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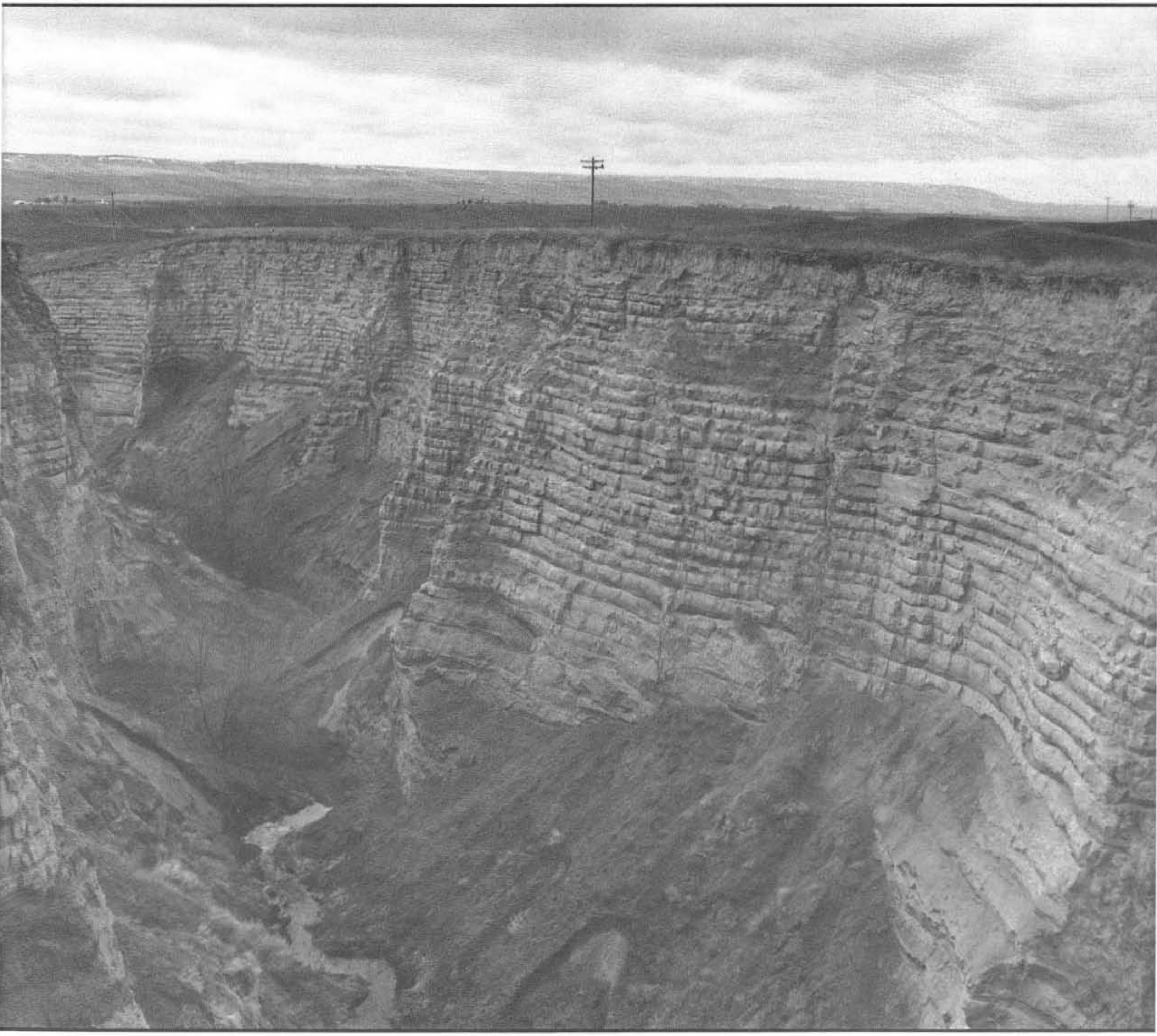

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Information for contributors

Oregon Geology is designed to reach a wide spectrum of readers interested in the geology and mineral industry of Oregon. Manuscript contributions are invited on both technical and general-interest subjects relating to Oregon geology. Two copies of the manuscript should be submitted, typed double-spaced throughout (including references) and on one side of the paper only. If manuscript was prepared on common word-processing equipment (IBM compatible or Macintosh), a file copy on diskette should be submitted in place of one paper copy (from Macintosh systems, 3.5-inch high-density diskette only). Graphic illustrations should be camera-ready; photographs should be black-and-white glossies. All figures should be clearly marked, and all figure captions should be together on a separate sheet of paper.

The style to be followed is generally that of U.S. Geological Survey publications. (See the USGS manual *Suggestions to Authors*, 7th ed., 1991, or recent issues of *Oregon Geology*.) The bibliography should be limited to references cited. Authors are responsible for the accuracy of the bibliographic references. Names of reviewers should be included in the acknowledgments.

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

Cover photo

Touchet (pronounced TOO-shee) beds at Burlingame Canyon near Touchet, Washington. The beds were exposed in 1926, when water escaping from an irrigation canal cut Burlingame Canyon. These layers settled out of turbid water during repeated inundations caused by catastrophic floods from Montana's ice-dammed glacial Lake Missoula. Article beginning on next page describes how Pleistocene floods and other catastrophic geologic events shaped the Pacific Northwest.

OIL AND GAS NEWS

Drilling at Mist Gas Field

Nahama and Weagant Energy Co., of Bakersfield, Calif., continues the multi-well drilling program at the Mist Gas Field in Columbia County. Of the first ten wells for the year, two have been completed as gas producers, three are suspended, four have been plugged and abandoned, and one was redrilled and is suspended. An eleventh well, HNR 24–22–64 was drilled to a total depth of 2,553 ft and was plugged and abandoned. Next, the well Johnston 11–30–65 reached a total depth of 2,794 ft and was plugged and redrilled to a total depth of 2,811 ft and then plugged and abandoned. The final well of the year, the Libel 32–15–65, was drilled to 2,835 ft, plugged, and abandoned. This concluded the Nahama and Weagant program for 1993.

Carbon Energy continues drilling

Carbon Energy International of Kent, Washington, continues drilling operations in Coos County, Oregon. The first well drilled, Coos County Forest 7–1, reached a total depth of 3,993 ft and is currently suspended. Drilling operations have been concluded at the second well, WNS–Menasha 32–1, but no results have been released.

Recent permits

Permit no.	Operator, well, API number	Location	Status, proposed total depth (ft)
498	Carbon Energy Intl. Menasha Timber 16–1 36-011-00028	SW¼ sec. 16 T. 26 N., R. 13 W. Coos County	Application; 2,650.

□

Who will catch the rain?

Under this theme, the Governor's Watershed Enhancement Board will hold its 1984 conference on Thursday/Friday, January 27 and 28, 1984, at the Ashland Hills Inn in Ashland, Oregon.

The Board consists of representatives from state commissions and agencies for natural-resource, environmental, and agricultural concerns and from several federal agencies.

The program will include sessions all day Thursday and until noon Friday, addressing such topics as watershed management, cooperation and partnerships, environmental education, and examples of watershed restoration and improvement projects. A banquet on Thursday will feature Steve Amen of Oregon Public Broadcasting, the executive producer of the television program *Oregon Field Guide*.

Further information is available from Liz Kraiter, Conference Coordinator, Northwest Rendezvous, 11700 SW Ashwood Court, Tigard, OR 97223, phone (503) 590-4240. □

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Beverly F. Vogt, Editor

Catastrophic events
created and continue to shape
the western edge of the North American continent.

Geologic catastrophes in the Pacific Northwest

by George W. Moore, Department of Geosciences, Oregon State University, Corvallis, Oregon 97331

The following article was prepared for the Convention Guidebook of the 1993 National Speleological Society Convention at Pendleton, Oregon, and is printed here with the permission of the publishers. — *eds.*

IN THE BEGINNING

Before the Cambrian Period, the time when most animal groups such as clams and trilobites acquired their hard shells and their remains began to document the fossil record, most of the Pacific Northwest did not yet exist.

The continent of North America has had a long geologic history, and indeed some of the world's oldest rocks crop out in Canada and Greenland. But before the Cambrian Period, North America was attached to Australia and Antarctica along its western side (Figure 1). Only later did the states of Oregon and Washington move in to occupy a continental rift that until then had been firmly closed.

The rifting, the first geologic catastrophe in a long series to affect the Pacific Northwest, started about 700 million years ago during the Precambrian. The tectonic plate bearing Australia and Antarctica (and also India and China on its far side) broke away and began a long swing through the ocean that with other later breakups brought us to the present world scene (Hoffman, 1991).

Continental crust is about 35 km (22 mi) thick, and an open vertical fissure with a new ocean in it did not form at the rift where Australia and Antarctica broke away from North America. The Earth is too weak for that. For more than 20 million years, each incremental expansion of the rift at the future position of Oregon and Washington was followed by massive crustal slides toward it from both sides. Therefore, no crack opened along the rift, but giant faults broke up a wide belt of the flanking terrain. When new oceanic crust finally did begin to form, belts of disrupted continental crust several hundred kilometers wide tapered toward it from each side.

The tapering former edge of North America is well preserved in Nevada, where richly fossiliferous rock layers from younger geologic periods blanket the new continental edge. In the Pacific Northwest, however, later catastrophic geologic events removed that original tapering continental margin and replaced it with alien continental blocks.

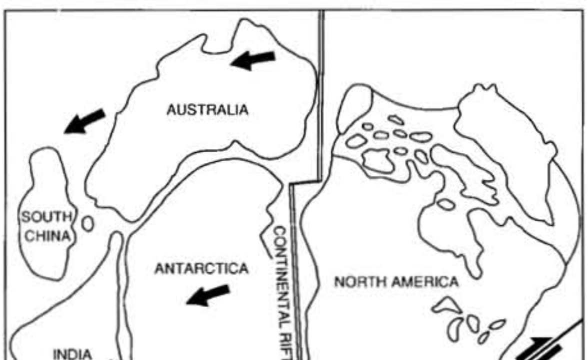

Figure 1. About 700 million years ago during the Precambrian, a continental rift separated North America from a much larger continent. Crustal stretching continued for 20 million years or more. Then a new ocean formed at the rift, and the Pacific Northwest established an anchorage on its North America margin.

GIANT BITES FROM THE CONTINENT

For a long period after the Precambrian breakup, the west coast of North America was tectonically quiet, and sediment banks and organic reefs built steadily seaward. Then, about 250 million years ago during the Triassic (some investigators say it was earlier), a disruption began, perhaps triggered by crustal stretching before the opening of the Atlantic Ocean and the consequent westward drift of the North America Plate (Howell and others, 1987). Sonomia, a large block of the Earth's crust now centered in western Nevada, was swept up and captured by the drifting continental plate of North America (Speed, 1983). This was followed about 200 million years ago, during the Jurassic, by the arrival of yet another big block, Stikinia, now centered in British Columbia (Figure 2).

These crustal blocks, which had formed as volcanic arcs and were plastered against the west side of North America, went a good way toward building the shoreline of North America out to roughly its present position. But after those blocks joined North America, giant bites were taken from the continental edge. In the first of these displacements, about 120 million years ago during the Cretaceous,

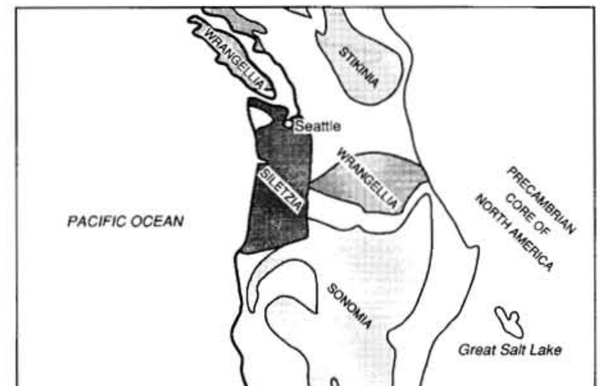

Figure 2. A succession of large blocks, mostly offshore volcanic arcs similar to today's Aleutian Islands, became attached to the Precambrian core of North America. First to arrive was Sonomia, then Stikinia. (Intervening onshore unpatterned areas are sea-floor materials squeezed between the blocks.) After Stikinia joined North America, it moved northward, reexposing the Precambrian core of the continent to the ocean. Into this gap came Wrangellia, the final great island-arc block. Then followed a series of displacements toward the north that separated Wrangellia into several fragments and left behind Siletzia, a tract of ocean floor. Later processes established the Cascade volcanic arc and understuffed and lifted up Siletzia to form the present Coast Range of the Pacific Northwest.

the previously captured Stikinia slipped toward the north, taking with it a part of Sonomia and much of the tapered continental margin of North America that had been left after Australia and Antarctica pulled away. In Idaho, this left a gap where oceanic crust of the Pacific Basin was juxtaposed against the Precambrian core of North America.

The nibbling of the continental edge was interrupted later during the Cretaceous by the arrival of Wrangellia (including the Blue Mountains of Oregon) into the gap at Idaho. Then a final great bite took place about 60 million years ago during the early Tertiary, when nearly all of what was then coastal Oregon and Washington was carried northward toward Alaska (Moore, 1984). This left behind Siletzia, the youngest tract of new ground in the Pacific Northwest.

Baja California of today may serve as a model for these dispersals of large tracts of land from Oregon and Washington. Baja California is moving northwestward along the San Andreas Fault, leaving behind new oceanic crust in the Gulf of California.

Siletzia is made of thin basaltic crust, and like the Gulf of California it, too, initially was a marine gulf underlain by new ground on the sea floor. Soon, however, a subduction zone was established along the margin of the Pacific Northwest, and the Cascade volcanic arc came into being. As part of the establishment of the new subduction zone, a wedge of buoyant sediment and rock was stuffed under the edge of Siletzia's new ground. The wedge lifted the edge of Siletzia above sea level, and today it forms the Coast Range of the Pacific Northwest.

But in eastern Oregon and Washington the land remained low; and sometime later, this interior lowland would become the site of yet another geologic catastrophe.

SWAMPED BY LAVA

About 17 million years ago, during the Miocene, fissures opened in eastern Oregon and Washington and began to deliver tens of thousands of cubic kilometers of basaltic lava to the land surface. Chemical analyses show that the basalt came from the Earth's mantle below the North America Plate. The repeated earlier disruption of the plate in this area may have played a role in the eruptions. Not known, however, is whether oblique crustal stretching related to movement of the San Andreas Fault was sufficient to trigger the lava outpourings (Hooper and Conrey, 1989), or whether a hot spot below the plate caused by large-scale overturn of mantle material was responsible (Duncan and Richards, 1991). The net result, however, was that the 3-km (2-mi)-thick Columbia River Basalt Group, representing one of the world's great flood-basalt provinces and consisting of over 300 individual lava flows, filled in the lowland of eastern Oregon and Washington (Figure 3).

Some individual lava flows ran all the way to the Pacific Ocean, protected from premature solidification by an insulating blanket of already hardened lava at the top of the flow. At the coast, the heavy lava entered the ocean through lava tubes and in places "floated" lighter sediment and sedimentary rocks to create a once-puzzling array of basaltic dikes and sills (Beeson and others, 1979).

Much of the scenic majesty of the Columbia River region owes its origin to these catastrophic outpourings of lava. Where the river has cut into them in the Columbia River Gorge, magnificent waterfalls punctuate the mighty cliffs that line the river.

