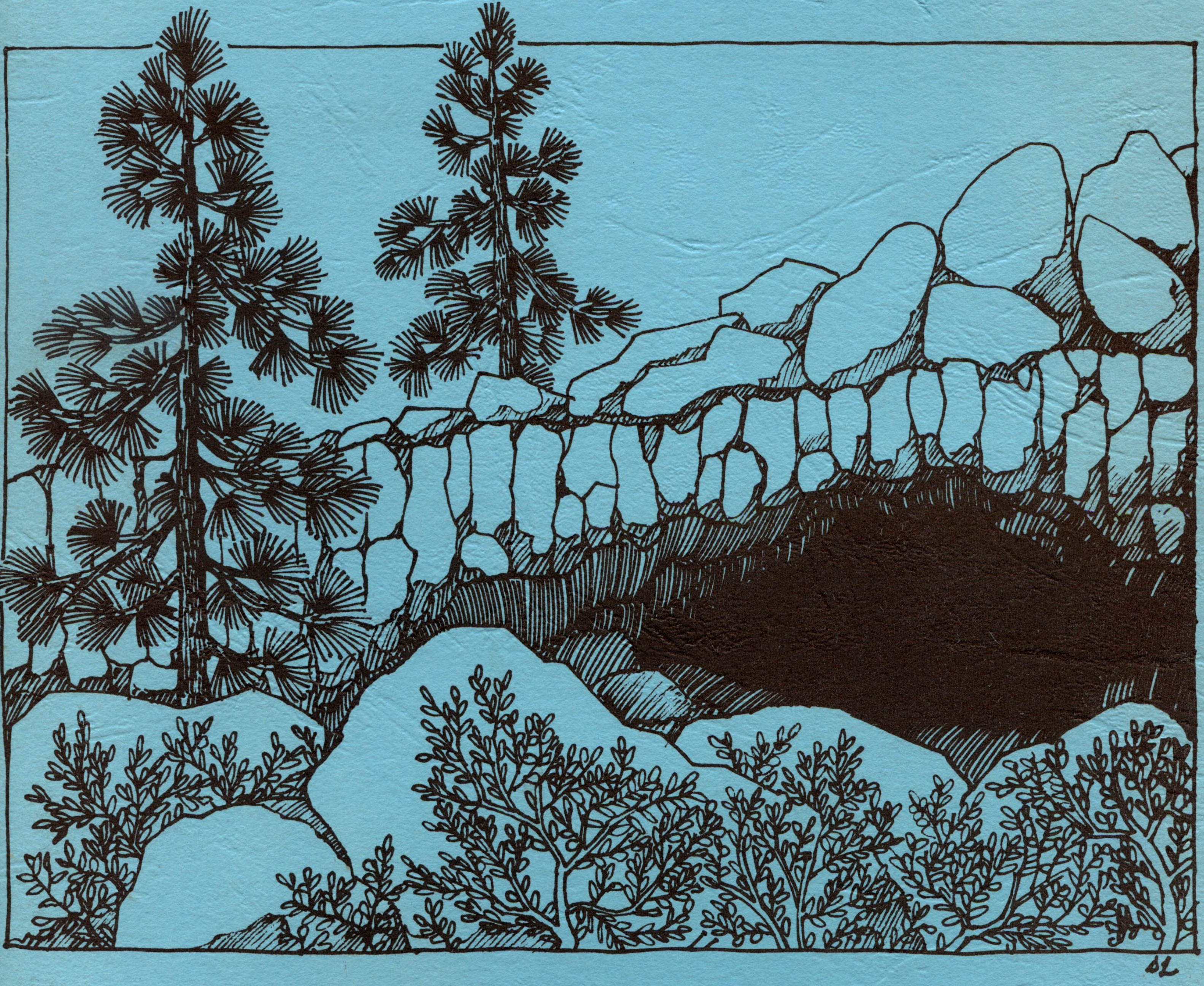
CAVES AND OTHER VOLCANIC LANDFORMS OF CENTRAL OREGON



Guidebook NSS Geology & Biology Field Trip 1982

Cover by Susan Lindstedt.

OREGON GROTTO PRESS

CAVES AND OTHER VOLCANIC LANDFORMS OF CENTRAL OREGON

Guidebook of the
Geology and Biology Field Trip
National Speleological Society Annual Convention
Bend, Oregon
June 27 - July 3, 1982

edited by
Lynne Sims &
Ellen M. Benedict

TRAVEL AND HIKING HINTS

FOR YOUR ENJOYMENT AND THAT OF OTHERS, AND FOR YOUR OWN SAFETY:

-- Bring CAVING LIGHTS, GOOD WALKING SHOES, WARM CAVING CLOTHING. In case the weather is hot, you will want lightweight clothing for surface travel and a jacket to wear at night.
-- Use caution if you smoke (or use a carbide lamp) -- the woods are dry during the summer.
-- Stay on marked trails when routes are designated.
-- Avoid throwing or kicking objects from high elevations -- someone could be standing below and get hurt.
-- Pack it out if you pack it in -- avoid littering.
-- Remember it took thousands of years of geologic and biologic activity to create the landscape of central Oregon, but only a few seconds of carelessness or thoughtlessness can destroy its features. Please do not collect or destroy plants, animals or rocks (this also applies to ice in ice caves).

IF YOU TAKE THIS FIELD TRIP ON YOUR OWN:

Remember that the "Oregon High Desert" east of Bend has only limited tourist facilities where you can buy gasoline or food, and get water! Therefore:

-- Fill your vehicle with gasoline before leaving an inhabited area. Gasoline is sold in the towns along U.S. Highway 97 and 20, at the resorts of East and Paulina Lakes (Newberry Volcano), and at the small communities of Fort Rock and Silver Lake. Stations close early. Carry water, food and toilet paper as these items are few and far between!
-- Carry and use a map of the Deschutes National Forest.
-- Keep your vehicle on a hard packed surface or an obvious parking area. Or you may spend most of your time digging out of loose cinder, volcanic ash or clay. Carry a shovel, axe and bucket.

ACKNOWLEDGEMENTS

Many individuals and institutions contributed either directly or indirectly to this Geology and Biology Field Trip Guidebook which is a logical outgrowth of my field trips over the past decade which focus on all aspects of the natural world, including geology. Special thanks are due to my students in the 1982 "Biota and Volcanic Landforms" class from the Malheur Field Station of Pacific University for testing part of the tour route during our week long camping trip in the Bend area; to my husband Ben for helping plan the route, copying the signs and reviewing the text; to Susan Lindstedt for drawing the biota; to Mike and Lynne Sims for typing the guidebook on their word processor; to Frank Ireton, Russ Harter and Bill Harter for contributing papers; to Larry Chitwood, Geologist, Deschutes National Forest, and Douglas Troutman, Wilderness Specialist for the Lakeview District, Bureau of Land Management, for answering question; to the U.S. Geological Survey and the Oregon Department of Geology and Mineral Industries for granting the use of the figures from their publications; and to Charlie Larson and his staff for producing the completed guidebook. Finally I owe a debt of gratitude to all the authors whose works provided information, especially the authors of Guides to Some Volcanic Terranes in Washington, Idaho, Oregon and Northern California, Geological Survey Circular 838, which was written for the field trips held in conjunction with the Pacific Northwest American Geophysical Union meeting held in Bend, Oregon, September 1979.

-- E.M.B. --

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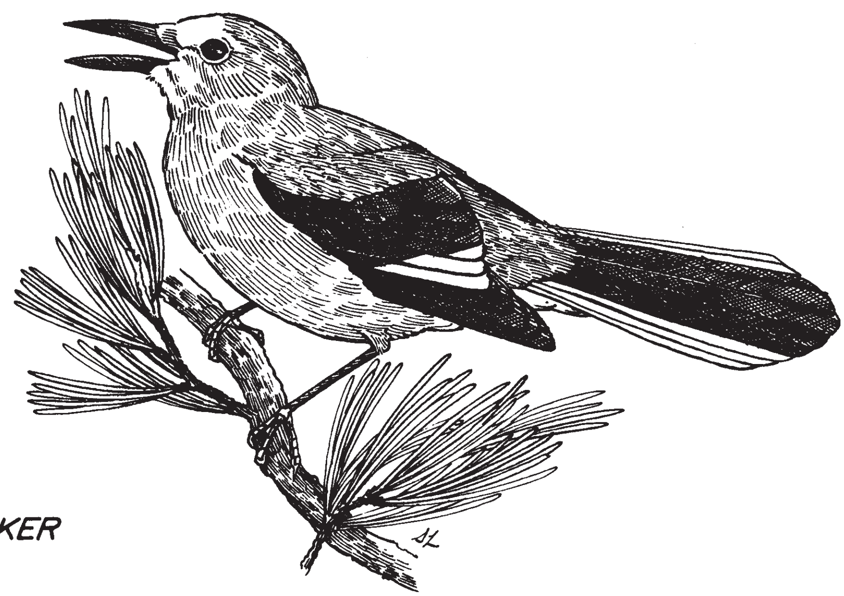

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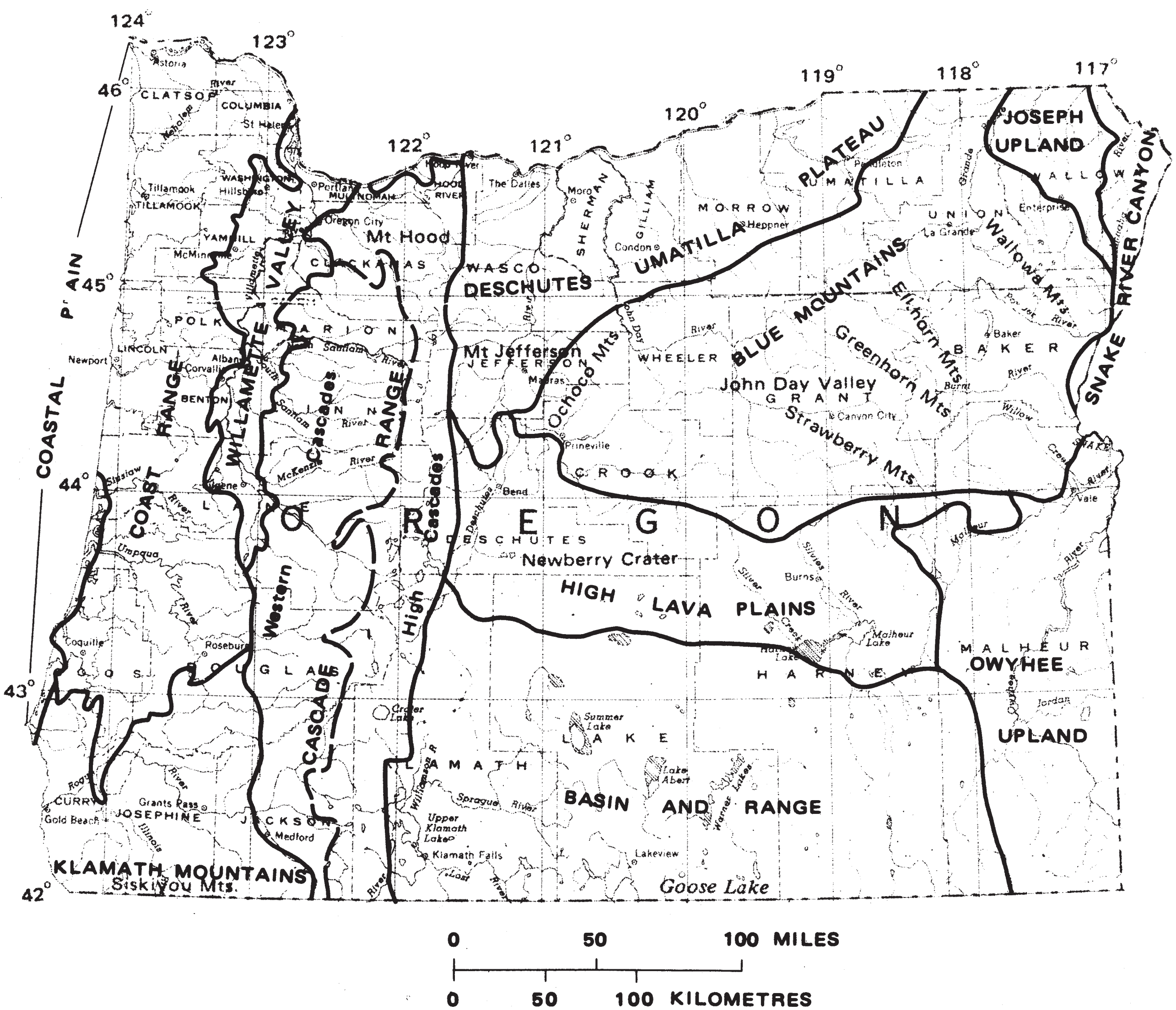

Fig. 1. Geomorphic divisions of Oregon. From Walker (1977).

PROLONGED COLLISION
LAND OF A THOUSAND VOLCANOES

Ellen M. Benedict*

This field trip through parts of the High Lava Plains and the Basin and Range physiographic provinces of Oregon (Fig. 1), exposes you to a diversity of outstanding volcanic features representing various chemical and physical forms of igneous rocks and to a variety of interesting organisms which are typical of the surface and subsurface habitats. Although this is the 39th Annual Convention of the National Speleological Society, it is the first one held in Oregon, and the second in a non-calcareous area. Therefore "Geology of Lava Tube Caves" by Russ and Bill Harter provides background on basaltic caves and "Prolonged Collision" relates plate tectonics and regional geology. Larry Chitwood gives the geologic overview (Convention Guidebook).

VULCAN'S REALM AND PLATE TECTONICS

When Vulcan, blacksmith of the gods, hammers at his forge, sparks and thunderbolts fly, creating volcanic eruptions, while smoke, flame and ash shoot up volcanic vents. Thus the ancients invoked the gods to explain mystifying events. To them our theories of sea floor spreading and plate tectonics might seem equally fanciful. Yet scientific evidence supports these theories and the geologic history of Oregon is being reinterpreted in these terms, e.g., David Alt and Donald Hyndman (1981:1), geologists from the University of Montana, write in their Roadside Geology of Oregon, "The geology of Oregon, indeed, the very existence of Oregon is the product of a prolonged collision between the North American continent and the Pacific Ocean floor which began about 200 million years ago and continues today" (Fig. 2). This is a rather newly accepted concept. To illustrate, the first edition of Geology of Oregon by Ewart Baldwin was published in 1964 before plate tectonics came into general acceptance in the United States. When Baldwin (1981:xiii) produced his third edition, after teaching at the University of Oregon for 33 years, he could say:

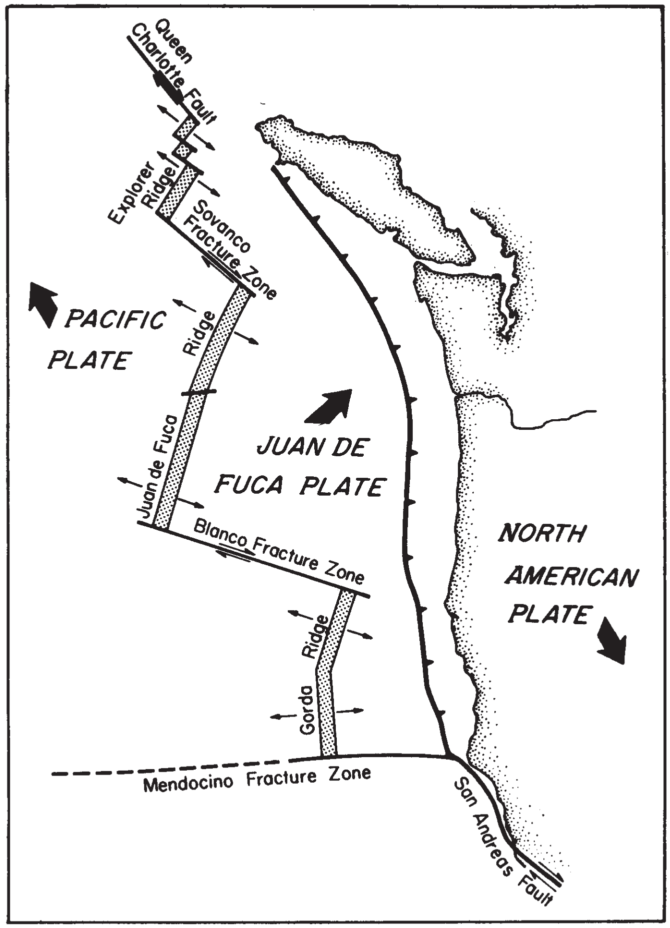

Fig. 2. Plate boundaries near Oregon. After Drake (1982).

> The study of geology in recent years has been influenced by plate tectonic theory which recognizes that rigid continental and oceanic plates have been moving and colliding with each other throughout geologic time... Oregon is located on the western margin of the North American continental plate near its junction with the underthrust Pacific oceanic plate. Recent movement between the plates appears to have been mainly lateral slippage, with the oceanic plate moving northward toward the Gulf of Alaska, and possible clockwise rotation of a segment of the shoreline. The Pacific plate formerly moved eastward from a spreading ridge or rise called the East Pacific Rise, where separation is taking place. At one time this spreading ridge was located well out in the Pacific, but subduction of perhaps 2,000 km (Hamilton 1969) caused the eastern side of the Pacific Plate, as well as most of the spreading ridge, to slip under the North American continent, melting and furnishing a magma source for intrusions, lava flows and volcanoes located inland along the Pacific coast. The East Pacific Rise is hidden from view beneath the continent from the Gulf of California to a point near the Oregon-California line where it appears as the western margin of the Gorda and Juan de Fuca plates.

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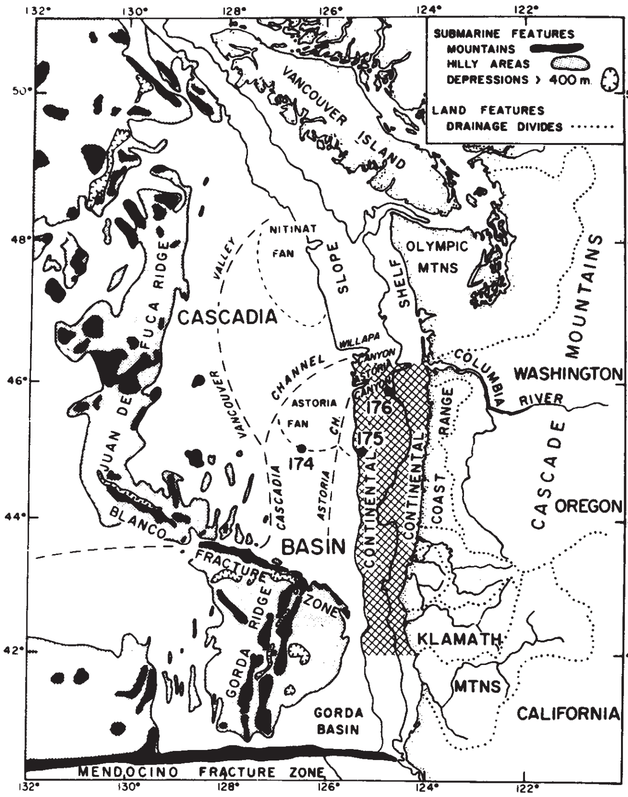


Fig. 3. The 10,000 ft deep Cascadia Basin is the "roof" of the narrow Juan de Fuca plate. Nos. 174-176 refer to the Deep Sea Drilling Project sites. From Drake (1982).

OFFSHORE VOLCANOES

In the 16 September 1981 Oregonian, Edward Clifton of the U.S.G.S. reported, "New crust is actually being made" by a sea volcano located 270 miles offshore from Oregon at a depth of 8,000 ft. "The discovery area is one where you get an almost continuous upwelling of volcanic material ...in fractures that go all the way around the Earth."

Apparently this sea volcano is part of the Juan de Fuca Ridge (Figs. 2,3), where convection currents bring basaltic magma up from the mantle of the Earth, forming crust between two oceanic plates. The small plates flooring the Pacific Ocean between Vancouver Island (southern British Columbia) and Cape Mendocino (northern California) aren't visible to geologists -- the plates can't be tapped with geologic hammers. Hence the nature of the plates is uncertain and every author uses different names (e.g., Francis 1976; Decker and Decker 1981; Baldwin 1981; Beaulieu and Peterson 1981; Drake 1982). In any case, imagine the Juan de Fuca Oceanic plate as a conveyor moving new crust eastward toward the North American plate.

CASCADES--SUBDUCTION VOLCANOES

A destructive plate boundary lies about 50 miles offshore from the Oregon and Washington line (Fig. 2). At this plate boundary, the dense Juan de Fuca oceanic plate bends downward as the more buoyant North American plate overrides it. At a depth of about 50 miles, the leading edge of the underthrust plate melts and the magma (molten rock) rises up through the North American plate, producing the Cascade volcanoes (Fig. 4) which parallel the Pacific coast 100 miles inland. The Cascades are "not the simple Pliocene-Pleistocene belt of andesite volcanoes commonly depicted in geology textbooks" (Taylor 1981:57), rather they are younger and exhibit a complex geologic history involving eruptions of the entire gradient of volcanic rocks during the Pleistocene and Holocene (Peterson et al. 1976).

Until recently, many geologists questioned whether a destructive plate boundary still existed offshore from Oregon. They reasoned that the inactivity of the Cascade volcanoes, the lack of subduction earthquakes, and the absence of a deep oceanic trench, suggested that the nature of the plate boundary had changed (Beaulieu 1972). Then Mt. St. Helens erupted, and out of the volcanic ashes came new ideas supported by new data. One idea is that the Juan de Fuca plate is so plastic due to its youth, thinness, and the high temperatures held in by thick Cenozoic sediments that it bends downward in an "aseismic creep" (Beaulieu and Peterson 1981). As a matter of interest, Bates McKee (1972) discussed turbidity currents. These currents carry copious quantities of sediments, originating in the Columbia River, down off the continental shelf and slope. The sediments sweep across the 10,000 ft deep Cascadia Basin (Fig. 3) which is the roof of the Juan de Fuca plate. One turbidity current extended out about 400 miles -- the narrow Juan de Fuca plate is only about 200 miles across its maximum width. No wonder the deep trench is obscured with sediment.

Geologists generally concede that subduction is occurring, but there is disagreement as to the rate. For example, Beaulieu and Peterson (1981:161) say, "Continued volcanism in the Cascades, although of a lower rate than sometimes in the past, also suggests continuing subduction." Drake (1982:20) refers to the Cascades as a "near-extinction system -- the 1980 eruption of Mount St. Helens notwithstanding."

Perhaps the Cascades are less active than "sometimes in the past" but the stratigraphic record suggests the contrary (Crandell and Waldron 1969). As Harris (1980:263) puts it, "Earlier in this century many geologists believed that the Cascade volcanoes were probably a dying species, if not already extinct. But thanks to more thorough field research in the past few decades, it appears that the present quiet period is no indication of approaching extinction. Instead, evidence is accumulating that there have been as many eruptions in the Cascades during the most recent 10,000 years as there were during the previous periods of comparable duration." Stephen Harris is a Professor of Humanities at the California State University at Sacramento and author of Fire & Ice, the Cascade Volcanoes. This book, first published in 1976, is the "only full-length work which brings together in a single, non-technical volume all published -- and much hitherto unpublished -- information about volcanic and glacial history of the major Cascade volcanoes" (1981 preface). Fire & Ice was checked for technical accuracy by Dwight Crandell, geologist with U.S. Geological Survey and specialist in volcanic hazards. Crandell is Harris' authority for statements about the activity of the Cascades. "Many persons who most admire their scenic magnificence do not know that these white cones -- the highest free-standing landforms in the conterminous United States -- are potentially the most dangerous mountains in the country".

