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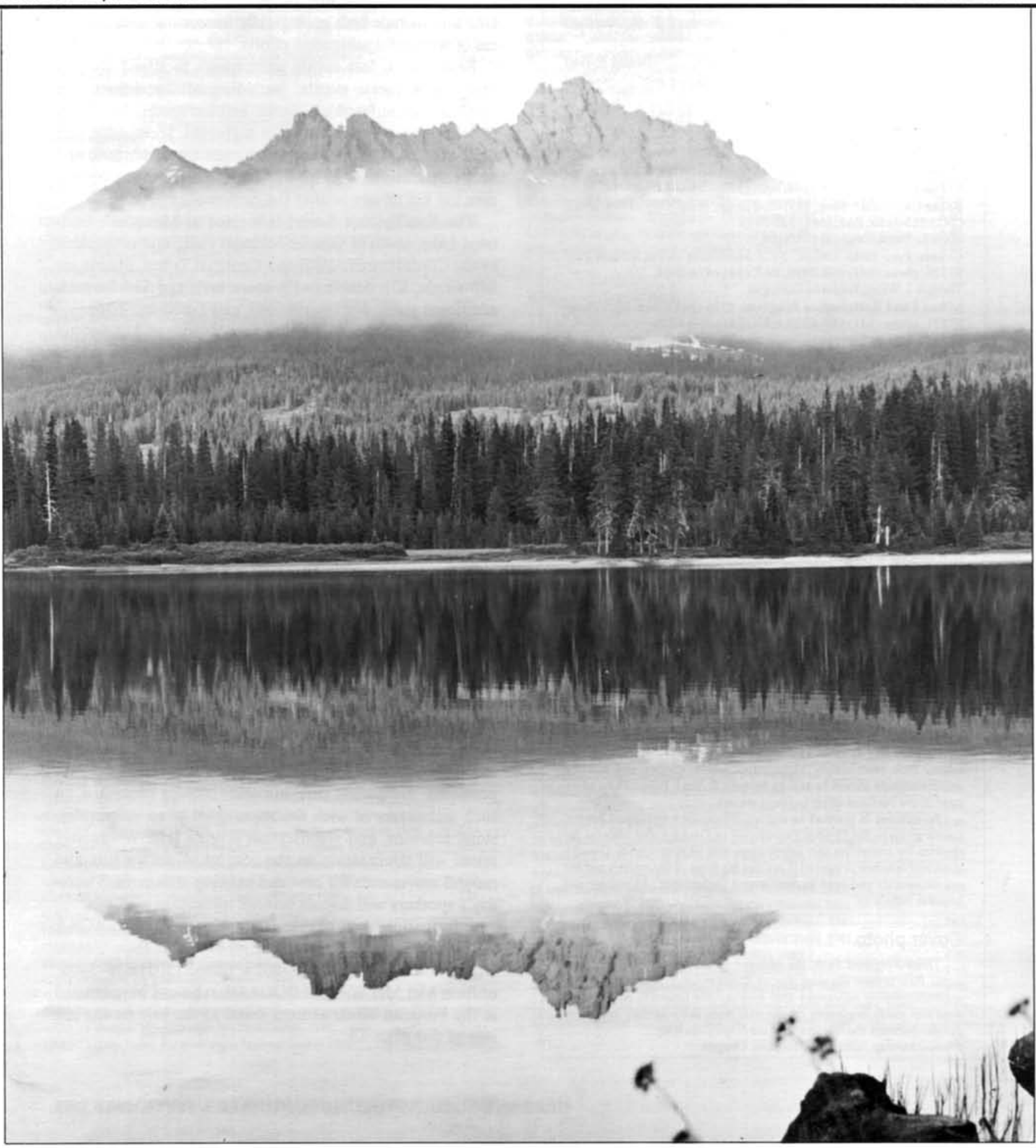

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**Main Office**: Suite 965, 800 NE Oregon Street # 28, Portland 97232, phone (503) 731-4100, FAX (503) 731-4066.

**Baker City Field Office**: 1831 First Street, Baker City 97814, phone (541) 523-3133, FAX (541) 523-5992.
Mark L. Ferns, Regional Geologist.

**Grants Pass Field Office**: 5375 Monument Drive, Grants Pass 97526, phone (541) 476-2496, FAX (541) 474-3158.
Thomas J. Wiley, Regional Geologist.

**Mined Land Reclamation Program**: 1536 Queen Ave. SE, Albany 97321, phone (541) 967-2039, FAX (541) 967-2075.
Gary W. Lynch, Supervisor.

**The Nature of the Northwest Information Center**: Suite 177, 800 NE Oregon Street # 5, Portland, OR 97232-2162, phone (503) 872-2750, FAX (503) 731-4066, Donald J. Haines, Manager.

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*Oregon Geology* is designed to reach a wide spectrum of readers interested in the geology and mineral industry of Oregon. Manuscript contributions are invited on both technical and general-interest subjects relating to Oregon geology. Two copies of the manuscript should be submitted. If manuscript was prepared on common word-processing equipment, a file copy on diskette should be submitted in place of one paper copy (from Macintosh systems, high-density diskette only). Graphics should be camera ready; photographs should be black-and-white glossies. All figures should be clearly marked; figure captions should be together at the end of the text.

Style is generally that of U.S. Geological Survey publications. (See USGS *Suggestions to Authors*, 7th ed., 1991, or recent issues of *Oregon Geology*.) Bibliography should be limited to references cited. Authors are responsible for the accuracy of the bibliographic references. Include names of reviewers in the acknowledgments.

Authors will receive 20 complimentary copies of the issue containing their contribution. Manuscripts, letters, notices, and meeting announcements should be sent to Beverly F. Vogt, Publications Manager, at the Portland office (address above).



## Cover photo

*Three Fingered Jack, the remains of a Pleistocene shield volcano. View is from the west, across Santiam Lake. This is one of the relatively young volcanoes that built up the Cascade Range. The field trip guide beginning on the next page leads largely along the border between the Western and the High Cascades.*
*Photo courtesy John Blum, Stayton, Oregon.*

## Seismic Policy Council to meet in Montana

The Western States Seismic Policy Council (WSSPC) will hold its annual conference September 18–21, 1996, at the KwaTaqNuk Resort in Polson, Montana. Conference sessions will deal with such topics as geology, earthquake information, preparedness, mitigation, emergency response, and partnerships. A field excursion will offer visits to interesting seismic sites in the Mission fault area of Montana and include both geologically interesting sites and areas of successful mitigation efforts.

Registration fees entitle participants to attend all programs and social events, including all breakfasts and lunches, the conference banquet, and the vendor fair. Early registration by August 1 is $210 registrant, $60 spouse, $25 field excursion; later registration costs are $240, $90, and $25, respectively. WSSPC will invoice prior to the conference but not on site or after the conference.

The KwaTaqNuk Resort is located at Montana's Flathead Lake, south of Glacier National Park, and is operated by the Confederated Salish and Kootenai Tribes. Rooms are $48 single, $78 double (+4% room tax), and $10 for each additional guest. For reservations, call 1-800-882-6363.

WSSPC receives conference registrations at 121 Second Street, 4th Floor, San Francisco, CA 94105, or by FAX at (415) 974-1747, or e-mail at wsspc@wsspc.org. The organization can also be reached by phone at (415) 974-6422 or at its web site http://www.wsspc.org. □

## Engineering seminar focuses on ground stabilization and seismic mitigation

The Oregon Section Geotechnical Group of the American Society of Civil Engineers (ASCE) and the Oregon Department of Geology and Mineral Industries (DOGAMI) will sponsor a seminar that presents the latest information on ground stabilization techniques and methods for reducing seismic liquefaction hazards. The seminar will be held Wednesday and Thursday, November 6–7, 1996, in Room 120C of the Oregon Building (State Office Building), 800 NE Oregon Street, in Portland.

Speakers from industry and universities will present a mix of recent research and its applications to engineering problems. Numerous case histories will be presented on such techniques as wick drains, tangent piles, micropiles, stone columns, and stabilization pilings. The Wednesday series will concentrate on the control of settlements and ground movements for new and existing structures. Thursday's speakers will discuss seismic mitigation methods.

Information is available from Wesley Spang, AGRA Earth and Environmental, Inc., 7477 SW Tech Center Drive, Portland, OR 97223–8025, phone (503) 639–3400; or from Mei Mei Wang of DOGAMI, who can be contacted at the Portland office address listed in the box on the left side of this page. □

# Water, rocks, and woods—A field excursion to examine the geology, hydrology, and geothermal resources in the Clackamas, North Santiam, and McKenzie River drainages, Cascade Range, Oregon

*by David R. Sherrod[1], Steven E. Ingebritsen[2], John M. Curless[3], Terry E.C. Keith[4], Nancy M. Diaz[5], Thomas G. DeRoo[5], and Sanford L. Hurlocker[6]*

This guide was prepared for a field trip conducted in conjunction with the Geological Society of America Penrose Conference on fluid-volcano interactions, Kahneeta, Oregon, October 4–9, 1992. Please be sure to read the warning notice at the end of this article.

## INTRODUCTION

Water—how it travels through the upper crust, how it is heated in hydrothermal systems above or adjacent to magma, how it alters rocks to reduce their permeability, how it disperses geothermal energy in the near-surface environment—these aspects of hydrogeology are the focus of a field trip that preceded an October 1992 Penrose Conference on fluid-volcano interactions. In the Cascade Range, some uncertainty still surrounds the interpretation of heat-flow data. Anomalously high heat measured in the Western Cascades may be an expression of localized deep magmatic heat sources. Or it may result from groundwater flowing laterally, flushing heat westward from beneath Quaternary volcanoes in the High Cascades to reappear at diffuse sites in the Western Cascades or locally focused at hot springs in valley floors there. These divergent interpretations have important implications for the assessment of geothermal resource potential and exploration of geothermal energy.

This trip covers 140 road miles from Estacada in Clackamas County to Santiam Pass on the border between Linn and Jefferson Counties (Figure 1). The route traverses parts of the Western and High Cascades, and the text emphasizes how topographic contrasts between these physiographic subprovinces influence hydrogeologic conditions in the Cascade Range. Two major hot-spring systems, Austin and Breitenbush, are passed along the route (Stops 2 and 4); and a third system, the McKenzie River group of springs, is discussed at the last stop (Stop 6). Driving time is about 3¾ hr plus the time taken for the 6 or 7 stops, which can vary from 30 minutes to 60 minutes each.

[1] U.S. Geological Survey, P.O. Box 51, Hawaii National Park, HI 96718.
[2] U.S. Geological Survey, 345 Middlefield Rd., Menlo Park, CA 94025.
[3] Dept. of Geosciences, Oregon State University, Corvallis, OR 97331.
[4] U.S. Geological Survey, 4200 University Dr., Anchorage, AK 99508.
[5] U.S. Forest Service, Mt. Hood National Forest, 2955 NW Division St., Gresham, OR 97030.
[6] U.S. Forest Service, Willamette National Forest, HC–73, Box 320, Mill City, OR 97360.

**MILEAGE** (interval/cumulative) — **DESCRIPTION**

0.0/0.0 — Estacada, traffic signal at intersection of Broadway Street and State Highway 224. **Follow Highway 224**. Route leads southeast towards Ripplebrook Ranger Station (Figure 1). The first 5.7 mi are along new road alignment built since 1985.

3.9/3.9 — **Optional stop,** viewpoint. Top of grade (crest of hill) with room to pull out on right, as road begins descent into Clackamas River valley.

From this vantage, on a clear day, the traveler can look southeast along the V-shaped Clackamas River canyon and southward along the western slope of the Cascade Range. Strata are gently west dipping in this area, and the view southeast from here has hints of that bedding orientation. Like many parts of the Cascade Range, however, topographic expression of bedding is difficult to discern, owing to thick forest cover, high rates of mechanical erosion, and myriad landslides that disrupt the development of ledges along some of the more continuous units.

More obvious are the clear-cuts that pattern the forest cover as we look east and south across the 1.1-million-acre Mount Hood National Forest. In the last 50 years, 0.18 million acres of this National Forest have been clear-cut, and an additional 0.1 million acres have had partial cuts. Wilderness and watershed preserves constitute about 0.26 million acres (Tom Ortman, USDA Forest Service [USFS], oral communication, 1992). Elsewhere in Oregon, clear-cutting has been shown to modify the timing and magnitude of peak streamflow (Fredriksen, 1970). Clear-cutting also is associated with increased sediment discharge, although this may be more a function of road building than greatly increased erosion of logged areas (e.g., Fredricksen, 1970; Swanson and Dyrness, 1975).

A subtle relationship exists between landforms, forest fires, and subsequent forest growth. Imagine a fire contained within the river valley, for example. Such fires tend

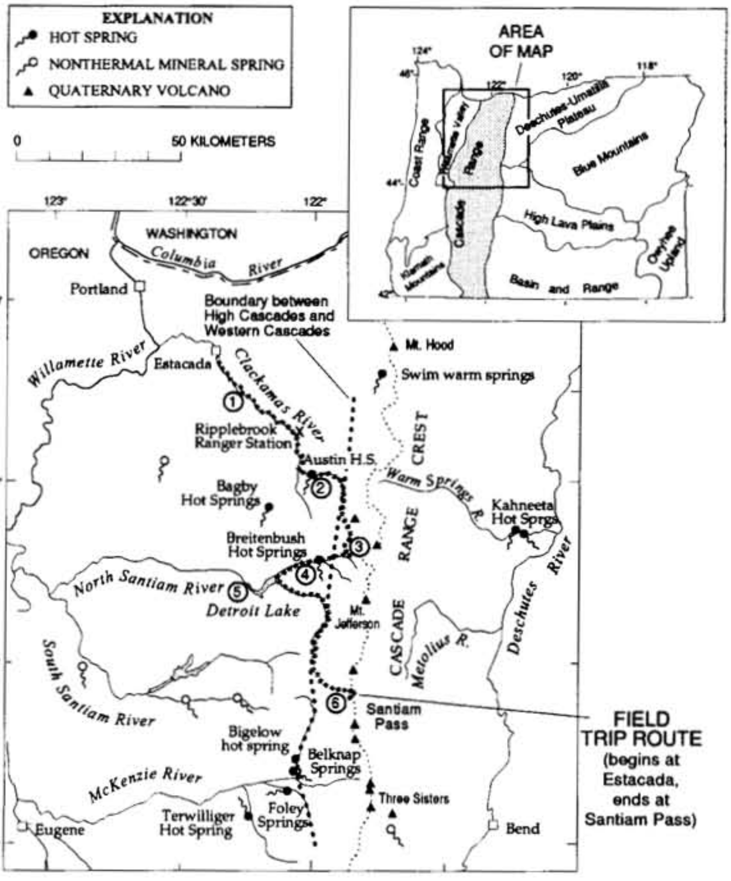



*Figure 1. Trip route from Estacada to Santiam Pass. Inset shows physiographic provinces of Oregon. Encircled numerals are field-trip stops. Naming of hot springs follows conventions on published topographic maps; names in lower case are informal.*

to be spotty, because wind patterns and wood supply work to minimize rampant burning. Natural reforestation afterwards results in a diverse, intricate pattern of forest species. In contrast, a fire on the broad upland slopes and flattish regions at higher elevations can burn quickly across large areas. Subsequent reforestation creates even-aged, homogeneous stands of timber. Wildlife is tied to habitat, and the fire-modified landscape will see changing use and (or) migration patterns, especially of large mammals and birds.

1.8/5.7 Route joins old road alignment, which may be the only road shown on many maps. Road to right leads back (west) to dam.

0.7/6.4 Mount Hood National Forest sign (entering National Forest lands).

3.3/9.7 **Stop 1—Big Cliff.** At road level are excellent exposures of Grande Ronde Basalt (Prineville chemical type), a formation in the Columbia River Basalt Group.

Our purpose at this stop is to consider the role that lithologic variation plays in some temperature profiles. The Columbia River Basalt Group here consists of nearly flat-lying lava flows and interflow breccia (Figure 2A). Most lava flows of the Columbia River Basalt Group were erupted between 17 and 13.5 Ma from dike swarms located 400 km east of the Cascade Range; they flowed west across the area of the present-day Columbia Plateau and lapped against older rocks of the Cascade Range (Figure 3). Some lava flooded through low gaps in the range in northern Oregon and southern Washington and progressed as far as the Pacific Ocean. The flows in the Clackamas River area have been mapped and described in detail by Anderson (1978).