THEN CAME THE DELUGE

The flood basalt of the Columbia River Basalt Group had long since solidified and begun to be deformed by younger Earth processes, when yet another great catastrophe hit the Pacific Northwest: stupendous floods of water that sculpted the Channeled Scablands in southeastern Washington. About 40 great floods, each containing roughly 2,000 km^3 (500 mi^3) of water and as much as 600 m (2,000 ft) deep, swept across approximately the same area as had been crossed by the basalt flows. They are the Earth's greatest known floods (Figure 4).

About 60 years ago, J Harlen Bretz, a professor of geology at the University of Chicago and the discoverer of the floods, first mapped and published the evidence for massive flooding in the State of Washington (Bretz, 1923). Thus began a long and difficult effort to convince the scientific community that the great floods indeed had occurred. Over the next 30 years, Bretz continued to map the area and to publish his evidence and conclusions, but acceptance of the concept was frustratingly slow. In the meantime, Bretz also did much other research, most notably his classic paper on the then also controversial topic that most limestone caves are formed below the water table (Bretz, 1942).

Part of the problem with Bretz' flood theory was that most people only read about it and never saw the evidence firsthand. Another part was that those who did investigate it were overly steeped in the doctrine of uniformitarianism (geologic processes have uniform intensity), which they interpreted to prohibit any form of geologic catastrophe.

Bretz' opponents were respected, and they were eloquent. Foremost among them was Richard Foster Flint, a former Bretz student (!) and a professor of geology at Yale University. Flint's major contribution was a paper in which he proposed that the Touchet beds, now recognized as the widespread deposits of the floods, were formed by uniformitarian processes of stream deposition beyond the front of an ice sheet during the ice age (Flint, 1938).

Year after teeth-gnashing year passed for J Harlen Bretz, but finally in the 1950s, aerial photographs became widely available. Suddenly, these revealed to everyone the fantastic patterns of giant ripple marks left by the floods (Bretz and others, 1956). Most of the ripples are difficult to recognize on the ground, but on the photographs they show up as giant water-laid dunes with heights measured in the tens of meters and wavelengths in the hundreds.

Bretz at first thought in terms of a single flood. We now know that this concept was derived from the evidence for the final molding of the ripples by the

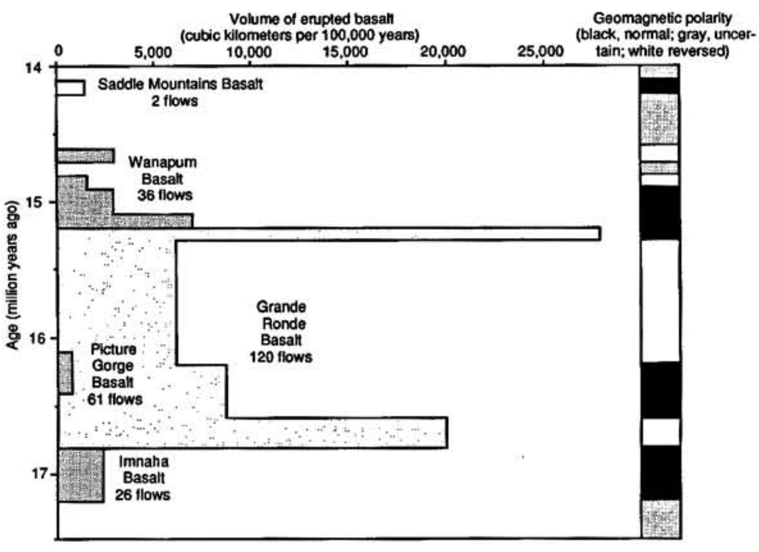

Figure 3. During a brief 3-million-year period, 170,000 km^3 (41,000 mi^3) of basalt flooded across the Pacific Northwest to produce the Columbia River Basalt Group. The over 300 flows in the formations of the group are identified by their structure, texture, and chemical composition, augmented by the magnetic polarity they recorded when the Earth's north and south magnetic poles repeatedly reversed. Abbreviated and simplified illustration based on data from Tolan and others (1989).

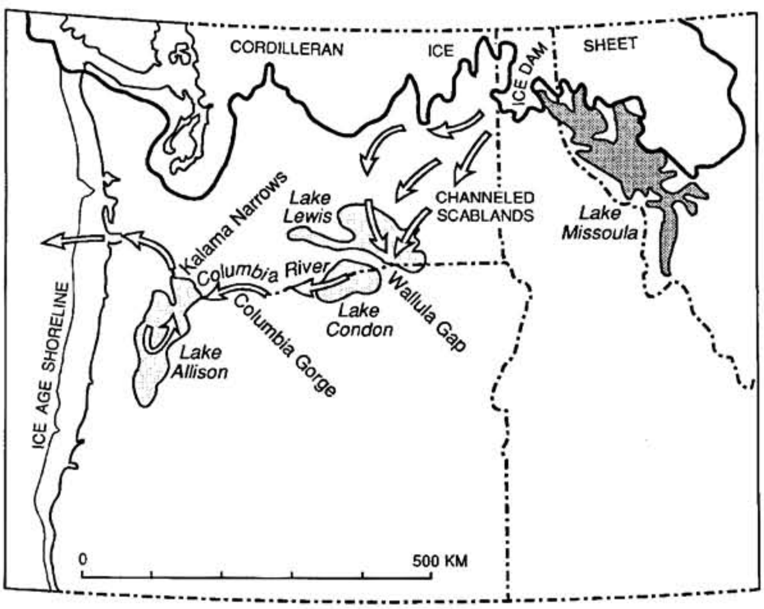

Figure 4. From 15,000 to 13,000 years ago during the ice age, a lobe of the Cordilleran Ice Sheet dammed Lake Missoula in Montana. When the lake reached a depth of 600 m (2,000 ft), its water floated the ice of the dam, flushing the lake water through the Pacific Northwest. Behind constrictions along the Columbia River valley, the water created giant temporary lakes. Where it rushed across high ground, it scoured out channels and laid down giant gravel ripples.

final flood in a long sequence. After later field work, he recognized that more than one flood had taken place, probably one for each major glacial stage. We now know, from the Touchet beds (cover photo) and other evidence, that 40 stupendous floods stripped off the surface of the Channeled Scablands and laid down the giant ripples and other deposits (Waitt, 1985).

The floods came from ancient Lake Missoula in Montana. A lobe of the Cordilleran Ice Sheet closed off the outlet to the lake with an ice dam. After a few decades with the dam in place, the lake filled, and when it reached a depth of about 600 m (2,000 ft), the water started to float the ice dam. Immediately, the dam burst, and the water of Lake Missoula swept down toward the state of Washington.

After each flood, the glacial lobe again moved slowly across the outlet, water filled the lake, the dam floated and burst, and the cycle was repeated—repeated 40 times. So, although they were catastrophic, these floods, recurring again and again over a period of 2,000 years, had a uniform intensity; hence they are, after all, an example of the doctrine of uniformitarianism.

ERUPTION PAST AND EARTHQUAKE FUTURE

Today, the Pacific Northwest has its own offshore tectonic plate, the Juan de Fuca Plate, and its own subduction zone (Figure 5). Subduction zones are notorious for two important types of geologic catastrophes: explosive volcanic eruptions and great earthquakes. The Pacific Northwest has had a long sequence of both.

The Juan de Fuca Plate moves eastward toward the coast and then curves downward and penetrates hundreds of kilometers into the lower mantle (Figure 6). At the same time, the North America Plate moves westward. One might think that the plates collide forcefully, but that is not so (Moore, 1992). The North America Plate overrides and pushes down the curve of the Juan de Fuca Plate and does not butt directly against it.

The lava of volcanic arcs above subduction zones differs from basalt delivered directly from the Earth's mantle in two important respects: it is lighter in color, and it is more viscous. Whereas highly fluid basaltic lava flows freely as a liquid—and makes the world's lava caves—the viscosity of subduction-zone lava causes it to push up into bulbous domes and then to explode violently. The most recent volcanic catastrophe of this sort in the Pacific Northwest was the eruption of Mount St. Helens in 1980.

About two months before the massive eruption May 18th at 8:32 a.m., which killed 57 people and devastated an area seven times the size of Manhattan Island, Mount St. Helens underwent several minor eruptions and began to swell measurably. The experts assumed that the activity would increase only gradually, and they laid out what then was considered a generous safety zone. But the swelling led to a bulge on the north side of the mountain, and on the day of the climactic eruption, the north side suddenly began to slide downward. The slip surface intersected the magma chamber within the mountain, and the unloading of the top abruptly released gas pressure inside.

The resulting explosion, similar to uncorking a champagne bottle, was wholly unexpected in size and force. Within seconds, a shock wave had turned a clear morning into deep overcast. A blast sped down the slope of the mountain at 330 km (200 mi) per hour, followed by a debris avalanche made of the former north side of the mountain and including giant blocks of glacial ice from the summit. An eruptive plume shot 16 km (10 mi) into the stratosphere and continued jetting steadily for the next nine hours. Mudflows of volcanic ash swept down the river valleys all the way to the Columbia River, 80 km (50 mi) away, disrupting river navigation for many months afterward.

The 1980 catastrophe at Mount St. Helens is the world's best studied volcanic eruption. We now know that magma depressurized and released by giant landslides has been common at other volcanoes elsewhere in the world, and the new knowledge will help to reduce the loss of life from such eruptions worldwide (Lipman and Mullineaux, 1981). But what about the other notorious natural hazard of a subduction zone? Should the Pacific Northwest expect a great earthquake in the future?

In historic time, Oregon and Washington have never had a great earthquake, that is, an earthquake larger than magnitude 7.5. And in Oregon even moderate-sized earthquakes are rare. This was long thought to be a good state of affairs, but we now know that a seismic gap of this sort is dangerous. The Pacific Northwest is waiting for a catastrophic earthquake.

American Indian tradition held that many lives were lost during a change in land level and the arrival of a great wave (now recognized as a tsunami) that took place not long before European fur traders arrived in the Pacific Northwest (Swan, 1870). Recent study on the basis of submerged coastal marshes and tree-ring dating shows, with an uncertainty of about 20 years, that this last great earthquake took place in 1680 (Atwater, 1987).

The experts know approximately when the last great earthquake occurred in the Pacific Northwest, but they are less certain about the interval between the great earthquakes. Intensive research continues on this topic, and several pre-1680 earthquakes have been identified. What remains uncertain is whether any preceding earthquakes were missed, because this is a critical ingredient in determining the recurrence interval and hence the probability of such an event soon. The best evidence now available points to a recurrence interval of 300 to 500 years. Hence, the Pacific Northwest should look for a great earthquake anytime from now to 200 years from now.

Future research may sharpen this estimate, and in the meantime building codes are being strengthened, and the public is being made

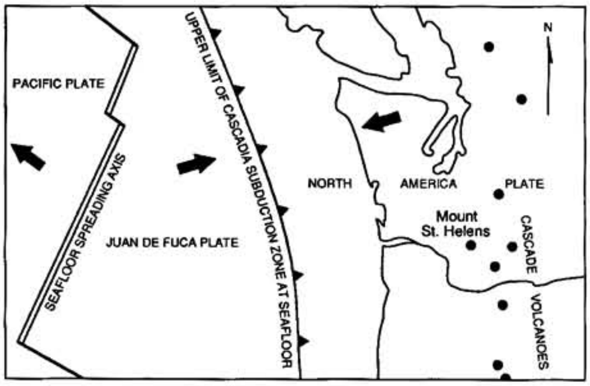

Figure 5. The Juan de Fuca Plate moves toward North America and bends down at the Cascadia subduction zone to produce the Cascade volcanoes and great subduction-zone earthquakes.

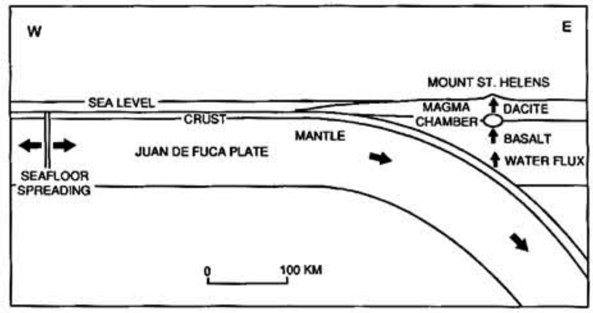

Figure 6. Cross section across the margin of the Pacific Northwest showing the downward bending of the Juan de Fuca Plate. Heat and water from the crust generate dark-colored basaltic magma in the overlying mantle, which in turn produces lighter colored magma below the volcanoes by the settling out of heavy, dark-colored minerals to change the composition of the remaining liquid.

aware of steps that can be taken before, during, and after a great earthquake to reduce the danger.

The good news about subduction-zone earthquakes is that the fault slip surface is relatively far away, 50 to 100 km (30–60 mi) below the surface. This reduces the earthquake intensity. The bad news is that the slip zone is relatively long: in the worst case, all the way from British Columbia to northern California. This leads to a long period of shaking, up to four minutes, which can shake down buildings or send down landslides that might have survived briefer earthquakes.

Let's hope that all the right things are being done to thoroughly understand the next geologic catastrophe in the Pacific Northwest, so as to reduce its effects and make it a small one for us. As we have seen, it will join a long history of catastrophes, some of which were very large indeed.

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Oregon Academy of Science announces 1994 meeting

The Oregon Academy of Science will hold its fifty-second annual meeting on Saturday, February 26, 1994, at Oregon State University in Corvallis.

The meeting usually draws about 400 participants, including 100 at the Junior Academy level. It is an excellent chance to make contact with scientists at other Oregon colleges, universities, and research facilities. The meeting will have papers presented in sections of anthropology, biology, chemistry, economics, geography, geology, history and philosophy of science, mathematics, physics, political science, psychology, science education, and sociology. The Junior Academy will also have a full slate of papers.

This year's "keynote address" will feature *A Visual Triptych Of Science* with three 15-minute presentations aimed at the Junior Academy level but appropriate for all members. The presenters and the tentative titles of their presentations will be: Dr. Gordon Matzke (OSU Geoscience), "Should we invite a zebra to lunch?"; Dr. Patricia Muir (OSU Environmental Science), "The chemistry of fog"; and Dr. Phil Brownell (OSU Zoology), "Scorpions—up close and personal."

The conference registration fee of $10 includes a luncheon with the keynote program. Additional information is available from Dr. Dick Thies, College of Science, Oregon State University, Corvallis, OR 97331-4608, phone (503) 737-3879. □

Ground-water anomalies associated with the Klamath Basin earthquakes of September 20–24, 1993

by Paul J. Lienau and John W. Lund, Geo-Heat Center, Oregon Institute of Technology, Klamath Falls, Oregon 97601
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Two moderate earthquakes occurred approximately 30 km northwest (122.1°W. and 42.3°N.) of Klamath Falls, Oregon, on the evening of September 20, 1993 (Figure 1). These two were measured at magnitudes (M) 5.9 and 6.0 by the University of Washington and occurred at an approximate depth of 12 km. (The U.S. Geological Survey [USGS] National Earthquake Information Center in Golden, Colorado, reported preliminary magnitudes of 5.4 and 5.2 at depths of 10 km.) Numerous aftershocks measuring between M 2.8 and M 4.3, occurring in the same general vicinity, were felt in the area through September 24 (Figure 1). The earthquakes were felt in Salem (320 km north) and in Redding, California (200 km south). One person was killed by falling rocks on U.S. Highway 97, approximately 25 km north of town, and one person died of a heart attack, probably induced by the events. Unfortunately, there were no seismometers located in southern Oregon during the earthquakes; thus the data, recorded by more distant seismometers, are not as precise as is liked. Figure 2 is a seismogram of the 8:29 p.m. earthquake of September 20, recorded at Corvallis, Oregon, 285 km northwest of Klamath Falls. Since the earthquake, the USGS has established eight seismometers in the area to record aftershocks. They have recorded over 400 events of M 1.5 and greater since installation.

