

# OREGON GEOLOGY

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Mount Bachelor—formerly Bachelor Butte



TWO-PART ARTICLE:

**Field trip guide  
to the  
central Oregon  
High Cascades**

IN THIS ISSUE:

**Part 1:  
Mount Bachelor-  
South Sister  
area**

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**Main Office:** 910 State Office Building, 1400 SW Fifth Ave., Portland 97201, phone (503) 229-5580, FAX (503)-229-5639.

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## Information for contributors

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The style to be followed is generally that of U.S. Geological Survey publications. (See the USGS manual *Suggestions to Authors*, 6th ed., 1978.) The bibliography should be limited to references cited. Authors are responsible for the accuracy of the bibliographic references. Names of reviewers should be included in the acknowledgments.

Authors will receive 20 complimentary copies of the issue containing their contribution. Manuscripts, news, notices, and meeting announcements should be sent to Beverly F. Vogt, Publications Manager, at the Portland office of the Oregon Department of Geology and Mineral Industries.

## Cover photos

Mount Bachelor (formerly Bachelor Butte), a major focal point in the field trip guide beginning on page 99.

Top photo shows view of west side of Mount Bachelor from south flank of South Sister, one of whose 2,000-year-old rhyodacite domes is in right foreground. Sparks Lake in middle distance; Cascade Lakes Highway visible along left edge. Mount Bachelor is composed of a steeper summit cone lying on a broad shield. Ski trails are on lava flows that issued from vent marked by small knob on north flank near snow line.

Bottom photo shows aerial view of upper north flank of Mount Bachelor. Visible features include moraines of early and late neoglacial ages, moraines of late glacial age, and lava flows of the mountain that predate and postdate late glacial moraines. Young vents are visible just above tree line. Photos by Lyn Topinka (top) and William E. Scott (bottom), U.S. Geological Survey.

# OIL AND GAS NEWS

## Rules to be presented for adoption

In November of this year, revised administrative rules relating to oil and gas exploration and development in Oregon will be presented to the Governing Board of the Oregon Department of Geology and Mineral Industries (DOGAMI) for possible adoption. Copies of these rules are available. For details, interested parties should contact Dan Wermiel at the DOGAMI office in Portland, phone (503) 229-5580.

## NWPA Field Symposium scheduled

The Northwest Petroleum Association (NWPA) will hold its 1990 Annual Field Symposium September 30 to October 3 in Roseburg, Oregon. The symposium will include one day of talks relating to energy development, primarily oil and gas, in the Pacific Northwest. Two days of field trips will be held to observe the strata of the Tyee Basin and Coos Basin areas. For details of the symposium, contact NWPA, P.O. Box 6679, Portland, Oregon 97228-6679. □

## DOGAMI publications released

Oregon's resource potential for oil and gas near and off the northern coast and potential for silica and industrial sand are the subjects of two new publications released by the Oregon Department of Geology and Mineral Industries (DOGAMI):

**Released August 17, 1990: *Onshore-offshore geologic cross section from the Mist Gas Field, northern Oregon Coast Range, to the northwest Oregon continental shelf and slope***, by A.R. Niem, P.D. Snively, Jr., and W.A. Niem. DOGAMI Oil and Gas Investigation 17, 46 p., 1 plate (transect), \$9.

The publication consists of a 36- by 76-inch ozalid sheet and a 46-page explanatory text. In addition to the geologic cross section and corresponding geologic strip map, the cross-section sheet shows several magnetic, gravity, and seismic-reflection profiles.

This is one of several geologic cross sections that have been or will be constructed in a cooperative effort among the U.S. Geological Survey, Oregon State University, oil companies, geologic consultants, and DOGAMI with funding from the U.S. Minerals Management Service.

The report consists of data and interpretation from offshore seismic-reflection profiles and onshore geological and geophysical studies, meeting at Tillamook Head, northwestern Oregon. The contents will serve to better explain the stratigraphic and tectonic framework and to evaluate the oil and gas potential of the northern Oregon continental margin.

Onshore interpretation is based on seismic profiles, field mapping, well logs, and microfossil age determinations. It extends geographically to the Mist Gas Field in Columbia County. Offshore seismic data are correlated with subsurface units encountered in deep exploratory wells drilled on the continental shelf in the 1960's.

Offshore stratigraphic units consist of (1) a 3,000- to 4,000-m-thick sequence of Tertiary sedimentary, volcanic, and intrusive rocks of the deep marginal Astoria Basin; (2) the upper(?) Oligocene to middle Miocene accretionary complex and slope basin units beneath the upper continental slope; and (3) thrust faulted and folded Pleistocene and Pliocene abyssal plain, slope, and submarine fan sediments. Onshore units include the Eocene Tillamook Volcanics overlain by a 2,500-m-thick forearc sequence of upper Eocene to middle Miocene marine mudstone, sandstone, and minor con-

(Continued on page 118, *DOGAMI publications*)

# Field trip guide to the central Oregon High Cascades

## Part 1: Mount Bachelor-South Sister area

by William E. Scott and Cynthia A. Gardner, David A. Johnston Cascades Volcano Observatory, U.S. Geological Survey, 5400 MacArthur Boulevard, Vancouver, Washington 98661.

This field trip guide was created for the September 1988 meeting of the Friends of the Pleistocene, which was held in the Mount Bachelor area. It was released in a slightly different form and with additional material as U.S. Geological Survey (USGS) Open-File Report 89-645 (Scott and others, 1989). The entire volume was edited by William E. Scott, Cynthia A. Gardner, and Andrei M. Sarna-Wojcicki, all of the USGS. Individual sections of the report by Scott; Gardner; Lundstrom and Scott; Scott and Gardner; Hill; Hill and Taylor; and Sarna-Wojcicki, Meyer, Nakata, Scott, Hill, Slate, and Russell are cited in the references. The complete report may be purchased from USGS, Books and Open-File Reports Section, Federal Center, Box 25425, Denver, Colorado 80225, phone (303) 236-7476, for \$10.25.

This first part of the field trip combines the first two days of the original trip and is accompanied by one connected paper by Scott. Part 2 of the central High Cascades field trip guide (the original third day of the field trip) will be published in the next issue of *Oregon Geology* and will continue with a guide to the ash-flow tuffs in the Bend area by Hill and Scott and a paper by Hill and Taylor. All references will be combined at the end of the second part in the next issue.

The mileage in this guide differs slightly from that in the open-file report, because this trip starts in a different location, and the first two days of field trip guides by Scott and Gardner have been combined here into one field trip. Readers may choose to run the trip in a different order, depending on where they are staying. There are several campgrounds near various portions of the trip. Readers are urged to obtain the USDA Forest Service map of the Deschutes National Forest or USGS topographic maps of the area before following the guide, because some features mentioned in the log are not easily found on the maps used for the guide. Also because some of the side roads are not paved, reasonable caution should be taken in following the road log.

### INTRODUCTION

This field excursion to the central Oregon High Cascades highlights aspects of the Quaternary volcanic and glacial history in the vicinity of Mount Bachelor (formerly Bachelor Butte) and South Sister (Figure 1).

### Regional geologic setting

The High Cascades of Oregon are a north-trending belt of upper Miocene to Quaternary volcanic rocks that were erupted on the east margin of the upper Eocene to Miocene Western Cascades volcanic province (Figure 2) (Taylor, 1981; Priest and others, 1983). Upper Pliocene and Quaternary rocks of the High Cascades form a broad platform of chiefly basalt and basaltic andesite volcanoes that fill a structurally subsided zone in the older rocks of the High Cascades (Taylor, 1981; Hughes and Taylor, 1986; Smith and others, 1987). Each of four major Quaternary volcanic centers along this platform (Mount Hood, Mount Jefferson, Three Sisters-Broken Top, and Crater Lake caldera [Mount Mazama]) have erupted lava flows and pyroclastic material that range in composition from basalt to dacite; except for Mount Hood, they have also erupted rhyolite. Newberry volcano, which lies east of the High Cascades, is also a compositionally diverse Quaternary volcanic center (MacLeod and others, 1981).

The Three Sisters-Broken Top area is a long-lived center of basaltic to rhyolitic volcanism (Taylor, 1981; Hill and Taylor, 1989). The clustering of large composite cones sets the area apart from others in the High Cascades, although the Mount Mazama area prior to the formation of Crater Lake caldera was also a cluster of composite cones (Bacon, 1983).

The ages of most volcanoes in the Three Sisters area are not precisely known. North Sister, a basaltic andesite pyroclastic and lava cone that rests on a shield volcano, is the oldest of the Three Sisters (Taylor, 1981) and postdates (Taylor, 1987) the approximately 0.3-million-year-old (Ma) (Sarna-Wojcicki and others, 1989) Shevlin Park Tuff of Taylor (1981). Middle Sister is intermediate in age between North and South Sister and, like South Sister, is compositionally diverse. Broken Top volcano is also younger than the

Shevlin Park Tuff (Hill and Taylor, 1989) and is older than South Sister, but its age relation to Middle and North Sister is not known. The relative degree of erosion of Broken Top suggests an age probably equal to or greater than that of North Sister. Broken Top is a complex composite cone of dominantly basaltic andesite that intermittently erupted andesite, dacite, and rhyolite as lava flows, pyroclastic flows, and pyroclastic falls (Crowe and Nolf, 1977; Taylor, 1978). Cayuse Crater, which is located between Broken Top and the Cascade Lakes Highway, and two nearby vents on the southwest flank of Broken Top (Figures 3 and 4) erupted during earliest Holocene or latest Pleistocene time, but these events were probably unrelated to the long-inactive Broken Top system.

South Sister is the youngest composite volcano of the Three Sisters-Broken Top center and has erupted lavas ranging from basaltic andesite through rhyolite (Taylor, 1981; Wozniak, 1982; Clark, 1983). Although not dated directly, most, if not all, of South Sister is probably of late Pleistocene age. This subjective judgment is based on the relatively little-eroded profile of the volcano and the reasonably good preservation of lava-flow levees and other features, especially on the south and west flanks. The cone of basaltic andesite that forms the summit of South Sister is probably of latest Pleistocene age (Wozniak and Taylor, 1981; Scott, 1987); its crater is still closed and is filled with 60 m (Driedger and Kennard, 1986) of ice and snow. Le Conte Crater (Figure 4), a basaltic andesite scoria cone on the south flank, is between about 15,000 and 6,850 years old. The youngest eruptions recognized on the volcano occurred at a series of vents on the south and northeast flanks that erupted rhyolite tephra and lava flows and domes between about 2,200 and 2,000 years before the present (yr B.P.) (Figures 4 and 5) (Taylor, 1978; Wozniak, 1982; Clark, 1983; Scott, 1987; Taylor and others, 1987).

### Mount Bachelor volcanic chain

The Mount Bachelor volcanic chain provides one example of the type and scale of eruptive activity that has produced most of the High Cascades platform, which consists chiefly of scoria cones and lava flows, shield volcanoes, and a few steep-sided cones of basalt and basaltic andesite. The chain is 25 km long;

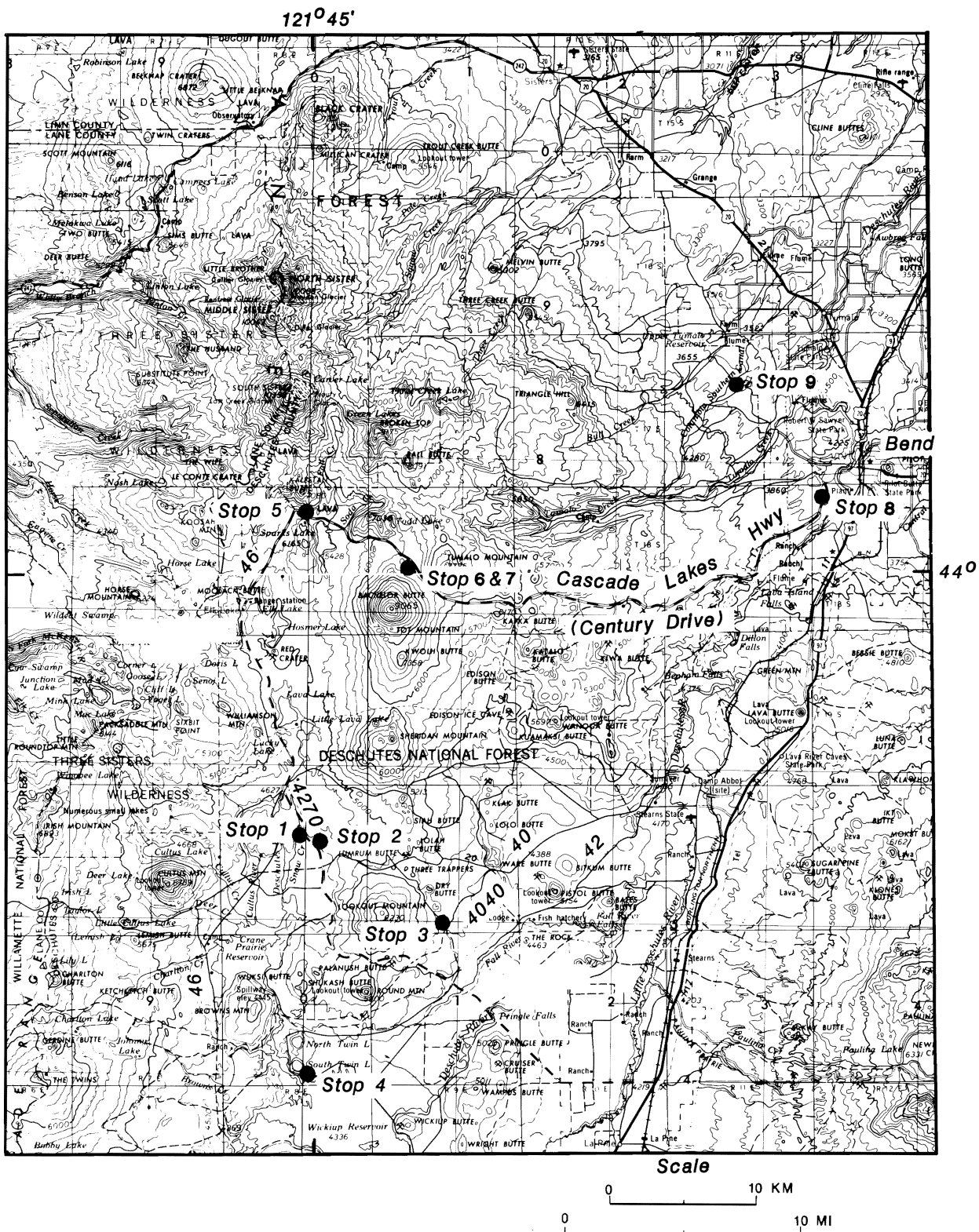


Figure 1. Map of field-trip area. Base map uses former name of Mount Bachelor, "Bachelor Butte." Selected USDA Forest Service roads are identified by 4-digit numerals.

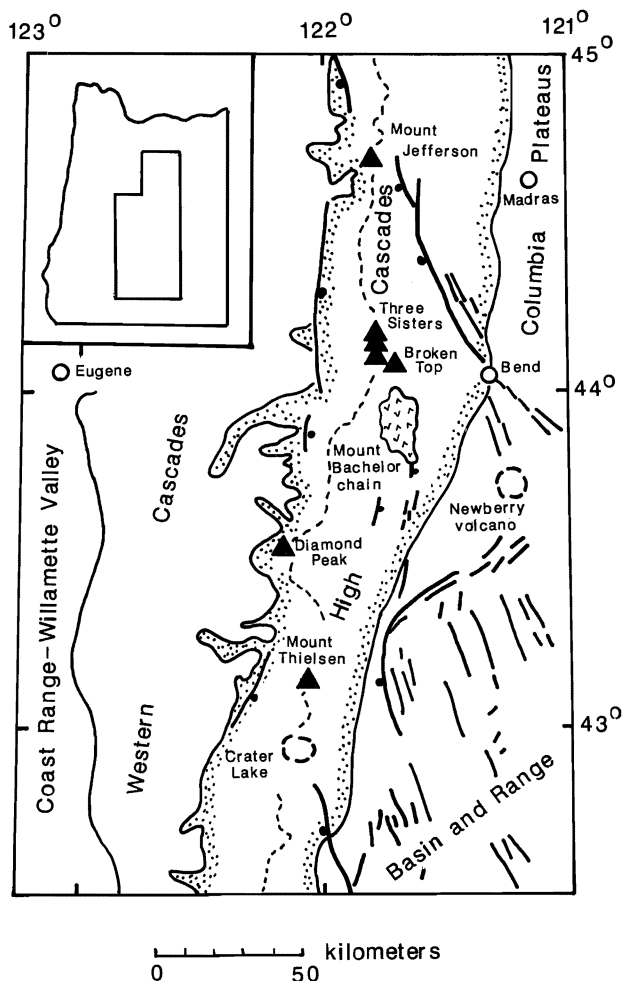


Figure 2. Geologic setting of the Three Sisters-Mount Bachelor area within the upper Miocene to Holocene High Cascades (stippled border). The Western Cascades are composed of upper Eocene to middle Miocene volcanic and volcanoclastic rocks. The parts of the Columbia Plateau and Basin and Range physiographic provinces shown on the map are composed dominantly of Tertiary volcanic and sedimentary rocks; Quaternary volcanic rocks cover most of the area near Newberry volcano. Heavy line = fault; where shown, bar and ball on downthrown side; dashed line = crest of Cascade Range. Broken circle = caldera; triangle = major volcano. Figure compiled from Hammond (1979), Priest and others (1983), and Sherrod (1986).

its lava flows cover 250 km<sup>2</sup> and constitute a total volume of 30-50 km<sup>3</sup> (Scott and Gardner, 1990).

