Field-Trip Guide to the Geologic Highlights of Newberry Volcano, Oregon

Scientific Investigations Report 2017–5022–J2

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

Cover: Newberry Volcano, Oregon, is the largest volcano in the Cascades volcanic arc. This north-facing view taken from the volcano's peak, Paulina Peak (elevation 7,984 feet), encompasses much of the volcano's 4-by-5-milewide central caldera, a volcanic depression formed in a powerful explosive eruption about 75,000 years ago. The caldera's two lakes, Paulina Lake (left) and the slightly higher East Lake (right), are fed in part by active hot springs heated by molten rock (magma) deep beneath the caldera. The Central Pumice Cone sits between the lakes. The mostly treeless, 1,300-year-old Big Obsidian Flow, youngest lava flow on the volcano, is surrounded by forest south of the lakes. Photograph by Robert Jensen.

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By Robert A. Jensen and Julie M. Donnelly-Nolan

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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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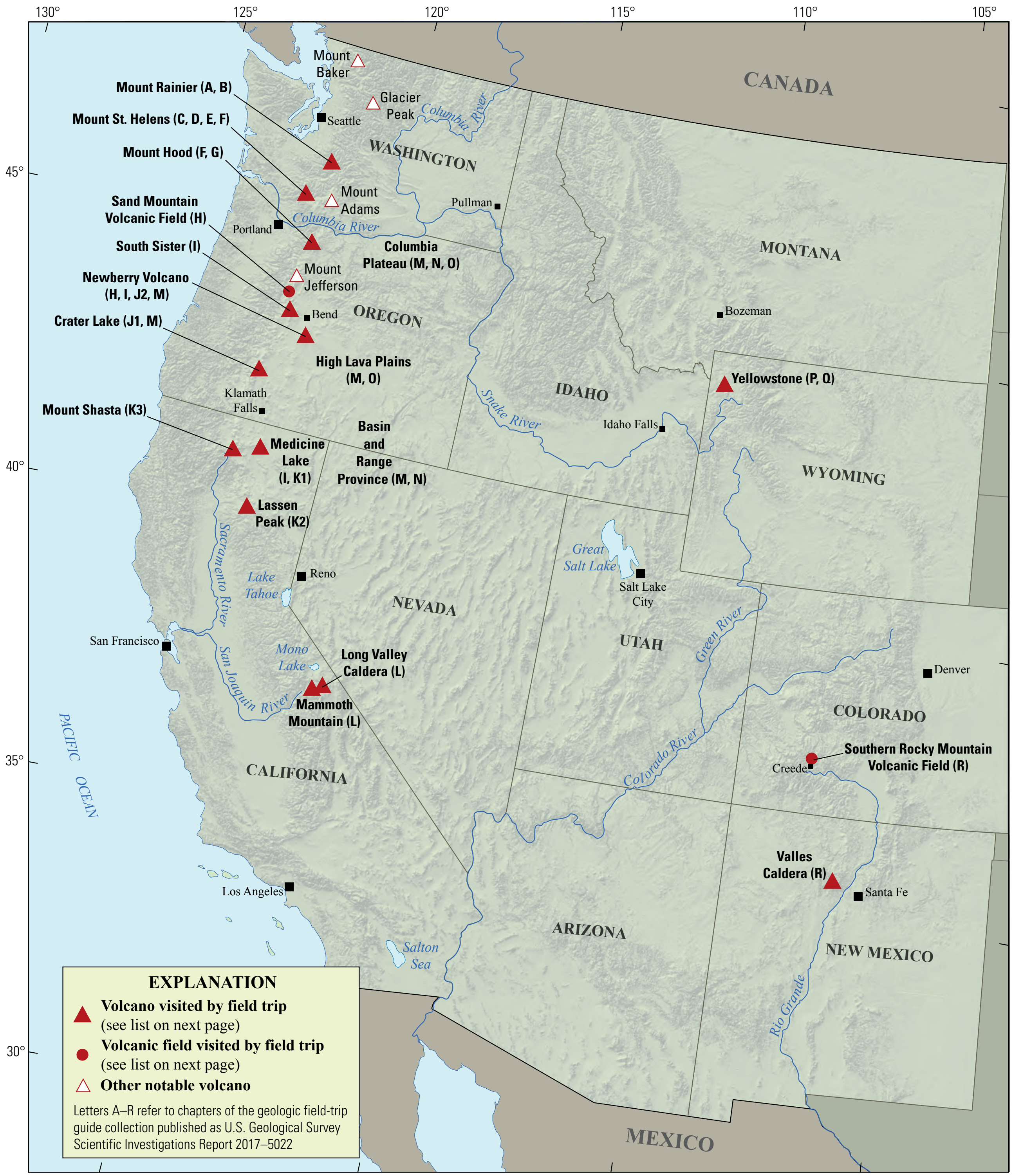
Field-trip committee, IAVCEI 2017



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.

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Field-Trip Guide to the Geologic Highlights of Newberry Volcano, Oregon

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Introduction

Newberry Volcano and its surrounding lavas cover about 3,000 square kilometers (km^2) in central Oregon (figs. 1, 2). This massive, shield-shaped, composite volcano (fig. 3) is located in the rear of the Cascades Volcanic Arc, ~60 km east of the Cascade Range crest. The volcano overlaps the northwestern corner of the Basin and Range tectonic province, known locally as the High Lava Plains, and is strongly influenced by the east-west extensional environment. Lava compositions range from basalt to rhyolite. Eruptions began about half a million years ago and built a broad composite edifice that has generated more than one caldera collapse event. At the center of the volcano is the 6- by 8-km caldera, created ~75,000 years ago when a major explosive eruption of compositionally zoned tephra led to caldera collapse, leaving the massive shield shape visible today. The volcano hosts Newberry National Volcanic Monument (fig. 4), which encompasses the caldera and much of the northwest rift zone (fig. 5) where mafic eruptions occurred about 7,000 years ago. These young lava flows erupted after the volcano was mantled by the informally named Mazama ash, a blanket of volcanic ash generated by the eruption that created Crater Lake about 7,700 years ago (Bacon and Wright, 2017). This field trip guide takes the visitor to a variety of easily accessible geologic sites in Newberry National Volcanic Monument, including the youngest and most spectacular lava flows. The selected sites offer an overview of the geologic story of Newberry Volcano and feature a broad range of lava compositions.

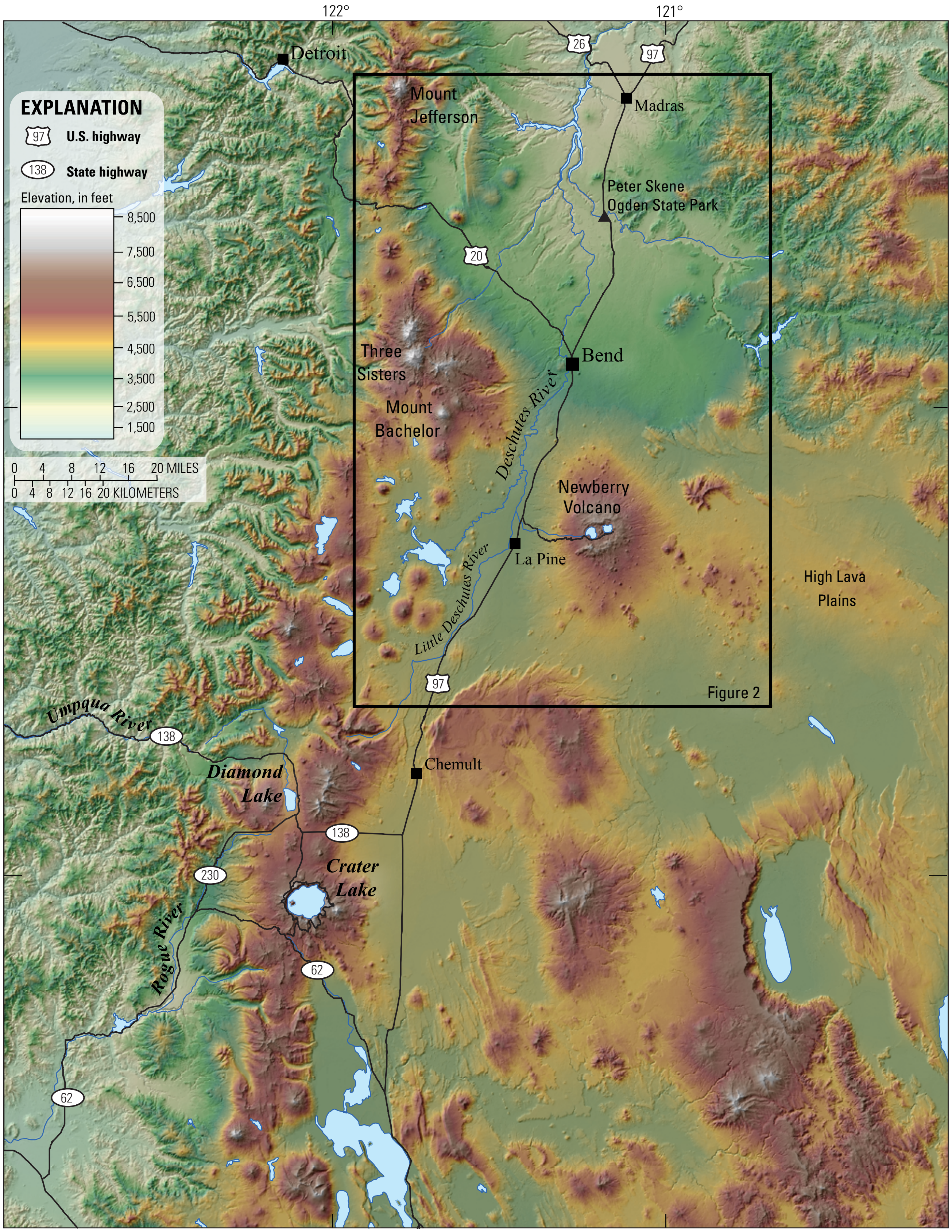
Newberry's most recent eruption took place about 1,300 years ago in the center of the caldera and produced tephra and lava of rhyolitic composition (Stop 2; fig. 6). A significant mafic eruptive event occurred (Mckay and others, 2009) about 7,000 years ago along the northwest rift zone. This event produced lavas ranging in composition from basalt to andesite, which erupted over a distance of 35 km from south of the caldera to Lava Butte (Stop 8) where erupted lava flowed west to temporarily block the Deschutes River (Stop 9). Because of Newberry Volcano's proximity to populated areas, the presence of hot springs within the caldera (Stop 3), and the long and recent history of eruptive activity (including explosive activity), the U.S. Geological Survey installed monitoring equipment on the volcano (Donnelly-Nolan and others, 2011). A recent geophysical study by Heath and others (2015) indicates the presence of magma at 3 to 5 km beneath the caldera.