Contrasts in permeability between massive lava and breccia are responsible for the stepped geothermal gradient seen in a hole drilled in the Columbia River Basalt Group across the Clackamas River from Estacada (Figure 2B). Slight differences in hydraulic head between breccia zones cause flow between zones when they are connected by the drill hole. Steep temperature gradients (subhorizontal steps on Figure 2B) are associated with each permeable zone, whereas low gradients (near-uniform temperatures over a large depth range) characterize the intervening massive flows.

The Columbia River Basalt Group, although not part of Cascade Range volcanism, forms an easily identified stratigraphic marker—and one well exposed in many localities because its lava is erosion resistant. Along the Clackamas River, the lava flows form cliffs and open sunny bluffs that support unique biological communities. Scorpions, poison oak, and perhaps rattlesnakes, while not common in the western part of the Cascade Range at this latitude, are found sporadically among outcrops of the Columbia River Basalt Group, especially the south-facing exposures. So, too, is found the Oregon white oak, a species far more common in the Willamette Valley and on eastern slopes of the Cascade Range, where the hotter, drier summers favor its growth. Note how the deciduous trees grow in shaded clefts and fractures.

0.7/10.4 Bridge, Memaloose Road to right. **Continue on main highway**. "Memaloose" is Chinook jargon for "dead" or "death." ("Jargon" used in its linguistic sense as a language group comprising words from several separate languages.) Folk legend holds that an Indian chief is buried along ridge at headwaters of Memaloose Creek (Beth Walton, USFS, oral communication, 1992).

Although not visible from our route along the canyon bottom, Pliocene basalt caps canyon walls on the northeast. These lava flows were emplaced along a broad paleovalley, before the ancestral Clackamas River began to carve its deep narrow gorge. The basalt flows along the Clackamas River are not directly dated, but they can be traced nearly to the High Rock area of the Cascade Range, where petrographically similar rocks form the lowest part of a conformable sequence of lava flows as young as 2.78±0.09 Ma (Sherrod and Conrey, 1988). For this reason, we assign the entire sequence an age between about 3 and 2 Ma. The modern gorge has been cut since that time.

0.4/10.8 Lazy Bend Campground (USFS).

0.8/11.6 Oak plant communities thrive on south-facing slopes above road.

3.4/15.0 Big Eddy picnic ground (USFS).

At Big Eddy, the northwest-trending channel of the Clackamas River turns abruptly northeast, forcing the main current to the outside of its bend. Outcrops of lava further constrict the channel. A short distance beyond the constriction, the channel width increases from 8 to 20 m and channel depth increases from 1 to 5 m or more. These increases combine to create two large ovoid eddy cells 6×15 m and 4.5×9 m. Many intermittent local vortices migrate in the larger eddy.

1.2/16.2 Carter Bridge picnic ground (USFS).

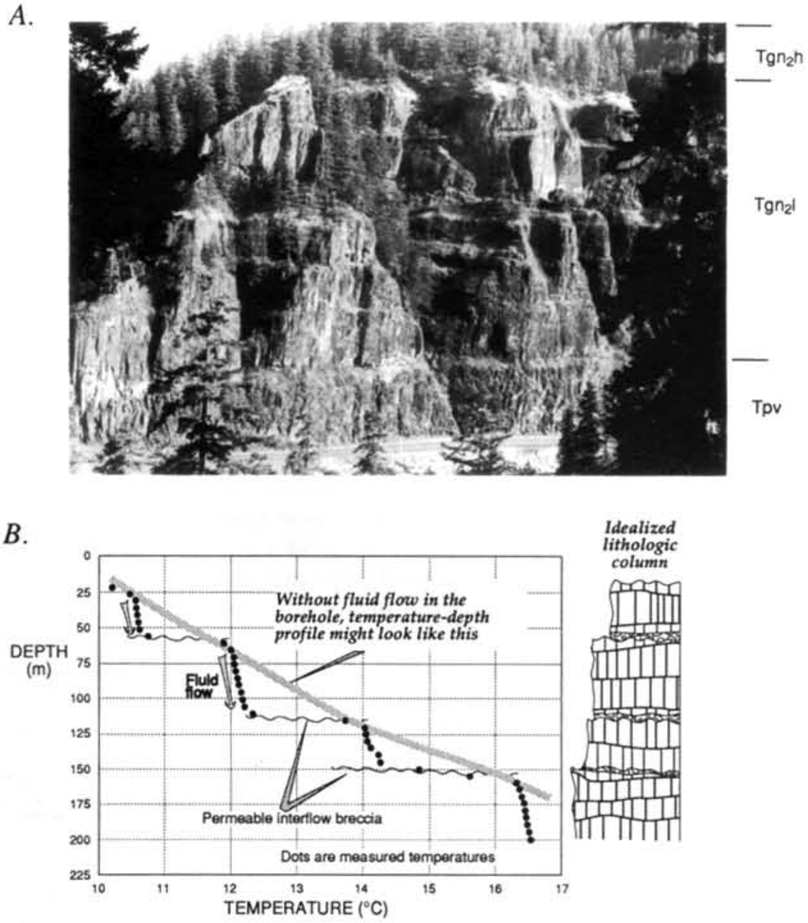



*Figure 2. Comparison of Big Cliff stratigraphic section (Stop 1) and disturbed temperature profile from heat-flow hole drilled into Columbia River Basalt Group: A—Informally named Prineville basalt of Nathan and Fruchter (1974) at road level (unit Tpv) overlain by low- and high-magnesium chemical types of normally polarized Grande Ronde Basalt (units $Tgn_2l$ and $Tgn_2h$, respectively). Photograph and stratigraphic interpretation from Anderson (1978). B—Temperature profile for hole drilled near Estacada (northwest corner of sec. 29, T. 3 S., R. 4 E.) with lithologic layering probably similar to that exposed at Big Cliff (from Ingebritsen and others, 1988).*

0.5/16.7 Highway bridge over Clackamas River.

0.2/16.9 Fish Creek Road to right. **Continue on main highway**. Temperature measurements from shallow wells in campgrounds nearby provide the only conductive heat-flow data for an area of about 300–400 $km^2$ centered here (holes no. 11, 12, 14, and 15 in appendix to Ingebritsen and others, 1991).

2.5/19.4 Roaring River Campground (USFS).

1.8/21.2 Road cuts on left show sedimentary interbeds that are lithostratigraphic equivalents of the Vantage Member of the Ellensburg Formation in eastern Washington (Anderson, 1978; Hammond and others, 1980) and separate Grande Ronde Basalt and overlying Wanapum Basalt, both units part of the Columbia River Basalt Group. Overall lack of volcaniclastic interbeds among Oregon Cascade Range exposures of the Grande Ronde and Wanapum Basalts indicates relative quiescence of arc volcanism from 17 to 14.5 Ma.

0.9/22.1 Quaternary terrace and talus deposits exposed in road cuts on left.

0.3/22.4 Three Lynx Road junction. **Continue ahead on main highway**.

1.1/23.5 Bridge, Indian Henry Road to right. Trip has been in narrow gorge carved in gently west-dipping lava flows of the Columbia River Basalt Group. Our southeast-directed travel has taken us downsection, and at this point we pass into Oligocene and lower Miocene volcanogenic rocks. The narrow gorge abruptly widens upstream (southeast) from here because of widespread landsliding, a consequence of slope failure in the altered tuffaceous volcanogenic rocks of the Western Cascades.

At about this point we enter a westward "bulge" in the map pattern of some geophysical features. For example, the apparent Curie point isotherm, which in the High Cascades is located at depths of 6–9 km, extends at similarly shallow depths into the Western Cascades here, although most of the Western Cascades have isotherm depths greater than 9 km (Figure 4). The concept "depth to apparent Curie point isotherm" is more correctly described as depth to the base of the magnetic layer, a geophysical property resulting from hydrothermal alteration or high temperature. Heat-flow contours for 60- and 80-mW/$m^2$ (milliwatts per square meter) also extend westward to enclose this area before sweeping back east toward the High Cascades (Figure 4).

1.1/24.6 Chronically rough road with sunken grade as a consequence of landsliding. As much as 6 m (20 ft) of asphalt reportedly has built up over the years, as the roadbed is continually relayered along this curve.

0.6/25.2 Boggy wetland. On warm days in late spring and summer the smell of skunk cabbage is unmistakable. (Try not to catch the eye of someone sitting near you!)

2.7/27.9 Timber Lake Civilian Conservation Corps work center.

A sawmill was built near this site toward

⇒

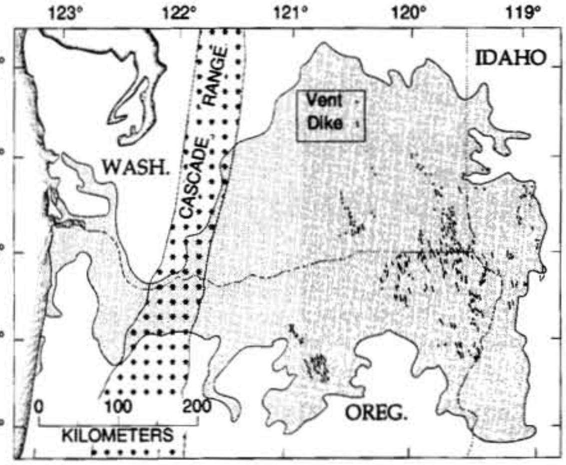



*Figure 3. Distribution of Columbia River Basalt Group and location of volcanoes and dikes that fed the lava flows in it. Generalized from Tolan and others (1989).*

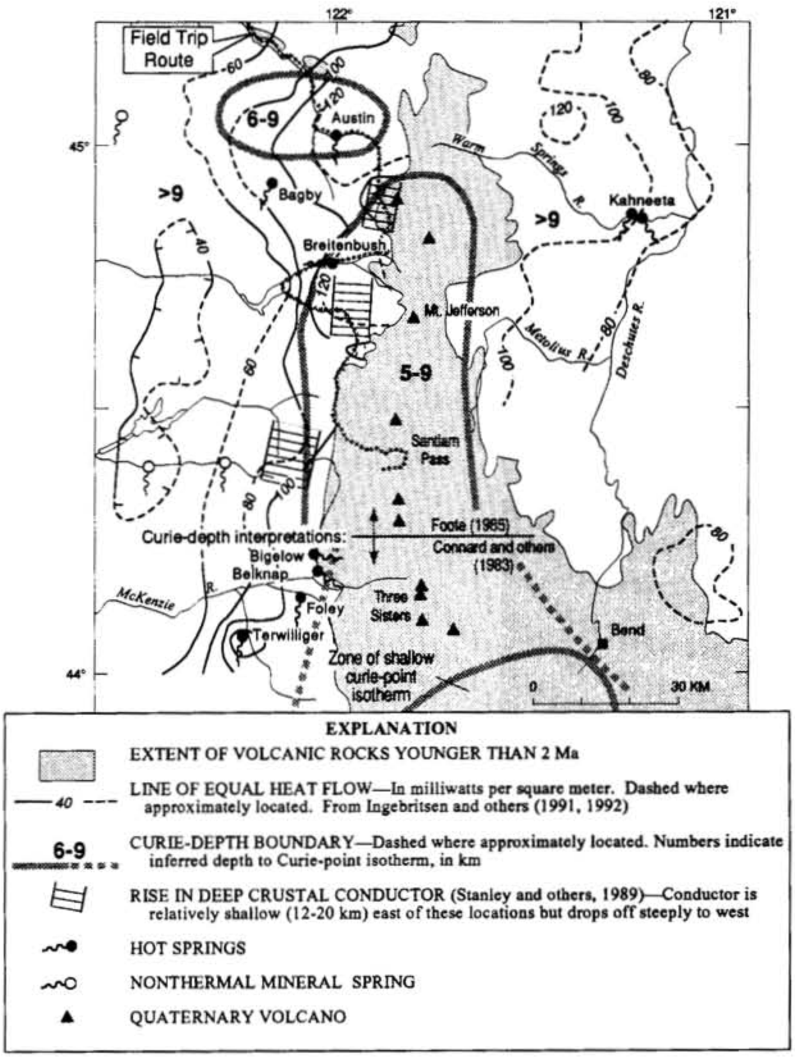



*Figure 4. Map showing relation between near-surface heat flow, apparent Curie-depth boundaries (Connard and others, 1983; Foote, 1985), and rise in deep crustal conductor (Stanley and others, 1989, 1990). Note westward "bulge" in heat-flow contour for 80 mW/$m^2$ and its approximate coincidence with shallow Curie-depth boundary in area of Austin Hot Springs. From Ingebritsen and others (1991, 1992).*

the end of World War II, the time when large-scale logging began to open up slopes along the Clackamas River drainage. With the development came attempts to drain bogs that dot the surface of this landslide. Forest planners presently are minimizing logging to preserve the landslide-prone area for the rich habitat it possesses. Bogs and moving water on the landslide surface create diverse openings favorable for wildlife. Wetlands here provide important winter forage for deer and elk.

1.0/28.9 Ripplebrook Ranger Station. Wilderness permits, pay telephone. Highway 224 becomes Forest Road 46. **Continue ahead.**

0.5/29.4 Junction, Forest Road 57 to left. **Keep right on Road 46.** The road not taken, Road 57, leads east to Timothy Lake along the Oak Grove Fork Clackamas River.

As discussed by Ingebritsen and others (1991), the watershed of the Oak Grove Fork encompasses relatively permeable lava flows of chiefly Pliocene and Pleistocene age. In contrast, the watershed of the main stem of the Clackamas River encompasses a wide area of relatively impermeable, altered Oligocene and Miocene tuffaceous strata. A hydrologic consequence of increased permeability is a much higher unit baseflow or recharge rate—$26 \times 10^{-9}$ m/s (~1 m/yr), nearly three times that for the Clackamas River downstream between Three Lynx and Estacada (Figure 5). Unit baseflow is an estimate of the minimum groundwater recharge rate per unit area. Thus, the Oak Grove Fork has a proportionately higher groundwater (baseflow) contribution to stream flow (50 percent of annual precipitation) and a much flatter hydrograph (less seasonal variation) than the main stem of the Clackamas River (baseflow 20 percent of annual precipitation).

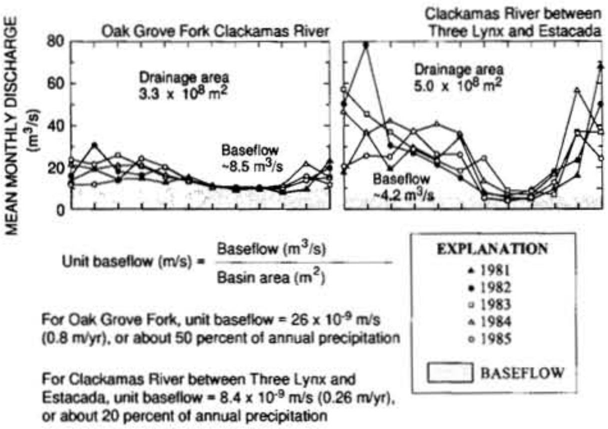



*Figure 5. Hydrographs showing contrasts in seasonal stream flow as a consequence of rock permeability in watersheds (from Ingebritsen and others, 1991). Oak Grove Fork Clackamas River encompasses relatively permeable Pliocene and Pleistocene lava flows.*

3.0/32.4 Riverside Campground.

0.7/33.1 Junction, Forest Road 63 (Collawash River Road) to right. **Keep left on Road 46.**

Although not part of our trip, the Collawash River Road is the way to Bagby Hot Springs, located about 10 km south of here on the Hot Springs Fork of the Collawash River. The Bagby Hot Springs site is unique among the Western Cascades hot springs for its dilute, high-pH, Na-mixed anion waters and its geographic setting isolated from the Quaternary arc by major drainage divides. Its location, chemical composition, and a relatively low $^3He/^4He$ ratio suggest that Bagby is the product of local, relatively deep circulation. The Na-mixed anion waters are similar to thermal waters associated with granitic rocks of the Idaho batholith (Mariner and others, 1980). Tertiary granitic or dioritic rocks are locally exposed in the Bagby Hot Springs area (Walker and others, 1985) and may be more widespread at depth.