Many vents in the field-trip area, including those of the Mount Bachelor volcanic chain and the Holocene rhyolite lava flows and domes on South Sister, define NNW-NNE-trending alignments (Figure 6) (E.M. Taylor and N.S. MacLeod, written communication, 1981, in Bacon, 1985; Hughes and Taylor, 1986; Scott, 1987). Normal-slip faults in the region, including one at the south end of the Bachelor chain, also have this orientation (Figures 2, 3, and 6) (Venkatakrishnan and others, 1980; Kienle and others, 1981). These alignments are oriented parallel to the north-south direction of maximum horizontal compressive stress that affects the region (Zoback and Zoback, 1980).

## ROAD LOG

This trip (Figure 1) consists of a drive on the Cascade Lakes Highway and adjacent side roads and a closer examination of Mount

Bachelor (formerly Bachelor Butte), including either a chairlift ride or hike to the summit for an overview, a trip down to mid-mountain, and a hiking tour of features that relate to the eruptive history of Mount Bachelor and to late Pleistocene and Holocene glaciation. Other stops focus on (1) the stratigraphic relations among some of the oldest recognized lava flows of the Mount Bachelor volcanic chain and end moraines and outwash fans of the Suttle Lake advance of late Wisconsin age, (2) the southernmost vents of the Mount Bachelor volcanic chain and the fault that extends south from them, (3) hydrovolcanic deposits and landforms in the Wuxsi Butte-Twin Lakes chain that lies west of the south end of the Mount Bachelor volcanic chain, and (4) rhyolite tephra and lava flows from vents on the south flank of South Sister volcano. The geologic map (Figure 3) shows most of the major geologic features that are mentioned in the road log.

The trip starts at the southern junction of the Cascade Lakes Highway and the Hosmer Lake-East Elk Lake road (no. 4625). Look for sign "Hosmer Lake-East Elk Lake." There are several campgrounds in this area. If you are starting in Bend, use the instructions in the following section to reach the starting point. Numbers at beginnings of paragraphs give cumulative miles.

## From Bend to field trip starting point (by mileage points)

0.0—Junction Highway 97 and Division Street. This is the exit to the Bachelor ski area and Cascade Lakes Highway. Follow exit on Division Street.

0.8—Revere-Division Street intersection. Continue on Division, which is the "Thru Route."

1.9—Turn right on NW Colorado Boulevard.

3.4—Intersection of NW Colorado Boulevard with Century Drive. Turn left on Century Drive. This is the start of the Cascade Lakes Highway (Road 46).

19.9—Junction with road to Sun River. Stay on Road 46.

22.4—Entrance to Sunrise Lodge, Mount Bachelor ski area. Continue on Road 46. (You will be returning here for Stop 7 later in the trip.)

23.0—Entrance to West Village of Mount Bachelor ski area. Continue on Road 46. (This is Stop 6 later in the trip.)

28.8—Devils Lake on left. (This is Stop 5 later in the trip.)

33.3—Intersection with road to Sunset View.

34.4—Turnout on left. View of Elk Lake.

36.2—Intersection of Road 46 with 4625, which is the marked turnoff to Hosmer Lake (note sign "Hosmer Lake-East Elk Lake"). This is the start of the field trip. Reset mileage to 0.0. **Mileage points and traveling directions are printed in boldface.**

## FIELD TRIP START

0.0—Intersection of Cascade Lakes Highway (Road 46) and Road 4625 near margin of Red Crater lava flow. The side road is a loop going past two campgrounds. This starting point is at the southernmost intersection with the highway where the large sign "Hosmer Lake-East Elk Lake" occurs. Go south on Cascade Lakes Highway.

0.7—Glacial striae and grooves on lava flows indicate direction of ice flow was to southeast, essentially parallel to road.

2.3—View on left of shield volcano of Sheridan Mountain (or Sheridan shield volcano; unit mb1, Figure 3) of the Mount Bachelor volcanic chain.

2.8—Junction with road to Lava Lake; continue south on Cascade Lakes Highway. Ahead, road cuts expose till overlying lava flows. For the next several miles, the highway traverses a belt of lateral and terminal moraines that record the apparently gradual retreat of the upper Deschutes glacier from its maximum advance of Suttle Lake age.

3.0—Meadow on left occupies a valley between two moraines that has been partly filled with sediment as a result of a locally raised base level caused by lava flows of the Sheridan shield volcano. Basal



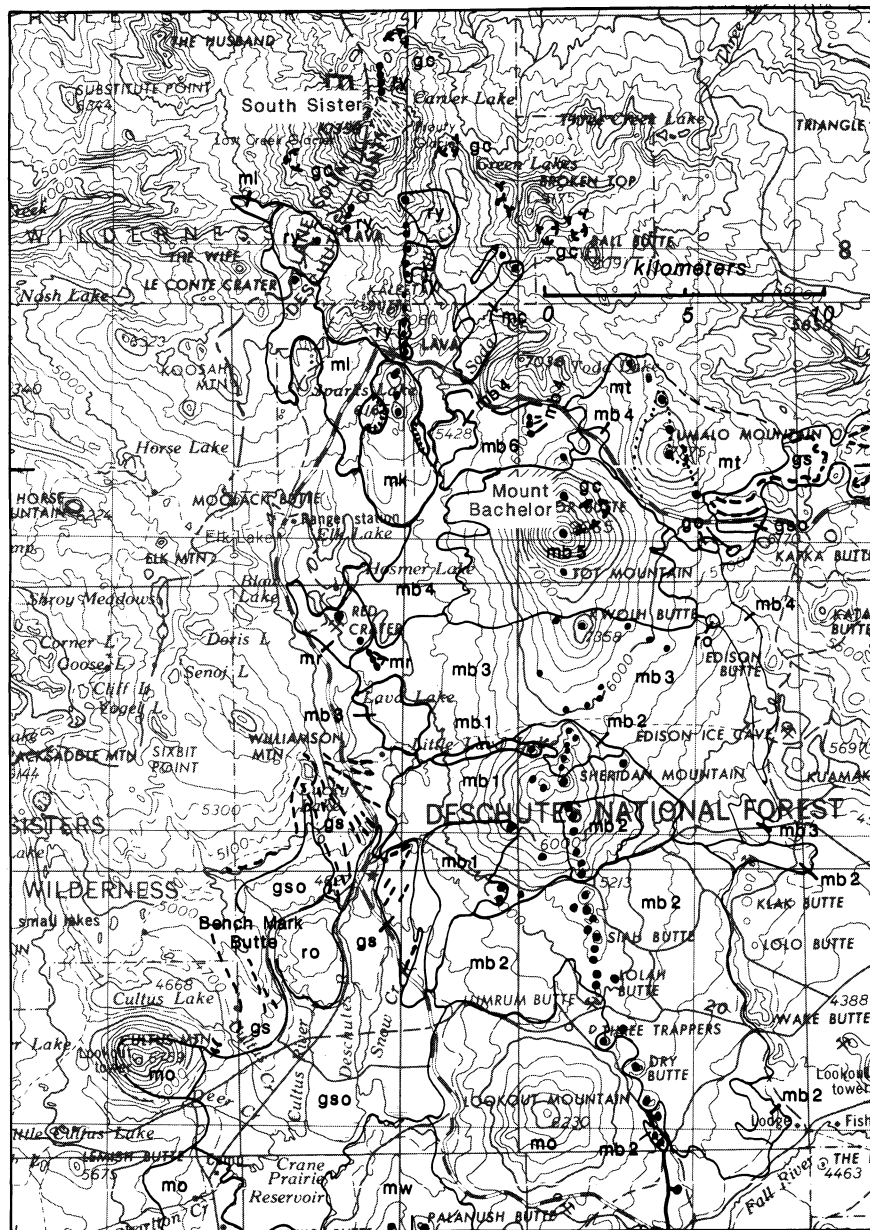


Figure 3. Generalized geologic map of the Mount Bachelor volcanic chain.

#### EXPLANATION

##### Glacial deposits

##### Neoglaciation

- gln late neoglacial drift
- gen early neoglacial drift

##### Cabot Creek glaciation of Scott (1977)

- gc Canyon Creek drift
- gs Suttle Lake drift
- go older drift

##### Volcanic rocks and deposits

- ry rhyolite lava flows and tephra of Rock Mesa and Devils Hill eruptive episodes
- ro rhyolite lava flows of pre-Suttle Lake age

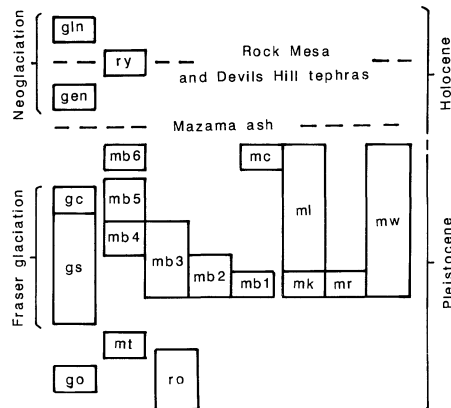
##### Mount Bachelor volcanic chain

- mb6 lava flows and tephra of Egan cone
- mb5 lava flows and tephra of Mount Bachelor summit cone
- mb4 lava flows and tephra of Bachelor shield volcano
- mb3 lava flows and tephra of Kwoh shield volcano
- mb2 lava flows and tephra of Siah chain of vents
- mb1 lava flows and tephra of Sheridan shield volcano
- mc lava flow and tephra of Cayuse Crater
- ml lava flow and tephra of Le Conte Crater
- mw lava flow and tephra of Wuksi, Shukash, and Palanush Buttes
- mk lava flows, tephra, and hyaloclastite of Katsuk and Talapus Buttes
- mr lava flows and tephra of Red Crater chain of vents
- mt lava flows and tephra of Tumalo Mountain
- mo undifferentiated mafic lava flows and tephra of pre-Suttle Lake age

##### Symbols

- vent
- moraine crest
- ... approximate glacial limit on Tumalo Mountain

#### CORRELATION OF MAP UNITS



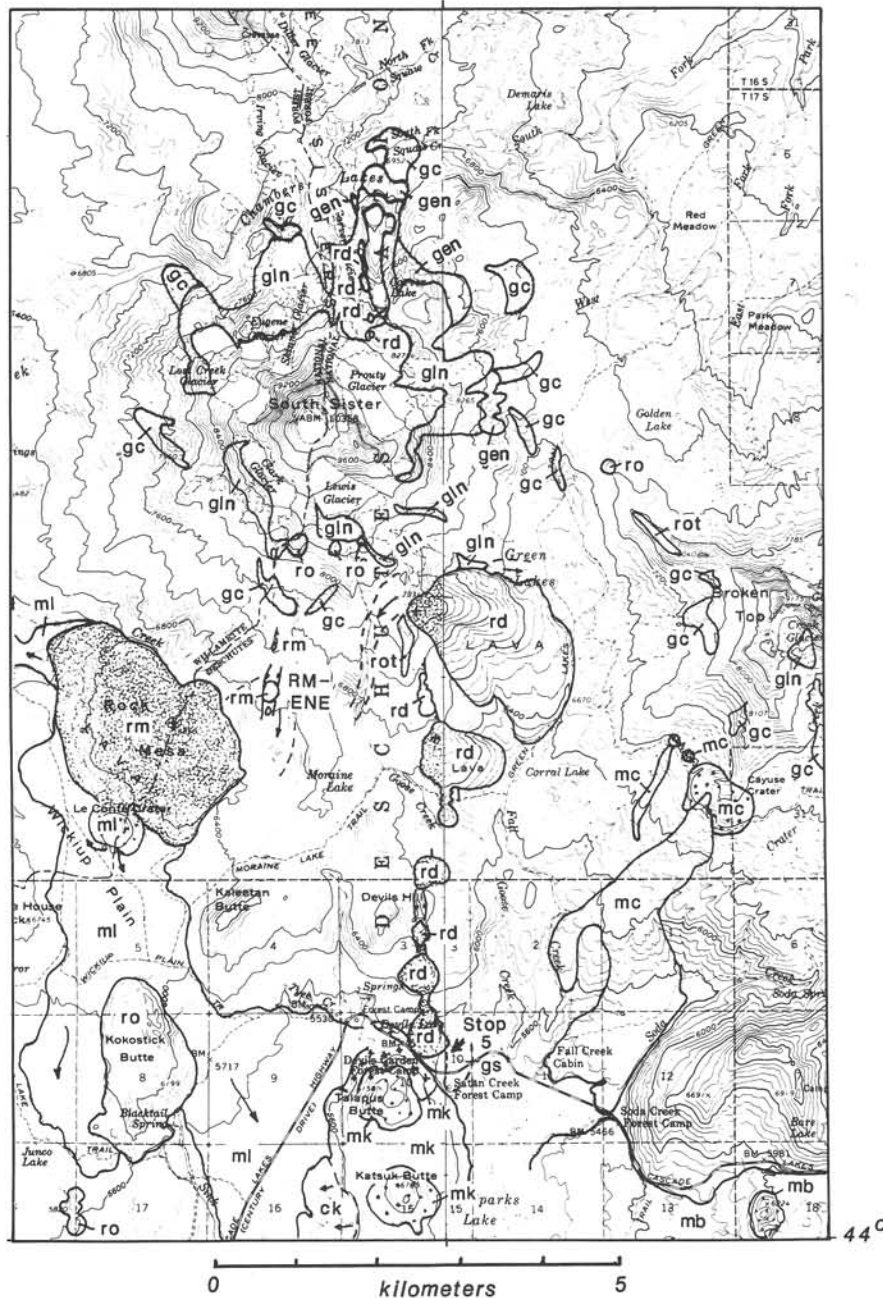
organic material in a 3.5-m-long core from the center of the meadow has an age of  $12,200 \pm 150$  yr B.P. (W-5210); the base of a 40-cm-thick layer of Mazama ash is at 2.4 m; tephra of the Rock Mesa and Devils Hill(?) episodes is at a depth of about 25 cm. The core bottomed in gravel and sand that contains reworked scoriaceous ash that probably originated as tephra from the Mount Bachelor volcanic chain. The radiocarbon age provides only a minimum limiting age for deglaciation and eruptions of the Mount Bachelor volcanic chain because (1) deposition of organic matter did not begin until after emplacement of the lava flows, (2) the thickness of material sampled to obtain enough organic matter for dating must have accumulated over a period at least

as long as several centuries, and (3) younger organic matter is probably contaminating the dated material.

**5.5—Junction with Road 4270; turn left and cross Deschutes River, passing Deschutes Bridge Guard Station and Campground.** The well-vegetated and stable river banks result from the river experiencing only small variations in discharge through the year owing to its being fed mostly by springs. Road ahead traverses flat surface of outwash fan of Suttle Lake age of Deschutes River.

**6.6—Cross Snow Creek, which is fed from springs that rise at the snout of a lava flow from the Sheridan shield volcano that occupies a narrow valley between two moraines. Road ahead climbs low scarp onto till.**

121° 45'



Left:

Figure 4. Map showing selected geologic features around South Sister and Stop 5. Glacial deposits: gln = late neoglacial till; gen = early neoglacial till; gc = till of Canyon Creek age; gs = till of Suttle Lake age (shown only near Stop 5). Mafic lava flows, scoria deposits (stippled), and hydrovolcanic deposits (crosses): mc = Cayuse Crater; mb = Mount Bachelor volcanic chain; ml = Le Conte Crater; and mk = Talapus and Katsuk Buttes. Unit ck is large landslide that originated on west side of Talapus-Katsuk plateau. Silicic volcanic rocks: rd = Devils Hill eruptive episode; rm = Rock Mesa eruptive episode (unit at about 7,200-ft altitude north-east of Rock Mesa includes only tephra vents, no lava flows or domes are present); ro = rhyolite and dacite lava flows and domes of pre-Suttle Lake age (numerous units around South and Middle Sister are omitted but include Devils Hill and Kaleetan Butte); rot = thick rhyolite tephra deposits of pre-Suttle Lake age on ridge tops (includes a mantle of Holocene tephra). Dashed lines near units rd and rm show approximate extents of pyroclastic flows. Thick tephra deposits associated with the eruptions of units rd and rm are not shown but surround most of the vents. Crosses on units rd and rm show locations of vents for large lava flows. Mapping taken or modified from Taylor (1978), Taylor and others (1987), Wozniak (1982), Clark (1983), Scott (1987), and Scott (unpublished mapping).