The writing of this guide was prompted by a field trip to Crater Lake and Newberry Volcano organized in conjunction with the August 2017 IAVCEI quadrennial meeting in Portland, Oregon. Both field trip guides are available online. These two volcanoes were grouped in a single field trip because they are two of the few Cascades volcanoes that have generated calderas and significant related tephra deposits.

A Short History of Geologic Work at Newberry Volcano

Newberry Volcano was named for John Strong Newberry (1822–92), who in 1855 was assistant surgeon and geologist on the Williamson and Abbot survey party, which was sent to explore for a railroad route between the San Francisco Bay area and the Columbia River. Although he was the first trained geologist to pass through central Oregon, he never explored Newberry Volcano. In 1903, Israel Russell visited the area during a horseback reconnaissance of central and eastern Oregon (Russell, 1905) and proposed the name Mount Newberry. The name was never adopted, but the caldera became formally known as Newberry Crater. During the early 1930s, Howell Williams did reconnaissance mapping of the volcano and introduced the name Newberry volcano (Williams, 1935). In 2003 the name Newberry Volcano was formally recognized after Larry Chitwood, former geologist for the Deschutes National Forest, championed the name through the geographic names process.

The combination of hot springs and young silicic volcanism suggested Newberry Volcano as a target for geothermal energy exploration. In 1978, the U.S. Geological Survey began research drilling in the center of the caldera (Sammel and others, 1988; Keith and Bargar, 1988) and encountered a temperature of 265 °C at 3,058 feet (ft) (932 m). Geothermal drilling by private industry (Swanberg and others, 1988) followed and has continued intermittently (Frone and others, 2014). Geologic and geophysical work that began at the volcano in the 1970s resulted in a variety of studies published in a special issue of the Journal of Geophysical Research (MacLeod and Sherrod, 1988). These studies, together with geologic mapping by MacLeod and others (1995), provided a basic framework for understanding the volcano.



Base derived from U.S. Geological Survey National Elevation Dataset 30-meter digital elevation model.

Figure 1. Shaded-relief map of central Oregon showing Crater Lake and Newberry Volcano as well as place names and principal roads relevant to IAVCEI 2017 field trip. Box indicates area of figure 2.

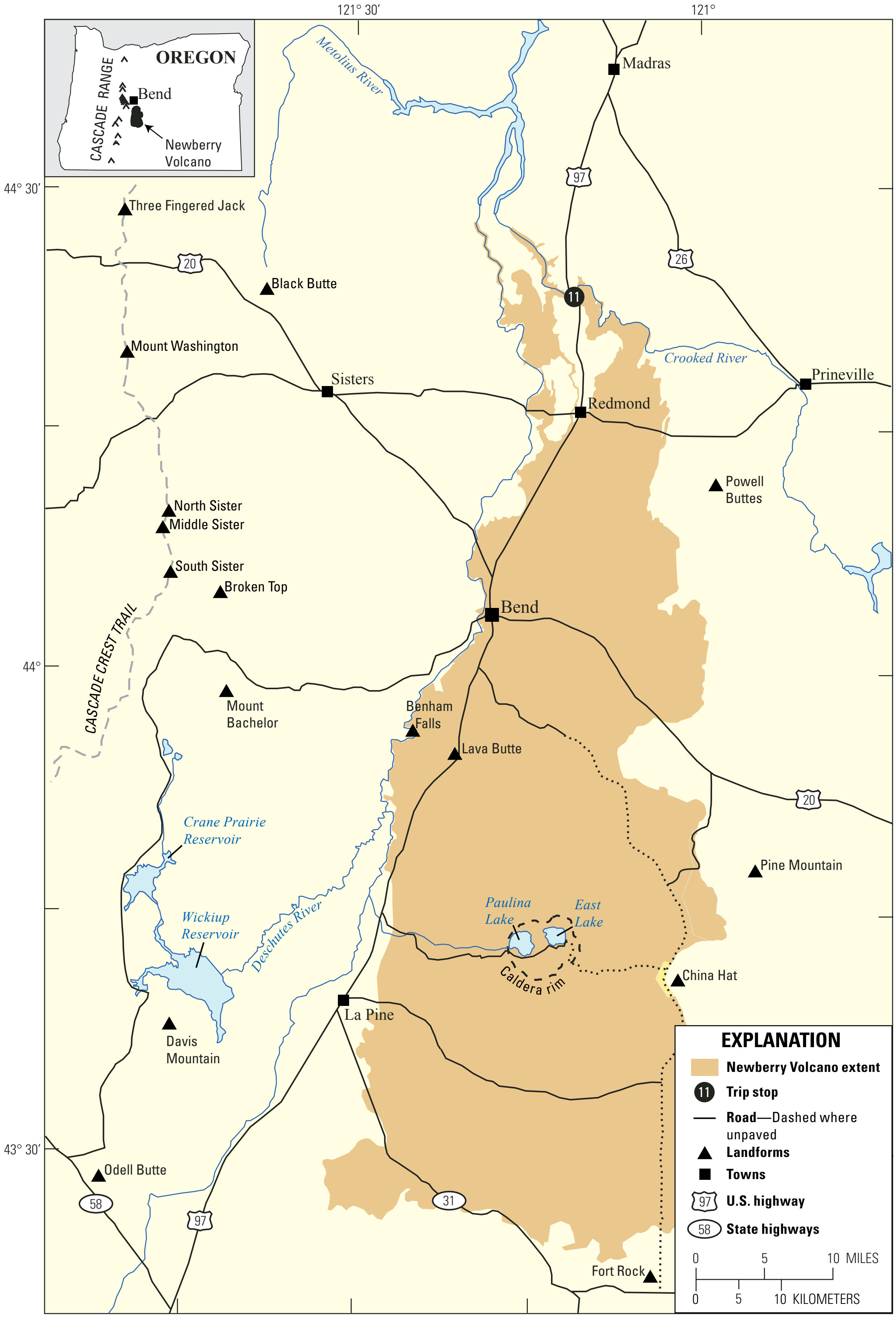


Figure 2. Map showing extent of lavas from Newberry Volcano (orange) and location of Stop 11.

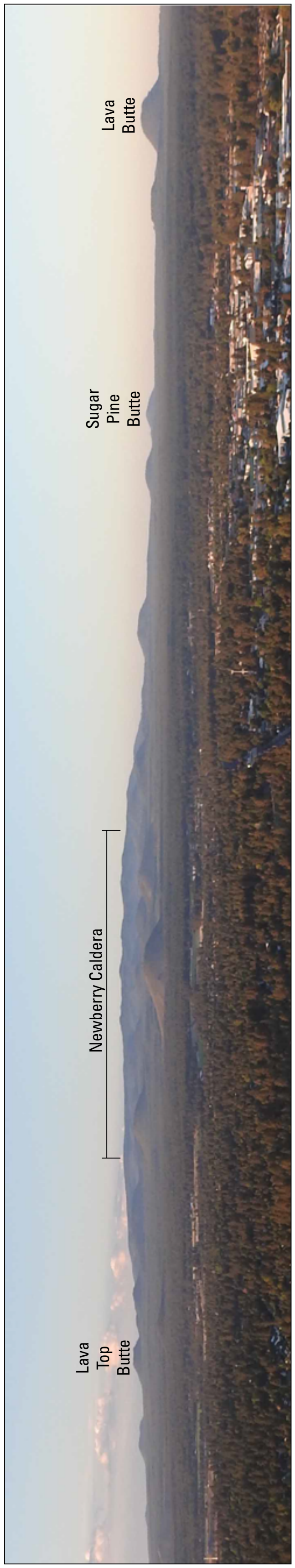


Figure 3. Panoramic photograph of Newberry Volcano, looking south from Pilot Butte (Stop 10) in the city of Bend. Stops 1–5 are in, or immediately adjacent to, Newberry caldera. Stop 8 is at the base of Lava Butte.

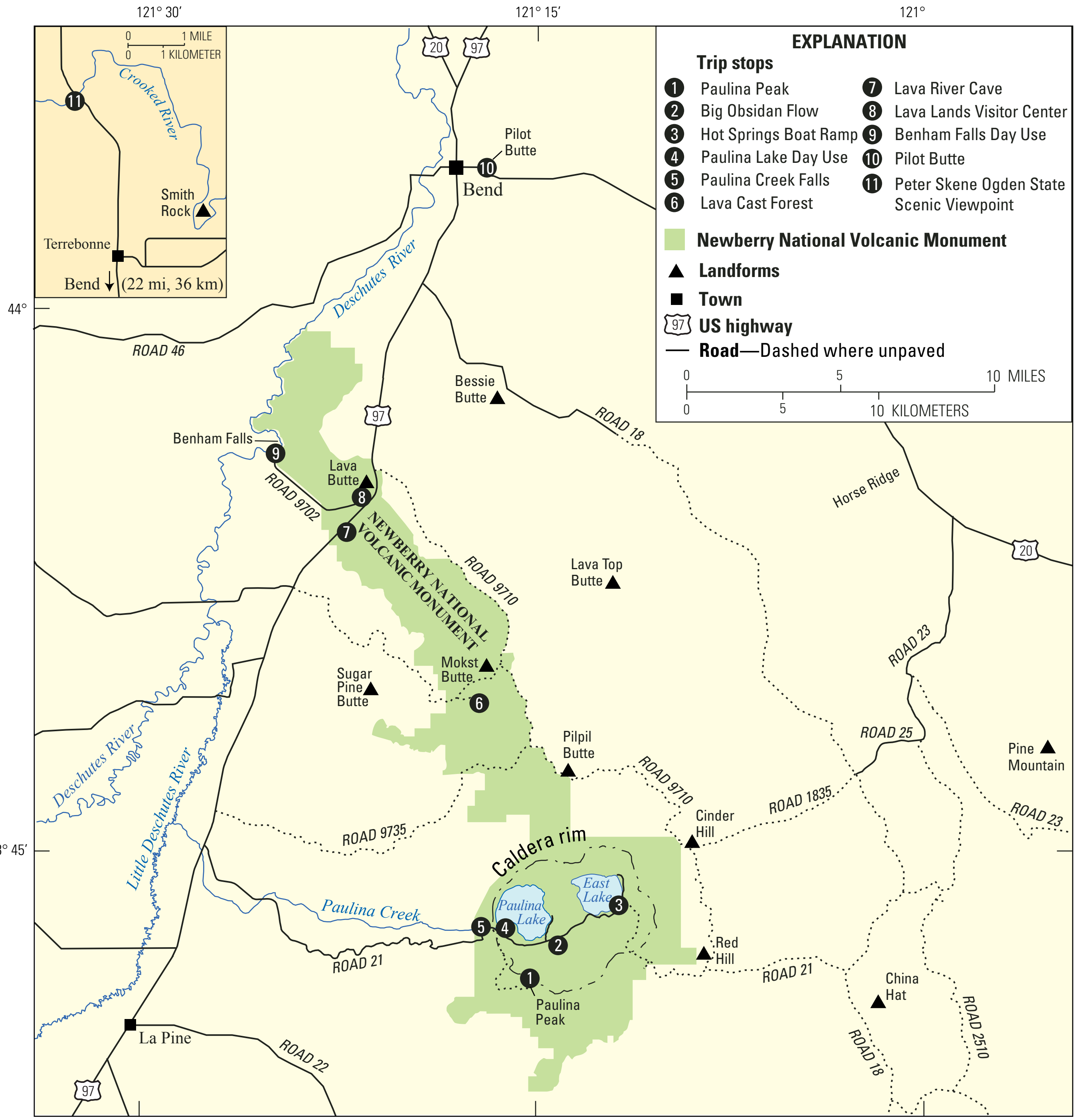


Figure 4. Map showing field-trip stops. Area in green is Newberry National Volcanic Monument, a U.S. Forest Service monument established in 1990 within Deschutes National Forest.