Two of these volcanoes erupted thus far in the 20th Century, Mt. St. Helens and Mt. Lassen. Harris (p. 16) describes the eruptions of Lassen. "Until upstaged by Mt. St. Helens, Lassen Peak was celebrated as the most recently active volcano (south of Alaska) in the continental United States. Beginning in May, 1914, and continuing sporadically until 1921, Lassen ejected steam, tephra, and lava; the climax occurred a year after the activity began, when it blew an enormous cloud an estimated seven miles into the stratosphere."

After Mt. Lassen erupted, the Cascades were quiet for over a half century -- a microsecond of geologic time, but a lifetime for some humans. Babies were born and grew up within sight of these peaks unaware of them as volcanoes. Students took geology classes and learned about volcanoes and plate tectonics. They heard that the Cascades were old and the plate margins had changed. Not all geologists agreed. Paul Hammond (1973:93), volcanologist at Portland State University, warned: "Volcanism at several sites around the world in recent years has shown that a number of volcanoes considered 'dead' were only dormant and that renewed activity is an ever-present possibility. Many geologists anticipate that within their lifetime one of the sleeping Cascade volcanoes will erupt. After all, Mounts Baker, Rainier, and St. Helens erupted several times in the 1800's, Mount Lassen in the early 1900's, and today Mount Rainier, Mount St. Helens, Mount Adams, and Mount Hood have active fumaroles and hot spots."

In 1975, Dwight Crandell, Donal Mullineaux and Meyer Rubin, all of U.S.G.S. wrote in Science: "Mount St. Helens, a prominent but relatively little known volcano in southern Washington...has been more active and more violent during the last few thousand years than any other volcano in the conterminous United States. Although dormant since 1857, St. Helens will erupt again, perhaps before the end of the century" (p. 41)."Because of the variable recent behavior of the volcano, we cannot predict whether the next eruption will be of basalt, andesite, or dacite, and whether it will produce lava flows, pyroclastic flows, tephra, or volcanic domes. But if the eruptive period lasts years or decades, a variety of eruptive events and lithologic types can be anticipated" (p.48).

Almost simultaneously with this warning, Mt. Baker appeared to be warming up. Campgrounds were closed and the news media alerted people to the dangerous situation. This activity was "the most significant volcanic change in the Cascades since the eruption of Mount Lassen in 1915" (Rosenfeld and Schlicker 1976:30). Thermal activity greatly increased during 1975 and 1976, but no earthquakes occurred and the mountain didn't erupt. The man on the street wondered who cried wolf! He would wonder again during March and April of 1980 when Mt. St. Helens renewed activity after 123 years.

On 20 March 1980, Leonard Palmer checked the seismograph at Portland State University, finding records of earthquakes at Mt. St. Helens. Earthquakes continued for the next few days.

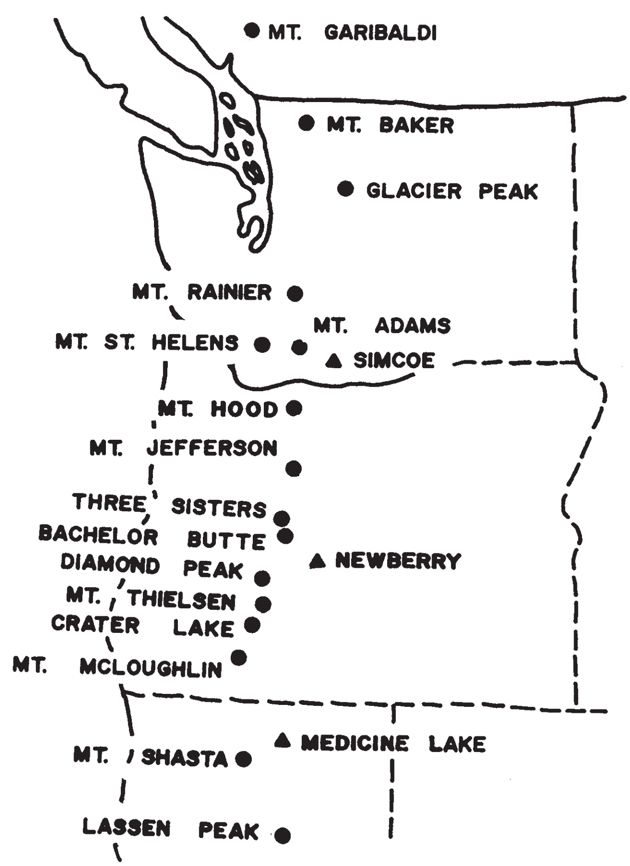


Fig. 4. Major stratovolcanoes of the Pacific Northwest: ● Cascade Range. ▲ "Discontinuous Belt."

Palmer (1980:20) predicted that the volcano could "blow in days," a quote circulated by the news media. Mt. St. Helens let off steam and ash on March 27th, one week after the first seismic activity. Two months later on May 18th, dacitic magma lifted the top off in a lateral explosion with the force of ten million tons of TNT, killing about 60 people. One cubic mile of earth blasted skyward -- the elevation of the mountain fell from 9,671 ft to 8,400 ft -- 6 ft disappeared earlier. Mt. St. Helens erupted before the end of the century, as predicted.

The May 18th blast was a relatively small one, one-fourth the size of an earlier eruption that occurred in 1900 B.C. (Anon. 1981). However it enables one to imagine other catastrophic blasts, such as Mt. Mazama about 6,600 to 6,700 years ago. Many Americans may not have heard of Mt. Mazama, but they do know of Crater Lake, the "Blue Gem of the Cascades" which lies in the "Hollowed out core of a giant volcano" (Harris 1980:86). Mazama had an estimated height of 12,500 ft (Baldwin 1981) -- the highest peak in the Oregon Cascades. Tephra (air borne volcanic ejecta) from Mazama blanketed vast areas of the western United States; Mazama ash is an excellent marker for dating other geologic events. Lava flows erupted and part of the summit collapsed back into the magma chamber. A huge caldera resulted. A caldera is a depression usually more or less circular in outline and over a mile in diameter, formed by collapse, explosion or erosion at the summit of a volcano. Renewed activity built Wizard Island and two other volcanic cones on the floor of the caldera. Water drained in, forming the magnificent Crater Lake of today, which is 1,996 ft deep. As much as 42 cubic miles of material probably disappeared in the Mazama eruptions (Lidstrom 1971).

Harris (1980:85) compares Newberry Volcano (Fig. 4), located about 20 miles southeast of Bend, to Crater Lake: "this enormous...volcano -- 20 miles in diameter and approximately 80 cubic miles in volume -- possesses some of the same remarkable attributes which make Crater Lake so famous. Like Mt. Mazama, Newberry lost its former summit, so that the top of the mountain is now occupied by a huge depression. Although slightly smaller than Mazama's caldera, that of Newberry contains not one but two lakes -- Paulina and East Lakes. Instead of only a single volcanic cone, like Wizard Island, visible in the caldera, Newberry can boast of many recent cinder cones, lava flows, and domes of glistening black obsidian. Judging by the dozens of parasitic vents and flows both within and without the caldera, its activity during the past few thousand years has been far more frequent and varied than that at Crater Lake" (Harris 1980:85).

Despite the similarities, Newberry is not a Cascade volcano. Instead it belongs to a discontinuous belt of broad composite volcanoes lying parallel to the Cascades at a distance of about 35 to 50 miles. This belt extends between Simcoe Volcano, east of Mt. Adams, and Medicine Lake Volcano, east of Mt. Shasta (Mertzman 1981). The flanks of Newberry and Medicine Lake Volcanoes contain lava tubes. "Both volcanoes have the same shape, are marked by summit calderas, contain abundant rhyolitic domes and flows, have widespread ash flows in addition to the more areally extensive basalt and basaltic-andesite flows and their related cinder cones, have similar petrochemistry, and have been the sites of eruptions of pumiceous tephra and obsidian flows during the last thousand years" (MacLeod et al. 1981:85).

Innumerable references allude to Newberry as a shield volcano (built of layers of basalt). Recent studies reveal that it is a strato or composite volcano composed of layers of lava flows and pyroclastics. To quote MacLeod et al. (1981a:85) who did the studies:

> Newberry Volcano...is among the largest Quaternary volcanoes in the conterminous United States. It covers an area in excess of 500 square miles, and lavas from it extend northward many tens of miles beyond the volcano. The highest point on the volcano, Paulina Peak with an elevation of 7,984 ft, is about 4,000 ft higher than the terrain surrounding the volcano. The gently sloping flanks, embellished by more that 400 cinder cones consist of basalt and basaltic andesite flows, andesitic to rhyolitic ash-flow and air-fall tuffs and other types of pyroclastic deposits, dacite to rhyolite domes and flows, and alluvial sediments produced during periods of erosion of the volcano. At Newberry's summit is a 4 to 5 mile wide caldera that contains scenic Paulina and East Lakes. The caldera has been the site of numerous Holocene eruptions, mostly of rhyolitic composition, that occurred as recently as 1,400 years ago.
>
> The north and south flanks of Newberry Volcano, which extend the greatest distances from the summit caldera, are almost exclusively veneered by basalt and basaltic andesite flows and associated vents. The basalt flows form much of the surface in a broad region extending far north of the volcano (Peterson and Groh 1976) as well as southward to the Fort Rock basin. Individual flows are a few feet to more that 100 ft thick and cover areas of less than one square mile to many tens of square miles. Flow margins are commonly well preserved even on older flows, but the flows are complexely interwoven and it is difficult and time consuming to trace individual flow boundaries. Most flows are of block or aa type; pahoehoe surfaces occur locally on a few lower flank flows. Lava tubes are common, and some extend uncollapsed for distances of one mile (Greeley 1971); some lower flank flows may have been fed by tube systems. Casts of trees occur in many flows, paricularly the younger ones.

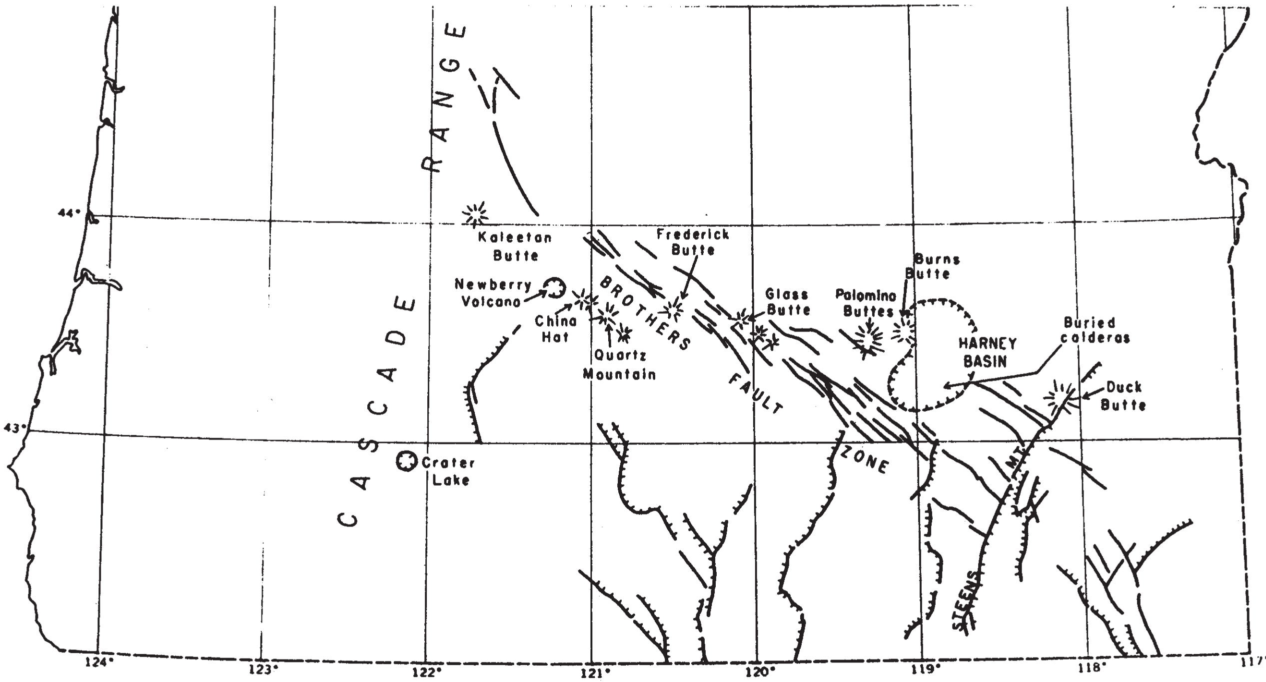


Fig. 5. Brothers Fault Zone in central and southeastern Oregon showing silicic domes and vents. From Walker (1974).

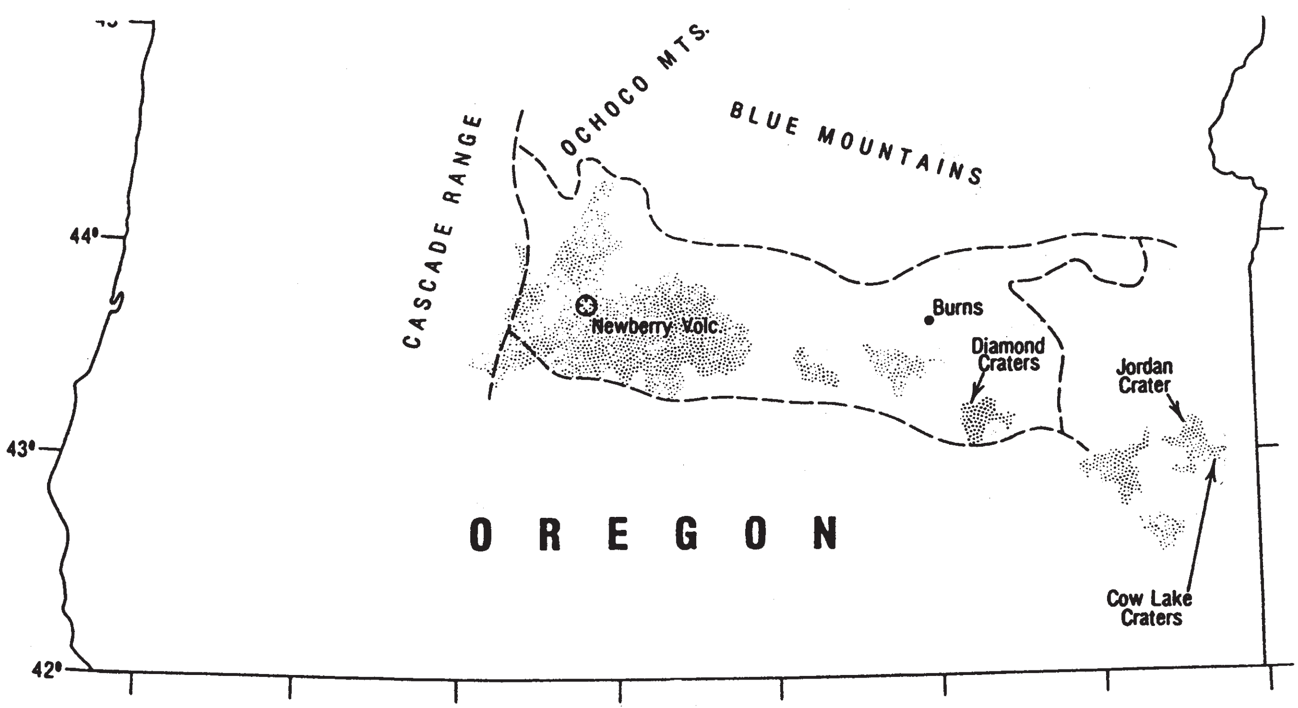


Fig. 6. Belt of non-randomly distributed basaltic fields along Brothers and subsidiary fault zones. High Lava Plains indicated by dashed lines. From Walker and Nolf (1981a).

TRIPLE BOUNDARY TWIST -- OREGON!

Along a passive plate boundary such as the San Andreas Fault the predominent movement is lateral slippage where neither plate is added to nor destroyed. However, the two plates can and do hook together as their margins slide past each other. Along Oregon and Washington, "the Pacific plate is moving northward, dragging the western part of the North American continent along" (Alt and Hydnman 1981:175). In the process, the small Juan de Fuca plate has been segmented as it rotates, twists and crunches between the San Andreas and Queen Charlotte Faults (Fig. 2) subducting at an oblique angle under the North American plate (Beaulieu and Peterson 1981). "The northeast Pacific is a unique plate-tectonic region. Movements of the Juan de Fuca Plate, a remnant of the ancient Farallon Plate, seems to have been the cause of many of the processes that have taken place at the Oregon continental margin. The complexity of the tectonic processes of the region is a challenge for investigators to unravel" (Drake 1982:15).

On land, east of the Cascades and south of U.S. highway 20 between Bend and Burns (Fig. 5), the terrain resembles a mirror run over by a heavy truck (Alt and Hydnman:172), "An interesting combination of crustal movement along faults accompanied by volcanic activity has been going on in south-central and southeastern Oregon for the last 10 to 15 million years and continues today. It is clear from the pattern of the fracturing and the direction the fault blocks are moving that the *western part of the state has been moving northward relative to the eastern part* -- with the displacement distributed through hundreds of faults spread over an east-west distance of at least 200 miles. No one has figured out the total amount of movement; that would be a tricky job. But it must be measurable in tens of miles, probably about 50 miles". (Italics added).

These fractures are bounded to the north by the Brothers Fault Zone (Fig. 5) which extends the length of the High Lava Plains. It is a fundamental structural boundary between the older, highly folded rocks to the north in the Blue Mountains province and the young, highly faulted volcanic rocks to the south in the Basin and Range which extends to Mexico (Walker and Nolf 1981a, 1981b). To the weary traveler along U.S. Highway 20 between Bend and Burns, the scenery appears dull, just low fault scarps in basaltic flows and moderately high silicic lava domes amidst expanses of sagebrush and juniper. The traveler sees the visible part of the deeply buried Brothers Fault Zone. The silicic domes, e.g., the Burns Butte, the Glass Buttes and Hampton Butte, form a well-defined age progression spanning the past 10 to 11 million years in which the oldest buttes are near Burns and the youngest ones near Bend.

A number of non-randomly distributed basalt flows (Fig. 6) occur along the Brothers Fault Zone or along subsidary faults paralleling this zone. Among these flows are (northwest to southeast): The Horse and Arnold Flows (Greeley 1971), Pot Holes (Glasby 1982, pers. comm.), Devil's Garden (Peterson and Groh 1965), Squaw Ridge (Peterson and Groh 1963; Skinner 1980), Four Craters (Peterson and Groh 1964a), Diamond Craters (Peterson and Groh 1964b; Walker and Nolf 1981b; Benedict 1981a); Saddle Butte (Ciesiel and Wagner 1969; Larson 1977b), and Jordan Craters (Otto and Hutchison 1977; Benedict 1981b). Most contain caves of varying sizes and significance (Larson 1977a; Convention Guidebook; Benedict, 1982).

75 POTENTIALLY ACTIVE VOLCANIC FIELDS

The March 1982 issue of Oregon Geology contains a brief article with a map (Fig. 7) which shows numerous volcanic fields concentrated in the Cascades and along the Brothers and subsidiary fault zones. Robert Smith and Robert Luedke of U.S.G.S. report at least 60 potentially active volcanic centers in the 11 western states in addition to about 15 in the Cascades. The distribution of volcanoes, volcanic fields, and volcanic rocks younger than 16 m.y. old suggests that (1) most volcanic activity occurred along major linear zones, (2) any volcanic field appearing during the last 5 m.y. is potentially active, and (3) new volcanic centers could form within linear zones at any time. Many volcanic centers have long life spans ranging from one to more than 10 m.y. The history of any volcanic field contains both major cycles of high activity and long cycles of no activity. For some volcanic centers the interval of dormancy may last 100 or 1,000 years; for others, 10,000 years; and for very large volcanic systems, 100,000 or even a million years may elapse between eruptions.

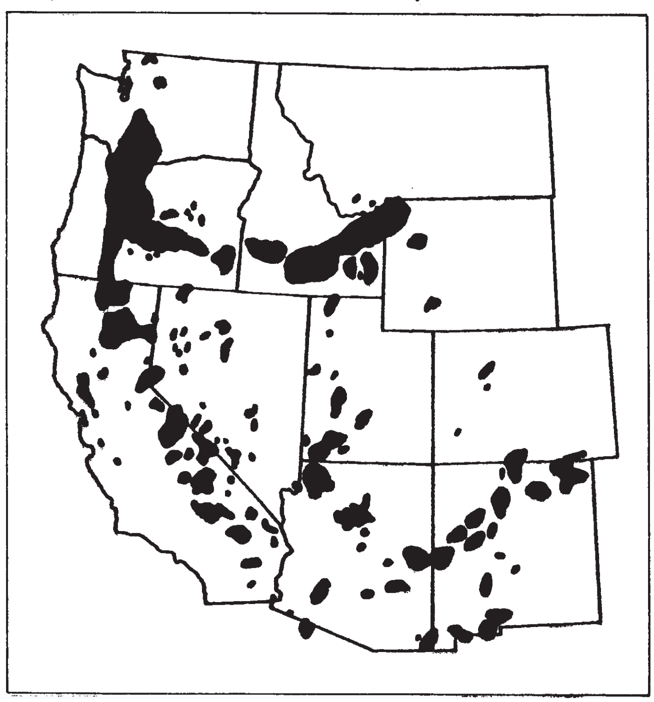


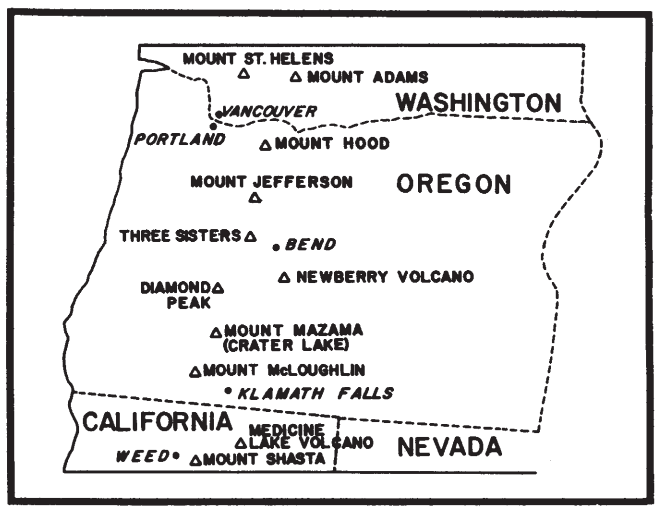
Fig. 7. The 11 western states contain at least 75 potentially active volcanic fields. U.S.G.S. map Anon. (1982).

SUMMARY

The geologic history of the Pacific Northwest is gradually being re-interpreted in terms of plate tectonics, a theory recognizing that rigid continental and oceanic plates have been moving and colliding with each other throughout geologic time. Oregon, on the western edge of the North American plate, is located at a complex triple plate boundary. As the Pacific plate slips northward toward subduction in the Gulf of Alaska, it's been dragging western Oregon northward, extending south-central and south-eastern Oregon as much as 50 miles over an original distance of 200 miles. The Brothers Fault Zone, traceable diagonally across the state, is a fundamental boundary (or pivot) overlying a "deeply buried structure" which separates the highly folded, older rocks of the Blue Mountains to the north from the highly faulted, younger rocks of the Basin-Range to the south. The highly plastic, small and thin, and warm Juan de Fuca plate, originating from a spreading center located about 270 miles offshore from the Oregon-Washington line, is subducting at an oblique angle under the more buoyant North American plate. In the process magma rises, forming stratovolcanoes. Although exact relationships are uncertain, a number of speleoliferous basaltic flows are also known to be associated with these major tectonic features: e.g., 1) the cave flows on the flanks of Mt. St. Helens and Mt. Adams in southern Washington, Newberry Volcano in central Oregon, and Medicine Lake Volcano in northern California; and 2) The non-randomly distributed flows in Oregon along the Brothers and subsidiary, parallel fault zones. The Pacific Northwest is truly a land of a thousand volcanoes.