Below:

Figure 5. Aerial view of area south of South Sister and Stop 5. Sparks Lake is at lower right, Katsuk Butte at lower left, part of South Sister at upper left, and in left of center are some features of the Devils Hill chain of vents and flows.



7.2—Low road cuts in till.  
7.6—Margin of lava flow of Sheridan shield. Park on side of road.

#### STOP 1—LAVA FLOW OF SHERIDAN SHIELD VOLCANO

This basaltic andesite lava flow (53.3 percent SiO<sub>2</sub>) was erupted from the Sheridan shield volcano (Figure 7) based on (1) its geometric relation with overlying flows that form the main part of the shield, and (2) its chemical composition and paleomagnetic direction (Gardner, 1989a,b,c), which are similar to those of other lava flows of the shield. North of the stop, the lava flow is divided into at least two lobes that are separated by left-lateral moraines of the upper Deschutes valley glacier. In a few localities, the base

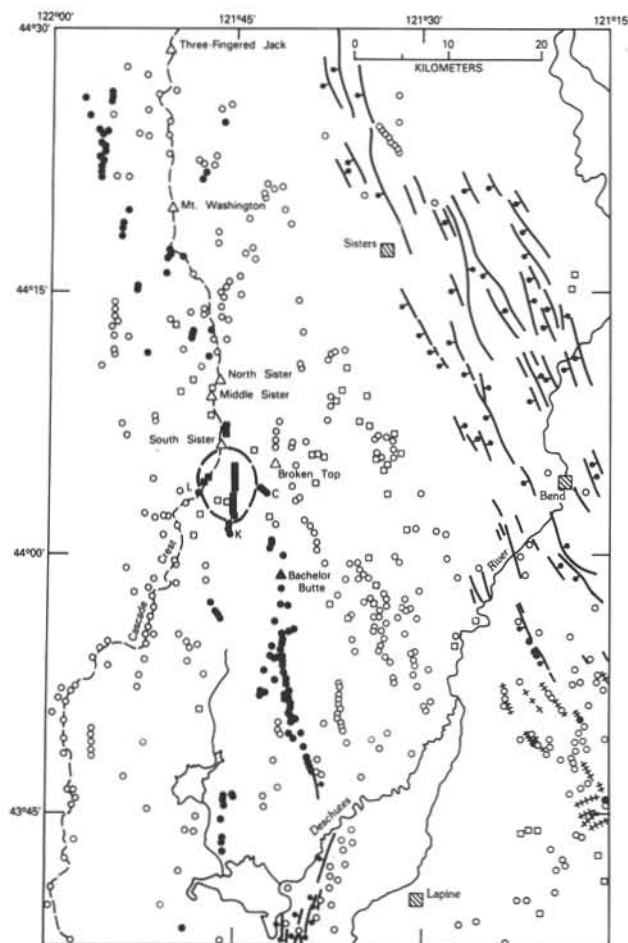


Figure 6. Compilation of vents of Quaternary age and faults in the Three Sisters area (Scott, 1987). Triangles are stratovolcanoes; circles are vents of mafic (basalt and basaltic andesite), mostly monogenetic volcanoes; squares are vents of silicic (dacite and rhyolite) lava domes and flows. Numerous silicic vents on the flanks of South and Middle Sister are not shown. Solid symbols represent vents of latest Quaternary (< 15,000 yr) age; open symbols are vents of pre-latest Quaternary age. L = Le Conte Crater; K = Katsuk and Talapus Buttes; C = Cayuse Crater. Heavy lines are faults; bar and ball on downthrown side. Crossed lines are fissures. The dashed circle represents the maximum extent of a hypothesized magma chamber south of South Sister (Scott, 1987).

of the flow is exposed above unweathered till, suggesting that the flow closely followed deglaciation.

In some places the margin of the flow is partly buried by outwash gravel, indicating that the drainage basin was producing coarse-grained outwash and therefore was probably still significantly glacierized. The lava flow is locally overlain by silty sand that probably originated as loess and eolian sand deflated from till and outwash surfaces. This relation suggests also that glacial conditions still prevailed in the area following the eruption of the lava flow and that active, unvegetated outwash surfaces existed along the Deschutes to provide a source of the eolian sediment. A soil formed in the mantle of eolian sediment and flow rubble is buried by Mazama ash and a scattering of young South Sister tephra.

#### Continue southeast on Road 4270.

**8.0**—Road descends margin of lava flow of Stop 1 onto outwash surface. **Junction with Road 4278. Turn left onto Road 4278 and park near Lodgepole Quarry.**



Figure 7. View to the south from Mount Bachelor. Tot Mountain is at lower right, Kwoh Butte at middle left, and Sheridan Mountain at right of center.

## STOP 2—OUTWASH OF SUTTLE LAKE ADVANCE

Outwash gravel in this quarry was transported from the north and contains clasts of silicic lava from the Three Sisters-Broken Top area. The outwash gravel exposed in a quarry near Deschutes Bridge in the center of the end-moraine belt and till of both right- and left-lateral moraines within several kilometers of the center lack these silicic clasts. This distribution of erratics indicates that the west and the central portion of the glacier consisted of ice from the east slope of the Cascades south of Three Sisters, which is composed mostly of basalt and basaltic andesite. Silicic clasts are abundant only in the far eastern part of the moraine and outwash belt. The relation of the outwash in this quarry to left-lateral moraines of the upper Deschutes glacier suggests that the streams that deposited the outwash probably occupied an ice-marginal position against a pre-Mount Bachelor volcanic chain upland area to the east.

The area north, west, and east of the quarry is now covered by lava flows from the Sheridan shield volcano (unit mb1) and from the Siah chain of vents (unit mb2). The steep-fronted lava flow directly north of the pit is from one of several scoria cones on the west flank of the Sheridan shield that were erupted after the shield was formed (episode 1b of Figure 8). The lava flows are lithologically distinct in both hand specimen and chemistry from lavas of the shield and also have a different paleomagnetic direction, suggesting that a significant period of time elapsed between the formation of the shield and the eruptions of the cones (Gardner, 1989a,b,c).

The low margin of the lava flow of Stop 1 west of the quarry suggests that the margin is partly buried by outwash. If so, the distribution of the lava flow and the pre-Mount Bachelor volcanic chain topography must have allowed meltwater streams to continue flowing east of the lava flow and to transport outwash through this reach.

A soil and surface lag of stones formed in the outwash is buried by about 50 cm of Mazama ash. The soil is formed in gravel and silty sand that is probably loess mixed with gravel. The soil is oxidized to a depth of 55 cm and consists of a Bw and oxidized C horizons. The outwash is gray and contains well-rounded pebble and cobble gravel in a sandy matrix.

**Return to Road 4270 and turn left (southeast).** The road continues on outwash; flow fronts of lavas of the Siah chain (unit mb2) lie in the forest to the left of the road.

**9.2—Junction with paved Road 40; turn left (east) on 40.** The road climbs the north flank of Lookout Mountain, a normally magnetically polarized shield volcano of middle(?) Pleistocene age.

**9.6—View to left of margin of lava flow of Siah chain.**

**10.5—Slow down for view to left of scoria cones of Siah chain, Sheridan shield, Mount Bachelor summit above**



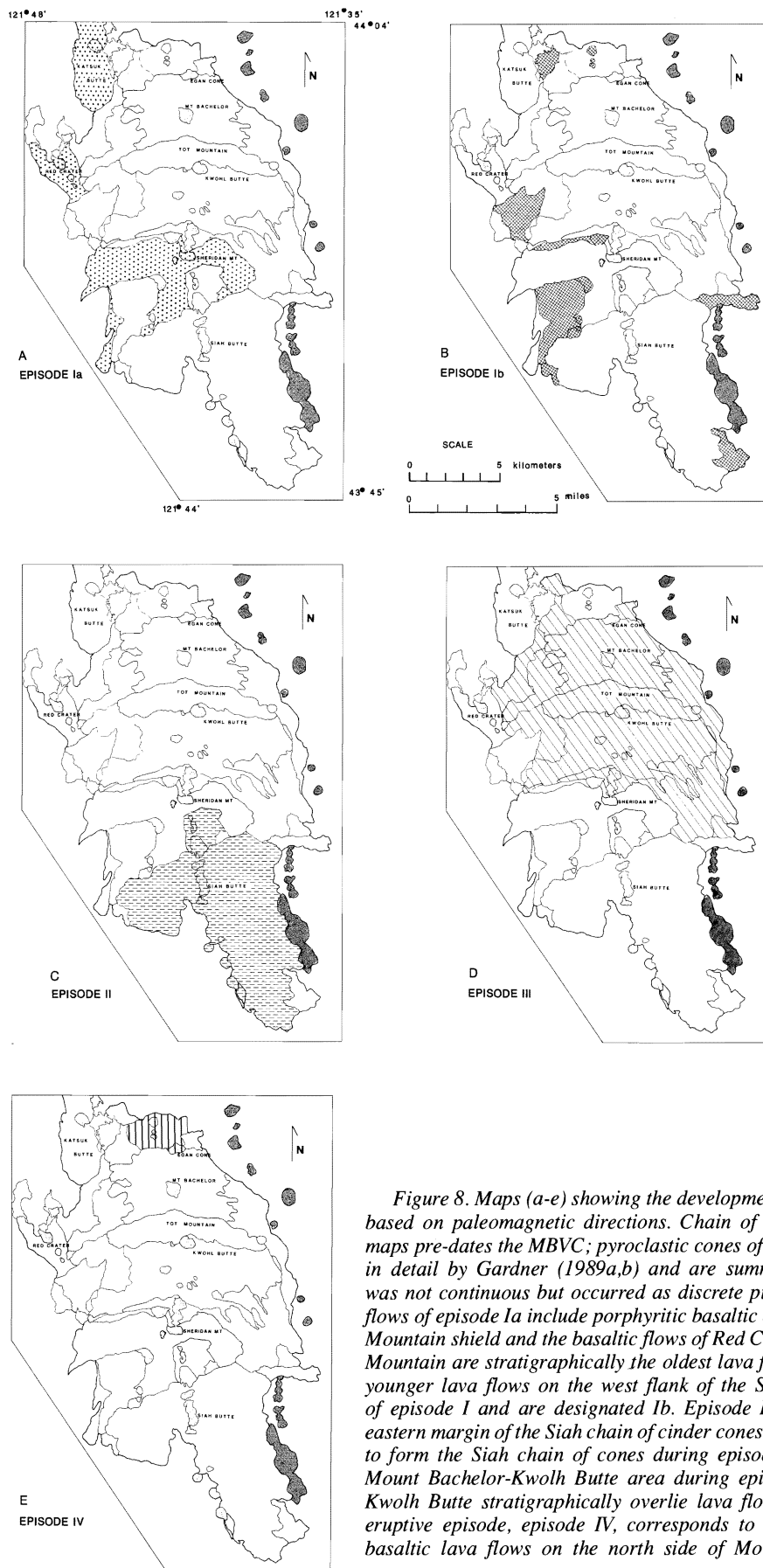


Figure 8. Maps (a-e) showing the development of the Mount Bachelor volcanic chain (MBVC) based on paleomagnetic directions. Chain of vents shown in dark screen along east edge of maps pre-dates the MBVC; pyroclastic cones of MBVC have light stipple. Episodes are discussed in detail by Gardner (1989a,b) and are summarized here. Eruptive activity along the chain was not continuous but occurred as discrete pulses from localized segments of the chain. Lava flows of episode Ia include porphyritic basaltic andesite lava flows from vents along the Sheridan Mountain shield and the basaltic flows of Red Crater and Katsuk Butte. Lava flows from Sheridan Mountain are stratigraphically the oldest lava flows exposed along the MBVC. Stratigraphically younger lava flows on the west flank of the Sheridan shield belong to a later eruptive phase of episode I and are designated Ib. Episode Ib also includes two basalt lava flows from the eastern margin of the Siah chain of cinder cones. Basalt lava flows from numerous vents coalesced to form the Siah chain of cones during episode II. Eruptive activity shifted northward to the Mount Bachelor-Kwohl Butte area during episode III. Lava flows from Mount Bachelor and Kwohl Butte stratigraphically overlie lava flows from the Sheridan and Siah areas. The last eruptive episode, episode IV, corresponds to the emplacement of Egan cone and associated basaltic lava flows on the north side of Mount Bachelor.

Sheridan, and South Sister. Note scoria cones on Sheridan's summit and flanks.

**Caution! The upcoming junction is easy to miss.**

**12.1—Junction with Road 4240; turn right on 4240.**

**12.8—**On left are the Three Trappers. Two of the scoria cones belong to the Siah chain, and one older cone is probably related to Lookout Mountain.

**13.8—**Dry Butte, another cone of the Siah chain, is on the left. Scoria of Dry Butte is exposed in road cuts.

**14.7—**Quarry on left is informally named "South Dry Butte," the southernmost scoria cone of the Mount Bachelor volcanic chain. The vents to the south are small fissures that erupted mostly spatter.

**15.0—**Road curves to right and crosses low spatter-rimmed pits that are difficult to see through the trees.

**15.3—**Road crosses fault scarp that is oblique to the trend of the Mount Bachelor volcanic chain.

**15.6—**Junction with Road 4040 and south end of the Mount Bachelor volcanic chain. **Park along side of Road 4240.**

### STOP 3—TWO VENTS AT THE SOUTH END OF THE MOUNT BACHELOR VOLCANIC CHAIN

The southernmost vents of the Mount Bachelor volcanic chain (Figures 3 and 9) lie just west of the road junction and are the only vents along the chain other than vents in the Katsuk area at the north end that show evidence of magma having interacted with ground water. The vents are marked by elongate craters about 100 m long, 50-75 m wide, and about 15-20 m deep. These vents are also the lowest in altitude of any in the Mount Bachelor volcanic chain and lie about 2 km north of and 30 m higher than the top of the sedimentary fill in the La Pine basin. This

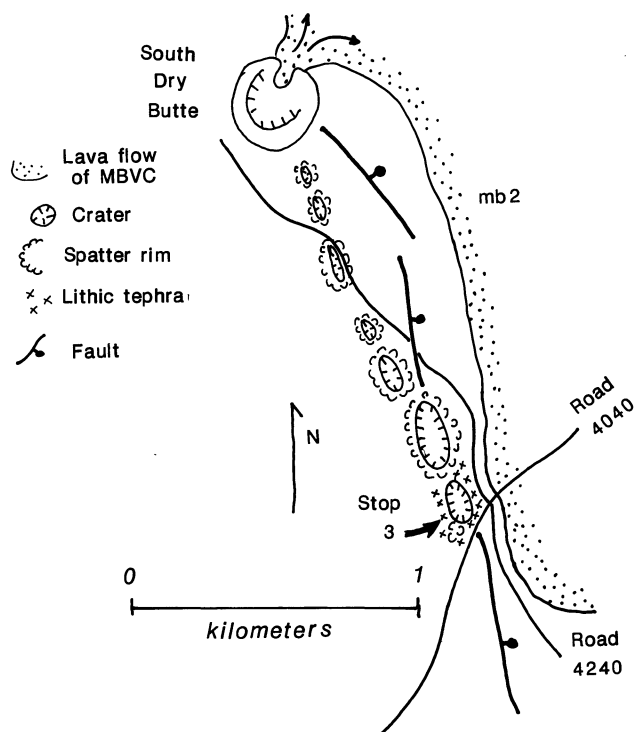


Figure 9. Sketch map of the south end of the Mount Bachelor volcanic chain near Stop 3.

basin lies between the High Cascades and Newberry volcano and may contain a sedimentary fill as thick as 1 km (Couch and Foote, 1985). The ground-water table in the La Pine basin was probably higher than that along many other parts of the Mount Bachelor volcanic chain, and therefore the chance for rising magma to interact with ground water was also greater. Of course, similar evidence in other parts of the Mount Bachelor volcanic chain may be buried by a thick cover of scoria and lava flows.