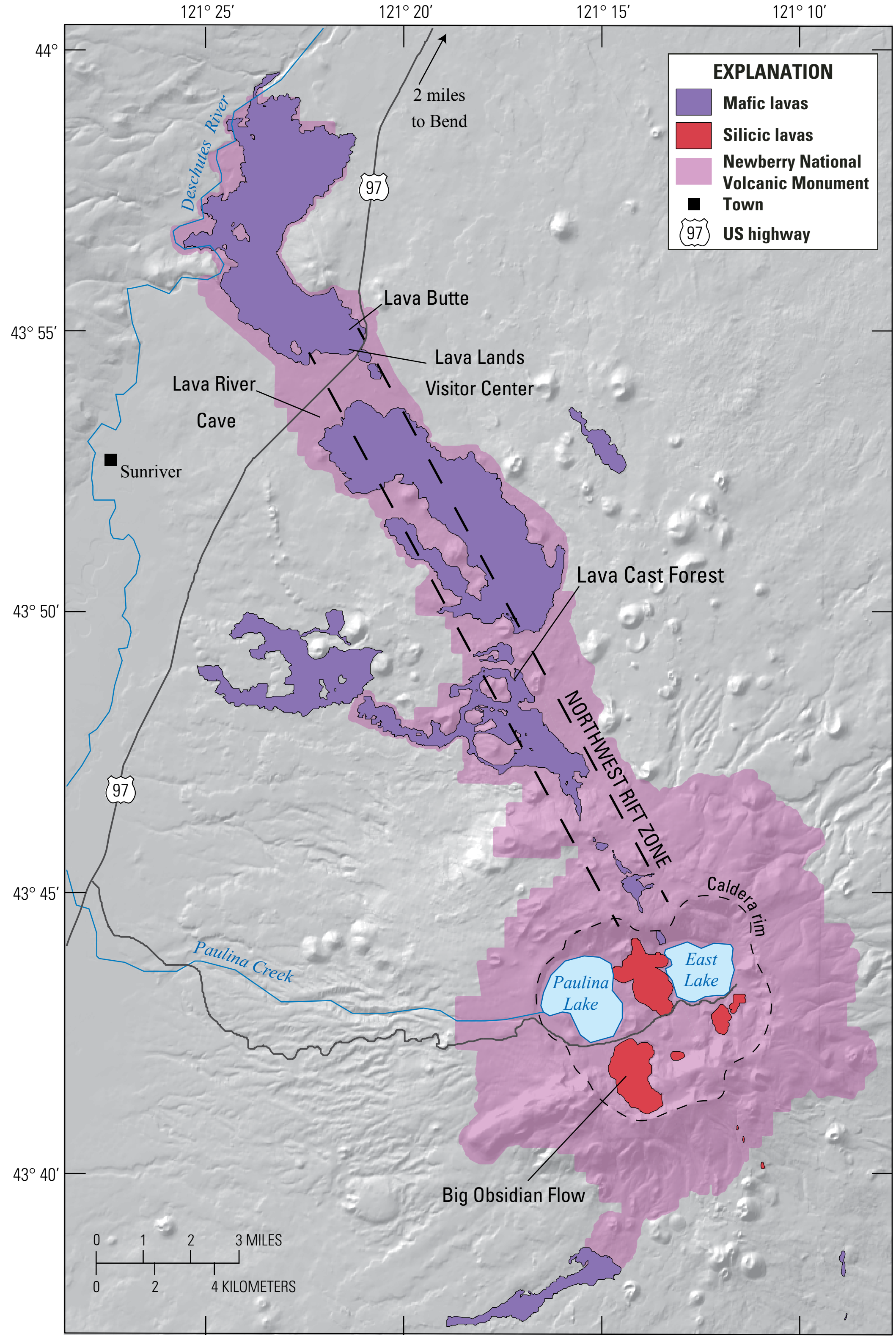


Figure 5. Shaded-relief image showing distribution of lavas that erupted at Newberry Volcano after the Mazama ash was deposited over the volcano ~7,700 years ago when Mount Mazama erupted catastrophically to form Crater Lake. Mafic lavas that erupted about 7,000 years ago are shown in purple. Silicic lavas from several different post-Mazama eruptions, including the youngest lava at Newberry Volcano, the Big Obsidian Flow, are shown in red (Stop 2).

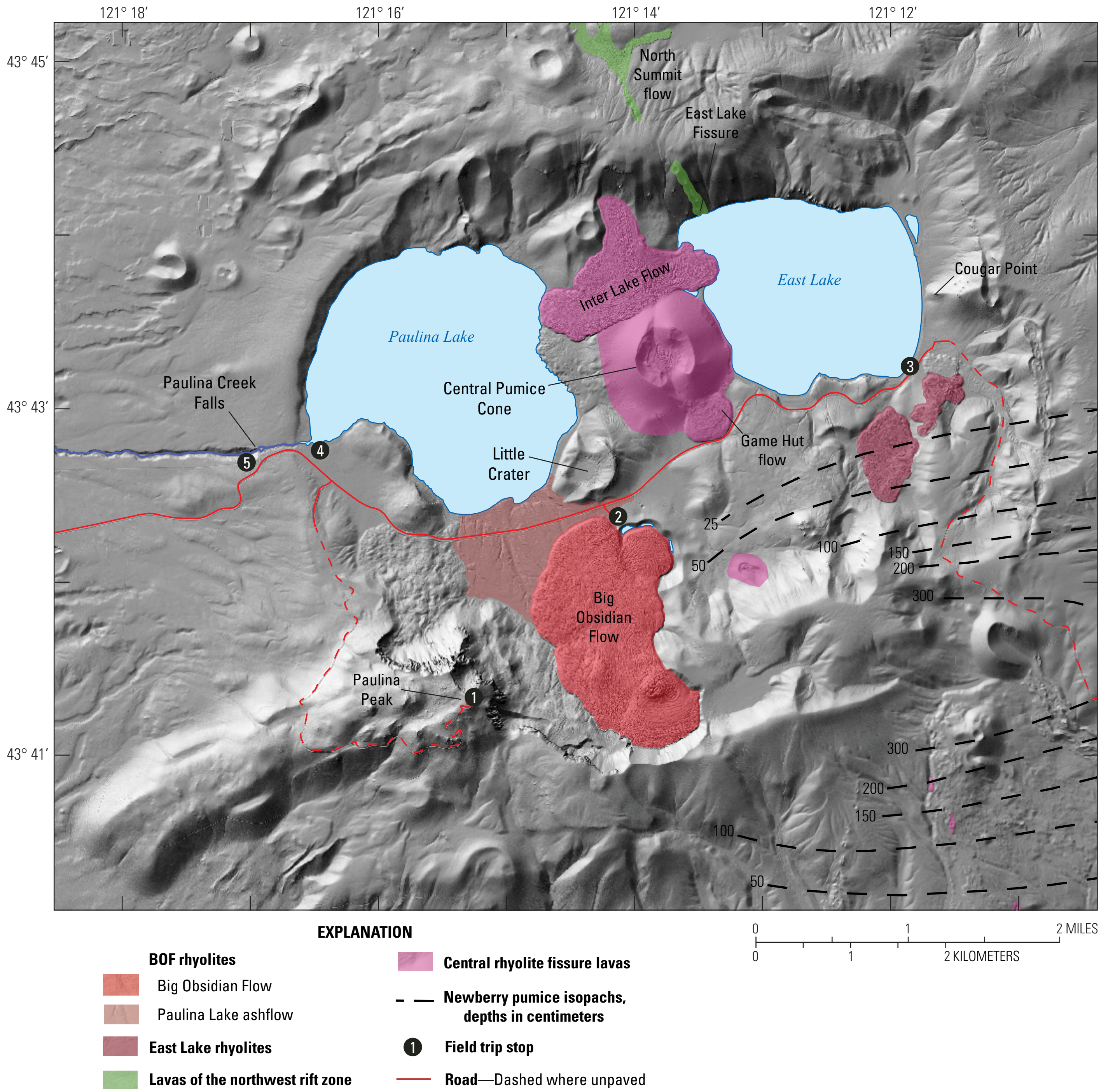


Figure 6. Lidar shaded-relief image of Newberry caldera shows the locations of Stops 1–5. Also shown are lavas erupted since deposition of the Mazama ash from the eruption of Mount Mazama ~7,700 years ago to form Crater Lake. Dashed contours show thickness of ash (MacLeod and others, 1995) erupted during early phase of the youngest eruption at Newberry Volcano, the ~1,300-yr-old Big Obsidian Flow eruption.

Subsequently, concerns about volcanic hazards prompted detailed geologic studies. New interpretations (Donnelly-Nolan and others, 2004) of the history and tectonic controls on the volcano resulted in a revised understanding of the origin and affinity of this sleeping giant (Donnelly-Nolan and others, 2011). Few studies have been published regarding the age of Newberry caldera. Preliminary argon dating of the pre-caldera rhyolite of Paulina Peak yielded an age of 83±5 ka (Donnelly-Nolan and others, 2004). Basalt that erupted soon after caldera formation, informally known as the basalt of Bend has an argon age of 78±9 ka (Champion and others, 2004). Given the uncertainties and the limited data, Donnelly-Nolan and others (2011) place the age of the caldera at about 75,000 years, and the volcano's oldest lavas at about 400,000 years.

