Field-Trip Guide to a Volcanic Transect of the Pacific Northwest

Scientific Investigations Report 2017–5022–M

U.S. Department of the Interior
U.S. Geological Survey

Cover: Sunlight streaming in through a skylight in Derrick Lava Cave, south-central Oregon. Photograph by Scott Cook.

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By Dennis Geist, John Wolff, and Karen Harpp

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U.S. Geological Survey
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Preface

The North American Cordillera is home to a greater diversity of volcanic provinces than any comparably sized region in the world. The interplay between changing plate-margin interactions, tectonic complexity, intra-crustal magma differentiation, and mantle melting have resulted in a wealth of volcanic landscapes. Field trips in this series visit many of these landscapes, including (1) active subduction-related arc volcanoes in the Cascade Range; (2) flood basalts of the Columbia Plateau; (3) bimodal volcanism of the Snake River Plain-Yellowstone volcanic system; (4) some of the world's largest known ignimbrites from southern Utah, central Colorado, and northern Nevada; (5) extension-related volcanism in the Rio Grande Rift and Basin and Range Province; and (6) the spectacular eastern Sierra Nevada featuring Long Valley Caldera and the iconic Bishop Tuff. Some of the field trips focus on volcanic eruptive and emplacement processes, calling attention to the fact that the western United States provides opportunities to examine a wide range of volcanological phenomena at many scales.

The 2017 Scientific Assembly of the International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI) in Portland, Oregon, marks the first time that the U.S. volcanological community has hosted this quadrennial meeting since 1989, when it was held in Santa Fe, New Mexico. The 1989 field-trip guides are still widely used by students and professionals alike. This new set of field guides is similarly a legacy collection that summarizes decades of advances in our understanding of magmatic and tectonic processes of volcanic western North America.

The field of volcanology has flourished since the 1989 IAVCEI meeting, and it has profited from detailed field investigations coupled with emerging new analytical methods. Mapping has been enhanced by plentiful major- and trace-element whole-rock and mineral data, technical advances in radiometric dating and collection of isotopic data, GPS (Global Positioning System) advances, and the availability of lidar (light detection and ranging) imagery. Spectacularly effective microbeam instruments, geodetic and geophysical data collection and processing, paleomagnetic determinations, and modeling capabilities have combined with mapping to provide new information and insights over the past 30 years. The collective works of the international community have made it possible to prepare wholly new guides to areas across the western United States. These comprehensive field guides are available, in large part, because of enormous contributions from many experienced geologists who have devoted entire careers to their field areas. Early career scientists are carrying forward and refining their foundational work with impressive results.

Our hope is that future generations of scientists as well as the general public will use these field guides as introductions to these fascinating areas and will be enticed toward further exploration and field-based research.

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Field-trip committee, IAVCEI 2017

Map of the western United States showing volcanoes and volcanic fields visited by geologic field trips scheduled in conjunction with the 2017 meeting of the International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI) in Portland, Oregon, and available as chapters in U.S. Geological Survey Scientific Investigations Report 2017–5022. Shaded-relief base from U.S. Geological Survey National Elevation Dataset 30-meter digital elevation model data.

Chapter letter	Title
A	Field-Trip Guide to Volcanism and Its Interaction with Snow and Ice at Mount Rainier, Washington
B	Field-Trip Guide to Subaqueous Volcaniclastic Facies in the Ancestral Cascades Arc in Southern Washington State—The Ohanapecosh Formation and Wildcat Creek Beds
C	Field-Trip Guide for Exploring Pyroclastic Density Current Deposits from the May 18, 1980, Eruption of Mount St. Helens, Washington
D	Field-Trip Guide to Mount St. Helens, Washington—An overview of the Eruptive History and Petrology, Tephra Deposits, 1980 Pyroclastic Density Current Deposits, and the Crater
E	Field-Trip Guide to Mount St. Helens, Washington—Recent and Ancient Volcaniclastic Processes and Deposits
F	Geologic Field-Trip Guide of Volcaniclastic Sediments from Snow- and Ice-Capped Volcanoes—Mount St. Helens, Washington, and Mount Hood, Oregon
G	Field-Trip Guide to Mount Hood, Oregon, Highlighting Eruptive History and Hazards
H	Field-Trip Guide to Mafic Volcanism of the Cascade Range in Central Oregon—A Volcanic, Tectonic, Hydrologic, and Geomorphic Journey
I	Field-Trip Guide to Holocene Silicic Lava Flows and Domes at Newberry Volcano, Oregon, South Sister Volcano, Oregon, and Medicine Lake Volcano, California
J	Overview for Geologic Field-Trip Guides to Mount Mazama, Crater Lake Caldera, and Newberry Volcano, Oregon
J1	Geologic Field-Trip Guide to Mount Mazama and Crater Lake Caldera, Oregon
J2	Field-Trip Guide to the Geologic Highlights of Newberry Volcano, Oregon
K	Overview for Geologic Field-Trip Guides to Volcanoes of the Cascades Arc in northern California
K1	Geologic Field-Trip Guide to Medicine Lake Volcano, northern California, including Lava Beds National Monument
K2	Geologic Field-Trip Guide to the Lassen Segment of the Cascades Arc, northern California
K3	Geologic Field-Trip Guide to Mount Shasta Volcano, northern California
L	Geologic Field-Trip Guide to Long Valley Caldera, California
M	Field-Trip Guide to a Volcanic Transect of the Pacific Northwest
N	Field-Trip Guide to the Vents, Dikes, Stratigraphy, and Structure of the Columbia River Basalt Group, Eastern Oregon and Southeastern Washington
O	Field-Trip Guide to Flood Basalts, Associated Rhyolites, and Diverse Post-Plume Volcanism in Eastern Oregon
P	Field-Trip Guide to the Volcanic and Hydrothermal Landscape of Yellowstone Plateau, Montana and Wyoming
Q	Field-Trip Guide to the Petrology of Quaternary Volcanism on the Yellowstone Plateau, Idaho and Wyoming
R	Field-Trip Guide to Continental Arc to Rift Volcanism of the Southern Rocky Mountains—Southern Rocky Mountain, Taos Plateau, and Jemez Volcanic Fields of Southern Colorado and Northern New Mexico

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Conversion Factors

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
kilometer (km)	0.5400	mile, nautical (nmi)
meter (m)	1.094	yard (yd)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Volume	
cubic kilometer (km^3)	0.2399	cubic mile (mi^3)
	Flow rate	
cubic meter per second (m^3/s)	70.07	acre-foot per day (acre-ft/d)
cubic meter per year (m^3/yr)	0.000811	acre-foot per year (acre-ft/yr)
meter per hour (m/h)	3.281	foot per hour (ft/h)
cubic meter per second (m^3/s)	35.31	cubic foot per second (ft^3/s)
cubic meter per second (m^3/s)	22.83	million gallons per day (Mgal/d)
meter per hour (m/h)	39.37	inch per hour (in/h)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as °F = (1.8 × °C) + 32.

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as °C = (°F – 32) / 1.8.

Field-Trip Guide to a Volcanic Transect of the Pacific Northwest

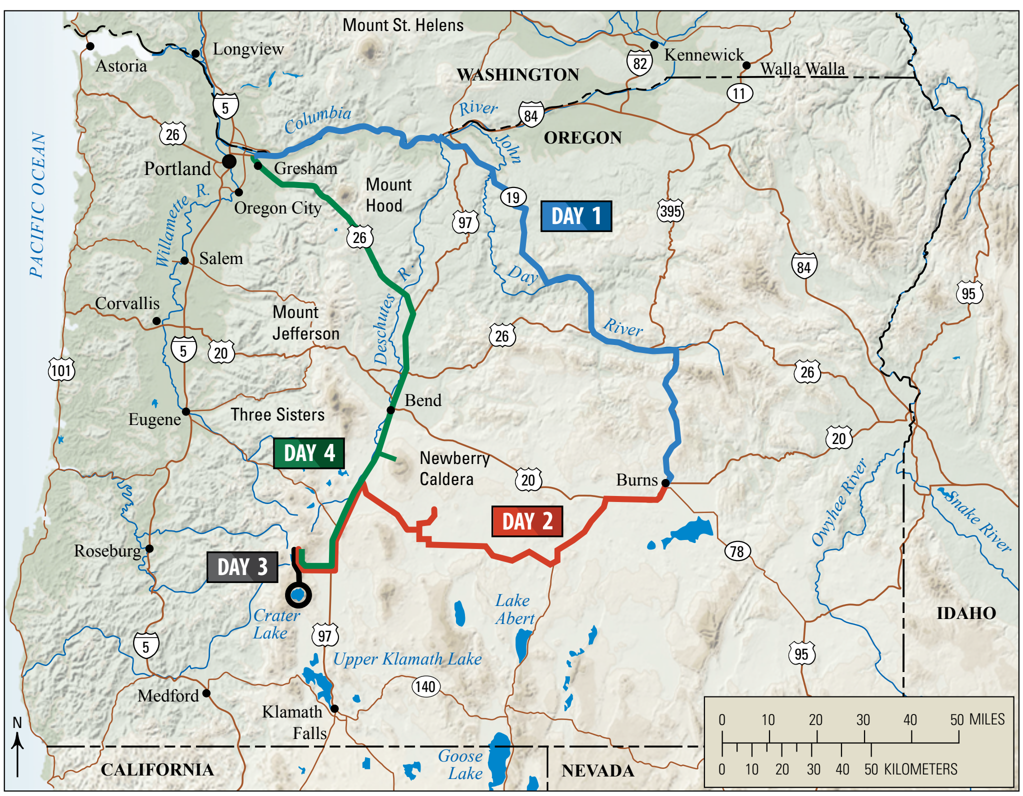
By Dennis Geist,[1] John Wolff,[2] and Karen Harpp[3]

Introduction

The Pacific Northwest region of the United States provides world-class and historically important examples of a wide variety of volcanic features. This guide is designed to give a broad overview of the region's diverse volcanism rather than focusing on the results of detailed studies; the reader should consult the reference list for more detailed information on each of the sites, and we have done our best to recognize previous field trip leaders who have written the pioneering guides. This trip derives from one offered as a component of the joint University of Idaho-Washington State University volcanology class taught from 1995 through 2014, and it borrows in theme from the classic field guide of Johnston and Donnelly-Nolan (1981).

For readers interested in using this field guide as an educational tool, we have included an appendix with supplemental references to resources that provide useful background information on relevant topics, as well as a few suggestions for field-based exercises that could be useful when bringing students to these locations in the future.

The 4-day trip (fig. 1) begins with an examination of lava flow structures of the Columbia River Basalt, enormous lava fields that were emplaced during one of the largest eruptive episodes in Earth's recent history. On the second day, the trip turns to the High Lava Plains, a bimodal volcanic province that transgressed from southeast to northwest from the Miocene through the Holocene, at the northern margin of the Basin and Range Province. This volcanic field provides excellent examples of welded ignimbrite, silicic lavas and domes, monogenetic basaltic lava fields, and hydrovolcanic features. The third day is devoted to a circumnavigation of Crater Lake, the result of one of the world's best-documented caldera-forming eruptions. The caldera walls also expose the anatomy of Mount Mazama, a stratovolcano of the Cascade Range. The last day is spent at Newberry Volcano, a back-arc shield volcano topped by a caldera. Newberry is compositionally bimodal with an abundance of explosive and effusive deposits, including the youngest rhyolites in the Pacific Northwest.



Base modified from National Elevation Dataset, 2017

Figure 1. Map showing the driving route of this 4-day field guide beginning and ending in Portland, Oregon.

[1]National Science Foundation and Colgate University.

[2]Washington State University.

[3]Colgate University.

Geologic Background

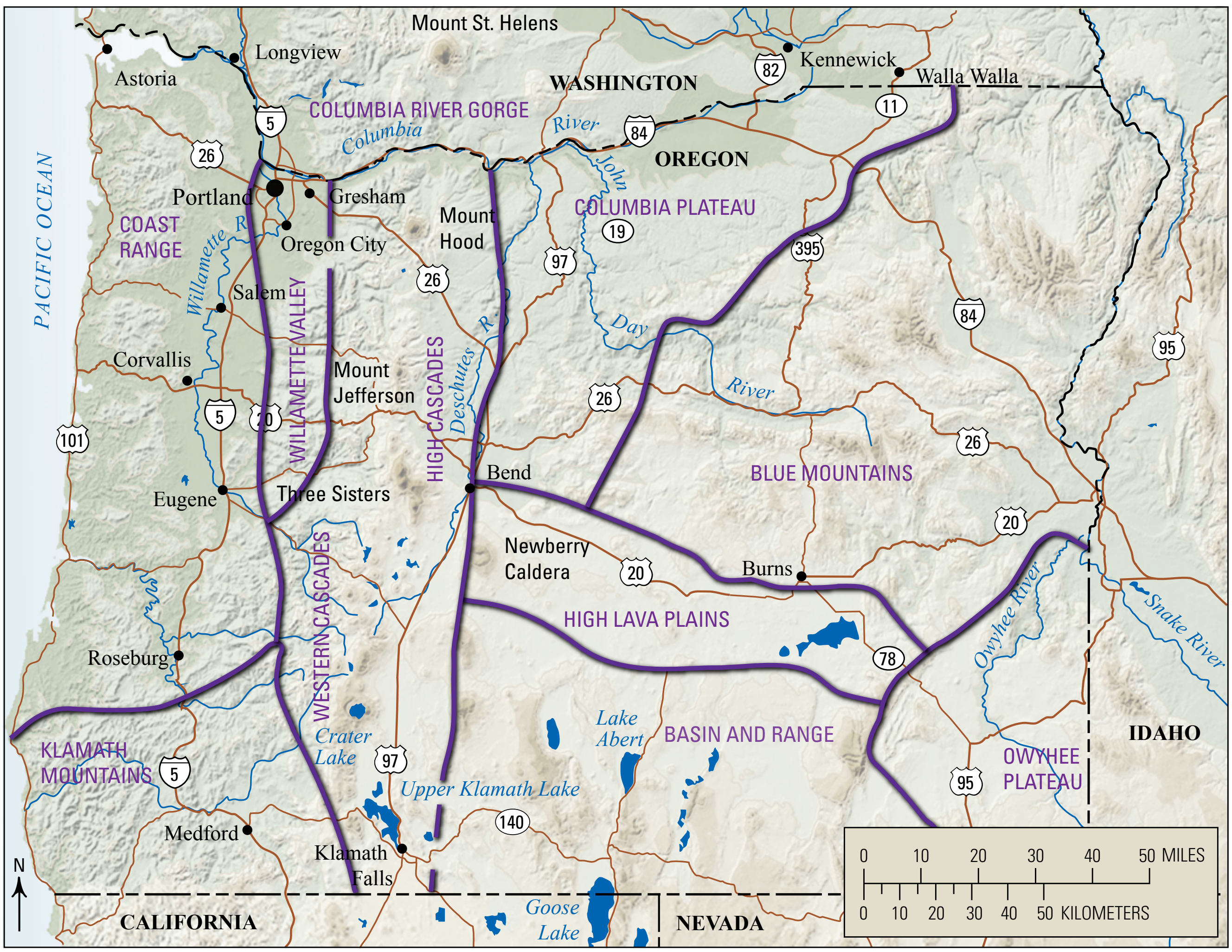
Basement

The Columbia River Basalt, High Lava Plains, and Cascade Range (fig. 2) are located in the Columbia Embayment, where the basement consists of late Paleozoic through Cenozoic accreted terranes (figs. 3, 4). These allochthonous rocks are a heterogeneous amalgamation of various lithologies and ages but are generally younger to the west. The boundary between the allochthonous terranes and Precambrian North America is just east of the Oregon-Idaho border and is a lithosphere-wide suture zone. We will be driving by outcrops of the accreted basement terrane on Day 1, as we cross the Blue Mountains (fig. 2). The rocks include low-grade metamorphic rocks cored by the Bald Mountain batholith, as well as the Canyon Mountain ophiolite (units JKg and PzMz in figs. 3–4).

Columbia River Basalt

The Columbia River Basalt Group (fig. 5) constitutes Earth's youngest and best-studied flood basalt province. Individual lavas are documented to have erupted from near the Idaho border and traveled westward to the Pacific Ocean, a distance of 500 kilometers (km). The volume of the basalts is estimated to be about 210,000 cubic kilometers (km^3), and around 350 individual lava flows have been recognized (Reidel and others, 2013).

Many explanations for the tectonic origin of the Columbia River Basalt have been proposed. One set of models notes that the Columbia River Basalt feeder dikes are parallel to and behind the Cascade Arc, suggesting back-arc rifting (Carlson and Hart, 1987), although it has been noted that the amount of extension at the time of eruption was trivial (Hooper, 1990). Others emphasize that most of the eruptive vents are just outboard of the boundary of Precambrian North America



Base modified from National Elevation Dataset, 2017

Figure 2. Map showing the major geologic provinces of Oregon. This trip starts in the Willamette Valley, then traverses the High Cascades and the Columbia Plateau. The basement of the Blue Mountains is then crossed to access the High Lava Plains, back to their intersection with the High Cascades.

