial cross section of the Mount Tabor cone of olivine basalt is exposed beside the basketball court and outdoor theater. Some of the cinder beds contain very large ejecta (more than 1 m in long dimension), whereas other beds, especially high in the section, are relatively fine grained and well sorted. The general dip is northwestward, away from the breached crater that the road traverses. Several fault surfaces suggest slumping of the flank of the cone during its formation. Gravel in some of the younger beds in the middle of the exposure were probably derived from the underlying Troutdale Formation [*Trimble*, 1963], and the younger beds at the north end of the exposure are partly palagonitized. This evidence suggests interaction with water.

Allen [1975] located more than 30 Boring vents within 21 km of here and more than 90 vents (about 50 of which he classified as "certain") within 32 km of Troutdale (5 km northeast of Gresham). The Boring in this area is between about 1.3 Ma (Rocky Butte, 3 km northeast of here) and 2.1 Ma (in bluffs near Oregon City, 18 km south of here), judging from unpublished K-Ar ages (D. R. Sherrod, oral commun., 1988) and a K-Ar age of 1.56 ± 0.2 Ma on a flow at Bear Prairie 29 km east-northeast of here [*Tolan and Beeson*, 1984].

The setting of the basalt field is puzzling and not understood. The vents lie well west of the crest of the Cascades, and those such as Kelly Butte, Mount Tabor, and the vents in the Portland Hills are in and even west of the Portland basin.

End of log.

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REFERENCES

Allen, J. E., Volcanoes of the Portland area, Oregon, *Ore Bin*, *37*, 145-157, 1975.

Alt, D., J. W. Sears, and D. W. Hyndman, Terrestrial maria: the origins of large basalt plateaus, hotspot tracks and spreading ridges, *J. Geol.*, *96*, 647-662, 1988.

Anderson, J. L., Pomona Member of the Columbia River Basalt Group: an intracanyon flow in the Columbia River Gorge, Oregon, *Oreg. Geol.*, *42*, 195-199, 1980.

Anderson, J. L. and B. F. Vogt, Intracanyon flows of the Columbia River Basalt Group in the southwest part of the Columbia Plateau and adjacent Cascade Range, Oregon and Washington, *Wash. Div. Geol. Earth Resources Bull.*, *77*, 249-267, 1987.

Anderson, J. L., M. H. Beeson, and T. L. Tolan, Tectonic evolution of the southwest Columbia Plateau, *Geol. Soc. Am. Abst. Prog.*, *19*, 354-355, 1987.

Armstrong, R. L., Cenozoic igneous history of the U.S. Cordillera from lat 42° to 49° N, *Geol. Soc. Am. Mem.*, *152*, 265-282, 1978.

Armstrong, R. L., W. P. Leeman, and H. E. Malde, K-Ar dating, Quaternary and Neogene volcanic rocks of the Snake River Plain, Idaho, *Am. J. Sci.*, *275*, 225-251, 1975.

Atwater, T., Implications of plate tectonics for the Cenozoic tectonic evolution of western North America, *Geol. Soc. Am. Bull.*, *81*, 3513-3536, 1970.

Bailey, M. M., The stratigraphy and petrochemistry of the Picture Gorge Basalt, north-central Oregon, M.S. thesis, 156 pp., Wash. State Univ., Pullman, 1986.

Bailey, M. M., Revisions to stratigraphic nomenclature of the Picture Gorge Basalt Subgroup, Columbia River Basalt Group, in *Volcanism and Tectonism on the Columbia Plateau*, edited by S. P. Reidel, P. R. Hooper, and J. L. Anderson, *Geol. Soc. Am. Spec. Pap.*, in press.

Baksi, A. J., Estimation of lava extrusion and magma production rates for two flood basalt provinces, *J. Geophys. Res.*, *93*, 11,809-11,815, 1988.

Barnosky, C. W., Late Quaternary vegetation near Battle Ground Lake, southern Puget Trough, Washington, *Geol. Soc. Am. Bull.*, *96*, 263-271, 1985.

Barrash, W., J. Bond, and R. Venkatakrishnan, Structural evolution of the Columbia Plateau in Washington and Oregon, *Am. J. Sci.*, *283*, 897-935, 1983.

Bates, R. G., M. E. Beck, Jr., and R. F. Burmester, Tectonic rotations in the Cascade Range of southern Washington, *Geology*, *9*, 184-189, 1981.

Beck, M. E., Jr., Paleomagnetic record of plate-margin tectonic processes along the western edge of North America, *J. Geophys. Res.*, *85*, 7115-7131, 1980.

Beck, M. E., Jr., and C. D. Burr, Paleomagnetism and tectonic significance of the Goble Volcanic Series, southwestern Washington, *Geology*, *7*, 175-179, 1979.

Becraft, G. E., Definition of the Tieton andesite on lithology and structure, M.S. thesis, 26 pp., Wash. State Coll., Pullman, 1950.

Beeson, M. H., K. R. Fecht, S. P. Reidel, and T. L. Tolan, Regional correlations within the Frenchman Springs Member of the Columbia River Basalt Group: new insights into the middle Miocene tectonics of northwestern Oregon, *Oreg. Geol.*, *47*, 87-96, 1985.

Bentley, R. D., Stratigraphy of the Yakima basalts and structural evolution of the Yakima Ridges in the western Columbia Plateau, in *Geological excursions in the Pacific Northwest*, edited by E. H. Brown and R. C. Ellis, pp. 339-389, Dept. Geology, Western Wash. Univ., Bellingham, 1977.

Bentley, R. D. and J. L. Anderson, Wrench tectonics in the Yakima ridges of the Columbia Plateau, Washington and Oregon, *Geol. Soc. Am. Abst. Prog.*, *12*, 267, 1980.

Bikerman, M., K-Ar ages of Laurel Hill pluton and dike, Oregon, *Ore Bin*, *32*, 211-215, 1970.

Birch, D. C., Big Eddy-McLoughlin Line Tower 36/2 Ladd Creek washout, *Bonneville Power Administration in-house memorandum*, 9 pp., 1961.

Blackwell, D. D. and J. L. Steele, A summary of heat flow studies in the Cascade Range, *Trans. Geotherm. Resour. Counc.*, *7*, 233-236, 1983.

Blackwell, D. D., R. G. Bowen, D. A. Hull, J. Riccio, and J. L. Steele, Heat flow, arc volcanism, and subduction in northern Oregon, *J. Geophys. Res.*, *87*, 8735-8754, 1982.

Borchardt, G. A., J. A. Norgren, and M. E. Harward, Correlation of ash layers in peat bogs of eastern Oregon, *Geol. Soc. Am. Bull.*, *84*, 3101-3108, 1973.

Brantley, S. R. and R. B. Waitt, Interrelations among pyroclastic surge, pyroclastic flow, and lahars in Smith Creek valley during first minutes of 18 May 1980 eruption of Mount St. Helens, USA, *Bull. Volcanol.*, *50*, 304-326, 1988.

Broughton, W. R., The exploration of the Columbia River, in *An extract from the journal of Captain George Vancouver*, Longview Daily News Press, Longview, Wash., 39 pp., 1929.

Brown, E. H., Geology of the Shuksan Suite, North Cascades, Washington, *Geol. Soc. Am. Mem.*, *164*, 143-154, 1986.

Brown, E. H., D. L. Wilson, R. L. Armstrong, and J. E. Harakal, Petrologic, structural, and age relations of serpentinite, amphibolite, and blueschist in the Shuksan Suite of the Iron Mountain-Gee Point area, North Cascades, Washington, *Geol. Soc. Am. Bull.*, *93*, 1087-1098, 1982.

Brown, G. C., Calc-alkaline intrusive rocks: Their diversity, evolution, and relation to volcanic arcs, in *Andesites: Orogenic Andesites and Related Rocks*, edited by R. S. Thorpe, pp. 437-461, John Wiley, New York, 1982.

Brugman, M. M., Groundwater discharge within a glaciated strato-volcano: what happens to missing surface runoff?, *Geol. Soc. Am. Abst. Prog.*, *20*, A115, 1988.

Buckovic, W. A., The Eocene deltaic system of west-central Washington, in *Cenozoic Paleogeography of the western United States*, Econ. Paleon. Mineral., Pac. Coast Paleog. Symp., Los Angeles, 147-163, 1979.

Byerly, G. R. and D. A. Swanson, Invasive Columbia River basalt flows along the northwestern margin of the Columbia Plateau, north-central Washington, *Geol. Soc. Am. Abst. Prog.*, *10*, 98, 1978.

Byerly, G. R. and D. A. Swanson, The transition from subaerial to invasive lava flows, Grande Ronde Basalt, northwestern Columbia Plateau, *Geol. Soc. Am. Abst. Prog.*, *19*, 363, 1987.

Cameron, K. A., Fumarole fields and thermal features at Mount Hood, Oregon, *Northwest Sci.*, *62*, 82, 1988.