FOOTNOTE

For years we have debated whether the "discontinuous belt of volcanoes" (Mertzman 1981) lying east of the Cascades, is part of the Cascades or not (Fig. 4). Observe that Mt. Adams is about the same distance east of Mt. St. Helens as Newberry is east of the Three Sisters and Broken Top, or Medicine Lake is east of Mt. Shasta, and that Lassen is almost due south of Medicine Lake. Greeley and Baer (1976:30) state, "The Medicine Lake Highland is an eastern extension of the Cascade volcanic province in northern California," and Harris (1980) includes a chapter on Newberry in Fire & Ice. Peterson et al. (1976), Taylor (1981) and MacLeod et al. (1981a) note similarities in the geologic history of the various volcanoes. The April 1982 Oregon Geology contained the map and caption (to the right) showing NEWBERRY and MEDICINE LAKE as part of the HIGH CASCADES RANGE.



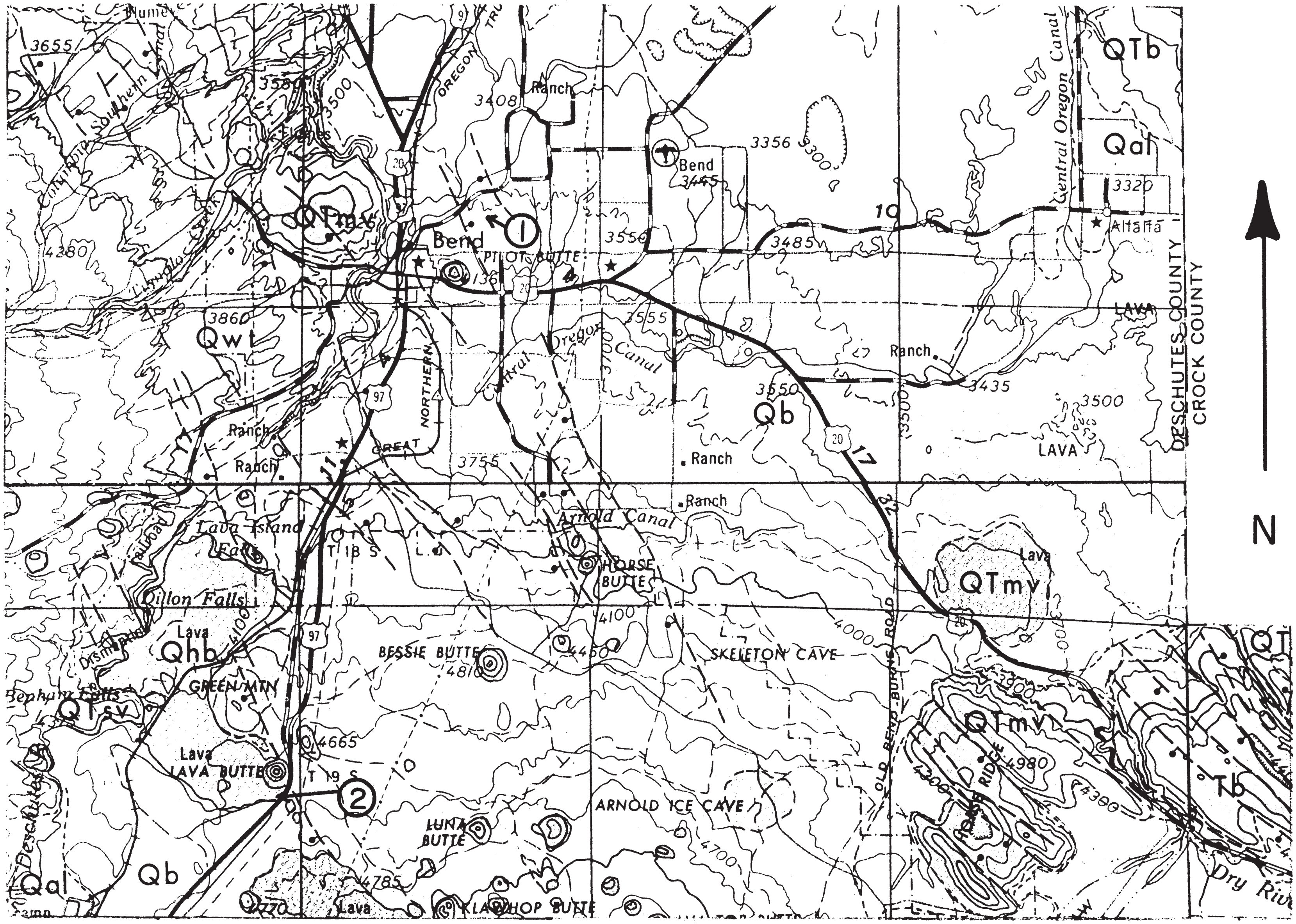


Fig. 9. Brothers Fault Zone in the vicinity of Bend, Oregon. Qhb - Holocene basalt. Qal - Alluvium and surficial deposits. Qb - Pleistocene basalt. Qwt - Ash-flow deposits. Qtb - Older basalts. Qtmv - Mafic vent rocks. Qtsv - Silicic vent rocks. Tb - Tertiary basalt. After Peterson et al. (1976).

ROADLOG

Ellen M. Benedict* and Ben A. Benedict**

Even though the Geology and Biology Field Trip was designed specifically to take one full day and evening during the N.S.S. Convention, this Guidebook is also intended for use by persons or small groups desiring to travel the route at a later date. You may wish to expand the length of time to three days or even to a week, camping enroute in the Deschutes National Forest. To this end, this Guidebook includes several "Recommended Side Trips."

The tour itself begins and ends at the south end of the circular driveway in front of Mountain View High School, 2755 N.E. Denser Road, Bend, Oregon -- 1.5 miles north of U.S. Highway 20 on the way to Burns. All turns are in capitals. Fig. 10 shows the field trip route.

STOP NO. 1: MOUNTAIN VIEW HIGH SCHOOL.

Several interesting geological and biological relationships are evident here. In fact, one could hold an exciting field trip without leaving the grounds.

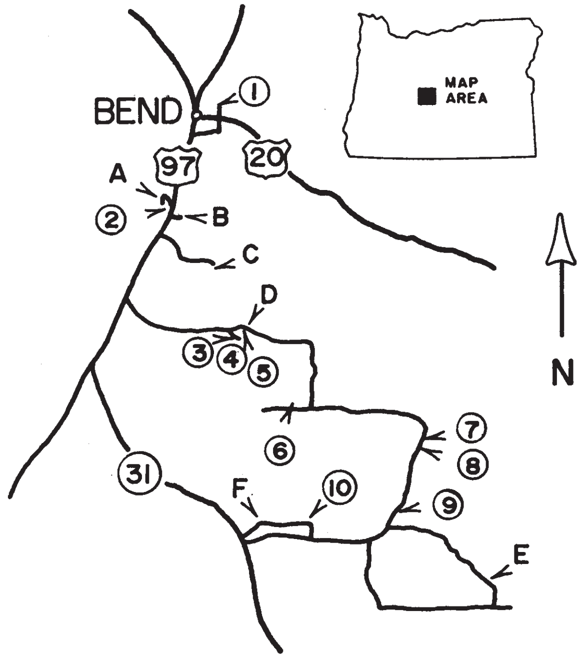


Fig. 10. Field trip route. Stops 1-10. Recommended Side Trips A-F.

MT. VIEW SCHOOL and the ST. CHARLES MEDICAL CENTER rest on a downthrown block of Pleistocene age basalt in this part of the BROTHERS FAULT ZONE (Fig. 9). The Brothers Fault Zone of west-northwest trending faults dominates the HIGH LAVA PLAINS (Fig. 1). The High Lava Plains, a middle to upper Cenozoic volcanic upland with elevations between 3,500 to 6,000 ft, is about 50 miles wide and 160 miles long; it extends from the Cascade Range (along western skyline) to the eastern margin of the Harney Basin. The Brothers Fault Zone is located along U.S. Highway 20 between Bend and Burns, and beyond (Baldwin 1981). It is a deeply buried structure which forms a fundamental boundary between the older, highly folded rocks to the north in the BLUE MOUNTAINS PROVINCE (Fig. 1) and the younger, highly faulted volcanic rocks to the south in the BASIN AND RANGE PROVINCE which extends to Mexico (Walker and Nolf 1981a, 1981b). In the vicinity of Mt. View School and PILOT BUTTE (the cinder cone to the southwest), the basalt is cut by northwest trending faults with displacements up to 125 ft. However, the relief is reduced or eliminated by sediments covering the downthrown blocks.

The town of BEND (elev. 3,628 ft) is underlain with BASALT. Examine a piece of basalt with a hand lens. The freshly fractured surface of this fine grained rock is almost black due to the very rich FERRO-MAGNESIUM content -- the light brown of the unfractured surface results from weathering of these minerals. The tiny, sea-green crystals are OLIVINE (a ferro-magnesium mineral); a PERIDOT, the August birthstone, is the gem form of olivine. Molten olivine basalts are highly fluid and sometimes form LAVA TUBE CAVES (see Harter and Harter, this volume). Even though lava tubes haven't been discovered here, YOUNG'S CAVE is within two miles (see Convention Guidebook). Not only is basalt rich in ferro-magnesium but it is poor in SILICA. Silica (silicone dioxide) is most often seen in fine-grained quartz -- the major component of Oregon beach sand. For an igneous rock to be called basalt, it must contain between 45.8% and 50.8% silica, among other components (Ireton, this vol.). Basaltic magmas (molten rock) are especially runny and normally flood quietly from vents, forming low relief landforms such as lava flows, lava plateaus and shield volcanoes.

PILOT BUTTE (elev. 4,138 ft) was named by early day travelers who used this CINDER CONE as a landmark as they trekked across the High Lava Plains (Brogan 1971). Little did they realize that Pilot Butte was formed by violent basaltic eruptions over a million years earlier (Walker and Nolf 1981b). When magma encounters water it flashes to steam, propelling gaseous globs of molten rock skyward in fire fountains. These air-cooled globs fall back around the vent, building up cinder cones (more properly called SCORIA cones). Scoria or cinder is cellular basaltic rock filled with air bubbles. The cinder piles up into a cone-shaped landform with an outside slope of about 33 degrees (angle of repose).

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The CASCADES (Fig. 4) are the "highest free-standing landforms in the conterminous United States" (Harris 1980, forward). These mountains don't seem exceedingly high from here, but they rise from sea level along their western base. Mt. Ranier (elev. 14,410 ft) in Washington is the highest peak in this range. The Cascades intercept most of the moisture from winds sweeping off the Pacific Ocean, creating a RAINSHADOW to the east of their crest. Mt. View School is near the ecotone (the boundary) between dense coniferous forests of the Cascades and the OREGON HIGH DESERT with its SAGEBRUSH-GRASSLAND STEPPE VEGETATION. You are looking at WESTERN JUNIPERS (Juniperus occidentalis). This species inhabits the driest of all the tree dominated vegetation zones of the Pacific Northwest (Price 1971; Franklin and Dyrness 1973). Of the trees in the Bend area, Western junipers (Fig. 11) can be distinguished by their broad crowns and spreading branches which end in gland-dotted, scalelike twigs. The powdery-looking, blue-black berries (actually fleshy cones) are sometimes used to flavor gin. These trees occur from central and southeastern Washington to southern California (Little 1980).

Fig. 11. Western juniper.

0.0 (0.0)
Begin mileage at the south end of the circular driveway, TURN RIGHT (south) on Denser Road. For several miles, you will be crossing the BROTHERS FAULT ZONE. Here the downthrown blocks are mostly obscured by air fall debris which is weathered to soil. PILOT BUTTE (to the right) is lapped by 1 to 2 million year old air fall material (Walker and Nolf 1981b). This cinder cone is not one of the parasitic cones associated with the Newberry Volcano (Chitwood 1982, pers. comm.). Newberry Volcano (Stops No. 3-5) is located about 25 air miles due south of Mt. View School (Fig 7).

1.5 (1.5)
Junction with U.S. Highway 20; continue across the highway.

1.3 (2.8)
RIGHT on Reed Market Road (marked as "Reed Street"). Follow Reed Market Road, until you come to U.S. Highway 97 (at the traffic signal).

2.0 (4.8)
TURN LEFT (south) on U.S. 97.

2.4 (7.2)
Road on left leads to several lava tubes (BOYD CAVE, 9 miles; SKELETON CAVE, 12 miles; ARNOLD CAVE SYSTEM, 13 miles). This road connects to USFS Road 1821 (the China Hat Road) which you will be on later.

2.9 (10.1)
Road on left leads to the newly opened OREGON HIGH DESERT MUSEUM (1/2 mile). This is a living museum of the natural and cultural heritage of the high desert. Only a few buildings are finished but it is well worth a visit.

0.7 (10.8)
You are now entering the DESCHUTES NATIONAL FOREST, "a 4,400 square mile scenic wonderland of sculptured peaks; tumbling cascades and waterfalls; crystal clear lakes, rivers, and streams; hundreds of different kinds of animals; four wilderness areas; and probably the best variety of outstanding volcanic formations anywhere on this continent" (USFS brochure, "Lava Lands, Where the Present Meets the Past").

Along here, the BROTHERS FAULT ZONE merges almost indistinguishably with the NORTHWEST RIFT ZONE (Fig. 12), a zone of nearly continuous northwest trending faults, fissures, and young lava flows extending between EAST LAKE in NEWBERRY VOLCANO and the northern edge of the LAVA BUTTE FLOW -- a distance of about 20 miles (Peterson and Groh 1965, 1969). Watch for glimpses of the LAVA BUTTE FLOW through the ponderosa pines to the right of U.S. 97 -- this lava flow of basaltic andesite (silica content 56.0%) extends northward about 5 miles from its source vent, LAVA BUTTE (MacLeod et al. 1981a). Lava Butte (elev. 4,970 ft) will be visible ahead. This cinder cone was first used in 1928 as a Forest Service Lookout -- the building contains an exhibit on volcanism. The "Crater Rim Trail" provides excellent views of the Cascades and Newberry Volcano. Recently, the Lava Lands Visitor Center was added.

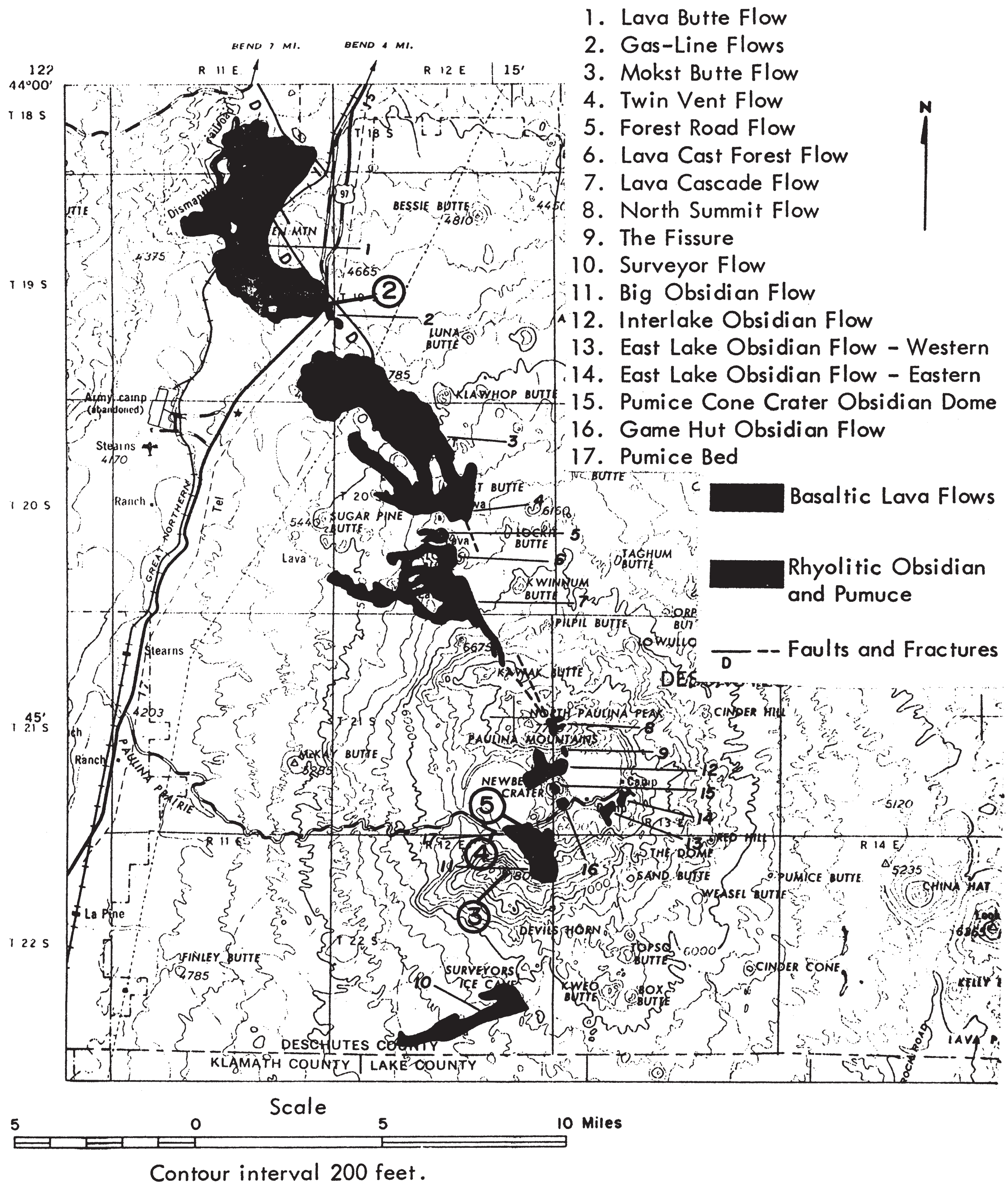


Fig. 12. Northwest Rift Zone showing the young lava flows associated with Newberry Volcano. From Peterson and Groh (1969).

2.5 (13.3)
Although LAVA BUTTE resembles Pilot Butte in shape, it is much younger. Roadcuts along here expose the cinder plume extending northeast from Lava Butte. Charcoal from the base of the cinders has been carbon 14 dated at about 6,100 years old (Chitwood et al. 1977).

0.7 (14.0)
As you travel along (without stopping), look quickly for a DEEP CRACK (or fissure) in the basalt to the left side of U.S. 97. This fault is part of the Northwest Rift Zone (Fig. 12). The GAS LIGHT FLOW of basaltic-andesite, south of the fissure, was C-14 dated at between 5,800 to 6,100 years (MacLeod et al. 1980b). The LAVA BUTTE FLOW is on the right side of the highway.

0.5 (14.5)
TURN RIGHT on the road to LAVA LANDS and follow the signs to the parking area near the Visitor Center. Mileage resumes once you return to the junction with U.S. 97.

STOP NO. 2: LAVA LANDS VISITOR COMPLEX.

Take the TRAIL OF THE MOLTEN LAND (Fig. 13) for a closer look at the LAVA BUTTE FLOW, located behind the Visitor Center. Be sure to look at the samples of volcanic rocks on display at the Visitor Center. (NOTE: Read about these rocks in Ireton, this vol.). The Visitor Center has other exhibits, free brochures, maps and books for sale including a recreational map of the Deschutes National Forest (with mile square sections). If you have additional time, walk the TRAIL OF THE WHISPERING PINE.

Fig. 13. Aa lava flow with Lava Butte as backdrop.

TRAIL OF THE MOLTEN LAND

Sign 1: Step Into the Past

"Follow the 1/2 mile loop trail through a land that once trembled and rumbled as flowing lava poured out upon it. Walk in channel of a once molten lava river. Pass between jumbled mounds of contorted lava formations. See the beginning of new life in this barren land. Learn the story of an outstanding example of a side breached volcano. Walking time approximately 20 minutes."

Sign 2: Aa Lava

"Several thousand years ago, molten lavas poured out of the side of Lava Butte, covering 6,117 acres and forming this large lava field. There are two principal types of basaltic lava, both described by Hawaiian terms. This flow is 'aa' (ah ah). As the surface cooled, the viscous 'aa' becomes very rough and jagged. Pahoehoe (Pah-hoy-hoy), the other type of lava is very fluid and cools with a smooth or ropy surface."

You will see pahoehoe at South Ice Cave (Stop No. 6) and at the Devil's Garden Geologic Area (Stops No. 7-9). "Lavas of basaltic composition that are highly charged with dissolved gases (termed 'pahoehoe') sometimes form crusts over the channels, making lava tubes" (Harter and Harter, this vol.). Aa is too viscous (i.e., resistant to flow) to form tubes.

Sign 3: Phil Brogan's Viewpoint

"The rugged peaks of the Oregon Cascades developed long before Lava Butte. Continued eruptions and large land uplifts formed a series of dome-shaped mountains. Weather and glacial erosion broke away the sides to form the sharp peaks of today's jagged skyline."

PHIL BROGAN, an Honorary Member of the Oregon Grotto of the N.S.S., has been recognized as the FATHER OF OREGON SPELEOLOGY. "For more than 50 years, Phil has been writing about Oregon caves. His contribution to Oregon Speleology is unequaled. It deals with virtually every aspect of contemporary speleology: discovery; exploration; origin; cave uses (domestic, recreational, commercial, scientific, military, illegal -- past, present, and future); geology, archeology, paleontology, biology, meteorology, and last, but not least, cave conservation." (Larson 1977a:iii).

Sign 4: Lava Butte's Fiery Beginning

"If you were standing here several thousand years ago, you could have watched the fiery creation of Lava Butte. Imagine!! Billowing clouds of smoke, ashes, and steam rising thousands of feet into the air. Glowing ejecta (material thrown out by super-heated gases) building layer upon layer around the central vent. The choking stench of harsh sulfur fumes surrounds you, and with each pulsating eruption, the ground beneath you shakes and trembles."

Sign 5: Lava Balls

"Molten 'aa' lava flows like a large river of mud. Large chunks of material are often broken from the sides of the molten river's channel. These chunks are rolled and tumbled along in the lava flow, gaining size like a snowball. The large lava balls around you were rafted along and cast into place as the lava cooled".

Sign 6: The Source

"The source of all the lava around you is Lava Butte. After its fiery creation, the bubbling magma (molten rock) boiled up into the central vent of the cone. Finding it plugged, the surging lava broke through the south side of the cinder cone and poured out across the land. Several different flows formed these large lava beds. About 2,000 years ago, the lava from the last eruption was very thick and slow moving. As the lava in the side breach cooled, it plugged the opening. Thus ended Lava Butte's fiery life."

Sign 7: Lava Gutters

"As molten lava poured out of the breach at the base of Lava Butte, it formed definite channels. When the lava quit flowing, it left gutters similar to the one we are standing in. The jumbled rock and lava balls along the bank of the levee indicate the depth of the lava flows."

Sign 8: The Molten Land

"No longer confined to a narrow channel, the lava river spread out, forming this large expanse of molten landscape. Large lava balls and chunks of levee bank were carried along like rafts on the molten flow and appear as islands in our view today. As the mass of lava gradually cooled and shrank, large cracks, like the crevasse in front of you, were formed. Some cracks in the Lava Butte flows are 40 to 50 feet deep."

Sign 9: Lava Squeeze--Ups

"When the lava reached this area, it had cooled enough to form a crust. Irregularities in the land surface caused the flow to crack as it moved forward. Molten lava oozed up through the cracks like toothpaste from a tube. It hardened into these long, grooved tongues called 'squeeze-ups' or 'lava wedges'."