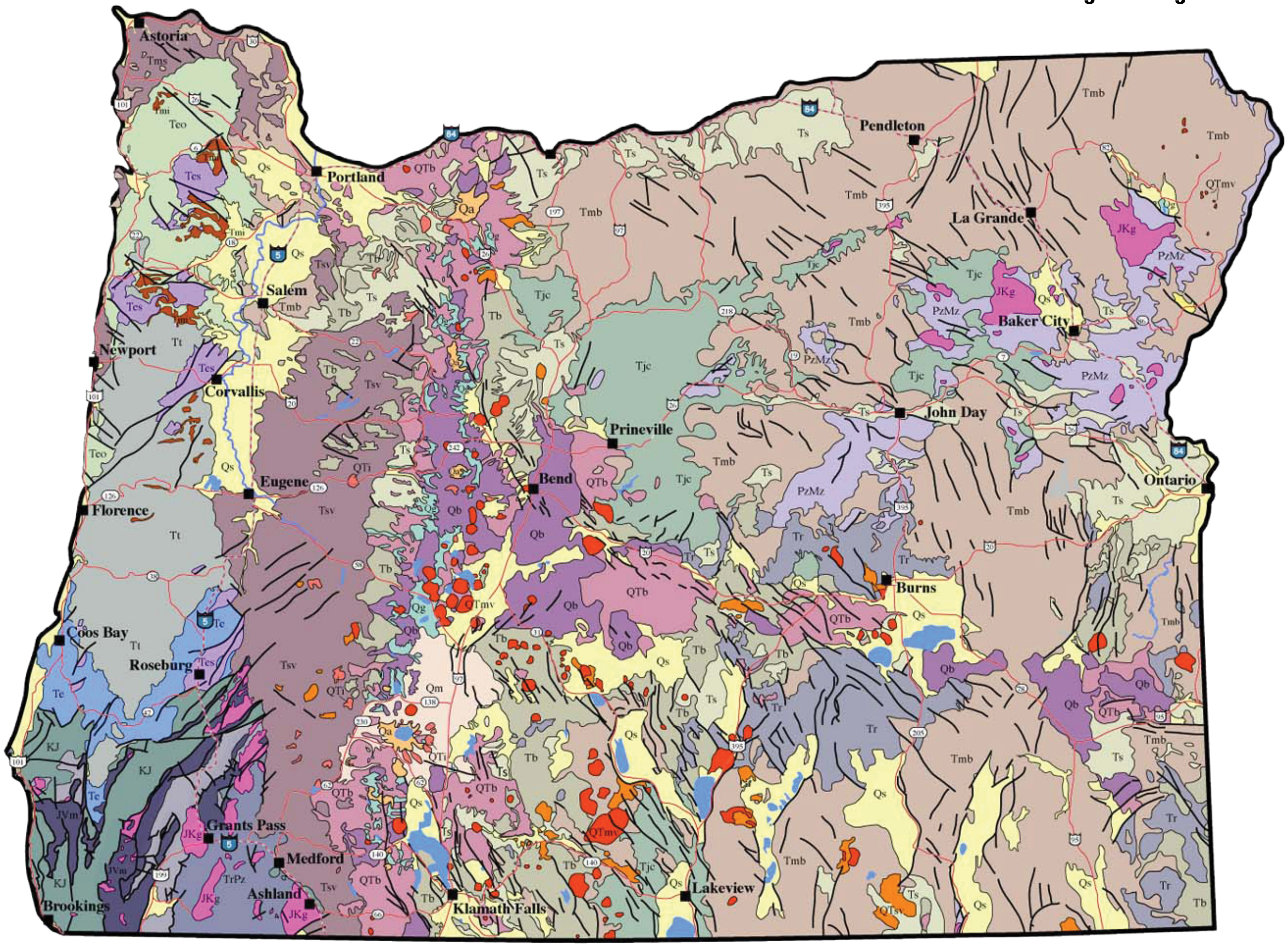


Figure 3. Geologic map of Oregon, provided by Marli Miller of the University of Oregon (Miller, 2014).

0 50 MILES
0 50 KILOMETERS
N

Modified from Walker and MacLead, 1991
By Marli Bryant Miller, University of Oregon

- **Qs** Quaternary sediment—Includes alluvium, colluvium, landslide, coastal dune,and terrace deposits.
- **Qm** Holocene Mazama ash and pumice—Includes air fall as well as flow deposits.
- **Qg** Quaternary Glacial Deposits
- **Qa** Quaternary Andesite
- **Qb** Quaternary Basalt and basaltic andesite—Forms some stratovolcanoes in the Cascades, and large basalt flows in eastern and central Oregon.
- **QTb** Quaternary, Pliocene, and some upper Miocene basalt flows
- **Ts** Miocene, Pliocene, and some Quaternary sedimentary rocks—dominantly tuffaceous and contains tuff and volcanic breccia. Locally grades into Tb
- **QTsv** Quaternary and Late Tertiary silicic vent complexes
- **QTmv** Quaternary and Late Tertiary mafic vent complexes
- **Tb** Middle to Upper Miocene and some Pliocene basalt
- **Tmb** Middle Miocene basalt—Predominantly the Columbia River Basalt Group, including the Saddle Mountain, Wanapum, Grande Ronde, Picture Gorge, Imnaha basalt, as well as the basalt of Steens Mountain and other undifferentiated early-Miocene basalts. Also includes minor intervening tuffaceous sedimentary rocks, lakebed deposits, and silicic flows
- **Tms** Lower to Middle Miocene marine sedimentary rock of the Coast Range
- **Tsv** Eocene through Lower Miocene sedimentary and volcanic rock of the western Cascades—Includes the marine Eugene Formation, and the non-marine Fisher Formation of the southern Willamette Valley
- **Tr** Eocene to Miocene rhyolite and rhyolitic tuff
- **Tjc** Eocene to Lower Miocene sedimentary and volcanic rocks of the Clarno and John Day Formations, and related rocks
- **Teo** Eocene to Oligocene marine volcanic-rich sedimentary and volcanic rocks—Includes Yamhill, Cowlitz, and Alsea Formations plus Yachats Basalt and Tillamook Volcanics
- **Tt** Eocene Tyee Formation of the Coast Range
- **Te** Eocene marine sandstone and siltstone that pre-dates Tyee Formation

Rock of Accreted Terranes

- **Tes** Paleocene to Eocene basaltic and related rocks of the Siletz River Volcanics ("Siletzia")
- **KJ** Jurassic and Cretaceaous sedimentary rock of the Franciscan Complex, found in the Klamath Mountains
- **Jvm** Jurassic volcanic, ultramafic, and metamorphic rock of the Klamath Mountains
- **TrPz** Paleozoic Triassic rock of the Klamath Mountains
- **PzMz** Paleozoic and Mesozoic rock of eastern Oregon

Intrusive Rock

- **QTi** Quaternary and Teritary silicic and mafic intrusions of the Cascades
- **Tmi** Teritary, mostly Miocene mafic intrusions of Coast Range
- **Jkg** Jurassic and Cretaceous granitic intrusions of the Klamath and Blue Mountains

Figure 4. Geologic units of map in figure 3.

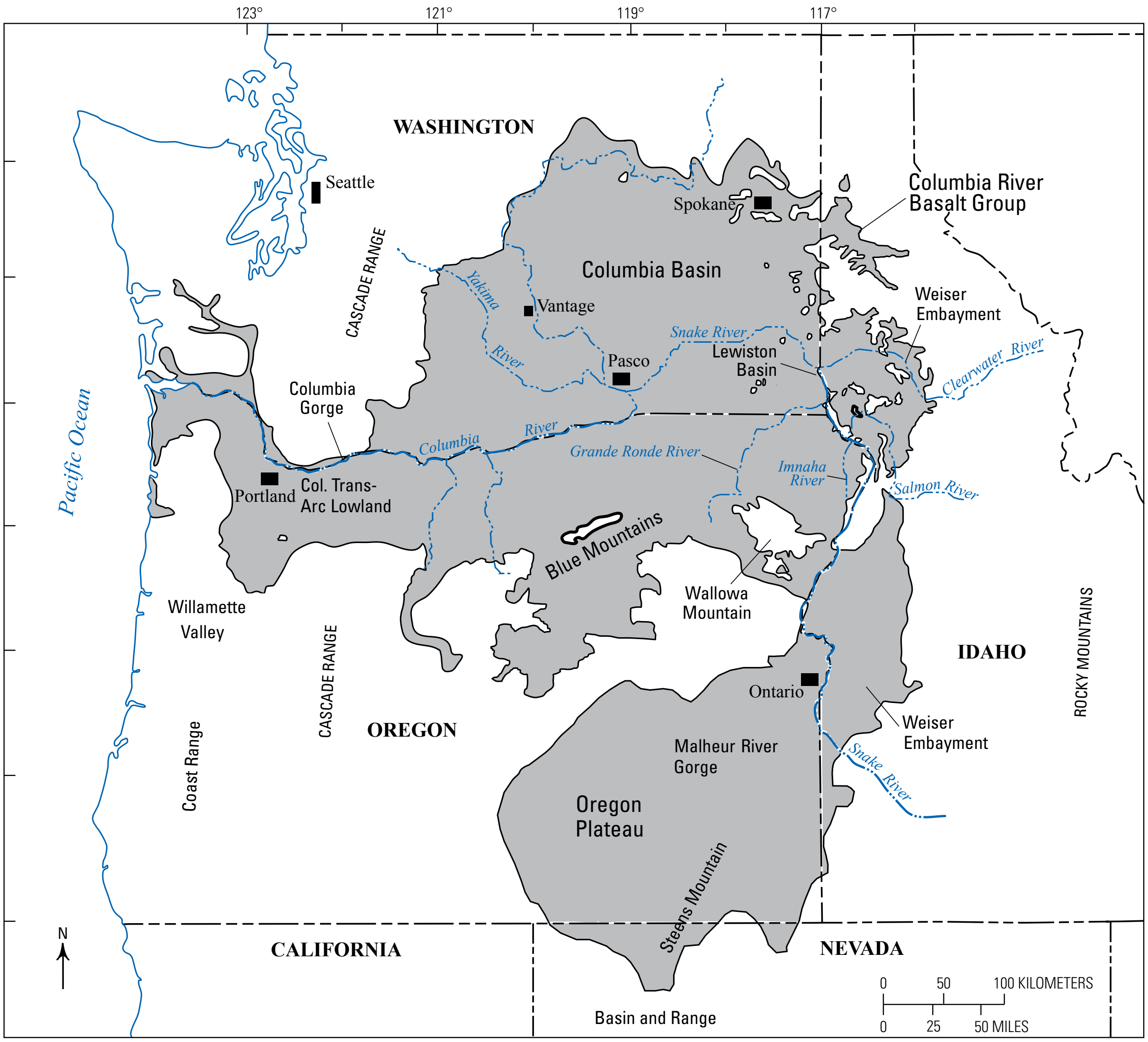


Figure 5. Map depicting the aerial distribution of the Columbia River Basalt Group (from Reidel and others, 2013).

and the accreted terranes of the Columbia Embayment and subparallel to that boundary. These models invoke edge-driven convection (King and Anderson, 1998), caused by buoyancy of the asthenosphere against a presumed step in the bottom of the lithosphere at the edge of Precambrian North America, as the mechanism for Columbia River Basalt formation.

Another explanation is that the flood basalts derive from the seismically imaged Yellowstone plume. A problem with this hypothesis is that the east-west line between the area of abundant Columbia River Basalt vents and Yellowstone is not parallel to the motion of the North American Plate (southwest). One possibility is that the Yellowstone plume was deflected by the Farallon subduction zone (Geist and Richards, 1993). Alternatively, magma may have been transported laterally for hundreds of kilometers in regional-scale dikes (Wolff and others, 2008). Another hypothesis emphasizes the concentration of subvolcanic dikes that cut the Mesozoic Wallowa batholith and attributes the basalts to the detachment of the dense residue leftover from granite generation (Hales and others, 2005).

Lava flows are correlated across the region on the basis of phenocryst assemblage, chemical composition, magnetic polarity, stratigraphic position, and geochronology. A generation of detailed study has revealed that the Columbia River Basalt Group can be divided into seven formations (Swanson and others, 1979; Reidel and others, 2013; figs. 6, 7): Steens, Imnaha, Grande Ronde, Picture Gorge, Prineville, Wanapum, and Saddle Mountains Basalts. The Imnaha and Grande Ronde lavas constitute more than 90 percent of the province, and they began erupting at approximately 16.7 million years ago (Ma) (Barry and others, 2010, 2013; Reidel and others, 2013). At the time of publication, the ages of the youngest Grande Ronde lavas (N2; fig. 7) and the termination of the Wanapum eruptions were being revised. Paleomagnetic and geochronologic data indicate that the top of the N2 lavas are 16.0 Ma (Jarboe and others, 2010). Precise age determinations of silicic ashes indicate that the latest stage of

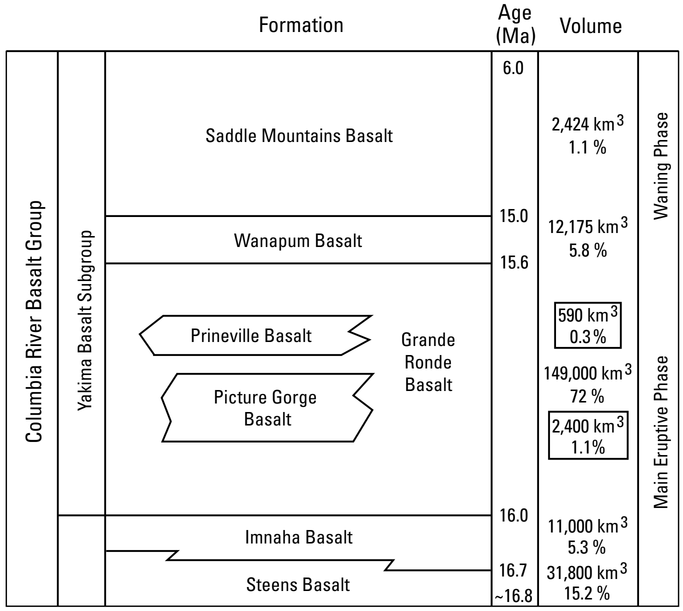


Figure 6. Illustration of the major members of the Columbia River Basalt Group (from Reidel and others, 2013), including ages and volumes. Note that the age of the top of the Grande Ronde basalt has been revised to approximately 16.0 Ma (Jarboe and others, 2010), and the age of the end of the Wanapum Basalt eruptions to >15.4 Ma (Ladderud and others, 2015).

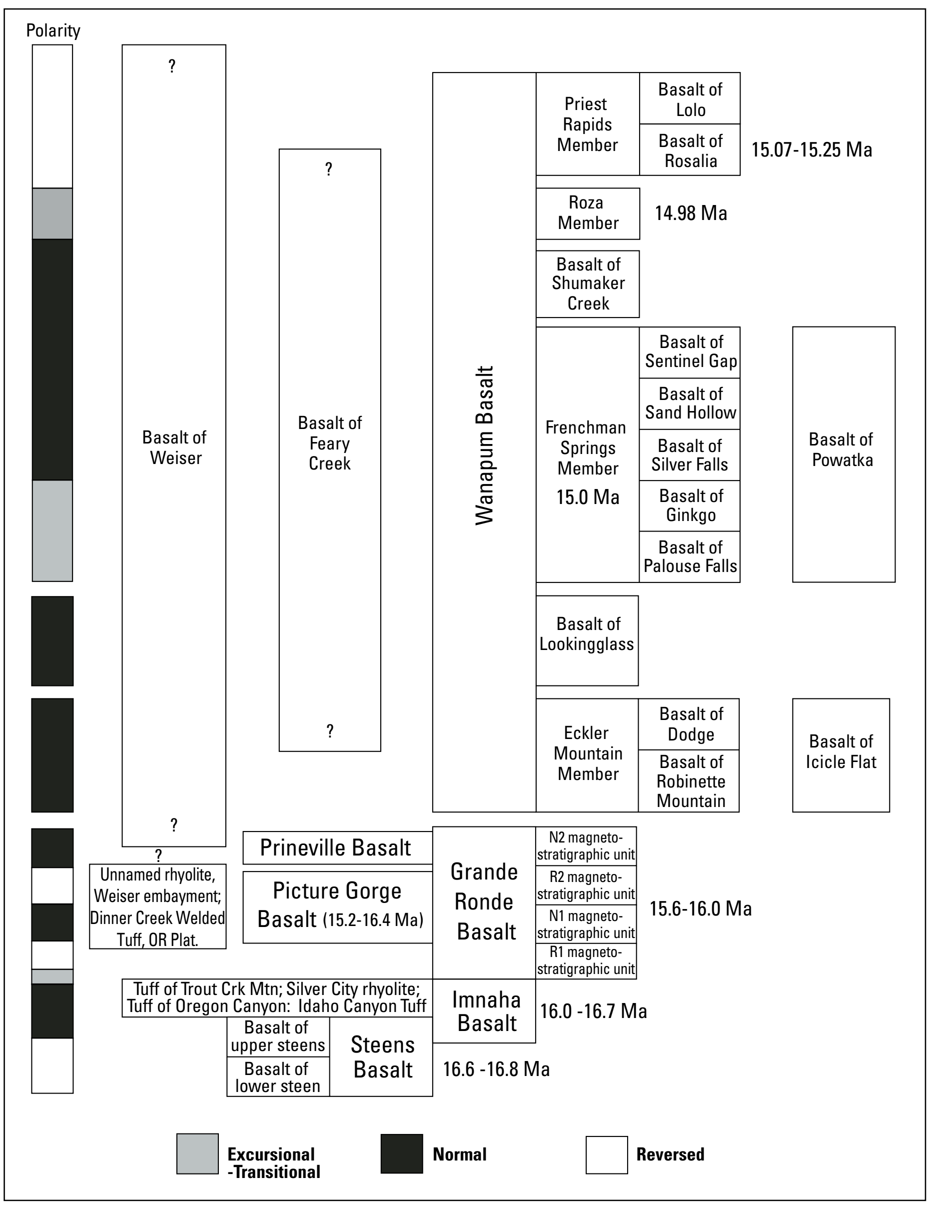


Figure 7. Correlation diagram showing detailed stratigraphy of the Columbia River Basalt Group, including ages and magnetic polarity (modified from Reidel and others, 2013). Note that the area of the boxes surrounding the individual units is related solely to duration of activity, not the volume or volume flux.