A shallow quarry and cuts along Road 4040 expose loose to moderately indurated lithic tephra. The tephra is composed of gray lapilli and ash that is much less scoriaceous than the tephra found elsewhere along the Mount Bachelor volcanic chain. Although not as glassy as the hyaloclastite of Katsuk and Talapus Buttes that will be seen at Stop 5, the density of the tephra and its contrast with the later agglutinate spatter suggests some quenching of magma occurred at depth, probably as a result of interaction with ground water. The deposit also contains large (> 1 m) dense, angular blocks of a diktytaxitic basalt lava flow that crops out on the flanks of Lookout Mountain and also in the southern vent. The lithic tephra has a local distribution; there is none in road cuts along Road 4040 just a few tens of meters west of the vent. Presumably the deposit was once there but has since been eroded.

The lithic tephra is overlain by agglutinate spatter and thin basalt lava flows (49.8 percent  $\text{SiO}_2$ ) that were erupted from the southwest corner of the southern vent and from much of the northern pit. An oxidized zone occurs along the contact of the spatter and lithic tephra in the part of the quarry adjacent to the southeast corner of the northern vent but is thought to be related to oxidation by shallow ground water moving along the base of the spatter rather than to soil formation. No such zone occurs in the road cuts, where thin lava flows directly overlie the lithic tephra. However, a lag of coarse rubble on the lithic tephra and below the spatter in the quarry suggests that there may be some time break between deposition of the two units.

The paleomagnetic direction obtained from the thin lava flows in the Road 4040 cuts is identical with others from the Siah chain

and suggests that eruptions of the southernmost vent were broadly synchronous with those that formed large scoria cones and numerous lava flows along other parts of the Siah chain.

A fault trends south of the Mount Bachelor volcanic chain and can be seen south of Road 4040 and west of Road 4240. The fault forms an asymmetric graben with a 2- to 4-m-high scarp on the west and a 1-m-high antithetic scarp on the east. The fault can be traced south for several kilometers as a discontinuous zone of scarps and flexures. Scarps are locally vertical and as high as 5 m, and some have up to 2-m-wide open cracks at their base. Rocks of the Mount Bachelor volcanic chain are apparently not offset by the fault. One possibility in light of historical Hawaiian rift eruptions (Pollard and others, 1983) is that at least some displacement on the fault occurred just before the initiation of eruptions along the southern end of the chain as a feeder dike neared the surface.

**Continue south on Road 4240.** Margins of lava flows of the Mount Bachelor volcanic chain are visible on left; the fault veers west of the road. The road is on lava flows of Lookout Mountain.

**17.4—Junction with paved Road 42 at Fall River Guard Station; turn right (west) on Road 42.**

**19.3—**Views to right of Round Mountain, a 350-m-high scoria cone on the south flank of Lookout Mountain shield volcano. No other scoria cones in the area come close to the size of Round Mountain.

**24.8—Junction with paved Road 4260 to Twin Lakes and Wickiup Reservoir; turn left onto 4260.**

**26.7—**Twin Lakes Resort; view of South Twin Lake.

**27.3—**Turn into small parking area on right side of road.

#### STOP 4—SOUTH TWIN LAKE TUFF RING

**Hike cross-country through the forest, up over a ridge and down to South Twin Lake, which occupies a tuff ring (Figure 10). As there is no trail, you may find it easier to look at the lake at Twin Lakes Resort.**

South Twin Lake is at the south end of a 7-km-long, north-trending chain of vents, the Wuksi Butte-Twin Lakes chain (WBTL, Figure 10), which erupted olivine basalt during latest Pleistocene time. The north end of the WBTL is offset about 8 km west of the south end of the Mount Bachelor volcanic chain in an en-echelon pattern. The WBTL eruptions may have been contemporaneous with some of the early eruptions of the Mount Bachelor volcanic chain. The northern vents of the WBTL are marked by scoria cones surrounded by broad aprons of lava flows; hydroclastic deposits are exposed locally but make up a small volume of the surface deposits. The southern vents produced only hydroclastic deposits and are marked by three tuff rings about 1 km in diameter and one about 0.5 km in diameter. The rings have steep inner walls and gently sloping outer flanks. The rings are composed of fall and base-surge deposits that were generated by numerous explosions as basaltic magma interacted with shallow ground water in the western part of the Shukash-La Pine basin.

**Hike back to the parking area and head to the exposures along the shore of Wickiup Reservoir, which here occupies a narrow valley of the Deschutes River.**

The shoreline exposures reveal about 1.5 m of indurated tuff at a distance of about 200 m from the shore of South Twin Lake. Plane-parallel and wavy bedded and low-angle, cross-stratified tuff (Figure 11) shows evidence of transport outward from the crater by base surges. The tuff overlies fluvial pebble gravel and sand, which, in turn, lie unconformably on strongly deformed fine-grained sediments and diatomite of the basin-fill sequence, visible only when the reservoir water level is low.

The age of the tuff and other eruptive products of the WBTL are not well constrained. Its lava flows east of Crane Prairie Reservoir are overlain by loess and ash in which a well-de-

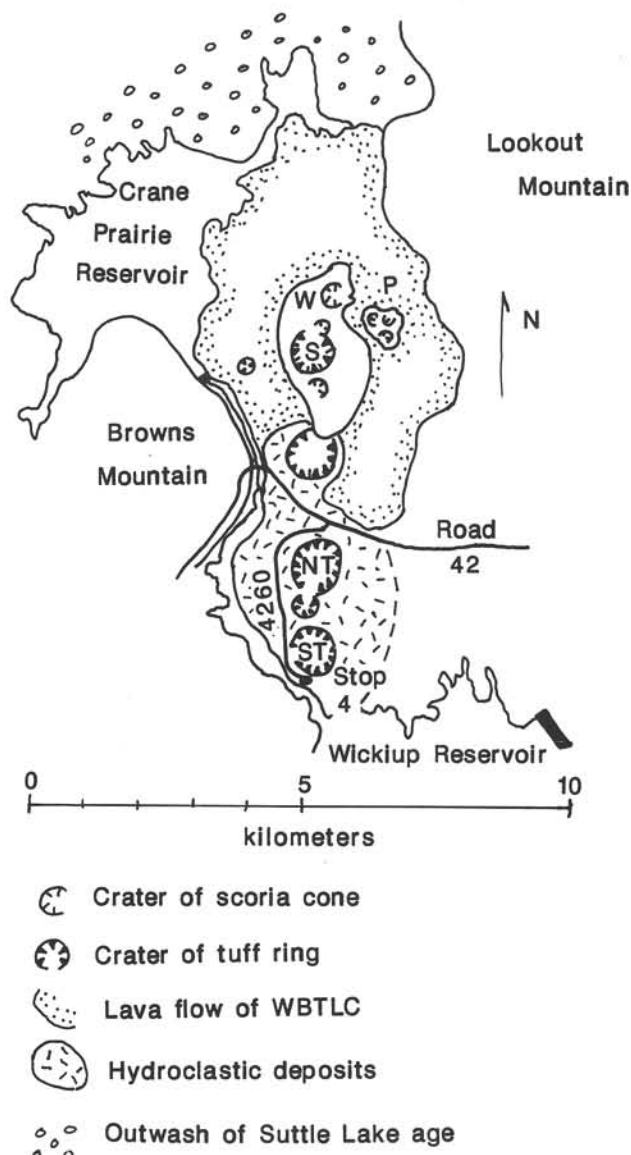


Figure 10. Sketch map of the Wuksi Butte-Twin Lakes volcanic chain and location of Stop 4. W = Wuksi Butte; S = Shukash Butte; P = Palanush Butte; NT = North Twin Lake; ST = South Twin Lake.

veloped soil (75 cm of oxidation; Bw and Cox horizons; 7.5 YR colors in Bw) formed prior to burial by Mazama ash. The lava flows overlie and are, in turn, partly buried by outwash of Suttle Lake age; the tuff at Stop 4 overlies unweathered gravel that is probably outwash of Suttle Lake age. These relations suggest that the WBTLC, as most of the Mount Bachelor volcanic chain, dates from the later part of the Suttle Lake advance and is considerably older than Mazama ash.

**Return to cars and head north on Road 4260 to Road 42.**

**29.8—Junction with Road 42; turn left (west) on 42.**

**31.1—Browns Mountain Crossing of the Deschutes River.** Above this point the Deschutes flows through a narrow valley between an old shield volcano, Browns Mountain, on the west and the latest Pleistocene lava flows and tuffs of the WBTLC on the east.

**31.2—Road to Crane Prairie Dam.** Road cuts ahead are in weathered lava flows of Browns Mountain. Rounded boulders are the result of incipient spheroidal weathering.

**33.7—**On left, margin of a young-appearing lava flow from The Twins, a large shield volcano on the crest of the High Cascades. These lava flows are buried by moraines of Suttle Lake age 4 km west of here, so they must be older than 20,000 years.

**34.3—Junction with Cascade Lakes Highway (Road 46); turn right (north).** Road cuts ahead are in the lava flows discussed at mile 33.7; note the locally well-preserved rubbly flow top beneath a mantle of eolian sediment and tephra.

**35.0—**Views ahead to Cultus Mountain, Middle and South Sister, Broken Top, and Mount Bachelor.

**35.7—**Road cuts expose Mazama ash over a well-developed soil formed in pebble gravel and sand. Gravel overlies well-bedded sand and silt. Significance of these sediments is not known, but they are definitely older than the Suttle Lake advance.

**35.9—**Lava-flow margin at north edge of meadow. Road ahead crosses late Pleistocene lava flows from vents along the Cascade crest. Numerous springs issue from the ends of these flows.

**38.0—**On right, turnoff to Osprey Observation Site.

**38.6—**Road is on outwash of Suttle Lake age, which floors much of the Crane Prairie basin. Cultus Mountain, on left, had major ice tongues of the High Cascades ice cap of Suttle Lake age terminating on both its southeast and northeast flanks; their moraines dam Little Cultus and Cultus Lakes.

**41.5—**Cross Cultus River, another spring-fed stream, which heads at the base of Bench Mark Butte.

**41.9—Junction with Road 40; continue north on Cascade Lakes Highway.**

**43.1—**Road cuts here, and for the next 1.5 mi, expose glassy dacite (65.7 percent  $\text{SiO}_2$ , one analysis) of Bench Mark Butte, which marks an isolated occurrence of dacite in an area that is covered mostly by basalt and basaltic andesite. The flow contains numerous mafic inclusions. The butte is up to 120 m thick, flat-topped, and composed of numerous steep-sided lobes. Its age is not well known, but till of end moraines and outwash of Suttle Lake age lap onto its north and west flanks. Its well-preserved morphology suggests a late Pleistocene age.

**44.7—**Road cuts in till of Suttle Lake age that marks the outermost moraine of the upper Deschutes valley glacier. Numerous other moraines are passed in the next 3 mi.

**45.5—Junction with Road 4270 at Deschutes Bridge; continue north, traveling in part over areas covered earlier in the trip.**

**51.0—Junction with Hosmer Lake-East Elk Lake road. Continue north.** Road follows east margin of lava flow of Red Crater that dams Elk Lake. Red Crater is the northernmost and largest of the 2.5-km-long chain of postglacial scoria cones

**51.9—**Road cut on right exposes a thin layer of 2,000-year B.P. pumice lapilli from the Rock Mesa vent on South Sister,



Figure 11. Bedded tuff exposed at Stop 4 on the shore of Wickiup Reservoir in late summer when the water level is low.

Mazama ash, as much as 50 cm of scoria of Red Crater, and till of Suttle Lake age. Lack of significant weathering of the till below the scoria indicates that the eruption of Red Crater occurred not long after deglaciation.

**52.7**—Turnout on right; view east across Elk Lake to the three major volcanoes of the Mount Bachelor chain (Mount Bachelor, Kwoh Butte, and Sheridan Mountain) and Red Crater.

**53.9**—Intersection with road to Sunset View. Road cuts expose till of Suttle Lake age. This is a good location at which to observe the degree of soil development in till of Suttle Lake age. The depth of the soil is exaggerated here by a mantle of Mazama ash that is mixed into the top of the till; weathering rinds on stones from the B horizon are <0.2 mm thick, which is typical for till of Suttle Lake age.

**56.3**—West margin of postglacial basaltic andesite lava flow from Le Conte Crater, a scoria cone just south of South Sister. The lava flow is older than Mazama ash and may be similar in age to parts of the Mount Bachelor chain. Note the thickening and coarsening blanket of Rock Mesa and Devils Hill tephra. Views of Broken Top ahead.

**56.9**—On right through trees are Talapus and Katsuk Buttes, scoria cones that rise above a steep-sided plateau, the upper part of which is composed of thin basalt lava flows. This plateau owes its peculiar shape to having been erupted against glacier ice. View ahead to Devils Hill, a glaciated rhyolite dome. The south end of the Holocene Devils Hill chain of vents lies on the east flank of Devils Hill. The rugged, blocky surface of the Holocene rhyolite lava domes and flows contrasts markedly with the glacially smoothed and rounded form of Devils Hill.

**58.4**—On right, Devils Lake, which is dammed by the lava flow from Le Conte Crater. Road cuts on left are in hyaloclastite formed by the initial eruptions that built Talapus and Katsuk Buttes and the surrounding basalt plateau. **Park here in turnout on right side of road.**

#### **STOP 5—DEVILS LAKE, TALAPUS AND KATSUK BUTTES, AND DEVILS HILL CHAIN OF DOMES**

This stop focuses on two topics: (1) The formation of Talapus and Katsuk Buttes, and (2) the rhyolite tephra and lava flows and domes of the late Holocene Rock Mesa and Devils Hill eruptive episodes of South Sister. Figure 4 shows the relations among key geologic units in the area around Stop 5.

##### **Talapus and Katsuk Buttes**

Katsuk and Talapus Buttes (Figure 12) are two scoria cones that sit atop a gently south-sloping plateau composed of thin (1-3 m) basalt lava flows. The flows display breccia, locallyropy surfaces, tumuli, and other well-preserved flow-top features. They have obviously not been glaciated, and the recon-



*Figure 12. Katsuk and Talapus Buttes from Mount Bachelor.*

struction of the upper Deschutes glacier shown in Figure 13 indicates that, had the plateau been present, it would have been overridden by ice about 200-300 m thick. The cones and flows are typical of those along the Mount Bachelor volcanic chain, except that they terminate in a steep slope that ranges in height from 25 to 110 m (higher slopes probably occurred near the north end, but they have been partly buried by the lava flow of Le Conte Crater on the west and sediments of Sparks Lake basin on the east). Another atypical feature are the hydrovolcanic deposits (hyaloclastite, in part palagonitized) (Figure 14) that are exposed in the lower slopes at the north end of the plateau and in road cuts both east and west of the young rhyolite flow. Till and erratics are locally present on the slopes underlain by hyaloclastite (Taylor, 1978).

These features imply the following origin: (1) Initial hydrovolcanic eruptions probably occurred in a lake melted into the receding glacier of Suttle Lake age; the glassy hyaloclastite resulted from the rapid quenching of basaltic lava in the water-filled vent followed by explosions that ejected the debris into the lake and onto the surrounding ice or till. The hyaloclastite consists of light-olive-gray to gray, poorly to well-bedded lapilli-and-ash tuff that contains scattered large clasts of juvenile basalt and accidental fragments. The upper part of the tuff in most exposures has been palagonitized and is orange-brown. In all localities, the tuff is pervasively faulted and deformed, probably as a result of syn- and post-depositional mass movements and subsidence caused by melting of underlying glacier ice. (2) As the lake filled with hyaloclastite or drained by opening of channels through the ice margin, water was excluded from the vent, and normal subaerial Strombolian eruptions ensued. The scoria cones of Talapus and Katsuk Buttes were then constructed. Subsequently, lava flows issuing from vents between and at the base of the cones filled the depression that remained in the glacier. Thus the thin flows "sky out" at the steep plateau margins against a now-vanished buttress and form a surface that may have coincided roughly with the surface of the glacier.

A glacier having the slope and thickness of the lava plateau would have had a basal shear stress of about 0.3 bars, which is less than the typical values of basal shear stress (0.5-1.5 bars). Such a low value of basal shear stress suggests that the glacier through which the eruptions occurred was thin and perhaps stagnant. Alternatively, the lava-flow surface may provide only a minimum estimate of ice thickness, and the glacier may have been somewhat thicker. The glacier was probably not greatly thicker than the plateau, in light of the lack of evidence of ice reforming over the plateau following the eruptions. Till and erratic clasts are found only along the base of the north end of the plateau and in road cuts immediately to the east, in which till overlies faulted, bedded hyaloclastite.

Slump blocks composed of the plateau-capping basalt flows lie along the central portions of both the east and west margins of the plateau. Slumping of the steep plateau margin occurred after deglaciation and was perhaps facilitated by underlying bodies of palagonitized hyaloclastite and/or sediments.

The paleomagnetic direction of lava flows at the plateau rim is similar to that of lava flows from the Red Crater area and of the earliest recognized lava flows of the Sheridan shield (episode 1a; Figure 8), which suggests that they could all be coeval.