Sign 10: One Giant Step for Mankind

"The awesome lava lands of Eastern Oregon were the training and testing grounds for the astronauts and their equipment in 1964 and 1966. Training and experience gained on these lava fields developed skills for the lunar explorers to make their first walk over the face of the airless moon. This small rest area is dedicated to those courageous men who trained here for that first historic 'giant step for mankind'."

The Lava Butte Flow is 10 square miles and between 30 to 100 ft thick. It is only one of the flows of Newberry Volcano.

AS YOU RETURN TO THE VISITOR CENTER, WATCH FOR THE BROAD, LOW OUTLINE OF THE NEWBERRY VOLCANO ALONG THE SKYLINE TO THE SOUTHEAST. This landform, popularly called "Newberry Crater", was named for John Strong Newberry who explored the area as a member of the Pacific Railroad Survey Party in 1855. I.C. Russell was the first geologist to visit Newberry as part of his horseback reconnaissance of central and southeastern Oregon in 1903. Russell interpreted the 4 by 5 mile depression in the summit as a glacial cirque. Howell Williams, who geologically mapped the flanks of Newberry in reconnaissance and studied the depression in detail, recognized it as a CALDERA. A caldera is a large depression, more or less circular and over a mile in diameter, which formed by collapse, explosion or erosion at the summit of a volcano. Recently Norman MacLeod, David Sherrod and Larry Chitwood mapped in detail the flanks of Newberry and studied the caldera; Edwin McKee age dated the rocks. This important work provides a new interpretation of Newberry Volcano and a detailed geologic map (MacLeod, in preparation).

Along the TRAIL OF THE WHISPERING PINE, you will see the most common three needle pine in Oregon (Pinus ponderosa). These trees can be told from other pines in the Bend area by their long (4 to 8 inch) needles in bundles of three (Fig. 14). Often the picture puzzle bark is cinnamon colored, but it can be black on small or young trees. Sometimes called Western yellow pine, this species is the most widely distributed pine in North America. It occurs from the Rocky Mountains to the Pacific Ocean between British Columbia and Mexico. Ponderosa pine grows best under conditions of high sunlight and low rainfall -- 10 to 30 inches annually (Price 1971; Franklin and Dyrness 1973; Little 1980).

Fig. 14. Ponderosa pine.

RECOMMENDED SIDE TRIP A: TOP OF LAVA BUTTE.

Return to your vehicle, following the signs and arrows to the top of Lava Butte, where you get spectacular views of the Cascades and Newberry Volcano. Note the exhibit which shows NEWBERRY as a STRATO or COMPOSITE VOLCANO (layers of lava flows and pyroclastic ejecta) rather than a shield volcano. If Newberry were a shield volcano, as is commonly stated, it would be built up of layers of basalt similar to the Hawaiian shield volcanoes. Instead, over half of Newberry is pyroclastic, accounting for its broad, rounded shape (Chitwood 1982, pers. comm.). Newberry is mostly composed of moderate to high silica rocks, similar to the stratovolcanoes of the Cascades (Taylor 1981); and the basalts are located on the extreme flanks. At the junction with U.S.97, adjust your mileage as you resume the trip log.

0.0 (14.5)
TURN RIGHT on U.S. 97, and continue south.

1.2 (15.7)

Fig. 15. Here's what the Lava River Cave harvestman looks like!

RECOMMENDED SIDE TRIP B: LAVA RIVER CAVE.

TURN LEFT on the road to LAVA RIVER CAVE (1/4 mile). Formerly supervised by the Oregon State Park System, this cave is now managed by the Deschutes National Forest. It is open to the public -- you can rent lanterns and get free brochures about the cave. Apparently Lava River Cave is a RIFT TUBE (Harter and Harter, this vol.). The cave formed in one of the older pahoehoe basalt flows along the Northwest Rift Zone. The lava tube extends in two directions from the entrance sink. The main cave, the longest known uncollapsed lava tube in Oregon, winds northwesterly for 5,211 ft on a gradual downhill slope towards the Deschutes River -- U.S. 97 crosses over this cave segment. The southeastern segment, closed to the public, extends another 1,500 ft. Although a biological inventory hasn't been conducted, it is known that the harvestman, Taracus sp. (Fig. 15), a millipede and several collembola species inhabit this cave. Return to U.S. 97 and adjust mileage.

0.0 (15.7)
Continue south on U.S. 97.

2.4 (18.1)
RECOMMENDED SIDE TRIP C: LAVA CAST FOREST.

This trip takes you to the CAMP ABBOT CINDER PIT (3/4 mile) and to the LAVA CAST FOREST (9 1/2 miles) as well as to several other young lava flows along the NORTHWEST RIFT ZONE (Fig. 12). At the Sun River and Lava Cast Forest junction, TURN LEFT on the paved road which soon becomes USFS road 195. At 0.8 mile, TURN RIGHT into the Camp Abbot Cinder Pit (no sign) where you can find brillant blue, green, gold, tan and red cinders which seem newly erupted but are much older. Also look at the way a cinder cone is layered. Return to road 195 and continue eastward for 8.0 miles, TURN RIGHT on road 195a (the other road goes to Mokst Butte Flow which is about 5,800 years old). Stay on road 195a for 0.7 miles (you should come to a one way sign); continue to the parking area and small compground/picnic area. The Lava Cast Forest campground has pit toilets but NO WATER. The sign at the head of the NATURE TRAIL says:

LAVA CAST FOREST GEOLOGIC AREA

"The Lava Cast Forest Geologic Area covers an area of about five square miles, and is situated on a fault line extending from Newberry Crater to Lava Butte. Flowing in a westerly direction through a virgin forest the hot lavas formed hundreds of tree molds, some upright, others up-rooted and many to drift into log jams. The area was discovered and named by Walter J. Perry of the U.S. Forest Service in 1925. It was designated as a geologic area by the Regional Forester on March 16, 1942".

You may find the brochure, "A Self-Guiding Nature Trail", in the box which is located a short distance beyond this sign. The trail where you can see TREE CASTS (Figs. 16-17) is about 0.9 mile long. According to Peterson and Groh (1969:74):

> Sporadic eruptions along fissure vents have produced lava fountains or 'fire fountains' which threw out bombs and scoria on the flowing lava... The hot, pasty aa lava flowed sluggishly northward and westward down the moderate slope, engulfing pine forests much like those growing in the area today. Some of the growing trees remained upright and were surrounded by quickly cooling lava; others were tilted or knocked down by the slowly moving molten mass. The smaller trees and shrubs were burned as the lava approached. It is believed that within a few minutes after the lava surrounds a tree it cools and forms a thin shell of dense rock; gases and steam are driven from the green wood and the tree is ignited. In most instances the vertical tree burns slowly but completely, leaving a mold the shape and size of the original trunk and extending through the lava flow to the surface ... Many of the vertical molds have a prominence or collar on the upstream side which may project a few feet above the surface of the lava. Countless fallen logs must have been covered completely by the flows from the Northwest Rift Zone and, in some places near the margins, subsequent collapse of the thin lava shell has exposed a long horizontal mold. Burning of the wood in these molds was not always complete, and charcoal has been found in a few places encased in the lava. This charcoal is ideal for radiocarbon dating.

The young flows in this part of the Northwest Rift Zone have been dated between 5,000 and 6,500 years (MacLeod et al. 1981b). Return to U.S. 97, adjusting mileage as you TURN LEFT (south).

0.0 (18.1)
Continue south on U.S. 97.

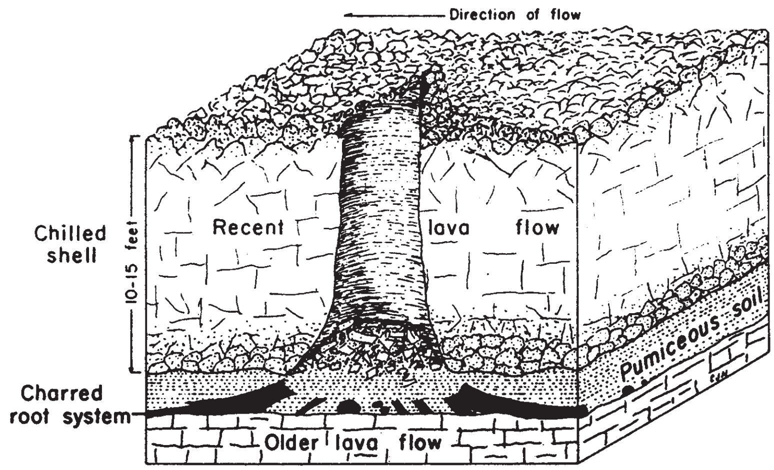
8.5 (26.6)
TURN LEFT (east) at the Paulina Lake junction (elev. 4,205 ft). As soon as you are clear of the intersection, pause on the shoulder along the road where you can see the broad silhouette of NEWBERRY CRATER against the eastern skyline. PAULINA PEAK (Stop No. 3) is visible as the highest point toward the southern part of the Volcano. Continue eastward on the Paulina Lake Road up into the Newberry Caldera.

The road crosses MAZAMA ash-covered alluvial sediments. This ash came from Mt. Mazama which is located approximately 70 miles to the southwest. About 6,600 to 6,700 years ago catastrophic eruptions from this volcano blanketed vast areas of the U.S. with tephra. CRATER LAKE now lies in the 5 by 6 miles wide caldera which resulted from these eruptions. Based on their pollen studies, Mehringer et al. (1977) concluded that Mazama ash fell into a lake in Montana during a 2 1/2 year period.

2.8 (29.4)
The road crosses PAULINA CREEK, the only stream on Newberry Volcano. This stream originates in PAULINA LAKE (Stop No. 4). The name PAULINA came from the "Renegade Chief Paulina of the Walapi tribe of the Snake Indians, who had outwitted soldiers in many skirmishes." He "died under the gunfire of a rancher on April 25, 1867" (Brogan 1971:48). "Despite his record as a killer and a raider, Paulina has been honored by having his name bestowed on more Central Oregon places than any other individual" (p. 58).

As you climb up the west flank of Newberry, watch for the change from a Ponderosa pine forest to forests of hemlocks and firs.

10.2 (39.6)
Road on north leads to PAULINA FALLS parking lot (0.1 mile). These Falls (elev. 6,240 ft) are approx. 1/2 mile from Paulina Lake. This is the FLOOR of NEWBERRY CALDERA (Fig. 18).



Figs. 16-17. Vertical tree casts: 16. Some casts are 20 ft deep. 17. Cross-section. From Peterson and Groh (1969).

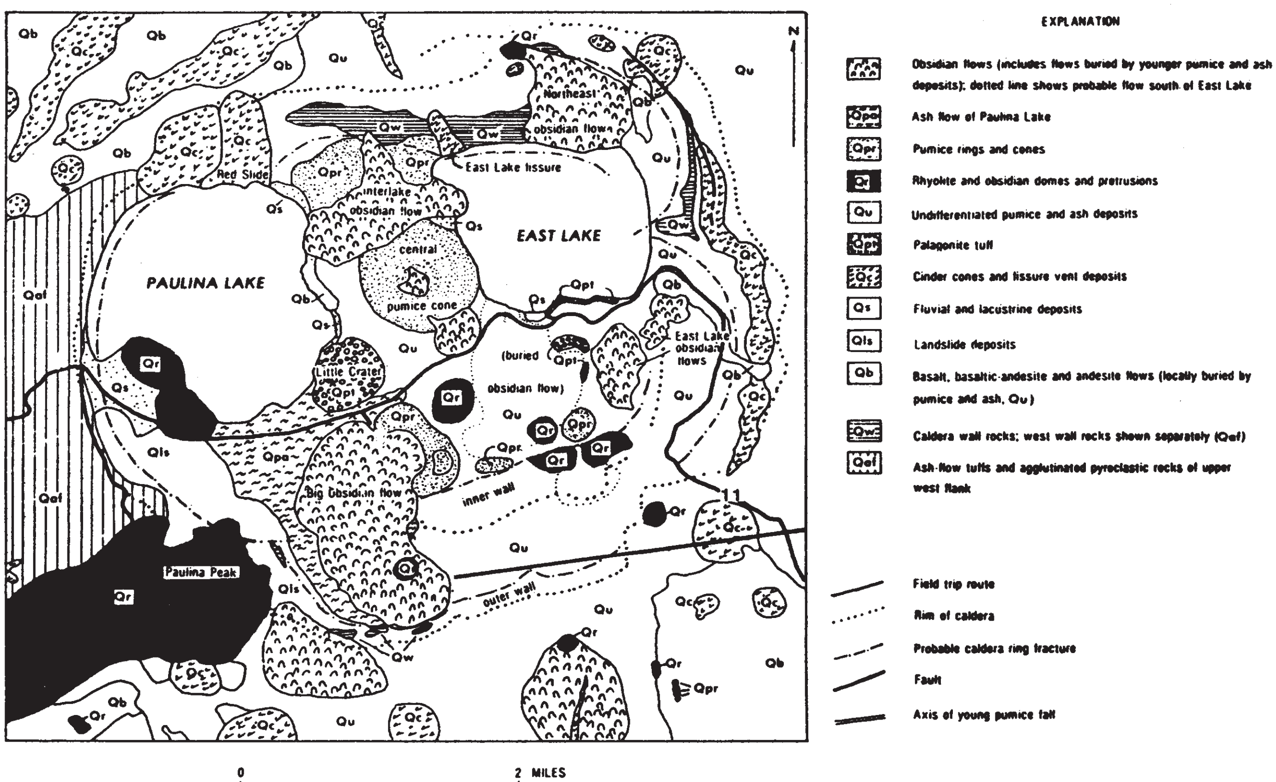


Fig. 18. Geologic sketch map of Newberry Caldera. After MacLeod et al. (1981a).

0.3 (39.9)
TURN RIGHT (south) on the PAULINA PEAK ROAD before you come to the pay booth.

3.0 (42.9)
You are traveling up the "outside" of the NEWBERRY VOLCANO. From this vantage point, you can see numerous cinder cones on the south flank, also the long narrow SURVEYOR LAVA FLOW (about 6,000 years old). SURVEYOR ICE CAVE is nearby. There are approximately 400 CINDER CONES (or parasitic cones) on the flanks of Newberry.

1.0 (43.9)
You are nearing the top of PAULINA PEAK (elev. 7,984 ft), a RHYOLITIC DOME, which extends 3 miles southwest down the flanks of Newberry and is about a mile wide. The spires of rock are rhyolite -- indirect evidence suggests that this silicic dome (silica content 72.02%) is about 0.4 m.y. old (MacLeod et al. 1981b). A dome of this type extrudes from the vent as a single mass of hot molten, exceedingly stiff and pasty rock which is too viscous to flow very far. Thus, a steep-sided dome results (picture tooth paste squeezing up out of a tube). Some of the rhyolite is flow-banded. "Nineteen rhyolitic bodies (domes, explosion craters, etc.) have been mapped on the flanks; some occur in zones radial to the caldera" (Baldwin 1981:133) -- this statement is based on Norman MacLeod's 1978 paper.

0.3 (44.2)
Pull into the parking area.

STOP NO 3: PAULINA PEAK.

Walk around the building where you can see the snow capped CASCADES. On a clear day with a heavy snow cover on the Cascades, you may be able to see Mt. Shasta, 14,161 ft, in northern California (look south from the highest part of Paulina Peak). In Oregon (from south to north) look for Mt. Scott, 8,926; Crater Lake; Mt. Thielson, 9,178; Diamond Peak, 8,792; Bachelor Butte, 9,060; Broken Top, 9,165; South Sister, 10,354; Middle Sister, 10,053; North Sister, 10,094; Mt. Washington, 7,802; Three Fingered Jack, 7,848; Mt. Jefferson, 10,495; Mt. Hood, 11,235; and in Washington, Mt. Adams, 12,286.

The CASCADES are a chain of SUBDUCTION STRATOVOLCANOES which parallel the Pacific coastline between northern California and southern British Columbia at a distance of about 100 miles inland. However, the Cascades are "not the simple Pliocene-Pleistocene belt of andesite volcanoes commonly depicted in geology textbooks". (Taylor 1981:57). The central High Cascade Range (includes Three Sisters, Broken Top and Mt. Bachelor) is "a broad Pleistocene platform of mafic composition in which open-textured basaltic lavas were at first predominate, then became subordinate to basaltic andesite. Silicic magma has invaded the platform throughout its development but only in isolated patches."

Look to the southeast of Newberry, and imagine the large tan area beyond the dark green trees as a vast lake. FORT ROCK-CHRISTMAS VALLEY contained water up to 200 ft deep from late Pliocene through late Pleistocene times (Allison 1979; Heiken et al. 1981). This basin, bounded by various fault scarps is about 40 miles from east to west. See the dark "whale shaped" landform? It is FORT ROCK (Stop No. 10). BEGGAR HEEL is the small "whale" about a mile to the west.

Newberry Volcano is surrounded by a COMPLEXLY FAULTED TERRAIN. Look along the eastern skyline for the 5 m.y. old GLASS BUTTES (S. 80 degrees E., 60 miles) and closer in (N. 35 degrees E., 11 miles), CHINA HAT (0.8 m.y.) and EAST BUTTE (0.9 m.y.) -- these are part of the well-defined age progression of silicic domes along the BROTHERS FAULT ZONE where the oldest are near Burns and the youngest are near Bend (Walker and Nolf 1981a, 1981b). The Brothers Fault zone extends across the extreme northeastern flanks of Newberry. This zone may extend "at depth or abut against the GREEN RIDGE -- WALKER RIM FAULT ZONE" which may curve beneath Newberry Volcano (MacLeod et al. 1981a:85). Look for WALKER MOUNTAIN (S. 42 degrees W., 35 miles) -- it is between here and Mt. Thielson, east of U.S. 97 and south of the towns of Gilchrist and Crescent. The Walker Rim Fault zone trends northeast toward Newberry, cutting only the older flows; it may be continuous with the Green Ridge Fault zone to the north, which trends northwest towards the Cascades and also cuts only the older flows. The NORTHWEST RIFT ZONE, associated with the young Newberry flows, begins at East Lake and extends northwest to the Lava Butte Flow and beyond. How these various fault zones relate to each other is unknown.

Use Fig. 18 to identify features of the CALDERA as you walk north along the inside of the fence. EAST LAKE (to the right) has a water level about 40 ft higher than that of PAULINA LAKE (Stop No. 4) and is about 170 ft deep while Paulina Lake is about 240 ft deep (bathymetric maps, Oregon State Game Commission 1964). Observe the BIG OBSIDIAN FLOW (Stop No. 5) and the CENTRAL PUMICE CONE. The caldera resulted from "voluminous tephra eruptions from the magma chambers below the former summit with concomitant collapse of the summit in a manner similar to that of most other calderas the size of Newberry's or larger. As there were several major tephra eruptions, it seems likely that collapse occurred several times, each collapse involving areas smaller than that of the present caldera. Accordingly, the present caldera is interpreted as SEVERAL NESTED CALDERAS OF DIFFERENT AGE" (MacLeod et al. 1981a:88).

As you return to your vehicle, look for trees which are wind pruned or "flagged" (branches

Fig. 19. Whitebark pine.

growing only on one side). Paulina Peak has the typical treeline species found in the Cascades. They are WHITEBARK PINE (Pinus albicaulis), MOUNTAIN HEMLOCK (Tsuga mertensiana) and SUBALPINE FIR (Abies lasiocarpa). They occur only in the western United States (Little 1980) and grow under very harsh winter conditions at high mountain elevations. Observe the growth pattern of WHITEBARK PINE. It shows spreading multiple crowns, short twisted trunks and long slender twigs with stout, stiff, short pointed needles in bundles of five which are clustered toward the tips of the twigs (Fig. 19). This 5 needle pine (with 1 1/2 to 2 3/4 inch needles) often grows at a higher elevation than the other trees. It is dispersed by CLARK'S NUTCRACKER (Nucifraga columbiana), a large noisy, gray, black and white jay-like bird. This nutcracker tears the Whitebark pine cones open, eats some seeds and stores others in the ground where they germinate. Otherwise the purple-brown, egg-shaped cones, 1 1/2 to 3 3/4 inches long, don't open until they decay. Several large MOUNTAIN HEMLOCKS grow to the east of the fence a few feet down the slope. Notice the "drooping leader" (the topmost twig) which characterizes hemlocks. Also the short (1/4 to 1 inch long), blue-green needles radiate all around the twig, clustering at the tip in a star shape. SUBALPINE FIRS can be seen during the first quarter mile as you descend Paulina Peak.

4.3 (48.5)
TURN EAST on the Paulina Lake Road.

0.1 (48.6)
TURN LEFT at the sign for the Paulina Lake Campground.

STOP NO. 4: PAULINA LAKE CAMPGROUND

The Paulina Lake campground (elev. 6,330 ft) is the LUNCH STOP for the N.S.S. Geology and Biology Field Trip. PAULINA LAKE, about 240 ft deep, has very steep walls and a flat floor. In the southern half there is an elongated cone (trending N. 30 degrees W.) which rises steeply from the bottom of the lake to within 80 ft of the surface (bathymetric map, Oregon State Game Commision 1964). As noted earlier, Paulina Lake is drained by Paulina Creek.

The trees are LODGEPOLE PINE (Pinus contorta), a widely distributed two needle pine (Fig. 20). The needles are 1 1/4 to 2 3/4 inches long. This tree may be tall with a narrow, dense conical crown, or it may be very short and stunted along the coast where it is salt and wind pruned. The cones are small, 3/4 to 2 inches long, stalkless, and one-sided at the base. This species occurs from Alaska to Baja, and from the Pacific Ocean to the Black Hills of South Dakota (Little 1980). Return to the main paved road and adjust mileage.

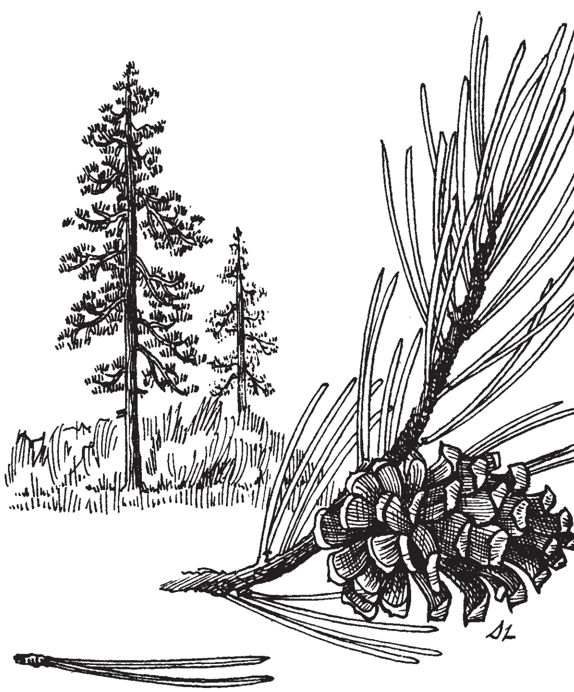


Fig. 20. Lodgepole pine.

0.0 (48.6)
TURN EAST on the main paved road.

2.2 (50.8)
TURN RIGHT at the sign for the Big Obsidian Flow. Continue to the parking area.

STOP NO. 5: BIG OBSIDIAN FLOW.