Newberry Volcano is located east of the High Cascades at the northwest end of the High Lava Plains, a subprovince of the extensional Basin and Range Province. Some authors view Newberry as a product of a propagating hot spot (Humphreys and others, 2000), which generated a northwest-younging rhyolite progression (Jordan, 2005). However, the preponderance of evidence from recent geologic, geophysical, isotopic, and petrologic work at Newberry Volcano (Donnelly-Nolan and Grove, 2015) indicates that despite its nontraditional shape, Newberry is a Cascades Volcanic Arc volcano fundamentally formed by subduction-related processes. This updated interpretation reflects the role of fluids from the downgoing slab in generating the Newberry magmas (Carlson and others, 2008; Graham and others, 2009; Grove and others, 2009; Till and others, 2013; Mandler and others, 2014). The subducting plate is now known to be at a depth of <100 km, less than 20 km deeper than its location under the Cascade Range crest (McCrory and others, 2012). Recent books intended for a popular audience (Bishop, 2014; Lillie, 2015; Miller, 2014) have not yet incorporated the most recent scientific findings and instead offer interpretations that exclude Newberry from the Cascades Volcanic Arc. Hildreth (2007) correctly placed Newberry in the Cascades rear arc along with the very similar Medicine Lake volcano (Donnelly-Nolan and others, 2008), which is located ~200 km farther south, although he incorrectly described this >1-km-high caldera-centric composite volcano as a distributed volcanic field.

Some Useful References

Numerous references to previous work are cited at the end of this document, but a few selected references will be especially useful to the person following this guide. Online references include a U.S. Geological Survey fact sheet (Donnelly-Nolan and others (2011), and a map poster featuring Newberry Volcano's youngest lavas (Robinson and others, 2015). Additional field trip stops and information are described in Jensen and others (2009), which also includes a table of chemical analyses. Jensen (2015) summarizes historical and geological information and describes several additional field trip routes. A study by Mckay and others (2009) of the lavas erupted ~7,000 years ago along the northwest rift zone includes chemical analyses of this compositionally zoned eruption.

Logistics

The guide describes 11 stops, the first 9 are in Newberry National Volcanic Monument. **No samples may be collected within the monument without a research permit**. Total road mileage from the beginning of the guide to the last stop is about 125 miles (mi). Most roads are paved, with the exception of the road to Stop 1 at the top of Paulina Peak (gravel road, seasonal only, steep and exposed, but worth the drive) and the road to Stop 7 at Lava Cast Forest (good gravel road). The roads to Stop 7 and into the caldera are closed in winter. Parking passes (https://www.fs.usda.gov/detail/deschutes/passes-permits/?cid=stelprdb5355040) are required for Stops 1 through 9, all of which are located within Newberry National Volcanic Monument. Passes can be purchased at the welcome station prior to entering the caldera and at Lava Lands Visitor Center. There is no cell phone coverage within the caldera at the date of this writing (summer, 2016). Weather can be variable from hot to cold and rainy. Boots are not necessary for this trip, but sandals are not recommended. Carrying water, wearing a hat, and using sunscreen are good ideas, as is bringing your camera.

About the Units Used in This Guide

The stop locations listed in this guide are referenced to the WGS84 datum. Road distances are given in miles because U.S. vehicle odometers are in miles (in bold type). Because odometers can vary slightly, be aware that the mileages can vary by ~0.1 mi. Elevations are given in feet because U.S. topographic maps show elevations in feet. Measures of depth are given in both feet and meters, as are trail distances, but other areas, distances, and dimensions are given in metric units.

Road Log (in miles)

0.0 **Newberry junction (U.S. Hwy 97 and County Road 21 to Newberry Caldera) (43°45.121′ N, 121°27.610′ W, Elev. ~4,205 ft)** Newberry junction is the intersection of U.S. Highway 97 and paved Road 21, which provides access to Newberry Caldera, and Paulina and East Lakes. The road junction is located along U.S. Hwy 97 about 6 miles north of La Pine and about 24 miles south of Bend. The road sign points to Newberry caldera. Follow Road 21 to the east.

Lacustrine and fluvial sediments of late Pleistocene age in the area of La Pine occupy a basin between the axis of the Cascade Range and Newberry Volcano. The growth of Newberry Volcano over the last half-million years has blocked channels of the ancestral Deschutes River and forced it to the west. The volcano's growth has also intermittently built a dam at the northern end of the La Pine basin (of which the Lava Butte Flow is the most recent). As the dam has risen, sediments have filled the basin. **2.8**

2.8 Cross Paulina Creek. Paulina Creek is the only flowing water on Newberry and is fed from Paulina Lake. Here, Paulina Creek is shallow and flow is low. Water flow decreases downstream from Paulina Lake as water is lost to the permeable volcanic rocks. An interesting feature of the Paulina Creek drainage is the lack of Mazama tephra (volcanic ash from the eruption that created Crater Lake) at most locations on the valley floor until 3 to 5 m above the current stream level. In addition to the missing Mazama tephra, there are gravel terraces, scoured bedrock surfaces, waterfalls, and boulder trains. These features indicate that since the ash fall ~7,700 years ago there was a large flood along Paulina Creek, which removed the ash in all but a few sheltered locations (Jensen and Chitwood, 1996).

For the next several miles the route primarily crosses nonwelded ash-flow tuff of the caldera-forming eruption that took place ~75,000 years ago. This poorly exposed deposit (MacLeod and others, 1995) covers much of the west flank of Newberry Volcano and is extensively channeled along Paulina Creek and several parallel dry channels. Underlying lava flows have been exposed beneath tuff >30 m thick. Donnelly-Nolan and Jensen (2009) interpreted the dry channels to be the result of erosion by glacial meltwater. **8.5**

11.3 Newberry National Volcanic Monument Welcome Station. Newberry caldera is typically accessible from late May through the end of October. Snow may limit access to some areas of the caldera, especially the road up Paulina Peak, until late June. Stop at the welcome station to purchase a pass, which will allow you to park at Stops 1 through 9 within Newberry National Volcanic Monument. **1.0**

12.3 Road on left to Paulina Creek Falls (sign says Paulina Falls). Bypass for now, we will visit the falls later. **0.3**

12.6 West rim of Newberry caldera. The route crosses over the low west rim (~6,340 ft elevation) of Newberry caldera at the Paulina Lake Lodge Road (left). The road to the lodge crosses a low dam at the outlet of Paulina Lake. From the lodge parking area, the view to the south-southeast shows the truncated pre-caldera rhyolite of Paulina Peak rising about 1,650 ft above the lake (fig. 7). The first dam across Paulina Creek was built at the outlet in 1899. This junction of paved roads covers the site of the oldest known dwelling constructed in the

Figure 7. View south-southeast from west margin of Paulina Lake toward Paulina Peak (Stop 1), at 7,984 feet the highest point on the rim of the caldera. The high viewpoint, ~1,650 feet above the lake, is on the beheaded rhyolite of Paulina Peak, which erupted from vents to the left of the view that were destroyed in the caldera collapse.

western United States, dated at ~9,500 years old. The earliest site use is estimated to be ~11,000 years ago (Connolly and others, 1991, Connolly, 1999). **0.3**

12.9 Paulina Peak junction. The route turns south (right) toward Paulina Peak. This road is not suitable for trailers or motorhomes. The gravel road is single lane with passing turnouts. It winds up the steep and exposed southwest and west sides of the Paulina Peak rhyolite and provides views to the west of the Cascade Range crest and south across the cinder-cone-dotted south flank of Newberry. **0.9**

13.8 Paulina Peak trailhead (2.1 mi [3.4 km] trail to summit of Paulina Peak). The parking area was constructed on the drilling pad for a geothermal drill site. During 1983 and 1984, Occidental Geothermal, Inc., drilled a stratigraphic test well (NC 72-03) at this site to a depth of 4,501 ft (1,372 m) and recorded a bottom temperature of 155 °C. According to Arestad and others (1988), the upper 1,800 ft (550 m) of the hole intersected numerous layers of cinders, lithic tuffs, pumice, mudflows and basalts. The interval from 1,800 to 2,300 ft (550 to 700 m) was predominantly silicic lava flows, from 2,300 to 4,501 ft (700 to 1,372 m) was basaltic andesite. **3.0**

16.8 **STOP 1: Paulina Peak Summit Parking Lot (43°41.367′ N, 121°15.272′ W, Elev. ~7,975 ft)** This spectacular viewpoint provides a panorama on a clear day that spans the state of Oregon and includes Mount Adams (270 km to the north) in Washington State and Mount Shasta (265 km south) in California. To the west is the Cascade Range crest, dominated by the Three Sisters (fig. 8). The view into the caldera encompasses both caldera lakes (Paulina and East Lake) and the rocky surface of the Big Obsidian Flow, which at ~1,300 years old is the youngest lava flow on Newberry Volcano (fig. 9 and Stop 2). The 360° view (fig. 10) from the top of Paulina Peak includes the numerous cinder cones of the volcano's south flank, the rim of Crater Lake caldera ~100 km to the southwest, and Steens Mountain ~250 km to the southeast. Paulina Peak, at 7,984 ft, is the highest point on the rim of the 45 km^2 caldera. In addition to East and Paulina Lakes and the Big Obsidian Flow, the caldera floor displays a wide variety of late Pleistocene and Holocene volcanic features (fig. 6). Between Paulina and East Lakes, Little Crater (basaltic tuff cone) and the Central Pumice Cone (rhyolitic tuff cone) can be seen. Caldera collapse about 75,000 years ago beheaded the rhyolite of Paulina Peak, which