##### **Holocene rhyolite eruptions of South Sister**

Two tephra units erupted from vents on the flank of South Sister between 2,300 and 2,000 years B.P. (Scott, 1987) are exposed at Stop 5 (Figure 15) and are best viewed in road cuts below the talus of the young rhyolite lava flow or in road cuts east of the flow. The tephras lie on a soil formed in Mazama ash and hydrovolcanic deposits of the Katsuk-Talapus area. The lower tephra is about 10 cm thick and consists of a basal lapilli and coarse ash bed about 3-4 cm thick and an upper light-gray to brownish-gray ash deposit that contains a conspicuous brick-



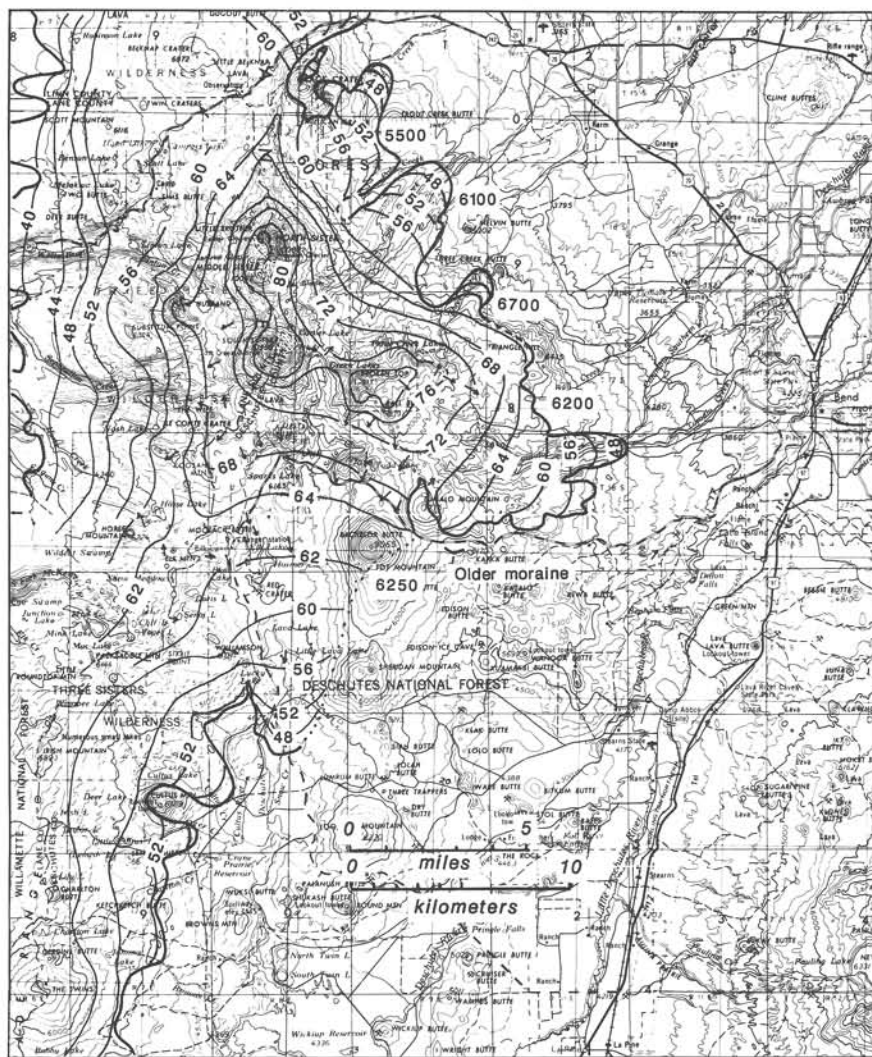


Figure 13. Map showing the reconstructed ice cap of Suttle Lake age in the Three Sisters-Broken Top area. Arrows indicate ice-flow direction as determined from geologic evidence. Contours on the glacier surface are in feet; contour interval is 400 ft, except in the upper Deschutes valley, where a supplementary 6,200-ft contour is shown. ELA (in feet) for several lobes is given by underlined numerals. Older moraine east of Mount Bachelor predates the Suttle Lake advance but is older than Tumalo Mountain.

red marker bed of fine ash about 0.5-1.0 cm thick. The upper tephra is about 65 cm thick and is much coarser grained than the lower unit; individual pumice bombs are as large as 20-30 cm. Lithic fragments are commonly more than 20 cm in diameter in the upper tephra, and several 50-cm-diameter blocks of dacite and rhyolite occur in the layer in nearby road cuts. A significant component of the tephra is juvenile, subpumiceous to glassy, light-gray to black rhyolite; many of the larger clasts display glassy, breadcrusted surfaces. Evidence of reworking, slight weathering, and the accumulation of thin peat between the two tephra layers, which is not well-displayed in the exposures at Stop 5, suggests that they were erupted at least 100 years apart, but no more than a few centuries (Scott, 1987).

The coarse grain size of the upper tephra indicates that it was erupted from nearby vents at the south end of the Holocene Devils Hill chain of vents (Devils Hill itself is a Pleistocene rhyolite dome that lies just west of the south end of the chain) (Figure 4). Lithic fragments of the Pleistocene rhyolite are abundant in the upper tephra layer.

The lower unit with its brick-red marker bed and underlying lapilli can be traced northwestward, thickening and coarsening, to an inferred graben that contains several small domes and lies 1.2 km east of Rock Mesa (RM-ENE, Figures 4 and 16). Thick rims of tephra along the graben indicate that it was a major tephra vent, even though it subsequently produced only small lava domes. This vent also erupted several small pyroclastic flows. A few small elongate craters and open cracks form a 400-m-long chain of vents beginning just a few hundred meters north of the graben. These vented a small amount of tephra, largely after tephra eruptions at RM-ENE had ceased.

Tephra presumably erupted from the vent that subsequently was the source of the Rock

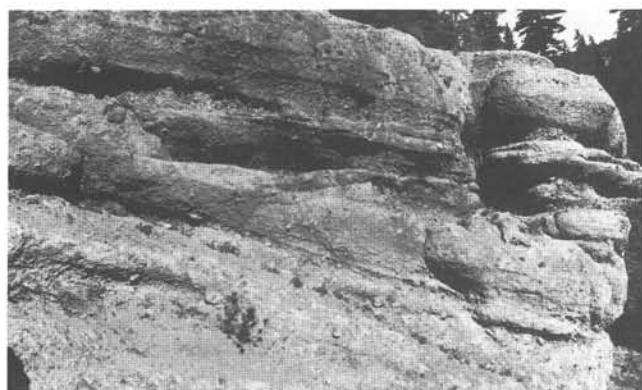
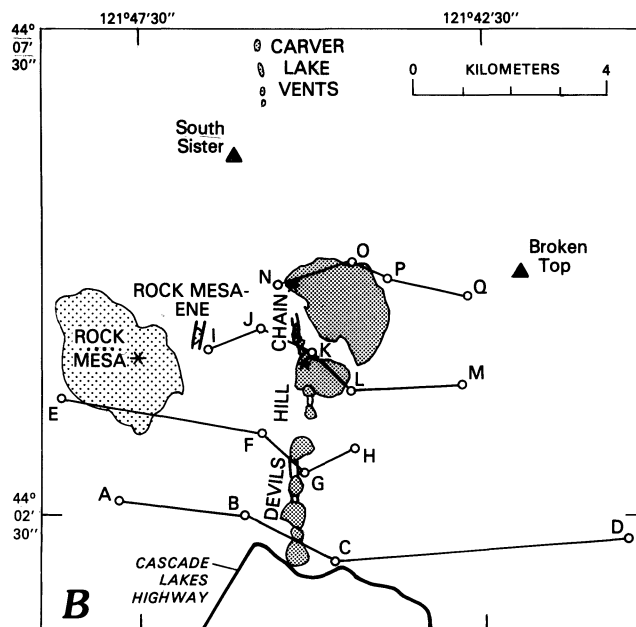
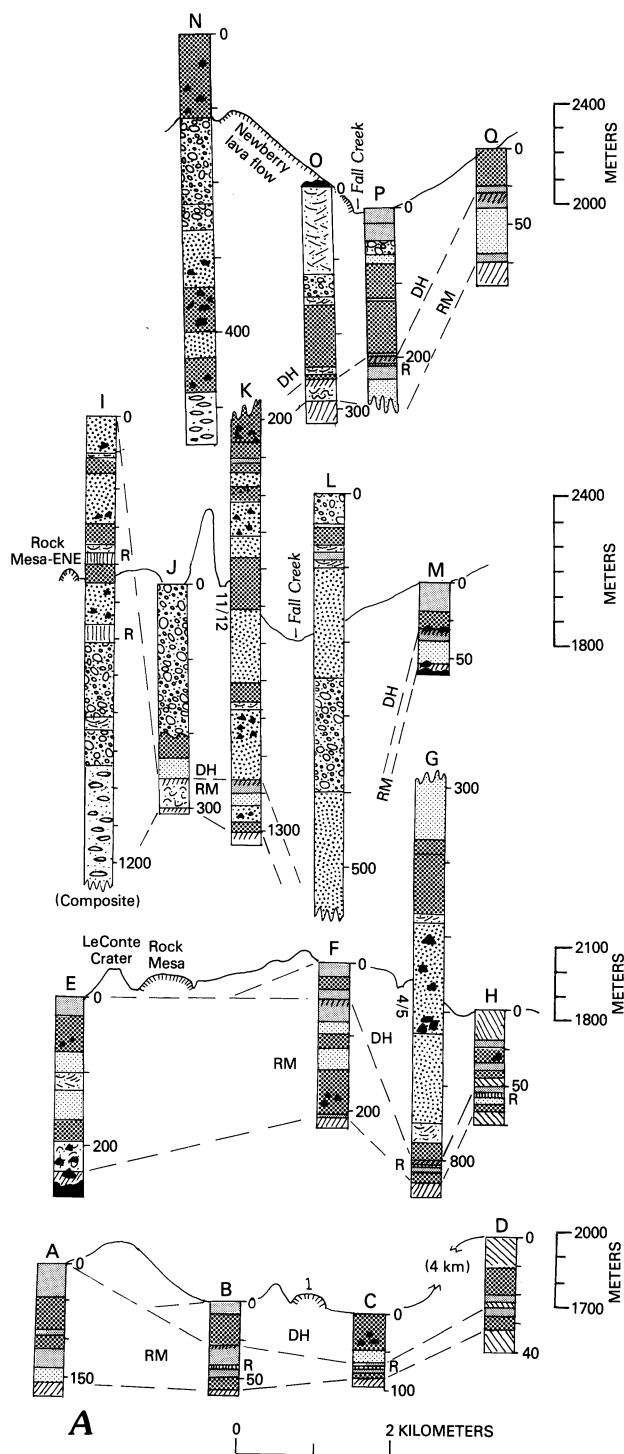


Figure 14. Palagonitized hyaloclastite of Katsuk Butte as it is exposed along the road at Stop 5. This glassy hyaloclastite was produced when, during an eruption, basaltic lava flowed into meltwater from a receding glacier of Suttle Lake age.



Figure 15. Two Holocene tephra described at Stop 5.



# Left and above:

Figure 16. Stratigraphic sections of fragmental deposits of the Rock Mesa (RM) and Devils Hill (DH) eruptive episodes (A) and index map (B) to locations of sections. Units are generalized, especially on longer sections. Most tephra-fall deposits are composed of a few to many beds. The altitude scales (in meters) refer to the topographic profiles; the tops of many sections are shown above the topographic profiles in order to save space on the figure. Note that the thickness scales (in centimeters) differ among sections. On sections K and G, the tops of the upper units are not shown. Section L is shown on the east side of Fall Creek, although it lies on the west side. Surface soils are not shown. The base of the Newberry lava flow is shown on section O. Figure from Scott (1987).

Mesa lava flow overlies the tephra of RM-ENE and forms a south-trending lobe (Figure 17), which is the source of much of the scattered pumice on the ground surface seen at earlier stops. The tephra from the Rock Mesa and RM-ENE vents are chemically identical but can be distinguished in proximal areas by their assemblages of accidental lithic fragments. The lithics of the RM-ENE tephra are dominantly andesite, dacite, and rhyolite, whereas the tephra from the Rock Mesa vent contains a conspicuous proportion of basalt and basaltic andesite.

The tephra units exposed at Stop 5 can be traced over several hundred square kilometers to the north and east (Figure 17). The pumiceous character of the tephra-fall deposits of the Rock Mesa and Devils Hill episodes, their pattern of dispersal (restricted largely to within 30 km of vents), and their associated pyroclastic-flow and surge deposits indicate the sub-Plinian nature (Walker, 1973, 1981) of these eruptions.

The rhyolite lava flow that overlies the tephra marks the south end of the Devils Hill chain of lava flows and domes that extends north in several segments for 5.5 km to an altitude of almost 8,000 ft on the southeast flank of South Sister (Figure 4). Following a gap of several kilometers, the chain continues as a 1.2-km-long segment of small domes on the northeast flank. Several lines of evidence developed at Medicine Lake volcano and the Mono and Inyo volcanoes (Bailey and others, 1983; Fink and Pollard, 1983; Miller, 1985; Eichelberger and others, 1985) suggest that eruptions along the chain were fed by dikes or segments of a single dike

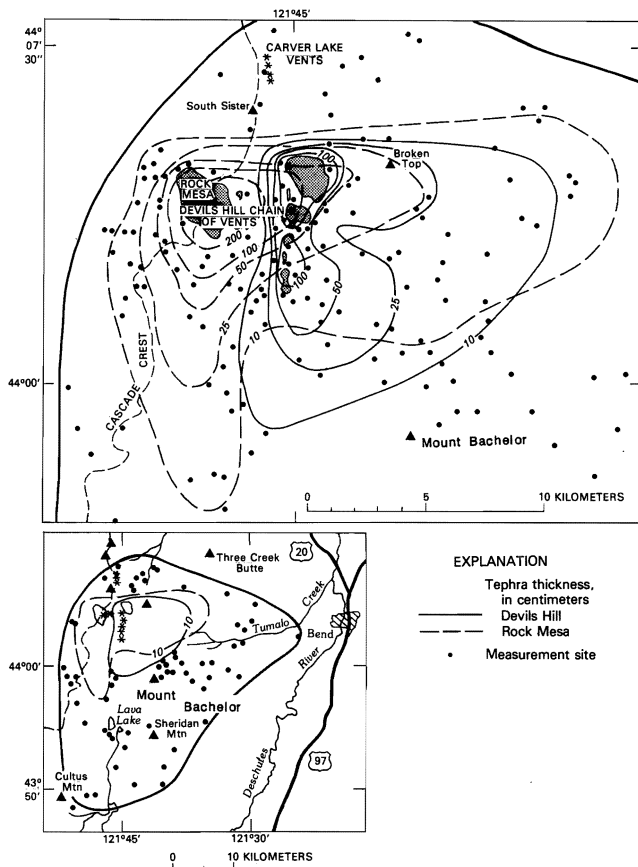


Figure 17. Isopachs of tephra-fall deposits erupted during the Rock Mesa and Devils Hill episodes. Where scale permits, lava flows and domes are outlined; others are located by asterisks. The heavy solid line delineates the approximate outer limit of tephra of both episodes except in the west and southwest, where only tephra of the Rock Mesa episode is present. Modified from Scott (1987).

(Figure 18) (Scott, 1987). These include: (1) Structural features, such as aligned vents, grabens, cracks, and linear fractures over vents of flows and domes parallel to vent alignments, occur; (2) tephra and lava erupted from numerous vents along the Devils Hill chain is of remarkably similar chemical composition (all samples are indistinguishable within analytical uncertainty), which suggests that eruptions were fed from a single source; and (3) eruptions along the chain were nearly synchronous, as shown by the tephra erupted from numerous vents forming a single depositional sequence without evidence of substantial interruptions.

During eruptions of the chain, the inferred feeder dikes were locally enlarged, probably by brecciation and erosion (e.g., Delaney and Pollard, 1981), and these areas emerged as principal conduits. Therefore, the dikes did not supply magma uniformly to vents, especially during the lava-extrusion stage that followed the tephra eruptions. The cumulative-volume curve of Figure 18 shows that several of the higher-altitude vents on the southeast flank of South Sister were the source of most of the erupted material.