Cameron, K. A. and P. Pringle, Post-glacial lahars of the Sandy River basin, Mount Hood, Oregon, *Northwest Sci.*, *60*, 225-237, 1986.

Cameron, K. A. and P. Pringle, A detailed chronology of the most recent major eruptive period at Mount Hood, Oregon, *Geol. Soc. Am. Bull.*, *99*, 845-851, 1987.

Camp, V. E., Geologic studies of the Columbia Plateau: Part II. Upper Miocene basalt distribution, reflecting source locations, tectonism, and drainage history in the Clearwater embayment, Idaho, *Geol. Soc. Am. Bull.*, *92*, 669-678, 1981.

Carey, S. and H. Sigurdsson, The May 18, 1980 eruption of Mount St. Helens 2. Modeling of dynamics of the Plinian phase, *J. Geophys. Res.*, *90*, 2948-2958, 1985.

Carkin, B. A., Geology and petrology of the Fifes Peak Formation in the Cliffdell area, central Cascades, Washington, *Geol. Soc. Am. Abst. Prog.*, *17*, 347, 1985.

Carlson, R. W., Isotopic constraints on Columbia River flood basalt genesis and the nature of the subcontinental mantle, *Geochim. et Cosmochim. Acta*, *48*, 2357-2372, 1984.

Carlson, R. W. and W. K. Hart, Flood basalt volcanism in the northwestern United States, in *Continental Flood Basalts*, edited by J. D. Macdougall, Kluwer Academic Pub., Dordrecht, in press.

Cashman, K. V., Crystallization of Mount St. Helens 1980-1986 dacite: a quantitative textural approach, *Bull. Volcanol.*, *50*, 194-209, 1988.

Cassidy, J. J., H. A. Coombs, and W. L. Shannon, Study of effects of potential volcanic activity on Lewis River projects, unpublished report to the Pacific Power and Light Co, Portland, Oregon, 91 pp., 1980.

Catchings, R. D. and W. D. Mooney, Crustal structure of the Columbia Plateau: evidence for continental rifting, *J. Geophys. Res.*, *93*, 459-474, 1988.

Chadwick, W. W., E. Y. Iwatsubo, D. A. Swanson, and J. W. Ewert, Measurements of slope distances and vertical angles at Mount Baker and Mount Rainier, Washington, Mount Hood and Crater Lake, Oregon, and Mount Shasta and Lassen Peak, California, 1980-1984, *U.S. Geol. Surv. Open-File Rept.*, *85-205*, 96 p., 1985.

Chadwick, W. W., R. J. Archuleta, and D. A. Swanson, The mechanics of ground deformation precursory to dome-building extrusions at Mount St. Helens 1981-1982, *J. Geophys. Res.*, *93*, 4351-4366, 1988.

Christiansen, R. L. and E. H. McKee, Late Cenozoic volcanic and tectonic evolution of the Great Basin and Columbia Intermontane regions, *Geol. Soc. Am. Mem.*, *152*, 283-311, 1978.

Clayton, G. A., Geology of the White Pass area, south-central Cascade Range, Washington, M.S. thesis, 212 pp., Univ. of Washington, Seattle, 1983.

Coleman, S. M. and K. L. Pierce, Weathering rinds on andesitic and basaltic stones as a Quaternary age indicator, western United States, *U.S. Geol. Surv. Prof. Pap.*, *1210*, 56 pp., 1981.

Condie, K. C. and D. H. Swenson, Compositional variation in three Cascade stratovolcanoes: Jefferson, Rainier, and Shasta, *Bull. Volcanol.*, *37*, 205-230, 1973.

Conway, T. R., Mount Hood in eruption, *Mazama*, *6*, 40-43, 1921.

Coombs, H. A., The geology of Mount Rainier National Park, *Univ. Wash. Pubs. Geol.*, *3*, 131-212, 1936.

Couch, R. W. and B. Baker, Geophysical investigations of the Cascade Range in central Oregon, final report, grant 14-08-001-G-393, 95 pp., U.S. Geol. Surv., Reston, VA, 1979.

Cox, K., A model for flood basalt volcanism, *J. Petrol.*, *21*, 629-650, 1980.

Crandell, D. R., Surficial geology and geomorphology of the Lake Tapps quadrangle, Washington, *U.S. Geol. Surv. Prof. Pap.*, *388-A*, 84 pp. 1963a.

Crandell, D. R., Paradise debris flow at Mount Rainier, Washington, *U.S. Geol. Surv. Prof. Pap.*, *475-B*, B135-B139, 1963b.

Crandell, D.R., Surficial geology of Mount Rainier National Park, Washington, *U.S. Geol. Surv. Bull.*, *1288*, 41 pp., 1969

Crandell, D. R., Postglacial lahars from Mount Rainier Volcano, Washington, *U.S. Geol. Surv. Prof. Pap.*, *677*, 75 pp., 1971.

Crandell, D. R., Recent eruptive history of Mount Hood, Oregon, and potential hazards from future eruptions; *U.S. Geol. Surv. Bull.*, *1492*, 81 pp., 1980.

Crandell, D. R., Deposits of pre-1980 pyroclastic flows and lahars from Mount St. Helens volcano, Washington, *U.S. Geol. Surv. Prof. Pap.*, *1444*, 95 pp. 1987.

Crandell, D. R. and R. P. Hoblitt, Lateral blasts at Mount St. Helens and hazard zonation, *Bull. Volcanol.*, *48*, 27-37, 1986.

Crandell, D. R. and R. D. Miller, Quaternary stratigraphy and extent of glaciation in the Mount Rainier region, Washington, *U.S. Geol. Surv. Prof. Pap.*, *847*, 59 pp., 1974.

Crandell, D. R. and D. R. Mullineaux, Potential hazards from future eruptions of Mount St. Helens, Washington, *U.S. Geol. Surv. Bull.*, *1383-C*, 26 pp., 1978.

Crandell, D. R. and M. Rubin, Late-glacial and postglacial eruptions at Mt. Hood, Oregon, *Geol. Soc. Am. Abst. Prog.*, *9*, 406, 1977.

Crandell, D. R. and H. H. Waldron, A recent volcanic mudflow of exceptional dimensions from Mt. Rainier, Washington, *Am. J. Sci.*, *254*, 349-362, 1956.

Crandell, D. R., D. R. Mullineaux, M. Rubin, E. Spiker, and M. L. Kelley, Radiocarbon dates from volcanic deposits at Mt. St. Helens, Washington, *U.S. Geol. Surv. Open-File Rept.*, *81-844*, 15 pp., 1981.

Criswell, C. W., Chronology and pyroclastic stratigraphy of the May 18, 1980, eruption of Mount St. Helens, Washington, *J. Geophys. Res.*, *92*, 10,237-10,266, 1987.

Davis, G. A., Late Cenozoic tectonics of the Pacific Northwest with special reference to the Columbia Plateau, Final Safety Analysis Report WNP-2, Amendment 18, appendix, 69 pp., Wash. Pub. Power Supply System, Richland, 1981.

Davis, G. D., J. W. H. Monger, and B. C. Burchfiel, Mesozoic construction of the Cordilleran "Collage", central British Columbia to central California, in *Mesozoic paleogeography of the western United States*, Soc. Econ. Paleon. Mineral., Pac. Coast Paleog. Symp. 2, Los Angeles, 33-70, 1978.

Davis, J. O., Quaternary tephrochronology of the Lake Lahontan area, Nevada and California, *Nevada Archeol. Surv. Res. Pap.*, *7*, Univ. of Nevada, Reno, 29 pp., 1978.

DeGraff, J. M. and A. Aydin, Surface morphology of columnar joints and its significance to mechanics and direction of joint growth, *Geol. Soc. Am. Bull.*, *99*, 605-617, 1987.

Doukas, M. P. and D. A. Swanson, Mount St. Helens, Washington, with emphasis on 1980-85 eruptive activity as viewed from Windy Ridge, *Geol. Soc. Am. Centennial Field Guide—Cordilleran Section*, 333-338, 1987.

Driedger, C. L. and P. M. Kennard, Ice volumes on Cascade volcanoes: Mount Rainier, Mount Hood, Three Sisters, and Mount Shasta, *U.S. Geol. Surv. Prof. Pap.*, *1365*, 28 pp., 1986.

Duncan, R. A., A captured island chain in the Coast Range of Oregon and Washington, *J. Geophys. Res.*, *87*, 10,827-10,837, 1982.

Dungan, M. A., J. A. Vance, and D. P. Blanchard, Geochemistry of the Shuksan greenschists and blueschists, North Cascades, Washington: variably fractionated and altered meta-basalts of oceanic affinity, *Contr. Mineral. Petrol.*, *82*, 131-146, 1983.

Dunn, J. R., M. Fuller, H. Ito, and V. A. Schmidt, Paleomagnetic study of a reversal of the Earth's magnetic field, *Science*, *172*, 840-845, 1971.

Dzurisin, D., R. Y. Koyanagi, and T. T. English, Magma supply and storage at Kilauea Volcano, Hawaii, 1956-1983, *J. Volc. Geotherm. Res.*, *21*, 177-206, 1984.