At least 300 structures were damaged by the quakes, several serious enough to be closed to public use. The most notable building severely damaged and closed to public use is the Klamath County Courthouse on Main Street in Klamath Falls. The Federal Emergency Management Agency (FEMA) has recommended that this structure be repaired, but it may take up to a year before the building can be occupied again. Buildings constructed of unreinforced masonry received the greatest damage, whereas buildings constructed of wood suffered little to no damage—typical of earthquake dam-

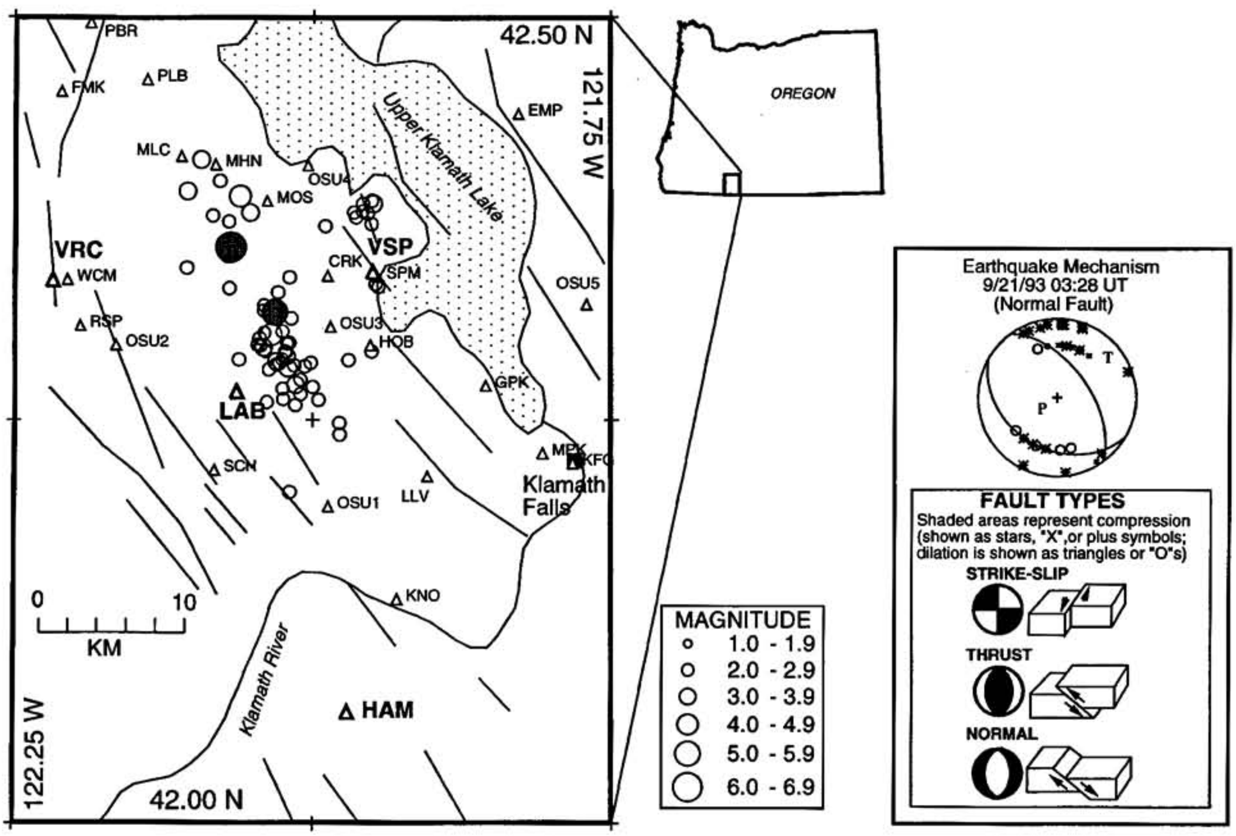

Figure 1. Plot showing best locations for earthquakes in the Klamath Falls, Oregon, area, third quarter of 1993. The two largest earthquakes (shaded circles) were on 9/21/93 at 03:28 (M = 5.9) and 04:45 (M = 6.0) UT. All locations contain arrival times from both CALNET (USGS, Menlo Park) and WRSN (UW, Seattle). Seismograph stations are shown as triangles. Most stations were portables deployed after the main shocks. Permanent stations VSP, VRC, LAB, and HAM (bold) were installed by the USGS in early October. Readings from portable stations are used for some aftershocks. Faults shown are from Pezzopane (1993). The normal focal mechanism (lower hemisphere, equal area) for the first main shock was determined from combined UW and CALNET polarities. The mechanism of the second main shock is similar. Computer image courtesy of Ruth Ludwin, University of Washington Geophysics Program.

age. Brick walls outside and inside buildings on the Oregon Institute of Technology (OIT) campus were also damaged, and some had to be closed temporarily. All are being used now, with some stairwells and entrances closed until the brickwork can be repaired. Throughout the city, no severe damage to utilities was found. Only minor leaks occurred in water lines and were quickly repaired. The total damage is at least several million dollars. It should be noted that none of the buildings in Klamath Falls meet the 1991 (adopted 1993) Uniform Building Code (UBC) earthquake zone 3 standards. Klamath County was originally in zone 1, then zone 2, and most recently in zone 2B according to UBC.

The Geo-Heat Center was especially interested in the effect of the earthquakes on the geothermal resource. In addition to measuring changes caused by the earthquakes, we also tried to document any precursor signals that may have occurred. These observations are discussed later in this paper.

Since 1945, at least 12 earthquakes have occurred within 33 km of Klamath Falls, but only seven of these were larger than M 3 (Jacobson, 1986). The largest recorded in this period was M 4.3 in 1948, and two of M 3.7 occurred in 1949. Based on the authors' personal conversations with local residents, minor building damage did occur in Klamath Falls from one or more of the 1948–49 earthquakes. Two earthquake swarms have also occurred within 150 km of Klamath Falls during the last 30 years: one in Warner Valley due east of Klamath Falls near Adel, Oregon (1968), and the other due south of the city at Stephens Pass near Mount Shasta, California (1978). The largest of these quakes was M 5.1.

The Klamath Basin is located at the western edge of the Basin and Range geologic province that extends eastward to Salt Lake City. The Klamath Basin, with the city of Klamath Falls located on its eastern edge, is a down-faulted graben. The horst blocks on either side have been estimated to have moved at least 500 m vertically. Several fresh fault scarps over 10 m high and several hundred meters long are visible in the basin. The absence of alluvial fans cutting across these fault scarps indicates that the faults have been active during the past several thousand years. These relatively young faults extend from Upper Klamath Lake southeastward to Tulelake, California, a distance of about 50 km, and probably extend northwestward to Crater Lake National Park (Figure 1). A study by the U.S. Bureau of Reclamation describes two recent fault zones along the west side of Upper Klamath Lake. One of these, the West Klamath Lake fault zone, has a fault scarp as high as 25 m cutting across glacial deposits less than 30,000 years old. Another scarp shows displacement of 1–2 m in deposits thought to be less than 10,000 years old. Geologists estimate that the West Klamath Lake fault zone is capable of generating earthquakes as large as magnitude 7.25. The September earthquakes appear to have originated in this fault zone.

Most of the original hot springs in the basin, the majority of which are located in the vicinity of Klamath Falls, are associated with the horst and graben structure. The geothermal utilization, mainly for space heating, is in the city of Klamath Falls. Approximately 500 wells tap geothermal fluids from 50°C to 110°C at depths from 30 to 600 m. The entire OIT campus, located at the northwest end of the well concentrations, uses 88°C geothermal water for space heating and domestic hot water (Lienau and others, 1989).

The September 20 earthquakes appeared to have had an effect on both the geothermal and cold-water aquifers in the Klamath Falls area. Long-term monitoring of both aquifers is done by well owners, the city of Klamath Falls, and the OIT Geo-Heat Center.

Well owners manually measure five residential wells daily for water level, using an electrical probe. After the earthquakes, all wells had water levels increase by 40–50 mm/day. Before the earthquakes, water levels were not changing. Generally, water-level increases in the hot-water well area have been 900 mm from September 15 to October 5. By comparison, during the same period in 1992 the water levels decreased by 208 mm, and in 1991 they increased by 18 mm.

Long-term monitoring of five cold-water wells for water-level changes and bottom-hole temperatures is required by the Oregon Department of Environmental Quality for the permit to inject geothermal fluids at OIT. Shaft encoder water-level instruments and thermistors are connected to data loggers, which record on a 6-hour interval. Immediately after the earthquakes, water levels in all five wells decreased dramatically, about 0.3–2.1 m, depending on the well, for a duration of one to two days and then stabilized at the lower water level. Figure 3 is an example of a hydrograph showing the water level decline.

The city of Klamath Falls monitors a hot-water well at Laguna and Herbert Streets using a chart recorder that produces a continuous

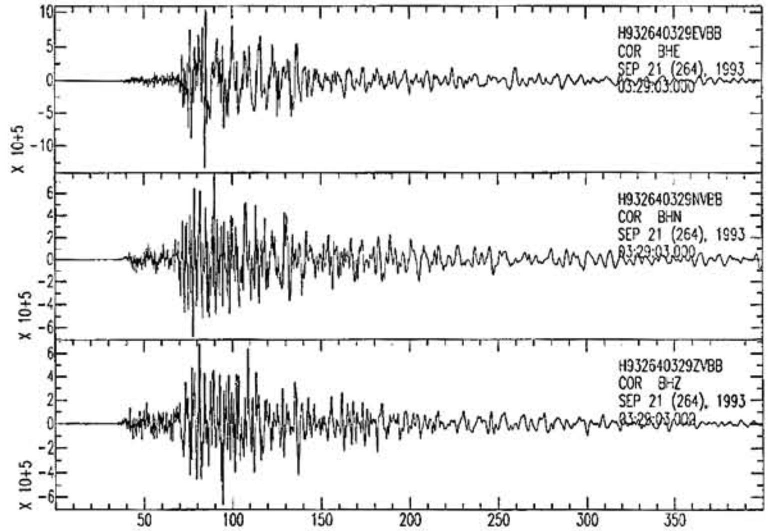

Figure 2. Three-component seismogram of the September 20, 1993, earthquake, recorded at Corvallis, Oregon, representing horizontal east-west (top), horizontal north-south (middle), and vertical (bottom) motions.

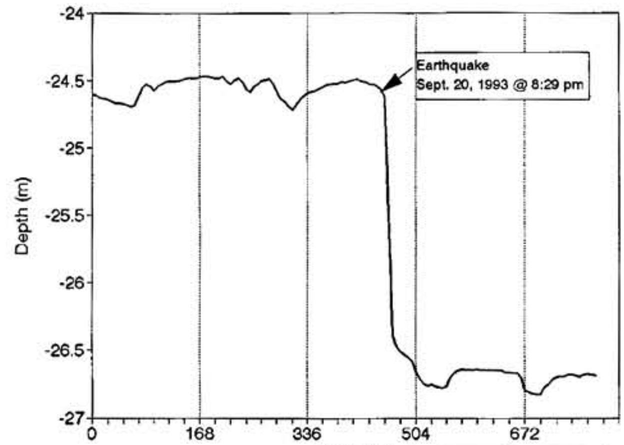

Figure 3. Hydrograph of motel observation well near OIT showing water-level decline as a result of the earthquakes. Data from September 1 to October 4, 1993; depth = 60 m, temperature = 13.5°C.

analog record of water level change. Prior to the earthquakes, there were very small changes in the water level. The earthquakes caused the cable to jump off the pulley, which was replaced on September 23. From September 23 to October 1, three aftershocks were recorded on the chart, and the water level increased about 150 mm from September 23 to September 24.

Ken Johnson, who manages Jackson Hot Springs in Ashland, Oregon, reported that the flow of the springs has increased by about 20 percent since the September 20 earthquake. The springs, which flow up to 100,000 gal/day, now allow him to fill his holding tank in about 43 hours instead of the previous 52 hours. The water temperature has not changed, remaining at between 86° and 96°F (Ken Johnson, personal communication, 1993).

Other hydrologic events that may be related to the earthquake include the following:

Klamath Medical Clinic geothermal well at 1905 Main Street started an artesian flow of approximately 115 liters per minute (L/min) about 1.5 months before the earthquakes. After the earthquakes, the flow increased to 570 L/min at 91°C (no apparent change in temperature).

A well behind City Hall used by Modoc Lumber Co. for makeup water to a boiler increased 5°C in temperature, from 18°C to 23°C after the earthquakes.

The Conger well field near Link River is used by the City as supply wells. After the earthquakes, these cold-water wells had an increase in water level of about 2.1 m.

Wells in an area about 25 km southeast of Klamath Falls in late July and early August 1993 reportedly began to smell and taste bad. In the same area, the Jim Moore well suddenly began producing 49°C water (estimated at 15°C before).

Finally, between 4:00 to 5:00 p.m. in the afternoon of September 20 (before the earthquake), water changed at the Gordon Aires well about 11 km south of the epicenter. The water was whitish gray in color with a tremendous amount of gas that had a strong "rotten egg" or hydrogen sulfide odor. Other well owners in the Keno area noticed similar changes to their wells. This area is southwest of the West Klamath Lake fault zone, along its structural trend.

Similar precursor changes in well water have been reported as far back as the sixth century B.C. in Greece. Springs in ancient Greece, in the Roman Empire, in Japan, and in China were reported to have become murky before a quake, with changes in taste and flow. Such changes were noted prior to the Haicheng, China, earthquake of 1975, when the entire city was evacuated just prior to a major earthquake. Approximately one month prior to this quake, well-water levels rose, hot springs stopped flowing, and some wells became muddy. Reports by the USGS indicated that earthquakes caused compression in some areas and tension in others, thus accounting for water-level changes after the events. Many cases of unusual behavior of animals prior to earthquakes have also been documented (Tributsch, 1982).

The March 27, 1964, Alaska earthquake caused significant changes in water levels in several artesian wells in the Anchorage area. In one, the water level initially dropped 4 m and then an additional 2 m. In others, the water levels within 5 days after the quake were 1–6 m lower. Wells in Palmer were also lower, and some in Chugiah were 1 m higher. The general rule was a lowering of the water level in artesian wells after the quake and a subsequent rise (Grantz and others, 1964; Waller, 1966).

According to Ferris and others (1962), "There will first be an abrupt increase in water pressure as the water assumes part of the imposed compressive stress, followed by an abrupt decrease in water pressure as the imposed stress is removed. In an attempt to adjust to the pressure changes, the water level in an artesian well first rises and then falls." This phenomenon has been noted in wells that are hundreds and even thousands of miles from epicenters. At these distances, the long-period waves of earthquakes cause the fluctuations; whereas in wells close to the epicenter, only the short-period waves can effectively move water rapidly into and out of wells (Thomas, 1940).

We are not sure about the meaning of the Klamath Basin events and whether or not some or all are related to the earthquakes. In any case, they are certainly out of the ordinary, based on about 20 years of monitoring the geothermal resource in the Klamath Falls area. We are continuing to monitor wells in the area and are also performing geochemical analyses of the water.

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Potentially new species of pond turtle discovered in Columbia River Gorge

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The deadly Pleistocene floods that buried Portland under nearly 400 ft of water, inundated the Willamette Valley as far south as Eugene, and scoured an area the size of the state of Delaware (approximately 2,000 mi^2) clean of all soil and vegetation may prove to be a creative force as well. (References to details of the floods from Allen and others, 1986).