Wanapum Basalt is >15.4 Ma (Nash and Perkins, 2012; Ladderud and others, 2015). Ages and volumes indicate that pre-Wanapum lavas erupted at an average rate of at least 0.2 cubic kilometers per year, but the true flux may be several times this, given the new age determinations (Jarboe and others, 2010). The volume of a typical Columbia River Basalt lava flow is approximately 600 km^3, and individual flows can be more than three times that volume. Reasonable estimates of the eruption durations are up to tens of years (Thordarson and Self, 1998; Ramos and others, 2005), yielding eruption rates of about 3,000 cubic meters per second. The average interval between eruptions is about 4,000 years (Reidel and others, 2013).

A variety of morphologies characterize the lavas of the Columbia River Basalt, but most extend laterally for tens of kilometers and are tens to hundreds of kilometers long, making them extensive sheet flows. Flow lobes only tens of meters across can be identified in places, especially near the margins of the flows.

It is generally accepted that most Columbia River Basalt flows were emplaced by inflation. A solid crust formed early and did not move laterally. Meanwhile, lava injected continually into the middle of the flow, pushing up the crust (Self and others, 1997). The recognition of this process has been an important breakthrough, particularly for understanding the great lengths of some lava flows. The flow of lava under a crust is insulated and thermally efficient, which explains how lava can be transported for hundreds of kilometers without cooling more than a few degrees (Ho and Cashman, 1997). Where the sides of lava lobes are identified, marginal monoclines provide unequivocal evidence of inflation (Chitwood, 1994; Self and others, 1997). Inflation pits and clefts have been identified in several extensive sheet flows of the Grande Ronde and Wanapum Basalts, suggesting this as the common mechanism of emplacement.

Sheet lavas have a characteristic structure, which we will observe in many lavas on this trip (fig. 8). The tops of some flows are pahoehoe surfaces. Others have a lava breccia, which could form from autobrecciation typical of ‘a‘a (Reidel and others, 2013), by rafting of ballistic scoria from near the vent (Reidel and others, 2013), or by disruption of an original pahoehoe surface by changes in the flux of lava in the interior of the flow (Keszthelyi and others, 2006). The top several meters of most lavas form the upper crust (Self and others, 1997), identified by vesicular material in which a viscoelastic crust traps bubbles. In some lavas, the vesicles form rhythmically layered structures. Manga (1996) developed a model in which the vesicle layers result from waves of bubbles that, in turn, formed from an initially homogeneous distribution. Alternatively, the vesicles could represent periodic depressurization of a thick, constantly inflating sheet flow. The strength of the flow front regulates periodic pressurization of the interior of the flow, and volatiles remain dissolved. When the pressure builds to the extent that the flow front fails, the magma instantly depressurizes, driving a bubble-forming event, and the bubbles are trapped beneath the elastic top of the flow. The periodicity is governed by the strength of the viscoelastic flow front and the rate of pressurization owing to inflation.

The interiors of most Columbia River Basalt lavas are massive and cut by numerous cooling fractures (fig. 8). The lower part of the interior is commonly organized into a colonnade, regularly spaced hexagonal columns that are as much as 3 meters (m) in diameter. Rarely, an upper colonnade also forms. The middle of some sheet flows is broken into decimeter-scale columns that curve and fan, known as the entablature. The interior contains sparse large vesicles, and some lavas have vesicle pipes and sheets, thought to be the result of late-stage diapiric ascent and pooling of volatile-rich residual melt. The entablature is typically glassier than the upper and lower colonnades. Thordarson and Self (1998) equate the entablature to the upper crust and the colonnade to the core of the flow. The base of most sheet flows has a chilled margin up to several centimeters thick. Pipe vesicles penetrate the basal zone of some lavas.

Intracanyon flows are especially common in the Saddle Mountains Basalt (the youngest formation); hiatuses of 100,000 years or more and regional deformation resulted in stream incision, and many lavas followed these steep-sided canyons. Intracanyon flows are recognizable not only for their map patterns and underlying fluvial sediments, but they also have lower colonnades that dip steeply where the lavas are in contact with the near-vertical walls of the paleocanyons. Intracanyon lavas also tend to have well-developed hackly entablatures.

Pillow lavas are common on the Columbia Plateau. An inevitable consequence of lava flowing downhill is that large-volume lavas eventually flow into a stream. Large-scale pillow beds form foreset lava deltas as the lavas progress downstream. Moreover, a common result of lava-stream interaction is the formation of transient lakes, which are then encountered by slightly younger lavas.

High Lava Plains

The High Lava Plains (figs. 2, 3) is a bimodal volcanic province, with roughly equal volumes of basalts and rhyolite (Ford and others, 2013). The silicic rocks erupted as 3 large-volume ignimbrites in the southeast and more than 60 small domes and lavas to the west. They progress from about 10 Ma southeast of Burns, Oregon, to Quaternary age near Newberry Volcano. Basalts erupted throughout the province over this entire interval. Most basalts of the High Lava Plains are high-alumina olivine tholeiites, although mildly alkaline basalts are present.

One set of models for the tectonic origin of the High Lava Plains emphasizes that the time-transgressive silicic rocks form a mirror image to the Snake River Plain, and hence were related to spreading of the Yellowstone plume (for example, Draper, 1991). Another possibility is that the volcanism was related to the Brothers Fault Zone, which forms the northern boundary of the Basin and Range Province (Christiansen and McKee, 1978). A third hypothesis is that the magmas resulted from back-arc upwelling in the mantle wedge (Carlson and Hart, 1987; Ford and others, 2013).

Recent seismic and petrologic studies (Long and others, 2012; Till and others, 2013) have shown that the High Lava Plains is a zone of extraordinarily thin lithosphere; for all

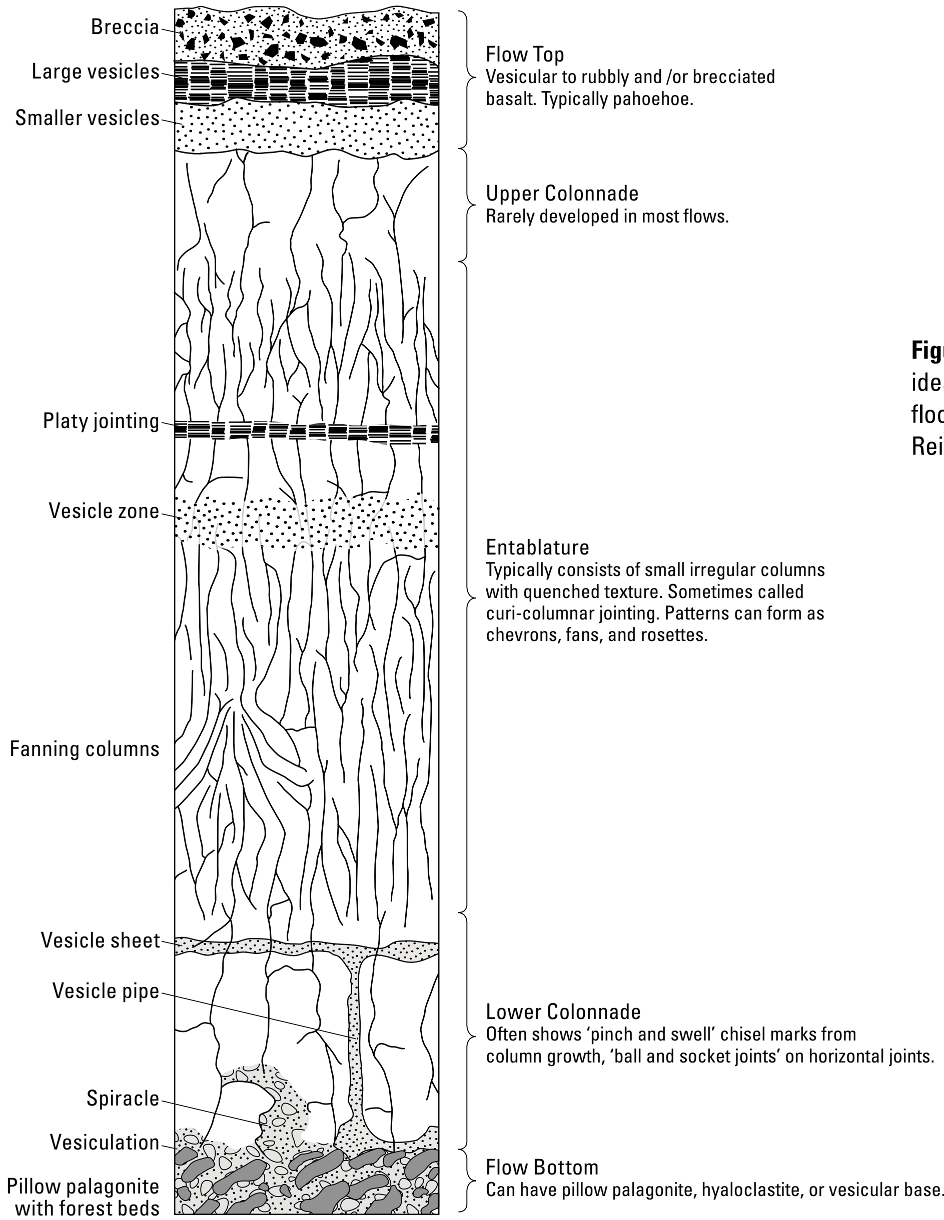


Figure 8. Diagram of an idealized section through a flood basalt sheet flow (from Reidel and others, 2013).

practical purposes, this means that the Moho (Mohorovicic discontinuity) is also the lithosphere-asthenosphere boundary. This geophysical evidence supports models of asthenospheric upwelling as the source of High Lava Plain magma.

The Cascades

The reader is referred to Hildreth's comprehensive 2007 monograph on the volcanic geology of the Cascades. The Cascades are a volcanic arc resulting from the subduction of the Juan de Fuca Plate beneath North America. The slab dips steeply in Oregon, about 60° just to the west of the arc and steadily steepening eastward. The convergence rate is approximately 31 kilometers per million years at an azimuth of 54°.

Although subduction has occurred beneath North America since the Triassic, the Cascades were not established until the Eocene. Prior to the Eocene, the active arc was to the east, owing to flat-slab subduction and later accretion of exotic terranes that make up the basement of the Pacific Northwest (fig. 3). Accretion of these exotic terranes and establishment of normal subduction dips resulted in a volcanic arc close to the current High Cascades. The ancient Cascades are to the west of the active arc in Oregon (Western Cascades; figs. 2, 3), but to the east of the arc north of Oregon. The High Cascades in Oregon lie within a northward-propagating graben.

Although 37 stratovolcanoes dominate the landscape, most of the Cascade Range is composed of approximately 2,300 small, mostly monogenetic, eruptive vents, including small shields, lava domes, and scoria cones (Hildreth, 2007).

Mount Mazama

Note that Mount Mazama and Newberry Volcano are located in a national park and national monument, respectively. Collecting rocks without a permit is prohibited.

This description of Mount Mazama comes from Bacon's 2008 geologic map of Mount Mazama and his 1989 field trip guide (Bacon, 1989, 2008). Mount Mazama is a composite stratovolcano that is best known for its caldera, which is partly filled by Crater Lake. The caldera collapsed during the explosive eruption of compositionally zoned rhyodacite to andesite 7,700 years ago. The cumulative eruptive volume of the climactic eruption is around 50 km^3. The evolution of Mount Mazama is unusually well recorded, owing to the exposures in the young caldera walls.

Mount Mazama lies in a region where north-south normal faults parallel the Cascade Range. The volcano is actually an amalgamation of five shields and stratovolcanoes that migrated westward with time. About 35 satellite vents decorate the flanks of Mount Mazama, but others may be eroded and buried. The earliest recognized activity of Mount Mazama volcano was about 420 thousand years ago (ka), and Mount Mazama continually erupted andesite and dacite to 40 ka, with no discernable hiatuses, although there were apparently pulses of increased activity.

The volcano began to produce rhyodacite at about 30 ka, culminating in the climactic eruption at 7.7 ka. The Llao Rock lava and pyroclastic rocks are a spectacular example of the young rhyodacite, whose eruption preceded the climactic eruption by a century or two. The Cleetwood lava and associated fallout deposits erupted just before the explosive climactic eruption, because the lava was still molten when the caldera collapsed. On the basis of existing slopes and glacial valleys, the volcano is estimated to have had an elevation of 3,700 m before caldera collapse.

The climactic eruption began with a Plinian column that dispersed fallout across much of the inland northwest to the east and north of the volcano. This is believed to have erupted from a single vent near the summit of Mount Mazama. Column collapse then produced the Wineglass Welded Tuff, which flowed down valleys to the east and north. Caldera collapse produced ring vents, which resulted in the emplacement of pyroclastic density current (PDC) deposits surrounding the volcano, to as much as 70 km distant.

Andesitic postcaldera volcanism constitutes about 4 km^3; the most prominent example is Wizard Island. Most postcaldera andesite erupted from three other sublacustrine vents. The most recent eruption was 4.8 ka, which produced rhyodacitic ash and a dome on the flanks of Wizard Island. Most of the features we will visit at Crater Lake are easily explored using Google Earth, as well, particularly using the streetview option.

Newberry Volcano

A comprehensive description of Newberry Volcano can be found in MacLeod and others (1995) and Jensen and others (2009). Newberry is an approximately 500 km^3 caldera-topped shield volcano that lies at the intersection of the Cascade Arc, the westward propagating rhyolitic volcanism of the High Lava Plains, and the Basin and Range Province. Newberry's eruptive products are distinctly bimodal. The intracaldera rocks are dominantly rhyolitic, whereas more than 400 mostly mafic satellite vents lie on the flanks of the volcano (about 20 silicic vents also exist on the flanks).

The exact origin of the caldera is difficult to pinpoint, but it likely is a multistage structure. The caldera may be related to voluminous 300 ka ignimbrites, with another collapse related to 70 ka pyroclastic activity (Jensen and others, 2009).

A recent detailed seismic study of Newberry reveals a low-velocity feature at a depth of 3 to 5 km, which is attributed to an active magma body (Heath and others, 2015; fig. 9). The velocities are best explained by mushy magma, with about 10 percent melt totaling 2.5 to 8 km^3, centered beneath the caldera. In contrast, the shallow crust beneath the flanks of the volcano have high seismic velocities and are thought to be solidified gabbroic intrusions. Most of the features we will visit at Newberry are easily explored using Google Earth; the obsidian flows, two lakes, cinder cones, and hydrovolcanic cones are particularly interesting to explore this way.

Spokane Floods

Although it is in no way related to volcanoes or tectonism, we will be driving through the heart of a renowned geologic cataclysm: the Spokane (or Missoula, if you are from Montana) floods (Bretz, 1923). During the Pleistocene, a tributary to the ancestral Columbia River was intersected by glaciers that flowed down tributary valleys, causing ice dams. These dams created glacial Lake Missoula, which occupied much of western Montana.

The ice dams failed periodically, perhaps more than 40 times, causing catastrophic floods throughout northern Idaho and eastern Washington. The floodwaters reached a hydraulic constriction at Wallula Gap, about 100 miles upstream of where we will depart the Columbia River. This constriction built a transient lake in southeastern Washington but sent the floodwaters down the Columbia River to the Pacific. The Columbia Gorge at The Dalles, through which we will be traveling, formed another constriction, creating the transient "Lake Condon" upstream into eastern Oregon.