Easterbrook, D. J., N. D. Briggs, J. A. Westgate, and M. P. Gordon, Age of the Salmon Springs Glaciation in Washington, *Geology*, *9*, 87-93, 1981.

Eaton, G. P., R. R. Wahl, H. J. Prostka, D. R. Mabey, and M. D. Kleinkopf, Regional gravity and tectonic patterns: their relation to late Cenozoic epierogeny and lateral spreading in the western Cordillera, *Geol. Soc. Am. Mem.*, *152*, 51-91, 1978.

Eichelberger, J. C. and D. B. Hayes, Magmatic model for the Mount St. Helens blast of May 18, 1980, *J. Geophys. Res.*, *87*, 7727-7738, 1982.

Ellingson, J. A., The rocks and structure of the White Pass area, Washington, *Northwest Sci.*, *46*, 9-24, 1972.

Endo, E. T., S. D. Malone, L. L. Noson, and C. S. Weaver, Locations, magnitudes and statistics of the March 20-May 18 earthquake sequence, *U.S. Geol. Surv. Prof. Pap.*, *1250*, 93-107, 1981.

Engels, J. C., R. W. Tabor, F. K. Miller, and J. D. Obradovich, Summary of K-Ar, Rb-Sr, U-Pb, Pb-alpha, and fission-track ages of rocks from Washington state prior to 1975 (exclusive of Columbia Plateau basalts), scale 1:1,000,000, *U. S. Geol. Surv. Misc. Field Studies Map*, *MF-710*, 1976.

Erikson, E. H., Jr., Petrology of the composite Snoqualmie batholith, central Cascade Mountains, Washington, *Geol. Soc. Am. Bull.*, *80*, 2213-2236, 1969.

Evarts, R. C. and R. P. Ashley, Preliminary geologic map of the Spirit Lake quadrangle, Washington, scale 1:48,000, *U.S. Geol. Surv. Open-File Map*, *84-480*, 1984.

Evarts, R. C., R. P. Ashley, and J. G. Smith, Geology of the Mount St. Helens area: record of discontinuous volcanic and plutonic activity in the Cascade arc of southern Washington, *J. Geophys. Res.*, *92*, 10,155-10,169, 1987.

Ewart, A., The mineralogy and petrology of Tertiary-Recent orogenic volcanic rocks: With special emphasis to the andesite-basaltic andesite range, in *Andesites: Orogenic Andesites and Related Rocks*, edited by R. S. Thorpe, pp. 25-95, John Wiley, New York, 1982.

Ewing, T. E., Paleogene tectonic evolution of the Pacific Northwest, *J. Geol.*, *88*, 619-638, 1980.

Fecht, K. R., S. P. Reidel, and A. M. Tallman, Paleodrainage of the Columbia River system on the Columbia Plateau of Washington state—a summary, *Wash. Div. Geol. Earth Res. Bull.*, *77*, 219-248, 1987.

Felts, W. M., A granodiorite stock in the Cascade Mountains of southwestern Washington, *Ohio J. Sci.*, *39*, 297-316, 1939.

Fiebelkorn, R. B., G. W. Walker, N. S. MacLeod, E. H. McKee, and J. G. Smith, Index to K-Ar determinations for the state of Oregon, *Isochron/West*, *37*, 3-60, 1983.

Finn, C. and D. L. Williams, An aeromagnetic study of Mount St. Helens, *J. Geophys. Res.*, *92*, 10,194-10,206, 1987.

Fiske, R. S., Subaqueous pyroclastic flows in the Ohanapecosh Formation, Washington, *Geol. Soc. Am. Bull.*, *74*, 391-406, 1963.

Fiske, R. S., C. A. Hopson, and A. C. Waters, Geology of Mount Rainier National Park, Washington, *U.S. Geol. Surv. Prof. Pap.*, *444*, 93 pp., 1963.

Flanagan, G. and D. L. Williams, A magnetic investigation of Mount Hood, Oregon, *J. Geophys. Res.*, *87*, 2804-2814, 1982.

Foster, R. J., Tertiary geology of a portion of the central Cascade Mountains, Washington, *Geol. Soc. Am. Bull.*, *71*, 99-125, 1960.

Frank, D. G., Hydrothermal processes at Mount Rainier, Washington, Ph.D thesis, 195 pp., Univ. Wash., Seattle, 1985.

Frizzell, V. A., Jr., R. W. Tabor, D. B. Booth, K. M. Ort, and R. B. Waitt, Jr., Preliminary geologic map of the Snoqualmie Pass 1:100,000 quadrangle, Washington, *U.S. Geol. Surv. Open-File Rept.*, *84-693*, 42 pp., 1984.

Frizzell, V. A., Jr., R. W. Tabor, R. E. Zartman, and C. D. Blome, Late Mesozoic or early Tertiary melanges in the western Cascades of Washington, *Wash. Div. Mines Geol Bull.*, *77*, 129-148, 1987.

Furlong, K. P. and D. M. Fountain, Continental crustal underplating: thermal considerations and seismic-petrologic consequences, *J. Geophys. Res.*, *91*, 8285-8294, 1986.

Gallino, G. L. and T. Pierson, The 1980 Polallie Creek debris flow and subsequent dam-break flood, East Fork Hood River basin, Oregon, *U. S. Geol. Surv. Open-File Rept.*, *84-578*, 37 pp., 1984.

Gill, J., *Orogenic andesites and plate tectonics*, 390 pp., Springer Verlag, New York, 1981.

Grant, R. Y., A John Day vertebrate fossil discovered in the Keechelus Series of Washington, *Am. J. Sci.*, *239*, 590-593, 1941.

Grant, W. C., C. S. Weaver, and J. E. Zollweg, The 14 February Elk Lake, Washington, earthquake sequence, *Bull. Soc. Am.*, *74*, 1289-1309, 1984.

Greeley, R., Basaltic "plains" volcanism, in *Volcanism of the eastern Snake River Plain, Idaho*, edited by R. Greeley and J. S. King, NASA CR-154621, 23-44, 1977.

Greeley, R. and J. H. Hyde, Lava tubes of the Cave Basalt, Mount St. Helens, Washington, *Geol. Soc. Am. Bull.*, *83*, 2397-2418, 1972.

Gresens, R. L., J. T. Whetten, R. W. Tabor, and V. A. Frizzell, Part III: Tertiary stratigraphy of the central Cascade Mountains, Washington state, in *Geological Excursions in the Pacific Northwest*, edited by E. H. Brown and R. C. Ellis, Geol. Soc. Am. Field Guide, Seattle, 84-126, 1977.

Grommé, C. S., M. E. Beck, Jr., R. E. Wells, and D. C. Engebretson, Paleomagnetism of the Tertiary Clarno Formation of central Oregon and its significance for the tectonic history of the Pacific Northwest, *J. Geophys. Res.*, *91*, 14,089-14,103, 1986.

Guffanti, M. and C. S. Weaver, Distribution of late Cenozoic volcanic vents in the Cascade Range: volcanic arc segmentation and regional tectonic considerations, *J. Geophys. Res.*,