Dan C. Holland, director of the Western Aquatic Turtle Research Consortium in Corvallis, believes the "Bretz floods" may have geographically isolated several rare populations of pond turtles found on the basalt ridges of the Columbia River Gorge. Holland believes the populations, which are currently classified as Western pond turtles, *Clemmys marmorata*, warrant listing as a new species (Holland, personal communication, 1993).

Holland, a herpetologist who has studied pond turtles in the west for more than 20 years, says the Gorge turtles are extremely difficult to tell apart from Western pond turtles, unless the animal is in hand. The forelimbs of older Western pond turtles are, for the most part, charcoal colored. The forelimbs of Gorge turtles bear charcoal scales tinged with pale yellow and thus have a slightly lighter appearance.

Just above the hind limbs, on folds of skin attached to the carapace (the upper shell), all these turtles bear a small scale called the "inguinal shield." In Gorge turtles, this is about half the size of the one found in Western pond turtles.

Less than 200 individuals of the potentially new species occur in a total of three locations in the Gorge. Two of the populations are in Washington; the third occurs in Oregon. In all cases, the pond turtles are found at elevations above the high-water mark postulated for the Bretz floods when they raced through the sections of the Gorge where the turtles occur.

"Bretz pond turtles" in the Columbia River Gorge differ visually from Western pond turtles in color and the construction of their shells.

J Harlen Bretz, the geologist for whom the catastrophic floods are named, first noted the erosive force of a massive Pleistocene flood in western Washington which he named the "Spokane flood" (Bretz, 1923). In subsequent papers, Bretz outlined how a series of cataclysms about 13,000 years ago carved the Channeled Scablands of Washington, fathered hundreds of hanging valleys and deserted plunge pools, and rafted hundreds of erratics (weighing up to 200 tons) as far south as Eugene.

Many geologists now believe that as many as 40 floods may have broken out from ancient Lake Missoula, a Pleistocene lake in western Montana formed (and reformed) when glacial ice repeatedly plugged the Clark Fork River. The 500 mi^3 of water that surged from the lake covered—at least in the largest of the floods—16,000 mi^2 of Montana, Idaho, Washington, and Oregon and stripped up to 150 ft of soil and loess from portions of the Columbia Plateau.

In the upper Columbia River Gorge, as John E. Allen puts it simply, "Anything under a thousand feet in elevation was wiped out" (personal communication, 1993).

Holland believes that the turtle populations high atop the basalt ridges of the Gorge may have narrowly escaped the floods, which in some areas brought a 1,000-ft-high wall of water racing through the Gorge. Sheltered and thus isolated, the turtles may have been genetically cut off from other populations by the disaster, says Holland. He notes that the nearest populations of Western pond turtles occur more than 60 mi away from the Gorge populations.

Holland, who received his doctorate in 1992 in environmental and evolutionary biology from the University of Southwestern Louisiana for his study of the relationship between geographic distance (and isolation) and morphological divergence in Western pond turtles, says he may propose naming the Gorge turtles after Bretz. Before the Gorge turtles would be accepted as a new species by the scientific community, Holland's findings would have to be published in a scientific journal and stand up to scientific scrutiny. Oregon's only other native turtle, the painted turtle (*Chrysemys picta belli*), shares a place on the Oregon state sensitive species list with the Western pond turtle.

Holland says that Bretz' work laid the foundation for his theory, which attempts to explain how Gorge turtles were differentiated from Western pond turtles in a process called "allopatric speciation"—the development of a new species through the geographic isolation of a population.

Isolation through geologic events is nothing new in natural history. Holland points out that the two species of Kaibab squirrels now present in the Grand Canyon (one species on the north rim, one on the south) are believed to have been derived from a single parent species. The gene pool of the squirrels, as the theory goes, was literally bisected in the ancient past by the downcutting of the Colorado River and the creation of the Grand Canyon.

Volcanism and orogeny, through time, have also acted as agents of geographic isolation, Holland notes.

The uniqueness of the geologic setting in the case of the Gorge turtles rests on the precision with which the event can be timed. "With the Columbia Gorge animals," Holland explains, "we have—hypothetically—a very recent event that we can determine with a high degree of accuracy. We not only know what physical event would have produced isolation, but we also know when it happened.

"When we look at patterns of differentiation in species," Holland continues, "it's rare that you can point out a specific geological event, and it's even rarer that you can point out the timing. This is one of the better documented cases we have."

Holland says that it was his reading of *Cataclysms on the Columbia* (Allen and others, 1986) that provided the hypothesis that led him to his theory about the isolation of the "Bretz" turtles.

To determine the extent to which the Gorge turtles vary from other pond turtle populations, Holland used a technique called "discriminate function analysis," a statistical system of calculating how far certain sets of variables deviate from other sets. By measuring variables (such as the size of the inguinal shield) not related to differences in sex or age, Holland came up with 13 variables in the Gorge turtles that, he says, set them distinctly apart from Western pond turtles.

"No matter how I did the calculations, the Gorge turtles always came up different," Holland explains.

If Charles Darwin had known about the Bretz turtles, perhaps his principal fears in publishing *The Origin of Species* would have been put to rest. Darwin noted in his 1859 text that the absence of intermediary links between species, in the geological record, formed a strong argument against the theory of evolution. (Darwin citations from Darwin, 1958).

Darwin stated that the record, due to its "extreme imperfection," failed to preserve evolutionary links between parent species and more recently evolved species. "Geology assuredly does not reveal any such finely graduated organic chain," Darwin said. "And this perhaps, is the most obvious and serious objection which can be urged against the theory."

Darwin noted that the principal of competition made quick work of parent species. "In all cases, the new and improved forms of life tend to supplant the old and unimproved forms."

But then Darwin never met the Bretz pond turtle. The Gorge turtles may, at the minimum, be considered intermediary forms, but their presence in the geologic record is illustrated in print, not in the strata. The "Bretz" turtle—if eventually classified as a distinct species—may be seen as an extremely rare, close link to a still-existing parent species, an animal that perhaps would have relieved Darwin of his principal worry.

Darwin would have appreciated the irony: the catastrophic Bretz floods providing a near-perfect geological record in regard to the isolation of the Gorge populations—and the floods themselves being the cause of the genetic isolation. "We continually forget how large the world is, compared with the area over which our geological formations have been carefully examined," Darwin noted, "we forget that groups of species may elsewhere have long existed."

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Inflated basaltic lava — examples of processes and landforms from central and southeast Oregon

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INTRODUCTION

Much of the land in central and southeast Oregon is relatively flat, notwithstanding extraordinary examples to the contrary. What processes are at work, and what landforms develop in basaltic lava that erupts onto these flat terrains? Fortunately, a number of young, accessible basalt flows offer relatively fresh, uneroded surfaces and landforms to study and enjoy. Road cuts, railroad cuts, and canyons offer cross-sectional views of the older, soil-covered lavas in these areas.

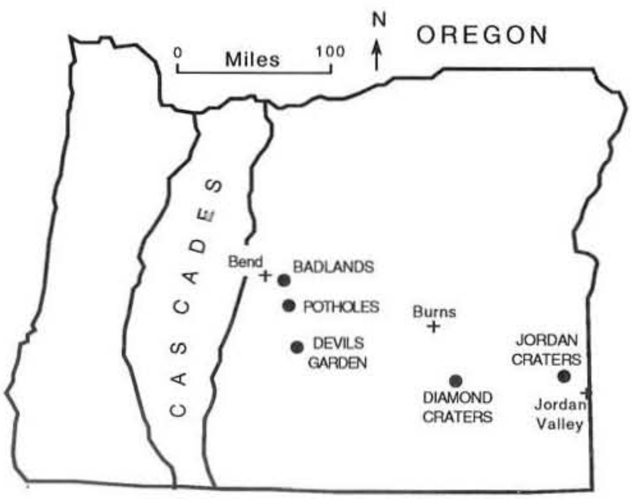

Figure 1. Location of basaltic lava fields discussed in this article.

Many of the youngest, highly fluid basaltic lava flows in central and southeast Oregon show distinctive forms and structures that have resulted from impressive swelling, or inflation (Chitwood, 1987, 1992, 1993a) (Figures 1-3). Beginning as thin flows only 20 or 30 cm (8–12 in.) thick, these lavas inflated in complex ways to thicknesses of generally 1.5–18 m (5–60 ft). Landscapes of low slope gradient, usually less than 2°, allow these pahoehoe lavas to spread out over wide areas and to develop elaborate tube-fed systems. Flow fronts, which initially advance rapidly, slow down as the lava fans out. Eventually, flow advance ceases when the strength and viscosity of a developing crust cannot be overcome by internal hydraulic pressures. But molten lava continues to flow into the system. The result is inflation. The surface crust rises, tilts, and cracks in complicated patterns.

Much of what is described and suggested in this article has been derived from observations of the remarkable landforms of basaltic lava fields around Bend, Oregon, and five basaltic lava fields of Quaternary age in central and southeast Oregon. The five fields include Badlands (Bergquist and others, 1990), Devils Garden (Keith and others,1988; Chitwood, 1990), Diamond Craters (Peterson and Groh, 1964; Brown, 1980), Jordan Craters (Calzia and others, 1988), and Potholes (Jensen, 1988) (Figure 4, Tables 1 and 2).

The term "inflated lava" was coined in 1972 by Robin Holcomb (personal communication, 1993) to describe fields of tube-fed pahoehoe lava that had swelled at Kilauea Volcano, Hawaii. He later included inflated lava in a morphologic classification of lava flows at Kilauea (Holcomb, 1987). Only in the past few years has detailed and exciting work begun on inflated lavas. Indeed, the term is only now becoming known among geologists and volcanologists. Geologic units described as "inflated lava" are appearing in increasing numbers on geologic maps (e.g., Kuntz and others, 1988). Inflated lava has been observed along the spreading center of the Juan de Fuca Ridge off the coast of Oregon (Appelgate and Embley, 1992). Many of the lavas of the Columbia River Basalt Group may be inflated (Hon and Kauahikaua, 1991; Self and others, 1991; Finnemore and others, 1993).

EVIDENCE FOR INFLATION

In the young basaltic lava fields of central and southeast Oregon, tilted slabs and surfaces of pahoehoe lava are common. The ropy or smooth surfaces of these slabs suggest they formed in essentially horizontal positions. The slabs usually make up the sides of raised areas of lava. Clefts or big cracks far too large to be accounted for by contraction during cooling often accompany tilted slabs. The tilted slabs, clefts, and raised areas suggest swelling from within the lava.

On lavas recently erupted from Kilauea Volcano, Hawaii, measurements of the surfaces of numerous tumuli show that swelling from within broke and tilted the overlying crust. When the tilted slabs are graphically made horizontal, the crustal pieces fit nicely back together (Walker, 1991).

Holcomb (1981, p. 94) describes evidence for inflation of lava during the eruption of Mauna Ulu on Hawaii: "The site is near the south wall of Makaopuhi pit crater, where a large boulder had fallen

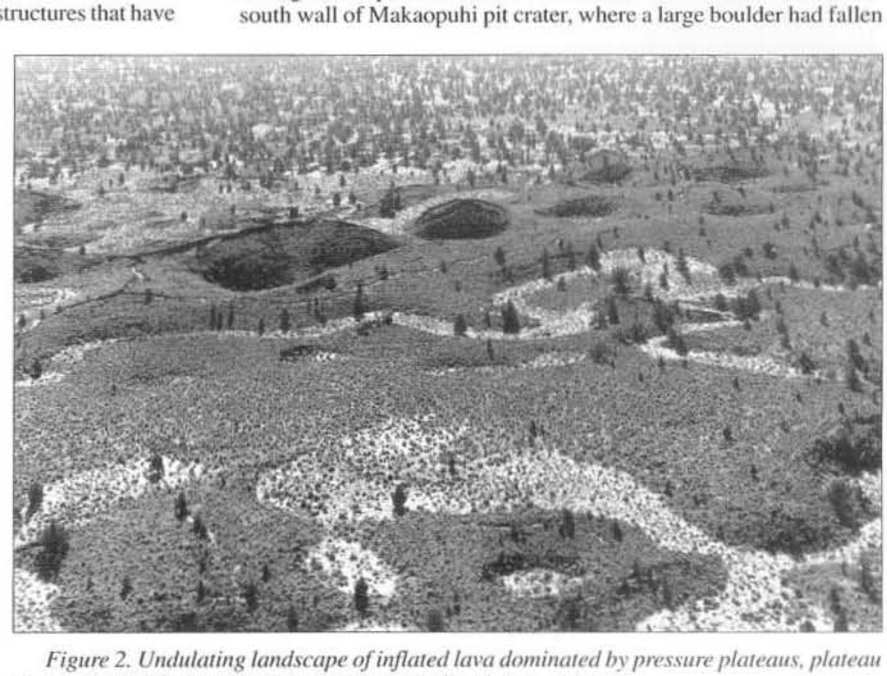

Figure 2. Undulating landscape of inflated lava dominated by pressure plateaus, plateau pits, and soil-filled residual depressions (Badlands lava field).

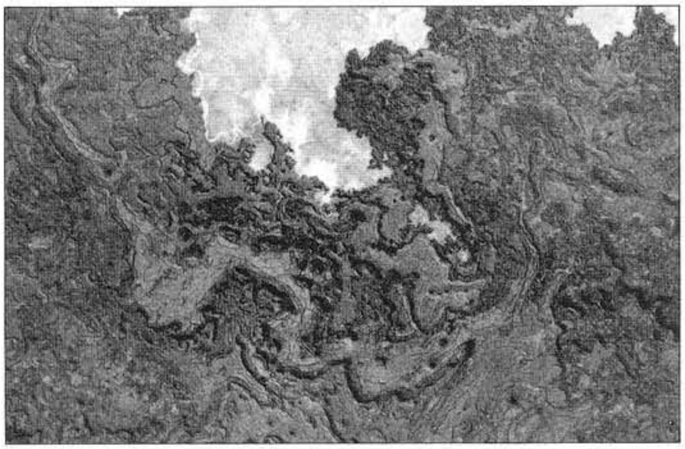

Figure 3. Air photograph showing several inflated flow units and features (5 mi northwest of Upper Cow Lake, Jordan Craters lava field).

onto the mezzanine. A small tree had grown from the top of the boulder. When the initially thin pahoehoe flow flooded the area, it chilled against the boulder, and where it was chilled it could not inflate. Inflation of the rest of the flow caused it to thicken about 4 m (13 ft), leaving the boulder in the center of a depression. The walls of the pit have an accordionlike structure that developed at the site of greatest differential expansion."

On the Mauna Loa lava flow of 1859, north of the Kona Airport in Hawaii, light-colored, angular rocks 8–25 cm (3–10 in.) across litter the surface in some areas. But you cannot pick up the rocks. The lower part of each rock is encased by and firmly held in the pahoehoe lava. They achieved their present situation when the first, thin flows surrounded them as they lay loose on the old, pre-1859 surface and encased them in a thin crust. Subsequent inflation of the flow carried these rocks vertically upwards 1.5–3 m (5–10 ft).

Lavas from the Puu Oo eruptions of Kilauea Volcano in Hawaii, which began in 1983, have encircled metal fence posts, cars, traffic signs, parts of incinerated homes, trees, and coconuts and carried them aloft 1.5–9 m (5–30 ft) as the lava inflated.

Lava flows have been observed and measured while inflating, but the rate of inflation is so slow that actual movement is seldom seen (Hon and Kauahikaua, 1991).