The unique geomorphology of the Columbia Gorge was caused by these floods. Much of the Gorge almost completely lacks soil (referred to as "scablands"), and sculpted landforms decorate the valley floor and walls. The canyon is much more U-shaped than most V-shaped fluvial valleys, accounting for the abundance of tributary waterfalls. The water level was at about 1,000 to 1,100 feet in elevation in the section of the Gorge we will traverse, which can be recognized by the bench at this level in many places as well as the triangular faceted spurs.

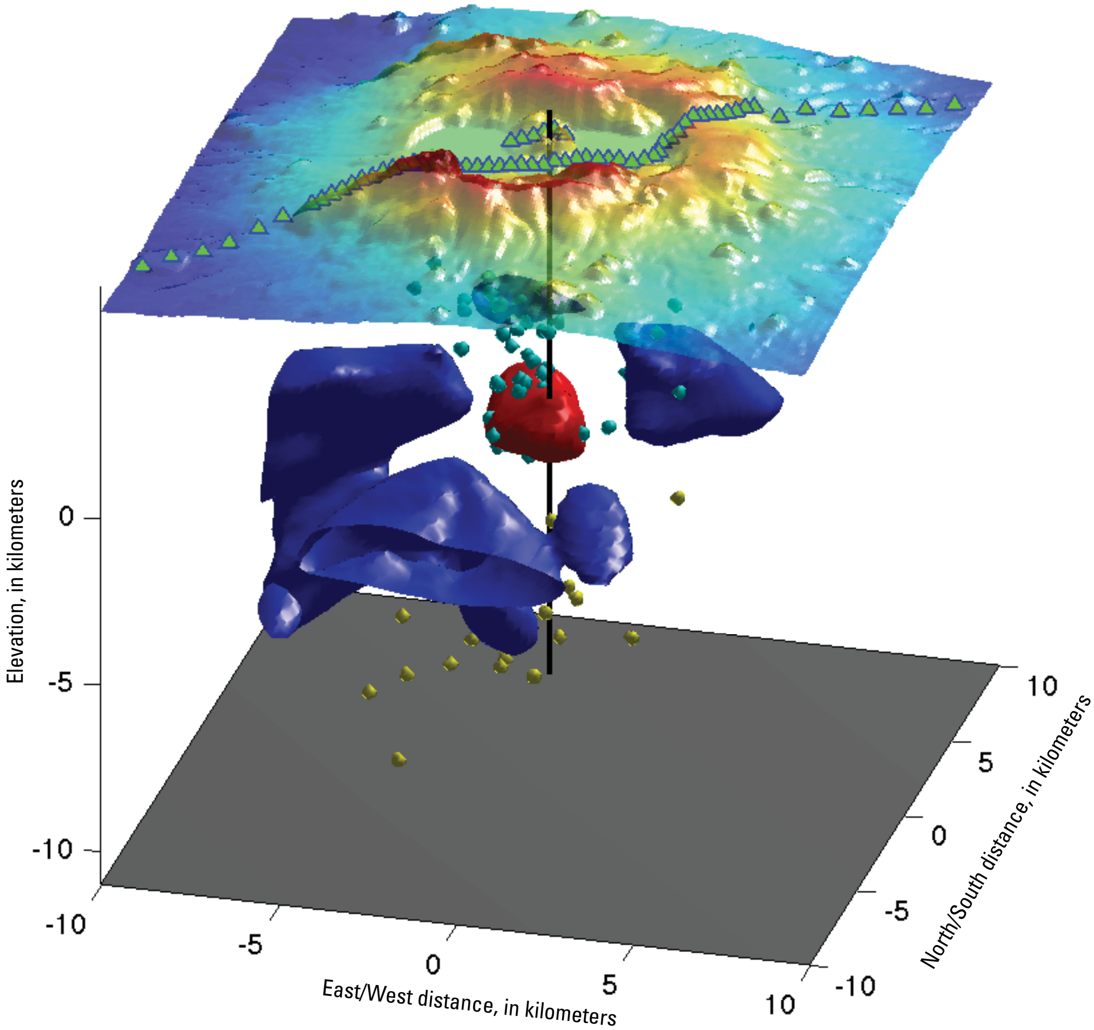


Figure 9. Three-dimensional perspective of the seismic tomography results from Newberry Volcano (Heath and others, 2015). Dark blue denotes areas of 0.08 or higher fractional velocity increase. Red volume denotes areas of –0.07 or lower fractional velocity decrease. Small blue spheres are earthquakes within the caldera recorded by Pacific Northwest Seismic Network (PNSN) stations from 2012 to 2015; small yellow spheres are deep, long-period events from the PNSN catalog. Topography is raised by 3 kilometers and exaggerated by a factor of 3. The seismically fast areas (blue) are interpreted to be cooled intrusions. The red volume is the inferred magma body. Triangles denote seismic stations.

Road Log

The field trip is designed as a 4-day traverse of the volcanic features of the Pacific Northwest, starting and ending in Portland, Oregon, with three overnight stops—one in Burns and two in Diamond Lake. All locations are in Oregon unless otherwise noted.

Day 1: Columbia River Basalt: Portland to Burns

The focus of the first day will be the Columbia River Basalt, taking advantage of the spectacular exposures in the gorges of the Columbia and John Day Rivers (fig. 10). Upon exiting the Columbia Gorge, the trip will cross the Blue Mountains and end in the Harney Basin, in the heart of the High Lava Plains. Many of the stops here are taken from Tolan and others (1984).

From Portland, proceed east on Interstate 84 (I–84). The mileage for this day begins at the Troutdale exit (Exit 17).

Drive 11 miles to Exit 28 (Bridal Veil) and proceed east on the Historic Columbia River Highway 3 miles to the Multnomah Falls parking lot.

The prominent cliff on the south side of the highway near milepost 18 is Crown Point, a thick section of the Priest Rapids Member of the Wanapum Basalt. The lower 60 m is hyaloclastite, from where the lava interacted with the ancestral Columbia River, overlain by 155 m of subaerial lava. The phallic promontory on the north side of I–84 is Rooster Rock, a landslide block that peeled off Crown Point.

Base modified from National Elevation Dataset, 2017

Figure 10. Map showing the route of Day 1 of this field trip, showing approximate locations of stops.

Stop 1: Multnomah Falls

The giant Spokane floods excavated the Columbia Gorge, creating a valley with unusually steep canyon walls and a diverse set of waterfalls from small tributary streams.

Exposed in the cliff face are 11 lavas of the Grande Ronde Basalt, recording a polarity reversal (5 other Grande Ronde lavas crop out above the lip of the fall; fig. 11). A pillow flow is exposed right at the brink of the upper falls. Pillow lavas are common throughout the Columbia River Basalt, as lavas disrupted and dammed fluvial systems and created vast intermittent lakes.

In 1995, a bus-sized block fell 50 m from the cliff and landed in the plunge-pool of the upper falls, generating a tsunami (fig. 12). Coincidentally, a 30-person wedding party was on the picturesque Benson Bridge at the same time. The tsunami and rock debris overwhelmed the party; 7 people were hospitalized and many others injured. In January 2014, a falling boulder landed on the bridge, causing severe damage to the bridge, which has been repaired.

Proceed east for 27 miles on I–84 to Exit 58. Park in the Mitchell Point Overlook lot.

The prominent dome-shaped monolith on the north side of the Columbia River near milepost 39 is Beacon Rock, a volcanic plug that was sculpted by the Missoula floods. It is a Pleistocene Cascades-forearc volcano.

Stop 2: Mitchell Point

Grande Ronde Basalt is exposed next to the parking lot (fig. 13). Mitchell Point itself is made of lavas of the Frenchman Springs and Pomona Members of the Wanapum and Saddle Mountains Basalts, separated by conglomerate of the Troutdale Formation. These conglomerates contain sparse metamorphic cobbles, likely derived from east or north of the Columbia Plateau, indicating transport by an ancestral Columbia River. The younger lavas are intracanyon flows; they were channelized by the ancient riverbed.

Figure 11. Photograph of Multnomah Falls with a view to the south (photograph provided by Teresa Kasner of Friends of Multnomah Falls, friendsofmultnomahfalls.org). Although many of the lavas are obscured by vegetation, the massive interior and rubbly margins of several Grande Ronde Basalt lavas are clear, particularly near the top of the section.

Figure 12. Photograph of the tsunami caused by a bus-sized rock fall in 1995 (photograph by Friends of Multnomah Falls, friendsofmultnomahfalls.org).

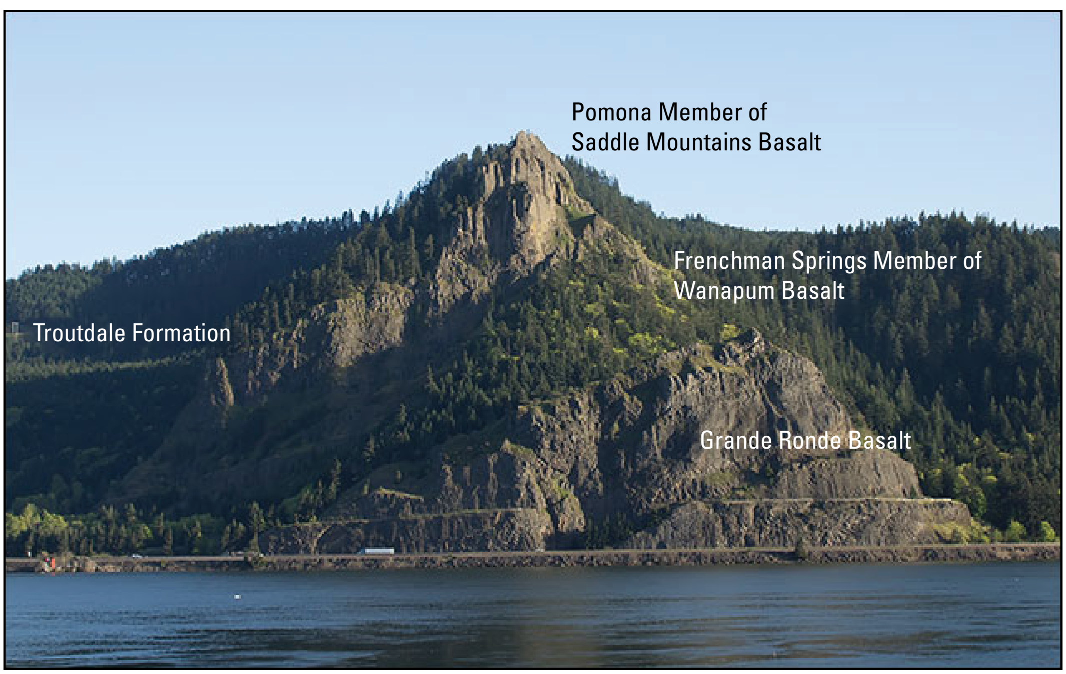


Figure 13. Photograph of Mitchell Point showing a view to the south. We will view this outcrop from the right (west) side. Note the ~20° eastward dip of the lavas, owing to post-emplacement deformation. Photograph courtesy of http://columbiariverhighway.com.

Drive 19.5 miles east on I–84 to milepost 78 and pull off to the right shoulder where there is a good view across the Columbia River.

Two miles east of Mitchell Point, an I–84 roadcut exposes a beautiful pillow delta complex, with foreset beds. This lava is high-alumina basalt of Cascades origin. Unfortunately, there is no safe pullout in the eastbound lane.

Stop 3: Ortley Anticline

The western part of the Columbia Plateau is strongly deformed in the Yakima Fold Belt, a compressional zone of deformation. The Ortley Anticline, a thrust-cored asymmetric fold, is well exposed on the north bank of the river. Younger Wanapum and Saddle Mountains Basalts pinch out against many of the Yakima folds, indicating that compressional deformation was contemporaneous with the later eruption of the flood basalts, but deformation has continued into the Holocene. In east-central Washington, the thrust-cored anticlines are north- to northeast-vergent, whereas here the vergence is clearly southwest. The tectonic origin of the compressional deformational event is elusive, although it could be related to clockwise tectonic rotation of Western Oregon and Washington (Wells and Heller, 1988).

Drive 8.6 miles east on I–84 to Exit 87 on the east side of The Dalles. Turn right (south) on U.S. Highway 30 (US–30). Cross the railroad and park in the gravel pullout on the west side of the junction of US–197 and US–30.

Stop 4: Lavas of the Priest Rapids Member of the Wanapum Basalt

At the base of the outcrop, basalt of Rosalia chemical type (Priest Rapids Member of the Wanapum Basalt; fig. 7) forms a palagonitized pillow complex, owing to lava having entered water. A subaerial lava flow of Lolo chemical type, with a prominent colonnade, overlies the pillowed flow. Sediments underlying the pillows have paleocurrent indicators directed westward.

The terrain around The Dalles typifies the sculpted landforms (known as scablands) caused by the Spokane flood, which entered the Columbia Gorge here.

You now have two options to get to Picture Gorge and Stop 5. Option A includes an optional stop, whereas Option B goes straight to Stop 5.

Option A, to Optional Stop

Drive 3.3 miles northward on US–197 into Washington State. Park on the narrow shoulder.

Option B, to Stop 5

Drive 17 miles east on I–84 to the Biggs exit (Exit 104) and turn right on US–97.

Go 8.5 miles south on US–97 and take the exit and then turn left on Oregon State Route 206 eastbound (OR–206) to Wasco.

Go 41 miles east on OR–206 to Condon and turn right on US–19.

Go 83 miles south on US–19 through Fossil and Kimberley and turn left on US–26. Proceed 0.6 mile southeast to a pullout on the left side of the road (where the road bends slightly right).

Optional Stop: Roza Member of the Wanapum Basalt

The Roza Member of the Wanapum Basalt, with prominent plagioclase phenocrysts, is one of the most petrographically distinctive of the Wanapum Basalts and consequently serves as an ironclad stratigraphic marker that has been subjected to several detailed studies (Martin, 1989; Thordarson and Self, 1998; Brown and others, 2014). The Roza Member consists of five separate lava flows, with a total volume of 1,300 km^3. It has been dated at 14.98 ± 0.06 Ma (Barry and others, 2013; Reidel and others, 2013), but regional silicic ash tephrochronology does not support ages younger than 15.5 Ma for the Wanapum Basalt (Nash and Perkins, 2012; Ladderud and others, 2015).

Drive southward on US–197 to return to I–84, then follow directions in Option B to Stop 5.

Stop 5: Picture Gorge

This is the type locality of a spectacular stack of Picture Gorge Basalt. The 61 known lava flows total about 2,400 km^3 (Bailey, 1989). They are coeval with the much greater volume Grande Ronde Basalts and erupted from dikes near Monument, located about 50 km northeast of here. The oldest units erupted onto a moderate-relief surface, thus many were channelized in river canyons. Picture Gorge itself formed by the incision of the John Day River into a tilted section of the lavas, which are in turn overlain by the sedimentary Mascall Formation and Rattlesnake Tuff.

Continue east on US–26 for 38 miles and turn right on US–395 towards Burns.

Go 63 miles south on US–395 towards Burns. Stop at the large pullout on the left side of the road, across from the resistant outcrop underlain by sediments and thick paleosol.

Stop 6: Rattlesnake Tuff

The Rattlesnake Tuff is exposed over 9,000 km^2 in southeastern Oregon and is estimated to be 280 km^3 dense rock equivalent (Streck and Grunder, 1995). It is part of the time-transgressive silicic High Lava Plains suite and is 7.1 Ma. The vent is not exposed but is likely a caldera buried in the Harney Basin, south of this outcrop.

The exposure here (fig. 14) is a single cooling unit of a strongly welded ignimbrite and displays the prototypical vertical welding zonation of a large-volume ignimbrite. The base of the exposure is made up of an unwelded white lapilli tuff, likely pre-ignimbrite fallout. This style of medium-grained bubble-shard fallout is typical of high-temperature rhyolites of the Yellowstone hotspot (Branney and others, 2008). Note the paucity of pumice clasts.

The base of the ignimbrite is marked by a 1-m unwelded tuff that transitions up into a poorly welded zone and a 1-m vitrophyric zone about 1 m above the base. The vitrophyre then passes into an 18-m-thick lithophysae zone, characterized by 1- to 3-centimeter (cm) solid and hollow lithophysae.

Drive to Burns by going 3.7 miles south on US–395 to the intersection of US–20, then turn right onto US–20 and continue west about 3 miles to the city center.

Day 2: Traverse of the High Lava Plains: Burns to Diamond Lake

The focus of the second day will be the diverse volcanic features of the High Lava Plains (figs. 15, 16), including basaltic lava fields and hydrovolcanic constructs.

Leave Burns and drive 97 miles west on US–20.

Turn left on Moffit Road.

After 3.0 miles, continue on Moffit Road around the sharp bend to the right.

After 5.4 miles, continue on National Forest Road 2312 (NF–2312).