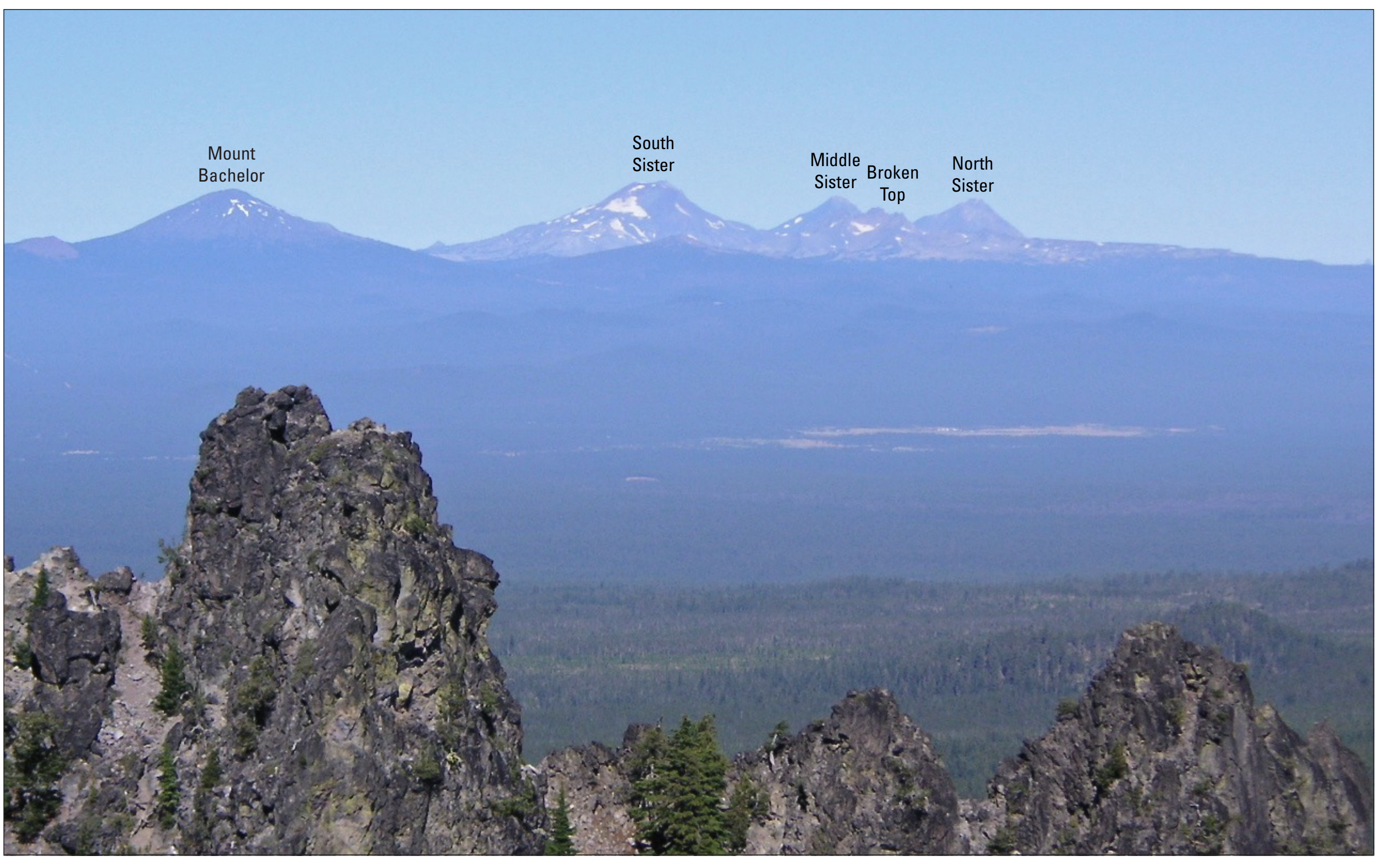


Figure 8. View northwest from top of Paulina Peak (Stop 1) toward the Cascade Range crest. Mount Bachelor is on the left. In the center of view are the Three Sisters (left to right, South, Middle, and North Sister).

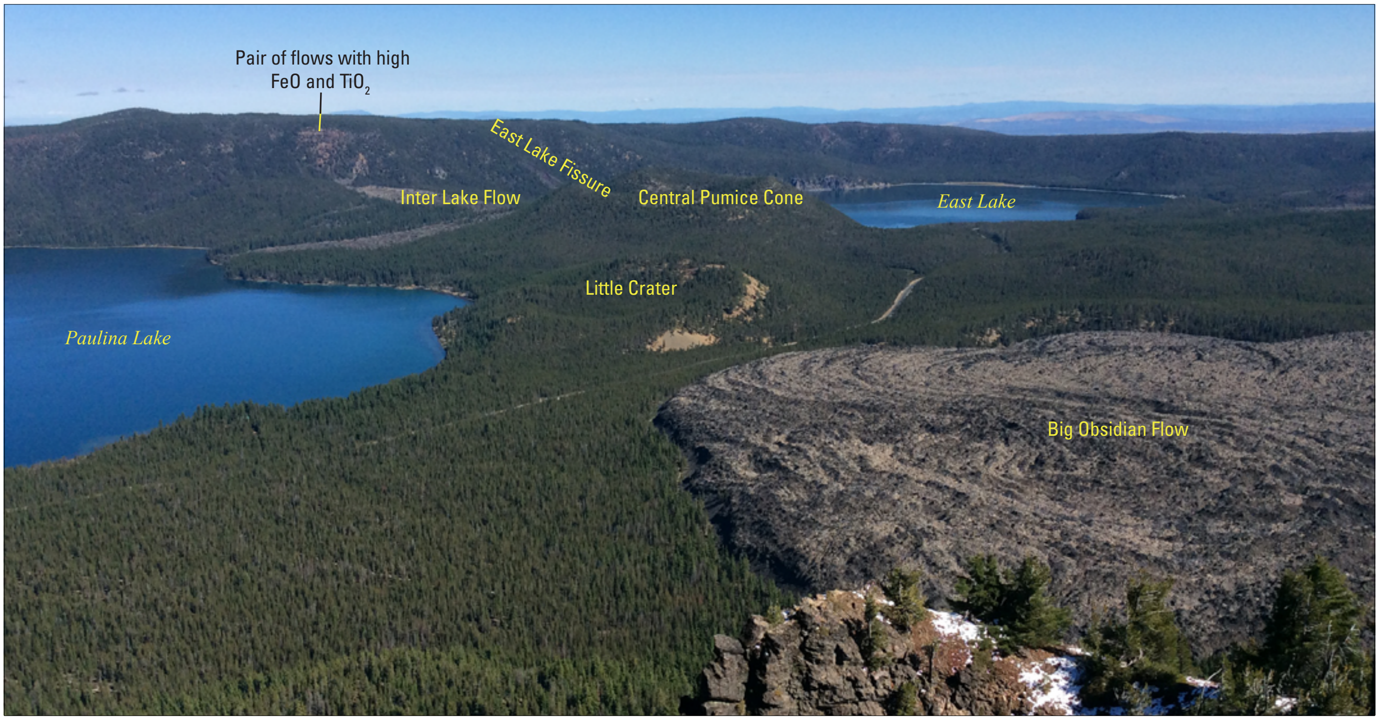


Figure 9. View northeast from Paulina Peak (Stop 1) into Newberry caldera shows the two caldera lakes, Paulina Lake on the left and East Lake on the right. The rocky gray area in the lower right field of view is the north end of the Big Obsidian Flow (Stop 2), which at ~1,300 years old is the youngest lava flow at Newberry Volcano.

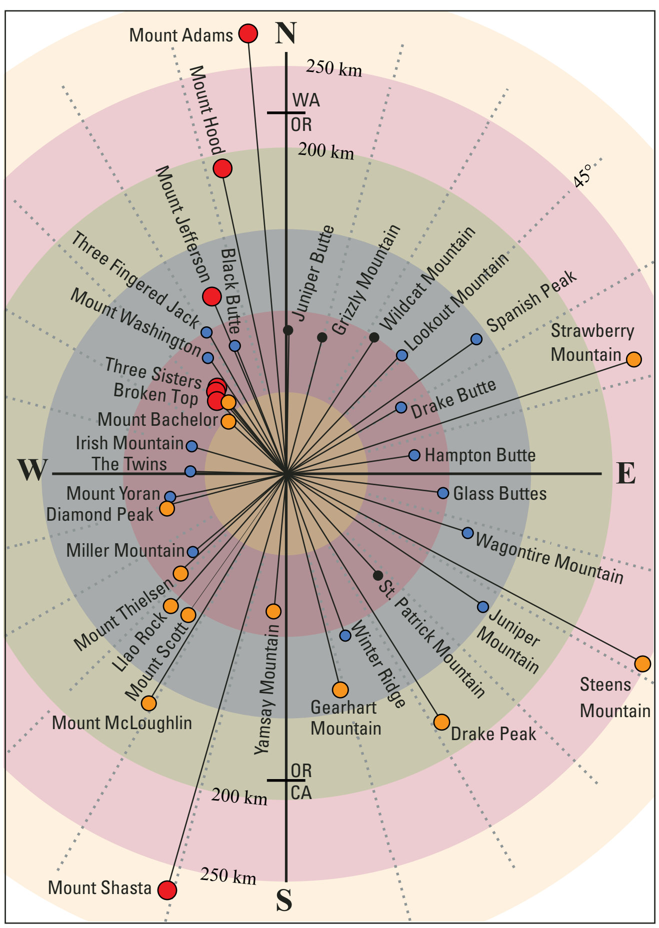


Figure 10. Plot with Paulina Peak (Stop 1) at the center showing azimuths to high points that can be seen from this remarkable viewpoint. On a clear day, the view extends from Mount Adams in Washington State to Mount Shasta in California, distances of ~265 kilometers (km) north and south. Colored circles are each 50-km in width. High points are labeled by height, with the red dots indicating peaks higher than 10,000 feet (ft), orange dots for peaks 8,000 to 10,000-ft-high, blue dots for peaks that are 6,000 to 8,000-ft high, and black dots for notable high points less than 6,000 ft in elevation. Mount Scott and Llao Rock to the southwest are on the rim of Crater Lake caldera.

vented from somewhere above the area of subsequent collapse. Glacial ice has removed the glassy carapace of this rhyolite.

A 1981 U.S. Geological Survey drill hole in the center of the caldera encountered a temperature of 265 °C at 3,051 ft (930 m) (Sammel and others, 1988). Chemistry of rocks and hydrothermal minerals encountered in this drill hole are discussed in Keith and Bargar (1988). Subsequent geothermal exploration involved drilling core holes on the flanks of the volcano. Two such holes are described in Swanberg and others (1988). The prospect of geothermal development within the caldera led concerned Bend citizens to promote the establishment of the Newberry National Volcanic Monument. The monument was established in 1990, precluding additional geothermal drilling within the caldera. Subsequent exploratory drill holes have been at sites outside of the monument, most recently on the upper west side of the volcano (Frone and others, 2014).

Use low gears and drive cautiously down the road to return to paved Road 21. **3.9**

20.7 Turn right (east) on Road 21. **1.9**

22.6 Turn right to Big Obsidian Flow trailhead and parking. **0.1**

22.7 **STOP 2: Big Obsidian Flow Parking Lot (43°42.397′ N, 121°14.143′ W, Elev. ~6,390 ft)** Walk up the paved trail and climb the stairs (fig. 11) to the first viewpoint (fig. 12) on this rhyolitic obsidian flow. The Big Obsidian Flow is the youngest volcanic feature at Newberry and covers just over 2.6 km^2. The flow overlies the Paulina Lake ash flow which was an early phase of the same eruption and has been radiocarbon dated at ~1,300 years old (MacLeod and others, 1995). The earliest phase of the eruption was explosive and produced a strongly eastward-focused (fig. 6) tephra deposit (MacLeod and others 1995) known as the Newberry Pumice, which extends into Idaho (Kuehn, 2002; Kuehn and Foit, 2006).