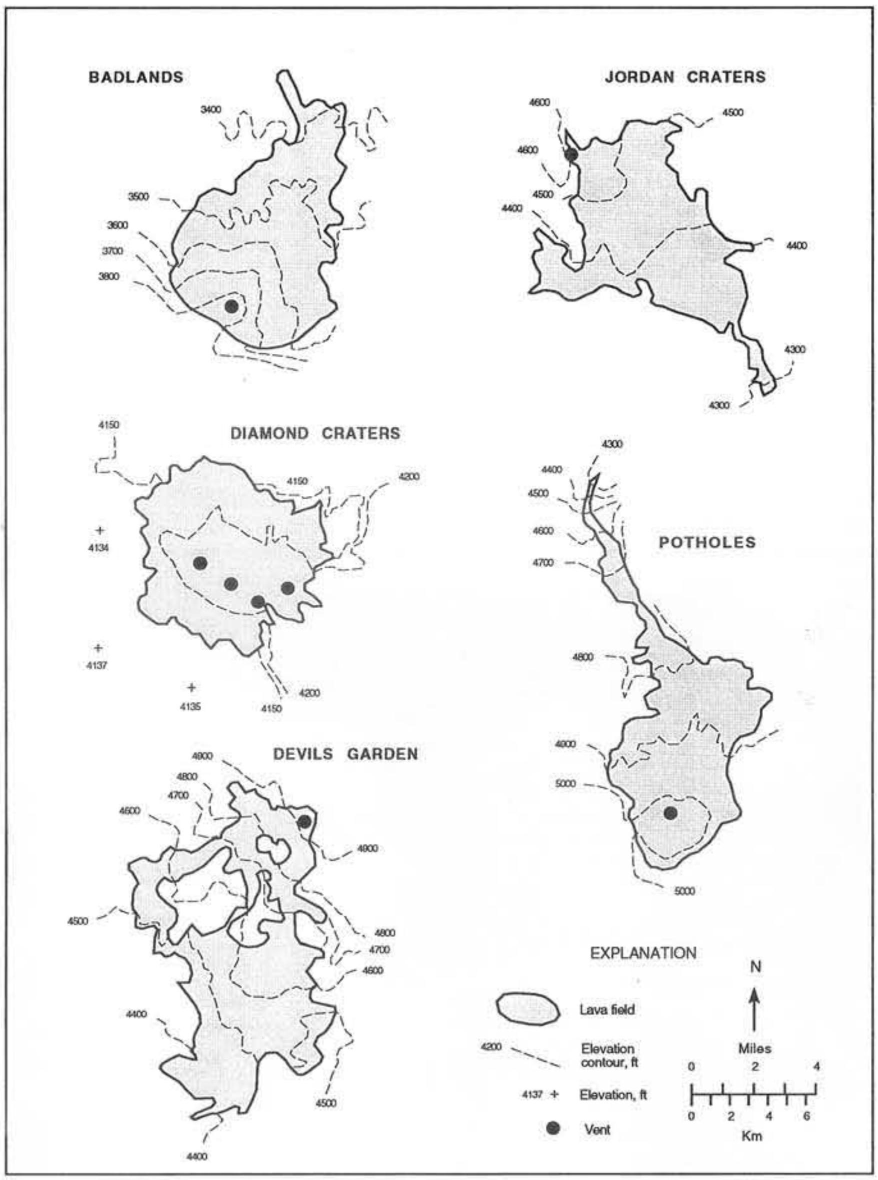

Figure 4. Overview maps of lava fields discussed in this article. Note low slope gradients in each field.

RHEOLOGICAL AND MECHANICAL BEHAVIOR

The ability of basaltic lava to inflate without rupturing depends on its rheological properties (i.e., properties pertaining to deformation and flow) at sub-liquidus temperatures. Above the liquidus, lava behaves essentially as a viscous (Newtonian) liquid. But below the liquidus, the rheologic properties are dependent on time and motion (Murase and McBirney, 1973; Hulme, 1974; McBirney, 1984; Dragoni and others, 1986; Solomatov and Stevenson, 1991). That is, lava held at a fixed, sub-liquidus temperature will have different viscosities and different yield strengths depending on how long the lava is held at the fixed temperature and how vigorously the lava is stirred. Viscosity and yield strength can increase greatly with time and with lack of stirring. Apparently, networks of atoms, molecules, and crystals grow and interact if allowed time and little disturbance.

For convenience, although vastly oversimplified, lava between the liquidus and solidus temperatures is in a zone here called the "zone of crystallization." For a slowly cooling lava lake of tholeiitic basalt in Hawaii, the zone of crystallization occurred between a liquidus temperature (100 percent liquid) of 1,210°C (2,120°F) and solidus temperature (95 percent solids) of about 980°C (1,706°F) (Wright and Okamura, 1977).

The potential for lava to inflate depends on the development of a tough, plastic region of high viscosity and yield strength that encloses lobes and sheets of lava (Figure 5). This plastic region thickens as molten lava cools conductively from its surface inward. The plastic region is within the middle of the thicker, migrating zone of crystallization within the lava flow. As the lava loses heat, the zone of crystallization thickens and moves inward at a rate approximately proportional to the inverse of time squared. The zone of crystallization con-

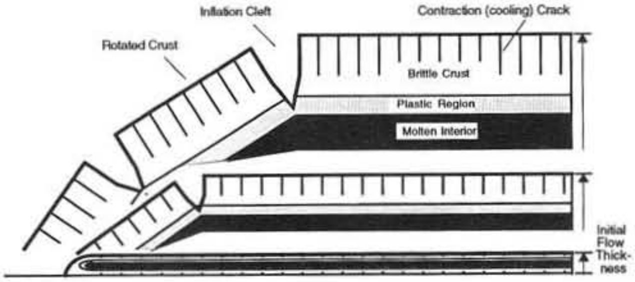

Figure 5. Cross-sectional diagram of inflating lava. A tough, plastic region surrounds the molten region and limits leakage and breakouts. During inflation, all zones thicken, contraction cracks lengthen, brittle crust tilts, and clefts open.

tains a wide range of crystal-to-melt proportions.

The rheological and mechanical properties at different places and times in the zone of crystallization will be strikingly different (Figure 6). The hotter, inner part of the zone contains few crystals and behaves essentially as a viscous liquid. This region has little or no yield strength, as evidenced by the rise of gas bubbles where lava has ponded. In the lava lake studied by Wright and Okamura (1977), bubbles ceased to rise when 55 percent crystals had formed at a temperature of 1,070°C (1,870°F).

The middle part of the zone of crystallization, the plastic region, contains a substantial percentage of crystals and behaves as a plastic with high viscosity and high yield strength. This material holds its shape until a sufficiently large force overcomes its yield strength, and the material begins to slowly bend, stretch, or flow.

The cooler, outer part of the zone of crystallization contains a high percentage of crystals, behaves as a brittle solid, and forms a crust over the plastic region. It fractures during cooling when tensional stress from contraction exceeds tensile strength. Blocks and columns of this brittle crust, which result from the fracturing, interlock to some degree and may support modest tensional forces.

DISTRIBUTION AND INFLATION

Fields of inflated lava are highly complex, hydrodynamic systems consisting of large numbers of flow units, most of which have inflated. An inflated flow unit is a region that has swollen or inflated to many times its original thickness. It possesses a relatively independent static or dynamic pressure regime and often develops from the breakouts or leaks of other flow units. Systems of inflated flow units spread out alongside, over the top of, and downslope from older systems.

Where lava pours from a breakout along a lava tube or an inflated feature, it floods an area by flowing and spreading rapidly. As it fans out, the velocity of the flow front decreases, and advance by flooding changes to advance by budding. Budding describes a process where small tongues or toes of red, rounded lava 10–20 cm or so (4–8 in.) in diameter break out, or "bud," from a crusted flow front (Figure 7). A toe emerges with a plastic skin that stretches as the toe elongates. A crust quickly develops and thickens, forming a rigid shell, and the toe ceases to advance. But increasing hydraulic pressure within causes a weak spot to distend and rupture, and another toe develops. The rate of advance by budding is quite slow, often on the order of 3–30 m (10–100 ft) per hour.

Flow units advance and inflate in at least two general styles: continuous and discontinuous. A continuous series of processes characterizes the continuous style of advance (Jackson and others, 1987). In the continuous style, the flow advances by budding (Figure 8). Toes and small lobes of lava branch and advance in all directions, while initially creating numerous, temporary kipukas (islands surrounded by other lava). The toes and small lobes run into and alongside each other, fuse, and coalesce. Lava passes through this

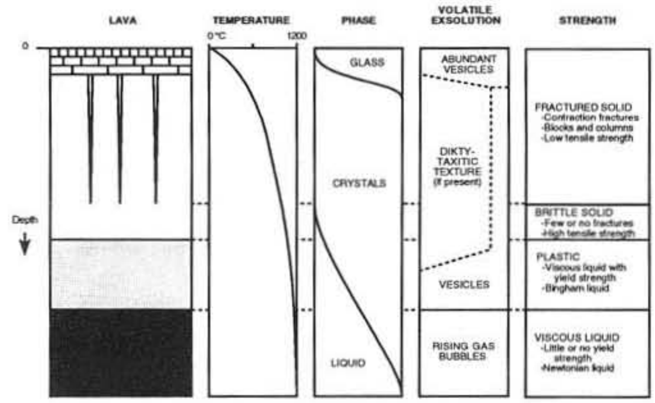

Figure 6. Physical properties of inflating basaltic lava. The zone of crystallization (where liquid changes to crystals) descends and thickens as heat is lost from the surface. Properties at different places and times within this zone will be strikingly different.

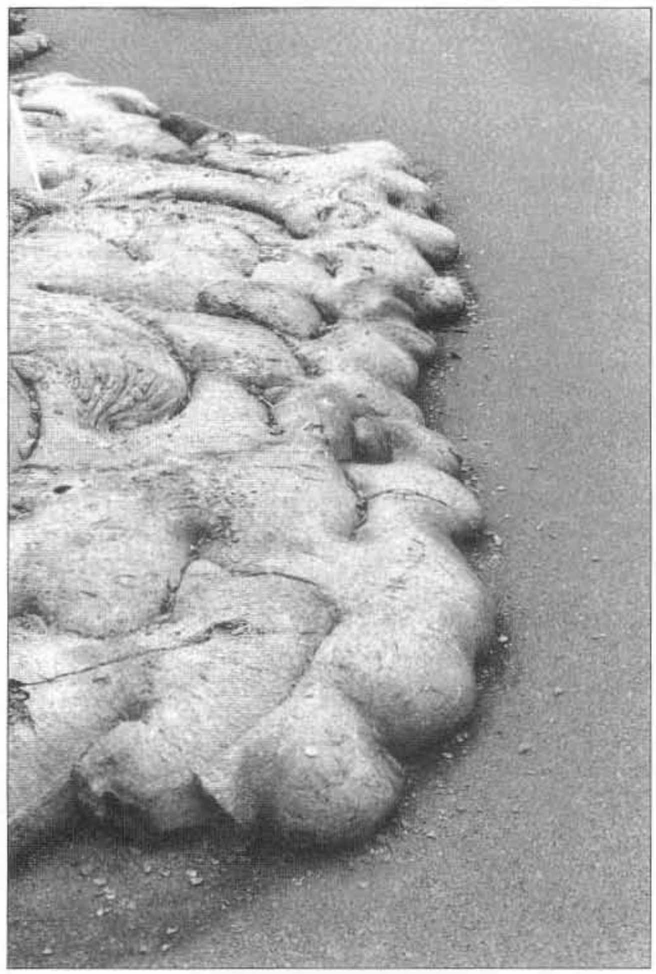

Figure 7. This 1990 lava flow in Hawaii advanced by budding as it flowed across Road 130, 1.5 km (1 mi) west of Kalapana townsite. Out of view to the left, the lava inflated to 30 times the thickness of these buds. Note penny on closest bud for scale.

interconnected maze, until the rigid septa (thin walls) between lobes become plastic by reheating. Hydraulic pressure then lifts a thickening crust upward. The septa pull apart as the flow inflates, and the interior of the lava flow becomes a more or less continuous molten

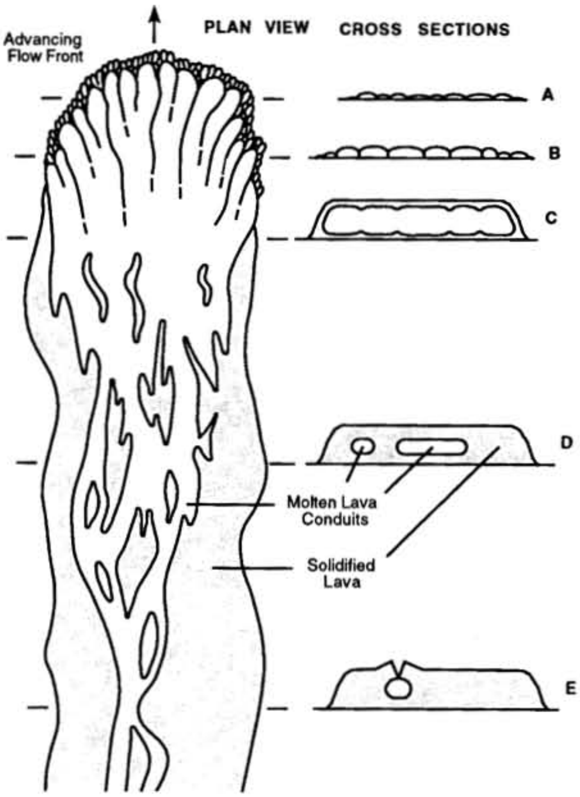

Figure 8. Continuous advance of an inflating flow unit. A. Flow front advances slowly by budding of pahoehoe toes. B. Septa between toes and lobes partially remelt; toes and lobes coalesce. C. Septa pull apart, and flow inflates. D. Slow-moving and stagnant regions solidify, while molten regions become confined to braided conduits. E. Molten lava confined to one or two conduits (lava tubes), which reinflate to create chain of tumuli and pressure ridges.

region. Later, this inflated region develops braided lava tubes. Eventually, as additional regions stagnate and freeze, only one or two lava tubes may remain active, which can reinflate to create a chain of tumuli and pressure ridges. A large area can be covered in such an inflated lava sheet, but in the field, unless the sheet is drilled, little evidence may exist to suggest that inflation has occurred.

In the discontinuous style of advance, an active flow unit spreads over a widening sector of land, advance eventually stops, the flow unit inflates and then develops one or more breakouts. Lava from the breakouts becomes the source for subsequent flow units. Breakouts seem to be sustained only when lava actively flows into an inflated flow unit and provides sufficient hydraulic pressure to maintain open cracks at breakout points. Inflated flow units can deflate catastrophically when a large breakout drains the unit before it gains structural integrity. Such drastic failures appear uncommon.

Routinely, the advancing lava develops inflated flow units that do not leak. Lava does not pass through them to feed downstream flow units but forms lava ponds perched on the land surface.

In Hawaii, large lava tubes that feed systems of inflated lava have been observed to fill and drain repeatedly. Measured elevations across the surface above these tubes show a corresponding and significant rise and fall (Kauahikaua and others, 1990). If a main tube remains drained for several tens of hours, the smaller branching tubes downstream become clogged with frozen lava. Refilling of the main tube may result in large breakouts from which new inflated systems develop.