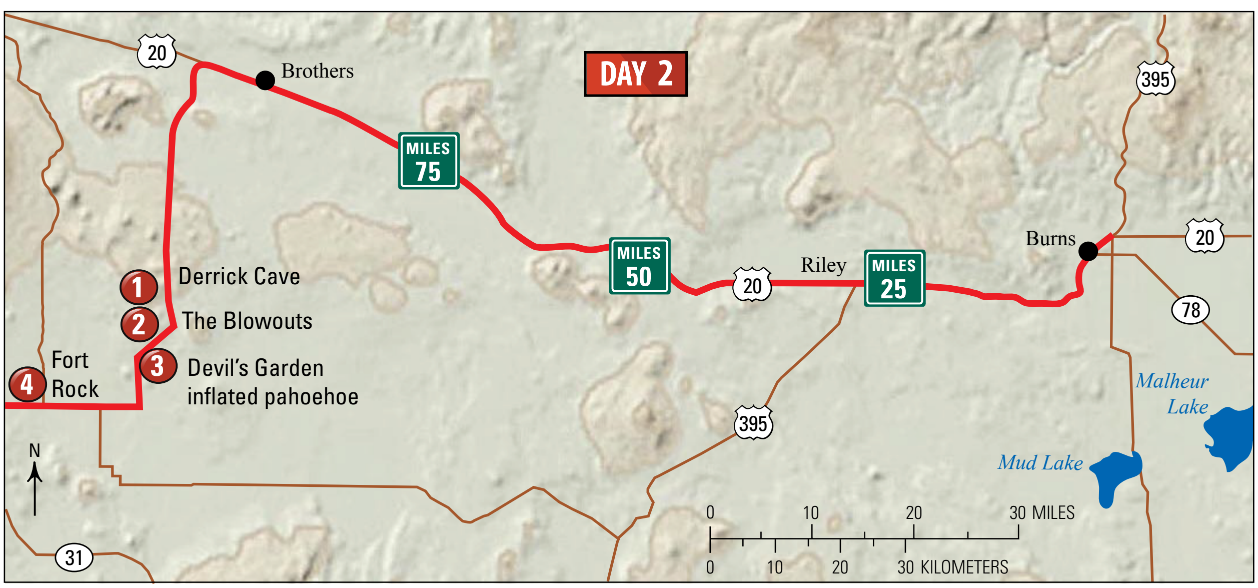
After 3.6 miles turn left on NF–23 (Sand Springs Road).

After 6.8 miles, continue straight on NF–2325 (do not cross under the power line here). You will be paralleling power lines for the entire distance to Stop 1.

After 0.6 miles, turn right (south) to continue on NF–2325.

Drive 6 miles south to the parking area for Derrick Cave. Walk to the mouth of the cave along the worn path.

Figure 14. Photograph of the type section of the Rattlesnake Tuff (Day 1, Stop 6). Bottom of outcrop (position of 3 sagebrush plants) is paleosol, bedded fallout, and lower poorly welded ignimbrite transitioning up into lower vitrophyre. The prominent outcrop above is entirely in the lithophysae zone. Photograph provided by Martin Streck.



Base modified from National Elevation Dataset, 2017

Figure 15. Map showing the route of the first half of Day 2 with approximate locations of the stops.

Base modified from National Elevation Dataset, 2017

Figure 16. Map showing the route for the second half of Day 2 with approximate locations of the stops.

Stop 1: Derrick Cave Lava Tube

The Devils Garden lava field (fig. 17) is one of the youngest basaltic lavas of the High Lava Plains. Although its precise age is unknown, it is obviously young, but fragments of Mazama pumice (7.7 ka) lie on top of the lava. The lava is slightly alkaline; note the groundmass olivine.

The lava erupted in a classic Hawaiian style from a fissure that eventually focused into a few central vents (fig. 18). The hill behind the parking lot is the northern end of the fissure. Just beside the road above the parking lot is a spectacular tumulus.

Flashlights or headlamps are necessary to explore the lava tube for more than a few meters. Once inside, note the conspicuous horizontal bathtub rings, marking waning cycles of lava being supplied to the tube. Over the years, we have discussed evidence of erosion into the substrate, without resolution.

Go 0.8 mile south on Derrick Cave Road.

Stop 2: The Blowouts

The southern end of the fissure is marked by an elongate spatter and scoria cone (fig. 18), where one can observe the different products of the proximal facies of a Hawaiian-style eruption. The different types of deposits reflect the combined effects of the distance the pyroclasts travel within and outside the incandescent fountain and the accumulation rate of the material. Scale the outer flanks of the cone, where the substrate is loose scoria lapilli. Once at the crater rim, one observes spatter in various states of fusion, ranging from unfused bombs, to welded bombs, intensely fused material, and clastogenic lava (some with ghost clasts).

Rader and Geist (2015) performed experiments simulating the emplacement conditions that formed these deposits. The eruption temperature was about 1,130 degrees Celsius (°C). The strength of the weld between clasts is quantified by the

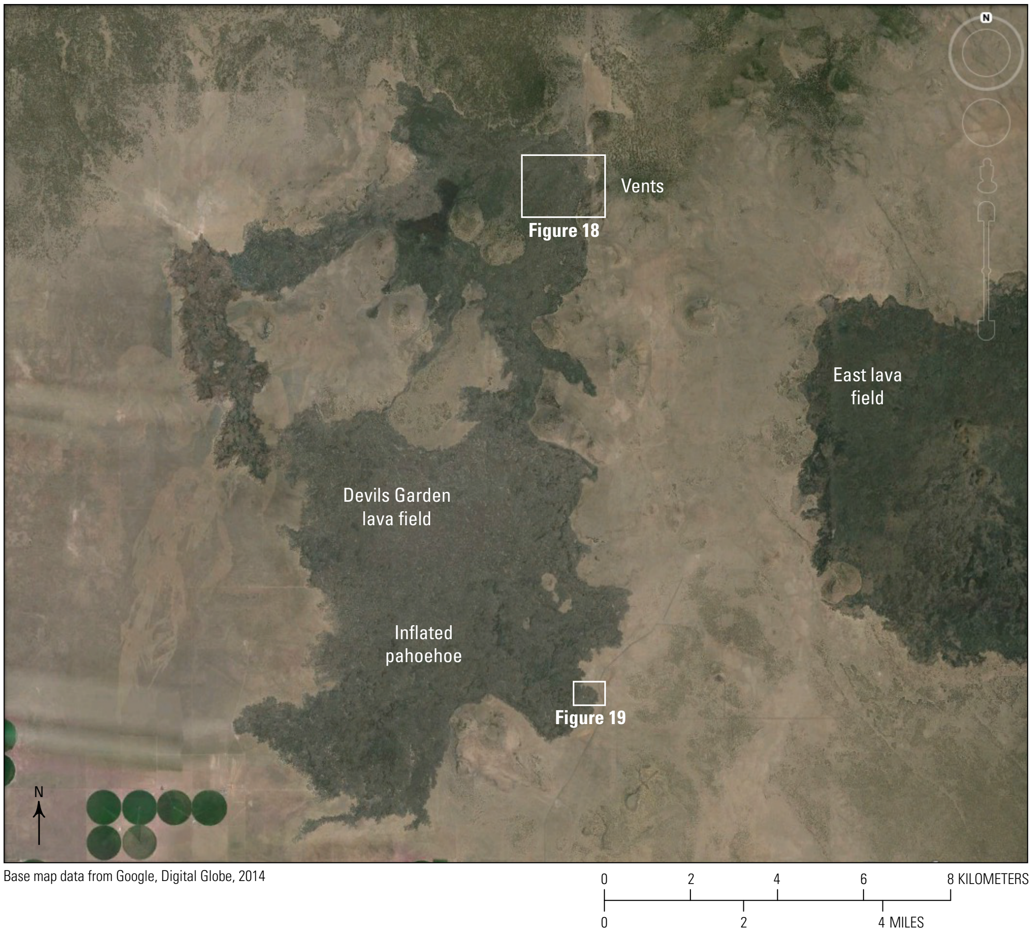


Figure 17. Annotated Google Earth view of the Devils Garden lava field, which resulted from a Hawaiian style eruption from a fissure vent near the north end of the flow field. Most of the lava is inflated pahoehoe.

Figure 18. Annotated close up Google Earth view of the vent area of the Devils Garden lava field, showing the location of The Blowouts and Derrick Cave lava tube.

tensile strength of the bond and found to be largely a factor of cooling rate, which is estimated to have been between 2.5 and 48 °C per minute. This then translates to accumulation rates of 0.5 to 1.8 meters per hour.

You now have two options to get to Fort Rock and Stop 3. Neither route should be attempted without a map. Option A includes an optional stop, whereas Option B goes straight to Stop 3. Option A crosses private land, which may not be accessible. If you do not have permission to cross this private land, skip the optional stop and follow the Option B route.

Option A, to Optional Stop

Continue south from the Blowouts, passing under the power lines. Go 3.3 miles, where the road passes between ranch buildings. This is where permission must be obtained. Please respect the private property.

Continue south on Derrick Cave Road 3.2 miles. Park on the side of the road and walk to the margins of the lava flow, under the power lines.

Option B, to Stop 3

Important Note: Between Derrick Cave and Cabin Lake Road, there is a maze of unmarked roads frequented by all-terrain vehicles. Several coordinates are provided, which may be useful in navigating.

From the Blowouts, return north 0.8 mile to Derrick Cave parking lot, then 2 miles further north to the intersection of NF–800. Turn left (west) on NF–800 (this intersection is at 43.547° N 120.662° W).

Go 0.7 mile and veer right (northwest) on NF–820.

Go 0.7 mile and turn left (west) on NF–700.

Stay on N–700 for 2.8 miles to the intersection with NF–23 (this intersection is at 43.573° N., 120.925° W.). Turn left (west) on NF–23. Continue 10 miles on NF–23 to the intersection with NF–18.

Turn left (south) on NF–18. Go 1.1 miles.

Veer left (southwest) onto Cabin Lake Road (NF–18 on some maps; intersection is at 43.502° N., 121.056° W.). Go 8.2 miles on Cabin Lake Road to County Road 5–11A and turn right (west). Go 0.6 mile and enter Fort Rock State Park.

Optional Stop: Inflated Pahoehoe, Devil's Garden

Marginal monoclines and axial clefts (fig. 19) provide evidence that this pahoehoe lava originated via inflation (Chitwood, 1994). One can see lava that was arrested in all stages of inflation from 1-m-thick toes to several-meter-thick lobes to a 5-m-thick sheet flow. Immediately to the north is a

Figure 19. Annotated Google Earth view showing details of the flow front at the distal (southern) end of the Devils Garden lava field, indicating inflationary lava features.

lava-rise pit (fig. 19), formed when lobes diverged around a small topographic barrier then inflated above it.

Continue south 4.4 miles on Derrick Cave Road and turn right (west) onto County Highway 5–12.

Go 1.0 miles, following road around to the left (south) as it makes a right angle turn.

Go 1.0 miles and follow road to the right (west) as it makes a right angle turn.

Continue 2.2 miles west on Derrick Cave Road, where it intersects Fort Rock Road. Go straight 5.8 miles to the town of Fort Rock.

Turn right (north) on Cabin Lake Road. Go 1.0 miles and turn left on County Road 5–11A and enter Fort Rock State Park.

Stop 3: Fort Rock

Fort Rock is the erosional remnant of a Pleistocene tuff ring (fig. 20). Note the prominent wave-cut terraces about 20 m above the current surroundings, which indicate the lake level shortly after construction of the tuff ring.

A comprehensive description of the landform and deposits is in Brand and Heiken (2009). The bedded orange palagonite tuff that surrounds the crater floor contains many accretionary lapilli. To the north of the crater, beds dip steeply inward; they were the crater wall. Stratigraphically upwards, scoria lapilli become more abundant, evidence that water-magma interaction became less important as the edifice built above lake level. On the west-southwest side of the crater, an angular unconformity provides evidence of a major syneruptive slump (Brand and Heiken, 2009).

Head east on County Road 5–11A for 0.8 miles and turn right (south) on Cabin Lake Road, then 1 mile to Fort Rock Road and turn right (west).

Drive 6.4 miles to the intersection with OR–31, then turn right (northwest).

Go 9.6 miles and turn left onto Forest Service Road 400 (FS–400).

Cross the first gravel road (0.2 mile) and veer left at the Y intersection (0.05 mile) beyond, staying on FS–400.

Proceed 1 mile beyond this Y intersection to another Y intersection with FS–460 staying right at the first two Y intersections (FS–490 at 0.1 mile and FS–480 at 0.5 miles) and turn left onto Road 460. Go 200 yards and park where the spur road climbs steeply uphill.

Walk up the steep slope to the prominent outcrops.

Stop 4: Big Hole

The cliffs in the eastern wall of this tuff ring expose an impressive sequence of hundreds of layers of pyroclastic deposits emplaced during the explosive eruption of a monogenetic hydrovolcano (fig. 21). These deposits contrast with those of Fort Rock, which we attribute to different amounts of water available inside the crater during the eruption (larger amounts of water at Fort Rock).

Most of the centimeter- and decimeter-scale layers are deposits from dilute pyroclastic density currents (PDCs), or surges in classic terminology. Cross-lamination and reverse and normal grading characterize many of the layers. Many of the interspersed massive layers are likely to be fallout

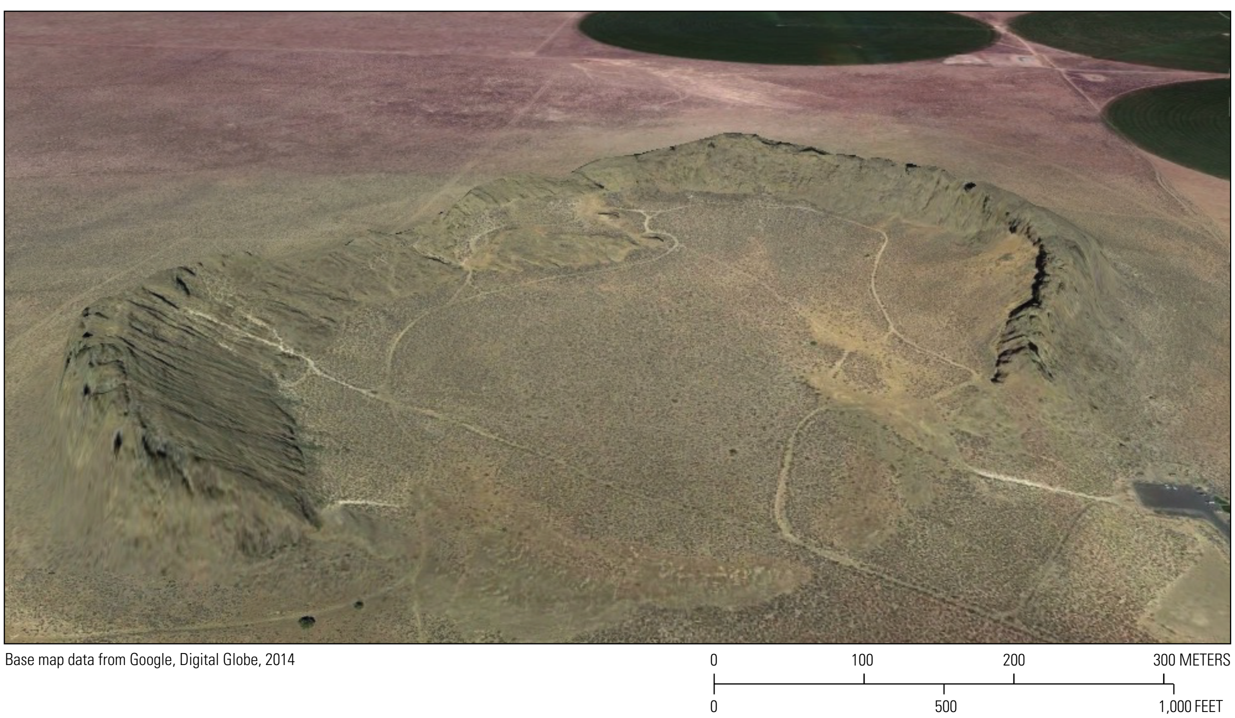


Figure 20. Google Earth three-dimensional satellite image of Fort Rock, an eroded Pleistocene tuff ring. View is to the north.