Continue along the unpaved 0.5-mi-long (0.8 km) loop trail to experience the rugged surface of this spectacular young lava flow. Return to paved road and turn right (east). **2.6**

25.3 Turn left into Hot Springs Boat Ramp and park.

25.3 **STOP 3: Hot Springs Boat Ramp Parking (43°43.203′ N, 121°11.870′ W, Elev. ~6,395 ft)** East Lake covers an area of ~4 km^2 and has an average depth of 66 ft (20 m) with a maximum depth of 180 ft (55 m). The lake has a typical surface elevation between 6,375 and 6,380 feet, ~40 feet higher than Paulina Lake. The lake has no outlet; instead, water drains westward underground.

The view from the southeast shore of East Lake (fig. 13) encompasses lava flows and tuffs of a variety of compositions and ages. Along the south shore to our left (west) are exposures of basaltic tuff from an eruption through water. Only a part of the tuff ring is preserved, but it presumably represents postcaldera mafic eruptive activity. Hot springs occur along the shoreline and were used from 1913 until 1941 by the former East Lake Health Resort. Morgan and others

Figure 11. Photograph showing stairs from Stop 2 that access a loop trail on the north end of the rugged Big Obsidian Flow, which at ~1,300 years old is the youngest lava flow at Newberry Volcano.

Figure 12. Viewpoint along the loop trail on Big Obsidian Flow provides an overlook of part of the rhyolite flow and of the southern caldera rim beyond.

Figure 13. View northwest across East Lake from the Hot Springs Boat Ramp (Stop 3). White Pumice Slide on lower flank of the Central Pumice Cone exposes layers of rhyolitic tuff that make up the rhyolitic tuff ring. The tuff ring is part of a central caldera fissure (fig. 6) eruption that took place after the Mazama tephra was deposited ~7,700 years ago, but prior to the ~7,000-yr-old northwest rift zone mafic lavas. Along the south shore of the lake, marked by greenish patches of algae, are hot springs. Mafic tuff on left is post-caldera in age. High ridge to right of Central Pumice Cone is the northern caldera wall.

(1997) report a temperature of 63.1 °C, but the hot spring water is typically diluted by cold lake water. There is a sizable offshore area of warm water and rising gas bubbles, indicating there are additional submerged hot springs near the shoreline.

Continuing clockwise around the lakeshore, is the White Pumice Slide on the east side of the Central Pumice Cone. This steep, bare area on the flank of the cone exposes rhyolitic tephra of the tuff cone. The cone formed when rhyolite erupted up through water along this part of the post-Mazama central rhyolite fissure. The fissure extends ~5 km south-southeast, from the base of the north caldera wall to a small dome east of the Big Obsidian Flow (fig. 6). The east end of the Inter Lake Flow, which erupted along the northern end of the fissure, is just to the right (north) of the Central Pumice Cone. Tephra that correlates to the central rhyolite fissure was radiocarbon dated and yielded a calibrated age of ~7,300 years (MacLeod and others, 1995).

High on the northern caldera wall is a pair of precaldera basaltic andesite flows of a distinctive composition, having high FeO and TiO_2 (Jensen and others, 2009). Higgins (1973) recognized that these lavas are present in the north, east, and south caldera walls. We have subsequently mapped lavas of this composition to the east and southwest of the caldera, as well as west down Paulina Creek. The distribution of these lavas indicates that the vent area was located above the present caldera.

At the northwest corner of the lake is the East Lake Fissure, which is part of the post-Mazama, ~7,000 year old, northwest rift zone (Mckay and others, 2009). This fissure eruption postdates the central rhyolite fissure eruption. The lava of the East Lake Fissure is andesitic in composition and contains multiple inclusions of rhyolite. On the north-northeast side of the lake is a post-caldera rhyolite flow whose upper part has been stripped of obsidian, presumably by ice.

To the right (east) above the east shore is the informally named Cougar Point, which consists of precaldera iron- and titanium-enriched basaltic andesite and is capped by welded tuff erupted ~75,000 years ago during the caldera-forming eruption.

Return to Road 21 and turn right. **4.7**

30.0 Turn right into Paulina Lake Day Use Area and park.

30.0 **STOP 4: Paulina Lake Day Use Parking Lot (43°42.737′ N, 121°16.552′ W, Elev. ~6,335 ft)** Paulina Lake (fig. 14) covers an area of ~6 km^2 and has an average depth of about 165 ft (50 m) with a maximum depth of 249 ft (76 m). The late Holocene failure of the lake outlet, which resulted in a flood down Paulina Creek, lowered the lake level by nearly 6.5 ft (2 m), creating a terrace around the lake. Subsequent tilting of the caldera floor has submerged the terrace along the west and north shores. The greatest uplift of the terrace is along the southeast shore of the lake (at Little Crater Campground) where the terrace is 18 ft (5.5 m) above the natural lake level (Jensen and Chitwood, 2000).

At the northeast corner of Paulina Lake is an area of hot springs along the shoreline with temperatures as high as 57 °C (Morgan and others, 1997). Offshore, along the northeast perimeter of the lake, a large area of above-normal temperatures and rising gas bubbles extends southward to the north end of Little Crater Campground.

Picnic tables and a rest room make this an appealing place for lunch. Across Road 21 is the small Paulina Lake Visitor Center of Newberry National Volcanic Monument.

Return to Road 21 and proceed west to Paulina Creek Falls. **0.4**

30.4 Turn right to Paulina Creek Falls trailhead and park (Forest Service sign says Paulina Falls but official name is Paulina Creek Falls).

30.4 **STOP 5: Paulina Creek Falls Parking Lot (43°42.652′ N, 121°16.988′ W, Elev. ~6,280 ft)** Take the short paved trail to the overlook. There is also a longer 0.25-mile (0.4 km) unpaved trail to the base of the falls if you have time.

At the falls, Paulina Creek drops nearly 100 ft (~30 m) over a cliff face of welded tuff (fig. 15). Mapped by MacLeod and others (1995) as unit Qat (Quaternary andesitic tuff), the tuff was interpreted as overlying unit Qbt (nonwelded Quaternary basaltic andesite lapilli tuff), which is dissected by Paulina Creek and adjacent dry channels on the west side of the volcano. Donnelly-Nolan and others (2004) recognized that units Qat and Qbt are part of the same compositionally zoned tuff that erupted ~75,000 years ago and contains 53 to 73 weight percent SiO_2 (Mandler and others 2014).

Abundant evidence exists for a large flood down Paulina Creek. Paulina Creek Falls is the uppermost of a series of waterfalls (including informally named Pipeline, Footbridge, and McKay falls along Paulina Creek where the creek crosses solid ribs of basaltic andesite) that were modified by the flood (Chitwood and Jensen, 2000). Just downstream from the viewpoint, the canyon nearly doubles in width and the stream channel is full of large boulders of andesitic tuff. From the viewpoint to the falls the canyon is much narrower, and was likely rapidly cut by the floodwaters.

About 0.5 km upstream is the outlet from Paulina Lake. Evidence suggests the outlet failed as the result of upstream migration of a 1.5–2.4-m-high knickpoint (waterfall) that reached the lake. The andesitic tuff at the lake's outlet is irregularly stratified with varied degrees

Figure 14. Photograph taken from boat ramp at Paulina Lake Day Use Area (Stop 4), looking north across Paulina Lake toward the northern caldera wall. A rocky post-caldera lava flow can be seen at the center of view just above the lake. Hot springs are present along the northern and eastern shores of the lake.

Figure 15. Paulina Creek Falls (Stop 5), where the only creek on Newberry Volcano flows west across eroded tuff that was erupted and deposited here close to what is now the caldera rim during caldera formation by collapse ~75,000 years ago. Height of falls is about 100 feet.

of welding. Erosion of weak layers in the tuff undercuts more resistant layers and could have been the cause of the sudden failure that resulted in the flood. Dating of a variety of flood-associated deposits indicates the flood occurred between about 1,700 and 4,900 years ago (Jensen and Chitwood, 1996).

Return to Road 21. Turn right and proceed west to U.S. Hwy 97. **12.5**

42.9 **Newberry Junction of U.S. Hwy 97 and Road 21 (43°45.121′ N, 121°27.610′ W, Elev. ~4,205 ft)** Turn right (north) on U.S. Hwy 97 to Bend. **8.4**

51.3 Take Exit 153 for South Century Drive (signs point to Sunriver and Lava Cast Forest). Keep right. **0.2**

51.5 Turn right (east) on Forest Service Road 9720 toward Lava Cast Forest. **0.7**

52.2 Pavement ends; continue east on graveled Forest Service Road 9720. To the right is Camp Abbot Cinder Pit, named after the former Camp Abbot that was located at the present site of Sunriver. Camp Abbot was an Army engineer's training center for about a year during World War II. The camp was named for Lieutenant Henry Larcom Abbot of the Pacific Railroad Survey, who camped at the site on September 2, 1855. The cinder pit was originally opened for the construction of Camp Abbot and is located on the largest of ten cinder cones along a 3-km-long mafic fissure. The pit contains iridescent blue, green, gold, and red cinders, which probably resulted from interaction with shallow groundwater, and is an excellent place to look at the materials that make up cinder cones. Depending on current exposures, there may be an exposed dike on the main pit floor. **7.7**

59.9 The informally named Forest Road flow of the northwest rift zone is visible to the left at road junction; keep right to continue to Lava Cast Forest. **0.7**

60.6 **STOP 6: Lava Cast Forest Trailhead (43°49.050′ N, 121°17.295′ W, Elev. ~5,760 ft)** Follow the paved ~1 mi long (1.6 km) loop trail as it passes numerous tree molds (both vertical, [fig.16] and horizontal) in the Lava Cast Forest flow, which is one of many lava flows erupted ~7,000 years ago along the volcano's northwest rift zone (fig. 5). Radiocarbon dates that range from 5,800 to 6,400 years ago initially suggested a span of several hundred years for emplacement of these post-Mazama mafic lavas and tephras. However, mapping of the lavas and tephra deposits (MacLeod and others, 1995) indicated that the eruptions overlapped in age, a conclusion confirmed by paleomagnetic results (Mckay and others, 2009), which show little range in average remnant directions for sample sites from the eruptive episode.

Return to U.S. Hwy 97. **9.1**

69.7 Turn right onto northbound onramp to U.S. Hwy 97. **1.8**

71.5 Take Exit 151 (Cottonwood Road and Lava Lands Visitor Center). **0.2**

71.7 Turn right toward Lava River Cave and Lava Lands Visitor Center. **0.8**

72.5 Turn left in to parking area for Lava River Cave.

Figure 16. Kneeling person looks into a tree mold preserved when post-Mazama mafic lavas of the volcano's northwest rift zone (fig. 6) erupted about 7,000 years ago and flowed through a forest, encasing trees in chilled lava. A paved path here at Lava Cast Forest (Stop 6) takes visitors past numerous tree molds and out onto the rough surface of the young lava flow.