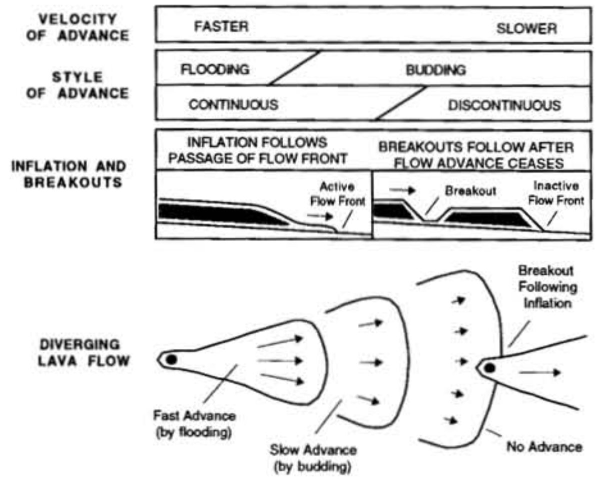

Figure 9. Styles of advance. Flow fronts advance continuously or discontinuously depending on velocity of advance.

The style of advance of a developing flow unit can change between continuous and discontinuous as topographic features influence the path and velocity of advance (Figure 9). Spreading of an active flow unit may be divergent, parallel, or convergent. If divergent, the velocity of the flow front decreases as it advances into a widening sector of land. The flow will tend to advance discontinuously. If parallel, the sides of the advancing flow unit remain roughly parallel, and the velocity and style of advance will tend to remain constant. If convergent, the velocity increases as the flow thickens and advances into a narrowing sector of land. The style of advance will tend to change from discontinuous to continuous. In fields of inflated lava, determining what style of advance occurred, what is or is not part of a flow unit, and how an inflated feature is connected to another is usually difficult and often impossible. However, places exist where these connections and the results of processes are well displayed.

Flow units that display a great range of widths can be traced routinely. Along its course, a single flow unit may consist of a web of one or more tumuli, pressure ridges, pressure plateaus, and narrow connecting channels. Notably, the narrower places are less inflated. Resistance to inflation in narrow regions is related in part to the radius of curvature of the conduit (lava tube). If the conduit is thought of as a pipe, then the tensile force that develops in the pipe wall is proportional to the radius of the pipe for a given hydraulic pressure. The yield strength of the plastic region in the conduit wall is often sufficiently high to reduce or prevent stretching.

Fields of inflated lava in central and southeast Oregon show a general organizing characteristic in which a wide, central, inflated flow unit that advanced in a continuous style is connected to and flanked on one or both sides by numerous inflated flow units that advanced discontinuously.

VESICLES AND FRACTURES

In vertical cross sections of inflated flow units, patterns of vesicles and fractures offer insight into processes once active (Figure 10). Inflated flow units display three vesicle zones (Aubele and others, 1988). In the upper vesicular zone, the abundance of vesicles decreases, and vesicle size increases, with depth. At the top of this zone, vesicles can account for more than half the volume of the rock. Within the middle nonvesicular zone, vesicles are rare (except for vesicle cylinders, vesicle sheets, and the microvesicles of diktytaxitic texture). In the lower vesicular zone, the trends of size and abundance are reversed compared to the upper zone. This zone is thinner than the upper zone, seldom exceeding 0.5 m (1.5 ft).

Table 1. *General descriptions of basaltic lava fields discussed in this article*

	(Units)	Badlands	Devils Garden	Diamond Craters	Jordan Craters	Potholes
Slope	(°)	0.8	0.6	0.5	0.9	0.5
Area	(km^2)	75	86	67	65	65
	(mi^2)	(29)	(33)	(26)	(25)	(25)
Volume	(km^3)	1.4	1.2	1.0	1.0	0.96
	(mi^3)	(0.34)	(0.31)	(0.24)	(0.24)	(0.23)
Thickness[1]	(m)	19	15	15	15	15
	(ft)	(62)	(50)	(50)	(50)	(50)
Age	(yr)	300,000[2]	20,000[2]	17,000[3]	3,200[4]	50,000[2]

[1] Estimated.

[2] Estimated age, this report. Hawkins and others (1989) report a K-Ar age of 700,000. However, the Bend pumice, approximately 370,000 yr old (Hill and Taylor, 1990), underlies Badlands lavas.

[3] Hydration rind age date (Friedman and Peterson, 1971, p. 1028).

[4] Radiocarbon age (Mehringer, 1987, p. 60).

Table 2. *Major element chemistry for basalts discussed in this article, in percent (FeO^* = total Fe expressed as FeO)*

	Badlands[1]	Devils Garden[1]	Diamond Craters[1]	Jordan Craters[2]	Potholes[1]
SiO_2	50.36	48.88	47.74	47.45	49.28
Al_2O_3	17.29	16.51	17.62	16.15	17.17
FeO^*	8.65	9.47	9.82	10.45	9.27
MgO	8.45	9.49	8.61	9.09	8.72
MnO	0.15	0.17	0.17	0.17	0.17
CaO	9.6	9.77	11.53	9.77	10.17
Na_2O	3.41	3.31	2.86	3.07	3.09
K_2O	0.54	0.56	0.3	0.69	0.53
TiO_2	1.28	1.48	1.17	2.38	1.28
P_2O_5	0.25	0.36	0.17	0.27	0.32
Total	99.98	100.00	99.99	99.49	100.00

[1]This article, Run 1391, 28 Sep 91, Wash. State University. Elements normalized on a volatile-free basis.

[2] Hart and Mertzman, 1983, p. 16.

The upper vesicular zone develops as bubbles nucleate and rise in the flowing, molten lava. The bubbles accumulate under the thickening crust and become trapped at progressively greater depths (Figure 10a). The thickness of this zone is primarily controlled by the length of time that gas-saturated lava flows through the unit (Cashman and others, 1993). When the flow rate decreases, the rate of bubble production decreases. Changing flow rates and pressures modulate the rate and size of bubble production. These fluctuations in flow rate and pressure are recorded as layers poorly or richly endowed with vesicles. A flood of bubbles can accumulate and coalesce under the descending solidification front to form gas pockets and cavernous layers. An alternating sequence of bubble-poor and bubble-rich regions can impart a striking layered appearance to the upper vesicular zone (Figure 11). Similar-looking but unrelated cavernous layers may develop when the level of lava in a lava tube or inflated unit temporarily drops and a new, thin crust develops in the open space (K. Cashman, personal communication, 1993).

In the lower vesicular zone, most bubbles that nucleate here rise before becoming trapped in the upward-moving solidification front. Consequently, this zone is much thinner than the upper zone.

Diktytaxitic texture, vesicle cylinders, and vesicle sheets are the primary features of the middle nonvesicular zone. ("Nonvesicular" is apt only in the sense that few or no vesicles are visible when a rock outcrop is viewed from a distance of 1–2 m (3–6 ft).) Diktytaxitic texture often extends beyond the middle zone to within 30 cm (1 ft) or so of the top and bottom of the flow unit. This diktytaxitic texture pervades most inflated basaltic lava of late Tertiary and Quaternary age in central and southeast Oregon. Fuller (1931) first described and named diktytaxitic texture when he encountered it in the Steens Basalt in southeast Oregon. The texture is characterized by numerous jagged, irregular microvesicles bounded by crystals (mostly plagioclase), some of which protrude into the cavities.

The first episode of gas exsolution from the lava created the bubbles of the upper and lower vesicular zones. A second episode created diktytaxitic texture (Figure 10b). The microvesicles develop as dissolved gases concentrate in the liquid part of a cooling inflated flow unit. At a critical concentration, the pressure of exsolving volatiles exceeds the mechanical strength of a growing crystal network (Chitwood, 1993b). The gas pressure creates microvesicles by distorting, rearranging, and opening up the crystal network. The microvesicles interconnect to a large degree, and at the moment of interconnection, gases gain sudden access to the atmosphere through a vast network of previously formed and interconnected microvesicles. Interconnection aborts growth of the microvesicles. At the Badlands and Potholes lava fields, diktytaxitic texture accounts for approximately 10 percent of the volume within inflated flow units.

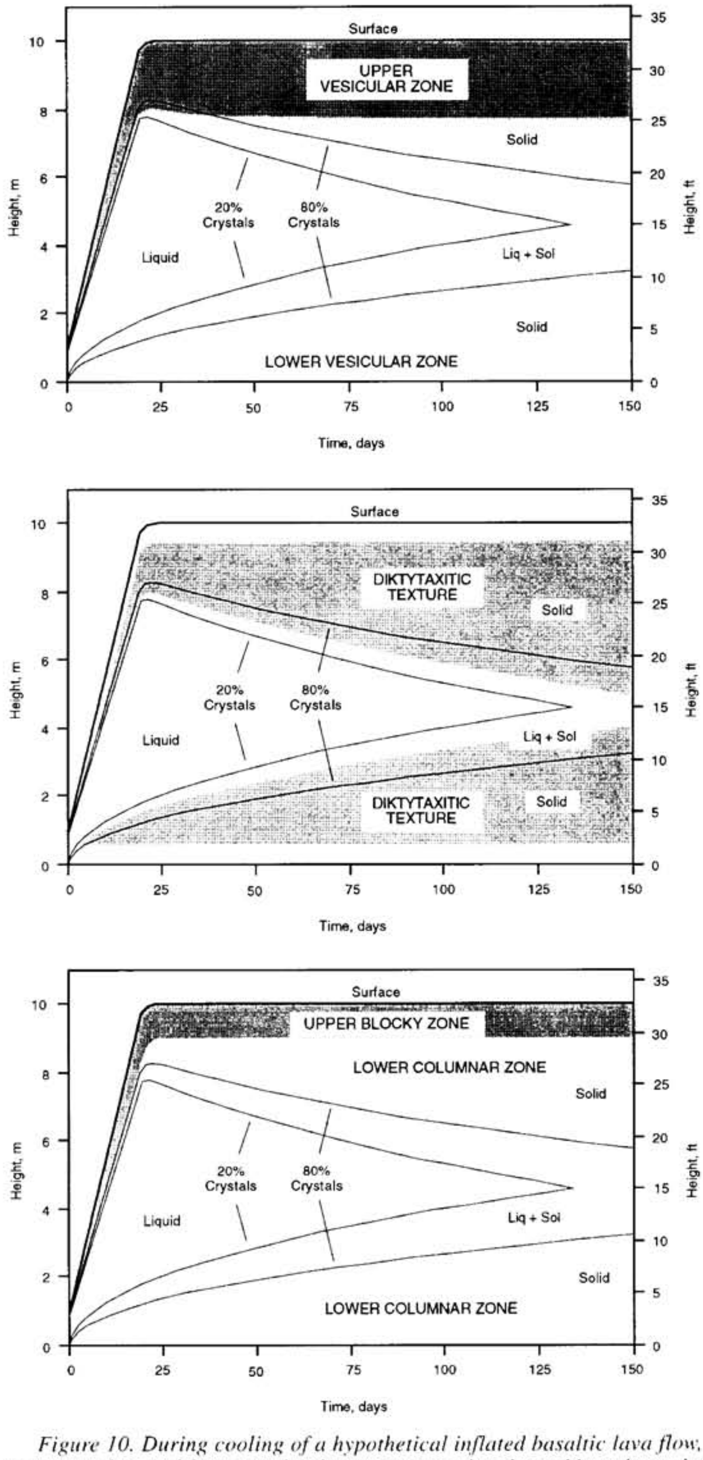

Figure 10. During cooling of a hypothetical inflated basaltic lava flow, gases exsolve, and fractures develop in patterns that depend largely on the mechanical properties at different places and times. 10a. Upper and lower vesicle zones grow only where gas-saturated lava contains less than approximately 50 percent crystals. 10b. Microvesicles of diktytaxitic texture nucleate and grow only where gas-saturated lava contains more than approximately 50 percent crystals. 10c. Cooling fractures develop following solidification. Initial rapid cooling produces closely spaced fractures; slower cooling produces more widely spaced fractures.

Diktytaxitic texture appears to predispose basaltic lava to cavernous and honeycomb weathering in central and southeast Oregon, especially where microvesicles are abundant (usually liftup caves and inflation clefts) (Figure 12). A crude relationship is apparent between age of lava and degree of cavernous weathering. For example, at the Jordan Craters lava field, weathering has removed up to 13 mm (0.5 in.) of lava in local areas, while at the Badlands lava field up to 1.2 m (4 ft) have been removed. Badlands lava is about 100 times older.

Fracture patterns develop in inflated lava from tensional stresses due to contraction during cooling (Aydin and DeGraff, 1988). Two fracture zones are notable (Figure 10c). The upper blocky zone consists of closely spaced fractures and short, stubby blocks and columns. These result from steep thermal gradients near the top of flow units that create strong, local stresses during and following solidification. These stresses may interact with vesicle-layered lava and produce striking platy and blocky layers.

In the lower columnar zone, distance between fractures increases where thermal gradients are less and stresses more widely distributed. Here, large, wide, crude columns develop that are often 1.5 m (5 ft) or so in diameter. The notably low strength of diktytaxitic lava may prevent the development of the well-organized, slender, prismatic columns characteristic of many flows of the Columbia River Basalt Group.

LANDFORMS AND STRUCTURES

Inflating lava develops distinctive morphologic features as well as an endless variety of hummocky and chaotic features not easily described (Figures 13 and 14).

The following are descriptions of distinctive and common landforms and structures found in fields of inflated lava. Many have been described previously (e.g., Wentworth and Macdonald, 1953), but their origin was poorly known. Several landforms described here have not been previously named. They include rotated crust, plateau pit, liftup cave, extrusion wall, and deflation lava cave.

Rotated crust is a coherent slab or block of lava crust that has been tilted or rotated. Crust tilts or rotates wherever inflation is greater in one area than in an adjacent area. Since the axis of rotation is not always horizontal or fixed, the term "rotated" describes the movement of the crust more accurately than "tilted."

An **inflation cleft** is an elongated crack or cleft on the surface of inflated lava and develops during bending and tilting of lava crust (Walker, 1991). The opposing walls of a cleft match up except low in the cleft, where widening and deepening takes place in the plastic region. At the bottom of the cleft, molten lava sometimes leaks or breaks out. Also, **squeeze-ups** of semi-rigid lava can be forced out in impressive wedges (Figure 15).

A **tumulus** is a circular or oval mound of inflated lava with rotated sides and usually a medial inflation cleft (Figure 16). Many tumuli have two or more inflation clefts. At others where no cleft forms, extension or spreading apart of the brittle surface during inflation is distributed among numerous small contraction fractures. A tumulus develops over part of an active, filled lava tube under enough pressure to force its roof upward. A highly elongated tumulus grades into a pressure ridge. Most tumuli are 1.5–6 m (5–20 ft) high, but Badlands Rock in the Badlands lava field is 30 m (100 ft) high.