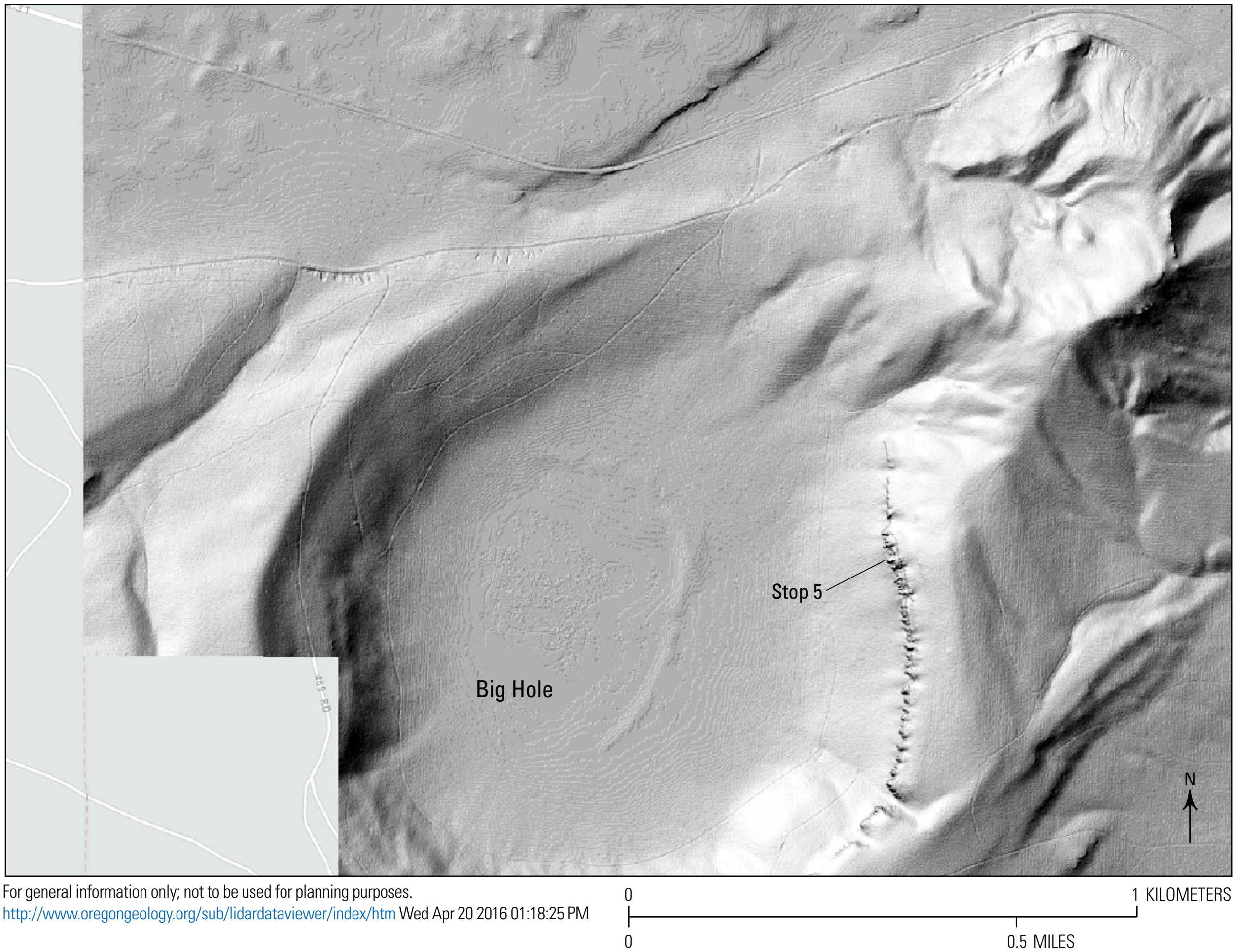


Figure 21. Lidar image of Big Hole, a tuff ring. Field trip stop is at the cliffs on the east side of the crater wall. An inner crater is visible on the west side of the crater floor.

deposits. Several of the layers have spectacular concentrations of armored lapilli, where a thin ash coating surrounds a perfectly rounded scoria fragment. We have not identified accretionary lapilli made solely of concentric layers of ash in these deposits.

The size and abundance of large (as much as 1 m) lithic bombs is evidence of the energetic eruption that created Big Hole. Many of them created bomb sags upon impact with the wet substrate, and the asymmetry of the sags indicates their flight direction.

Lithic clasts provide evidence of the rocks that underlie the maar. They include lithified lacustrine sediments and basalt related to the High Lava Plains, as well as rocks from the crystalline basement.

Return 1.4 miles to US–31 and take a left.

Go 20 miles to the intersection with US–97 and turn left (south).

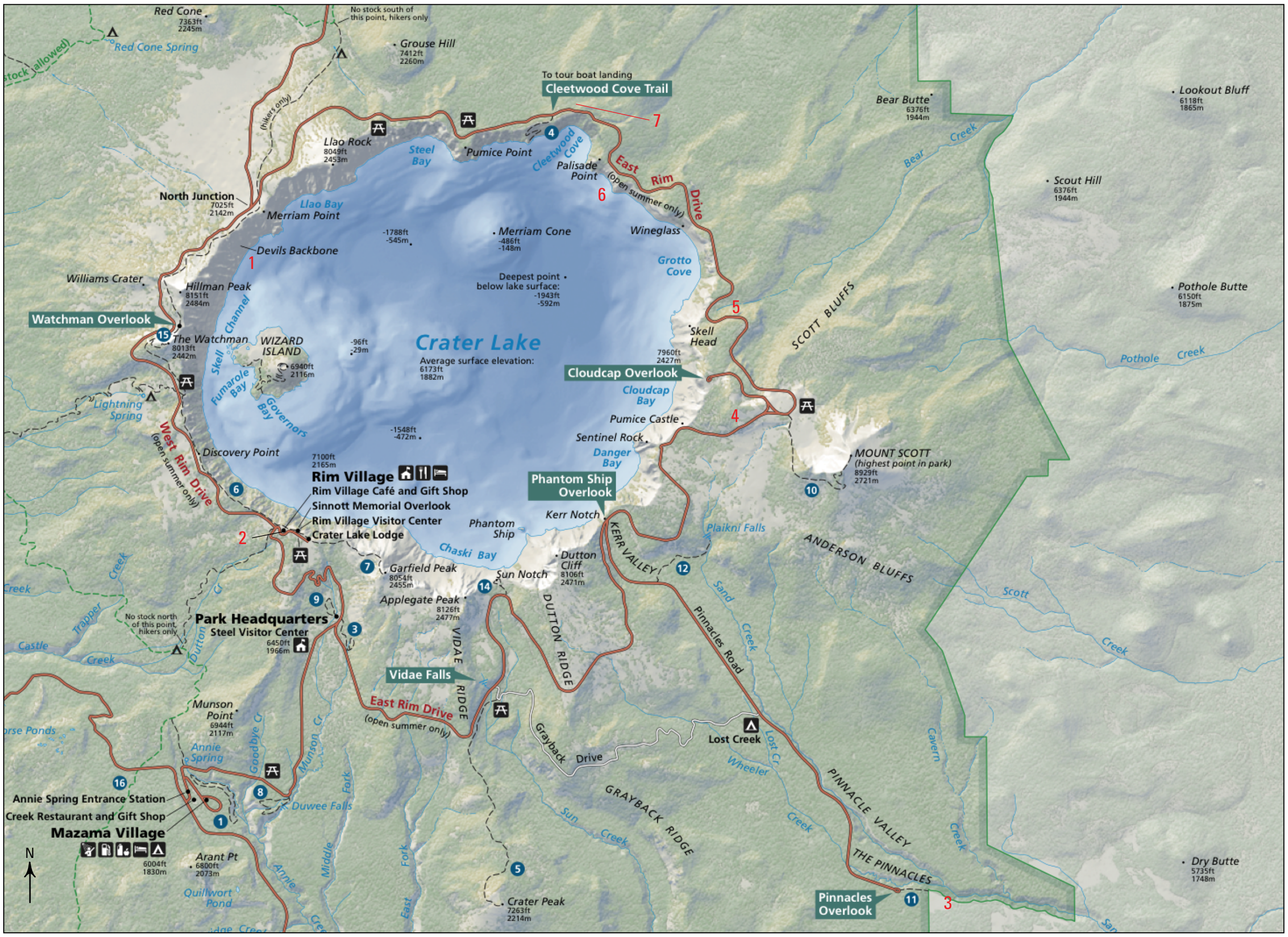
Go 43 miles and turn right onto OR–138.

Go 22 miles and turn left into Diamond Lake Loop.

Night at Diamond Lake Resort. There are also hundreds of campsites at Diamond Lake, although a reservation is needed during high season.

Day 3: Circumnavigate Crater Lake: Diamond Lake to Diamond Lake

This day is devoted to a circumnavigation of Crater Lake, one of the world's classic calderas (fig. 22). The field trip guide is mostly derived from that of Bacon (1989) and



Base map is the U.S. National Park Service map for Crater Lake National Park.

0 5 10 KILOMETERS
0 5 MILES

Figure 22. Map showing the route for Day 3 with approximate locations of the stops. Base map is the U.S. National Park Service map for Crater Lake National Park.

makes use of his comprehensive geologic map of the volcano (2008). **Note that Mount Mazama is located in Crater Lake National Park. Collecting rocks without a permit is prohibited.**

From Diamond Lake, return to OR–138 and turn right (south).

Go 7.2 miles and take the slight right onto North Entrance Road. The entrance is in 0.7 miles.

Go 8.1 miles to the intersection with Crater Rim Drive and pull into the parking area on the uphill side of the intersection.

Stop 1: Overview, North Rim

On the drive up the north slope of Mount Mazama, the most prominent feature is the Pumice Desert (fig. 23), which is the surface of a thick section of valley-filling ignimbrite from the climactic eruption 7,700 years ago; this lobe reached Diamond Lake. Red Cone to the north is a kipuka of older rocks.

There are excellent views of Cascade volcanoes to the north: Mount Bailey, Diamond Peak, and Mount Thielsen being the closest.

The details of the volcano's geology will be discussed at Stop 2, but note how the interior of the edifice is very well exposed by the caldera wall. Llao Rock is the prominent dacite lava to your left. Crater Lake Lodge, the next stop, can be seen beyond Wizard Island.

Take a left (west) out of the parking area and drive 6 miles west then south on Rim Drive to the Rim Village parking lot. Proceed to the overlook of Crater Lake.

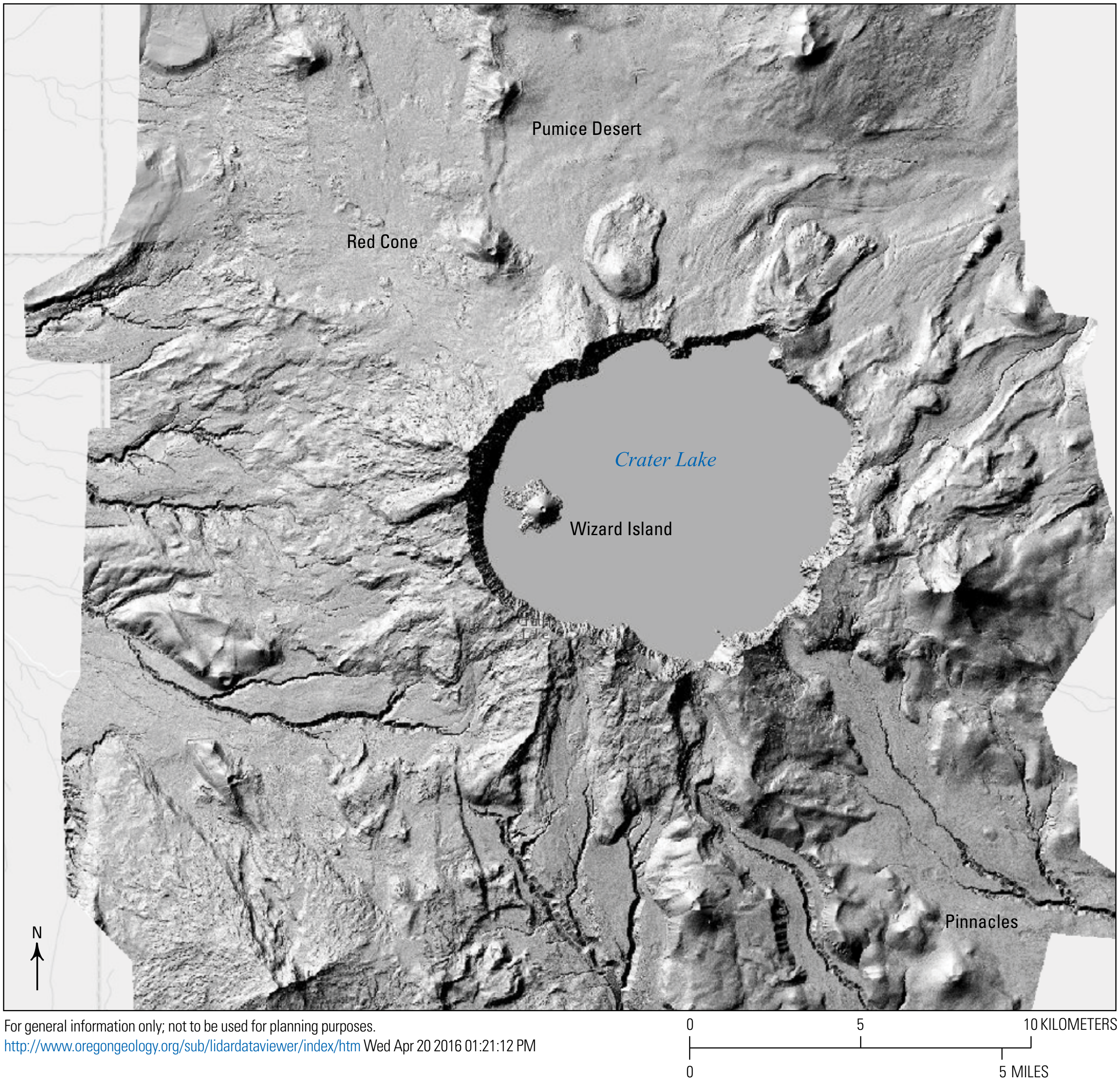


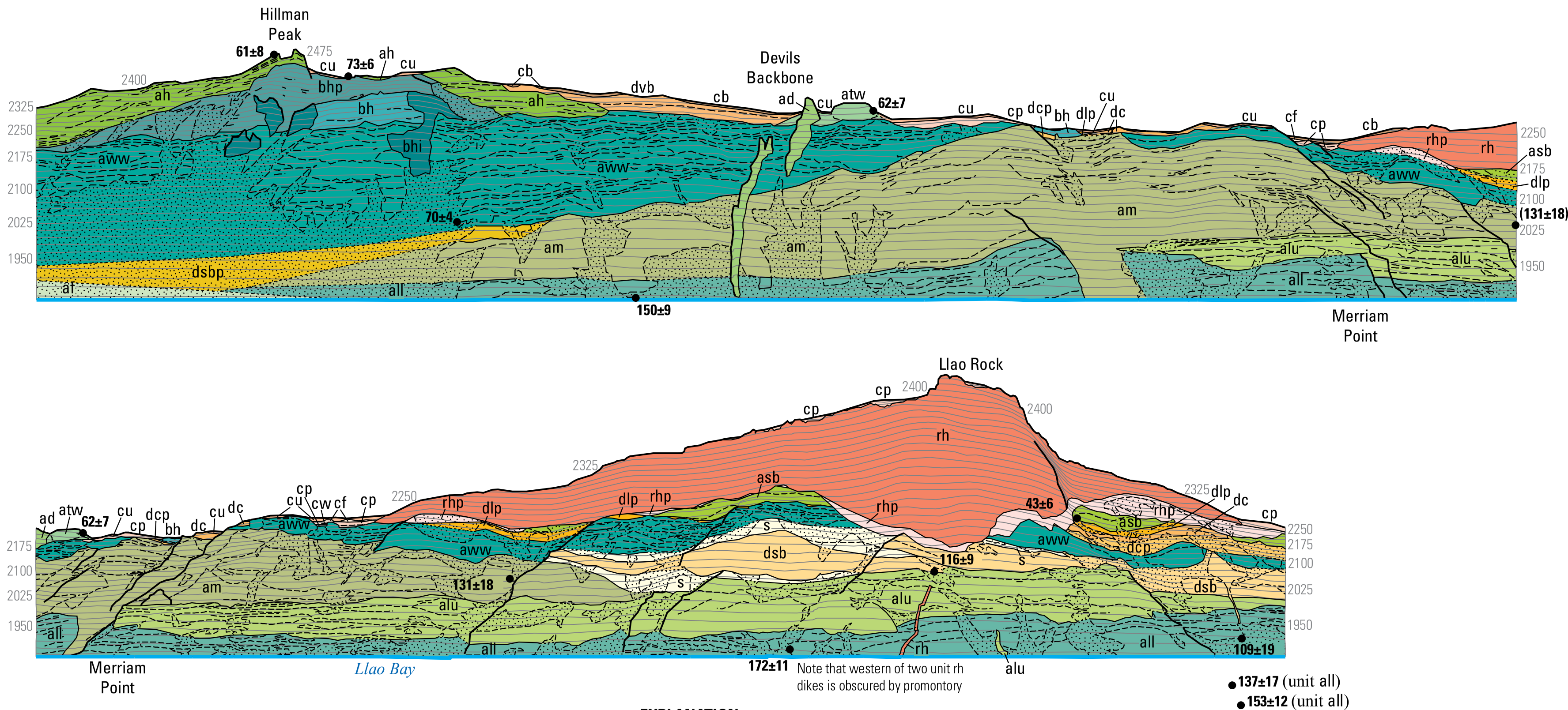
Figure 23. Lidar image of Mount Mazama and Crater Lake. Note the smoothing of topography by the climactic ignimbrite. Lidar imagery is from the Oregon Department of Geology and Mineral Industries.

Stop 2: Crater Lake Lodge

The iconic panorama across the lake reveals the deposits and structural outcomes of the climactic eruption as well as the unique perspective of the guts of a Cascade volcano, owing to the exposures provided by the caldera wall (figs. 24 and 25, taken directly from sheet 4 of Bacon, 2008).