The dilute Bagby Hot Springs water contributes negligible chloride flux to the Clackamas River. Anomalous chloride flux (50 grams per second [g/s]) at the Three Lynx gage downstream from the confluence of the Collawash and Clackamas Rivers is almost entirely from Austin Hot Springs (also about 50 g/s).

## WHAT'S IN A MEGAWATT?

At current U.S. rates of electrical power consumption, one megawatt (MW) is sufficient power for about 1,000 people. The Clackamas River power network creates 170 MW of electrical power ($MW_e$) through its series of 5 dams and 16 generators. In the Pacific Northwest, hydroelectric power supplies about 16,600 $MW_e$ or 74 percent of the average electrical energy use (J.C. King, Northwest Power Planning Council, written, communication, 1992). In contrast, geothermal energy presently is used only for space heating in a few scattered locations. Nationwide, geothermal energy ranks third behind hydroelectric energy and energy from biomass burning in the renewable energy scheme, and these energy sources rank far behind electricity generated from power plants fueled by coal, gas, or nuclear fission. About 2,800 $MW_e$ of electric power generating capacity has been installed since the early 1960s at about 20 geothermal sites in the western United States, and it is projected that 7,000 $MW_e$ of geothermal power will be installed by the year 2010 (Bush, 1992). The Geysers field in northern California is the largest geothermal complex in the United States, producing about 1,500 MW of electricity from 25 operating units. The Geysers field is eminently successful because the wells produce pure steam, whereas other producing geothermal fields commonly yield hot liquid or mixtures of steam and relatively saline liquid.

0.5/33.6 Gabbro sill forms cliffs at left. Its age is known only as younger than the lower Miocene strata that bound it. At this point, we are on the east limb of a broad arch, and our travel eastward begins taking us up through the stratigraphic sequence.

0.5/34.1 This stretch of the Clackamas River is an outdoor biological laboratory. The logs seen spanning the river just below water level have been placed purposely to create riffles, pools, and gravel beds in an attempt to diversify the habitat for fish.

0.2/34.3 Austin slide.

This prehistoric landslide was reactivated after the toe was removed by a 1964 flood. The landslide has obstructed traffic on Road 46 and, at one time, partially dammed the river. Timber was removed from the slide in 1972. Another flood in 1974 caused further erosion and renewed landslide movement. In 1976, after an extensive geotechnical investigation, a large rock fill was placed at the toe to improve slope stability. The rock fill, which is keyed below the slide plane, is 175 m long, 11 m wide, and ranges in height from 16 to 25 m. Total weight of the fill is about 37,000 tons, or about 7 percent of the total weight of the lower part of the slide. The rock fill functions not as a gravity-resisting buttress but as a shear key.

Total cost of the rock fill was approximately $1 million. Periodic monitoring indicates that the rock fill has not moved since its installation in 1976, although some parts of the slide are moving at a rate of 5–7 cm/yr.

1.4/35.7 Road 46 crosses private lands of Austin Hot Springs.

0.6/36.3 **Stop 2—Austin Hot Springs. Stop at east end of area, in view of the main orifice, which is located on south bank of river.** Other springs seep from river bottom. Hot-spring aficionados have built many small, stone-lined pools in the river.

Austin Hot Springs is the largest hot-spring system in the Cascade Range. It discharges 120 liters per second (L/s) of fluid (Table 1) at an orifice temperature of 86°C; heat discharge amounts to 90 $MW_t$ (megawatts of thermal energy), calculated using a geothermometer temperature of 186°C. The heat, if being swept westward by lateral flow from the High Cascades, represents the heat generated by magmatism along 30 km of arc length. Alternatively, the heat could be supplied by a single, large magmatic system, either locally or in the High Cascades.

Like nearly all hot springs in the Western Cascades, Austin is positioned in a canyon floor between 460- and 760 -m (1,500- and 2,500-ft) elevation; its elevation is 510 m (1,680 ft). The springs emerge ~400 m below the top of the Breitenbush Tuff, a widespread sequence of Oligocene and lower Miocene tuff, lapilli tuff, and minor lava flows. These rocks are stratigraphically equivalent to the Little Butte Formation (Peck and others, 1964) elsewhere in the Oregon Cascade Range and to units such as the Skamania Volcanic Series, Ohanapecosh Formation, and Stevens Ridge Formation in Washington. The overlying middle Miocene rocks of the Columbia River Basalt Group are exposed at an elevation of about 850–910 m (2,790–2,990 ft), 370–400 m above us in the canyon walls.

Early visual estimates grossly underestimated the discharge of Austin Hot Springs. For example, U.S. Geological

Table 1. *Chemical composition, geothermometer temperatures, and discharge data for hot springs in the field-trip area (from Ingebritsen and others, 1991). Dashes indicate absence of data. Acidity (pH) in standard units. Temperatures (T) are in degrees Celsius (°C). Concentrations are in milligrams per liter (mg/L) and were determined as follows: cations by inductively coupled plasma; bicarbonate by acid titration; chloride by colorimetry or mercurimetric titration; bromide by ion chromatography; sulfate by turbidimetry; silica by atomic adsorption and molybdate blue*

| | | Ca | Mg | Na | K | $HCO_3$ | Cl | Br | $SO_4$ | $SiO_2$ | $T_d$* | $T_g$** | $Q_t$*** | $^3He/^4He$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Name | pH | (mg/L) | | | | | | | | | (°C) | | (L/s) | $(R/R_a)$**** |
| **Austin** | 7.4 | 35 | 0.10 | 305 | 6.4 | 36 | 390 | 1.2 | 130 | 81 | 86 | 186 | 120±6 | 5.7 |
| **Bagby** | 9.4 | 3.3 | <0.05 | 53 | 0.7 | 69 | 14 | — | 42 | 74 | 58 | 52 | 1 | 1.2 |
| **Breitenbush** | 7.0 | 95 | 1.1 | 745 | 31 | 137 | 1,200 | 4.2 | 140 | 163 | 84 | 174 | 13±2 | 6.5 |
| **McKenzie River Group** | | | | | | | | | | | | | | |
| Bigelow | 7.8 | 195 | 0.53 | 675 | 15 | 22 | 1,250 | 3.8 | 140 | 73 | 59 | 155 | | — |
| Belknap | 7.6 | 210 | 0.34 | 660 | 15 | 20 | 1,200 | 3.9 | 150 | 91 | 73 | 152 | 20±3 | — |
| Foley | 8.0 | 510 | 0.08 | 555 | 8.7 | 20 | 1,350 | 4.0 | 510 | 63 | 79 | 100 | 11±4 | — |
| Terwilliger | 8.5 | 215 | 0.07 | 405 | 6.1 | 21 | 790 | 2.2 | 240 | 47 | 46 | 135 | 5 | — |
| **Kahneeta** | 8.1 | 13 | 0.05 | 400 | 11 | 603 | 240 | 0.8 | 31 | 78 | 83 | 137 | 50±5 | — |

* Discharge temperature.

** Chemical geothermometer temperatures based on anhydrite saturation except for Kahneeta and Bagby, which are based on silica (quartz) and cation geothermometers. Solubility of anhydrite ($CaSO_4$) provides a geothermometer indicating maximum temperature (Ellis and Mahon, 1977). Anhydrite saturation values for the Na-Cl and Na-Ca-Cl waters that discharge in the Western Cascades correlate well with sulfate-water isotope temperatures (Mariner and others, 1993). Temperatures listed for Kahneeta and Bagby are averages of the quartz and cation geothermometers. These and other geothermometers are discussed by Fournier (1981).

*** Discharge ($Q_t$) based on chloride-flux measurements except for Bagby Hot Springs, where discharge was measured directly.

**** Isotopic ratio of $^3He$ to $^4He$ reported as the measured ratio (R) normalized by atmospheric ratio ($R_a$).

## KEY OBSERVATIONS AND POSSIBLE INTERPRETATIONS OF THE AUSTIN HOT SPRINGS SYSTEM

| Observation | Interpretation |
|---|---|
| High heat discharge (90 $MW_t$) | Capture of regional heat flow over large lateral-flow area (100 $mW/m^2$ over 900 $km^2$) and (or) lateral flow from a known magmatic heat source (for example, the Mount Jefferson area); alternatively, a local magmatic heat source with no surface expression |
| Isotopically depleted with respect to local meteoric water | Holocene recharge at a relatively high elevation (about 1,500 m) or alternatively, local recharge during colder times (glacial epochs) of the Pleistocene (more than 10,000 years ago). Pleistocene recharge unlikely if current discharge rate (120 L/s) is typical for the system |
| High $^3He/^4He$ ratio (5.7 times atmospheric ratio) | Input of magmatic $^3He$, either from localized magmatic sources or from beneath the High Cascades |
| Elevated Cl content (390 mg/L) | May indicate Cl leached from marine rocks below the volcanic arc. Chlorine content of these and similar waters correlates with $^{15}N$ content (R.H. Mariner, written communication, 1992). Iodine-129 in Na-Ca-Cl waters to the south indicates an Eocene-age source |
| No $CaCl_2$ component | May indicate relatively little water-rock interaction (owing to relatively short residence time?). In Austin Hot Springs waters, Cl is ionically balanced by Na. In other NaCl hot-spring waters of the Western Cascades, a $CaCl_2$ component is present, perhaps derived from the albitization of plagioclase |
| Relatively low $SiO_2$ (like most Na-Cl and Na-Ca-Cl hot springs in the Cascade Range). Geothermometer temperatures $T_{K\text{-}Mg}$ (118°C) and $T_{quartz}$ (126°C) much lower than $T_{SO4\text{-}H2O}$ (186°C) and $T_{anhydrite}$ (188°C) | Probably indicates appreciable water-rock reaction in a long outflow structure. $T_{K\text{-}Mg}$ and $T_{quartz}$ indicate temperatures in the outflow structure. $T_{SO4\text{-}H2O}$ and $T_{anhydrite}$ indicate maximum system temperatures at considerable distance from the hot springs (R.H. Mariner, written communication, 1992) |

Survey (USGS) Circular 790 (Brook and others, 1979) cites a value of 16 L/s. More recent measurements, using the solute inventory method, indicate discharge of 120±6 L/s (six sets of measurements from 1984 to 1989; see Figure 6). The solute inventory method measures downstream increases in Na and Cl loads of streams and has proven reliable for the Cascade Range because most of its thermal waters are rich in Na and Cl, whereas the streams are generally very dilute (Mariner and others, 1990). Visual estimates of hot-spring flow rates fail to measure diffuse discharge or multiple orifices that leak directly into streams.

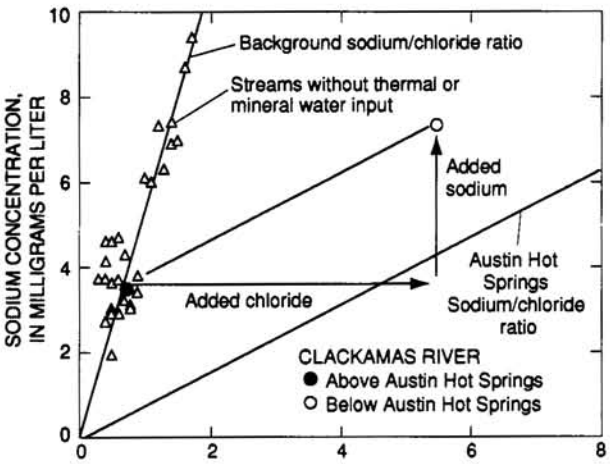



*Figure 6. Example showing how hot-spring discharge is calculated by a solute-flux method. Discharge of Clackamas River was 9,400 L/s; hot-spring discharge was 120 L/s determined by Na increase, 120 L/s determined by Cl increase (from Ingebritsen and others, 1991).*

The signs posted in this area to warn of scalding temperatures are a result of people's trespassing to the orifice, badly burning themselves, and then seeking legal redress by suing the landowner. A limited population of thermophilic algae and perhaps some bacterial organisms live in the orifice of Austin Hot Springs.

**Resume travel eastward on Road 46.**

2.5/38.8 Dating locale, 13-Ma andesite. The Columbia River Basalt Group has pinched out and is absent south of here, so we ascend through the stratigraphic sequence without seeing it. (It would crop out about here.)

4.7/43.5 Hydrothermally altered hornblende dacite (middle or upper Miocene) in road cut on left.

0.6/44.1 Bridge on right, Road 4650.

0.2/44.3 Junction, Road 4660 to left. **Continue ahead (right) on the main highway**. Road enters Big Bottom area of the Clackamas River. This is the western limit of late Pleistocene glacial advances, and the river floodplain broadens upstream as a consequence.

Rhododendron becomes a common shrub upslope beginning at about this elevation. Rhododendron seems to like coarser textured soils and soils with low nitrogen levels, both of which characterize the middle-elevation slopes in the snow zone of the Cascades. A well-developed understory of rhododendron is a nightmare to anyone conducting traverses through the woods. Surprisingly, rhododendron diminishes abruptly in the Cascades near the Columbia River and is nearly absent northward in Washington to about the Nisqually River on the west side of Mount Rainier.

3.1/47.4 Junction, Road 42 (Skyline Road) to left. **Continue ahead on main highway**. The road proceeds on Pleistocene outwash gravel that forms several terrace levels; the active Clackamas River floodplain is nested among these terrace deposits.

5.8/53.2 Bridge over Clackamas River.

1.1/54.3 Junction, Road 4690 (to Olallie Lake) on left. **Continue ahead**.

Olallie Lake is one of many lakes in the glacially scoured lavas of the High Cascades north of Mount Jefferson. It shares its name with Olallie Butte, a late Pleistocene basaltic andesite shield volcano. The lake is a popular summer fishing area with rustic setting. In winter, Olallie Lake Resort boasts excellent cross-country skiing. Guests and their equipment are transported to the snowbound lake by Sno-Cat.

0.8/55.1 **Stop 3—Clackamas-Breitenbush divide**.

If the weather is clear, attention turns quickly to the dramatic views of Mount Jefferson and several silicic domes that dominate the skyline southeast at the headwaters of the North Fork Breitenbush River. Our present knowledge of the Mount Jefferson area comes from mapping and geochemical study by Richard M. Conrey during the 1980s (Conrey, 1991). Mount Jefferson is a composite volcano built mainly in the last 100,000 years. Main-cone silicic andesite lava (62-63 percent $SiO_2$) sits atop an older mafic andesite volcano (57–58 percent $SiO_2$), and as many as six volcanoes can be distinguished within the entire edifice. Age of oldest lava ascribed to the eruption of Mount Jefferson proper is about 280 ka (see also age of 290±170 ka reported by Priest and others, 1987). The bulk of the cone, however, is composed of units emplaced about 70 ka.