A **pressure ridge** is a relatively narrow but long ridge of inflated lava with sides that have been uplifted and rotated outward. It forms above an active, overpressured lava tube. Usually, one or more inflation clefts develop lengthwise

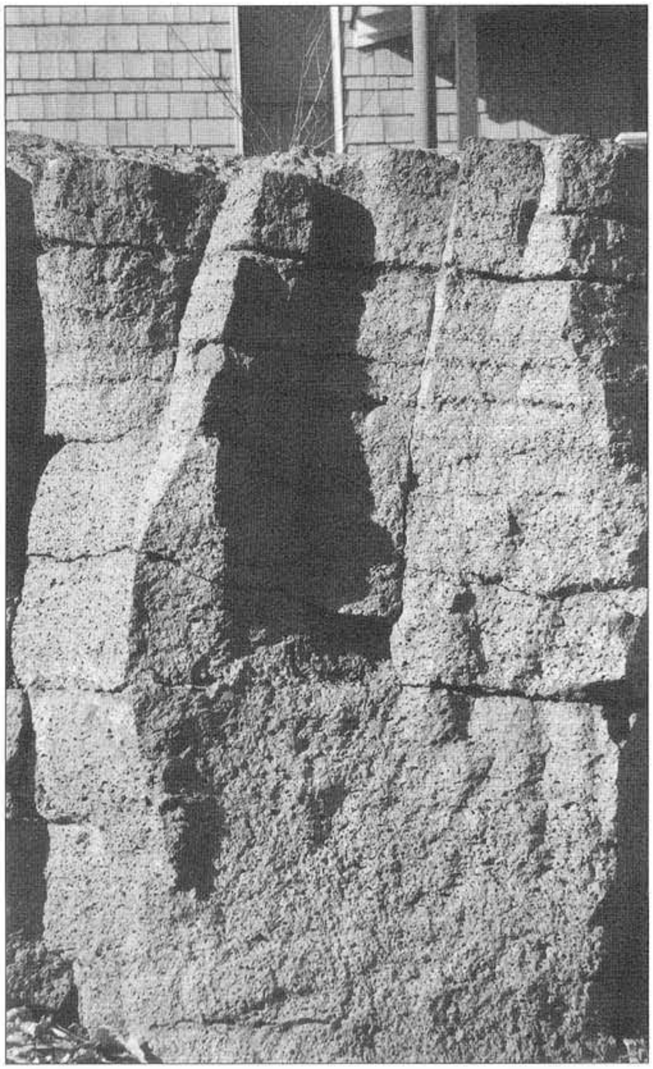

Figure 11. Changing pressure and alternating batches of gas-saturated and unsaturated lava created these vesicle-rich and vesicle-poor layers near downtown Bend, Oregon. Height of outcrop is 1.5 m (5 ft).

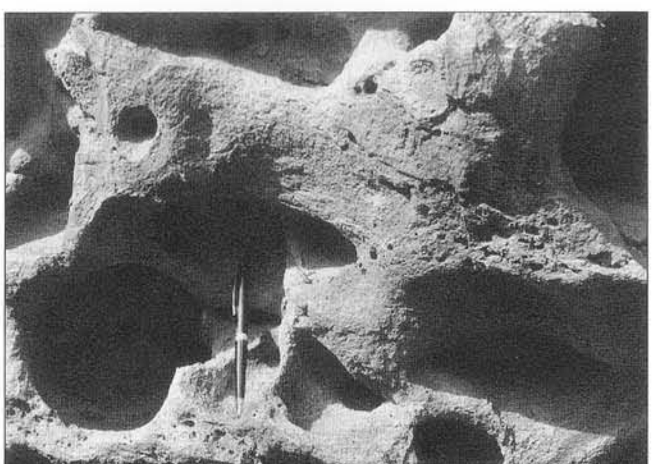

Figure 12. The presence of diktytaxitic texture may predispose inflated basaltic lava to cavernous and honeycomb weathering (The Castle, Badlands lava field).

Figure 13. This pahoehoe lava flow from Kilauea Volcano, Hawaii, inflated after burying part of Highway 130 (southwest of Kalapana townsite) in 1990. Initial flow lobes that crossed the road were thin, similar to the one at far left foreground. The morphology of inflated lava often appears hummocky and chaotic as seen here.

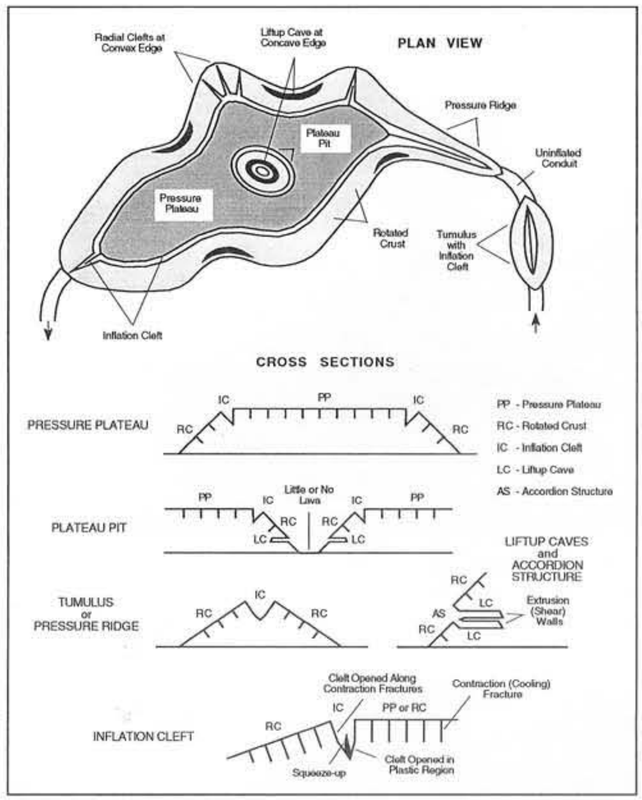

Figure 14. Generalized drawing and cross sections depicting common landforms and structures of inflated basaltic lava.

along its crest. (The term "pressure ridge" is also used to describe an elongate uplift of lava caused by a compressive crumpling of crust.)

A **pressure plateau** is a broad, extensive area of inflated lava that has a horizontal or subhorizontal, elevated surface and sides of rotated crust (Figures 17 and 18). Inflation clefts usually develop around the perimeter of, and sometimes in, the elevated surface and in the rotated crust. The flat, elevated surface represents hydrostatic equilibrium when the pressure plateau possessed a molten interior. A pressure plateau can extend laterally from several meters to more than 1.5 km (1 mi), and its thickness can range from 1 m to more than 21 m (3–70 ft).

A **residual depression** is any closed basin within a field of inflated lava that has sides of contemporaneous lava (Holcomb, 1987). These depressions are common and vary widely in size.

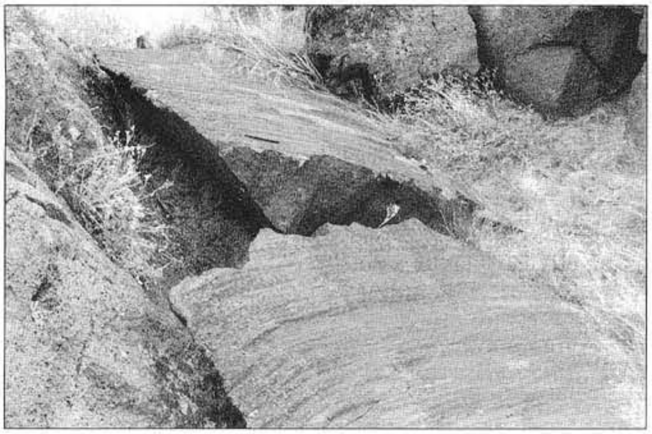

Figure 15. Example of squeeze-ups. These grooved wedges of pasty lava were extruded out of the bottom of an inflation cleft. Other squeeze-ups may be bulbous, linear, and smooth. Pen is 14 cm (5.4 in.) long (Devils Garden lava field).

Figure 16. This tumulus, like other tumuli, developed in the roof of a lava tube from the pressure of the molten lava within the tube. Note inflation cleft and rotated sides (Badlands lava field).

Figure 17. The surface of this pressure plateau stands nearly 18 m (60 ft) above the surrounding landscape. It was raised up by hydraulic pressure of molten lava that once underlay the entire feature. Note the wide inflation cleft that completely surrounds the elevated block (The Castle, Badlands lava field).

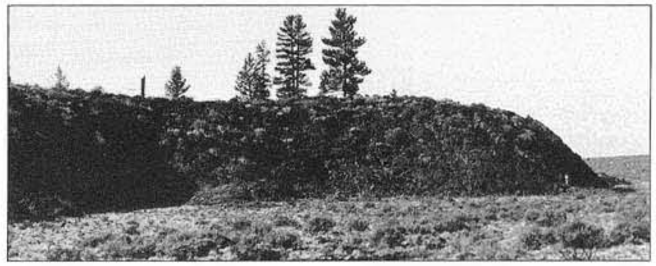

Figure 18. Side of a pressure plateau. This lava inflated to a thickness of 18 m (60 ft) from an initial thickness of perhaps 30 cm (1 ft). The side is a series of slabs of rotated crust. Note person at far right for scale (Potholes lava field).

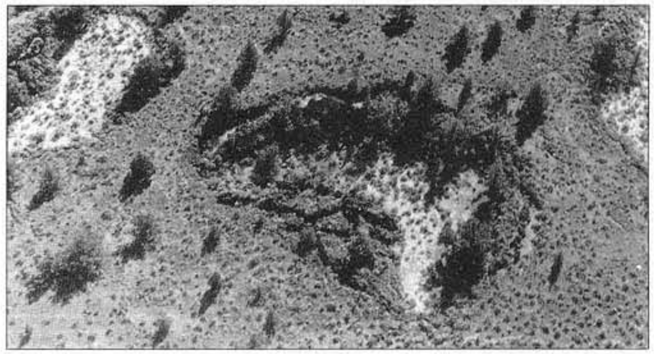

Figure 19. Example of a plateau pit. These pits develop within pressure plateaus at sites that do not inflate. Plateau pits were originally called collapse depressions, which in most cases incorrectly suggest their origin (Badlands lava field).

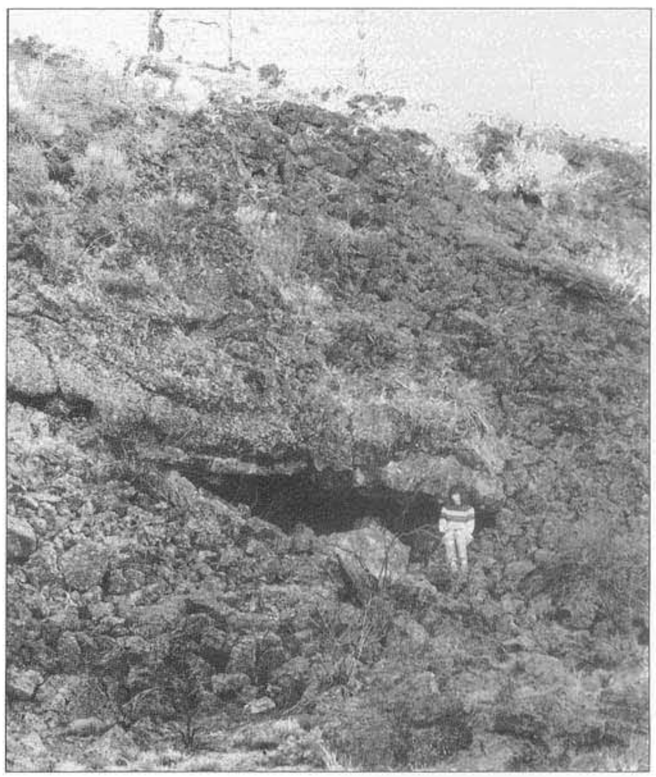

Figure 20. Example of a liftup cave. Caverns form along concave edges of flow units where blocks and columns of crust are compressed and uplifted during inflation. This liftup cave extends 7.6 m (25 ft) horizontally back from the entrance (Potholes lava field).

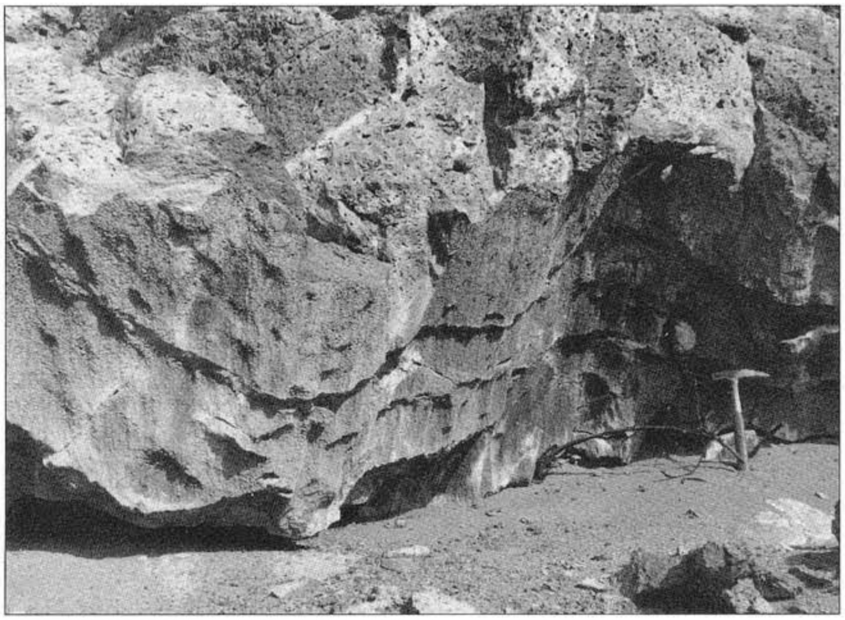

Figure 21. Example of an extrusion wall. The back wall of a liftup cave slowly extrudes at a steep angle out of the plastic region. It often displays grooves and has the appearance of draperies. Some extrusion walls are not associated with liftup caves. Note rock hammer for scale (Badlands lava field).

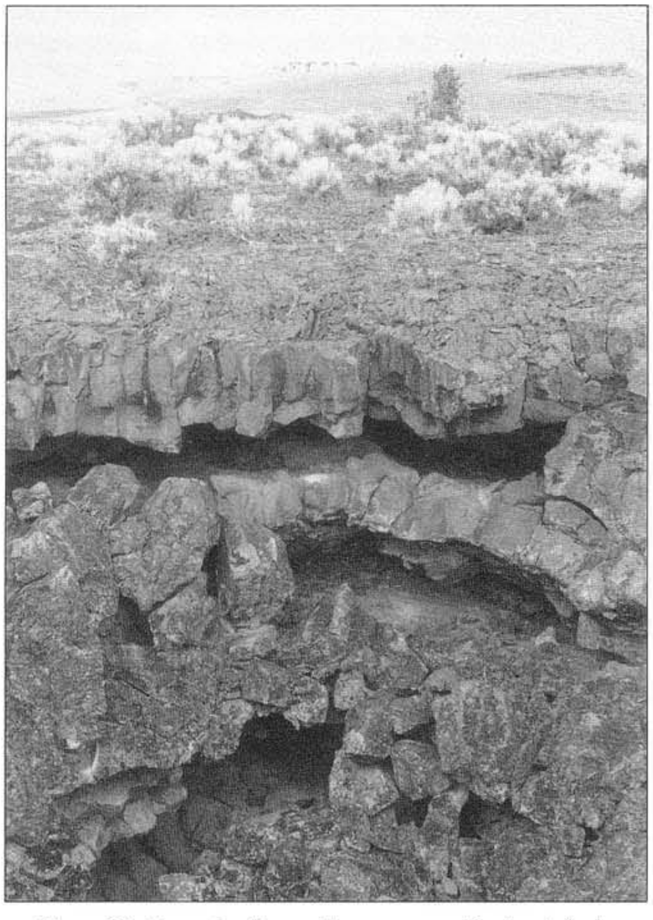

Figure 22. Example of accordion structure. During inflation, a series of liftup caves form one under the other in the continuously concave and circular walls of this plateau pit (Manatee Pit, Diamond Craters).

What begins as a minor, shallow low area often becomes an exaggerated and deep depression as the surrounding lava inflates. Residual depressions usually form where inflated flow units intermingle. A subsequent flow unit that fills and inflates within a residual depression can turn the depression into an elevated, positive landform—a kind of inverted topography.