From left to right, the major features are: Wizard Island, The Watchman, Hillman Peak, Devils Backbone, Llao Rock, the Cleetwood "Dribble", Cloudcap, Sentinel Rock, Kerr Notch, and Garfield Peak. Wizard Island is an ash and scoria cone, with a late-stage lava flow, obviously a post-caldera vent. The Watchman lava is about 50 ka; note the feeder dike toward Hillman Peak (fig. 24). Hillman Peak is formed by a sequence of ~70 ka andesites. Devil's Backbone is formed by a dike.

Llao Rock is the most prominent cliff-former in the caldera wall and is a crater-filling rhyodacite that erupted one or two centuries before the climactic eruption (fig. 25). The caldera walls below and surrounding Llao Rock are mostly andesite and dacite



EXPLANATION

- ad — Andesite of Devils Backbone (late Pleistocene)
- af — Andesite west of Fumarole Bay (middle Pleistocene)
- ah — Andesite of Hillman Peak (late Pleistocene)
- all — Andesite of Llao Bay, lower unit (middle Pleistocene)
- alu — Andesite of Llao Bay, upper unit (late Pleistocene)
- am — Andesite of Merriam Point (late Pleistocene)
- apu — Andesite of Pumice Point (late Pleistocene)
- apw — Andesite west of Pumice Point (late Pleistocene)
- asb — Andesite of Steel Bay (late Pleistocene)
- atw — Andesite south of The Watchman (late Pleistocene)
- aww — Andesite of the west wall (late Pleistocene)
- bh — Basaltic andesite of Hillman Peak (late Pleistocene) Lava
- bhi — Basaltic andesite of Hillman Peak (late Pleistocene) Intrusive
- bhp — Basaltic andesite of Hillman Peak (late Pleistocene) Pyroclastic
- bs — Basaltic andesite of Steel Bay (late Pleistocene) Lava
- bsp — Basaltic andesite of Steel Bay (late Pleistocene) Pyroclastic
- cb — Deposits of the climactic eruption of Mount Mazama (Holocene) Lithic breccia
- cf — Deposits of the climactic eruption of Mount Mazama (Holocene) Ring-vent-phase ignimbrite
- cp — Deposits of the climactic eruption of Mount Mazama (Holocene) Plinian and other Holocene pumice-fall deposits
- cu — Deposits of the climactic eruption of Mount Mazama (Holocene) Fine-grained lithic- and crystal-rich ignimbrite
- cw — Deposits of the climactic eruption of Mount Mazama (Holocene) Wineglass Welded Tuff of Williams (1942)
- dc — Dacite of Pumice Castle (late Pleistocene) Lava
- dcp — Dacite of Pumice Castle (late Pleistocene) Pyroclastic
- dlp — Dacite below Llao Rock (late Pleistocene)
- dsb — Dacite of Steel Bay (late Pleistocene) Lava
- dsbp — Dacite of Steel Bay (late Pleistocene) Pyroclastic
- dvb — Dacite of Munson Valley (late Pleistocene) Prismatically jointed block unit
- re — Evolved Pleistocene preclimactic rhyodacite (late Pleistocene) Felsite
- rh — Holocene preclimactic rhyodacite (Holocene) Felsite
- rhp — Holocene preclimactic rhyodacite (Holocene) Pyroclastic
- s — Sedimentary deposits, undivided (late and middle Pleistocene)

Figure 24. Geologic cross sections of the northwest caldera wall at Crater Lake, viewed from Stop 2, beginning just to the east (right) of Wizard Island, all from Bacon (2008). The reader is referred to that map for detailed unit descriptions. The sections are arranged from west (top) to east.

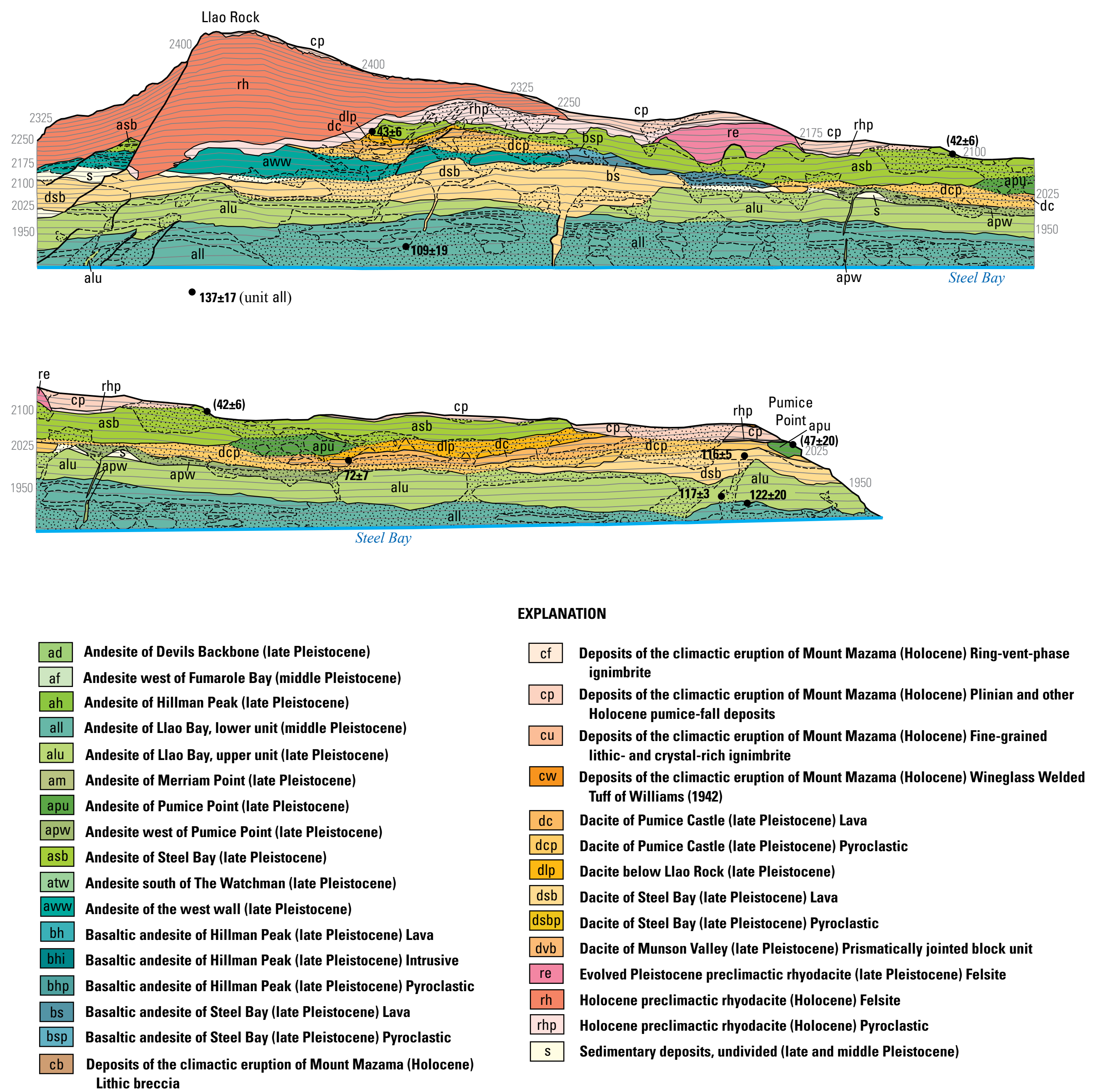


Figure 25. Geologic cross sections of the north wall of Crater Lake caldera, from Bacon (2008). The reader is referred to that map for detailed descriptions and the key for the units. The sections are arranged from west (top) to east.

erupted from a sequence of 5 migrating composite volcanoes. The andesite below Llao at the lake surface is 190 ka. Just to the east, a thick deposit of pumice is from the climatic eruption.

Note the geometry of the Cleetwood lava, draped on the caldera wall; its unique origin will be discussed when we are on that side of the caldera.

Drive 2.8 miles south on Rim Drive and turn left to continue east on Rim Drive.

Drive 3 miles and turn right on Grayback Drive.

Go 4.6 miles and turn right at the intersection with Pinnacles Road. Proceed to the end of the road in 2.8 miles.

Stop 3: The Pinnacles

This widely misunderstood exposure of valley-filling ignimbrite is a classic example of a compositionally zoned deposit (fig. 26). The misunderstanding is centered on the obvious color break from light to dark: the color break has little to do with the

Figure 26. Photograph of a section through the climactic ignimbrite of Mount Mazama, at the Pinnacles. The ignimbrite is about 60 meters thick. Photograph courtesy of http://www.nationalparksblog.com.

composition of the erupted pumice. Instead, the dark color is attributable to post-deposition crystallization of oxide microlites in the rhyodacitic glass.

The upper 10 m or so of the deposit contains an increasing abundance of andesitic scoria, mostly red in color, with abundant coarse hornblende crystals that are from a disaggregated cumulate mush (Bacon and Druitt, 1988; Druitt and Bacon, 1989). These mafic pyroclasts are the main artifact of the compositional zoning.

The pinnacles themselves are fossil fumarole chimneys, whereby ascending hydrothermal vapors lithified the ignimbrite in chimneys, making them more resistant to erosion.

Proceed back to Rim Drive and turn right (east) and go 3.6 miles past the intersection, taking a left turn onto Cloudcap Road. Go 0.8 mile and pull off against the large rocks on the right.

Stop 4: Precaldera Dacite and Welded Fallout

The outcrop at road level reveals a sequence of precaldera rhyodacitic lava and tephra, with relatively steep primary dips. The top of the right side of the outcrop is a resistant deposit of the climactic fallout deposit, underlain by Cleetwood and Llao tephra.

Scramble along the top of the right side of the outcrop at the edge of the vegetation. About 20 m above the top of the roadcut, traverse left onto the steep face to the resistant bands of red pumice. This is a rare example of welded pyroclastic fallout, attributable to the proximity of these deposits to the eruptive vent. The good sorting reveals these rocks as fallout, but most of the clasts are deformed, with their long axes horizontal, partly fused, and exceptionally oxidized.

Optional: continue up to Cloudcap overlook for a west-looking view of the caldera.

Return to the intersection of Rim Drive and turn left and go 2.7 miles, where there is a hard-to-see parking area in the trees on the left side of the road.

Stop 5: Magmatic Inclusions

Walk 100 m northwest through trees, along an overgrown bulldozer track, down the bank to Rim Drive, then left to the andesitic lava exposed in the roadcut. **Be extremely careful of traffic; there is not much room between the road and outcrop here.**

This precaldera lava contains abundant magmatic inclusions that are slightly more mafic than the host. Note that the larger inclusions are porous and have dense, fine-grained rinds. Bacon (1989) attributes the texture to gas-driven filter pressing, which expelled rhyolitic melt that was vapor saturated and formed when the inclusion partly crystallized. As a consequence, the cores of the large inclusions are the more mafic residue.

Turn back heading northwest (left turn out of parking area) on Rim Drive and go 2.1 miles. Park at the west end of the paved turnout on the Crater Lake side of the road.

Stop 6: Wineglass Welded Tuff

The surface here is paved with the Wineglass Welded Tuff, the earliest-phase ignimbrite of the climactic eruption. The deposit thins to the west and thickens to the east, marking the paleovalley into which it was deposited. Its strong welding is in contrast to most of the volume of the climactic ignimbrite and is attributed to eruption from a single vent, as opposed to a voluminous ring-vent. Note the gashes subparallel to the caldera rim, indicating that the rock slumped into the caldera while still hot.

Drive 1.5 miles northwest to a pullout on the lake side of the road.

Stop 7: Cleetwood Lava, Welded Fallout, and Coignimbrite Lag

First, observe the Cleetwood lava that is draped over the caldera wall. This is paradoxical, because the lava is older than the climactic eruption that produced the caldera. Thus, the lava must have still been hot and plastic when the caldera collapsed, and backflowed toward the former summit of the volcano.

Across the road, note the strongly oxidized partly welded fallout deposit on top of the Cleetwood lava. The alteration and welding at the base of the deposit are interpreted as resulting from hot proximal pumice landing on lava that was itself still hot. A deposit of very coarse fallout with thermally oxidized cores in the largest pumices (typical of proximal fallout) lies up the slope, in turn overlain by coignimbrite lag breccia, including one giant block (we are not entirely sure that this block is in place).

Return to Diamond Lake by continuing west on Rim Drive 5 miles to the intersection with the North Entrance Road (Stop 1), turning right down the North Entrance Road, then left (west) on OR–138.

Day 4: Newberry Caldera: Diamond Lake to Portland

The focus of the final day will be the explosive and effusive eruptive products of Newberry caldera (figs. 27, 28). Most of the information reported here comes from the field trip guides of MacLeod and others (1981) and Jensen and others (2009). **Note that Newberry Volcano is located in a national monument. Collecting rocks without a permit is prohibited.**

From Diamond Lake, drive south then east on OR–138 for 22 miles to the intersection with US–97.

Turn left (north) on US–97 and go 62 miles.

Turn right (east) on Paulina Lake Road (FS–21) and drive 13 miles.

Turn right toward Paulina Peak. Drive 4 miles to the summit. This road is steep and rough and cannot be navigated by bus or with trailers.

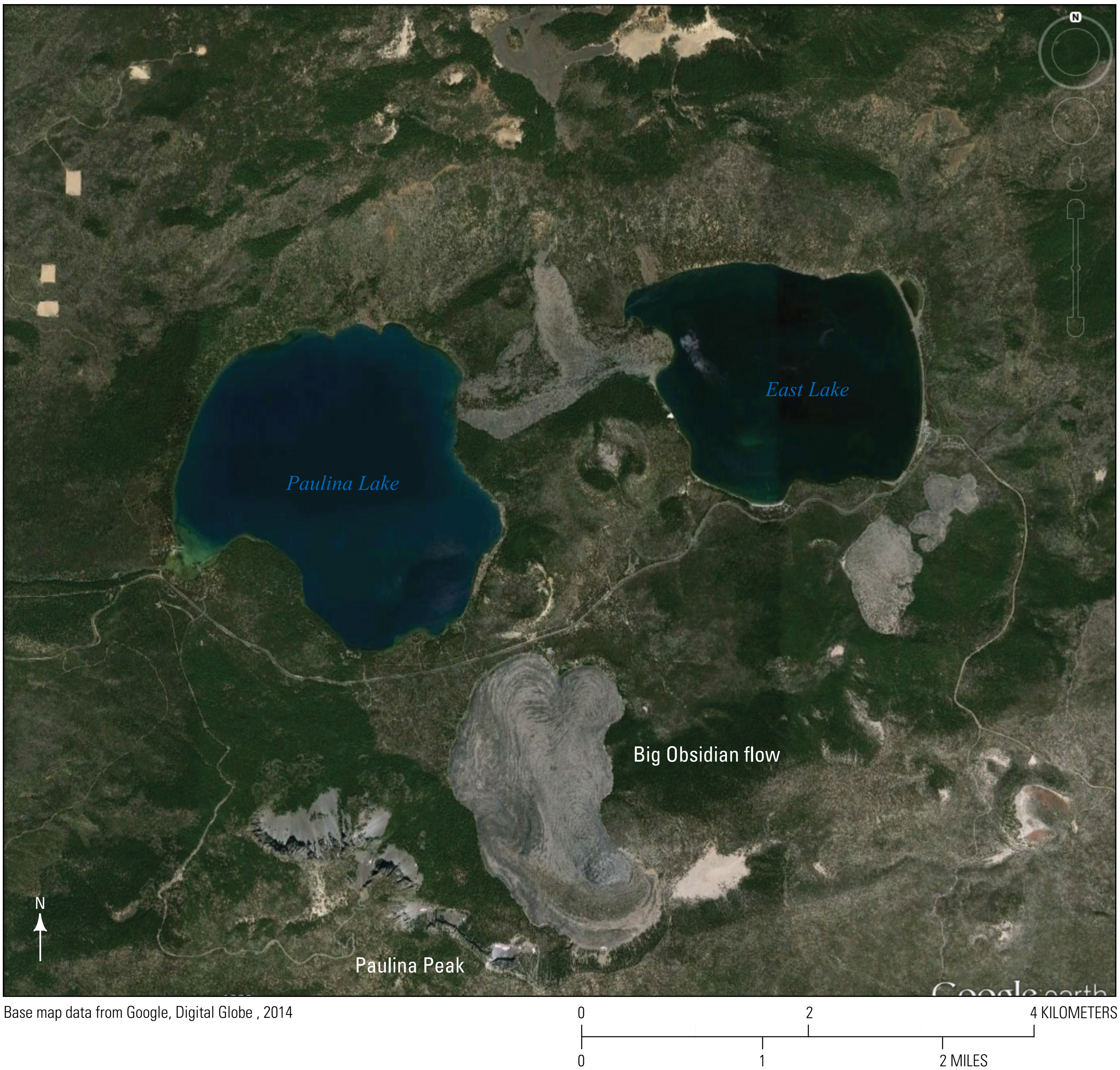
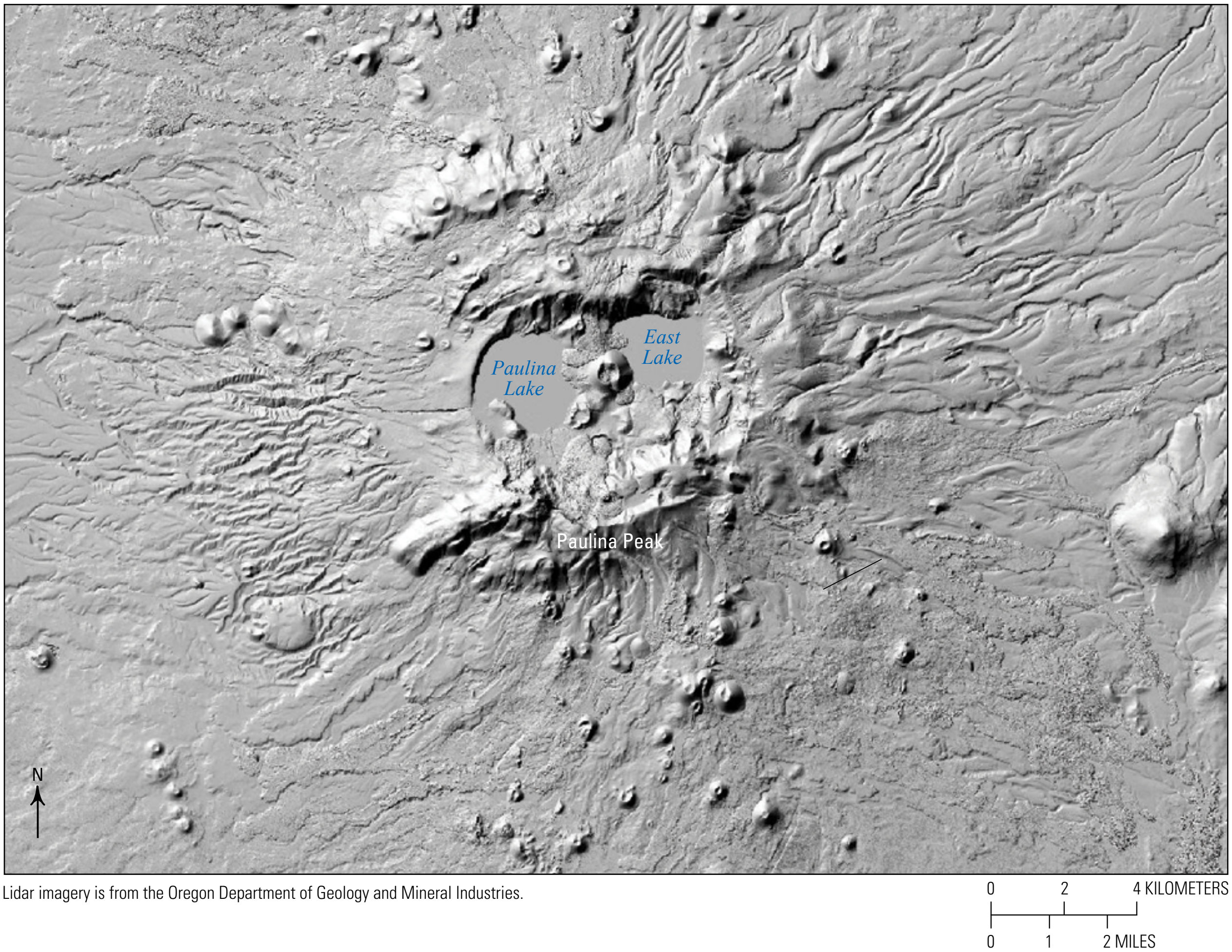