Although an earlier interpretation held that Mount Jefferson was an isolated andesitic cone built entirely upon a basaltic field (Sutton, 1974; McBirney and White, 1982), Conrey's exhaustive mapping and more than 600 chemical analyses indicate that Mount Jefferson is part of a much larger, long-lived field of chiefly Quaternary andesite and dacite (Figure 7). Dacite and rhyodacite domes form the prominent bulbous hills visible in the middle distance; most high-temperature hydrothermal systems worldwide are related to Quaternary silicic rocks like these. Silicic volcanic rocks are probably erupted from upper-crustal storage chambers, whereas mafic volcanic rocks commonly arise from deeper rooted, more diffuse magmatic systems (Figure 8). The Cascade Range has one of the lowest extrusion rates for volcanic arcs worldwide, 3–6 $km^3/km/m.y.$ (Sherrod and Smith, 1990), and the magmatic systems that supply most

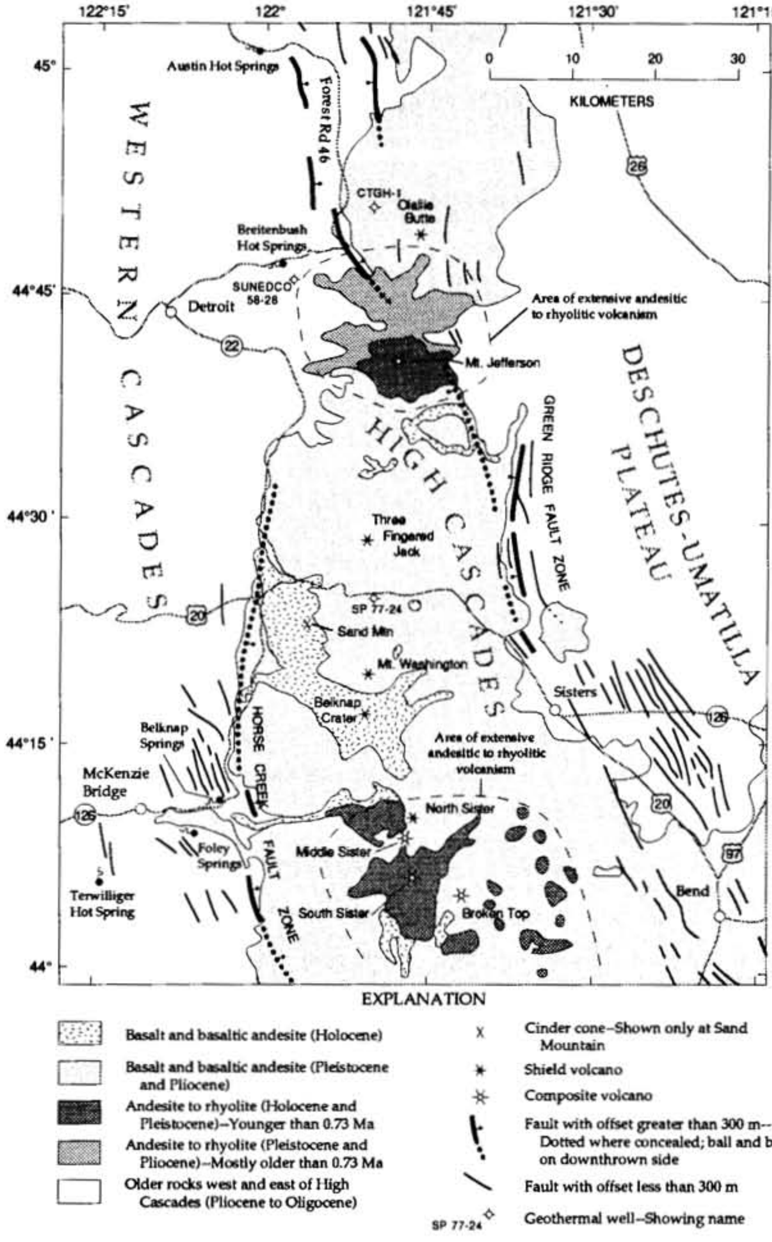



*Figure 7. Distribution of Quaternary mafic rocks (basalt and basaltic andesite) and andesitic to rhyolitic rocks in the High Cascades (generalized from Sherrod and Smith, 1989). Note similar size of the andesitic to rhyolitic fields in the Mount Jefferson and Three Sisters areas. Figure 8 compares probable magmatic systems associated with mafic and andesitic to rhyolitic volcanism.*

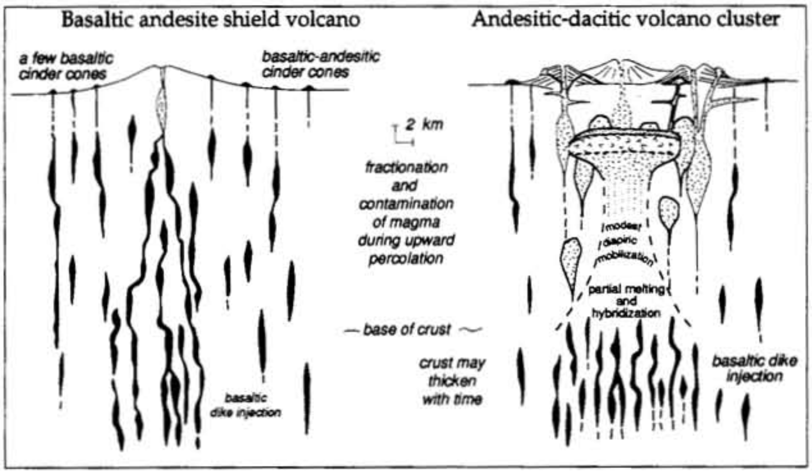



*Figure 8. Contrasting volcano-structural setting of mafic shield volcano and andesitic-dacitic volcano cluster (from Hildreth, 1981).*

Cascade mafic shield volcanoes are probably insufficient to focus heat and create an economic geothermal resource potential. In contrast, the longer lived Quaternary andesitic-dacitic volcano cluster and its associated crustal melting and magma storage are capable of sustaining a hydrothermal system of economic proportion (Smith and Shaw, 1975).

From this stop, we can view the pronounced physiographic differences between Western and High Cascades. Eastward, the High Cascades form a broad ridge with gentle slopes. Volcanic construction has kept pace with erosion in most areas; strata are late Pliocene and younger in age. Nearly every circular hill is a vent of some kind (cinder cone, dome, shield volcano, composite volcano), and many vents are younger than 0.73 Ma (formed in Brunhes Normal-Polarity Chron). Westward, the Western Cascades form a moderately incised terrane with steep slopes (commonly 70-percent slopes, as any Western Cascades field geologist will quickly point out). Lower Pliocene basalt flows cap several of the rudely concordant ridge tops near the margin with the High Cascades, and underlying strata are volcanogenic in origin and Oligocene or Miocene in age. Canyon cutting has occurred in the last 3 million years, and most of the canyons had their present form (and two-thirds or more of their depth) by 2 Ma.

This physiographic divide is a good place to ponder the location of heat sources and origin of hot springs in the Western Cascades (Breitenbush Hot Springs is 7 km west in valley floor of the Breitenbush River). The High Cascades physiographic subprovince, which terminates the orographic slope, forms a broad catchment area for precipitation. Rates of groundwater recharge are high; as much as 50 percent of precipitation infiltrates to recharge groundwater systems (Figure 5 and discussion at milepoint 29.4 apply equally here). Groundwater recharge in the Western Cascades, where rocks are older and less permeable, generally amounts to between 1 and 10 percent of precipitation. Groundwater moves along hydraulic gradients into the Western Cascades, some of it going deep enough to be heated by magmatic sources in the High Cascades and to reappear at hot springs in the Western Cascades. Total hot-spring discharge in the Western Cascades is less than 0.2 percent of inferred groundwater recharge in the High Cascades (Ingebritsen and others, 1991). Breitenbush Hot Springs is readily explained by lateral flow of water heated in the Mount Jefferson area. In contrast, Austin Hot Springs, located 25 km north-northwest of here (41 km from Mount Jefferson), is separated from Mount Jefferson by this major topographic divide. Its hydraulic connection to the Mount Jefferson area is more tenuous.

Perhaps the single feature common to hot springs of the Western Cascades is their location at the bottom of major stream valleys and between elevations of 460 and 760 m (1,500 and 2,500 ft) (Figure 9). Stratigraphic and structural controls are more difficult to define. Most hot springs in the Western Cascades are located near the top of a widespread sequence of altered tuff and tuffaceous strata of Oligocene to Miocene age, which suggests some stratigraphic control resulting from permeability contrasts. The McKenzie River group of springs, however, is in relatively permeable middle Miocene lava flows. Structural control by major faults seemingly applies to several hot springs, notably the McKenzie River group, but the majority of springs are at some distance from major faults.

**Resume southerly travel on Road 46** into the valley of the Breitenbush River. Long downgrade ahead. Power lines overhead were installed by Bonneville Power Administration in the 1950s to bring power into western Oregon from the Columbia River power network.

4.9/60.0 Road 4685 to left. **Stay on Road 46.**

Road parallels a stretch of the Breitenbush River (on left or south in woods) that was reamed out by floods of 1964. At that time, it was thought that large logs in the stream acted as battering rams to speed streambank destruction; therefore logs were removed. Forest practice has changed since 1979, and now logs are maintained in the streams for habitat (see milepoint 34.1 for example). Downstream log migration is monitored in this stretch of the Breitenbush River to better understand the interactive processes of downed vegetation and stream flow (G.E. Grant, USFS, written communication, 1989).

Road 46 is a proposed scenic byway, part of a USFS program to engender economic diversity and tourism by promoting passenger-car travel along the more accessible and paved parts of the logging road network. Another part of

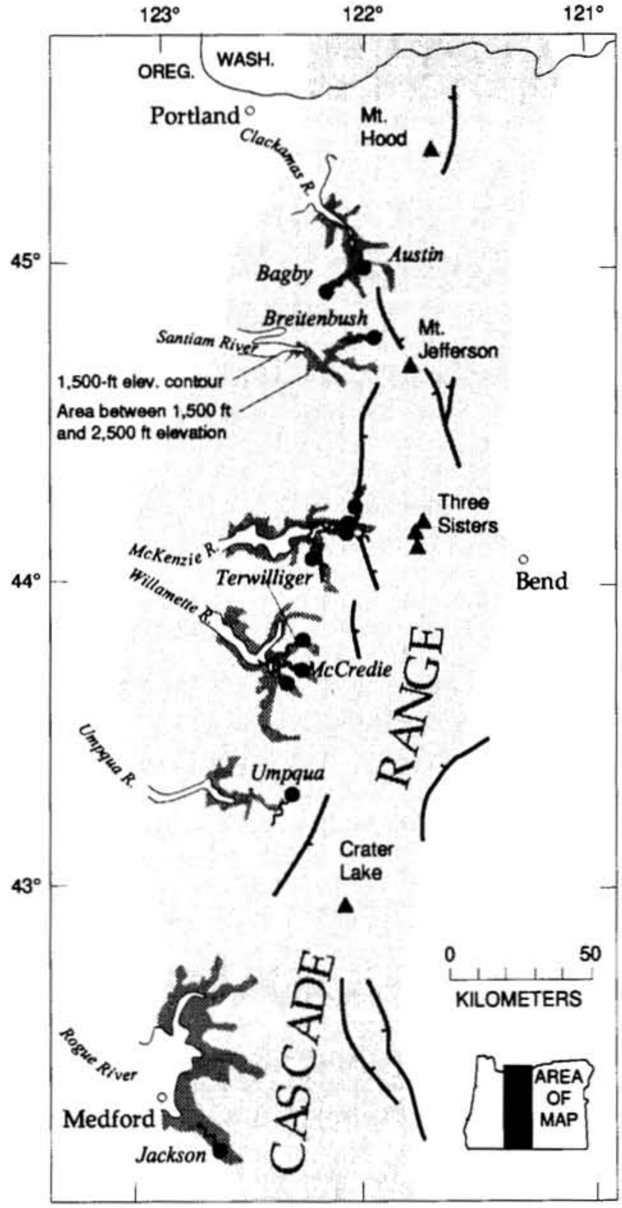



*Figure 9. Hot springs in Western Cascades of Oregon lie between 1,500-ft and 2,500-ft elevation, with exception of Umpqua Hot Springs (2,650 ft). Dark shading shows areas in major stream drainages bounded by 1,500- and 2,500-ft contours. Major faults shown by bold line; tick on downthrown side (from Sherrod and Smith, 1989).*

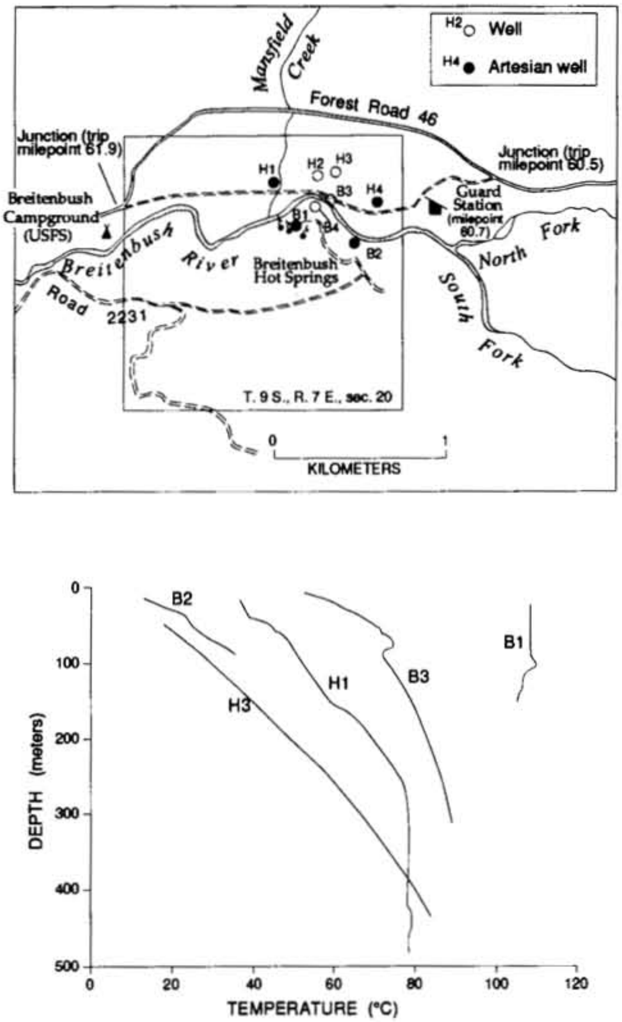



*Figure 10. Temperature profiles for Breitenbush Hot Springs area; data from Ingebritsen and others (1988).*

the program will display new perspectives in forest practices through the use of numbered stops and printed road guides.

0.5/60.5 **Obscure junction, be alert. Turn left** from pavement onto dirt Road 4600-050. This road passes near Breitenbush Hot Springs before reconnecting with main road.

0.2/60.7 Breitenbush Guard Station (USFS). The station was built in 1935 and is now listed on the National Register of Historic Places. A fire-prevention technician lives on-site during fire season from June until autumn rains have begun in earnest.

0.2/60.9 Artesian well north of road (H4 on Figure 10) can produce 20–40 L/s, which is double or triple the output of nearby Breitenbush Hot Springs (10–11 L/s). Water from the well, about 85°C, is chemically similar to Breitenbush thermal waters.

0.2/61.1 Breitenbush Hot Springs and Breitenbush Community, a spiritual conference center, across river. We will pause long enough to glimpse the setting but will not stop here out of courtesy to landowners, instead discussing the hot springs while at Stop 4.

0.8/61.9 Dirt road rejoins pavement (Road 46) near Breitenbush Campground. **Continue straight ahead on pavement.**

0.7/62.6 Cleator Bend. Outcrops of altered pumiceous tuff, whose pale-grayish-green colors result from celadonite, a K-Fe illite-structured clay mineral formed by alteration of glass.

This unit, known as the Cleator Bend Tuff of Hammond and others (1982) or part of the quartz-bearing tuff in the Breitenbush Tuff of Priest and others (1987), has a plagioclase K-Ar age of 20.3±0.2 Ma (Sutter, 1978; sample DMS-43 recalculated, using new decay constants). This age may be too young, inasmuch as overlying rocks in this area have ages as old as 24.9±0.3 Ma (see Priest and others, 1987, for summary).

0.9/63.5 **Stop 4—Quarry in quartz-bearing ash-flow tuff.**

This tuff is one of many small- to moderate-volume ash-flow tuffs (a few tens of cubic kilometers) found in the Cascade Range. It is rhyolitic in composition (72.6 percent $SiO_2$, recalculated water-free) (White, 1980, sample BX-102) and contains abundant plagioclase crystals and lithic and pumice fragments. Quartz crystals are locally abundant in the tuff, and altered ferromagnesian crystals, probably originally orthopyroxene and clinopyroxene, are present in minor amounts throughout. Ash-flow tuffs in the Oregon Cascade Range generally lack quartz as a phenocryst phase; sanidine is always absent, and biotite is found only in rare instances.

Hydrothermal alteration is pervasive in this tuff, with the once-glassy pumiceous lapilli and matrix replaced by zeolite (mainly mordenite and heulandite) and clay minerals (celadonite and smectite). This mineralogy indicates alteration temperatures between 90°C and 150°C (Figure 11). The nearly isochemical alteration of glass in the tuff has reduced pore volume and interstitial permeability. Thin veinlets of celadonite, zeolite, opal, and (or) calcite occur locally. A K-Ar celadonite age of 17–18 Ma was recently obtained from the Cleator Bend sample locality (milepoint 62.6), and an age of about 20.5 Ma was obtained from fine-grained illite in silicified tuff on Boulder Ridge, 8.5 km southwest from here (M. Shafiqullah and T. Keith, unpublished data, 1992). Thus, the zeolite-clay alteration greatly predates the present hydrothermal system.