A **plateau pit** is a residual depression completely within a pressure plateau (Figure 19). It may be circular or irregularly shaped with steeply sloping sides. A plateau pit is a region within a pressure plateau that did not inflate. The pit floor did not inflate due to a minor, preexisting topographic high area that either was not covered with lava or not covered to a sufficient depth to inflate with the rest of the lava of the pressure plateau.

Most features called collapse depressions by many earlier geologists are now considered to be plateau pits. A collapse depression was believed to be a collapsed part of the roof of a lava tube. Ironically, Hatheway (1971), who did a major study of collapse depressions, noted that "accessible tubes are extremely rare in terrain of collapse depressions."

A **lava tube** is a tube-shaped conduit within a solidified lava flow that is actively transporting lava, is plugged with solidified lava, or is open because lava drained away. Lava tubes form in two major ways (Wentworth and Macdonald, 1953). On steeper slopes (> 2°), lava flowing in an open channel develops a crust that becomes the roof of a lava tube. On gentle slopes (< 2°), conduits develop unseen in the complex distributary systems of inflated lava (Gillett and others, 1991) (Figure 8). Lava tubes that form in fields of inflated lava tend to develop from multiple, interconnected, and adjacent conduits.

Other important features of inflated lava are related to the shape of the edge of a flow unit. The slopes above the edge often react differently to inflation, depending on whether they occur along concave, straight, or convex edges.

During inflation at a concave edge (looking toward lava flow), the slabs, blocks, and columns of crust that make up the uplifting and tilting sides of pressure plateaus and ridges compress to form a more or less rigid, curved block that rises as a unit. A cavern, called a **liftup cave**, may open up under the rising block (Figure 20). The back wall of the cave, an **extrusion wall**, extrudes at a steep angle out of the pasty crystal mush of the plastic region (Figure 21). Sometimes, extrusion is cyclic as inflation proceeds by discrete uplifts, as evidenced by chattermarks or small ledges that mark each period of quiescence between uplifts. In a circular plateau pit where the edge of the lava is continuously concave, liftup caves may completely encircle the pit floor. Usually two or more liftup caves develop sequentially, the newer forming under the older. A group of such caves compose an accordion structure (Holcomb, 1981), a feature roughly analogous to horizontally oriented pleats in the bellows of an accordion (Figure 22 and 23).

Along straight edges, one or more inflation clefts may develop approximately parallel to the edge of the flow at the top of the rotated sides of pressure plateaus and ridges.

Above convex edges, groups of slabs, blocks, and columns of crust may spread apart during inflation. Pie-shaped wedges of rotated crust alternate with inflation clefts.

A **deflation lava cave** forms when molten lava partly or completely drains from an inflated feature such as a pressure plateau. The rigid exterior of the feature remains essentially intact. A deflation lava cave is distinguished from a lava tube by a lack of cave lining and smooth, frozen flow features. However, drainage from inflated features is uncommon.

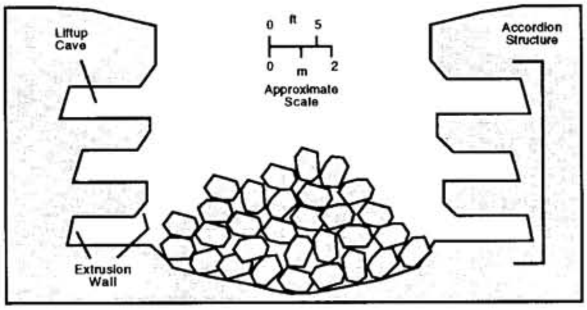

Figure 23. Generalized cross section of plateau pit in Figure 22. The position of extrusion walls shifts discontinuously and alternately from front to back of developing liftup caves. Cooling and thickening of the floor of each cave cause it to attach to the extrusion wall at the back of the cave and be lifted up.

SUMMARY

Highly fluid lava flows of basalt in central and southeast Oregon developed distinctive landforms and internal structures and textures when they erupted onto landscapes of low topographic gradient (< 2°). These lavas swelled or inflated to several times their initial thickness. Excellent examples of inflated lava can be found in the well-preserved Quaternary lava fields of Badlands, Devils Garden, Diamond Craters, Jordan Craters, and Potholes.

Lavas in these fields spread and divided in complex, tube-fed, distributary systems. The advancing fronts of active flow units slowed as lava spread into widening sectors of land. The lava eventually ceased to advance when it developed sufficient strength due to cooling to resist continued movement. The ability of this lava to inflate depended on the development of a strong, plastic region within the lava.

An inflated flow unit develops in the wake of a slowly advancing flow front, which consists of a maze of pahoehoe toes and small lobes that progressively coalesce, interconnect, develop into a continuously molten region, and then inflate.

Within inflated flow units, three vesicle zones develop from gas-saturated lava: the upper vesicular zone, middle nonvesicular zone, and lower vesicular zone. The thickness of the upper vesicular zone is related to the length of time that lava flowed through the unit. In the middle nonvesicular zone, diktytaxitic texture, vesicle cylinders, and vesicle sheets are common. Likewise, three fracture zones develop in response to cooling rates: the upper block zone, middle column zone, and lower block zone (often absent).

Inflation of lava produced distinctive landforms and structures including tilted and rotated crust, inflation clefts, tumuli, pressure ridges, pressure plateaus, plateau pits, residual depressions, liftup caves, accordion structures, extrusion walls, squeeze-ups, lava tubes, and deflation lava caves. Tumuli, pressure ridges, and pressure plateaus stand typically 1.5–18 m (5–60 ft) above their immediate surroundings. Badlands Rock, a 30-m (100-ft)-high tumulus in the Badlands lava field, is the tallest known inflated feature in central and southeast Oregon.

ACKNOWLEDGMENTS

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(Continued on next page)

BOOK REVIEW

Beautiful scenery is geology at its best!

A review of *Newberry National Volcanic Monument: an Oregon Documentary*, by Stuart G. Garrett, 1991, Webb Research Group, Medford, Oregon, 125 p.

by Lanny H. Fisk, F & F GeoResource Associates, Inc., 66928 West Highway 20, Bend, Oregon 97701

Oregon's newest National Monument now has a helpful guidebook for visitors. The author is Bend family physician Dr. Stuart Garrett, who chaired the committee that proposed National Monument status for Newberry Volcano and successfully hammered out the compromises necessary to get agreement and wide support for its designation. Dr. Garrett's book is meant to serve as a general introduction to the history and natural features of Newberry Volcano, located in central Oregon southeast of Bend. The guidebook contains chapters on "The Making of the Monument," "Cultural and Exploration History," "Geologic History," "Geothermal Resources," "Plant and Wildlife," and "Recreation Opportunities in the Monument and Outlying Areas." The book also contains a brief biography of John Strong Newberry, for whom the volcano was named, and, finally, a helpful bibliography and an index.

Although designed as a sightseer's guide, the book exceeds this usage. The author's hope that the book "will whet the appetite of visitors and will encourage them to delve deeper into the fascinating story of Newberry Volcano" will certainly be realized. As he points out, Newberry Volcano is truly "a mountain of superlatives . . . a geologic wonderland of lava flows, ash flows, pumice cones, and tuff cones,"—and a clear illustration that beautiful scenery is geology at its best!

The chapter on discovery and early exploration quotes extensively from the journals of explorers Peter Skene Ogden and John C. Fremont, which adds much liveliness to the generally interesting presentation. In 1826 Ogden wrote: "This is really a wretched country and certainly no other inducement but filthy lucre can induce an honest man to visit it . . ." Very few people would agree with his assessment today!

The chapter on geologic history, though brief, is excellent, thanks in part to the help of U.S. Forest Service geologists Larry Chitwood and Bob Jensen. For a more complete coverage, geologists will also want to pick up copies of Jensen's *Roadside Guide to the Geology of Newberry Volcano* (1988, CenOreGeoPub, 75 p.) and the *Geologic Map of Newberry Volcano* by Norm MacLeod, Dave Sherrod, and Larry Chitwood (U.S. Geological Survey Open-File Report 82-847, 1982). Dr. Garret gives fair treatment to the geology of such features as Lava Butte, Lava River Caves, Lava Cast Forest, Paulina Falls, Paulina and East Lakes, Central Pumice Cone, Big Obsidian Flow, and Paulina Peak found within Newberry Monument. He also provides geological snapshots of such nearby features as Fort Rock (a tuff ring), Hole-in-the-Ground and Big Hole (both volcanic explosion craters or maars), and Dry River Canyon (a relict Pleistocene erosional feature).

An annoying flaw of the book is the generally poor quality of the publisher's editing, including poor word divisions (such as Nor-thwest, dep-th, and hun-ting) and inconsistent spelling and capitalization (such as archeologist/archaeologist, native/Native Americans, and central/Central Oregon). Typographical errors are too numerous to mention. Awkward sentence structure is not uncommon, such as: "One of these young cinder cones and flows is Lava Butte which is near Lava Lands Interpretive Center, the top of which is easily reached by car"!

Inaccuracies are rare but exist, such as ". . . the escarpments of Hart Mountain and Steens Mountain can be observed" from Paulina Peak. Although it is true that from the top of Paulina Peak, on a clear day, observers can see both these large fault-block mountains when looking east; the *escarpments*, however, are east facing and thus *not* visible.

It is unfortunate that the maps of the Monument boundaries (p. 28) and caldera features (p. 34) are not introduced or referenced earlier in the text so that readers could use them for orientation. A map showing the locations of the outlying features described in the book would also be helpful.

However, these shortcomings do not seriously detract from the book's value to the user. It still fulfills its primary purpose well: to serve as a general guide to Newberry National Volcanic Monument. Overall, this book is a valuable compilation of information and an excellent guidebook to Newberry Volcano and the surrounding area. Anyone planning to visit central Oregon should pick up a copy of Dr. Garrett's book and read it before arrival. I bought my copy at the Nature of Oregon Information Center in Portland, but it may be available now at a bookstore near you. □

(Continued from last page)

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DOGAMI PUBLICATIONS

First digital geologic map published by DOGAMI

The Oregon Department of Geology and Mineral Industries (DOGAMI) has released *Geology and Mineral Resources of The Elbow Quadrangle, Malheur County, Oregon*, on the geology and mineral resources for an area around northern Lake Owyhee. It is DOGAMI map GMS-62, and its purchase price is $8.

Production of GMS-62 represents a milestone in DOGAMI's publication history. It is the first DOGAMI geologic map that was prepared largely through digital (computerized) techniques by the DOGAMI staff and technical partners at the University of Oregon. It is one of the first geologic maps produced anywhere in the country in which full-color digital techniques have achieved a product that meets high standards of map quality.

The publication consists of two plates. Plate 1 includes the map, two geologic cross sections, explanations of the 26 identified rock units, and a brief discussion of the mineral resources. Plate 2 contains four tables with analytical data from over 60 samples.

Map GMS-62 is the product of the cooperative work of geologists under the leadership of Mark L. Ferns of the DOGAMI Baker City office and Michael L. Cummings of the Portland State University Department of Geology. Production was funded jointly by DOGAMI, the Oregon State Lottery, and the COGEOMAP Program of the U.S. Geological Survey as part of a cooperative effort to map the west half of the 1° by 2° Boise sheet in eastern Oregon.

Portland quadrangle hazard maps released

DOGAMI has released map GMS-79 in its Geological Map Series: *Earthquake Hazard Maps of the Portland Quadrangle, Multnomah and Washington Counties, Oregon, and Clark County, Washington*.

After Metro (the Portland area regional government) in 1993 released the *Relative Earthquake Hazard Map* of the same quadrangle, the new, more technical, multi-map publication now presents maps of the hazard aspects that were studied and combined to produce the initial map. It will be most useful to technical consultants who are concerned with earthquake safety in the construction of public buildings, bridges, and utility systems, as well as with hazard-mitigation and emergency-response.

The new publication consists of three full-color maps (scale 1:24,000) and a 106-page text. The maps depict hazard levels for liquefaction (liquefaction susceptibility and lateral spread displacement), ground motion amplification, and dynamic slope instability, as they may be produced at a given location in the quadrangle when earthquakes of various types occur. The text contains a separate chapter for each map and for the earlier relative hazard map, discussing the methods and results of the compilations and models that led to the maps.

Text and maps were authored by Matthew A. Mabey and Ian P. Madin of DOGAMI and T. Leslie Youd and Celinda F. Jones of the Department of Civil Engineering at Brigham Young University. The cartography work was done by L.D. Freedman of Metro. The studies were funded, in part, by the U.S. Geological Survey. The purchase price of GMS-79 is $20.

The new maps are now available over the counter, by mail, FAX, or phone from the Nature of Oregon Information Center, Suite 177, State Office Building, 800 NE Oregon Street #5, Portland, Oregon 97232-2109, phone (503) 731-4444, FAX (503) 731-4066; and the DOGAMI field offices: 1831 First Street, Baker City, OR 97814, phone (503) 523-3133, FAX (503) 523-9088; and 5375 Monument Drive, Grants Pass, OR 97526, phone (503) 476-2496, FAX (503) 474-3158. Orders may be charged to Visa or MasterCard. Orders under $50 require prepayment except for credit-card orders.

Report on abandoned mines added to library open file

A listing of abandoned mines has been placed on library open file by DOGAMI and is available for public inspection in the DOGAMI library in Portland.

The library open file contains reports that have not been reproduced in the traditional manner of publication. Only single copies of such reports are available for inspection in the DOGAMI library, and photocopies may be obtained at cost.

Report O-93-12 is entitled *Abandoned Mines and Mills That May Be Classified as a Hazardous Waste Site Under Section 120 of the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA)* and was produced by Jerry J. Gray of DOGAMI. It contains a computer printout that lists detailed information and hazardous-matter classifications for over 1,100 abandoned sites in Oregon.

The basis of the report is DOGAMI's database MILOC (Mineral Information Layer for Oregon by County), currently available for purchase ($25) in its recently updated version as Open-File Report O-93-8. □

Letter to the editor

Thank you so much for sending me the November issue of *Oregon Geology* in response to my inquiry concerning the Klamath Falls earthquakes. I found the article very interesting and enjoyed the whole booklet. In fact, I subscribed to it the same day I received it.

There was, however, an error on the Figure 1 Location Map on page 127 [in the article on the Klamath Falls earthquakes—ed.]. It shows Tulelake, California, as being located on Highway 97. Tulelake is actually located along Highway 139. Dorris and Macdoel are located along Highway 97.

Also, I would like to tell you I responded to your earthquake survey form right after the earthquakes. I responded that my residence did not suffer any damage. That was premature. I later found one living-room window cracked in three places and numerous cracks in the plaster in the interior of the house. These range in size from hairline to clearly visible from across the room.

Susan Crawford
Malin, Oregon

Yes, we apologize for the slip on the location map. Dorris is indeed the place that was placed on the map but then mislabeled. Tulelake actually is located some 25 mi to the east but just about as far south of the state line as Dorris. Highway 139 was not represented on the sketch map, and that may have contributed to the confusion.

We want to thank you for the correction but also for all the other good things you included in your letter! All our readers, we feel, can profit from knowing what you did: Beginning with subscribing to Oregon Geology, *reading carefully, and letting us know about it; to sending in the earthquake survey questionnaire; to pointing out that earthquake damage sometimes may not be found immediately.*

For many an editor this must appear as the model of a good reader. We hope that others will follow your example. —*ed.*

REMEMBER TO RENEW

Remember that the code number on your address label ends in four digits that identify the expiration date (month and year) of your subscription. And remember that all you need to do is use the renewal form on the last page to make sure you will continue receiving *Oregon Geology*. And remember to renew, please. By the way—why not consider a gift subscription for a friend?

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