Near the parking area look for fragments of RHYOLITE, PUMICE and OBSIDIAN -- these rocks are different physical forms produced by thick, pasty, highly silicic rhyolitic magma (Fig. 35, Ireton this vol.). Rhyolite is fine grained and crystalline, while obsidian and pumice are glassy. Obsidian, the "glass of volcanoes," is as dense as other rocks. It is generally black, although it can be red, brown or gray, depending upon the ionic state of the iron traces which color the rock like ink in water. PUMICE is light colored and resembles frozen soap suds (Alt and Hyndman 1981) or dried whipped egg white. Pumice with many cells floats on water. How rocks differing so much in appearance can be chemically similar is a puzzle. Alt and Hyndman (1981:223) discuss the problem: "Generations of geology students have learned that obsidian is a glass because magma cooled so quickly that it didn't have time to crystalize. Whoever thought of that explanation obviously didn't know about the big obsidian flows in Newberry Caldera or the similar ones elsewhere in Oregon and other parts of the western states. There is no possible way that a lava flow the size of those in Newberry Caldera could cool quickly. Flows that size would probably take months to cool well below the freezing point. There must be a better explanation for the fact that obsidian is a glass; probably its lack of water prevents crystals from beginning to form." Obsidian is one of the driest rocks known and probably forms when rhyolitic magma erupts without picking up water either as the melt develops or as it rises through the earth's crust. Rhyolitic magma, however, can hold large quantities of water dissolved as steam. When this wet magma first reaches the surface, it puffs up like bread dough and explodes as fragments of pumiceous tephra. Thus, the moisture content may determine whether obsidian forms or pumice blasts forth.

Take the TRAIL OF GLASS up through the Lodgepole pines, past LOST LAKE, and walk on the BIG OBSIDIAN FLOW. Look for obsidian that is flow-banded, pumiceous or brown streaky which was pumiceous before it collapsed. BIG OBSIDIAN FLOW is about 1,350 years old and is essentially uniform in chemical composition with a silica content of 72% (MacLeod et al. 1981b). As you return to the parking lot, look at LITTLE CRATER (Fig. 18) north of the road. Adjust mileage at the main paved road.

0.0 (50.8)
TURN RIGHT on the main road and continue eastward.

0.4 (51.2)
Road on south leads to the drill site of the U.S.G.S. CORE HOLE. The CALDERA of Newberry is deeper than you might suspect. The core "penetrated 1,700 ft of caldera fill deposits, mostly pumiceous tephra, with a few rhyolitic and dacitic flows, and lake sediments 1,000 ft below the surface" (MacLeod et al. 1981a:89; Sammel 1981).

1.3 (52.5)

RECOMMENDED SIDE TRIP D: EAST LAKE CAMPGROUND.

TURN LEFT at the East Lake Campground. Park and walk along the shore. As you look westward, you can see the CENTRAL PUMICE CONE (Fig. 18). The EAST LAKE FISSURE, along the northern wall, is the southernmost vent of the Northwest Rift Zone. This flow is about 6,100 years old and contains abundant inclusions of obsidian, rhyolite, etc. (MacLeod et al. 1981b). The EAST LAKE OBSIDIAN FLOW, about 3,500 years old, reaches the northeastern shore. Adjust mileage at the main paved road.

0.0 (52.5)
EAST LAKE is about 170 ft deep. The water where you see green algae and other debris, is warmed by thermal springs with temperatures as high as 80 degrees C. However it is diluted by snow melt lake water (Black 1982).

0.4 (53.5)
TURN RIGHT on gravel road 2129 toward China Hat. Notice the changes in vegetation from nearly pure stands of Lodgepole pine to hemlocks and firs.

2.0 (55.5)
This is the EAST RIM OF NEWBERRY CALDERA (elev. 7,008 ft). The PUMICE, about 8 ft deep, came from the vent of the BIG OBSIDIAN FLOW. It is about 1,600 years old (MacLeod et al. 1981b). Continue eastward on road 2129. Watch for glimpses of the "whale shaped" Fort Rock beyond the trees.

1.9 (57.4)
Junction with the China Hat Road (elev. 5,250). TURN RIGHT (south). This road (1821) is just west of CHINA HAT (0.8 m.y.), EAST BUTTE (0.9 m.y.), and QUARTZ MOUNTAIN (1.1 m.y.), young rhyolitic domes of the age progression of silicic domes extending eastward along the BROTHERS FAULT ZONE (Fig. 5). POTHOLES FLOW, one of the non-randomly distributed basaltic flows aligned along the zone, is just east of these buttes.

0.9 (58.3)
Major intersection. Stay on road 1821. The road to the right leads to the MATZ CAVE SYSTEM. These small but interesting lava caves are difficult to find even with directions. LAVA PASS FLOW is also along the Brothers Fault Zone.

7.5 (65.8)
Major intersection. TURN RIGHT (west) on paved road 2226.

1.1 (66.9)
TURN RIGHT on the very short road to SOUTH ICE CAVE. You may not see a sign, but you should spot a peeled log fence through the trees. Park and walk to the entrance sink.

STOP NO. 6: SOUTH ICE CAVE.

SOUTH ICE CAVE (elev. 5,020 ft) formed in one of the flank flows of Newberry Volcano (Greeley 1971). Originally a single, continuous lava tube, South Ice Cave now consists of two segments separated by a large entrance sink which is floored by breakdown and soil. Breakdown blocks cover the floors of both segments, generally choking the passages down to crawl spaces. This is especially true of the north segment beyond the first small room, and of the south segment beyond the first two large rooms. In the large rooms of the south segment, water accumulates in low places forming either "ice rinks" or shallow pools on top of ice depending upon the season.

New ice doesn't accumulate during the fall of the year, as is generally presumed (Kamp 1970, 1973 and other papers). The cave rocks are too warm after the summer and early fall input of warm air. As the cave rock cools below freezing, the melt water freezes and relative humidities drop below 10%. The dry snow on the surface mostly evaporates, so water doesn't run into the cave during the fall and winter months; some wind blown snow hardens into ice in the entrance zone. Once the warm spring and early summer rains begin, water seeps in through the overburden and new ice accumulates rapidly. In California it took only a half hour for a cave to "fill" with ice crystals seeded by Kamp's breath. Both freezing temperatures and moisture must be present simultaneously for ice formation. This microclimate cycle is extremely important to the biota (millipedes, spiders, diplurans and grylloblattids) in South Ice Cave. Kamp, biologist from the University of British Columbia, studied GRYLLOBLATTIDS (Fig. 21) and took microclimate measurements in SOUTH ICE, EDISON ICE and LAVA TOP BUTTE ICE CAVES.

GRYLLOBLATTIDS ("cockroach crickets") are primitive, wingless insects of the genus *Grylloblatta* in the Order Notoptera erected by Kamp for *Grylloblatta* and a genus from Japan. Once considered among the rarest insects of the world, grylloblattids are now known to be relatively common in COLD CAVES and MONTAINE ICE FIELDS of the western U.S. and Canada. These insects inhabit caves maintaining a spring to fall temperature range between -3 and +5 degrees C and relative humidities above 80%. As relative humidities drop toward 70%, the temperatures tolerated by these insects narrow toward zero (i.e., freezing). They leave the cave for the snow pack on the surface. When the snow melts in the spring, they again enter the cave where relative humidities have risen above 70%. Now they are troglophiles ("cave lovers"), they are confined to the cave where they reproduce from late spring to late fall. Apparently these insects evolved in the montaine ice fields and then secondarily invaded caves along with the other biota. As Peck (1973) puts it: "Much of the fauna probably came from higher elevations, reaching the caves overland by migration during the cooler and more moist conditions during the last glaciation...As the glacial ice retreated and the warming and drying trends of the present interglacial continued, some of the populations retreated into suitable environments offered by the caves." In support of this idea, grylloblattids of both caves and ice fields exist under similar conditions of temperature and relative humidity. Oregon wasn't covered by an ice sheet during the Pleistocene as is commonly thought. Instead the glaciers in the mountains enlarged and the low lying basins of central and southeastern Oregon filled with water forming vast lake systems, e.g., the pluvial FORT ROCK LAKE whose shores were within 10 miles of South Ice Cave (Fig. 22). Return to road 2226 and adjust the mileage.

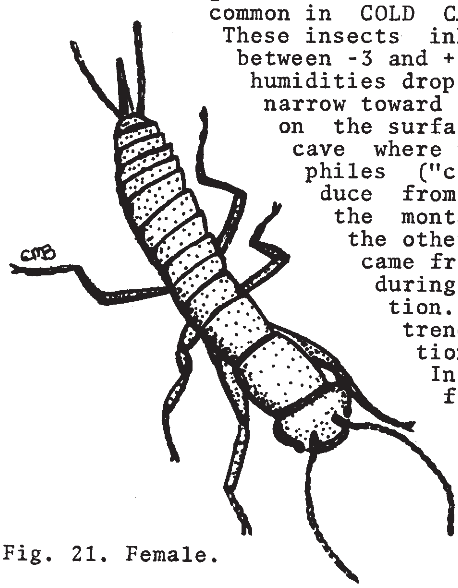


Fig. 21. Female.

0.0 (66.9)
TURN LEFT on road 2226 and continue east.

1.1 (68.0)
Junction with China Hat Road (1821). The route to the Devils Garden Lava Field (Stops No. 7-9) is a bit tricky and mileages are estimated, therefore refer to Fig. 23. Continue east on road 2226. Enroute you will cross the LAVA PASS FLOW.

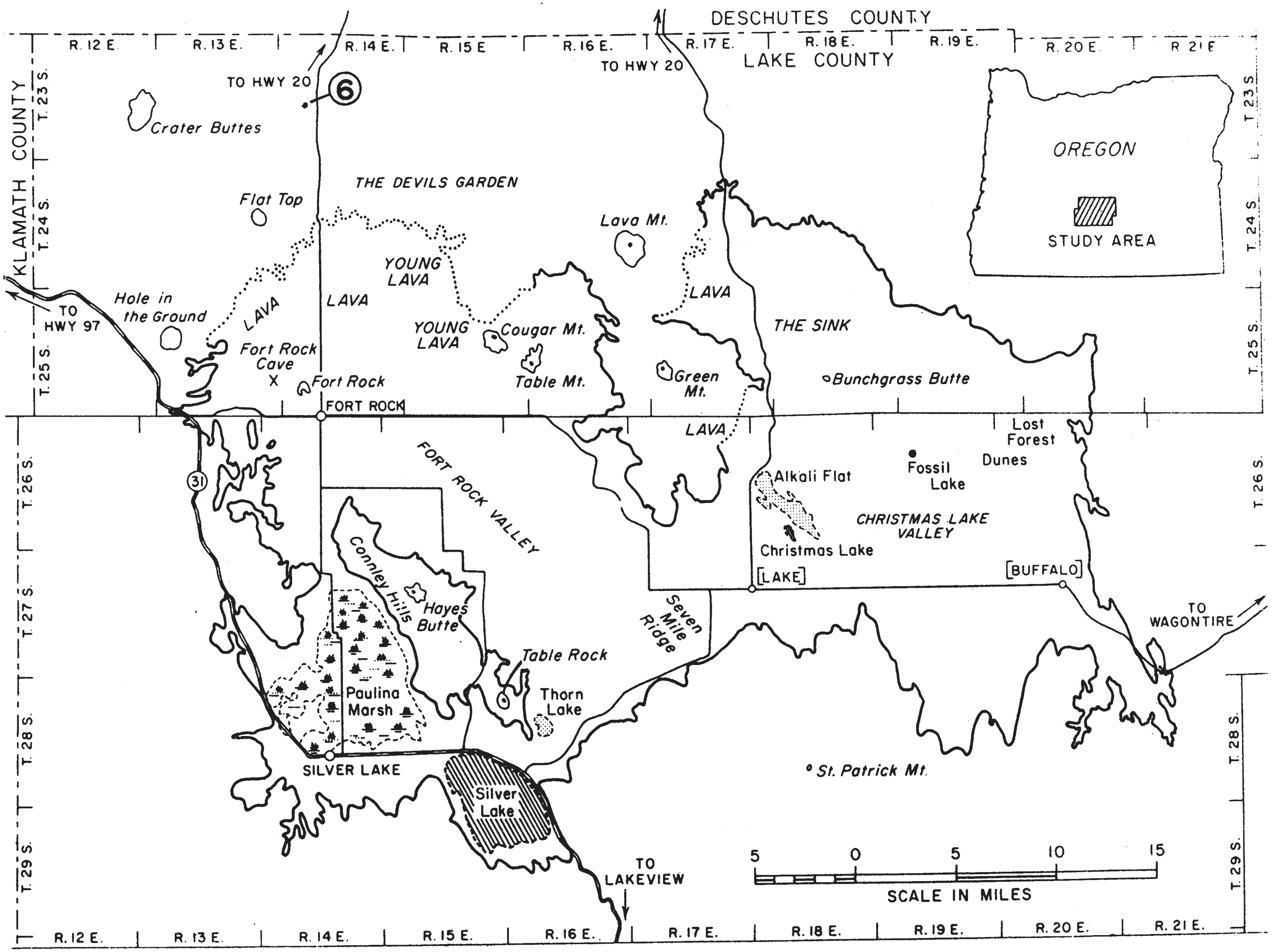


Fig. 22. Fort Rock area with the boundaries of the pluvial Fort Rock Lake. From Allison (1979).

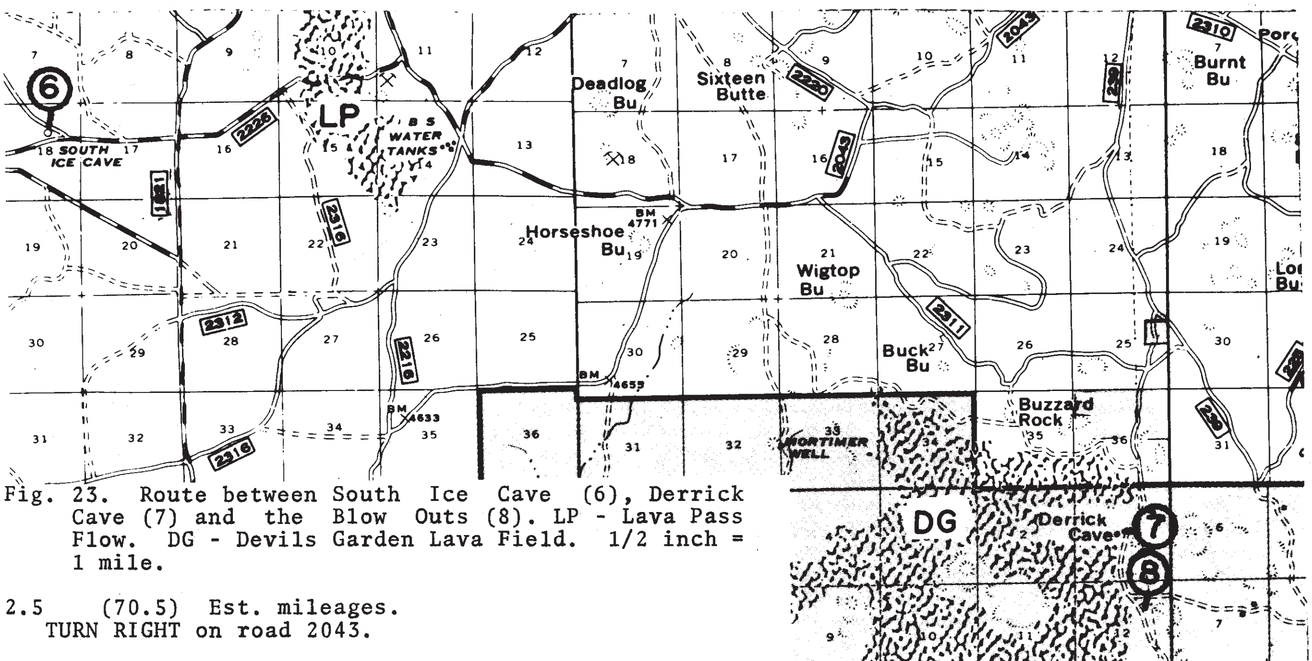


Fig. 23. Route between South Ice Cave (6), Derrick Cave (7) and the Blow Outs (8). LP - Lava Pass Flow. DG - Devils Garden Lava Field. 1/2 inch = 1 mile.

2.5 (70.5) Est. mileages.
TURN RIGHT on road 2043.

5.0 (75.5) Est. mileages.
TURN RIGHT on road 2311. Follow it until you cross under the large 500 KV powerline (faint dashed line on Fig. 23).

5.0 (80.5) Est. mileages.
TURN RIGHT on the unmarked dirt road just east of the powerline to go south along the eastern edge of the DEVILS GARDEN LAVA FIELD (Figs. 23-24). In March 1980 the Bureau of Land Management designated 29,640 acres of the 25 square mile lava field as a WILDERNESS STUDY AREA. A WSA is "an area inventoried and determined to be wilderness in character, having few human developments and providing opportunities for solitude and primitive recreation." West of DERRICK CAVE one finds a rugged terrain of lava and dense vegetation which screens the road and the 500 KV powerline. Devils Garden isn't "Wilderness" yet since only Congress can designate an area as Wilderness.

2.0 (82.5) Est. mileages.
To your left, look at the SPATTER CONES (Fig. 24) aligned along a fissure. Several are at least 30 ft in diameter. Spatter cones form as pasty clots of semi-molten basalt splatter up around steam jets from temporary vents, like oatmeal boiling.

0.1 (82.6) Est. mileages.
TURN RIGHT on unmarked dirt road and park. The entrance sink of DERRICK CAVE (Fig. 24) is at the end of this road.

STOP NO. 7: DERRICK CAVE.

"The lava originated from fissure vents in the north and northeast part of the Devils Garden and spread to the south and southwest. Several rounded hills and slightly higher areas of older rocks are now 'kipukas' completely surrounded by the fresh black lava. The eruptions were of a quiet type, with only moderate fire fountaining at the two vents from which all the lava flowed." The main vent is "bordered by low spatter ramparts. From here there was flowage northwest through a narrow, open lava gutter and also to the south where the lava was distributed through a large, sinuous, well-developed lava tube, Derrick Cave" (Peterson and Groh 1965:19).

DERRICK CAVE extends both north and south from the large entrance sink which is floored with breakdown from the collapse of lava, once roofing the tube. Although the overburden is only a few inches thick at the entrance of the south segment, it is about 85 ft thick at the lower end. As you walk toward the skylights, notice the thick layer of tephra. Both NEWBERRY and MAZAMA TEPHRA fell here. Near the skylights look at the red wall lining (see Fig. 37, Harter and Harter, this vol.). As you go deeper observe the very steep slope and feel the cold air drainage. Examine the floor and wall linings, the tubes within tubes, the flow lines and the drip formations. Avoid stepping on the white MILLIPEDES (Plumatyla humerosa). This troglophilic species occurs in cold caves and mines in Oregon and California and is presumed to be relictual from the last glaciation. Rock temperatures deep in Derrick Cave are below freezing and relative humidities are above 80%. This cave could provide habitat for grylloblattids but none are known.

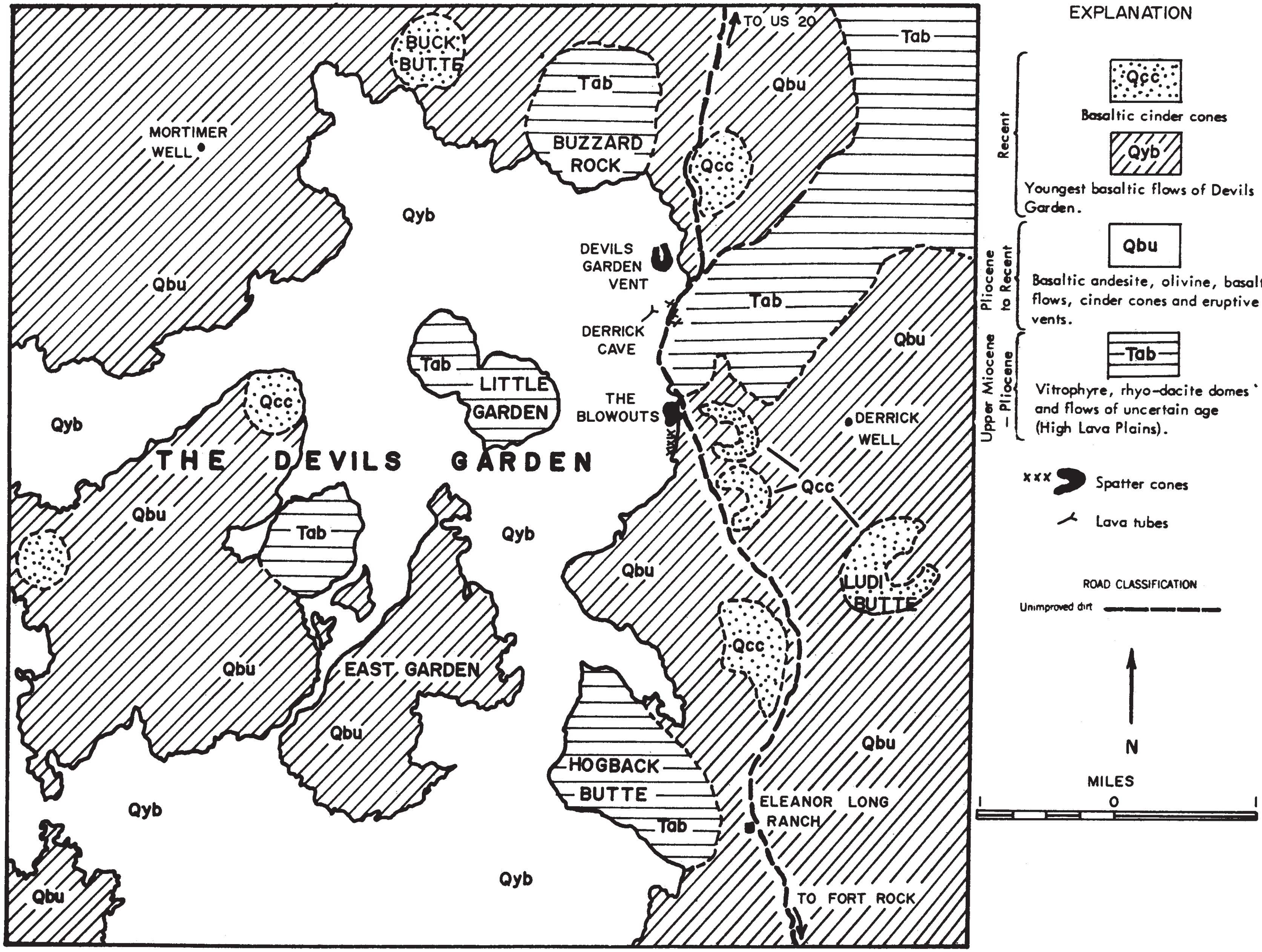


Fig. 24. Geologic sketch map of the northern part of the Devils Garden Lava Field. After Peterson and Groh (1965).

Return to the entrance sink and look in the north segment where there are massive deposits of shiny, black tar-like RATAMBER (fossilized pack rat urine). Peter Mehringer Jr., paleoecologist at Washington State University, says, "You can recognize ratamber because it smells like rat and tastes like urine." PACK RATS (Neotoma spp.) forage only within a hundred yards of their den. The ratamber forms as they urinate on huge middens of twigs, bones, rocks, etc. In dry caves or protected crevices, the ratamber can be preserved for thousands of years. Mehringer separates out the plant macrofossils, identifies them to species and age dates them. With this information, he can reconstruct some of the ecological history of the past.

As you return to your vehicle, look at the Western juniper, Ponderosa pine, and CURLLEAF MOUNTAIN-MAHOGANY (Cercocarpus ledisfolius). These low, evergreen trees with compact, rounded crowns of widely spreading, curved and twisted branches (Fig.25) are typical of the lower mountain slopes of sagebrush deserts. Deer browse the foliage. The Navajo Indians (in other areas) grind the roots and mix them with juniper ashes and powdered alder bark to make a red dye. These trees range from extreme southeastern Washington to southern Montana, south to northern Arizona and west to southern California at elevations of 4,000 to 10,500 ft (Little 1980). Return to the main dirt road and adjust the mileage.

Fig. 25. Curlleaf Mountain-mahogany.