93, 6513-6529, 1988.
Hague, A., Glaciers of Mount Hood, *Am. J. Sci., 3rd series, 1*, 165-167, 1871.
Hammond, P. E., Part IV: Stratigraphy, structure, and plutonism along the upper Yakima and South Fork Snoqualmie River valleys, central Cascade Range, Washington, in *Geological Excursions in the Pacific Northwest*, edited by E. H. Brown and R. C. Ellis, Geol. Soc. Am. Field Guide, Seattle, 292-308, 1977.
Hammond, P. E., A tectonic model for evolution of the Cascade Range, in *Cenozoic paleogeography of the western United States*, Soc. Econ. Paleon. Mineral., Pac. Coast Paleog. Symp. 3, Los Angeles, 219-237, 1979.
Hammond, P. E., Reconnaissance geologic map and cross sections of southern Washington Cascade Range, *Pubs. Dept. Earth Sci.*, Portland State Univ., Portland, Oreg., 1980.
Hammond, P. E., Indian Heaven, S. Washington Cascade Range: a basaltic volcanic field supplied by a central magma system?, *Geol. Soc. Am. Abst. Prog., 16*, 528, 1984.
Hammond, P. E., Lone Butte and Crazy Hills: Subglacial volcanic complexes, Cascade Range, Washington, *Geol. Soc. Am. Centen. Field Guide—Cordilleran Section*, 339-344, 1987.
Hammond, P. E. and M. A. Korosec, Geochemical analyses, age dates, and flow-volume estimates for Quaternary volcanic rocks, southern Cascade Mountains, Washington, *Wash. Div. Geol. Earth Resources Open-File Rept., 83-13*, 36 pp., 1983.
Hammond, P. E., S. A. Petersen, K. D. Hopkins, D. Aiken, D. S. Harle, Z. F. Daneš, D. L. Konicek, and C. R. Stricklin, Geology and gravimetry of the Quaternary basaltic volcanic field, southern Cascade Range, Washington, in *Proc. Second U.N. Symp. on Development and Use of Geothermal Resources, 1*, San Francisco, 397-405, 1976.
Harris, B. L., Genesis, mineralogy, and properties of Parkdale soils, Oregon, Ph.D. thesis, 174 pp., Oreg. State Univ., Corvallis, 1973.
Hart, W. K. and R. W. Carlson, Tectonic controls on magma genesis and evolution in the northwestern United States, *J. Volcanol. Geotherm. Res., 32*, 119-136, 1987.
Heliker, C. C., Inclusions in the 1980-1983 dacite of Mount St. Helens, *Eos Trans AGU, 64*, 894, 1983.
Heliker, C. C., Inclusions in the 1980-83 dacite of Mount St. Helens, Washington, M.S. thesis, 185 pp., West. Wash. Univ., Bellingham, 1984.
Heller, P. L., R. W. Tabor, and C. A. Suczek, Paleogeographic evolution of the United States Pacific Northwest during Paleogene time, *Can. J. Earth Sci., 24*, 1652-1667, 1987.
Helz, R. T., The petrogenesis of the Ice Harbor Member, Columbia Plateau, Washington—a chemical and experimental study, Ph.D. thesis, 284 pp., Penn. State Univ., University Park, 1978.
Hildreth, E. W., and J. Fierstein, Mount Adams: Eruptive history of an andesite-dacite volcano at the focus of a fundamentally basaltic volcanic field, *U. S. Geol. Surv. Open-File Rept., 85-521*, 44-50, 1985.
Hildreth, W., J. Fierstein, and M. S. Miller, Mineral and geothermal resource potential of the Mount Adams Wilderness and contiguous roadless areas, Skamania and Yakima Counties, Washington, *U.S. Geol. Surv. Open-File Rept., 83-474*, 50 pp., 1983.
Hoblitt, R. P. and C. D. Miller, Comment, *Geology, 12*, 692-693, 1984.
Hoblitt, R. P., D. R. Crandell, and D. R. Mullineaux, Mount St. Helens eruptive behavior during the past 1,500 yr, *Geology, 8*, 555-559, 1980.
Hodge, E. T., Geology of the Lower Columbia River, *Geol. Soc. Am. Bull., 49*, 831-930, 1938.
Hooper, P. R., The Columbia River basalts, *Science, 215*, 1463-1468, 1982.
Hooper, P. R., Physical and chemical constraints on the evolution of the Columbia River basalt, *Geology, 12*, 495-499, 1984.
Hooper, P. R., W. D. Kleck, C. R. Knowles, S. P. Reidel, and R. L. Thiessen, The Imnaha Basalt, Columbia River Basalt Group, *J. Petrol., 25*, 473-500, 1984.
Hopson, C. A. and J. M. Mattinson, Ordovician and Late Jurassic ophiolitic assemblages in the Pacific Northwest, *Geol. Soc. Am. Abst. Prog., 5*, 57, 1973.
Janda, R. J., K. M. Scott, K. M. Nolan, and H. A. Martinson, Lahar movement, effects, and deposits, *U.S. Geol. Surv. Prof. Pap., 1250*, 461-478, 1981.
Johnson, S. Y., Eocene strike-slip faulting and nonmarine basin formation in Washington, *Soc. Econ. Paleon. Mineral. Spec. Pub., 37*, 283-302, 1985.
Jones, J. G., Intraglacial volcanoes of the Laugarvatn region, southwest Iceland—I, *Quar. J. Geol. Soc. Lond., 124*, 197-211, 1969.
Keith, T. E. C., M. H. Beeson, and K. E. Bargar, Geologic map of the Mount Hood Wilderness, Clackamas and Hood River Counties, Oregon, *U.S. Geol. Surv. Misc. Field Studies Map, MF-1379A*, 1982.
Keith, T. E. C., J. M. Donnelly-Nolan, J. L. Markman, and M. H. Beeson, K-Ar ages of rocks in the Mount Hood area, Oregon, *Isochron/West, 42*, 12-16, 1985.
Kieffer, S. W., Blast dynamics at Mount St. Helens on 18 May 1980, *Nature, 291*, 568-570, 1981a.
Kieffer, S. W., Fluid dynamics of the May 18 blast at Mount St. Helens, *U.S. Geol. Surv. Prof. Pap., 1250*, 379-400, 1981b.
Kjartansson, G., The Moberg Formation, in *On the geology and geomorphology of Iceland*, edited by S. Thorarinsson, T. Einarsson, and G. Kjartansson, *Geografisk Annaler, 41*, 135-169, 1959.
Kleinspehn, K. L., Cretaceous sedimentation and tectonics, Tyaughton-Methow Basin, southwestern British Columbia, *Can. J. Earth Sci., 22*, 154-174, 1985.
Korosec, M. A., Geologic map of the Mount Adams quadrangle, Washington, *Wash. Div. Geol. Earth Resources Open-File Rept., 87-5*, 33 pp., 1987a.
Korosec, M. A., Geologic map of the Hood River quadrangle, Washington and Oregon, *Wash. Div. Geol. Earth Resources Open-File Rept., 87-6*, 41 pp., 1987b.
Kuntz, M. A., P. D. Rowley, N. S. MacLeod, R. L. Reynolds, L. A. McBroome, A. M. Kaplan, and D. J. Lidke, Petrography and particle-size distribution of pyroclastic-flow, ash-cloud, and surge deposits, *U.S. Geol. Surv. Prof. Pap., 1250*, 525-539, 1981.
Lachenbruch A. H. and J. H. Sass, Heat flow in the United States and the thermal regime of the crust, *Am. Geophys. Union Geophys. Monog., 20*, 626-675, 1977.
Lander, E. B., A review of the Oreodonta (Mammalia, Artiodactyla), Ph.D. thesis, 474 pp., Univ. of California, Berkeley, 1977.
Laubscher, H. P., Models of the development of Yakima deformation, *Final Safety Analysis Report WNP-2*, Amendment