This quartz-bearing tuff is exposed near the orifices at Breitenbush Hot Springs and is believed to be the same unit that hosts a thermal aquifer at the depth from 752 to 782 m in the SUNEDCO 58–28 drill hole south of the hot springs (Priest and others, 1987). The 115°C of measured temperature in the SUNEDCO thermal aquifer and the projected bottom-hole temperature of approximately 140°C are too low to modify the previously developed zeolite-clay alteration. Fluid-inclusion homogenization temperatures measured from late-formed calcite and anhydrite in the SUNEDCO drill cuttings are generally within 15°C of measured temperatures except in the thermal aquifer, where homogenization temperatures in calcite are all hotter than

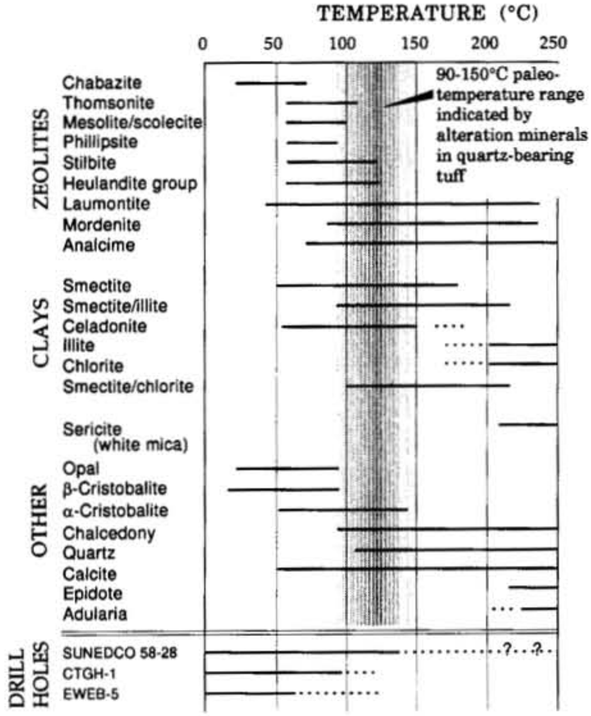



*Figure 11. Selected hydrothermal minerals found in Breitenbush-Austin Hot Springs area plotted against temperatures of occurrence in well-defined active geothermal systems. Dashed lines indicate uncertain temperature range. Shown at bottom are inferred maximum temperature ranges for three drill holes from this part of Cascade Range; present maximum temperature (measured) shown by solid line, and past possible maximum temperature (inferred from alteration mineralogy) shown by dashed line. Gray shading shows paleotemperature indicated by alteration minerals in quartz-bearing tuff of Stop 4. Figure modified from Keith (1988); see that reference for sources of mineralogical information.*

measured temperatures and reach as much as 150°C (K.E. Bargar, USGS, oral communication, 1992).

Why this particular ash-flow tuff would serve as a thermal aquifer remains unclear, inasmuch as similar, stratigraphically adjacent tuff layers are not aquifers. Primary permeability of partially to moderately welded tuff is low (Winograd, 1971), and the alteration seen here further reduces primary permeability. Secondary permeability owing to fracturing may enhance water-carrying capacity of the unit.

In general terms, rock fracturability and secondary permeability are enhanced by higher temperature minerals (>200°C), which are anhydrous (quartz, epidote) or nearly so (chlorite, actinolite, or biotite) relative to lower temperature minerals (zeolites, clays). Pervasive alteration to higher temperature minerals results in rock that is hard, brittle, and more readily fractured than rock from lower temperature minerals, which tends to tear and compress rather than fracture cleanly. Rocks that have undergone high-temperature alteration tend to sustain open fractures. Those fractures, however, can be filled subsequently by secondary minerals precipitating from fluids.

Fracturing is spatially variable in this quartz-bearing ash-flow tuff because of variable alteration. At the quarry of Stop 4, alteration of glass is complete, and pore spaces are filled. Much of the tuff contains open vertical fractures suitable for sustaining an aquifer. A short distance away on either side of the quarry exposure, however, the same tuff is more pumiceous, contains open pore spaces, and is much softer than the quarry rock.

The Breitenbush Hot Springs lie within an electrically conductive zone, identified from telluric data, that comprises either two linear, electrically conductive structures (Figure 12) or curvilinear intertwined structures that splay and converge along a broadly northeast trend (H. Pierce and colleagues, USGS, written communication, 1989). The conductive zone also encompasses two unusual low-discharge $Na\text{-}HCO_3$ mineral springs. The conductive zone may represent fractures that channel thermal water to the surface or a relatively impermeable barrier that blocks lateral movement of thermal water (Ingebritsen and others, 1992). The 100°C isotherm, whose broad upwarp in the Breitenbush area may be further evidence for a stratigraphically controlled thermal aquifer, deepens abruptly northwest of the conductive zone (Figure 12).

A 6- to 7-km-deep integrated-finite-difference grid (Figure 13) was used to simulate groundwater flow and heat transport in the Breitenbush section (Figure 14) (Ingebritsen and others, 1992). Simulations using only conductive heating, with either narrow or wide basal heat-flow anomalies, failed to reproduce the low, near-surface conductive anomaly in the Quaternary arc or the elevated heat flow between Breitenbush Hot Springs and the Quaternary arc: some permeability is required. We simulated a 1-km-wide section of arc length. With appropriate permeability, most of the groundwater recharged in the Quaternary arc (303 kg/s) discharges locally in topographic lows (301 kg/s) but carries little heat. Simulated discharge in the Breitenbush Hot Springs area (~1 kg/s) is a small fraction of total recharge in the Quaternary arc, but this relatively small mass flux transports substantial amounts of heat from the Quaternary arc to the Western Cascades. Using the permeability values shown in Figure 13, the ratio of hot-spring discharge to recharge in the Quaternary arc (0.003) is similar to the ratio (0.002) estimated from measured groundwater recharge and hot-spring discharge rates (Ingebritsen and others, 1992).

0.2/63.7 View upslope ahead (across Breitenbush River) of area burned in the 1967 Eagle Rock fire. That fire began after a several-year drought period.

0.9/64.6 Eagle Rock, on left at 11:00 o'clock, is a tholeiitic basalt plug (White, 1980; Priest and others, 1987).

2.5/67.1 Junction, Road 4696 to right, Humbug Creek Campground on left. **Continue ahead toward Detroit.**

View ahead of rocky bluff at skyline is area of Canyon Creek fire, another major fire of the 1960s. The blocky lava flows that form the rimrock were erupted from the Battle Ax shield volcano, one of the few Quaternary volcanoes in the Western Cascades physiographic subprovince. Battle Ax volcano was active some time between 0.73 and 2.4 Ma (Matuyama Reversed-Polarity Chron) (White, 1980). Youngest lava is reversely polarized. Potassium-argon ages range from 1.2 to 1.8 Ma but are poorly constrained owing to low contents of radiogenic argon. Most lava issued from a vent complex near Battle Ax Mountain (White, 1980).

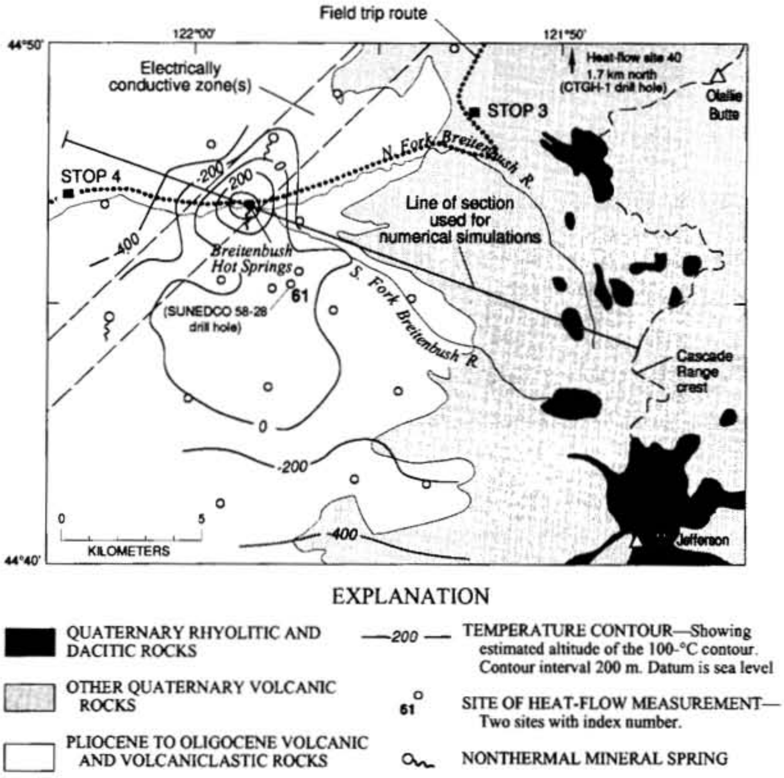
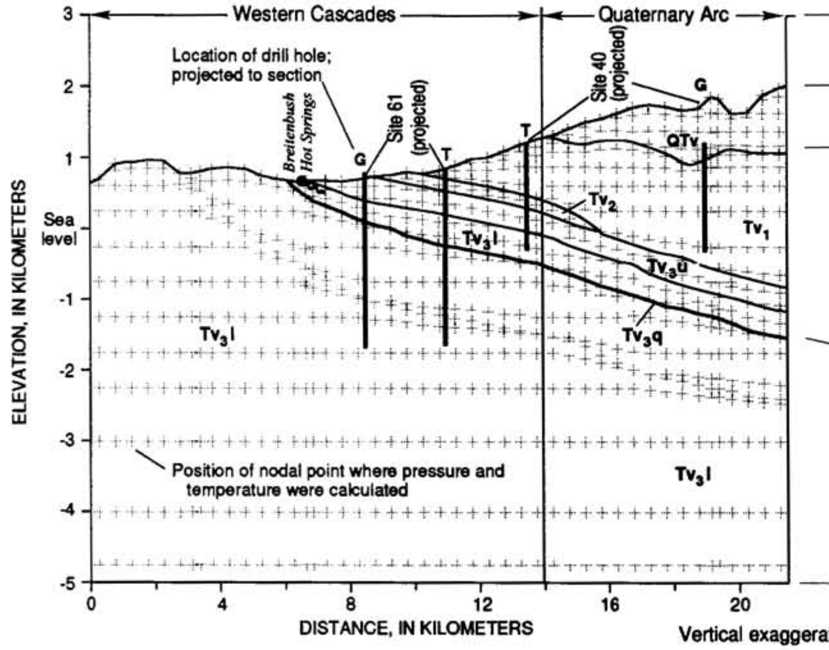



*Figure 12. Map of Breitenbush Hot Springs area showing line of section used in numerical simulations, electrically conductive structures identified by H. Pierce and colleagues (written communication, 1989), and estimated elevation of the 100°C isotherm. Geologic data from Priest and others (1987) and from D.R. Sherrod and R.M. Conrey (unpublished data, 1988). This figure appeared originally in Ingebritsen and others (1991, 1992).*




| LITHOLOGY AND AGE | PERMEABILITY ($m^2$) | POROSITY |
|---|---|---|
| QTv: Chiefly lava flows and domes; < 2.3 Ma | $1.0 \times 10^{-14}$ | 0.15 |
| $Tv_1$: Chiefly lava flows; 4-8 Ma | $5.0 \times 10^{-16}$ | 0.10 |
| $Tv_2$: Lava flows; 8-13 Ma | $1.0 \times 10^{-16}$ | 0.05 |
| $Tv_3u$: Volcanic and volcaniclastic strata; 18-25 Ma | $Tv_3u$: $5.0 \times 10^{-17}$<br>$Tv_3l$: $1.0 \times 10^{-17}$ | 0.05 |
| $Tv_3q$: Quartz-bearing tuff | $2.5 \times 10^{-14}$ | 0.02 |
| $Tv_3l$: Volcanic and volcaniclastic strata; 18-25 Ma | $Tv_3l$: $1.0 \times 10^{-17}$ | 0.05 |

Vertical exaggeration approximately x2

*Figure 13. Cross section used for numerical simulation of the Breitenbush Hot Springs system (from Ingebritsen and others, 1992). Heat-flow site 40 (drill hole CTGH–1) and site 61 (hole SUNEDCO 58–28), which lie off the section (Figure 12), are projected in two different ways to indicate their appropriate contexts: G = geologic projection locating the holes relative to stratigraphic contacts; T = topographic projection putting the collar elevation at land surface.*

4.5/71.6 Junction, U.S. Highway 22, town of Detroit. **Turn right (west) for side trip** (Stop 5) to view propylitic alteration and shallow plutonic rocks.

1.5/73.1 Ranger Station, Detroit Ranger district, on right. On left is Detroit Lake, a reservoir completed in 1953 by the U.S. Army Corps of Engineers.

The Detroit Lake project was designed chiefly for controlling runoff and providing flood control. Total electrical generating capacity is 118 MW, with most of that (100 MW) coming from the two generator units in Detroit Dam. Big Cliff Dam, a reregulating dam placed below Detroit Dam to control daily downriver variations in stream flow, has a single generator capable of producing 18 MW.

5.8/78.9 Detroit Dam. **Turn left onto road that crosses dam**. The prominent double notch in the road cut (well above road level and visible from a distance) was introduced during dam construction to provide a base for the aerial tracks that carried the concrete bucket. The straight-faced dam (no joking) fills slots cut into bedrock abutments.

0.3/79.2 Road turns left (southeast on south side of dam). This is Forest Road 2212; **continue ahead**.

0.1/79.3 Small turnaround area marked by pavement paint. **Park near here** and walk south ~30 m farther along road to road cut above the Cumley Creek arm of Detroit Lake.

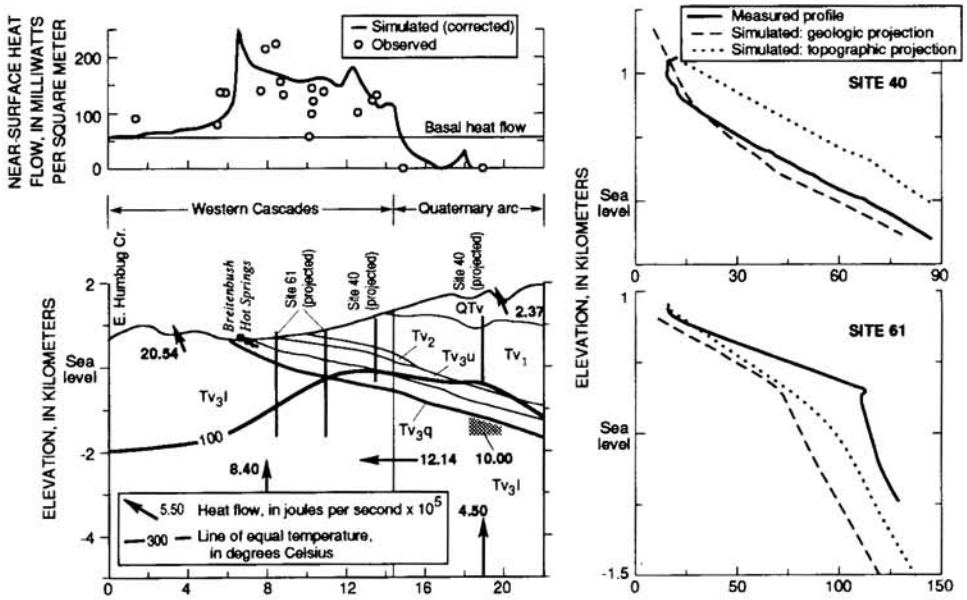
**Stop 5—Intrusive phases of the Detroit stock.**

Road cut exposes four intrusive phases of the Detroit stock, a composite intrusion covering about 9 $km^2$ (Figure 15). Lithologic features and alteration seen at this stop are characteristic of the small intrusive masses associated with hydrothermal mineralization in the Western Cascades of Oregon. Fine-grained quartz diorite is the earliest, most widespread phase. Cutting it are coarser grained, lighter colored rocks such as hornblende-bearing quartz diorite and hornblende granodiorite. The hornblende granodiorite contains visible quartz. Porphyritic andesite, thought related to the stock, forms a dike at the northwest end of the road cut. Sparse tonalitic aplite veins cut all rocks. Chemical analyses from the stock are listed in Table 2; modal analyses are shown in Figure 16.