#### Return to cars and continue on Cascade Lakes Highway.

**58.6**—On right, hyaloclastite at base of Talapus Butte. On left, southernmost rhyolite lava flow of 2,000 year B.P. Devils Hill chain of vents. Chain extends 10 km from here to northeast flank of South Sister (Figures 3 and 4). Rhyolite flow overlies tephra of the Devils Hill eruptive episode, tephra of the Rock Mesa eruptive episode, Mazama ash, and hyaloclastite of Talapus

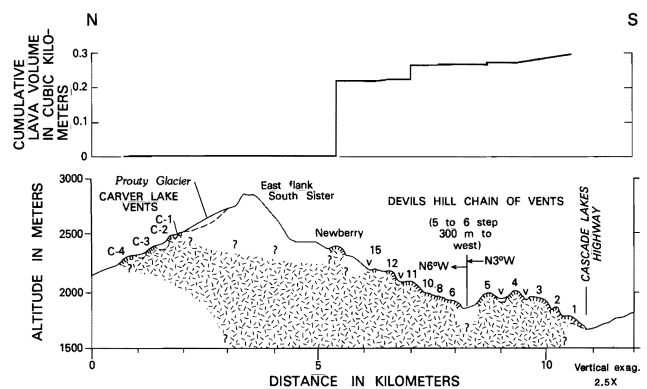


Figure 18. Vertical section along the trend of the Devils Hill chain of vents (1-Newberry) and Carver Lake vents (C-1 to C-4) showing inferred extent of feeder dike (patterned; lower sketch) and the cumulative volume of lava erupted from vents or groups of vents (upper graph). The vents from 6 to C-4 are projected onto a section oriented N. 6° W., even though the strike of individual segments ranges up to N. 13° W. V's show locations of grabens not filled by lavas. Queries indicate great uncertainty in estimating the extent of the inferred dike. The volume erupted from each vent is shown by a vertical line, except where small volumes from closely spaced vents are represented by a gently sloping line. Tephra volume is not included, as it represents only about 5 percent of the total volume of erupted magma. Based on the tephra's distribution (Figure 17), subequal amounts were erupted from the 1-5 and the 6-Newberry vent areas, and an insignificant volume was erupted from the C-1 to C-4 vent areas. Figure from Scott (1987).

and Katsuk Buttes. In road cuts immediately to east, till of Suttle Lake age overlies the hyaloclastite.

**59.6**—View of Mount Bachelor to east. Note prominent vent on north flank skyline (lodge lies just south of vent) that is the source for an apron of lava flows (covered with ski trails) that were erupted following formation of the upper part of Mount Bachelor. View to left of Broken Top volcano and postglacial (> 9,500, < 12,000 yr B.P.) Cayuse Crater (red scoria cone; Figures 3 and 4) that are visible just above trees at edge of meadow.

**60.2**—Road cuts through the end of the basalt lava flow from Cayuse Crater. Immediately past the Cayuse flow is Soda Creek. On October 7, 1966, a flood and debris flow originating from the moraine-dammed lake of the glacier on the east flank of Broken Top descended the channel and piled debris on the road (Nolf, 1969). Fine-grained flood sediment covered about 35-45 percent of Sparks Lake meadow south of the road. Lava flow south of the highway and east of Soda Creek is one of several lava flows that form the youngest unit of the Mount Bachelor volcanic chain and that dam Sparks Lake. They were erupted from Egan cone (informal name), a scoria cone on the north flank of Mount Bachelor (unit mbb, Figure 3). Their stratigraphic relation to the Cayuse flow is unknown, as the flows are not in contact; however, several lines of evidence suggest that the Egan flows are younger (see Stop 6). Road ahead rises onto flank of Todd Lake volcano (Taylor, 1978), a glaciated dacite volcano that predates Broken Top volcano.

**62.2**—On right, margin of basaltic andesite lava flows from Egan cone. On left, unweathered or only slightly weathered till of Suttle Lake age is overlain by basaltic scoria from the northernmost vents of the Mount Bachelor volcanic chain that lie south of highway. Mazama ash and tephra of the Rock Mesa and Devils Hill eruptive episodes overlie the scoria.

**63.5**—On left, glaciated outcrops of basaltic andesite lava

flow from a cone of the Tumalo Mountain chain that is locally overlain by scoria of Bachelor chain, Mazama ash, and tephra of the Rock Mesa and Devils Hill eruptive episodes. Tumalo Mountain is the shield volcano ahead on the left. On the right is a glaciated scoria cone. Ahead is Dutchman Flat, a basin that is closed on the south by lava flows of the Bachelor shield volcano. The upper part of the basin fill is composed mostly of fluvial gray sand, minor silt, and fine gravel; much of the sediment is reworked tephra.

**64.2—Turn right at entrance road to West Village of Mount Bachelor Ski Area; at next intersection bear right.** Egan cone, composed of red scoria, is visible ahead.

**65.0—Park in the southwest corner of the parking area.**

## STOP 6—MAZAMA ASH

A shallow excavation in the southwest part of the West Village parking lot contains a good exposure of Mazama ash, which serves as a valuable stratigraphic marker in the central High Cascades. The age of Mazama ash is  $6,845 \pm 50$   $^{14}\text{C}$  years B.P. (Bacon, 1983; about 7,700 calendar years ago). The ash (Figure 19) lies on unweathered or slightly weathered scoria from nearby Egan cone, the youngest vent of the Mount Bachelor volcanic chain. This lack of substantial weathering suggests that the tephra eruptions of Egan cone are only slightly older than Mazama ash. Mostly reworked Rock Mesa and Devils Hill tephra lies above Mazama ash.

The original thickness of Mazama ash at this site is about 38 cm. The in-place fall deposit is buried by about 70 cm of reworked Mazama ash and scoriaceous ash of Egan cone. The position of this site at the base of a slope probably ensured rapid burial of the fall deposit by reworked material.

Mazama ash exposed here is composed of two distinct units.

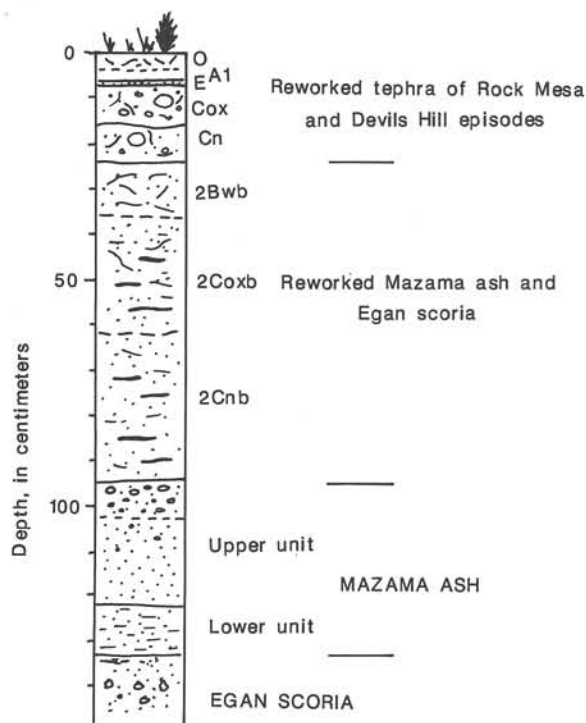


Figure 19. Stratigraphic section of Mazama ash exposed at Stop 6 in excavation at West Village parking lot. Letter and number symbols to right of column are horizon designations of surface and buried soils.

The lower unit is fine- to medium-grained, light-gray to white ash, and contains abundant ferromagnesian minerals and lithic fragments. It is also conspicuously laminated. The upper unit is thicker, coarser grained, and distinctly more yellow than the lower unit. The upper unit ranges from medium to coarse ash at its base to coarse ash and fine lapilli in its upper part. This sequence is typical of Mazama ash in azimuths north-northeast of Crater Lake.

Mazama ash serves as an important stratigraphic marker in central Oregon; its thickness and character make it readily identifiable in the field. Determining the relation of a deposit or surface to Mazama ash is a fundamental task, and, although obvious at this stop, the relation is not always so clear. The deposit of thick reworked ash seen here indicates that the ash has been thinned or removed entirely from other places. The problem of reworking is especially significant at high altitudes where slope processes occur at high rates, as we shall see on the upper slopes of Mount Bachelor.

**Return to Cascade Lakes Highway.**

**65.9—Cascade Lakes Highway. Turn right.** Good view of Broken Top and the Three Sisters to northwest.

**66.4—Turn right into entrance road to Sunrise Lodge; follow road 0.4 mi. to parking lot.**

## STOP 7—MOUNT BACHELOR

(As of 1990, the chair lift was operating for scenic rides between June 30 and September 3 from 10 a.m. to 4:00 p.m. Check each year for dates and times of operation.)

**Ride Sunrise Chairlift (Figure 20) to mid-mountain.** Lift towers are numbered with metal tabs on the cross bar.



Figure 20. Dave and Jenda Sherrod, participants of the 1988 Friends of the Pleistocene meeting in Bend, riding the chairlift up Mount Bachelor.

**Base—**Sunrise Lodge and the base of the lift are on an outwash fan that heads at the only significant stream channel on Mount Bachelor (Figure 21). The channel originates in the cirque on the northeast flank; the drainage proceeds around the northeast and east margin of Bachelor lava flows as Dutchman Creek. Dutchman Creek is typically dry except during spring and early summer snowmelt periods. During lift and lodge construction, excavations in this area exposed, from top down, 1 m of gravel and sand with no or slight soil development, 4-5 cm of Rock Mesa and Devils Hill tephra, 4 m of gravel and sand, about 40 cm of Mazama ash, and several meters of gravel and sand. At a depth of 7 m, the base of the outwash was not exposed but is assumed to be on Bachelor lava flows.

**Tower 5—**Approaching head of outwash fan (just past tower 6). Prior to construction and grading, this area contained a sequence of bouldery debris-flow and/or flood levees. The excavation for tower 5 exposed 1.3 m of levee deposit of late neoglacial age that overlies a weakly oxidized soil developed in Rock Mesa and Devils Hill tephra.



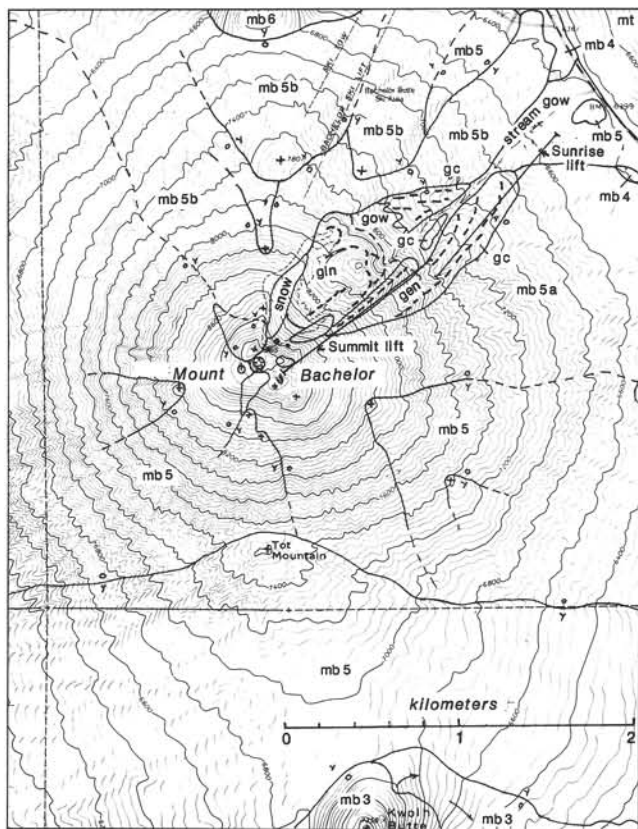


Figure 21. Geologic map of the upper flanks of Mount Bachelor. Unit symbols are the same as in Figure 3 except that the lava flows of the Mount Bachelor summit cone (unit mb5) are locally subdivided into lava flows that predate (unit mb5a) and post-date (unit mb5b) the moraines of Canyon Creek age (gc). mo = lava flows of Tumalo Mountain.

and underlying gravel and sand of probable early neoglacial age. Charcoal fragments on the contact between the buried soil and levee deposit yielded an age of  $1,240 \pm 70$  years B.P. (W-5023). The buried soil consisted of a 2- to 3-cm-thick A1 horizon; a 5-cm-thick patchy E horizon; and a 15-cm-thick, weakly oxidized C horizon.

**Towers 7, 8, 9**—Basaltic andesite lava flows of Mount Bachelor summit cone.

**Tower 10**—Distal slope of end moraine of Canyon Creek age that overlies lava flows of summit cone. Remainder of lift line is in drift of Canyon Creek age. Scoria of Egan cone, Mazama ash, and Rock Mesa and Devils Hill tephra locally lie on the till.

**Top**—The top of the lift is on a thick drift of reworked Mazama ash. Take Summit Chairlift to top of Mount Bachelor.

#### Summit Chairlift

**Up to tower 11**, the Summit Lift crosses the distal slope of a right-lateral moraine that postdates Mazama ash and is of early neoglacial age. Clasts of Rock Mesa and Devils Hill tephra are scattered on the crest and upper slopes of the moraine but typically do not form a layer. Excavations for the lift towers and power cables formerly exposed till, colluvium derived from till, and Rock Mesa and Devils Hill tephra in beds, lenses, and as scattered clasts in colluvium. Little of the tephra is in place; most has been reworked by wind and slope processes.

**Above tower 11**, the lift crosses a lava-flow surface eroded by glaciers of Canyon Creek age (and somewhat smoothed by bulldozers); glacial grooves and striae are common on outcrops of dense



Figure 22. Aerial view of the upper northeast flank of Mount Bachelor, showing moraines of early and late neoglacial ages, moraines of late glacial age, and lava flows of Mount Bachelor that predate and postdate late glacial moraines.

rock. Till and drifts of Mazama ash are present locally. The terminal building at the summit is nestled between several vents.

**Summit**—The summit of Mount Bachelor (Figures 21 and 22) has numerous vents, most of which discharged basaltic andesite lava flows. The summit vents and plugs exposed in the headwall of the cirque are arrayed in a northwest-southeast-trending cluster that forms an elongate summit ridge. The vents are marked mostly by low, blocky domes but also by several shallow collapse craters. Pyroclastic material is scarce, forming only a few remnants of cones of dense scoria that are older than most of the dome vents. The scarcity of pyroclastic material at the summit and on the flanks of the cone indicate that at least the latter summit eruptions were dominantly effusive.

Views from the summit include Newberry volcano to the southeast and the Mount Bachelor volcanic chain to the south. Farther to the south and southwest, numerous shield volcanoes form the bulk of the High Cascades. Some of these shields predate the Brunhes Polarity Chron. Diamond Peak, Mount Thielsen, and Mount Scott (on the east side of Crater Lake) are prominent distant peaks. To the southwest and west, the upper Deschutes River valley contains several lakes dammed by lava flows. The four northern ones (Sparks, Elk, Hosmer, and, except for brief periods, Lava) have no surface outlets; water drains out through the permeable post-glacial lava flows and emerges as springs along the down-valley margins of the flows. Little Lava Lake (and, during high water, Lava Lake) usually forms the head of the Deschutes River. The Three Sisters, Broken Top, and the silicic highland of Taylor (1981) (renamed the Tumalo volcanic center by Hill, 1988, and Hill and Taylor, 1989) east of Broken Top dominate the northern view, with Three-Fingered Jack, Mount Jefferson, Mount Hood, and Mount Adams in the distance.

**Return to base of Summit Chairlift.**

#### Mid-mountain

**From the base of the Summit Chairlift, hike west** to view the moraine sequence of late glacial and neoglacial age and late lava flows of Mount Bachelor that overlie moraines of Canyon Creek age (Figure 21).

**Return to cars in parking lot. Return to Cascade Lakes Highway, and turn right (east).**

**67.2—Cascade Lakes Highway.** For next mile on right, lava flows of the Mount Bachelor summit cone and shield are partly buried by outwash of late-glacial and neoglacial age derived from the glacier on the north flank of Mount Bachelor. On left are lava flows of Tumalo Mountain, which predate the maximum of

the last glaciation. Thick deposits of reworked Mazama ash and underlying scoria of the Mount Bachelor volcanic chain are exposed locally.

**69.5**—On the left is bouldery outwash of Suttle Lake age that lies just south of moraines deposited at margin of ice lobe that wrapped around the east side of Tumalo Mountain (Figure 3).

**69.7**—**Junction with road to Sun River; stay on Road 46.** Most of the hills on both sides of the road are scoria cones that are much older than Mount Bachelor and Tumalo Mountain; a few of the hills are rhyolite domes related to the Tumalo volcanic center.

**72.8**—Road follows narrow outwash channel from ice lobe that terminated just north and northwest of highway. Lack of streams today reflects high permeability of fractured volcanic bedrock.

**76.9**—Road cuts on left expose colluvium that contains a large proportion of matrix. The degree of soil formation is similar

to that in till of Suttle Lake age, which suggests that during the last glaciation colluvial transport (solifluction?) was a very active process on these gentle to moderate slopes.