18, appendix, 69 pp., Washington Public Power Supply System, Richland, 1981.
Law, L. K., D. R. Auld, and J. R. Booker, A geomagnetic variation anomaly coincident with the Cascade volcanic belt, *J. Geophys. Res.*, *85*, 5297-5302, 1980.
Lawrence, D. B., The "floating island" lava flow of Mount St. Helens, *Mazama*, *36*, 41-44, 1941.
Lawrence, D. B., Mount Hood's latest eruption and glacier advances, *Mazama*, *30*, 22-29, 1948.
Le Bas, M. J., R. W. Le Maitre, A. Streckeisen, and B. Zanettin, A chemical classification of volcanic rocks based on the total alkali-silica diagram, *J. Petrol.*, *27*, 745-750, 1986.
Lipman, P. W. and D. R. Mullineaux (Eds.), The 1980 eruptions of Mount St. Helens, Washington, *U.S. Geol. Surv. Prof. Pap.*, *1250*, 844 pp., 1981.
Lipman, P. W., J. G. Moore, and D. A. Swanson, Bulging of the north flank before the May 18 eruption–geodetic data, *U.S. Geol. Surv. Prof. Pap.*, *1250*, 143-155, 1981a.
Lipman, P. W., D. R. Norton, J. E. Taggart, E. L. Brandt, and E. E. Engleman, Compositional variations in 1980 magmatic deposits, *U.S. Geol. Surv. Prof. Pap.*, *1250*, 631-640, 1981b.
Long, P. E., and R. A. Duncan, ^{40}Ar-^{39}Ar ages of Columbia River basalt from deep boreholes in south-central Washington, *Eos*, *64*, 90, 1983.
Long, P. E. and B. J. Wood, Structures, textures and cooling histories of Columbia River basalt flows, *Geol. Soc. Am. Bull.*, *97*, 1144-1155, 1986.
Lowry, W. D. and E. M. Baldwin, Late Cenozoic geology of the lower Columbia River Valley, Oregon and Washington, *Geol. Soc. Am. Bull.*, *63*, 1-24, 1952.
Luedke, R. G. and R. L. Smith, Map showing distribution, composition, and age of late Cenozoic volcanic centers in Oregon and Washington, *U.S. Geol. Surv. Misc. Invest. Map*, *I-1091D*, 1982.
Mackin, J. H., A stratigraphic section in the Yakima Basalt and the Ellensburg Formation in south-central Washington, *Wash. Div. Mines Geol. Rept. Invest.*, *19*, 45 pp., 1961.
MacLeod, N. S., G. W. Walker, and E. H. McKee, Geothermal significance of eastward increase in age of upper Cenozoic rhyolitic domes in southeastern Oregon, in *Proc. United Nations Symposium on Development and Use of Geothermal Resources 2nd*, *1*, 465-474, 1975.
Magill, J., A. Cox, and R. Duncan, Tillamook volcanic series: further evidence for tectonic rotation of the Oregon Coast Range, *J. Geophys. Res.*, *86*, 2953-2970, 1981.
Majors, H. M., Three newly discovered accounts of activity on Mount St. Helens, 1898, 1903 and 1921, *Northwest Discovery*, *1*, 36-41, 1980.
Malone, S. D. and Swanson, D. A., Twentieth century unrest at Cascades volcanoes, *Inter. Volcanol. Cong. Abst. Vol.*, Auckland-Hamilton-Rotorua, New Zealand, 260, 1986.
Mangan, M. T., Wright, T. L., Swanson, D. A., and Byerly, G. R., Regional correlation of Grande Ronde Basalt flows, Columbia River Basalt Group, Washington, Oregon, and Idaho, *Geol. Soc. Am. Bull.*, *97*, 1300-1318, 1986.
Mankinen, E. A. and G. B. Dalrymple, Revised geomagnetic polarity time scale for the interval 0-5 m.y. B.P., *J. Geophys. Res.*, *84*, 615-626, 1979.
Mattinson, J. M., Emplacement history of the Tatoosh volcanic-plutonic complex, Washington: ages of zircons, *Geol. Soc. Am. Bull.*, *88*, 1509-1514, 1977.
McBirney, A. R., Volcanic evolution of the Cascade Range, *An. Rev. Earth Planet. Sci.*, *6*, 437-456, 1978.
McKee, E. H., D. A. Swanson, and T. L. Wright, Duration and volume of Columbia River basalt volcanism, Washington, Oregon, and Idaho, *Geol. Soc. Am. Abst. Prog.*, *9*, 463-464, 1977.
McKee, E. H., P. R. Hooper, and W. D. Kleck, Age of the Imnaha Basalt–oldest flows of the Columbia River Basalt Group, northwest United States, *Isochron/West*, *31*, 31-33, 1981.
McMillan, K., R. W. Cross, and P. E. Long, Two-stage vesiculation in the Cohassett flow of the Grande Ronde Basalt, south-central Washington, *Geology*, *15*, 809-812, 1987.
Mellors, R. A., R. B. Waitt, and D. A. Swanson, Generation of pyroclastic flows and surges by hot-rock avalanches from the dome of Mount St. Helens volcano, USA, *Bull. Volcanol.*, *50*, 14-25, 1988.
Melson, W. G., Monitoring the 1980-82 eruptions of Mount St. Helens: compositions and abundances of glass, *Science*, *221*, 1387-1391, 1983.
Michaelson, C. A. and C. S. Weaver, Upper mantle structure from teleseismic P-wave arrivals in Washington and northern Oregon, *J. Geophys. Res.*, *91*, 209-250, 1986.
Miller, R. B., The Ingalls ophiolitic complex, north-central Cascade Mountains, Washington, *Geol. Soc. Am Bull.*, *96*, 27-42, 1985a.
Miller, R. B., The pre-Tertiary Rimrock Lake inlier, southern Cascades, Washington, *Wash. Div. Geol. Earth Resources Open-File Report*, *85-2*, 16 pp., 1985b.
Minor, R., Dating the Bonneville landslide in the Columbia River Gorge, *Heritage Research Associates Report No. 31*, Eugene, Oreg., 19 pp., 1984.
Misch, P., Tectonic evolution of the northern Cascades of Washington state: a west-Cordilleran case history, *Can. Inst. Min. Metal. Spec. Vol.*, *8*, 101-148, 1966.
Misch, P., Dextral displacements at some major strike faults in the North Cascades, *Geol. Assoc. Canada Prog. Abstracts*, 37, 1977.
Moen W. S., St. Helens and Washougal mining districts of the southern Cascades of Washington, *Wash. Div. Geology Earth Resources Info. Cir.*, *60*, 71 pp., 1977.
Morgan, W. J., Hotspot tracks and the opening of the Atlantic and Indian oceans, in *The Sea*, *7*, 443-487, John Wiley, New York, 1981.
Morgan, W. J., Flood basalts and mass extinctions, in *Global catastrophes in Earth history: an interdisciplinary conference on impacts, volcanism, and mass mortality*, Lunar Planet. Inst. Contrib. 673, 126, 1988.
Moyer, T. C. and D. A. Swanson, Secondary hydroeruptions in pyroclastic-flow deposits: examples from Mount St. Helens, *J. Volc. Geotherm. Res.*, *32*, 299-319, 1987.
Mullineaux, D. R., Pumice and other pyroclastic deposits in Mount Rainier National Park, Washington, *U.S. Geol. Surv. Bull.*, *1326*, 83 pp., 1974.
Mullineaux, D. R., Summary of pre-1980 tephra-fall deposits erupted from Mount St. Helens, Washington state, USA, *Bull. Volcanol.*, *48*, 17-26, 1986.
Mullineaux, D. R. and D. R. Crandell, The eruptive history of Mount St. Helens, *U.S. Geol. Surv. Prof. Pap.*, *1250*, 3-15, 1981.
Mullineaux, D. R., R. E. Wilcox, W. F. Ebaugh, R. Fryxell, and M. Rubin, Age of the last major scabland flood of the

Columbia Plateau in eastern Washington, *Quat. Res.*, *10*, 171-180, 1978.
Mundorff, M. J., Geology and ground-water conditions of Clark County, Wash., with a description of a major alluvial aquifer along the Columbia River, *U.S. Geol. Surv. Water Supply Pap.*, *1600*, 268 pp., 1964.
Mundorff, M. J. and A. A. Eggers, Tumtum Mountain, a late Pleistocene volcanic dome in southwestern Washington, *Northwest Science*, *62*, 10-15, 1988.
Myers, C. W. and S. M. Price (Eds.), *Geologic studies of the Columbia Plateau*, Rockwell Hanford Operations, Richland, WA, RHO-BWI-ST-4, III-23-III-32, 1979.
Nehring, N. L., H. A. Wollenberg, and D. A. Johnston, Gas analyses of fumaroles from Mt. Hood, Oregon, *U.S. Geol. Surv. Open-File Rept.*, *81-236*, 9 pp., 1981.
Niem, A. R. and W. A. Niem, Oil and gas investigation of the Astoria Basin, Clatsop and northernmost Tillamook Counties, northwest Oregon, *Oreg. Dept. Geol. Min. Indust. Oil and Gas Invest. Rept.*, *OGI-14*, 1985.
Okazaki, R., H. W. Smith, R. A. Gilkeson, and J. Franklin, Correlation of West Blacktail Ash with pyroclastic layer T from the 1800 A.D. eruption of Mt. St. Helens, *Northwest Sci.*, *46*, 77-89, 1972.
Phillips, W. M., M. A. Korosec, H. W. Schasse, J. L. Anderson, and R. A. Hagen, K-Ar ages of volcanic rocks in southwest Washington, *Isochron/West*, *47*, 18-24, 1986.
Phillips, W. M., Geologic map of the Mount St. Helens quadrangle, Washington and Oregon, *Wash. Div. Geol. Earth Resources Open-File Rept.*, *87-4*, 59 pp., 1987.
Pierson, T. C., Initiation and flow behavior of the 1980 Pine Creek and Muddy River lahars, Mount St. Helens, Washington, *Geol. Soc. Am. Bull.*, *96*, 1056-1069, 1985.
Pierson, T. C. and K. M. Scott, Downstream dilution of a lahar: transition from debris flow to hyperconcentrated streamflow, *Water Resources Res.*, *21*, 1511-1524, 1985.
Porter, S. C., Pleistocene glaciation in the southern part of the North Cascade Range, Washington, *Geol. Soc. Am. Bull.*, *87*, 61-75, 1976.
Power, S. G., C. W. Field, R. L. Armstrong, and J. E. Harakal, K-Ar ages of plutonism and mineralization, western Cascades, Oregon and southern Washington, *Isochron/West*, *31*, 27-29, 1981.
Price, E. H., Structural geometry, strain distribution, and mechanical evolution of eastern Umtanum Ridge, and a comparison with other selected localities within Yakima fold structures, south-central Washington, Rockwell Hanford Oper., Richland, Wash., RHO-BWI-SA-138, 109 pp., 1982.
Priest, G. R., M. H. Beeson, M. W. Gannett, and D. A. Berri, Geology, geochemistry, and geothermal resources of the Old Maid Flat area, Oregon, *Oreg. Dept. Geol. Min. Indus. Spec. Pap.*, *14*, 16-30, 1982.
Qamar, A., W. St. Lawrence, J. N. Moore, and G. Kendrick, Seismic signals preceding the explosive eruption of Mount St. Helens, Washington on 18 May 1980, *Bull. Seis. Soc. Am.*, *73*, 1797-1813, 1983.
Rampino, M. R. and R. B. Stothers, Flood basalt volcanism during the past 250 million years, *Science*, *241*, 663-668, 1988.
Rasmussen, J. and E. Humphreys, Tomographic image of the Juan de Fuca plate beneath Washington and western Oregon using teleseismic P-wave travel times, *Geophys. Res. Lett.*, *15*, 1417-1420, 1988.
Reidel, S. P., The Saddle Mountains—the evolution of an anticline in the Yakima fold belt, *Am. J. Sci.*, *284*, 942-978, 1984.
Reidel, S. P., P. E. Long, S. W. Myers, and J. Mase, New evidence for greater than 3.2 km of Columbia River basalt beneath the central Columbia Plateau, *Eos Trans AGU*, *64*, 173, 1982.
Reidel, S. P., T. L. Tolan, P. R. Hooper, M. H. Beeson, K. R. Fecht, and J. L. Anderson, The Grande Ronde Basalt, Columbia River Basalt Group: stratigraphic descriptions and correlations in Washington, Oregon, and Idaho, in *Volcanism and Tectonism on the Columbia Plateau*, edited by S. P. Reidel, P. R. Hooper, and J. L. Anderson, *Geol. Soc. Am. Spec. Pap.*, in press.
Rite, A. and H. M. Iyer, July 1980 Mt. Hood earthquake swarm, *U.S. Geol. Surv. Open-File Rept.*, *81-48*, 21 pp., 1981.
Riddihough, R., Recent movements of the Juan de Fuca plate system, *J. Geophys. Res.*, *89*, 6980-6994, 1984.
Rosenbaum, J. G. and R. B. Waitt, Jr., Summary of eyewitness accounts of the May 18 eruption, *U.S. Geol. Surv. Prof. Pap.*, *1250*, 53-67, 1981.
Rutherford, M. J., H. Sigurdsson, S. Carey, and A. Davis, The May 18, 1980, eruption of Mount St. Helens 1. Melt composition and experimental phase equilibria, *J. Geophys. Res.*, *90*, 2929-2947, 1985.
Sager, J. W. and D. R. Chambers, Design and construction of the Spirit Lake outlet tunnel, Mount St. Helens, Washington, *Am. Soc. Civ. Eng. Geotech. Spec. Pub.*, *3*, 42-58, 1986.
Scandone, R. and S. D. Malone, Magma supply, magma discharge and readjustments of the feeding system of Mount St. Helens during 1980, *J. Volc. Geotherm. Res.*, *23*, 239-262, 1985.
Schmincke, H.-U., Petrology, paleocurrents, and stratigraphy of the Ellensburg Formation and interbedded Yakima Basalt flows, south-central Washington, Ph.D thesis, 425 pp., Johns Hopkins Univ., Baltimore, 1964.
Schmincke, H.-U., Stratigraphy and petrography of four upper Yakima basalt flows in south-central Washington, *Geol. Soc. Am. Bull.*, *78*, 1385-1422, 1967a.
Schmincke, H.-U., Graded lahars in the type sections of the Ellensburg Formation, south-central Washington, *J. Sed. Petrol.*, *37*, 438-448, 1967b.
Schmincke, H.-U., Fused tuff and pépérites in south-central Washington, *Geol. Soc. Am. Bull.*, *78*, 319-330, 1967c.
Schmincke, H.-U., Flow directions in Columbia River basalt flows and paleocurrents of interbedded sedimentary rocks, south-central Washington, *Geologische Rundschau*, *56*, 992-1020, 1967d.
Schuster, R. L., Effect of the eruptions on civil works and operations in the Pacific Northwest, *U.S. Geol. Surv. Prof. Pap. 1250*, *1250*, 701-718, 1981.
Scott, K. M., Lahars and lahar-runout flows in the Toutle-Cowlitz River system, Mount St. Helens, Washington, *U.S. Geol. Surv. Prof. Pap. 1447A*, 74 pp., 1988.
Shaw, H. R. and D. A. Swanson, Eruption and flow rates of flood basalts, in *Proc. Second Columbia River Basalt Symp.*, Eastern Wash. State Coll. Press, Cheney, 271-299, 1970.
Sherrod, D. R. and J. G. Smith, Preliminary map of upper Eocene to Holocene volcanic and related rocks of the Cascade Range, Oregon, scale 1:500,000, *U.S. Geol. Surv. Open-File Rept.*, in press.
Siebert, L., H. Glicken, and T. Ui, Volcanic hazards from