The Detroit stock has a whole-rock K-Ar age of 9.94±0.18 Ma (Sutter, 1978; recalculated using new decay constants), but the rocks are altered, and the age may be too young. Intrusions in the Western Cascades range in age from 22 to 8 Ma (Bikerman, 1970; Sutter, 1978; Power and others, 1981; Keith and others, 1985).

Potassic alteration is indicated by hydrothermal biotite, which forms pseudomorphs after hornblende and pyroxene, especially in the hornblende granodiorite. Other minerals in the potassic assemblage of the Detroit stock are magnetite, potassium feldspar, pyrite, and chalcopyrite (Curless

*A. Advective model, with a localized heat source in Quaternary arc*




*B. Advective model, with a wider, more intense deep heat-flow anomaly*

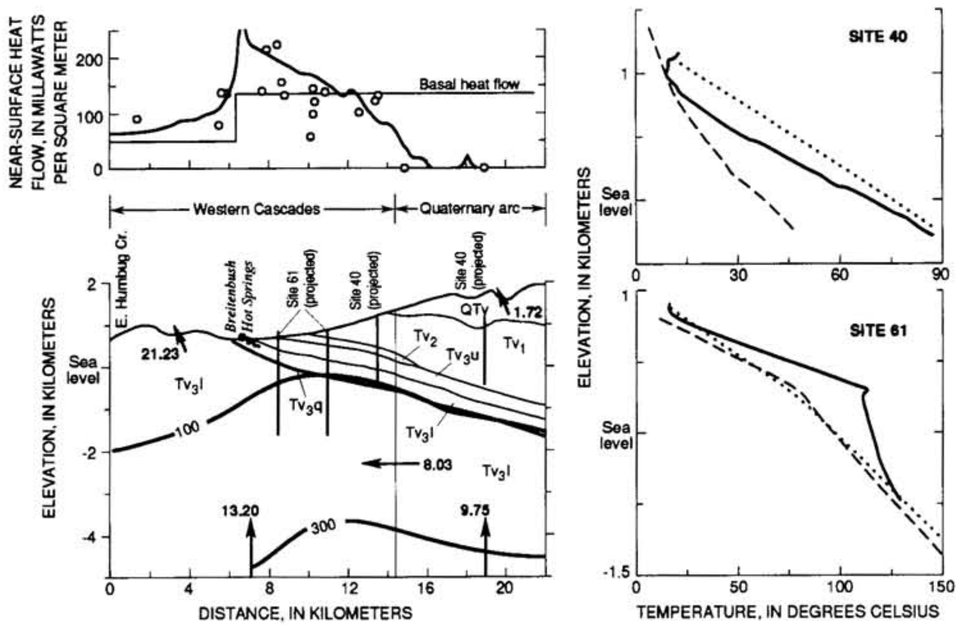



*Figure 14. Numerical simulations for area of Breitenbush Hot Springs, showing that the thermal observations can be produced reasonably well with two very different deep thermal structures (from Ingebritsen and others, 1992): A, advective model with localized heat source in Quaternary arc, which corresponds to lateral-flow model (Ingebritsen and others, 1989, 1992). B, advective model with a wider, more intense deep heat-flow anomaly, which corresponds to the midcrustal heat source model (Blackwell and others, 1982, 1990). Map-unit symbols same as for Figure 13.*

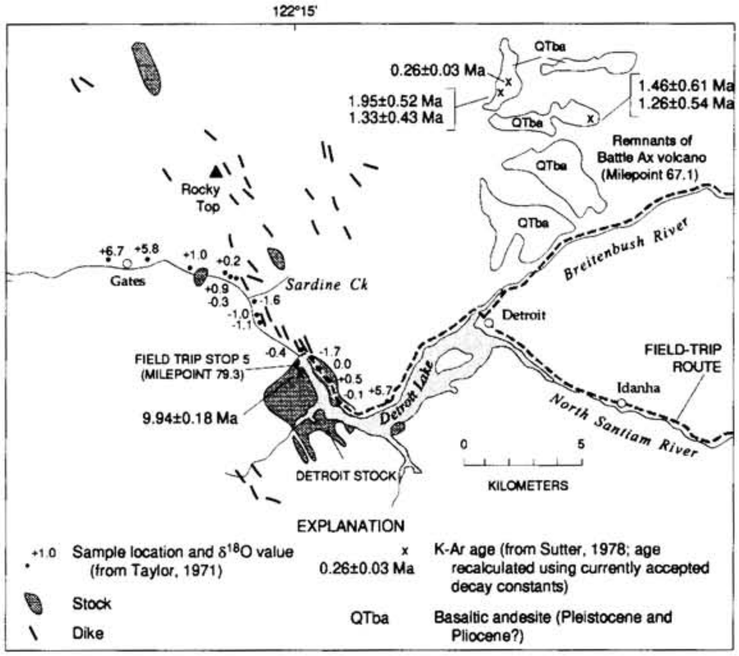



*Figure 15. Detroit stock and pattern of oxygen-isotope depletion. Geologic data from Pungrassami (1970), Walker and Duncan (1989), and Curless (1991); isotope data from Taylor (1971).*

and others, 1989, 1990). Potassium silicate selvages associated with quartz-magnetite veinlets may be as wide as 2 cm but locally coalesce to form zones of pervasive wall-rock alteration. Magnetite is the dominant opaque mineral; it is present as disseminated crystals in the groundmass, as intergrowths with secondary biotite, and in quartz veinlets. Pyrite and to a lesser extent chalcopyrite are also present in veinlets and as widespread disseminations. Potassic alteration grades outward into weak propylitic alteration, with weak sericitic alteration of plagioclase phenocrysts and hornblende phenocrysts surrounded by reaction rims of chlorite and magnetite. The rocks here are propylitized, characterized by a secondary mineral assemblage of epidote + chlorite + quartz + sericite ± calcite ± albite ± hematite ± pyrite. Veinlets of magnetite-quartz and epidote-quartz cut all rocks. Late-stage sericitic and argillic alteration are structurally controlled and overprint earlier alteration with sericitization of secondary K-feldspar and chloritization of secondary biotite.

Oxygen isotope values are lowered in the vicinity of the Detroit stock, owing to exchange with meteoric water during hydrothermal circulation (Taylor, 1971). Samples from a traverse along Highway 22 at the north edge of the stock shows $\delta^{18}O$ values as low as −1.7 per mil (Figure 15); whereas unaltered intermediate plutonic and volcanic rocks commonly have values ranging from +6 to +8 per mil. These data correlate poorly with early depictions of northeast-trending regional propylitic alteration and a broad syncline (Peck and others, 1964), which had been based on rapid reconnaissance work. Subsequent mapping and isotopic dating have challenged the theorized northeast-trending syncline (Walker and Duncan, 1989; Curless, 1991), but the accurate depiction of regional alteration surrounding the Detroit stock remains undetermined.

A 5-km-wide zone of dikes and faults extends northwest from the Detroit stock through Rocky Top (Figure 15). Intrusive rocks within the adjacent Sardine Creek and Rocky Top areas have mineralogical, textural, and chemical features similar to the Detroit stock. The main stocklike bodies of hornblende granodiorite were emplaced at a minimum depth of 1 km, whereas older quartz diorite may have been emplaced as shallow as 500 m, depending on the thickness of coeval middle or late Miocene volcanic rocks at the time of emplacement. (Elevation at the base of the volcanic sequence is ~1,350 m, whereas granodiorite stocks are as high as 480 m, and quartz diorite is as high as 1,000 m.) Dikes of coarse-grained intrusive rocks were emplaced at even shallower depths.

Mineralized samples from Detroit Dam to Rocky Top are zoned with respect to copper, lead, and zinc. The samples display a trend from Cu-rich porphyry- and breccia-type mineralization at Detroit Dam to Pb-Zn vein-type mineralization at Rocky Top. The trend is probably related to lateral and vertical distance from the Detroit stock (Curless, 1991). Most mining districts in the Western Cascades were developed in vein deposits and are located

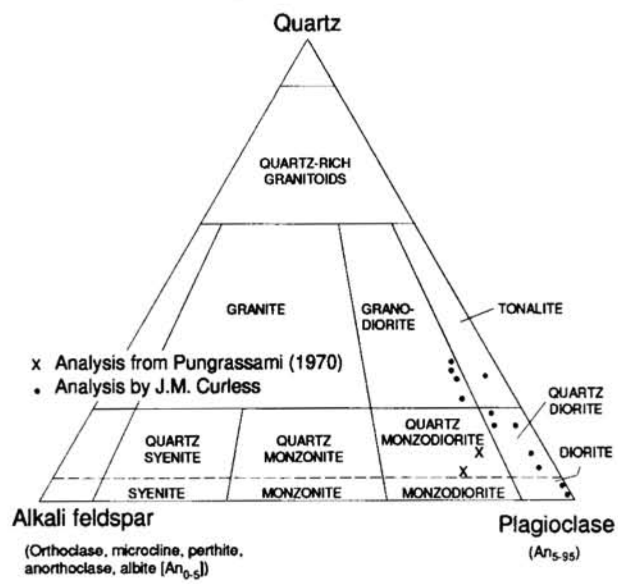



*Figure 16. Classification of plutonic rocks from Detroit stock (after Streckeisen, 1976). Modal analyses from Pungrassami (1970) and Curless (unpublished data, 1991).*

from 600 to 1,000 m higher on ridges than the associated intrusive masses exposed in adjacent canyon floors.

**Return to cars and retrace route across dam**. View to northwest from dam is toward the Rocky Top area of the Western Cascades; see Curless (1991, section A-A') for cross section corresponding to this view. **Turn right (east) onto State Highway 22 after crossing dam**. Route continues east toward Detroit, Oregon.

5.4/84.7 View of Mount Jefferson to right (east) across Detroit Lake.

2.1/86.8 Detroit. **Continue east on main highway**. Last auto services until Sisters, Oregon (55 mi).

4.1/90.9 Idanha town limit.

Idanha probably originated as the upstream terminus of the Corvallis and Eastern Railroad, a railroad started in the late 1800s to connect the Oregon coast with rail lines near the Idaho border at Ontario, Oreg. Tracks were laid from Toledo (near Newport, central Oregon coast) through Albany in the Willamette Valley and into the North Santiam River valley as far as here (Mills, 1950).

Table 2. *Major- and trace-element analyses of plutonic rocks from the Detroit stock (Curless 1991). n.d. = not determined; LOI = loss on ignition.*

| Rock name | Quartz diorite | Hornblende quartz diorite | Hornblende granodiorite | Tonalite |
|---|---|---|---|---|
| Sample no. | MV-13 | MV-32 | MV-70 | MV-31 |
| | **Major-element analyses (weight percent)** | | | |
| $SiO_2$ | 55.70 | 59.14 | 67.21 | 74.80 |
| $Al_2O_3$ | 18.32 | 15.97 | 15.36 | 13.37 |
| $Fe_2O_3$ | 4.18 | 2.90 | 1.69 | 0.40 |
| FeO | 3.16 | 2.91 | 2.00 | 0.37 |
| MgO | 3.16 | 3.63 | 1.55 | 0.64 |
| CaO | 6.43 | 5.97 | 3.33 | 1.26 |
| $Na_2O$ | 3.48 | 3.90 | 3.77 | 5.85 |
| $K_2O$ | 0.65 | 0.84 | 3.30 | 0.66 |
| $TiO_2$ | 0.86 | 0.80 | 0.51 | 0.43 |
| $P_2O_5$ | 0.30 | 0.29 | 0.22 | 0.13 |
| MnO | 0.16 | 0.09 | 0.10 | 0.02 |
| LOI | 4.05 | 4.10 | 1.60 | 3.74 |
| Total | 100.45 | 100.54 | 100.64 | 101.71 |
| $SiO_2$ water-free | 57.8 | 61.3 | 67.9 | 76.4 |
| | **Trace-element analyses (parts per million)** | | | |
| Rb | 23 | 40 | 88 | 25 |
| Sr | 431 | 378 | 326 | 269 |
| Cs | 1.8 | 2.2 | 1.5 | 0.4 |
| Ba | 335 | 376 | 564 | 239 |
| Th | 1.9 | 4.3 | 9.1 | 11.0 |
| Sc | 19.9 | 16.8 | 8.5 | 6.5 |
| Cr | 54 | 155 | 29 | 103 |
| Co | 25.8 | 20.2 | 10.2 | 3.3 |
| Ni | 56 | 80 | n.d. | 16 |

1.1/92.0 Green Veneer lumber mill. A 210-m-deep well at the Green Veneer plant produces water enriched in sodium (120 mg/L), bicarbonate (158 mg/L), and chloride (89 mg/L) relative to local shallow groundwater (typically Na <5 mg/L, $HCO_3$ <60 mg/L, Cl <1 mg/L).

Upstream from Idanha, the North Santiam River is eligible for consideration as a National Wild and Scenic River by virtue of its recreational values. Under provisions of that act, eligible rivers are examined to identify the remarkable values possessed— recreation, scenic, or wild. Rules for management become increasingly stringent along the scale from recreation to scenic to wild. The intensity of development, bridge crossings, and other characteristics limit the rating for this stretch of river.

5.5/97.5 Junction, Whitewater Creek Road to left.

0.4/97.9 Road cut on left exposes block-and-ash (pyroclastic flow) deposit erupted from Mount Jefferson 15 km to the east.

Although once interpreted as Holocene in age (Hammond and others, 1982) or Pleistocene and Holocene (Priest and others, 1987), the deposits characteristically are deeply weathered, older than those of the Fraser glaciation, and entirely late Pleistocene in age. This particular deposit is overlain by a biotite-bearing tephra thought to be the Mount St. Helens set C, which is about 50,000 yr old (W.E. Scott and R.M. Conrey, unpublished data, 1989). The pyroclastic flow could be thousands of years older because a soil representing thousands to tens of thousands of years of development formed prior to deposition of the biotite-bearing tephra (W.E. Scott, written communication, 1992).

3.3/101.2 Riverside Campground.

2.1/103.3 Marion Creek. Marion Forks restaurant on right. Last food services until Sisters (40 mi).

9.4/112.7 Cross North Santiam River. River is eligible for consideration as a wild and scenic river by virtue of its administratively defined scenic values upstream from here.

4.6/117.3 Highway crosses Holocene basaltic andesite lava flows erupted from Little Nash Crater.

1.4/118.7 Santiam Junction, end of State Highway 22 at its junction with State Highway 128 (from Eugene, along McKenzie River) and U.S. Highway 20 (from Corvallis, along South Santiam River). **Continue ahead (east) on Highway 20** toward Santiam Pass.

1.3/120.0 The road rounds a curve built against a Holocene cinder cone, one of three in the Lost Lake chain of cones. These cinder cones dammed Lost Creek, creating shallow Lost Lake (ahead 1 mi on left). As the highway crosses the Lost Lake valley, views at 10:00 o'clock are of craggy Three Fingered Jack, the central pyroclastic cone of a Pleistocene basaltic andesite shield volcano.

The brownish to grayish color of the forest on the slopes above Lost Lake results from extensive tree damage by the spruce budworm. The budworm is a 1-cm-long caterpillar that has attacked about 7 million acres of trees in the Pacific Northwest during the past decade (Bella, 1992a). The pest prefers a climate drier than characterized by Cascade Range slopes but has expanded its range during the last seven years of drought. Trees stressed by drought are less able to survive predation by the budworm; budworm-devastated trees become easy prey for western bark beetle and other insects.

2.8/122.8 Hogg Rock, a flat-topped andesite dome. The dome has a K-Ar whole-rock age of 0.09 Ma (Hill and Priest, 1992). Hogg Rock is named for Colonel T.E. Hogg, promoter of the long-defunct Corvallis and Eastern Railroad. A short section of grade was prepared near Hogg Rock before the project's demise (Mills, 1950).