0.0 (82.6)
TURN RIGHT and continue south. PLEASE! REFASTEN GATES WHICH YOU OPEN.

0.7 (83.3)
Park at the edge of the road within a few feet of the Y-junction.

STOP NO. 8: THE BLOW OUTS.

The north BLOW OUT is about 400 ft in diameter and about 150 ft high, the south one is slightly smaller. Although the green, blue, tan and gold SPATTER looks newly erupted, it may be several thousand years old. Several small spatter cones are just south of the Blow Outs -- all formed along a common eruptive fissure. Look for the SURFACE TUBE on the southern flank of the south Blow Out. Return to the Y-junction and adjust mileage.

0.0 (83.3)
TURN EAST on the road which almost immediately crosses under the 500 KV powerline. Figs. 24, 26 show the route.

1.8 (85.1)
TURN RIGHT and continue south.

2.4 (87.5)
RANCH BUILDINGS. This is the ELEANOR LONG RANCH on Fig. 24, and the DERRICK RANCH on Fig. 26. Continue south.

2.7 (90.2)
Road to east goes to the BLM Guard Station. The southern part of the DEVILS GARDEN LAVA FIELD (Fig. 26) is to your right.

0.5 (90.7)
Park at the side of the road just before you cross under the powerline.

STOP NO. 9: DEVILS GARDEN LAVA FIELD.

Examine the PAHOEHOE surface. Compare it to the AA texture of the LAVA BUTTE FLOW. The pahoehoe surface is pockmarked by depressions formed as the lava drained from under the hardening, ropy, wrinkled crust. "Where resistance to the further spreading of the lava was too great, the crust swelled upward into low rounded, cracked-open domes or tumuli" (Peterson and Groh 1965:19).

Both PAHOEHOE and AA BASALT can form from the same magma. Pahoehoe can change into aa but not the reverse. Imagine a red hot, runny and highly gaseous, molten pahoehoe lava flowing out in a thin layer. The chilling crust wrinkles as the inside still flows. As the lava cools and degases, it gets thicker and less fluid -- aa begins forming. The viscous crust fragments and

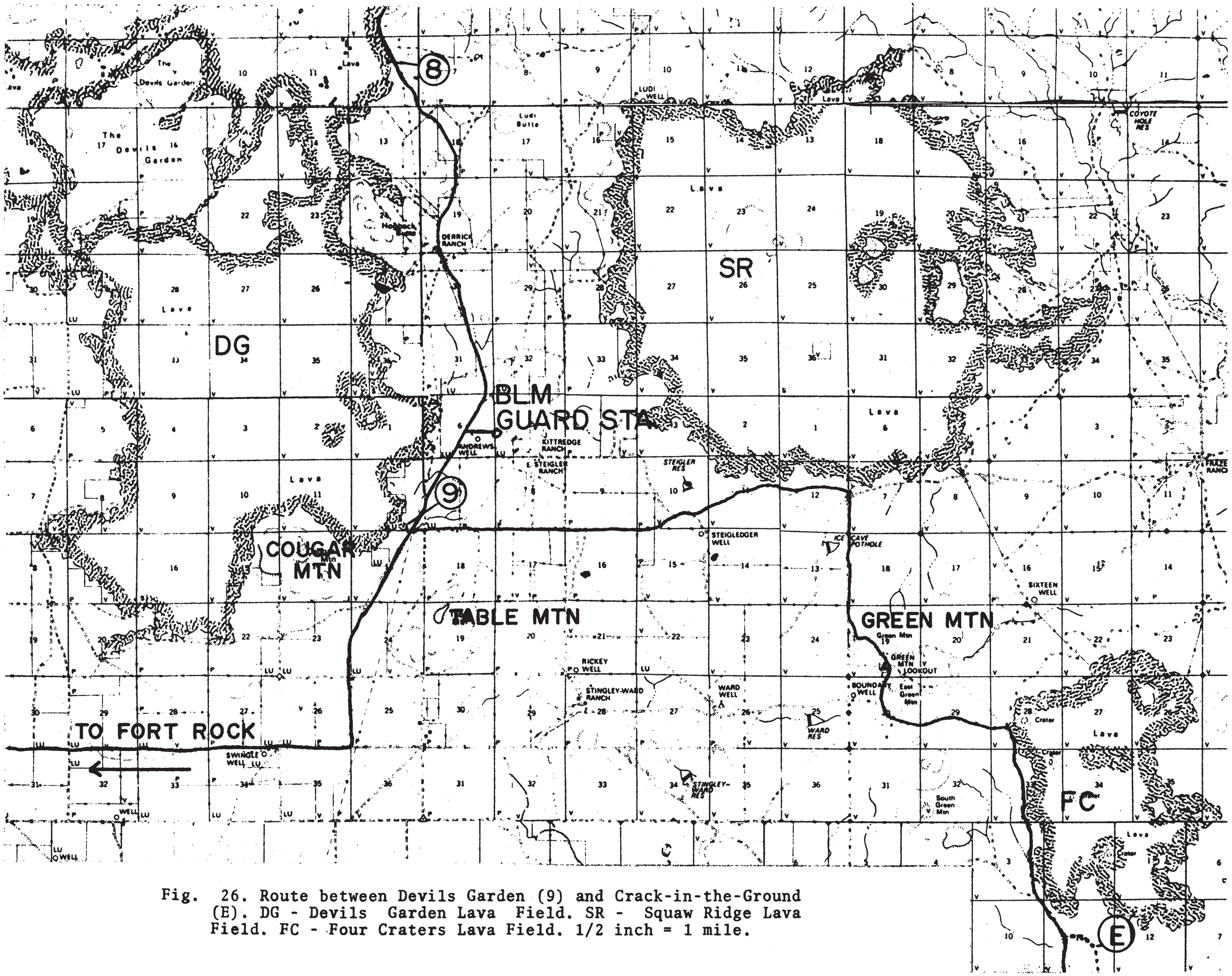


Fig. 26. Route between Devils Garden (9) and Crack-in-the-Ground (E). DG - Devils Garden Lava Field. SR - Squaw Ridge Lava Field. FC - Four Craters Lava Field. 1/2 inch = 1 mile.

lava piles up in front of the advancing toe. The hotter lava continually advances over the solid chunks. Pieces break off and topple in glowing cascades. The inside moves only a few yards per hour (from Francis 1976).

COUGAR MOUNTAIN (elev. 5,140 ft) is south of the road. DEVILS GARDEN LAVA FIELD lapped around Cougar Mountain as it encroached upon the FORT ROCK LAKE basin (Fig. 22). Waves ground out LITTORAL CAVES at the 4,450 ft level on this 4 m.y. old eroded RHYOLITIC DOME. FORT ROCK CAVE MEN (Brogan 1971) left CHARCOAL in the caves about 11,950 years ago and a tule fiber SANDAL about 8,500 years ago.

"Fort Rock Lake, the most northwesterly of the large Pleistocene pluvial lakes in south central Oregon...occupied an irregular basin which extends about 40 miles north-south...its outer boundaries originated by faulting" (Allison 1979:4). "Eruptions of basaltic magma occurred along faults that trend diagonally across the basin and adjacent highland, forming maar volcanoes within and on lake margins and forming cinder cones with flows beyond the lake margins" (Heiken et al.1981:119). A maar is caused by EXPLOSIONS; it consists of a crater extending below the ground level which is wider than deep and has a rim of ejecta. In the Fort Rock Basin many of the maar craters are obscured by debris. TABLE MOUNTAIN (Fig. 27), to the east, is an eroded remnant of a MAAR VOLCANO.

"Young lavas encroach upon the Fort Rock Basin north of Fort Rock, at the Devils Garden near Cougar Mountain, and west of The Sink" (Allison 1979:4). The dotted lines in Fig. 22 indicate the areas of encroachment, while Figs. 26-27 show three of the "young" basaltic lava fields in this part of the BROTHERS FAULT ZONE. Continue south.

1.2 (91.9)
Junction with the unmarked, graded dirt road to CRACK-IN-THE-GROUND (Figs. 26-29). To take Trip E, TURN LEFT. You will adjust mileage for this loop at the town of Fort Rock.

IF YOU DO NOT GO TO CRACK-IN-THE-GROUND, CONTINUE SOUTH. At 3.1 miles, TURN RIGHT (west) on the pavement and leave the 500 KV powerline behind. Follow this paved road westward to the small TOWN OF FORT ROCK across beach ridges and bars, which were constructed by waves and shore currents (Allison 1979) and then travel over the flat dry lakebed of pluvial Fort Rock Lake.

RECOMMENDED SIDE TRIP E: CRACK-IN-THE-GROUND.

Follow this road east. At 2.4 miles you will see LAVA MOUNTAIN, the highest point of the 40 mile square SQUAW RIDGE LAVA FIELD (Figs. 22, 26). "Lava Mountain, a magnificent basaltic shield-type lava cone apparently of recent age, covering a township, borders The Sink on the northwest. Its fresh lavas reach down to 4,445 ft on the southeast and to 4,380 ft on the east, where one lava tongue protrudes about 2 miles beyond the base of the cone" (Allison 1979:21). "One or more cinder cones top this shield-shaped cone and probably were formed during the last eruptive phases" (Peterson and Groh 1963:9). This basaltic field contains both AA and PAHOEHOE. TALUS CAVES occur in tension cracks (Fig. 27) north of this lava field. "The Squaw Ridge Rift System is an approximately two-mile long tension fracture (fault) in basalt bordering the Squaw Ridge Lava Field...Geologically, the origin and morphology of this system appear to be almost identical to that of Crack-in-the-Ground, another tension fault on the border of the Four Craters Lava Field" (Skinner 1980:101). The SQUAW RIDGE LAVA FIELD is one of BLM's WILDERNESS STUDY AREAS.

At 6.2 miles, TURN RIGHT (south) away from the Squaw Ridge Lava Field. You will begin climbing the flanks of GREEN MOUNTAIN (elev. 5,190 ft), a low SHIELD some 10 to 12 miles in diameter of pahoehoe lavas, whose upper slopes average 4 degrees (Allison 1979). Several small cinder cones near the summit retain most of their initial characteristics even though covered by vegetation (Peterson and Groh 1964a).

As you descend Green Mountain, watch for the ERODED REMNANT OF A MAAR or tuff ring of late Pliocene to Pleistocene age (Fig. 28). "This mass of yellow-brown tuff and breccia is similar in composition and layering to Fort Rock and other remnants of maars and tuffs rings, which once were numerous and widely distributed in and around the edges of the large lake basins of central Oregon" (Peterson and Groh 1964a:164).

Lava flowed over the top of the Green Mountain basalt along a northwest trending fissure forming the FOUR CRATERS LAVA FIELD (Fig. 28), just to the east of the eroded maar. This field contains four main cinder cones, 250 to 400 ft high. The distance between the northern and southern cones is about 2 1/4 miles. Several sectors of the southern cone rafted to the southeast on a slightly later lava flow (Peterson and Groh 1964a:164).

Explore the side roads to the east as you travel south along the western edge of the lava field. Locate the place where lava flowed into CRACK-IN-THE-GROUND, a system of open tension fissures in Green Mountain basalt (Figs. 28-29). The main fissure, more than 2 miles long, is 10 to 15 ft wide at the top and up to 70 ft deep. The walls consist of two or more flows with an overall thickness of 70 feet. They are rough, irregular, and show no lateral and only slight vertical movement. The soil is fine pumice, windblown sand, and silt from dry lake beds

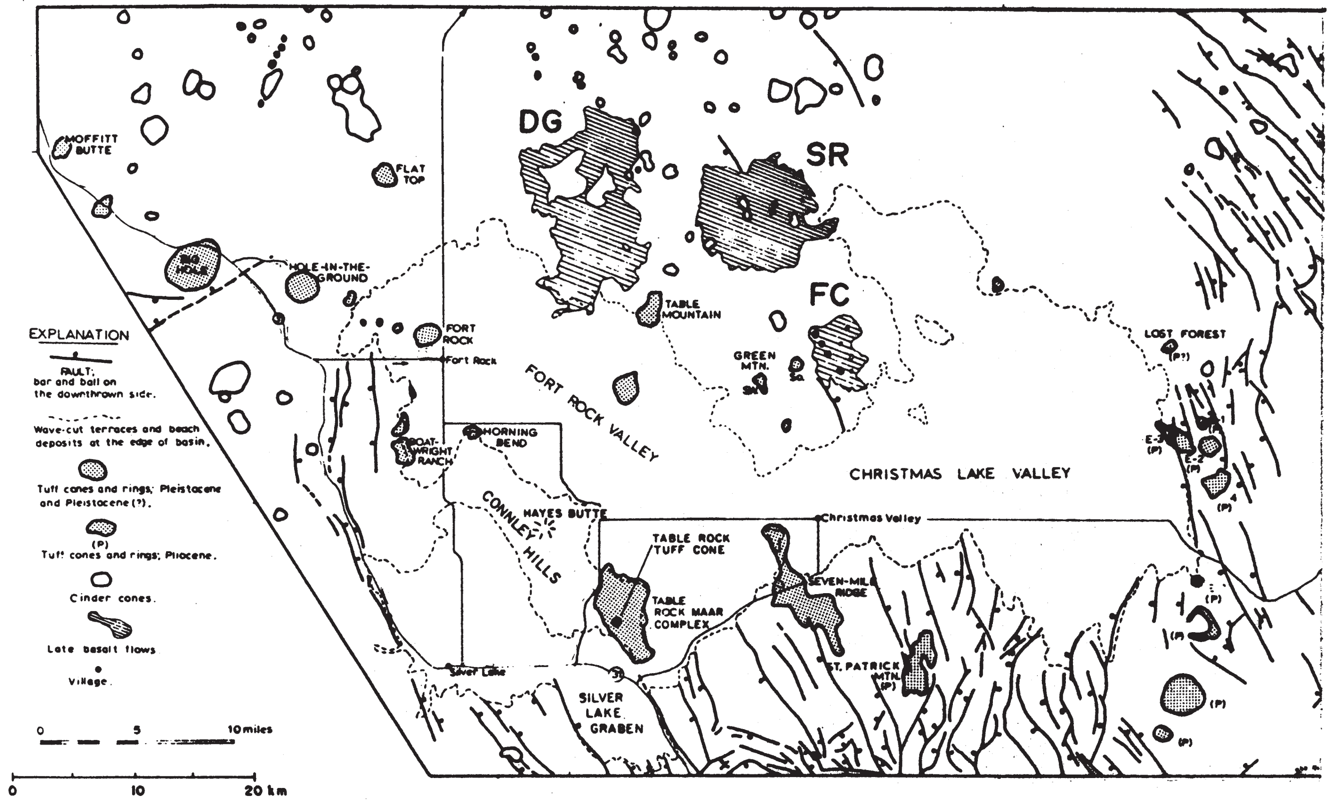


Fig. 27. Fort Rock - Christmas Valley basin of pluvial Fort Rock Lake. Here eruptions of basaltic magma occurred along faults that trend diagionally across the basin and adjacent highlands, forming maar volcanoes within and on lake margins and forming cinder cones with flows beyond the lake margins. DG - Devils Garden Lava Field. SR - Squaw Ridge Lava Field with the Squaw Ridge Rift System extending mortward. FC - Four Craters Lava Field with Crack-in-the-Ground extending southeastward.

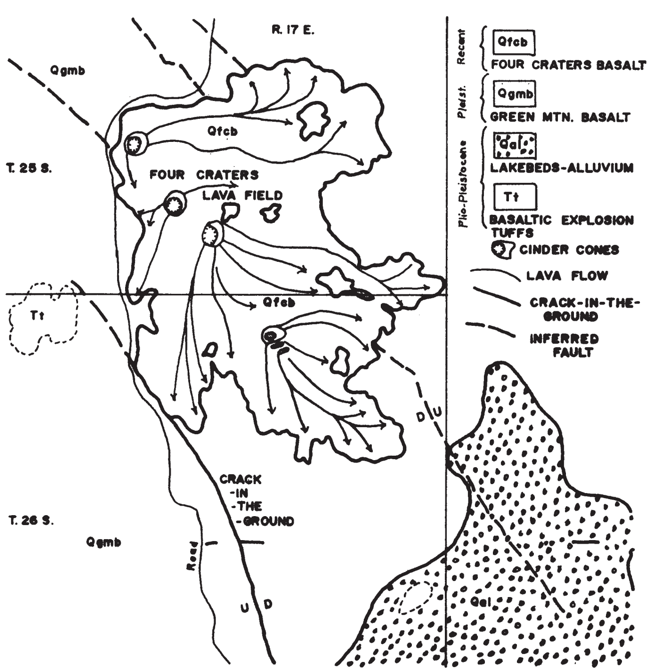


Fig. 28. Geologic sketch map. After Peterson and Groh (1964a).

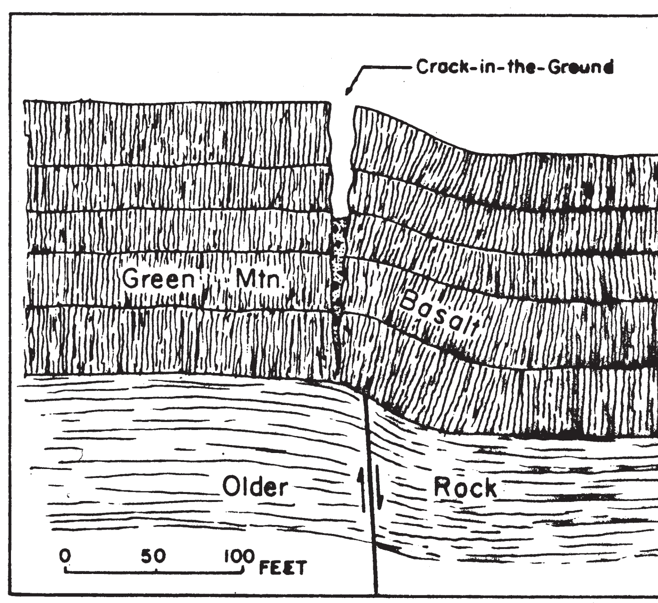


Fig. 29. Cross-section. From Peterson and Groh (1969a).

(Peterson and Groh 1964a). The FOUR CRATERS LAVA BEDS is a BLM WILDERNESS STUDY AREA.

Continue southward to the town of CHRISTMAS LAKE, and follow the signs westward to the town of FORT ROCK. At Fort Rock adjust your mileage.

13.0 (104.9)
TOWN OF FORT ROCK. Opposite the Post Office, TURN RIGHT on the China Hat Road. Ahead is the imposing volcanic landform called FORT ROCK, an eroded remnant of a TUFF RING. TUFF is compacted volcanic ash with particles finer than 1/6 of an inch in diameter. Fort Rock is a type of MAAR VOLCANO formed by repeated BASE SURGES. As Nolf explains it (in Hatton 1977: 90), "The eruptions forming tuff rings occur when rising basaltic magma encounters abundant ground water at significant depths beneath the earth's surface, causing a violent steam explosion which drives a highly compressed column of fragmented ash, steam, and water rapidly upward to the surface. At the ground surface the base of the eruptive column expands at high velocity, depositing wet ash in a ring-like form which is concentric about the vent." Atomic explosions suggested the idea of base surges. In these explosions, a ring-like basal cloud expands horizontally as the main vertical explosive column rises into a mushroom cloud. When geologists examine tuff rings such as Fort Rock, they find layers of density flow debris from base surges interbedded with the air borne ejecta. "A base surge is not a separate kind of eruption, but is a phenomenon associated with various kinds of vertical explosion...The initial velocity is commonly greater than 50 m per second, and it can carry clastic material for many kilometers. Ash, mud, lappilli, and blocks can all be transported...The base surge may deposit material beyond the range of ejecta that simply fall through the air...Wood neither burns nor chars, and it is possible that the temperature in a basal surge is less than 100 degrees C" (Ollier 1967:15).

1.0 (105.9)
TURN LEFT.

0.6 (106.5)
TURN RIGHT at FORT ROCK STATE PARK and pull into a parking space. Here you will find restrooms, water and a few picnic tables. This is the DINNER STOP for the N.S.S. Geology and Biology Field Trip.

STOP NO. 10: FORT ROCK STATE PARK.

The sign here at Fort Rock is misleading about the age of FORT ROCK LAKE. It existed from late Pliocene through late Pleistocene times (Heiken et al. 1981). It probably terminated by evaporation about 10,000 years ago (Allison 1979). Snail shells from about 10 ft below the surface of Fossil Lake (Fig. 22) were C 14 dated at 29,000 years. Even older mammal bones were recovered from a deeper level (Allison 1966, 1979). The text of this sign is as follows:

FORT ROCK

Fort Rock, towering above you to the north and west, is one of Oregon's most interesting geologic features. Geologists believe it was formed near the end of the Ice Age some 10,000 - 12,000 years ago during a period of frequent volcanic activity in Central Oregon. Molten lava rising from deep within the earth came into contact with water-saturated rocks beneath a shallow lake which then covered Fort Rock Valley. The resulting steam produced a rapid series of volcanic eruptions which hurled great quantities of hot ash and rock fragments into the air. This debris fell in a circular pattern around the volcanic vent, forming a ring which may have reached a height of 500 ft. Geologists feel that formations such as Fort Rock may have formed in a relatively short period of time -- from a few days to a few months. When the volcano had ceased to erupt, the ring of ash and rock fragments was hardened by heat and pressure into its present-day, brick-like form. The geologic term for the type of rock which forms Fort Rock is "tuff," and the circular formation of the rock is known as a "tuff ring."

Whipped by the wind, waves from the lake which covered Fort Rock Valley began to erode the walls of Fort Rock. Because the prevailing winds were mostly from the southwest, this side of the tuff ring was eventually breached and Fort Rock took on its present-day cresent-shaped appearance. Evidence of this wave action can be clearly seen in the prominent wave-cut terraces at both ends of the cliffs on the open side of the formation.

It is also believed that the wave action produced the vertical cliffs on the outside of the rock, many of which are over 200 feet high. Slumping of the rock walls and further erosion by wind and rain during the last 10,000 years have brought the present height of Fort Rock to about 325 feet at its highest point. The formation is about one-third of a mile in diameter.