Bezymianny- and Bandai-type eruptions, *Bull. Volcanol.*, *49*, 435-459, 1987.
Simpson, R. W. and A. Cox, Paleomagnetic evidence for tectonic rotation of the Oregon Coast Range, *Geology*, *5*, 585-589, 1977.
Smith, D. R., The petrology and geochemistry of High Cascade volcanics in southern Washington: Mount St. Helens volcano and the Indian Heaven basalt field, Ph.D. thesis, 409 pp., Rice Univ., Houston, Texas, 1984.
Smith, D. R. and W. P. Leeman, Petrogenesis of Mount St. Helens dacitic magmas, *J. Geophys. Res.*, *92*, 10,313-10,334, 1987.
Smith, G. A., Coarse-grained nonmarine volcaniclastic sediment: terminology and depositional process, *Geol. Soc. Am. Bull.*, *97*, 1-10, 1986.
Smith, G. A., Neogene synvolcanic and syntectonic sedimentation in central Washington, *Geol. Soc. Am. Bull.*, *99*, 1479-1492, 1988.
Smith, G. A., Campbell, N. P., Deacon, M. W., and Shafiquallah, M., Eruptive style and location of volcanic centers in the Miocene Washington Cascade Range: reconstruction from the sedimentary record, *Geology*, *16*, 337-340, 1988.
Smith, G. O., The rocks of Mount Rainier, *U.S. Geol. Surv. Ann. Rept.*, *18*, 416-423, 1897.
Smith, G. O., Description of the Mount Stuart quadrangle, Washington, *U.S. Geol. Surv. Geol. Atlas Mount Stuart, Folio 106*, 10, 1904.
Smith, G. O. and F. C. Calkins, Description of the Snoqualmie quadrangle, Washington, *U.S. Geol. Surv. Geol. Atlas Snoqualmie, Folio 139*, 14, 1906.
Smith, H. W., R. Okazaki, and C. E. Knowles, Electron microprobe analysis of glass shards from tephra assigned to set W, Mt. St. Helens, Washington, *Quat. Res.*, *7*, 207-217, 1977.
Smith, J. G., New compilation geologic map of the Cascade Range in Washington, *Trans. Geotherm. Resour. Counc.*, *11*, 309-314, 1987.
Smith, J. G., Geologic map showing upper Eocene to Holocene volcanic and related rocks in the Cascade Range of Washington, *U.S. Geol. Surv. Misc. Invest. Map*, in press a.
Smith, J. G., Geologic map of the Yakima 2-degree sheet, *U.S. Geol. Surv. Misc. Invest. Map*, in press b.
Southwick, D. L., Geology of the alpine-type ultramafic complex near Mount Stuart, Washington, *Geol. Soc. Am. Bull.*, *85*, 391-402, 1974.
Stanley, W. D., Tectonic study of the Cascade Range and Columbia Plateau in Washington State based upon magnetotelluric soundings, *J. Geophys. Res.*, *89*, 4447-4460, 1984.
Stanley, W. D., C. Finn, and J. L. Plesha, Tectonics and conductivity structures in the southern Washington Cascades, *J. Geophys. Res.*, *92*, 10,179-10,193, 1987.
Stout, M. L., Geology of a part of the south-central Cascade Mountains, Washington, *Geol. Soc. Am. Bull.*, *75*, 317-334, 1964.
Swanson, D. A., The middle and late Cenozoic volcanic rocks of the Tieton River area, south-central Washington, Ph.D. thesis, 330 pp., Johns Hopkins Univ., Baltimore, 1964.
Swanson, D. A., Tieton volcano, a Miocene eruptive center in the southern Cascade Mountains, Washington, *Geol. Soc. Am. Bull.*, *77*, 1293-1314, 1966.
Swanson, D. A., Yakima Basalt of the Tieton River area, south-central Washington, *Geol. Soc. Am. Bull.*, *78*, 1077-1100, 1967.
Swanson, D. A., Magma supply rate at Kilauea Volcano, 1952-1971, *Science*, *175*, 169-170, 1972.
Swanson, D. A., Geologic map of the Tieton River area, Yakima County, south-central Washington, scale 1:48,000, *U.S. Geol. Surv. Misc. Field Studies Map*, *MF-968*, 1978.
Swanson, D. A. and G. A. Clayton, Generalized geologic map of the Goat Rocks wilderness and roadless areas (6036, Parts A, C, and D), Lewis and Yakima Counties, Washington, *U.S. Geol. Surv. Open-File Rept.*, *83-357*, 10 pp., 1983.
Swanson, D. A. and R. T. Holcomb, Regularities in growth of the Mount St. Helens dacite dome, 1980-86, in The Mechanics of Lava Flow Emplacement and Dome Growth, *IAVCEI Proceedings in Volcanology*, *2*, Springer Verlag, Heidelberg, in press.
Swanson, D. A. and T. L. Wright, Paleogeography of southeast Washington during the middle and late Miocene based on the distribution of intracanyon basalt flows, in *Cenozoic Paleogeography of the western United States*, Pac. Div. Soc. Econ. Paleon. Mineral., Pac. Coast Paleog. Symp., Los Angeles, 31, 1979.
Swanson, D. A., T. L. Wright, and R. T. Helz, Linear vent systems and estimated rates of magma production and eruption for the Yakima Basalt on the Columbia Plateau, *Am. J. Sci.*, *275*, 877-905, 1975.
Swanson, D. A., T. L. Wright, P. R. Hooper, and R. D. Bentley, Revisions in stratigraphic nomenclature of the Columbia River Basalt Group, *U.S. Geol. Surv. Bull.*, *1457-G*, 59 pp., 1979a.
Swanson, D. A., J. L. Anderson, R. D. Bentley, G. R. Byerly, V. E. Camp, J. N. Gardner, and T. L. Wright, Reconnaissance geologic map of the Columbia River Basalt Group in eastern Washington and northern Idaho, *U.S. Geol. Surv. Open-File Rept.*, *79-1363*, 26 pp., 1979b.
Swanson, D. A., J. C. Brown, J. L. Anderson, R. D. Bentley, G. R. Byerly, J. N. Gardner, and T. L. Wright, Structure contour maps on the top of the Grande Ronde and Wanapum Basalts, eastern Washington and northern Idaho, *U.S. Geol. Surv. Open-File Rept.*, *79-1364*, 1979c.
Swanson, D. A., T. L. Wright, V. E. Camp, J. N. Gardner, R. T. Helz, S. M. Price, S. P. Reidel, and M. E. Ross, Reconnaissance geologic map of the Columbia River Basalt Group, Pullman and Walla Walla quadrangles, southeast Washington and adjacent Idaho, *U.S. Geol. Surv. Misc. Invest. Map*, *I-1139*, 1980.
Swanson, D. A., J. L. Anderson, V. E. Camp, P. R. Hooper, W. H. Taubeneck, and T. L. Wright, Reconnaissance geologic map of the Columbia River Basalt Group, northern Oregon and western Idaho, *U.S. Geol. Surv. Open-File Rept.*, *81-797*, 32 pp., 1981.
Swanson, D. A., T. J. Casadevall, D. Dzurisin, S. D. Malone, C. G. Newhall, and C. S. Weaver, Predicting eruptions at Mount St. Helens, June 1980 through December 1982, *Science*, *221*, 1369-1376, 1983.
Swanson, D. A., T. J. Casadevall, D. Dzurisin, R. T. Holcomb, C. G. Newhall, S. D. Malone, and C. S. Weaver, Forecasts and predictions of eruptive activity at Mount St. Helens, 1975-1984, *J. Geodynamics*, *3*, 397-423, 1985.
Swanson, D. A., D. Dzurisin, R. T. Holcomb, E. Y. Iwatsubo, W. W. Chadwick, Jr., T. J. Casadevall, J. W. Ewert, and C. C. Heliker, Growth of the lava dome at Mount St. Helens, Washington (USA), 1981-83, *Geol. Soc. Am. Spec. Pap.*,