1.3/124.1 Summit of Santiam Pass. **Turn right at junction with road to Hoodoo ski area** (Road 2690, Big Lake Road). Hayrick Butte, another flat-topped andesite dome similar to Hogg Rock, is directly ahead (south).

Santiam Pass drill hole (SP 77-24) is located 1.6 km east of the Hoodoo junction and a few meters south of U.S. Highway 20 on a narrow dirt road. The hole, drilled to a depth of 929 m, was completed in two phases. The upper 140 m were drilled by rotary method during November 1990, and the remaining 789 m were completed by diamond-core drilling during August and September 1991 (Hill and Benoit, 1992). Basaltic andesite lava flows constitute 95 percent of the core, whereas cinders and volcaniclastic strata constitute the remaining 5 percent; core recovery was 99.7 percent. A K-Ar age of 1.81±0.05 Ma was obtained from a sample at 928-m depth, which indicates that most or all of the core is Pleistocene in age (Hill, 1992). Bottom-hole temperature was 25°C when last measured on September 3, 1991. Temperature gradients are about 50–60°C/km at 700- to 900-m depth and 103–116°C/km below 910 m (Blackwell, 1992). Average thermal conductivity is 1.66 W/m/K, a value that characterizes sequences of lava flows in other parts of the Cascade Range. Heat-flow values from lower parts of the hole range from 86 to 204 $mW/m^2$ (Blackwell, 1992).

0.9/125.0 **Veer left on Big Lake Road (Rd 2690).**

The road straight ahead leads a short distance into the Hoodoo ski area. Hoodoo Butte, with ski lift tower at its summit, is a geomorphically youthful, late Quaternary cinder cone. The basaltic andesite lava flows that issued from it have been glaciated, an indication that their age is late Pleistocene, not Holocene.

0.2/125.2 Big Lake Road rounds the east flank of Hayrick Butte.

0.6/125.8 View of Mount Washington, a basaltic andesite shield volcano.

Although undated by isotopic methods, Mount Washington has an erosional form characteristic of shield volcanoes ranging in age from about 0.3 to 0.5 Ma and located at the Cascade Range crest. Farther east, older volcanoes are better preserved because of their position in the Cascade Range rain shadow.

1.3/127.1 Minor road intersection. **Keep right on main road toward Big Lake.**

0.1/127.2 **Turn right, leaving the paved road for cinder Road 2690-810 to Sand Mountain.** Note the gently rolling constructional topography, an extreme contrast to the steep, dissected slopes of the Western Cascades. This contrast will become even more obvious from the summit of Sand Mountain.

2.4/129.6 Obscure junction, one of several as this road anastomoses westward. **Continue west, following the small, orange, diamond-shaped tags nailed to trees**, which are the snowmobile route indicators for this same road.

This large area across Santiam Pass was burned by the Airstrip fire of 1967; see Jones and Johnston (1968) for graphic description of the fire. Reforestation is almost entirely with lodgepole pine.

0.5/130.1 **Turn left to remain on Road 2690-810.** Do not continue straight ahead on the poorly maintained spur Road 2690-866.

1.7/131.8 **Parking area at end of Sand Mountain Road**; locked gate bars vehicle passage beyond this point. The summit viewpoint can be easily reached by foot.

**Stop 6—Sand Mountain.**

A short trail leads to the summit of Sand Mountain. The Sand Mountain Natural Research area was once open range for off-road vehicles but has since been preserved, thanks to the almost single-handed efforts of Don Allen and the Sand Mountain Society. Allen spent part of his youth on Sand Mountain as the son of a fire lookout. The trail (an abandoned road) ascends above the crater of Sand Mountain, which is still scarred by off-road vehicle tracks. The lookout tower at the summit survived the Airstrip fire of 1967 but burned accidentally in 1968. It has since been replaced by an architecturally authentic grange-hall style lookout (gabled roof is diagnostic). Windows and some of the framing for the replacement structure came from a tower that once sat on Whiskey Peak in the Siskiyou National Forest; restoration has been completed in the last five years. An historic outhouse (diagnostic criteria uncertain) was being relocated to Sand Mountain from Black Butte in the summer of 1992. Presumably some equally historic part of the outhouse remains at Black Butte.

Sand Mountain is the highest geographic feature of the Sand Mountain chain of 23 cinder cones and associated lava flows. Eruptions occurred in two principal episodes, approximately 3,800 and 3,000 years ago, and the composition of lava ranges from subalkaline basalt to basaltic andesite (Taylor, 1981, 1990). Figure 7 shows the extent of Holocene lava flows in vicinity of Santiam Pass. The mountain's summit affords excellent views of prominent peaks in the central Oregon High Cascades—from the Three Sisters on the south to Mount Jefferson on the north—and on a clear day it is possible to pick out Diamond Peak, 110 km south-southwest. Santiam Pass, the low divide between Mount Washington and Three Fingered Jack, has been a major Cascade crossing throughout recorded history. Directly east 24 km is Black Butte, a 1.4-Ma basaltic andesite shield volcano (Hill and Priest, 1992), spared the ravages of glaciation by its position in the Cascade Range rain shadow.

Three geothermal drill holes at least 500 m deep have been sited in the area (Figure 17). Eugene Water and Electric Board (EWEB) drilled two geothermal prospect holes on the western slope of the High Cascades during 1979 (Youngquist, 1980). The first, EWEB–1, was drilled to a depth of 560 m and is located 4.5 km west of Sand Mountain near Clear Lake (Keith and Boden, 1981a). The second, EWEB–2, was drilled to a depth of 587 m and is located 18 km north-northwest of Sand Mountain near Twin Meadows (Keith and Boden, 1981b). During 1990–91, a third, 929-m-deep scientific observation hole SP 77–24 (see milepoint 124.1), was drilled 7 km northeast of Sand Mountain at Santiam Pass to assess the geothermal resource potential along the axis of the High Cascades (Hill and others, 1991; Hill and Benoit 1992).

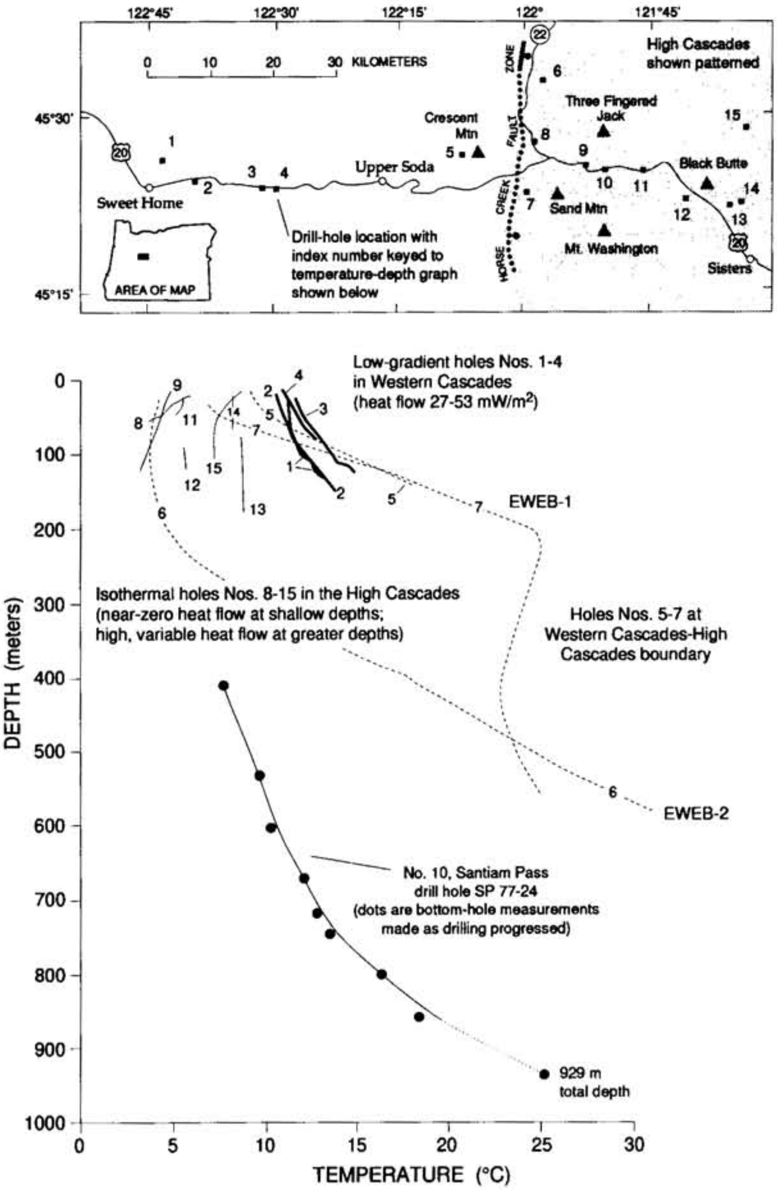



*Figure 17. Map showing geothermal-gradient holes located along east-west transect crossing Santiam Pass. Note how temperature-depth gradients are grouped according to geographic position: bold lines show low-gradient holes from Western Cascades; dotted lines show high-gradient holes at Western Cascades-High Cascades boundary; and thin lines show isothermal holes in High Cascades. The 929-m-deep hole SP 77–24 at Santiam Pass (no. 10 on map and graph) penetrated so-called "rain-curtain" that results from large amounts of groundwater infiltrating in the High Cascades. That hole was isothermal above about 400-m depth.*

The geomorphic contrast between Western and High Cascades is strikingly visible from Sand Mountain: the broad volcanic ridge of the High Cascades contrasts with deeply incised canyons of the Western Cascades. Also visible here is a marked structural contrast between Western and High Cascades not present everywhere along the arc. From south of Mount Jefferson to nearly the Three Sisters, the High Cascades are in a distinct graben that formed after about 4.5 Ma (Taylor, 1981; Smith and Taylor, 1983). The eastern graben-bounding faults form the Green Ridge fault zone (Figure 7). The western graben-bounding faults form the Horse Creek fault zone, which coincides with the topographic boundary between High Cascades and Western Cascades from about McKenzie Bridge northward nearly to Mount Jefferson (Figure 7). Hot springs south-southwest of Sand Mountain are found in the McKenzie River valley (Belknap and Foley Springs, and the Bigelow hot spring). Farther west, Terwilliger Hot Spring is separated from potential magmatic heat sources in the High Cascades by topographic barriers resulting from eastside-down offset on the Horse Creek fault zone and by the canyon of the South Fork McKenzie River.

Displacement on the Green Ridge and Horse Creek fault zones took place in late Miocene and early Pliocene time. Motion along the Green Ridge fault zone isolated the Deschutes basin from now-buried volcanic centers in the High Cascades beginning about 5.4 Ma (Smith and others, 1987). Rocks as young as about 5 Ma are exposed at the top of the 650-m escarpment of Green Ridge (Armstrong and others, 1975), whereas the downthrown block is mantled by Pliocene and Quaternary sedimentary deposits. Displacement is at least 1 km, on the basis of an age of 1.81 Ma from the base of drill hole SP 77–24 at Santiam Pass (Hill and Priest, 1992).

The Horse Creek fault zone has displaced 5- to 6-Ma strata as much as 670 m down along one fault trace north of the McKenzie River (Brown and others, 1980); cumulative mapped offset is as much as 850 m south of the McKenzie River (Priest and others, 1988). An additional 400 m of offset may be indicated by a steep unconformity perhaps resulting from lava buttressing a fault escarpment in the vicinity of Scott Creek (Priest and others, 1988). Thus, demonstrable graben subsidence is on the order of about 1.4 km. Headward erosion by the McKenzie River breached the escarpment by late Pliocene time, and the basalt of Roney Creek flowed from a source in the High Cascades westward across the fault trace and along the McKenzie River valley at about 1.7 Ma (Priest and others, 1988). The fault has been inactive since the emplacement of the basalt of Roney Creek.

COCORP (Consortium for Continental Reflection Profiling) seismic reflection experiments were conducted across the Cascade Range between lat 44°10′ and 44°15′. The seismic line has high noise-to-signal ratios and fails to establish the magnitude of offset on the Horse Creek fault zone (Keach and others, 1989). The line ends eastward near the town of Sisters, where offset on the Green Ridge fault zone may have decreased to less than 100 m.

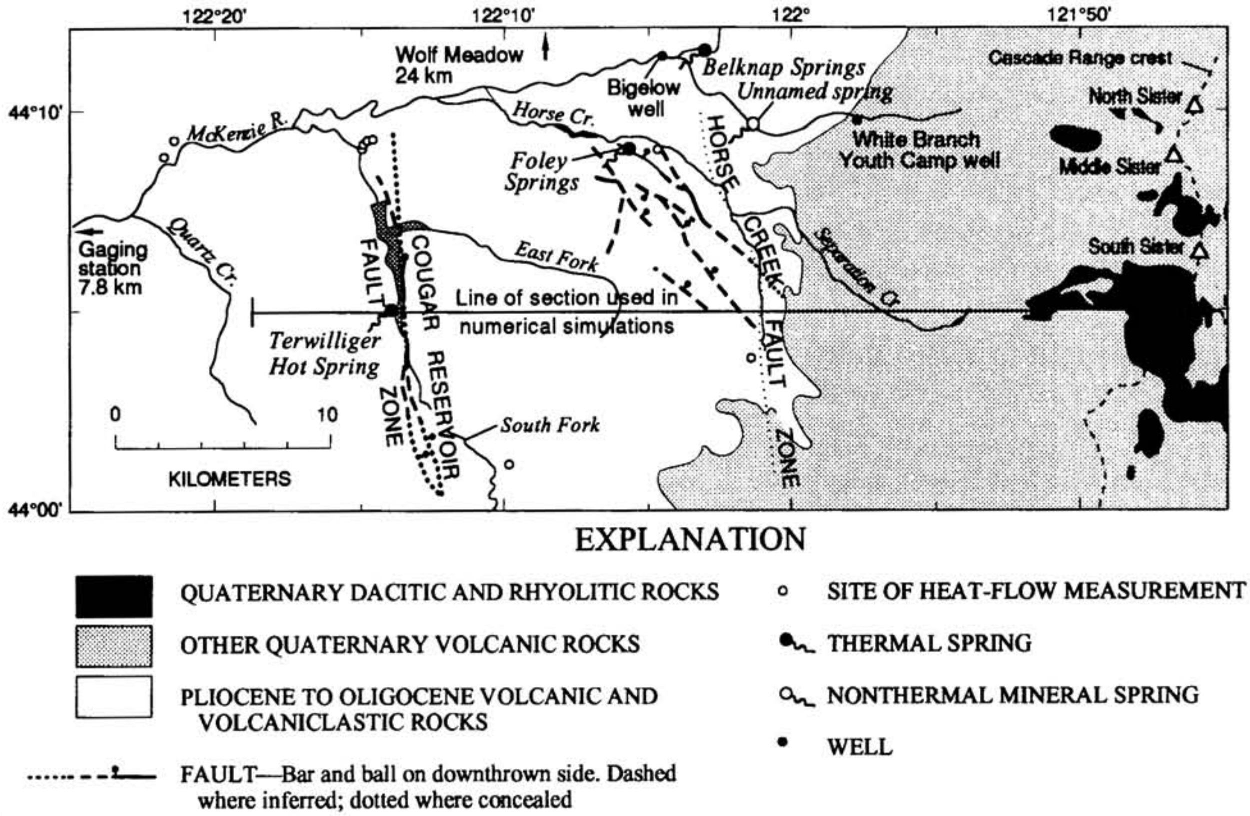



*Figure 18. Map and line of section for numerical simulation of McKenzie River area (from Ingebritsen and others, 1992).*