As the Ice Age ended, much of south Central Oregon was inundated by large lakes. The lakes which covered Fort Rock Valley stretched eastward over 40 miles to Christmas Lake Valley and Fossil Lake and south almost 30 miles to Silver Lake, reaching a depth of 200 feet. It contained fish, including species similar to the present-day Chinook

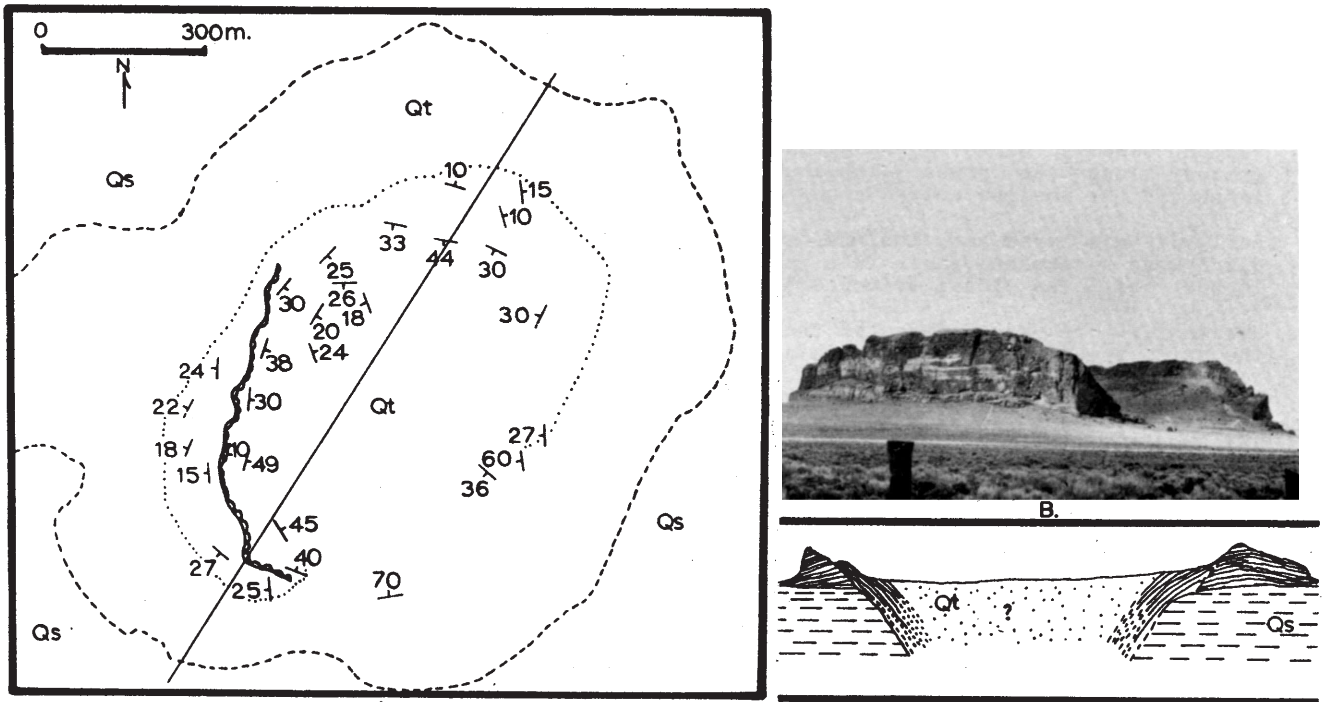


Fig. 30. Fort rock tuff ring. A. Map: Qs - Pleistocene lake sediments, mostly diatomites. Qt - tuffs, lapilli-tuff breccias. Scalloped line is an unconformity. Dotted line is cliff edge. B. View from the southwest. C. Cross-section. After Heiken et al. (1981).

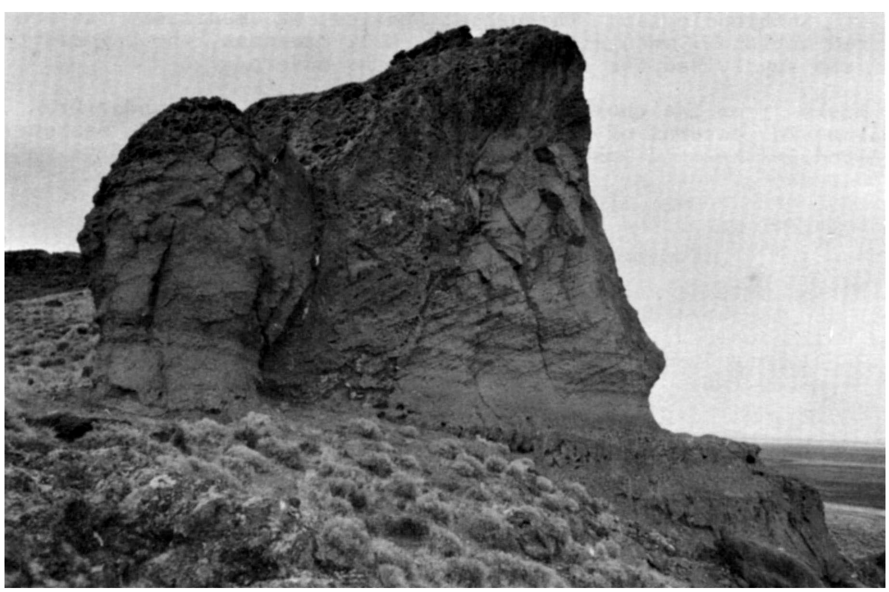


Fig. 31. View from south on a terrace of Fort Rock showing wave cut grooves and nips on the north end of this horseshoe shaped maar volcano.

Salmon. Camels, mammoths, mastadons, horses, bison, and other animals of the Ice Age grazed along the grassy lakeshore; and birds including flamingos and waterfowl, inhabited the shallow waters along the lake's edge.

Early-day man lived here too, in rocky caves overlooking the lake. Sagebrush sandals discovered by archeologists in a nearby cave have been radio carbon dated at more than 10,000 years, the oldest evidence of human habitation in Oregon.

Eventually, the vast lakes of the region dried up as the climate changed, resulting in the arid, sageburgh-covered terrain which is typical of the Fort Rock Rock area today.

Stories of the use of Fort Rock by settlers as a defensive position against Indian attacks have appeared over the years, although none have ever been substantiated. It is believed that Fort Rock was named by William Sullivan, a rancher who settled in Central Oregon in 1873. His reason for naming the prominent landmark "Fort Rock" was a logical one -- the high, rocky walls and circular formation gave it the appearance of a large natural fort.

Be sure to look closely at the texture of the BASALTIC TUFF with its inclusions of coarser debris. The CENTRAL VENT of Fort Rock is buried under materials washed into it from the slopes (Nolf in Hatton 1977). The INWARD DIPPING BEDS, parallel to the crater walls, suggest that the crater is funnel shaped (Fig. 30). The innermost beds dip inward at angles of 20 to 70 degrees (Heiken et al. 1981). Examine the WAVE CUT TERRACES, GROOVES and NIPS (Fig. 31). There are even a couple of very shallow LITTORAL CAVES on Fort Rock.

However, the famed FORT ROCK CAVE is on BEGGAR HEEL (Houghton 1976) or Menkenmaier Butte (Allison 1979). You can see Beggar Heel, "the low north rim of the tuff ring in which the famous sandal cave occurs" (Nolf in Hatton 1977), from the top of the west wall of Fort Rock. This cave is about 15 ft high, 70 ft wide at the entrance and 60 ft deep. To quote Brogan (1971:20):

> A SHALLOW, ROCK-STREWN CAVE, in the remnant of a wave-cut volcanic cone of the Fort Rock basin, is the oldest known habitation of man in the Oregon Country. Sagebrush sandals unearthed from the dust of Fort Rock Cave have a radio-carbon date of around nine thousand years. The sandals -- some of them scorched by hot pumice from a nearby volcano -- were discovered deep in the debris of the cavern. Fort Rock Cave, once the home of hunters who tipped their spears and arrows with obsidian, is now part of the Reuben Long ranch in northern Lake County.
>
> Those ancient Oregonians wove sagebrush bark into durable sandals and wore them along the muddy shores of a lake never seen by white men. Some of the sandals, when found still bore mud from the rim of the lake that spread over the broad Fort Rock Valley thousands of years ago. The discovery, in 1938, of these prehistoric sandals attracted the attention of anthropologists throughout America. It modified the pre-history of Oregon and earned national recognition for Dr. L.S. Cressman, the University of Oregon anthropologist who supervised the exploration of the cavern.
>
> Protected by masks from the choking dust, students working under Dr. Cressman in earlier research in caverns of the region had found matting and basketry, bones of animals that lived in the old lake country, and implements shaped from volcanic glass. Lying deep in cave litter and under rocks which had fallen from the ceiling, were scrapers, knives, arrowheads, stone awls, and even sinkers used in weighting nets. Those stone-anchored nets once saw service in a lake-filled basin, across which dust devils now whirl on warm summer days.

After Reub Long's death in 1974, Phil Brogen suggested that FORT ROCK CAVE BE RENAMED REUB LONG CAVE. In 1963 Reub and Eleanor Long donated this cave to the National Park Service as an HISTORIC SITE. The name was confirmed by the State and Federal boards of geographic names. "Over the years, Reub Long Cave has been known under many names: Cow Cave, Menkenmeir Cave, Sandal Cave, Fort Rock Cave and during its excavation by U. of O. students who dug up more than 76 fiber sandals there, as the 'Shoe Store'" (Larson 1976:93). The Longs also donated 30 acres of land to the FORT ROCK STATE PARK which contains a monument to Reub Long and a sign saying that Fort Rock is a REGISTERED NATIONAL LANDMARK.

WE RECOMMEND ONE OF THE FOLLOWING ROUTES TO U.S. 97 on your way back to Bend:

1. Take the gravel-cinder CHINA HAT ROAD northward about 52 miles until you get to U.S. 97 which is about 7 miles south of Mt. View School. Enroute you may wish to visit the ARNOLD LAVA TUBE SYSTEM.

2. Take the CHINA HAT ROAD for about 21 miles until you get to USFS road 2226 (near South Ice Cave). TURN LEFT on 2226 and follow this paved road about 27 miles to La Pine where it joins U.S. 97. La Pine is about 44 miles south of Mt.View School.

3. Return to the TOWN of FORT ROCK and follow the signs via Lake 5-10, State 31 and U.S. 97 to Bend, a distance about 62 miles over paved roads.

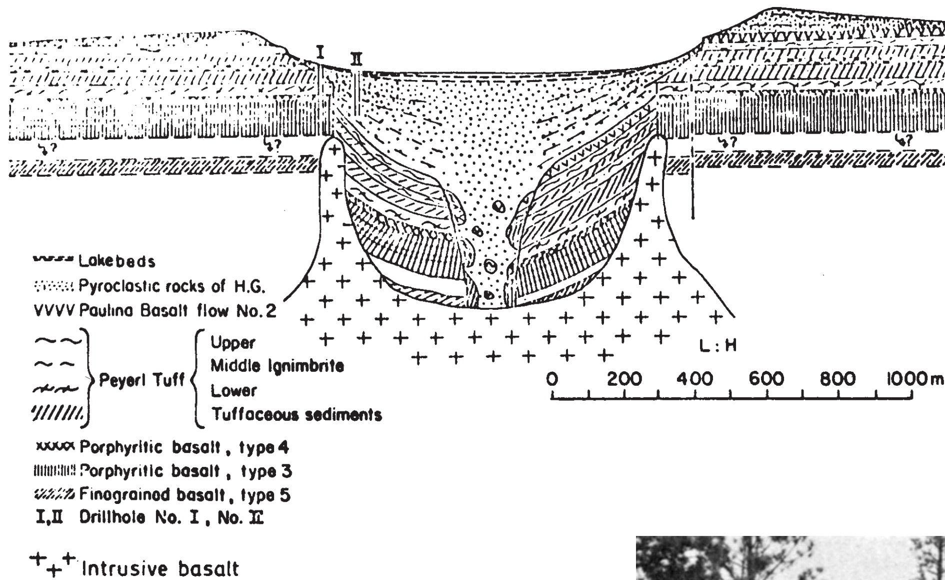


Fig. 32. Hole-in-the-Ground. Cross section based on surface exposures, drill holes and geophysical data as interpreted by Lorenz (1971). After Heiken et'al. (1981).

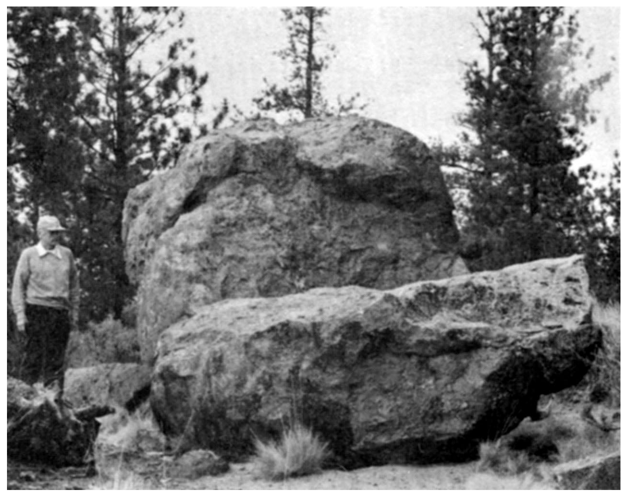


Fig. 33. Blocks on west rim ejected during explosions.

Fig. 34. Oblique aerial of Hole-in-the-Ground showing crater which is more than a mile in diameter; floor is 500 ft below east rim. From Peterson and Groh (1965).

4. OR visit HOLE-IN-THE-GROUND (10.3 miles west) before taking Oregon 31 to U.S. 97.

RECOMMENDED SIDE TRIP: HOLE-IN-THE-GROUND.

Travel out of the park and TURN RIGHT. Pause briefly where you can see both FORT ROCK AND BEGGAR HEEL as well as the other small buttes which were once islands in Fort Rock Lake. These buttes are bordered by wave cut cliffs, wave cut terraces, stripped benches, beaches, bars and spits. Waves haven't reached REUB LONG CAVE during the last 13,000 years. Charcoal of that age was recovered from the top of the gravel in front of the cave (Allison 1979). REUB LONG CAVE IS SURROUNDED BY PRIVATE PROPERTY AND YOU MUST HAVE PERMISSION TO VISIT IT. Continue west.

At 4.6 miles, TURN RIGHT toward FREMONT, a cluster of ranch buildings which was a small town during the homestead days prior to World War I. "Before Fremont folded, it had a creamery, cheese factory, hotel, general store, livery, blacksmith shop, dance hall and PO, and was an important stagecoach stop. When the homesteaders went broke, they quit the desert in droves. The towns they left behind soon fell prey to the elements, wood gatherers and vandals. The locations of most of these towns -- there were dozens of them -- have been obliterated. Fremont is lucky. It still shows the splinters of the dance hall and a mounting block, made of steps sawed into a juniper stump. Block was used by long-skirted women who wanted to step into buggies without giving male onlookers a glimpse of their ankles. The windmill was put up about 1955 by Reub Long" (Friedman 1973:173).

At 5.1 miles, TURN LEFT and travel up the low fault scarp which bounded Fort Rock Lake. At 8.2 miles, TURN RIGHT on USFS road 245. At 8.5 miles, TURN LEFT (road unmarked). At 10.1 miles, TURN RIGHT to climb the low outside rim of HOLE-IN-THE-GROUND. At 10.3 miles, park on the west rim of this MAAR.

Although HOLE-IN-THE-GROUND (Figs. 32-34) doesn't look like FORT ROCK, it formed by a "similar, but shallower, steam explosion, which deroofed the explosion chamber very violently (Nolf in Hatton 1977:90). According to Lorenz (1971):

> At the time the crater was formed between 13,500 and 18,000 years ago a lake occupied most of the basin and the site of the eruption was close to the water level near the shore. The crater is now 112 to 156 m below the original ground level and is surrounded by a rim that rises another 35 to 65 m higher...The volume of the crater below the original surface is only 60 percent of the volume of the ejecta. The latter contains only 10 percent juvenile basaltic material, mainly sideromelane produced by the rapid quenching of the lava. Most of the ejecta material is fine grained, but some of the blocks of older rock reach dimensions of 8 m. The largest blocks are concentrated in four horizons and reached distances of 3.7 km from the center of the crater. Accretionary lapilli, impact sags, and vesiculated tuffs are well developed.
>
> The crater was formed in a few days or weeks by a series of explosions that were triggered when basaltic magma rose along a northwest-trending fissure and came into contact with abundant ground water at a depth of 300 to 500 m below the surface. After the initial explosion, repeated slumping and subsidence along a ring-fault led to intermittent closures of the vent, changes in the supply of ground water, and repeated accumulations of pressure in the pipe. Four major explosive events resulted...
>
> Geophysical measurements indicate a domical intrusion below the crater floor and extending upward as a ring dike around the margins of the crater.

To see more of Hole-in-the-Ground, travel in either direction around the crater rim. To get to State 31 (2.8 miles) via road 245, TURN LEFT and then TURN RIGHT.

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GOLDEN-MANTLE

GROUND SQUIRREL

IGNEOUS ROCKS

M. Frank Ireton*

Rocks exposed at the earth's surface can be broken into three generic groups or types. The first is metamorphic rocks, those which have been altered by heat and pressure from another rock type, such as quartzite metamorphosed from quartz sandstone, or marble from limestone.

The second is sedimentary rocks, those deposited as sediments in ocean basins or, occasionally, lakes. These rocks are familiar to most cavers as limestones or dolomites.

The last group is igneous rocks or those rocks originating from a rock melt (magma). These are the rocks that will predominate on this trip.

Origins of magma are not clearly understood, though pressure changes (as in deeply-buried rocks), friction from crustal movements, convection of heat from the earth's core, and radioactive decay are current theories. The end results are igneous rocks, which are grouped according to both origins and composition.

Composition of igneous rocks falls into two general categories: one, rich in iron-magnesium and poor in silicas, is called ferro-magnesium or basaltic; the other poor in iron-magnesium and rich in silicas, is called non-ferro-magnesium or granitic. The first group forms rocks that, as a general rule, tend to be darker in color, while the latter usually forms lighter-colored rocks.

Texture is influenced by origin or cooling rate. Deep underground, magma can cool slowly to form intrusive or plutonic rocks, while near the earth's surface, it cools rapidly to form extrusive or volcanic rocks. Origin of an igneous rock can be deduced by studying the size of its crystalline minerals. Slow cooling of intrusive rocks allows time for ions to migrate toward crystalline centers, resulting in larger crystals which are visible to the unaided eye. This type of texture is referred to as phaneritic. Extrusive rocks cool too rapidly to allow for migrating. The resulting texture is fine-grained or aphanitic.

Using texture and composition, igneous rocks can be identified with ease using the igneous rock chart (Figure 35): at the same time, information about the rocks' origin can be understood.

Fig. 35. Igneous Rock Chart.

Non-ferromagnesium intermediate (Light color) — Ferromagnesium (Dark color)

Decreasing silica content →

Decreasing crystal size (faster cooling rate) ↓

INTRUSIVE	GRANITE	DIORITE	GABBRO
EXTRUSIVE	RHYOLITE	ANDESITE	BASALT
TEPHRA	PUMICE, SCORIA, TUFF, BRECCIA, AND OBSIDIAN		

Cellular fragments or glassy

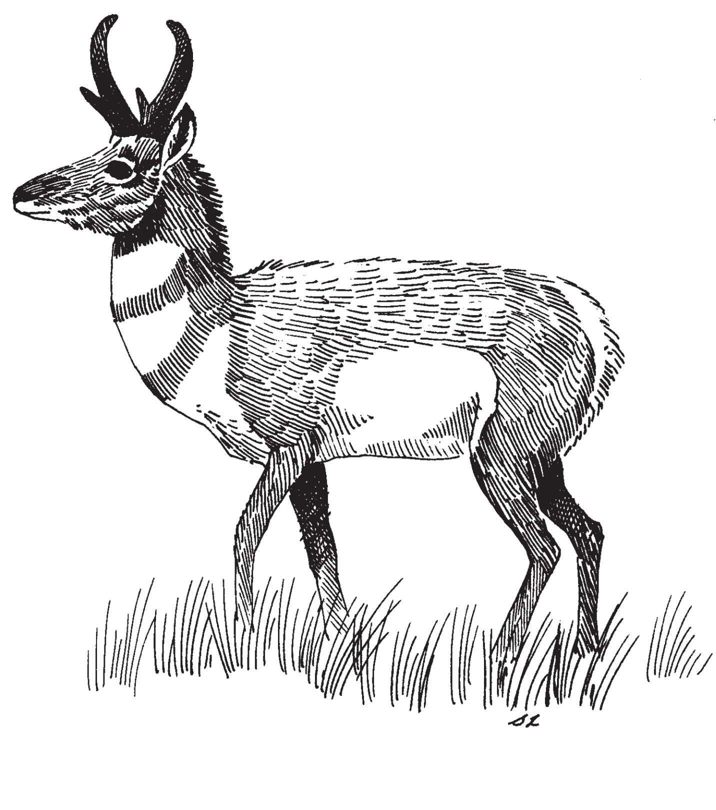
*Geologist, Box 356, Mountain Home, ID 83647.

Granite is a light-colored (non-ferro-magnesium) rock with a coarse texture. This rock can be found in the table by intersecting the column of composition with the line of texture. Notice that granite is an intrusive rock. If the same or similar magma had been extruded on the surface as volcanic rock, the texture would be finer (aphanitic) and the rock would be called rhyolite. Gabbro is the intrusive form of a ferro-magnesium magma, while basalt is the extrusive or volcanic form.

An intermediate group of rocks, andesite if extrusive, or diorite if intrusive, exist between the other two types. These rocks are relatively richer in quartz and poor in olivine. This rock-type is thought to originate when oceanic crustal plates are subducted under continents to melt and form chains of volcanoes along continental margins, such as the Cascade volcanoes or the Andes Mountains, from which the rock derives its name.

Material ejected out of a volcano is called tephra. Rapid cooling of these rocks produces two types of textures. One is cellular (full of gas bubbles), while the other is pyroclastic (made up of fragments of broken rocks welded together). Cellular rocks are called pumice if granitic in composition (light-colored) or scoria if basaltic (darker-colored). Pyroclastic rocks are called tuff if fragments are small (less than 4 mm) or breccia if large (more than 4mm).

One last texture is glassy or obsidian. This rock tends to be rhyolitic in composition and originates when flows of silica-rich lava cool rapidly. Obsidian is usually black, but green and brown varieties are often found. A brown and black combination called double-flow obsidian is found locally and is highly prized by lapidarians.



PRONGHORN

ANTELOPE

THE GEOLOGY OF LAVA TUBE CAVES+

Russell Harter* and J.W. Harter, III**

ABSTRACT

Lava flowing across the ground surface tends to develop well-defined channels. Lavas of basaltic composition that are highly charged with dissolved gasses (termed 'pahoehoe') sometimes form crusts over the channels, making lava tubes. Lava tube caves are drained portions of roofed lava channels. Lava channels are primarily distributary in nature, serving to transfer lava from a volcanic vent to the advancing flow edge lower on the volcano.

Differing conditions, largely involving preflow topography and lava eruption rate, result in several distinct types of lava channels, and hence, of lava tubes. Rift tubes are formed where large open cracks are utilized as channels by the lava flow. Passages of rift tubes tend to be high and narrow; the shape of the rift. Walls of rift tubes consist of preflow country rock or soil. Leveed lava channels have walls built up by the lava streams they confine. Leveed channels are subdivided into true trenches which have walls consisting of only one flow unit, and semitrenches that have walls built of numerous thin flow units. True trenches are usually of short length and are uncommon. Semitrenches are common, and a flow containing a semitrench generally makes a low, broad ridge with the tube on the ridge axis. A small lava stream can form a crust arching over the entire flow unit, making a surface tube that is perched on top of the ground.

Characteristic tube types tend to be found in specific parts of lava flows. Rift tubes tend to be found near the vent, and portions of the eruptive rift are the most likely to become rift tubes. Rift tubes are likely to form large semitrenches, which in turn feed smaller semitrenches and surface tubes.

Modifications of lava tubes occur as the eruption progresses. A temporary lessening of erupted lava allows tubes to cool, and rockfall occurs. Renewed flow may carry away the breakdown, and a lining will chill against the inner walls when a cool tube is refilled. Lava tubes are often buried by lava that overflows from the tube, or by lava from other sources. Hot gas and radiant heat remelt the inside of lava tubes, making small stalactites. Lava droplets accumulate on floors, making lava stalagmites.

Lava channels of all types play an important role in the growth and development of volcanoes, because they transmit lava from the vent to the advancing flow front. Although open channels form in lava flows of various chemical composition, nearly all reported roofed lava tubes are in pahoehoe basalts. Lava tubes differ from other lava channels only in that they are roofed. Lava tube caves are portions of lava channels that have roofed and subsequently drained. The tube and open channel network of a lava flow is the plumbing system by which the lava flow was emplaced. By studying lava tubes, a more thorough understanding may be gained of the geologic structure of some volcanoes.

TYPES OF LAVA TUBES

Based on the structure of the wall rock, there are five possible types of lava tubes. These are rift tubes, true trenches, semitrenches, surface tubes, and interior tubes (Fig. 36). Examples of lava tube caves can be identified for all of these types except the last one.