72.6 **STOP 7: Lava River Cave (43°53.712′ N, 121°22.093′ W, Elev. ~4,505 ft)** After parking, rent a lantern if needed, then follow the trail into the collapsed area that allows access into the cave. The cave is cold and unlighted.

Lava River Cave (fig. 17) extends almost 2 km to the northwest. This large lava tube fed a major flow lobe of the informally named post-caldera basalt of Bend (fig. 18) that erupted soon after the caldera formed ~75,000 years ago. This lobe of the basalt flowed west to the Deschutes River where it temporarily blocked the river south of Benham Falls. Other flow lobes extend north into downtown Bend and beyond, as far as the south edge of Redmond, ~50 km from the source. The vents for the basalt are buried by younger lavas to the southeast, but coarse spatter that was likely deposited near the vents has been identified about 3 km north of Lava Cast Forest at an elevation of ~5,600 ft (Jensen and others, 2009).

The cave was discovered by Leander Dillman in about 1889, and was known as Dillman's Cave until 1921. The Shevlin-Hixon Lumber Company deeded 22.5 acres (9.1 hectares) of land surrounding the cave entrance to the State of Oregon in 1926 for a state park. The area remained a state park until 1981 when it was acquired by the Deschutes National Forest in a land exchange. The main northwestern part of the cave is 6,180 ft (1,880 m) long and drops 170 ft (52 m) in elevation. The southeastern (closed) part of the cave is 1,600 ft (490 m) long.

Continue through parking area and then turn left toward Lava Butte. **1.4**

74.0 After passing under U.S. Hwy 97, turn right and then left to access Lava Lands Visitor Center. **0.1**

74.1 Lava Lands Visitor Center Welcome Station. Parking fee required. Lava Lands Visitor Center and the road to the summit of Lava Butte are typically open from mid-May through mid-October. Check the Deschutes National Forest website for current information about schedules and access to the summit of Lava Butte.

The route turns left toward Visitor Center parking. **0.1**

Figure 17. Photograph taken from inside Lava River Cave toward the cave entrance (Stop 7). This large lava-tube cave extends almost 2 kilometers (km) to the northwest within the basalt of Bend, an extensive basalt flow that erupted in immediate post-caldera time about 75,000 years ago from buried vents near Lava Cast Forest. The basalt flowed west to the Deschutes River, where it temporarily blocked the river upstream of Benham Falls (Stop 9), and north under downtown Bend as far as the south end of Redmond (fig. 2), a distance of about 40 km from Lava River Cave and about 50 km from vents presumed located near Lava Cast Forest.

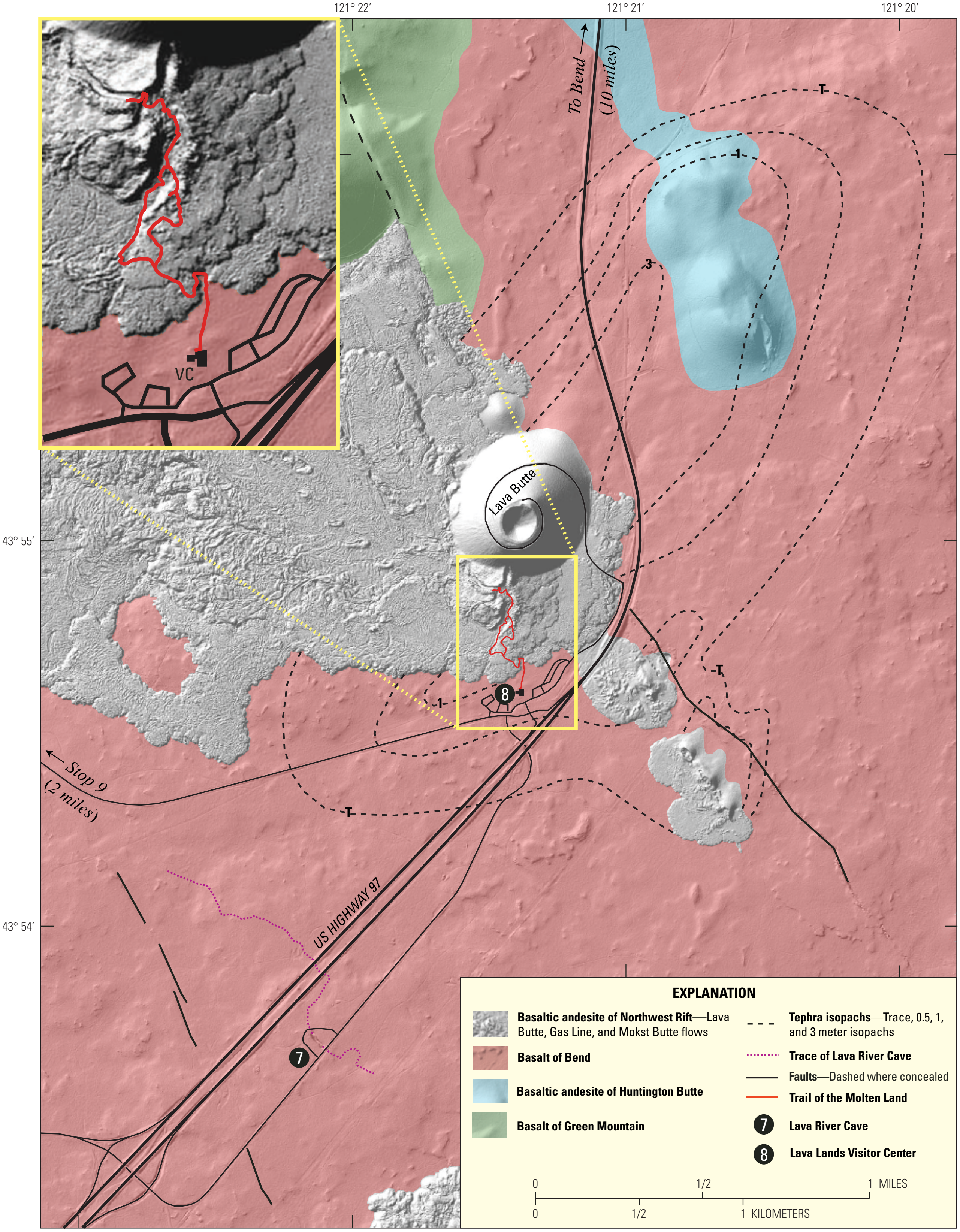


Figure 18. Map centered on Lava Lands Visitor Center (Stop 8) is based on shaded-relief lidar image (Robinson and others, 2015). Rough-surfaced lavas in gray erupted ~7,000 years ago as part of an eruptive event that produced mafic lavas along the northwest rift zone of the volcano. Inset box shows the Trail of the Molten Land that begins at the visitor center and takes the visitor to the vent where lava emerged from the base of Lava Butte. Early tephra deposited by the eruption is shown with dashed thickness contours (MacLeod and others, 1995). The surface projection of Lava River Cave (Stop 7) is also shown.

74.2 **STOP 8: Lava Lands Visitor Center Parking (43°54.555′ N, 121°21.462′ W, Elev. ~4,405 ft)** Park and visit the Lava Lands Visitor Center for an introduction to the area. Be sure to hike the interpretive Trail of the Molten Land (fig. 19) to the base of Lava Butte. The ~1.1-mi-long (1.8 km) paved loop trail crosses the flow, passes through the gutter system, and goes up to a viewpoint overlooking the flow and the Cascade Range (fig. 20).

If you choose to go to the top of Lava Butte, a 360° view from the summit on a clear day (fig. 21) includes the Cascade Range from Mount Scott on the east rim of Crater Lake to Mount Adams in Washington State. To the southeast is the cinder-cone-dotted north flank of Newberry Volcano.

Lava Butte is the northernmost vent along the ~7,000-yr-old northwest rift zone, a nearly continuous zone of mafic vents and flows extending southeast from

Figure 19. Photograph showing one of many interpretive signs along the Trail of the Molten Land on the ~7,000-yr-old Lava Butte flow, with the eponymous cinder cone in the background. The paved trail begins at the Lava Lands Visitor Center (Stop 8) of the Newberry National Volcanic Monument.

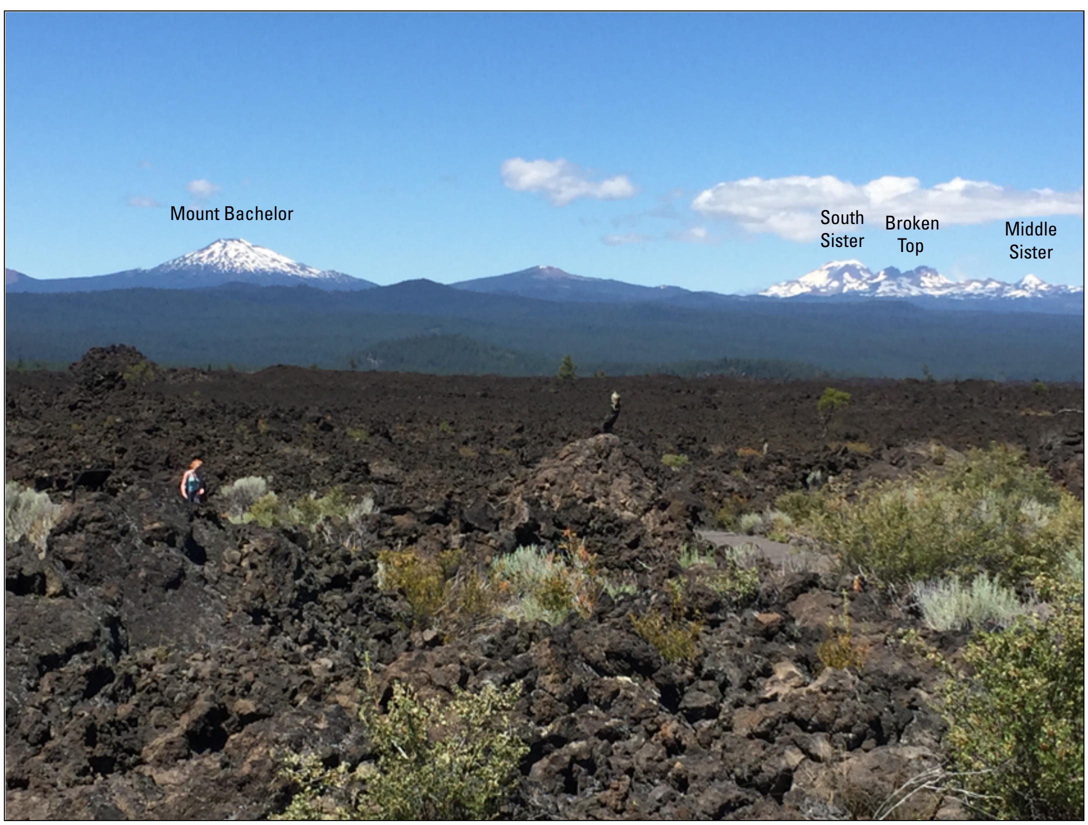


Figure 20. View northwest across the Lava Butte flow from the loop Trail of the Molten Land toward the snow-capped peaks of the Cascades crest.