212, 1-16, 1987.
Tabor, R. W. and D. F. Crowder, Of batholiths and volcanoes: Intrusion and eruption of Late Cenozoic magmas in the Glacier Peak area, north Cascades, Washington, *U. S. Geol. Surv. Prof. Pap.*, *604*, 67 pp., 1969.
Tabor, R. W., V. A. Frizzell, Jr., D. B. Booth, J. T. Whetten, R. B. Waitt, Jr., and R. E. Zartman, Preliminary geologic map of the Skykomish River 1:100,000 quadrangle, Washington, *U. S. Geol. Surv. Open-File Map*, *82-747*, 1982a.
Tabor, R. W., R. B. Waitt, Jr., V. A. Frizzell, Jr., D. A. Swanson, G.R. Byerly, and R.D. Bentley, Geologic map of the Wenatchee 1:100,000 quadrangle, central Washington, *U.S. Geol. Surv. Misc. Invest. Map*, *I-1311*, 26 pp., 1982b.
Tabor, R. W., V. A. Frizzell, Jr., J. A. Vance, and C. W. Naeser, Ages and stratigraphy of lower and middle Tertiary sedimentary and volcanic rocks of the central Cascades, Washington: application to the tectonic history of the Straight Creek fault, *Geol. Soc. Am. Bull.*, *95*, 26-44, 1984.
Tabor, R. W., R. E. Zartman, and V. A. Frizzell, Jr., Possible tectonostratigraphic terranes in the North Cascades crystalline core, Washington, *Wash. Div. Geol. Earth Res. Bull.*, *77*, 107-127, 1987.
Taubeneck, W. H., Dikes of Columbia River basalt in northeastern Oregon, western Idaho, and southeastern Washington, in *Proc. Second Columbia River Basalt Symp.*, East. Wash. State Coll. Press, Cheney, 73-96, 1970.
Taylor, E. M., Field geology of the northwest quarter of the Broken Top 15' quadrangle, Deschutes County, Oregon, *Oreg. Dept. Geol. Mineral Indust. Spec. Pap.*, *21*, 20 pp., 1987.
Thiruvathukal, J. V., J. W. Berg, and D. F. Heinrichs, Regional gravity of Oregon, *Bull. Seis. Soc. Am.*, *81*, 725-738, 1970.
Tolan, T. L. and M. H. Beeson, Exploring the Neogene history of the Columbia River: Discussion and geologic field trip guide to the Columbia River Gorge. Part I. Discussion, *Oreg. Geol.*, *46*, 87-97, 1984a.
Tolan, T. L. and M. H. Beeson, Exploring the Neogene history of the Columbia River: Discussion and geologic field trip guide to the Columbia River Gorge. Part II. Road log and comments, *Oreg. Geol.*, *46*, 103-112, 1984b.
Tolan, T. L. and M. H. Beeson, Intracanyon flows of the Columbia River Basalt Group in the lower Columbia River Gorge and their relationship to the Troutdale Formation, *Geol. Soc. Am. Bull.*, *95*, 463-477, 1984c.
Tolan, T. L., S. P. Reidel, M. H. Beeson, J. L. Anderson, K. R. Fecht, and D. A. Swanson, Revisions to the areal extent and volume of the Columbia River Basalt Group (CRBG), *Geol. Soc. Am. Abst. Prog.*, *19*, 458, 1987.
Tolan, T. L., S. P. Reidel, M. H. Beeson, J. L. Anderson, K. R. Fecht, and D. A. Swanson, Revisions to the estimates of the areal extent and volume of the Columbia River Basalt Group, in *Volcanism and Tectonism on the Columbia Plateau*, edited by S. P. Reidel, P. R. Hooper, and J. L. Anderson, *Geol. Soc. Am. Spec. Pap.*, in press.
Treasher, R. C., Geologic history of the Portland area, *Oreg. Dept. Geol. Mineral Indust. Short Paper*, *7*, 17 pp., 1942.
Trimble, D. E., Geology of Portland, Oregon and adjacent areas, *U.S. Geol. Surv. Bull.*, *1119*, 119 pp., 1963.
Turner, D. L., V. A. Frizzell, Jr., D. M. Triplehorn, and C. W. Naeser, Radiometric dating of ash partings in coals of the Eocene Puget Group, Washington: implications for paleobotanical stages, *Geology*, *11*, 527-531, 1983.
Vallance, J. W., Late Quaternary volcanic stratigraphy of the southwestern flank of Mount Adams volcano, Washington, M.S. thesis, Univ. Colorado, Boulder, 1986.
Vance, J. A., Early and middle Cenozoic arc magmatism and tectonics in Washington state, *Geol. Soc. Am. Abst. Prog.*, *11*, 132, 1979.
Vance, J. A., Cenozoic stratigraphy and tectonics of the Washington Cascades, *Geol. Soc. Am. Abst. Prog.*, *14*, 241, 1982.
Vance, J. A., Early Tertiary faulting in the North Cascades, *Geol. Soc. Am. Abst. Prog.*, *17*, 415, 1985.
Vance, J. A. and R. B. Miller, The movement history of the Straight Creek fault in Washington State, *Cordilleran Sect. Geol. Assoc. Canada, Prog. Absts.*, 39-41, 1981.
Vance, J. A. and C. W. Naeser, Fission track geochronology of the Tertiary volcanic rocks of the central Cascade Mountains, Washington, *Geol. Soc. Am. Absts. Prog.*, *9*, 520, 1977.
Vance, J. A., N. W. Walker, and J. M. Mattinson, U/Pb ages of early Cascade plutons in Washington state, *Geol. Soc. Am. Abst. Prog.*, *18*, 194, 1986.
Vance, J. A., G. A. Clayton, J. M. Mattinson, and C. W. Naeser, Early and middle Cenozoic stratigraphy of the Mount Rainier-Tieton River area, southern Washington Cascades, *Wash. Div. Geol. Earth Res. Bull.*, *77*, 269-290, 1987.
Vine, J. D., Preliminary geologic map of the Hobart and Maple Valley quadrangles, King County, Washington, scale 1:24,000, *Wash. Div. Mines Geol. Map*, *GM-1*, 1962.
Vine, J. D., Geology and coal resources of the Cumberland, Hobart, and Maple Valley quadrangles, King County, Washington, *U.S. Geol. Surv. Prof. Pap.*, *624*, 67 pp., 1969.
Voight, B., H. Glicken, R. J. Janda, and P. M. Douglass, Catastrophic rockslide avalanche of May 18, *U.S. Geol. Surv. Prof. Pap.*, *1250*, 347-377, 1981.
Voight, B., R. J. Janda, H. Glicken, and P. M. Douglass, Nature and mechanics of the Mount St Helens rockslide-avalanche of 18 May 1980, *Geotechnique*, *33*, 243-273, 1983.
Waitt, R. B., Late-Cenozoic deposits, landforms, stratigraphy, and tectonism of Kittitas Valley, Washington, *U.S. Geol. Surv. Prof. Pap.*, *1127*, 18 pp., 1979.
Waitt, R. B., Deposits and effects of devastating lithic pyroclastic density current from Mount St. Helens on 18 May 1980–field guide for northeast radial, *U.S. Geol. Surv. Open-File Rept.*, *84-839*, 10 pp., 1984a.
Waitt, R. B., Comment, *Geology*, *12*, 693, 1984b.
Waitt, R. B., Case for periodic, colossal jökulhlaups from Pleistocene glacial Lake Missoula, *Geol. Soc. Am. Bull.*, *96*, 1271-1286, 1985.
Waitt, R. B. and N. S. MacLeod, Minor explosive eruptions at Mount St. Helens dramatically interacting with winter snowpack in March-April 1982, *Wash. Div. Geol. Earth Res. Bull.*, *77*, 355-379, 1987.
Waitt, R. B. and D. A. Swanson, Geomorphic evolution of the Columbia Plain and River, *Geol. Soc. Am. Centennial Spec. Vol.*, *2*, 403-423, 1987.
Waitt, R. B., T. C. Pierson, N. S. MacLeod, R. J. Janda, B. Voight, and R. T. Holcomb, Eruption-triggered avalanche, flood, and lahar at Mount St. Helens–effects of winter snowpack, *Science*, *221*, 1394-1397, 1983.
Walker, G. P. L., Lengths of lava flows, *Phil. Trans. Roy. Soc. Lond. A*, *274*, 107-118, 1973.
Walker, G. P. L. and L. A. McBroome, Mount St. Helens