RIFT TUBES: When lava comes to the surface in a volcanic eruption, it flows out of a large crack in the ground. Commonly some part of the crack, or rift, continues downhill from the point of eruption. Once erupted, lava flows downhill. Since the rift is a low place, the lava tends to follow the rift, using it as a channel. This channel may roof, and then drain. Because this is a lava tube in a rift, it is a rift tube. This type of tube makes cave passages that usually are high and narrow; the shape of the rift. The walls are made of country rock that was present before the eruption. Most rift tubes contain linings on the walls that obscure the preflow rock. A rift cave is a drained tube in a fissure of a rift zone; it is a hollow, near surface dike. The correct identification of rift tube caves can precisely locate volcanic rifts whose surface expression is otherwise obscured by lava flows.

TRUE TRENCHES: These caves are channels incised into a semisolid flow unit by differential solidification. In areas of low ground slope, the lava can pond, making a single mass (a flow unit), with a channel through it. The channel geometry resembles that of a water stream channel incised into a silted-up lakebed. The cave wall consists of a single thick layer of lava.

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+Reprinted from The 1979 Far West Cave Management Proceedings, Redding, California.

SEMITRENCHES: If the walls of a tube are composed of a number of thin layers rather than a single lava layer, the tube is a semitrench. Semitrench walls are formed by repeated overflows to the sides of the channel, and make levees that slope gradually away from the channel. The overflows are small flow units and sheets of lava, that cool in place. Inside a cooled lava tube of this type the edges of the sheet overflows are horizontal layers in the walls, while the flow units appear as interlocking but discrete blobs of rock. Thickness of the layers is typically about seven to eighty centimeters.

SURFACE TUBES: A small lava stream can form a crust over its entire outer surface. This makes a tube with roof and walls consisting of a single arched stratum. The tube is formed entirely above the adjacent ground surface, so is called a surface tube. Surface tubes are typically small in size, and are fed from larger tubes (trenches and rifts).

INTERIOR TUBES: Within a single thick lava flow unit, channels can form within the interior of the lava mass. The tubes lie entirely within a single flow unit, with a fairly flat top on the flow surface,so are termed interior tubes. The cross sectional shape is elliptical, with the width about 10% greater than the height. The interior tube is the thermal equilibrium shape, so other types of tubes tend to modify toward this shape. Although plugged interior tubes have been identified, no such open lava caves are known to the writers. Lava tube caves that have been identified as interior tubes by Ollier and Brown (1956), Hatheway and and Herring (1970), and Greeley (1971b) are readily identifiable by other workers as either semitrenches or rift caves. Furthermore, a theoretical relationship between interior tubes and hypothetical shearing within the lava flow has yet to be demonstrated in any manner.

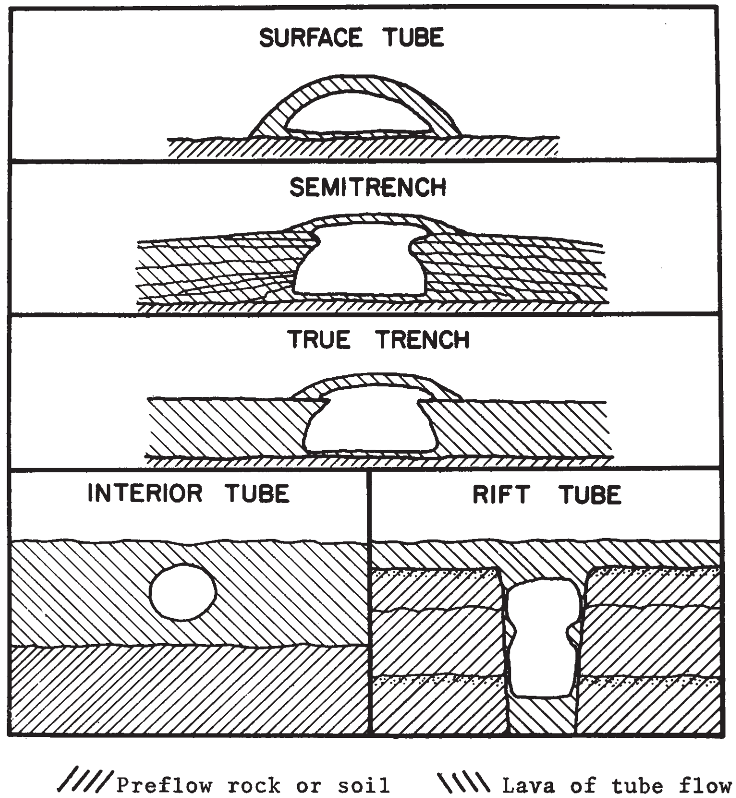

Fig. 36. Idealized cross sections of dfferent types of lava tubes. Surface tubes can be a variety of shapes and usually form small passages. The roof and wall of a surface tube are a single layer of lava. Semitrenches have levee walls built up of overflows from the lava stream. A true trench has walls made of a single stratum. Rift tubes form in large fissures. Interior tubes lie entirely within a single layer of lava and do not form caves.

IDENTIFYING TUBE TYPE

The structure of the walls of a lava tube can be identified at points within the tube where the lining is missing, exposing the wall strata. Since rift caves have walls made of preflow country rock, these often are much older lava flows with fossil soil horizons. In semitrenches the strata may be very thin flow units, that are readily identifiable as such because they were deposited separately and successively, allowing at least the surface of one to cool before the next flowed over it. The underside of each flow unit makes a cast of the flow unit below. Open gas pockets near the middle of the thin flow units often occur, due to degassing of the lava as it cools.

LAVA TUBE MORPHOLOGY

Since a semitrench is a leveed channel, the main tube is located at the axis of a very wide, low ridge. A flow width of a kilometer is typical for a tube height of ten meters. The advancing toe of a flow that is building a semitrench ridge extends itself as numerous thin flow units and toes, forming braided channels at first. Later, many of the small branches are plugged or cut off as the main tube develops. The levees of a moderate to large size semitrench generally contain numerous small surface tubes, and these sometimes make an elaborate complex of crawlway side passages.

Any type of tube may overflow through a hole in the roof. Such overflows frequently bury the lower tube completely, adding significantly to the roof thickness (Anderson 1910:630; Wentworth and MacDonald 1953:45). When a roof overflow drains only partially, it leaves a cupola in the passage ceiling. More complete drainage often yields a complex of surface tubes radiating outward from the cupola. Overflows to the side of any open lava channel may make tubes that become side passages when the main channel roofs and then drains. This occurs most commonly in semitrenches.

Rift tubes tend to overflow on a grand scale. The entire complex of flows and channels produced by an eruption is merely the overflow from the eruptive rift. Repeated minor overflows of a rift being utilized as an open channel can construct a semitrench atop the rift, increasing its capacity. Such structures are difficult to distinguish from semitrenches that have deeply eroded floors and usually can be identified only by careful consideration of several geometric factors.

Rift tubes take on the geometry of the fissures they follow, with the primary modifications being linings and filling of adjoining parts of the fissure system. Because tension cracks are irregular and not straight, the plan view of a rift cave may appear to show meanders. The lava stream may actually have had the tendency to meander, but was restricted by the rift walls. A rift tube cannot curve or branch unless the fissure does. Restriction by the rift walls also means that rift tubes often have a characteristic high and narrow passage shape that other types of tube cannot obtain. Vertically superposed passages can form by roofing over the rift at different levels within the confining walls. Stacked lava tubes of other types will not be exactly superposed, because a tube roof is a small ridge and the upper tube will flow away from it.

The mechanics of flow unit advance (Nichols 1936) often produce chambers along a lava tube. In surface tubes, the chambers are individual flow units. In a cave the boundary between two flow units is a short, small, connection between two much larger rooms. The connection is a hole that burst through the skin of an inflating flow unit.

Individual caves are generally just segments of a much larger lava distributary system. If one lava tube cave is found, others are very likely to be found in the same flow. Since the basic function of lava tubes is to transfer and distribute lava in a downhill direction, the overall pattern is that channels diverge downhill, and cave passages that converge in the direction of flow are nearly always branches of a braided stream, rather than streams coming from separate vents.

PASSAGE MODIFICATIONS

Because the interior tube shape represents thermodynamic equilibrium, as a lava tube develops it slowly evolves toward the passage shape of an interior tube. A lava tube often has a complex history wherein rock is repeatedly added within the tube as linings, while other rock is removed by rockfall during cooling episodes. Rock may also be removed through the erosive action of flowing lava. Modifications that occur after the initial tube formation generally have little relation to the remainder of the lava flow.

BREAKDOWN: When lava cools, it shrinks and breaks. Over a lava tube, unless the pieces key together to form an arch, the roof will fall in. This may happen due to temporary cooling during periods of slack flow, as well as during final cooling. Fragments that fall while the tube is still active are often carried away by the flowing lava, although a large block or breakdown pile may jam between the floor and ceiling, making a pillar. When rockfall occurs upon final cooling, portions of the ceiling stope out, and breakdown piles up on the floor. Most entrances of lava tube caves are formed by collapse of a portion of the roof. Nearly all breakdown in lava tubes occurs during or shortly after formation, as a result of cooling. Once a lava tube has withstood the stress of cooling shrinkage, it is ordinarily very stable.

LININGS: A floor lining is present in every lava cave, because lava chills against the cold ground below it and drainage of the tube is not complete. The floor lining can be considered a small lava flow. It can be either pahoehoe or aa, and can form channels or tubes. If the lava withdraws from beneath a crust, it may leave a deflated floor lining. A passage with a deflated floor lining may be near round in cross section, even though additional drainage would have left a flat floor. If additional lava is injected beneath a crust, the floor lining can be inflated. In both cases, the edge of the crust is anchored to the wall, while the center deflects (Fig. 37).

Wall-ceiling linings are deposited when renewed flow within a temporarily drained tube partially or completely refills it. If a rigid crust forms on the lava stream when the tube flows at less that full capacity, the crust may bridge across the tube. This makes a lining partition or false floor, resulting in two vertically superposed passages. False floors tend to form near skylights where outside air chills the crust.

PLUGS: The end of a lava tube cave often is a spot where the passage simply pinches out. This usually is a plug, and the actual tube continues even though the cave does not. In the lower portions of a lava tube network, the tubes often plug from a simple failure to drain. Where a

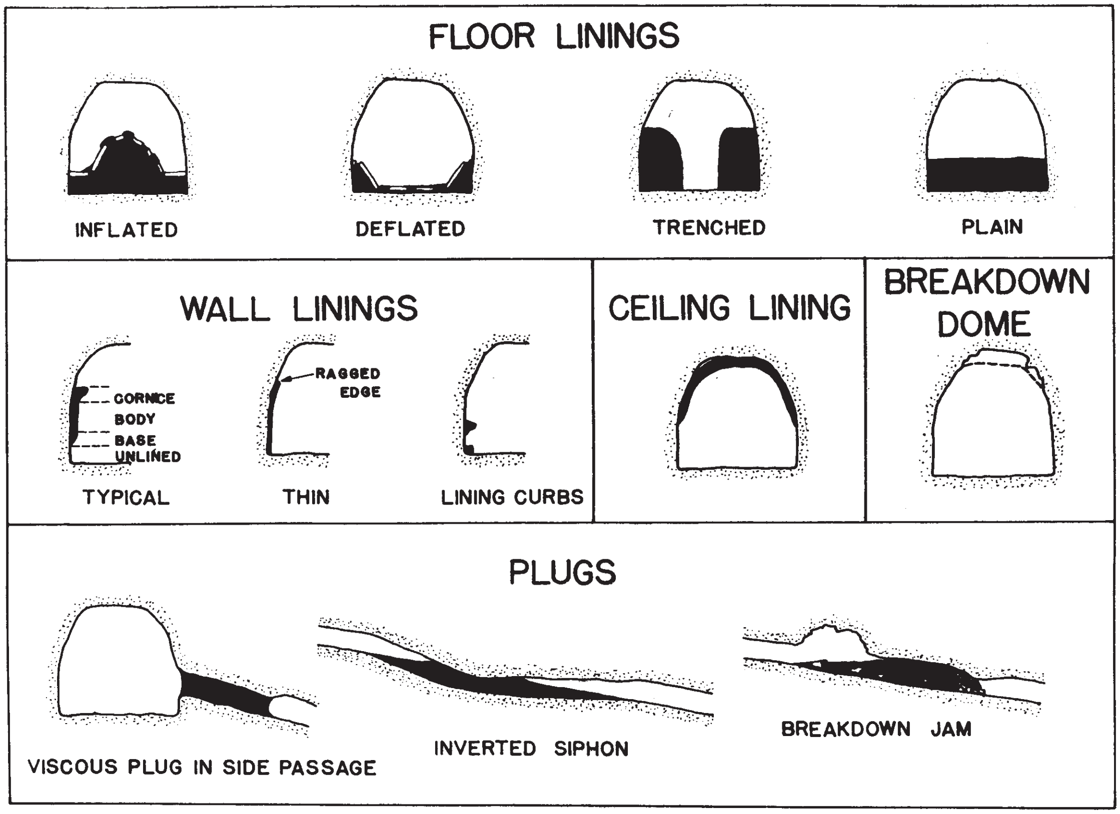

Fig. 37. Common passage modifications.

lava stream is choked by breakdown, the tube tends to plug. The individual blocks may remain visible, or they can be completely hidden within a mass of lava that they chilled. Upper ends of major caves often are breakdown plugs.

Viscous plugs are closely related to linings. As a cool tube refills, it may produce enough chilled lava to completely fill the passage, resulting in a viscous plug. An upper level above a lining partition is especially prone to plug if refilled while the somewhat warmer lower level tends to remain open. Since even thin linings reduce the passage size, repeated lining eventually leads to plugging -- with the final viscous plug being produced in the same manner as the linings that surround it.

EROSION: Lava flows usually have insufficient heat to melt the underlying rock. However, a lava stream can sometimes erode its walls and bed by scouring and plucking. Eroded material initially is cold, but if it is carried far by the flowing lava it must be at or near the temperature of the lava stream. If too much material requires heating, erosion will cease and a lining will deposit. In extreme cases the chilling produces a plug, which will completely block the lava tube. Thus, the erosional processes of scouring and plucking (as well as melting) are limited by the available heat. If any type of erosion is to be extensive (such as cutting of a channel into preflow rock or soil) great quantities of heat must be present. If the eruption is of a long enough duration, sufficient excess heat may be available to erode the bed of a lava stream on a large scale. In the case of a lava tube of Mauna Ulu (Kilauea Volcano, Hawaii), the floor reportedly eroded downward a maximum of 15 meters between early September 1970 and mid-May 1971 (Swanson 1973:621).

Erosion normally occurs only on a small scale, where its overall effect is to round off sharp corners and projections, leaving smooth curves.

MINOR MODIFICATIONS

As pahoehoe lava flows, it loses dissolved gas. When a lava stream has a crust over it, the gas accumulates as a frothy layer beneath the crust. The froth soon begins to break down, forming a continuous layer of gas. As the gas layer accumulates, the crust becomes a roof that is separate from the stream. At the time of separation, the under surface of the roof is still molten, held in place only by surface tension of the gas bubbles which have not yet broken. As the ceiling froth continues to break down, the remaining molten material migrates toward low points (peaks of froth) and drips off. The result is a small, blunt, pyramidal stalactite. Such stalactites are known as common stalactites.

REMELT: Heat transfer through solid lava is less efficient than radiation across open space. Therefore, the ceiling and walls of an active lava tube have almost the same temperature as the lava flowing through the tube. While this temperature seldom is high enough to remelt bulk lava, it often is able to surficially remelt some components of the lava. This produces a variety of thin glazes that often are much different in color (black, reddish brown, or silver) from the underlying rock.

More extensive remelting allows flowage of the glaze. Since the more refractory components of the lava can be transported as a suspension of crystals in the remelt, the migrating material may be almost indistinguishable from that associated with common stalactities. Both produce small ribs, gours, slumps, and similar lava flowstone structures on walls.

When the migrating material drips from a ceiling or an overhang, it can produce a variety of stalactite known as a drip pendant. Drip pendants vary in shape: small beads, conical shafts, short cylinders, and shafts with delicate narrow waists. A drip pendant actually is a single hanging drop, so the various shapes represent stages of the drip cycle. Drip pendants formed by remelting of smooth or dense surfaces tend to be small. Those associated with common stalactites hang from the tips of the pyramids, and consist of a large pyramidal base with a drip pendant tip.

LAVACICLES: A third type of lava stalactite is the lavacicle. Lavacicles are cylindrical or only slightly tapered, with little or no base. Some lavacicles have been reported (for example, Dana 1889:452) that were soda straws at least 75 cm long, but most are even shorter than drip pendants (less than 3 cm). Linear striations and concentric rings indicate that lavacicles are extruded from the ceiling, but the mechanism is not well understood. Lavacicles often are helictitic, having several sudden changes of size and direction within a short length. This appears to result from irregularities of the extrusion process.

LAVA STALAGMITES: Stalagmites form when many droplets of lava fall onto the same spot on the floor. If the floor is a moving lava stream, the droplets are lost and no stalagmite can accumulate. Small stalagmites occasionally are found below drip pendants, and consist of solid droplets of lava. Most lava stalagmites that are more than a few centimeters in height are found below lavacicle stalactites, and consist of bubbles of lava.

BLOWOUT POCKETS: Blowout pockets form when a flat gas pocket behind a remelt layer or thin lining blows the lava covering it into the lava tube. The pressure appears to come from superheating the pocket of steam or air as the lava surface inside the tube is remelted. The most common form of blowout is a final, removal, step in the degeneration of a stand of common stalactites. In this case it is related to the roof-separation mechanism, and the gas pressure involved may be quite small.

ROOF STRATA

Lava tubes are distinguished from open lava channels by the presence of a roof. Roof strata of lava tube caves may be observed in section at breakdown entrances and at areas of roof breakdown within caves. Three general types of strata occur in lava tube roofs: initial roof strata, overlying lava, and linings. The various strata can be identified in cooled lava tubes by their surfaces and geometric interrelationships. The presence of either overlying lava or of ceiling linings in a cave roof is evidence that the initial lava tube roof has been modified. Detailed sequences in the formation of lava tube roofs can be determined through examination of roof strata in cooled lava tube caves.

Lava channels can form roofs in at least six ways:
1. Wholesale crusting of the lava stream (Peterson and Swanson 1974:211).
2. Agglutination of lava splash and spatter in arched levees (Greeley 1971:222-223).
3. Jamming and fusion of floating crustal plates (Wentworth and MacDonald 1953:45).
4. Crusting of whole lava toes (Wentworth and MacDonald 1953:43).
5. Underriding of cooled lobes by the lava stream (Baldwin 1953:3).
6. Lining shut of the upper walls of a deep lava channel.

The mechanism of roofing (that is, formation of the initial roof stratum) can be established for cooled lava tubes if sufficient exposures are present. Indications of the mode of initial roof stratum formation include: single crusts with no internal complexities, lumpy or clotted outer surfaces, plates with sutures at distinct boundaries, lobes connected to a continuous layer below, or a roof consisting of vertical linings.

Cooling rates of lava tube roofs (with lava flowing below) should be somewhat similar to measured cooling rates of crusts on ponded lava (which has internal convection). In addition, flow units that cool outside should have cooling rates generally similar to those of lava lakes.

Fig. 38 gives a first approximation of lava crust thickness as a function of time.

AFTER THE FLOW HAS COOLED

Whereas limestone caves form during time spans on the order of thousands to hundreds of thousands of years, a lava cave forms during a time span that may range from a few hours to perhaps a year and a half. Differential cooling of lava leaves caves that are essentially complete before the entire lava flow has cooled.

After cooling, processes of weathering and erosion begin immediately to obliterate the lava cave. Depending on the climate, especially the quantity of rainfall, a lava cave may last only a few years, or be nearly as long lived as a limestone cave. Since the cave is topographically a low spot, sediment tends to accumulate and fill it. Portions of a tube roof that are only marginally stable will fall when weakened by weathering.

Various soluble salts are leached from the lava by rain and redeposited in cooling cracks and cave passages below. These secondary minerals include thenardite, mirabilite, gypsum and calcite. Various types of silicates have been identified, usually reported as "opal".

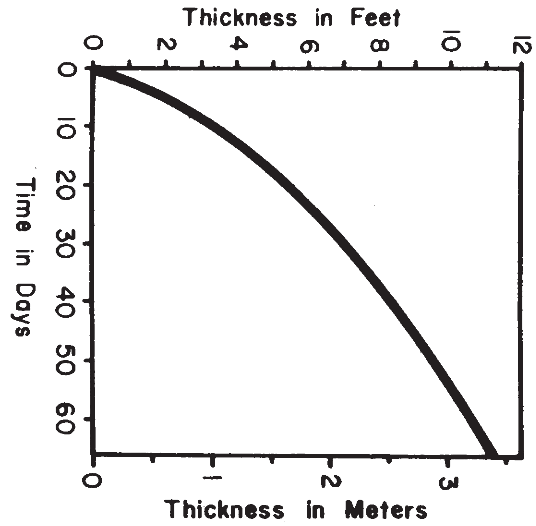

Fig. 38. Graph of lava crust thickness versus time. The curve represents the approximate mean values of the experimental data. Data from Peck et al. (1966).

FINDING CAVES

One of the simplest ways to locate lava tubes is by linearity. If several collapse sinks lie roughly along a line, it can be assumed that there is (or was) a connecting lava tube. The uncollapsed portions would be the first places to check for caves.

Surface tubes lie in small abrupt ridges. Semitrenches lie in low, broad, ridges. Lava streams that follow rifts frequently overflow the rift and build semitrench-type walls, making a low broad, ridge over a rift cave. Any of these ridges may be level areas if they are buried by later lava flows.

The ridges show where the lava tubes were at the time the flow was emplaced. Unfortunately, this is not necessarily where present caves are. The ridge includes plugged tubes and segments of open tubes that do not have entrances. Digging may be futile, since more than half of the tube segments without entrances are probably plugged. So, finding caves becomes a matter of finding entrances to known lava tubes.

Some entrances remain open from the initial formation of the tubes. These include gas vents, overflows, or other places where the tube failed to roof. Although this type of entrance is common on the island of Hawaii, in the western continental United States most lava tube entrances were formed by collapse during cooling. Weathering seems to fill lava caves with soil rather than make their roofs fall in.

Entrance collapses tend to occur at points that were flaws during formation. These points include roof overflows, passage junctions, joints between roof crustal plates, sharp changes in slope along the tube axis, and any thin spot in the roof. Inconveniently, these relationships are in most instances noted only after the cave entrance is found by accident. Such is the present state of the art.

MANAGEMENT PROBLEMS OF LAVA CAVES

The problems of managing lava caves, as with other types of caves, can be reduced to two. These consist of protecting the cave from people (preservation), and protecting people from the cave (safety).

Matters of safety in lava caves are largely like those of other caves. Within a lava tube cave there may be unsteady breakdown, vertical drops, and slippery slopes of mud or ice. In cool climates lava tubes tend to be especially cold, so hypothermia may be a constant problem for cave visitors. As with other caves, it is occasionally possible for inexperienced people to become lost or trapped.

Lava caves are often thought to be featureless and indestructable. In spite of this viewpoint, lava formations exist and are highly vulnerable to both accidental and malicious breakage. The potential for damage has greater significance when we realize that lava stalagmites, soda straws, and helictites are rarer than similar formations in limestone caves. Spray paint is nearly impossible to remove from lava. Litter can cause serious lasting damage (carbide dumps, batteries) and may be especially difficult to remove from caves (broken glass).

Lava caves are no more expendable than are any other type of cave. Once a cave is lost by quarrying, flooding, road building, or land development, it is gone. Even the constructive efforts of volcanoes cannot keep ahead of the unrestricted destructive habits of man.

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