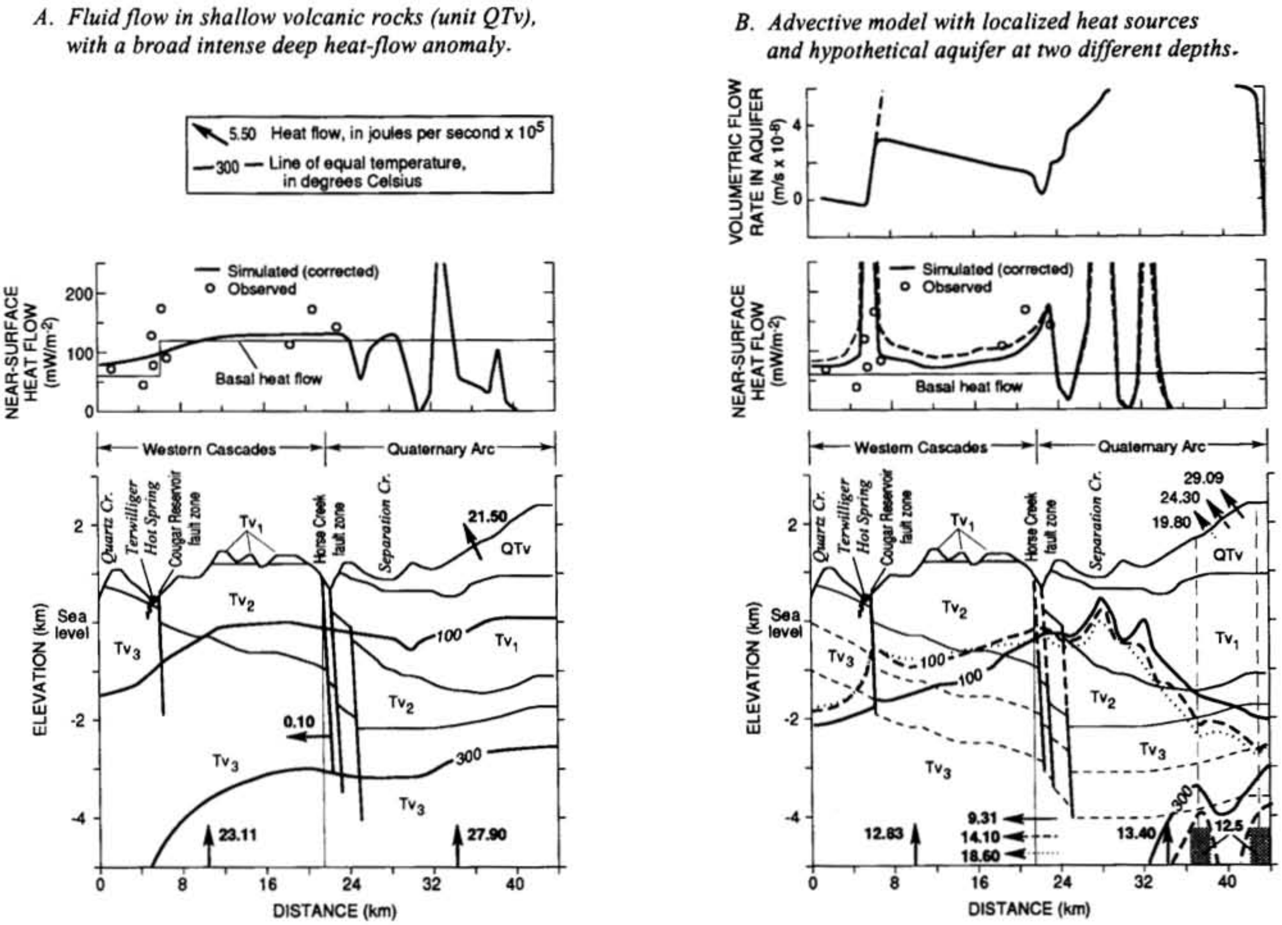



*Figure 19. Numerical simulations for area of McKenzie River group of springs, showing matches to the sparse near-surface heat-flow observations (from Ingebritsen and others, 1992): A—Conduction-dominated model involving fluid flow only in shallow volcanic rocks. B—Advection-dominated model with localized heat sources. Map-unit symbols same as Figure 13.*

Numerical simulations of a cross section through Terwilliger Hot Spring (Figures 18 and 19) show that any flow across topographic and structural barriers between the hot springs and the High Cascades must be at depths of several kilometers (Ingebritsen and others, 1992). At shallower depths, lateral flow is interrupted by faults and (or) topographically low areas. For example, the simulation models predicted substantial discharge of heated groundwater in the topographically low area along Separation Creek in the Three Sisters Wilderness (Figure 19). Subsequent measurements identified an anomalous Cl flux near the predicted location; the flux, about 10 g/s, is larger than the fluxes from some of the known hot springs in the McKenzie River group. Thus, the predictive value of the numerical simulations was established in at least this limited respect.

**Retrace route back to Big Lake Road (pavement) and then north to U.S. Highway 20.**

7.7/139.5 Junction, Highway 20. **This ends the field trip.** For a field-trip guide that continues east or west, the traveler is referred to Taylor (1981).

## GEOTHERMAL POWER IN PERSPECTIVE

Investigations of geothermal energy resources led to much of the research reported in this guide. High petroleum prices in the 1970s prompted a surge of such studies, but interest in alternative power sources sagged during the energy-easy 1980s. The Pacific Northwest has lived through a decade of power surplus, but the next decade may find the region in an energy deficit. Indeed, in July 1992, the Bonneville Power Administration (BPA) announced plans to build its first new power plant since the completion in 1983 of Washington Public Power Supply System's nuclear plant in Richland, Washington (Koberstein, 1992). The new plant, to be built near Tacoma, Washington, will burn natural gas in combustion turbines to produce an average 240 $MW_e$, enough power for a city of 150,000 (slightly larger than Eugene, Oreg.). An additional 1,380 $MW_e$ of power is needed by the year 2003 to avoid building any expensive nuclear or coal-fired power plants for at least the next 20 years (Bella, 1992b). BPA reportedly can obtain 780 $MW_e$ (the equivalent of one nuclear plant or Portland's energy use for 16 months) from increased energy conservation and improved efficiency of transmission lines and turbine generators at dams. Another 50 $MW_e$ would come from major electricity users who find ways to shave their loads in exchange for billing credits. The agency also has agreed to purchase 300 $MW_e$ of power from producers of renewable energy, such as geothermal wells and windmills (Bella, 1992b). Portland General Electric (PGE), a northwest power company, is involved in more than a dozen programs that focus on both residential and commercial energy saving. In 1991, the programs accounted for 5 $MW_e$ of energy saved, enough energy to run about 3,500 homes. For example, low-flow showerheads distributed by PGE are expected to save more than 1 $MW_e$ by the end of 1992, enough energy saved to serve 800 residences (Christensen, 1992).

Given the magnitude of projected energy needs, renewable energy sources will only slightly satisfy our insatiable desire for power. The promise of geothermal energy from the Cascade Range remains cloaked by hydrogeologic problems that make exploration and development a challenge.

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## Important notice on this issue's field trip

We have learned from the Oregon Department of Transportation (ODOT) that the stretch of Highway 224 between this trip guide's cumulative milepoints 23.5 and 28.9 is **closed indefinitely**. Access to the point of continuation, milepoint 29.4, from the north (Portland) would be via Highway 26, Forest Road 42 (Clear Lake to Timothy Lake), and Forest Road 57. From the south, access to Forest Road 46 is from Highway 22 at Detroit (including part of the field trip in reverse direction).

ODOT offers telephone information on highway conditions for a charge of 30 cents at (503) 976-7277 and (541) 889-3999. National Forest Ranger Stations may provide similar (but less official) information. □

## ABSTRACTS OF PAPERS

*The following abstract is of a paper given at an international conference in May 1995 at the University of Washington. The conference, titled "Tsunami deposits—geologic warnings of future inundation," was sponsored by the Quaternary Research Center, the National Oceanic and Atmospheric Administration, and the U.S. Geological Survey. Among the 80 registered participants were scientists from Canada, Germany, Japan, Norway, the Philippines, the United Kingdom, and the United States.*

***Tsunami disaster planning in Clatsop County, Oregon*, by** Paul Visher, Tsunami Coordinator.

The Clatsop County oceanfront extends south from the mouth of the Columbia River for about 40 mi to Tillamook County. It includes four incorporated cities and two oceanfront communities.

On first impression, one might consider a common disaster plan for all, but, on more detailed analysis, the actual plan varies from location to location, depending on bridges and local topography. [The following discussion proceeds] from north to south:

The City of Warrenton is protected from tsunamis by a major foredune system having a 50-ft elevation and by the south jetty of the Columbia River. This jetty was initially built in the 1880s and extended in the 1930s. According to the Corps of Engineers, the jetty was built with major rocks of 3–6 ft in diameter with seismic considerations. What will happen to this structure during a magnitude 8+ quake? No one knows for sure, but the best guess would postulate a pile of rocks at a lower elevation but still high enough to significantly restrict the flow of water into the mouth of the Columbia from the projected 16-ft-high tsunami. This projected elevation comes from the Alaska Tsunami Warning Center (ATWC), whose studies indicate a residual 3- to 4-ft wave at Warrenton. Of equal concern in Warrenton is the failure of the 14-ft-high dikes that protect the city from tidal flooding. None of these dikes was engineered to any seismic standards. Warrenton's major threat appears to come from flooding due to dike failure, not a tsunami velocity threat.

Surf Pines is the next area south. Homes are constructed on two parallel dunes—a coastal frontal dune about 30 ft high and a landward dune of 50-ft elevation. The ATWC computer model indicated a 16+ ft wave. Prudence indicates an evacuation to the 50-ft elevation.

At Gearhart, the primary dune, about 600 ft landward of the oceanfront, varies in elevation from 60 to 70 ft. There are large areas of residential construction along lower areas to the east. Much of this construction is at 14 ft, which is the FEMA 100-year storm flood elevation. There is evidence of tsunami deposits at higher elevations. The general evacuation route is to move people to the 60 ft dunetop elevation.

The next town south, Seaside, provides the most complex disaster-planning challenge. The town is located on two sand dunes running parallel to the ocean. The frontal dune is about 20 to 25 ft high and is protected from ocean erosion by a 20 ft-high seawall that was constructed in the 1920s. The second dune varies from 18 to 25 ft in elevation. These dunes are separated by a river crossed by several bridges, none of them designed with seismic consideration. They are assumed to fail. Major motels are located on the forward dune system that can act as a breakwater against the tsunamis, which are projected by the ATWC to be 17 ft high during a magnitude 8.8 quake. Behind the second dune system is a 5,000+ acre storage sump for water below the 18-ft elevation. The tsunami "inundation" area is defined by the in- and out-flow of water that passes the 1,000-ft gap in the dunes between Gearhart and Seaside. The difference in the input and output flows will define the amount of water that must be stored by the sump and raise its water level. There is a reasonable chance that the second dune would provide an island of safety except for the most severe tsunami.

Seaside is planning to reinforce some of the bridges between these lower dunes, as well as some of the bridges from the east dune to the foothills. When these bridges are reinforced, the evacuation route should clearly go to the 40+ ft elevations on the hills east of town.

In Cannon Beach, the next town south, the computer model from ATWC indicates a 17-ft wave from a magnitude 8.8 event. The school and the major downtown area are located at about 12-ft elevation. Fortunately, the town has 40+ ft elevations within 15 minutes walking distance. People in parts of the city can easily walk to the 50- and 60-ft elevations. A bond issue was recently passed to build a new fire station at 40-ft elevation, and a bond issue is being discussed to move the school to a "tsunami-safe" location.

Further south, the area of Arch Cape is confronted by a computer model of a 18 ft wave and walking evacuation routes of 15 minutes or less to reach 50-ft elevations away from the beach.

Except for Seaside, every person in Clatsop County can walk, in 20 minutes or less, to an elevation 10 ft or more above the computer-model tsunami for a magnitude 8.8 subduction zone earthquake event. How good is the model?

Dr. Peterson is using core borings, landward of barriers, to measure the sand deposited in past events. This will bound some of the uncertainties. Dr. Baptista is inputting some of Dr. Peterson's data to revise the model.

At the present time, the disaster planning is based on the ATWC model and the subsidence event occurring at the highest tide, about a 10-ft maximum range; the measured subsidence of about 5 ft, different from the 2 ft in the model; and a time of arrival of about 25 minutes after the event. To me, the most unexpected information from the computer program is the long period, four to five hours, that people should stay away from the lower areas because of repetitive waves.

The computer model from the ATWC, modified by measured subsidence information from Dr. Peterson, is the best information that we now have for planning. When better data are available, the tsunami disaster plan will be modified.

In the meantime every coastal resident in Clatsop County has been provided with instructions as to action he or she should take in case of an earthquake. Programs are being developed to strengthen the bridges, change the locations of the schools and fire stations, and design them to survive a magnitude 8+ event.

We hope it doesn't happen during our lifetimes, but it could happen tomorrow. □

## Unusual landscapes and geologic problems in the Pacific Northwest

*by John Eliot Allen, Emeritus Professor of Geology, Portland State University, P.O. Box 751, Portland, OR 97207–0751*

Geologists and laypersons alike are familiar with the chain of High Cascade volcanoes (Williams, 1953; Allen, 1984), which reach from British Columbia to northern California, the most prominent being Mount Rainier in Washington, Mount Hood in Oregon, and Mount Shasta in California. Most of us are also familar with the two great collapsed volcanoes known as "calderas," Crater Lake (Williams, 1942) and Paulina or Newberry Crater (Williams, 1935).

There are, however, at least five other unusual and remarkable landforms in the Pacific Northwest that are less familiar and may have origins that are of interest, since there are still questions to be answered and alternate hypotheses to be considered. These are the Channeled Scablands, the Mima Mounds, coastal and Willamette Valley terraces, great landslides, and great Tertiary rivers.

**I. Channeled Scablands:** Areally, the most widespread landform, the Scablands cover nearly 16,000 $mi^2$ of eastern Washington and affect the Columbia River Gorge, Willamette Valley, and a small area north of Newberg, Oregon, known as the "Tonkin Scablands." J Harlen Bretz first suggested in 1923 that these dry valleys were cut in the loess and underlying basalt by a gigantic flood. Later authors have proposed at least 40 and perhaps a hundred floods, occurring between 15 and 12 thousand years ago at the end of the Pleistocene (Allen, 1986; O'Connor and Waitt, 1995).

**II. Mima Mounds:** One of the still puzzling landscapes in the Pacific Northwest consists of "Mima Mounds", whose type locality is south of Tenino, Washington. More than a dozen hypotheses have been advanced to explain the fields of hundreds of mounds, which are about a yard high and 4-5 yards in diameter. Similar mounds occur in Oregon in such places as upon the basalt of Tom McCall State Park in the Columbia River Gorge. Hypotheses include gophers, earthquakes, glacial deposits, and wind erosion of volcanic ash over depressions in basalt. It is highly probable that Mima Mounds have multiple origins, but although many papers have been published, the issue is still moot.

**III. Terraces:** Most of the coastal towns along Highway 101 are located upon the lowermost (50-foot) of a series of marine terraces first described by Diller in 1902. These are wave-cut platforms resulting from upper Tertiary and post-Pleistocene changes in sea level, and so far few of their ages and locations have been mapped. Little attention has been paid to the terraces, first noted by Condon and later by Allison (1936). (Madin and others [1995] mapped such terraces in the Charleston quadrangle. —ed)

**IV. Landslides:** Great landslides have recently been recognized as having been caused by great earthquakes. The 14-$mi^2$ Cascade Landslide in the Columbia River Gorge at Bonneville has been dated at about 800 to 1,000 years ago. The mud slide that buried an Indian village on the Olympic Peninsula coast west of Ozette occurred about 400 years ago. Landslides that formed Triangle and Loon Lakes in the southern Coast Range have yet to be dated.

**V. Great Tertiary rivers of eastern Oregon:** High-level gravel deposits, many of them gold-bearing, have been found high on the summits of the Wallowa Mountains and on the crests of many other ridges (Allen, 1991). They contain numerous and sometimes very large boulders of quartzite and other metamorphic rocks from the Rocky Mountains and must represent at least one very large Tertiary river, either an ancestral Columbia or Snake River. Little has been published as yet on these rivers.

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## BLM offers grace period for mining claims

The U.S. Bureau of Land Management (BLM) is urging mining claim holders to apply for a one-year "grace period" that will give them extra time to comply with a new rule published in July 1996 that is intended to stop squatters from illegally occupying land on mining claims they are using for nonmining purposes.

Current claimants may continue their occupancies for one year, provided they fill out and sign a simple form available from any BLM office. The forms must be received in a BLM office or postmarked by October 15, 1996. □

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