Figure 27. Google Earth view of Newberry caldera, with approximate locations of Day 4 stops indicated.



Lidar imagery is from the Oregon Department of Geology and Mineral Industries.

Figure 28. Lidar image of Newberry Volcano, topped by the caldera that contains Pauline and East Lakes, and bearing hundreds of satellite vents that decorate its flanks.

Stop 1: Paulina Peak

This is an overlook of Newberry caldera from the highest point on the volcano (figs. 27, 28). From here, one can observe the southern set of the more than 400 monogenetic vents that exist on the flanks of Newberry Volcano, as well as East and Paulina Lakes in the caldera floor. Little Crater is a mafic tuff cone in the isthmus between the lakes. Central Pumice Cone is likely from a sub-Plinian eruption of rhyolitic pumice. Just to the north is the Interlake Obsidian Flow (~7,100 years ago). East Lake fissure (~6,100 years ago) can be seen cutting the caldera wall north of its namesake. To the southeast is the conspicuous Big Obsidian Flow (1,250 years ago). The rocks beneath your feet are part of the 83 ± 5 ka Paulina Peak obsidian dome.

Walker Rim, a normal fault just north of Crater Lake, can be seen in the distance to the south, with Mount Mazama immediately to the west (right). On a clear day, one can see the stratovolcanoes of the High Cascades, including Mounts Shasta, Scott, Mazama (Crater Lake), Thielsen, Diamond Peak, all of Three Sisters, Bachelor Butte, Broken Top, Washington, Three Fingered Jack, Jefferson, Hood, and Adams. Fort Rock and Fort Rock Valley are to the southeast.

Return the 4 miles to FS–21. Drive 1.5 miles east on FS–21 and turn left into Little Crater Campground. Proceed to the boat ramp. The outcrop of interest is the bank against the shore.

Stop 2: Paulina Lake Ignimbrite

The ignimbrite of Paulina Lake is the deposit of a pyroclastic density current that was emplaced after the Plinian ash flow but before the lava of the Big Obsidian Flow. The terrain between here and the crater forms ridges and furrows, which are likely primary features. Abundant elutriation pipes are attributable to deposition on the wet ground of the shoreline.

Return to FS–21, and take a left (east). Go 0.5 mile to the Big Obsidian Flow parking lot.

Stop 3: Big Obsidian Flow

Hike to the upper viewpoint at the end of the trail. Note the features characteristic of rhyolitic lavas during the ascent: flow banding, spatially variable vesiculation, and isoclinal folded flow banding. More than 40 explosion craters are characteristic features of the Big Obsidian Flow, believed to form when gas-rich magma erupts vigorously through the solid crust.

Turn right (east) on Road 21. Go 1.7 miles and turn left into the East Lake picnic area and boat ramp.

Stop 4: East Lake Tuff Ring

Walk about 100 m east along the lakeshore. Variably stratified palagonite tuff, consisting of interbedded deposits of dilute pyroclastic density currents and fallout, is exposed by wave erosion from the lake; impressive bomb sags deform the strata. Some of the layers are made almost entirely of spherical armored lapilli. The striking change in dip along the shoreline indicates the boundary between the inward-dipping crater-filling beds and the outward-dipping flank deposits, hence marking the upward-and-outward migration of the crater rim.

Return to FS–21 and turn left (east). Proceed 1 mile then turn right onto Newberry Crater Road. Follow Newberry Crater Road for 2 miles to just past the caldera rim, keeping left at the Y intersection with FS–2127.

Stop 5: Plinian and Sub-Plinian Fallout

This is the fallout from the initial phase of the Big Obsidian Flow eruption, and its total volume and dispersal indicate sub-Plinian to Plinian eruptive style. It is more than 2 m thick at this location and thins to about 50 cm at the eastern base of Newberry Volcano. The isopachs of this deposit are almost straight east and very narrow in north-south section (Gardner and others, 1998).

Note the prismatic fracture patterns in many of the pumices, suggesting late-stage fragmentation, perhaps some on impact. Most of the lithic fragments are centimeter-scale prismatically faceted obsidian chunks. Obsidian in the lower and upper parts of the deposit is accompanied by subequal amounts of lithic fragments and therefore is thought to have originated from predecessor dikes and wallrock (Rust and Cashman, 2007). Obsidian greatly increases in proportion to lithic clasts immediately above the fine ash-rich layer and is thought to be from mobilization of magma that had previously solidified within the conduit.

About half way up the deposit is a fine-grained layer that may be an intra-Plinian surge (that is, a dilute pyroclastic density current) deposit. The fallout is narrowly dispersed, indicating very strong winds from the west. Fine ash from this deposit has been identified in central Idaho.

Return to Portland, about 4 hours from Stop 5, by returning to US–97, turning right (north) and then west onto US–26.

Acknowledgments

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Appendix—Supplemental Educational Materials Relevant to Field Trip

It is our hope that educators at all levels might make use of this guide. We include online resources that may be helpful, followed by exercises that can be adopted for teaching in the field.

Educational Resources

Columbia River Basalt

USGS summary about the Columbia River Basalt:
https://volcanoes.usgs.gov/observatories/cvo/cvo_columbia_river_basalt.html
Summary of basic background information on the Columbia River Basalt:
http://volcano.oregonstate.edu/book/export/html/486
Great photos of pillow basalt exposures in the Columbia River Basalt:
http://blogs.agu.org/mountainbeltway/2016/05/18/pillow-basalt-exposures-columbia-river-basalts/
Digital Geology of Idaho module 10, summarizing information about the Columbia River Basalt province:
http://geology.isu.edu/Digital_Geology_Idaho/Module10/mod10.htm
Lava flow inflation time lapse videos (from Hawaii):
https://www.youtube.com/watch?v=MJJYk9MiNuY;
https://www.youtube.com/watch?v=0-XwsJpUM60
Pillow lava formation video:
https://www.youtube.com/watch?v=DdIUuUY0L9c
Examples of basic eruption rate calculations (using Hawaii):
http://serc.carleton.edu/quantskills/activities/botec_erupt.html;
http://serc.carleton.edu/quantskills/activities/botec_lava.html
Alternative formation mechanism for the Columbia River Flood Basalts:
http://www.icr.org/article/were-huge-columbia-river-basalts-formed-flood/ (really just kidding; but this could actually serve as fodder for an interesting class debate)

Mantle Plumes

Exercise using age of volcanism and ash distribution thickness to explore mantle plume activity at Yellowstone:
http://serc.carleton.edu/NAGTWorkshops/intro/activities/28909.html
Structured debate about the plume controversy:
http://serc.carleton.edu/NAGTWorkshops/deepearth/activities/40441.html

Crater Lake

Geologic resources inventory of Crater Lake National Park (includes geological and GIS-based downloadable files):
http://nrdata.nps.gov/geology/gri_data/gis/crla/crla_gis_readme.pdf
Petrology exercise exploring compositional diversity in volcanic materials from Yellowstone and Crater Lake:
http://serc.carleton.edu/NAGTWorkshops/geochemistry/activities/9324.html
Summer field course in geology and biology to Crater Lake and Newberry Volcano:
http://nagt.org/nagt/teaching_resources/field/fieldtrips/crater_newberry.html
Exercise to guide students through calculating the volume of water in Crater Lake:
http://serc.carleton.edu/sp/ssac/national_parks/examples/crater_lake_volume.html
USGS website on Mount Mazama and Crater Lake's formation:
https://pubs.usgs.gov/fs/2002/fs092-02/

Newberry Crater

Description of a cinder cone study examining their history and erosion at Newberry Volcano, which could be used as a basis for a useful field exercise:
http://serc.carleton.edu/vignettes/collection/36642.html
USGS background information on Newberry Crater:
https://volcanoes.usgs.gov/volcanoes/newberry/newberry_geo_hist_81.html

Spokane Flood

Extensive USGS source on the Spokane Flood:
https://www.nps.gov/parkhistory/online_books/geology/publications/inf/72-2/sec4.htm
NASA site discussing the Spokane Flood (and its relevance to research about Mars):
http://www.nasa.gov/topics/earth/features/megaflood-legacy.html
NOVA website about megafloods of the Ice Age:
http://www.pbs.org/wgbh/nova/earth/megafloods-of-the-ice-age.html

Educational Activities for Selected Locations

Day 1, Stop 6: Rattlesnake Tuff

The type locality of the Rattlesnake Tuff (fig. 14) is an ideal place for students to construct a stratigraphic section through a classic variably welded ignimbrite sequence and deduce the processes responsible for each zone.

Day 2, Stop 2: The Blowouts

This is a superb location for students to map the distribution of different vent facies, using average clast size and the extent of fusion of spatter clasts. This takes from 1 to 2 hours.

Another informative exercise is for the students to determine the eruptive history (order of eruption) of the spatter and the lavas that erupt from the conjoined craters along the fissure. Such an exercise takes 1 to 2 hours.

Day 2 or 4: Crater Lake Fall Deposits

The fall deposits from the 7,700-year-old Mount Mazama climactic eruption are distributed to the north-northeast of the volcano and are well exposed along Route 97. While driving south toward the park on Day 2 following Stop 4, stop every few miles from La Pine to Chemult (in areas that have not been developed) in order to create isopach and isopleth data to examine changes in fall distribution. Have students measure the five largest pumice and five largest lithic clasts at each location (for an isopleth map) and collect field observations of the deposits, which change dramatically along this route. If time allows, also have students collect a bucket of fall material from locations set back from the highway. Be sure that the material is undisturbed by road construction or other human activities. If sufficiently undisturbed, have students dig pits to measure the thickness of the fall deposit as well (for an isopach map). Using a set of sieves and a balance, determine the mass of each size fraction and have students construct histograms of the material's size distribution to determine average clast size and degree of sorting at each site (granulometric analysis). Once completed, histograms of the clast-size data illustrate the concepts of how clast diameter increases and how the deposits becomes more poorly sorted toward the vent. Isopach and isopleth data can either be extrapolated from this transect or reconciled with existing maps of the available Mazama deposits (such as, Young, 1990). From Chemult to the caldera itself, the fall deposits are mostly covered by ignimbrite. If there is no time for this exercise on Day 2, this may also be done in reverse (Chemult to La Pine) on Day 4 on the way to Stop 1. It is worth a full day's effort.

Day 3, Stop 7: Cleetwood Lava

The Cleetwood lava location is a superb place for a thought exercise based on field observations of fall deposits on various types of lava. Have students construct a stratigraphic column or simple sketch of the lava exposure along the road at this stop (fig. 29), as well as the overlying fall and pyroclastic density current deposits. Be sure that they include detailed field observations about the color, texture, and extent of fusion between clasts. Ask them to compare these pumice clasts with those observed at other nearby locations. Their ultimate goal should be to propose an explanation for the appearance of these pumices and their relationship to the red and grey Cleetwood lava samples (fig. 29). This exercise is a useful illustration of how dramatically fall deposits can be altered simply by landing on a hot lava flow.

Day 4, Stop 2: Paulina Lake Ignimbrite

Have students perform a granulometric analysis using the same methods as they did for the fall deposits around Mount Mazama. Comparison of the histogram from this single site to the ones for the fall will illustrate the distinct difference in the extent of sorting between a fall deposit and a pyroclastic density current.

Day 4, Stop 4: East Lake Tuff Ring

The East Lake tuff ring is an ideal location to deduce the process responsible for forming a tuff ring (hydrovolcanic processes). Have students sketch the deposits and make detailed field observations of the tuff ring. See field stop description above for relevant details. This is a particularly effective exercise if it can be paired with a similar set of field observations from a cinder cone.

Day 4, Stops 4 to 5: Newberry Fall Deposits

Similar measurements of Newberry fall deposits (thickness of fall deposits, maximum pumice and lithic clast sizes) can be performed on Road 21 leading away from East Lake at Newberry Crater. Granulometric analysis is particularly effective in this area owing to the lack of disturbance of the deposits along the unpaved road. Have students prepare a histogram for each sample site, then examine how extent of sorting and average clast sizes change with distance from the vent.

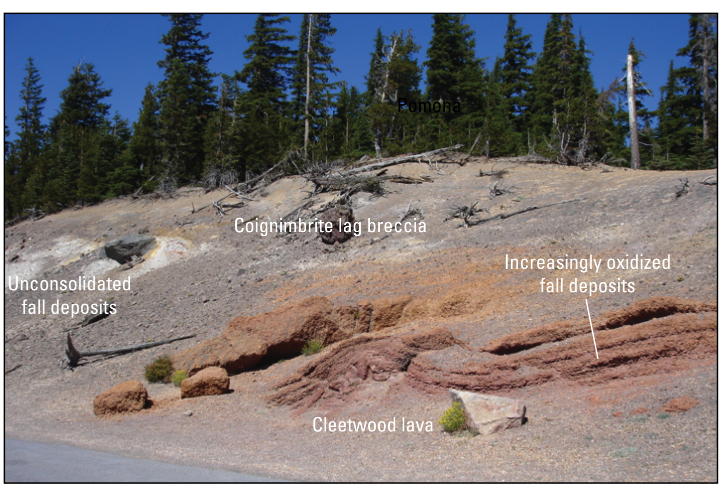

Figure 29. Photograph of Mazama fall deposits over Cleetwood Cove Dacite. Note progression from unconsolidated, white pumice (left) to increasingly welded and oxidized pumice, which were deposited more directly on top of the still-hot Cleetwood flow.

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