**79.3**—View to southeast of Newberry volcano, a shield-shaped volcano with a 5-km-wide summit caldera. Newberry is composed of silicic ignimbrites, silicic domes and lava flows, and hundreds of basaltic scoria cones, fissure vents, and related lava flows (MacLeod and others, 1981). Although not high in altitude, the volcano is among the largest (by volume) Quaternary volcanoes in the western conterminous U.S.

**80.5**—Abandoned quarries in outwash gravel that was transported in channel of mile 72.8. Outwash deposits of both Suttle Lake and pre-Suttle Lake age (on basis of weathering-rind thickness) are present.

**85.1**—**Bend city limits. End of field trip part 1.**

Paper connected with field trip

## Temporal relations between eruptions of the Mount Bachelor volcanic chain and fluctuations of late Quaternary glaciers

by William E. Scott, U.S. Geological Survey, Cascades Volcano Observatory, Vancouver, Washington

### INTRODUCTION

Eruptions of the 25-km-long Mount Bachelor volcanic chain (MBVC) and some other nearby vents (Figure 3) coincided with or closely followed the retreat of late Pleistocene glaciers (Scott and Gardner, 1990). These eruptions were dominantly effusive and covered a 250-km<sup>2</sup> area with lava flows. Owing to limited radiocarbon dating of the volcanic deposits, information about the timing of the eruptions relies heavily on the stratigraphic relation of various volcanic units to glacial deposits. Additional details of the volcanic history have been obtained through stratigraphic relations among the volcanic units, which are defined on the basis of their lithology and source, and especially through the use of secular-variation, paleomagnetic dating techniques (Gardner, 1989a,b). The age constraints derived from these studies suggest that the bulk of the chain was formed during a period of less than 10,000 years, perhaps substantially less.

This short paper discusses the glacial-stratigraphic framework of the central Oregon Cascades, the eruptions of the Mount Bachelor volcanic chain and how they fit into the glacial framework, and the neoglacial deposits on the mountain. The stratigraphic nomenclature used in this report and key radiocarbon ages are given in Table 1.

### REGIONAL GLACIAL STRATIGRAPHY

#### Suttle Lake advance

A mountain ice sheet covered the Oregon High Cascades during the last major glacial advance (Russell, 1905; Crandell, 1965), which is locally called the Suttle Lake advance (Scott, 1977). Although not radiometrically dated, the Suttle Lake advance is broadly equivalent in age to the Evans Creek stade of the Fraser glaciation of Washington (Crandell, 1965; Crandell and Miller, 1974) on the basis of similarities in soil development, weathering-rind thickness, and morphology (Scott, 1977). Although not dated directly in the United States, the Evans Creek stade probably culminated about 18,000-22,000 years before the present (18-22 ka), a conclusion based on radiocarbon ages from British Columbia (Porter and others, 1983).

The maximum extents of glaciers of Suttle Lake age are marked in most valleys by conspicuous belts of end moraines (Figure 3). Valleys are typically free of well-developed moraines between these belts and a younger moraine belt that occupies

many valley heads. This distribution of moraines implies that, following their maximum stands, glaciers gradually retreated, with minor stillstands and readvances, leaving a considerable volume of drift in the outer moraine belt. Rates of retreat must have been greater during the time that termini crossed the mid-sections of valleys, because these areas contain no conspicuous moraines and relatively thin drift. Rates of retreat again slowed (and glaciers may even have readvanced some distance) as ice tongues became restricted to valley heads and built conspicuous moraine belts.

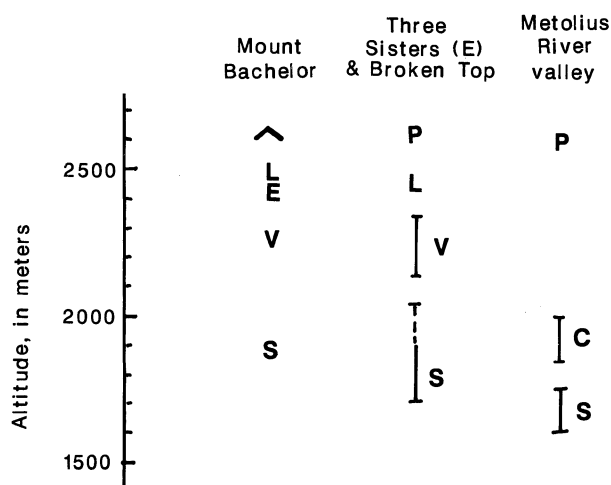


Figure 23. Equilibrium-line altitudes (ELAs) of present-day and reconstructed glaciers in central Oregon. Values for Mount Bachelor and Three Sisters-Broken Top area east (E) of Cascade crest are from Dethier (1980) and this study; values for the Metolius River valley are from Scott (1977). P = present-day glaciers, ^ indicates minimum value; L = glaciers of late neoglacial age; E = glaciers of early neoglacial age; V = valley-head moraines; C = valley-head glaciers of the type Canyon Creek advance; S = glaciers of Suttle Lake age. Bars represent ranges of values that result from ELAs defining surfaces that have substantial gradients.

Table 1. *Stratigraphic framework of selected volcanic and glacial deposits in the Three Sisters-Mount Bachelor area. Parenthetical terms are for correlative events in Washington*

Glacial events		Eruptive products	Age
Neoglaciation	Late neoglacial advance		Culminated during mid?-19th century
		Younger lava flows of Belknap Crater	1,400-1,600 B.P.
		Collier Cone tephra and lava flows	1,600 ± 100 B.P.
		Four-in-One Cone tephra and lava flows	1,980 ± 160 B.P.
		Devils Hill tephra and lava flows and domes	ca. 2,000 B.P.
		Rock Mesa tephra and lava flows and domes	2,150 ± 150 B.P.
	Early neogla- cial advance		
		Mazama ash	6,845 ± 50 B.P.
		Egan cone tephra and lava flow	6,845-12,500 B.P.
		Cayuse Crater tephra and lava flow	9,500-12,500 B.P.
Cabot Creek (Fraser) glaciation	Canyon Creek (Hyak) advance	Late lava flows (and tephra) of Mount Bachelor summit cone	6,845-12,500 B.P.
		Mount Bachelor summit cone and shield	11,000-12,500 B.P.
		Shield of Kwoh Butte	2,000-18,000 B.P.
		Siah chain of vents tephra and lava flows	12,000-18,000 B.P.
		Red Crater tephra and lava flows	12,000-18,000 B.P.
		Le Conte Crater tephra and lava flows <sup>a</sup>	2,000-18,000 B.P.
		Katsuk-Talapus hyaloclastite, tephra and lava flows	6,845-18,000 B.P.
		Wuksi-Twin Lakes chain of vents <sup>a</sup>	15,000-18,000 B.P.
		Summit cone of South Sister <sup>b</sup>	6,845-18,000 B.P.
Suttle Lake ad- vance (Evans Creek stade)		> 11,000 B.P.	
		Culminated	
		18,000-22,000 B.P.	
Jack (Hayden) Creek glaciation			
	South Sister tephtras		
	Formation of Tumalo Mountain shield and chain of scoria cones		
	Much(?) of South Sister		
		75,000 or 140,000 B.P.	

<sup>a</sup> Stratigraphic relations to Red Crater, Sheridan, Siah, Kwoh, Mount Bachelor, and Cayuse units uncertain.

<sup>b</sup> Stratigraphic relation to Suttle Lake advance uncertain.

### Valley-head moraines and the Canyon Creek advance

The belts of moraines in valley heads cover a broad altitude range and are deposits of glaciers that represent a range of equilibrium-line altitudes (ELAs; Figure 23). The moraines extend up to several kilometers beyond moraines of neoglacial age and record the final activity of late Pleistocene glaciers. Unfortunately, these deposits are not well dated. The only radiometric-age control from central Oregon indicates that moraines on Broken Top, which represent an ELA similar to that of the moraines on Mount Bachelor, predate the scoria of Cayuse Crater, which is older than 9,500 years B.P. (Table 1).

The type Canyon Creek drift (Scott, 1977) is composed of a broad belt of valley-head moraines that lies on the northeast side of Three-Fingered Jack in the Metolius River valley (50 km north of Mount Bachelor). Canyon Creek drift is correlated with Hyak drift (Porter, 1976; Porter and others, 1983) of the Washington Cascades on the basis of similarity of reconstructed glacier ELAs relative to those of present-day glaciers and those of glaciers of Fraser age. The age of the Hyak is between 12.5 and 11 ka (Porter and others, 1983).

Many valley-head-moraine systems in the Three Sisters-Mount Bachelor area have ELAs that are up to several hundred meters higher relative to present-day, neoglacial, and Suttle Lake ELAs than those of Canyon Creek age on Three-Fingered Jack (Figure 23). By assuming that ELAs rose steadily with minor halts and

reversals as the last glaciation ended, the moraines on Mount Bachelor could be somewhat younger than the Hyak and type-Canyon Creek moraines. Alternately, some of these differences in late-glacial ELAs may relate to variations of ELA gradients in the region, and the valley-head moraines may all be broadly correlative in age.

One view of late-glacial history is of a time interval of several thousand years during which ELAs were generally rising, glaciers were retreating into valley heads, and glacier termini were becoming more debris laden as their distance from cirque headwall decreased. Conspicuous moraines were built during successive short pauses or readvances. The configuration of valleys was also important in determining the character of the moraine record. For example, on lower-altitude peaks such as Three-Fingered Jack and Mount Washington, the valley-head moraines of Canyon Creek age were deposited by short glaciers largely confined to cirques. In contrast, glaciers with similar ELAs in high-altitude areas like the Three Sisters-Broken Top area would have covered broad upland areas and probably not left much of a depositional record. Not until ELAs had risen to the level at which the glaciers were confined to cirques could conspicuous moraines have been deposited. By that time, glaciers on lower peaks like Mount Washington and Three-Fingered Jack might have been very small or absent, unless, as mentioned above, regional variations in ELA gradients are responsible for some of the observed differences.

Some of the moraines in the Three Sisters-Broken Top area that are older than Mazama ash but lie close to neoglacial moraines

may date from the early Holocene (Dethier, 1980) as has been suggested for moraines in the North Cascades of Washington (Beget, 1984; Waitt and others, 1982). However, no compelling evidence has been found to support such an interpretation for the late-glacial moraines discussed here. The relationship of the > 9,500-year-old Cayuse Crater tephra to moraines on Broken Top shows that they and correlative moraines on Mount Bachelor are pre-Holocene in age. In addition, the 25- to 50-m difference in ELAs between the early Holocene and maximum neoglacial glaciers in the North Cascades is less than the > 100-m difference between glaciers of neoglacial and late-glacial age on Broken Top and Mount Bachelor.

### Neoglaciation

In the field-trip area, I recognize evidence of two minor glacier advances that postdate the deposition of Mazama ash and informally call them "early" and "late" neoglacial. Evidence for an early neoglacial advance is typically found immediately beyond late neoglacial ice limits. However, many glaciers reached their post-Mazama maxima during late neoglacial time and obliterated any moraine record of early neoglacial advances. Moraines of early neoglacial age are less steeply sloping and more round crested than those of late neoglacial age; they commonly support stands of whitebark pines. Soils are typically poorly developed owing to active erosional processes; however, where best preserved their profiles consist of a 5-cm-thick A1 horizon and a 15- to 25-cm-thick weak color B or oxidized C horizon. The ca. 2-ka Rock Mesa and Devils Hill tephra are found on early neoglacial drifts, and ca. 7-ka Mazama ash is found on surfaces immediately beyond them.

### RECONSTRUCTED GLACIERS OF SUTTLE LAKE AGE

During the Suttle Lake advance, a continuous mountain ice cap covered the crest of the Cascade Range in southern and central Oregon, and outlet glaciers flowed down valleys draining both the east and west sides of the range. The highland area around Broken Top provided a broader accumulation area than in other parts of the range, making the ice cap there larger and more complex (Figure 13). In the field-trip area, ice flowed east from the crest of the Cascade Range and south from the Three Sisters-Broken Top area into the upper part of the Deschutes valley to form a large south-flowing glacier that terminated immediately north of Bench Mark Butte (referred to here as the upper Deschutes glacier) (Figures 3 and 13). The eastward extension of the ice cap that occupied the highland east of Broken Top terminated north of the Cascade Lakes Highway and formed a major outlet glacier in the canyon of Tumalo Creek.

A longitudinal profile of the reconstructed upper Deschutes glacier (Figure 24) illustrates several general characteristics of the ice cap. Basal shear stresses of the glacier calculated using the method of Pierce (1979) range from 0.5-1.4 bars (50-140 kPa), which is within the range observed for modern and other reconstructed glaciers (Pierce, 1979; Patterson, 1981). In addition, the lower values occur in areas of compressing (decelerating) flow, and the higher values occur in areas of extending (accelerating) flow, as is typical. The maximum thickness of the glacier, about 1,400 ft (425 m; altitudes of the reconstructed glacier are given in feet to agree with base map), lay near Elk Lake, where the surface slope was small. On the steep upper slopes of South Sister, maximum ice thickness was probably no more than 200 ft (60 m), which is not much greater than the thickness of present-day glaciers (Driedger and Kennard, 1986).

Equilibrium-line altitudes on the ice cap in the Three Sisters-Broken Top area varied greatly (Figure 13), probably largely as a result of differences in precipitation rate. ELAs in the northeastern part of the area near Three Creek Butte were much higher than those farther west. ELAs on the west slope of the High Cascades were more than 1,000 ft (300 m) lower than those on the east side. These patterns probably result from moisture sources lying to the west and southwest and precipitation rates decreasing strongly across the range in a northeasterly direction, which is similar to present conditions.

### TEMPORAL RELATIONS OF ERUPTIVE AND GLACIAL EVENTS

#### Early eruptive history

End moraines of the upper Deschutes glacier of Suttle Lake age form a 7-km-wide belt between Lava Lake and Bench Mark Butte (Figure 3). Lava flows of the Sheridan shield (unit mb1), which include some of the earliest recognized lava flows of the Mount Bachelor volcanic chain, bury much of the east margin of the moraine belt. Therefore, activity along the chain began after about 22-18 ka, the assumed age of the culmination of late Wisconsin alpine glaciation in the Pacific Northwest (Porter and others, 1983). However, it is possible that eruptions began earlier, and their products are buried by younger lava flows.

The following three lines of evidence suggest that some of the earliest eruptions of the Mount Bachelor volcanic chain and eruptions at other vents in the area date from a time after glaciers had retreated from their maximum stands, but while glacial conditions still prevailed in the area.

(1) Lava flows of the Sheridan shield and Siah chain (units mb1 and mb2) on the east side of the outwash-covered basin north

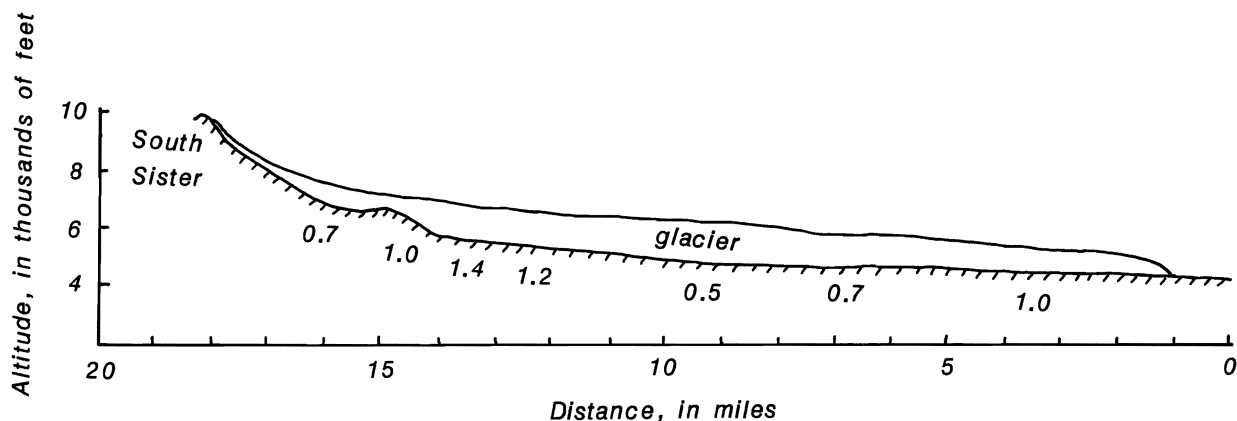


Figure 24. Longitudinal profile of the reconstructed glacier in the upper Deschutes valley. Values along the glacier are basal shear stresses in bars calculated using the method of Pierce (1979).



of Crane Prairie Reservoir, as well as nearby till of the Suttle Lake advance, have thin (< 40 cm) mantles of loess (windblown silt and fine sand). The loess must have been deflated before the end of outwash deposition and before the outwash surfaces became stabilized by vegetation.