1980 and Mount Pelée 1902–flow or surge?, *Geology*, *11*, 571-574, 1983.

Walsh, T. J., M. A. Korosec, W. M. Phillips, R. L. Logan, and H. W. Schasse, Geologic map of Washington–southwest quadrant, scale 1:250,000, *Wash. Div. Geol. Earth Resources Geol. Map*, *GM-34*, 28 pp., 1987.

Warren, W. C., Relation of the Yakima basalt to the Keechelus andesitic series, *J. Geol.*, *49*, 795-814, 1941.

Waters, A. C., Geomorphology of south-central Washington, illustrated by the Yakima East quadrangle, *Geol. Soc. Am. Bull.*, *66*, 663-684, 1955.

Waters, A. C., Stratigraphic and lithologic variations in the Columbia River basalt, *Am. J. Sci.*, *259*, 583-611, 1961.

Waters, A. C., The Columbia River Gorge: basalt stratigraphy, ancient lava dams, and landslide dams, *Oreg. Dept. Geol. Mineral Indust. Bull.*, *77*, 133-162, 1973.

Weaver, C. S. and G. E. Baker, Geometry of the Juan de Fuca plate beneath Washington–evidence from seismicity and the 1949 south Puget Sound earthquake, *Bull. Seis. Soc. Am.*, *78*, 264-275, 1988.

Weaver, C. S. and S. D. Malone, Overview of the tectonic setting and recent studies of eruptions of Mount St. Helens, Washington, *J. Geophys. Res.*, *92*, 10,149-10,154, 1987.

Weaver, C. S. and C. A. Michaelson, Seismicity and volcanism in the Pacific Northwest: evidence for the segmentation of the Juan de Fuca plate, *Geophys. Res. Let.*, *12*, 215-218, 1985.

Weaver, C. S. and S. W. Smith, Regional tectonic and earthquake hazard implications of a crustal fault zone in southwestern Washington, *J. Geophys. Res.*, *88*, 10,371-10,383, 1983.

Weaver, C. S., S. M. Green, and H. M. Iyer, Seismicity of Mount Hood and structure as determined from teleseismic *P* wave delay studies, *J. Geophys. Res.*, *87*, 2782-2792, 1982.

Weaver, C. S., W. C. Grant, and J. E. Shemata, Local crustal extension at Mount St. Helens, Washington, *J. Geophys. Res.*, *92*, 10,170-10,178, 1987.

Wells, R. E. and R. S. Coe, Paleomagnetism and geology of Eocene volcanic rocks of southwest Washington, implications for mechanisms of tectonic rotation, *J. Geophys. Res.*, *90*, 1925-1947, 1985.

Wells, R. E. and P. C. England, Continuum model of rotations recorded in Miocene flows of the Columbia River Basalt Group, Oregon and Washington, *Eos*, in press.

Wells, R. E. and A. R. Niem, Geology of the Columbia River Basalt Group in the Astoria Basin, Oregon and Washington: evidence for invasive flows, *Geol. Soc. Am. Abst. Prog.*, *19*, 462-463, 1987.

Wells, R. E. and R. W. Simpson, More paleomagnetic results from the Miocene Columbia River Basalt Group, Oregon and Washington: stratigraphic and tectonic implications, *Geol. Soc. Am. Abst. Prog.*, *19*, 463, 1987.

Wells, R. E., R. W. Simpson, R. D. Bentley, M. H. Beeson, M. T. Mangan, and T. L. Wright, Correlation of Miocene flows of the Columbia River Basalt Group from the central Columbia Plateau to the coast of Oregon and Washington, in *Volcanism and Tectonism on the Columbia Plateau*, edited by S. P. Reidel, P. R. Hooper, and J. L. Anderson, *Geol. Soc. Am. Spec. Pap.*, in press.

Westgate, J. A., D. G. W. Smith, and H. Nichols, Late Quaternary pyroclastic layers in the Edmonton area, Alberta, in *Pedology and Quaternary Research*, Univ. Alberta Printing, Edmonton, Alberta, pp. 179-186, 1970.

White, C., Geology and geochemistry of Mt. Hood volcano, *Oreg. Dept. Geol. Mineral Indust. Spec. Pap.*, *8*, 26 pp., 1980.

Williams, D. L. and T. E. C. Keith, Aeromagnetic and Bouguer gravity maps of Mount Hood Wilderness, Clackamas and Hood River Counties, Oregon, *U.S. Geol. Surv. Misc. Field Studies Map*, *MF-1379D*, 1982.

Williams, D. L., G. Abrams, C. Finn, D. Dzurisin, D. J. Johnson, and R. Denlinger, Evidence from gravity data for an intrusive complex beneath Mount St. Helens, *J. Geophys. Res.*, *92*, 10,207-10,222, 1987.

Williams, D. L., C. Finn, R. W. Couch, Z. F. Danes, G. S. Pitts, W. M. Phillips, and R. P. Riddihough, Residual Bouguer gravity anomaly map of the Cascade Range, California, Oregon, Washington, and British Columbia, *U.S. Geol. Surv. Geophys. Invest. Map*, *GP-973*, 1988.

Wise, W. S., The geology and mineralogy of the Wind River area, Washington, and the stability relations of celadonite, Ph.D. thesis, Johns Hopkins Univ., Baltimore, 1961.

Wise, W. S., Geology of the Mount Hood volcano, *Oreg. Dept. Geol. Mineral Indust. Bull.*, *62*, 81-98, 1968.

Wise, W. S., Geology and petrology of the Mount Hood area: a study of High Cascade volcanism, *Geol. Soc. Am. Bull.*, *80*, 969-1006, 1969.

Wise, W. S., Cenozoic volcanism in the Cascade Mountains of southern Washington, *Wash. Dept. Nat. Resources Bull.*, *60*, 45 pp., 1970.

Wright, T. L., M. Mangan, and D. A. Swanson, Chemical data for flows and feeder dikes of the Yakima Basalt Subgroup, Columbia River Basalt Group: constraints on a petrogenetic model, *U.S. Geol. Surv. Bull.*, *1821*, in press.

Yamaguchi, D. K., New tree-ring dates for recent eruptions of Mount St. Helens, *Quat. Res.*, *20*, 246-250, 1983.

Yamaguchi, D. K., Tree-ring evidence for a two-year interval between recent prehistoric explosive eruptions of Mt. St. Helens, *Geology*, *13*, 554-557, 1985.

Zoback, M. L. and G. A. Thompson, Basin and Range rifting in northern Nevada, clues from a mid-Miocene rift and its subsequent offsets, *Geology*, *6*, 111-116, 1978.