(2) As discussed in the road guide (Stop 5), eruptions that formed Katsuk and Talapus Buttes probably began in a lake melted into the retreating glacier that occupied the area around present Sparks Lake.

(3) Scoria erupted from Red Crater (unit mr) directly overlies gray, unweathered till of Suttle Lake age in road cuts along the Cascade Lakes Highway (road log, mi 51.2). The lack of a recognizable weathering profile in the till in a location that appears to be geomorphically stable indicates that the eruptions must have occurred shortly after that site had been deglaciated.

### Later eruptive history

Stratigraphic evidence on Mount Bachelor indicates that the eruptive activity along the chain was waning by the end of late-glacial time (Figure 21). The moraines of Canyon Creek age on Mount Bachelor postdate the construction of most of the summit cone, which is among the youngest features of the Mount Bachelor volcanic chain. The left-lateral moraine is overlain by lava flows erupted from vents on the lower north flank of Mount Bachelor (Figure 3); these flows account for only a small fraction of the cone's volume. Some lava flows on the west, south, and east flanks may also postdate the Canyon Creek advance, but these are separated geographically and cannot be related stratigraphically to the moraines.

As discussed in the previous section on glacial history, the moraines of Canyon Creek age on Mount Bachelor may be somewhat younger than those of the type Canyon Creek drift, which is thought to be 12.5-11 ka on the basis of correlations with the Hyak drift of the Washington Cascades. Evidence obtained locally suggests that the moraines of Canyon Creek age on Mount Bachelor are no younger than 9.5 ka, because a correlative moraine on Broken Top is overlain by the >9.5-ka tephra of Cayuse Crater. Thus, the construction of most of the Mount Bachelor summit cone must have been completed before 9.5 ka and perhaps as early as 12.5 ka.

Stratigraphic evidence indicates that all eruptive activity ended by about 7 ka, because the products of the Mount Bachelor volcanic chain are overlain by Mazama ash, which was erupted from the Crater Lake area 6,850 years B.P. (Bacon, 1983). The original thickness of the ash was about 50 cm at the south end of the chain and about 30-40 cm at the north end (Stop 6). The degree of soil development in scoria of the summit cone and shield volcano of Mount Bachelor (units mb5 and mb4) prior to deposition of Mazama ash suggests that these deposits predate the ash by at least several thousand years. Typically, the soil buried by Mazama ash consists of a cambic B horizon that is 10-20 cm thick and displays weak oxidation extending an additional 10-30 cm into the scoria. In contrast, minimal weathering occurs in the scoria of Egan cone (unit mb6), where it is buried by Mazama ash. This suggests that unit mb6, the youngest of the eruptive products of the Mount Bachelor volcanic chain, may be close in age to Mazama ash. □

## Western Mining Council to meet

The Bohemia Mine Owners' Association will host a Northwest Regional meeting of the Western Mining Council on the weekend of October 13-14, 1990, at Our Lady of Perpetual Help School in Cottage Grove, Oregon (13 miles south of Eugene). All interested prospectors and miners are welcome. Preregistration is required; and the registration deadline is September 25.

For more information, write Sue Hallet, 25199 Perkins Road, Veneta, OR 97487, or call (503) 935-1806. □

## ABSTRACTS

*The Department maintains a collection of theses and dissertations on Oregon geology. From time to time, we print abstracts of new acquisitions that in our opinion are of general interest to our readers.*

### ELEMENTAL ANALYSIS OF ZIRCON SAMPLES FROM PACIFIC NORTHWEST BEACHES BY INAA, by Bilqees Azim (M.S., Oregon State University, 1989), 111 p.

Fifteen sand samples from beaches along the Pacific North were analyzed for their elemental content by the method of instrumental neutron activation analysis (INAA). A separation technique was employed to separate the zircon (a heavy nonmagnetic mineral with a specific gravity of 4.67) from the rest of the sample. This technique worked fairly well for most of the samples. The zircon content of the heavy nonmagnetic samples was in the range of 58-95 percent, except for two northern California beaches which contained appreciable quantities of rutile. The hafnium content of the heavy nonmagnetic sample was fairly constant. The rare-earth pattern in the heavy nonmagnetic samples was similar to that observed in geological samples.

At present, the Oregon beaches are not economically mineable for zircon.

### GEODETIC DEFORMATION OF THE OREGON CASCAIDIA MARGIN, by Paul Vincent (M.S. University of Oregon, 1989), 86 p.

The purpose of this study is to characterize crustal strain and deformation in western Oregon using high-precision vertical and horizontal geodetic data collected by the National Geodetic Survey. North-south leveling data from surveys between 1930 and 1988 along the Oregon coast were differenced and plotted to show change in benchmark elevations with time; a downward tilt toward the Newport-Tillamook region was found. This is interpreted to be the result of a nonuniform coupling between the subducting Juan de Fuca Plate and the overriding North American Plate. East-west leveling data show landward (down-to-the-east) tilt of the Coast Range which supports earlier findings. Historical triangulation data have been analyzed and show no significant horizontal strain accumulation in the Salem area. A GPS survey of the Columbia River network has recently been completed and is expected to yield additional strain information. □

## AMC Mining Convention '90 meets in New Orleans

The American Mining Congress Mining Convention '90 will be held September 23-26 at the Fairmont Hotel in New Orleans. Theme of the Convention is "Challenges in a Changing World."

As featured keynote speaker, U.S. Labor Secretary Elizabeth H. Dole will address labor challenges for the 1990's and beyond. Altogether, 19 sessions will deal with areas of policy and technology concerning the mining industry. □

## BLM office moves

The BLM Oregon/Washington State Office has changed its location in Portland from the Lloyd Tower Building to Providence Office Park, two blocks east of the Tri-Met Hollywood Transit Center in Portland's Hollywood District. The new street address is 1300 NE 44th Avenue, while the mailing address remains the same: P.O. Box 2965, Portland, OR 97208.

—BLM News

# MINERAL EXPLORATION ACTIVITY

## MAJOR METAL-EXPLORATION ACTIVITY

Date	Project name, company	Project location	Metal	Status
April 1983	Susanville Kappes Cassiday and Associates	Tps. 9, 10 S. Rs. 32, 33 E. Grant County	Gold	Expl
May 1988	Quartz Mountain Wavecrest Resources, Inc.	T. 37 S. R. 16 E. Lake County	Gold	Expl
June 1988	Noonday Ridge Bond Gold	T. 22 S. Rs. 1, 2 E. Lane County	Gold, silver	Expl
September 1988	Angel Camp Wavecrest Resources, Inc.	T. 37 S. R. 16 E. Lake County	Gold	Expl
September 1988	Glass Butte Galactic Services, Inc.	Tps. 23, 24 S. R. 23 E. Lake County	Gold	Expl
September 1988	Grassy Mountain Atlas Precious Metals, Inc.	T. 22 S. R. 44 E. Malheur County	Gold	Expl, com
September 1988	Kerby Malheur Mining	T. 15 S. R. 45 E. Malheur County	Gold	Expl, com
September 1988	Jessie Page Chevron Resources Co.	T. 25 S. R. 43 E. Malheur County	Gold	Expl
October 1988	Bear Creek Freeport McMoRan Gold Co.	Tps. 18, 19 S. R. 18 E. Crook County	Gold	Expl
December 1988	Harper Basin American Copper and Nickel Co.	T. 21 S. R. 42 E. Malheur County	Gold	Expl
May 1989	Hope Butte Chevron Resources Co.	T. 17 S. R. 43 E. Malheur County	Gold	Expl, com
September 1989	East Ridge Malheur Mining	T. 15 S. R. 45 E. Malheur County	Gold	App
June 1990	Racey Billiton Minerals USA	T. 13 S. R. 41 E. Malheur County	Gold	Expl
June 1990	Grouse Mountain Bond Gold Exploration, Inc.	T. 23 S. Rs. 1, 2 E. Lane County	Gold	Expl
June 1990	Freeze Western Mining Corporation	T. 23 S. R. 42 E. Malheur County	Gold	Expl

Explanations: App=application being processed. Expl=Exploration permit issued. Com=Interagency coordinating committee formed, baseline data collection started. Date=Date application was received or permit issued.

## STATUS CHANGES

No status changes in DOGAMI permits were recorded since the last issue of Oregon Geology. Public scoping workshops for an Environmental Impact Statement that is being prepared for the Grassy Mountain project proposed by Atlas Precious Metals, Inc., were held by the Bureau of Land Management in Ontario and Portland on August 21 and 22, respectively.

Numerous new applications for exploration projects are expected in the next few months, as companies comply with the lower thresholds included in House Bill 2088. Many companies active in Oregon are already following the procedures required by the new rules, and no major implementation problems are anticipated.

## EXPLORATION AND BOND CEILING RULES

Rules implementing House Bill 2088 regarding exploration were adopted by the Governing Board of the Department of Geology and Mineral Industries (DOGAMI) on July 9. The rules were filed with the Secretary of State on August 3 and became effective on that date. All companies engaged in mineral exploration in Oregon should get in contact with the Department's Mined Land Reclamation (MLR) office in Albany immediately to make sure that their projects are in compliance with the new revised statutes and new rules.

Questions or comments about mineral-exploration permitting should be directed to Gary Lynch or Allen Throop at the MLR office, 1534 SE Queen Street, Albany, Oregon 97321, phone (503) 967-2039. □

## Mining companies honored

At the Northwest Mineral Industry Meeting in Portland in May, the Eastern Oregon Mining Association (EOMA), Hecla Mining Company, and THC, Incorporated, received special recognition certificates from the U.S. Bureau of Land Management (BLM) and the USDA Forest Service (USFS) for their demonstrations of good land stewardship in Oregon.

EOMA was named Region 6 Mineral Operator of the Year by the USFS for its voluntary reclamation of two mine sites, the Peerless and Old Crow 80, on Wallowa-Whitman National Forest land. The mines had been abandoned in 1896 with little or no reclamation accomplished.

Hecla Mining Company of Coeur d'Alene, Idaho, and THC, Inc., of Pasco, Wash. were honored by BLM for their cooperation during exploration drilling operations within the Oregon Trail Area of Critical Environmental Concern and the National Historic Oregon Trail Interpretive Center site at Flagstaff Hill near Baker City.

The operators were commended for creating only minimal surface disturbance and for reclaiming the site after completion of the project. The companies also granted easements to BLM so that work on the Interpretive Center could proceed without interruption, and Hecla volunteered to provide up to \$100,000 for the interpretation of modern mining at the Center, if the company should develop an open-pit mine at the site. —BLM News

(DOGAMI publications, continued from page 98)

glomerate. This sequence correlates with the offshore marginal sequence of the Astoria Basin beneath the inner continental shelf.

**Released September 4, 1990: *Silica in Oregon***, by staff geologist R.P. Geitgey, Appendix by staff geochemist G.L. Baxter. DOGAMI Special Paper 22, 18 p., 2 plates (1 sample-location index on a 1:1,000,000-scale base map and 1 sheet containing analytic data in tables and histograms), \$7.

Silica is produced by three companies in Oregon for various end uses including nickel smelting and production of colored container glass; ferrosilicon; filter bed media; and decorative rock for exposed-aggregate panels, roofing, and landscaping. The new report reviews these operations and surveys other silica occurrences to identify additional sources of silica and industrial sand. Basic chemical, mineralogical, and screen-size data are presented for 45 samples from a variety of geologic environments throughout the state. Nine broad areas where silica occurs are described, and resources of potential commercial interest are identified in Clatsop, Malheur, and Morrow Counties.

Both publications are now available at the Oregon Department of Geology and Mineral Industries, 910 State Office Building, 1400 SW Fifth Avenue, Portland, Oregon 97201-5528. Orders may be charged to credit cards by mail, FAX, or phone. FAX number is (503) 229-5639. Orders under \$50 require prepayment except for credit-card orders. □

## AVAILABLE DEPARTMENT PUBLICATIONS

### GEOLOGICAL MAP SERIES

	Price ✓
<b>GMS-4</b> Oregon gravity maps, onshore and offshore. 1967	3.00
<b>GMS-5</b> Geologic map, Powers 15-minute Quadrangle, Coos/Curry Counties. 1971	3.00
<b>GMS-6</b> Preliminary report on geology of part of Snake River canyon. 1974	6.50
<b>GMS-8</b> Complete Bouguer gravity anomaly map, central Cascade Mountain Range. 1978	3.00
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<b>GMS-13</b> Geologic map, Huntington and parts of Olds Ferry 15-minute Quadrangles, Baker and Malheur Counties. 1979	3.00
<b>GMS-14</b> Index to published geologic mapping in Oregon, 1898-1979. 1981	7.00
<b>GMS-15</b> Free-air gravity anomaly map and complete Bouguer gravity anomaly map, north Cascades, Oregon. 1981	3.00
<b>GMS-16</b> Free-air gravity and complete Bouguer gravity anomaly maps, south Cascades, Oregon. 1981	3.00
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<b>GMS-18</b> Geology of Rickreall/SalemWest/Monmouth/Sidney 7½-minute Quadrangles, Marion/Polk Counties. 1981	5.00
<b>GMS-19</b> Geology and gold deposits map, Bourne 7½-minute Quadrangle, Baker County. 1982	5.00
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<b>GMS-24</b> Geologic map, Grand Ronde 7½-minute Quadrangle, Polk and Yamhill Counties. 1982	5.00
<b>GMS-25</b> Geology and gold deposits map, Granite 7½-minute Quadrangle, Grant County. 1982	5.00
<b>GMS-26</b> Residual gravity maps, northern, central, and southern Oregon Cascades. 1982	5.00
<b>GMS-27</b> Geologic and neotectonic evaluation of north-central Oregon. The Dalles 1° x 2° Quadrangle. 1982	6.00
<b>GMS-28</b> Geology and gold deposits map, Greenhorn 7½-minute Quadrangle, Baker and Grant Counties. 1983	5.00
<b>GMS-29</b> Geology and gold deposits map, NE¼ Bates 15-minute Quadrangle, Baker and Grant Counties. 1983	5.00
<b>GMS-30</b> Geologic map, SE¼ Pearsons Peak 15-minute Quadrangle, Curry and Josephine Counties. 1984	6.00
<b>GMS-31</b> Geology and gold deposits map, NW¼ Bates 15-minute Quadrangle, Grant County. 1984	5.00
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<b>GMS-34</b> Geologic map, Stayton NE 7½-minute Quadrangle, Marion County. 1984	4.00
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### BULLETINS

<b>33</b> Bibliography of geology and mineral resources of Oregon (1st supplement, 1936-45). 1947	3.00
<b>35</b> Geology of the Dallas and Valselt 15-minute Quadrangles, Polk County (map only). Revised 1964	3.00
<b>36</b> Papers on Foraminifera from the Tertiary (v. 2 [parts VII-VIII] only). 1949	3.00
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<b>46</b> Ferruginous bauxite, Salem Hills, Marion County. 1956	3.00
<b>53</b> Bibliography of geology and mineral resources of Oregon (3rd supplement, 1951-55). 1962	3.00
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<b>65</b> Proceedings of the Andesite Conference. 1969	10.00
<b>67</b> Bibliography of geology and mineral resources of Oregon (4th supplement, 1956-60). 1970	3.00
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17 Onshore-offshore cross section, from Mist Gas Field to continental shelf and slope. 1990	9.00

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Geologic map of Oregon east of 121st meridian (U.S. Geological Survey Map I-902). 1977 (blackline copy only)	6.10
Geological highway map, Pacific Northwest region, Oregon, Washington, and part of Idaho (published by AAPG). 1973	5.00
Landforms of Oregon (relief map, 17x12 in.)	1.00
Oregon Landsat mosaic map (published by ERSAL, OSU). 1983	10.00
Geothermal resources of Oregon (published by NOAA). 1982	3.00
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Bend 30-minute Quadrangle geologic map and central Oregon High Cascades reconnaissance geologic map. 1957	3.00
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Mist Gas Field Map, showing well locations, revised 1990 (Open-File Report O-90-1, ozalid print, incl. production data)	7.00
Northwest Oregon, Correlation Section 24. Bruer and others, 1984 (published by AAPG)	5.00
Oregon rocks and minerals, a description. 1988 (DOGAMI Open-File Report O-88-6; rev. ed. of Miscellaneous Paper 1)	5.00
Mining claims (State laws governing quartz and placer claims)	Free
Back issues of <i>Ore Bin/Oregon Geology</i> , 1939-April 1988	1.00
Back issues of <i>Oregon Geology</i> , May/June 1988 and later	2.00
Color postcard: Oregon State Rock and State Gemstone	.50

Separate price lists for open-file reports, geothermal energy studies, tour guides, recreational gold mining information, and non-Departmental maps and reports will be mailed upon request. The Department also sells Oregon topographic maps published by the U.S. Geological Survey.

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