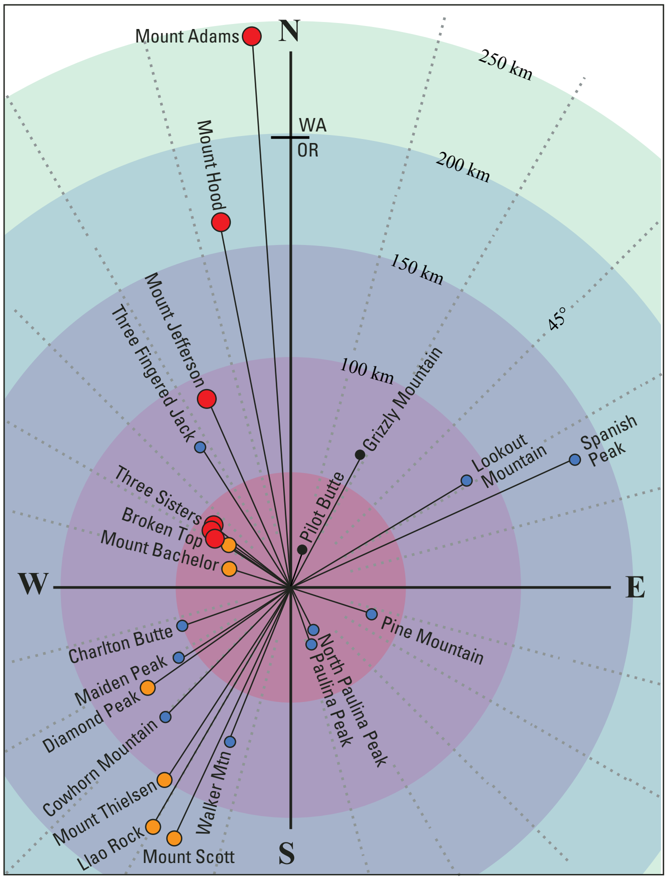


Figure 21. Plot showing azimuths to high points that can be seen from the top of Lava Butte. In 2016, shuttle bus service provided easy access to the top of the cone. Pedestrian access is available all year. Colored circles are 50 kilometers wide; colored dots indicate approximate height of peak with the red dots indicating peaks higher than 10,000 feet (ft), orange dots for peaks 8,000 to 10,000-ft-high, blue dots for peaks that are 6,000 to 8,000-ft high, and black dots for notable high points less than 6,000 ft in elevation. Two of the peaks include Paulina Peak (Stop 1) and Pilot Butte (Stop 10), both of which also provide outstanding views.

the far end of the Lava Butte flow at the Deschutes River to the north wall of Newberry caldera (fig. 5). Also in this eruptive episode are two mafic fissures on the south flank including the northwest-trending vents for the Surveyors Flow. Erupted lavas range in composition from 51.3 to 58.4 weight percent SiO_2 (Mckay and others, 2009).

The eruptions postdated deposition of the Mazama tephra that mantled Newberry Volcano when Mount Mazama erupted to form Crater Lake ~7,700 years ago. MacLeod and others (1995) listed 11 radiocarbon dates from 8 flows along the rift zone as reported by 5 different sources. As discussed in Mckay and others (2009), we use an age of ~7,000 years as the best estimate of the eruption age. The Lava Butte eruption began on a 2.4-km-long fissure and then became localized at the site of Lava Butte. The eruption produced a 500-ft-high cinder cone, several spatter ramparts, and lava flows extending northwest to the Deschutes River and covering over 23 km^2. Chemical analyses of Lava Butte and its lavas yield silica contents of 55.3–56.2 weight percent (Mckay and others, 2009).

Exit visitor center parking and turn right on paved road to Benham Falls. **3.3**

77.5 Cross Burlington Northern Santa Fe Railroad tracks. **0.6**

78.1 **STOP 9: Benham Day Use Area Parking (43°55.858′ N, 121°24.797′ W, Elev. ~4,150 ft)** Soon after the caldera formed about 75,000 years ago, the basalt of Bend (flowing by way of the Lava River Cave lava tube) blocked the paleo-Deschutes River. The river then established a new channel along the margin of the flow, eventually cutting a deep canyon at this location. Approximately 7,000 years ago, the Lava Butte flow spilled into the canyon of the paleo Deschutes River (fig. 22) and filled the old canyon, creating a 30-m wall of lava blocking the river. The margin of the basalt of Bend with encroachment by the Lava Butte flow can be seen in figure 23*A*. Figure 23*B* shows the margin of the Lava Butte flow about 200 m east of the footbridge. The lake resulting from the damned river extended upstream for more than 22 km and covered ~48 km^2 at its maximum stage (fig. 24). The river found an outlet across a low saddle on Benham Buttes and formed Benham Falls. Lake sediments filled the old channel and a new base level resulted in a meandering section of channel more than 50 km in length.

A similar eruption today could potentially destroy power lines, pipelines, telecommunication lines, a major highway, a railroad line, and again dam the Deschutes River. The damming of the river would flood a large area upstream from the dam. Once the lake over-topped the lava dam, the resulting downcutting could cause flooding downstream.

Follow the paved road back to Lava Lands Visitor Center. **3.9**

82.0 At Lava Lands Visitor Center, turn right on the road toward Lava River Cave to return to U.S. Hwy 97. **2.0**

84.0 At U.S. Hwy 97, turn right onto the northbound onramp to the highway and continue toward Bend. **9.3**

93.3 Take Exit 141 on to U.S. Hwy 97 Business Route through Bend. **3.4**

96.7 Traffic light at Third Street and Greenwood Avenue in Bend. Turn right (east) on Greenwood Avenue. **0.7**

97.4 Road junction to summit of Pilot Butte, enter left turn lane. **1.1**

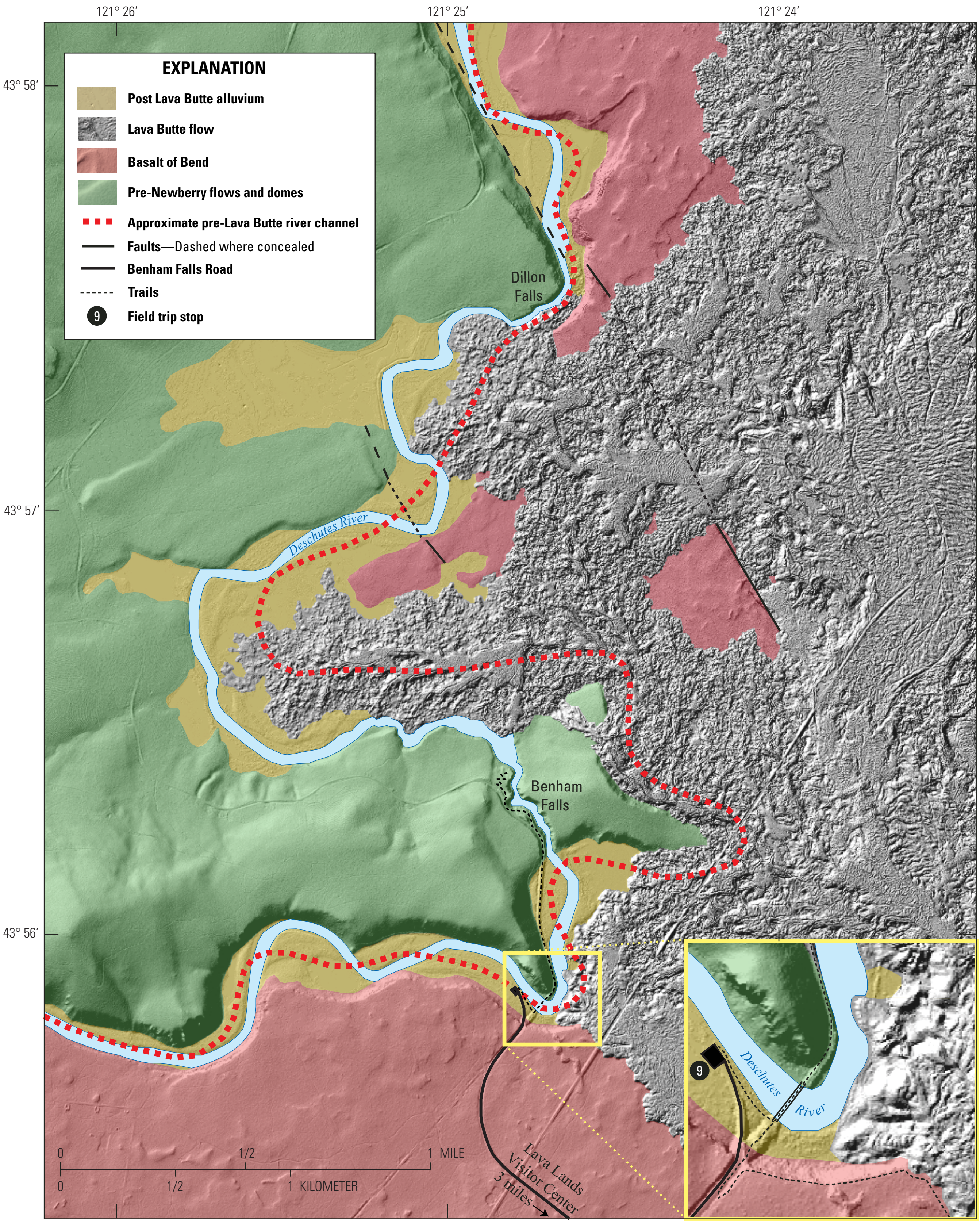


Figure 22. Map of the Benham Falls area (Stop 9) with shaded-relief lidar image as background shows changes in Deschutes River channel because of emplacement of the ~7,000-yr-old Lava Butte flow. This post-Mazama lava flow pushed the river to the west, as did the basalt of Bend about 75,000 years ago. Figure 23 photographs were taken of, and from, the bridge, which is shown as a black line across the river in the inset map in the lower right corner.

Figure 23. Photographs showing basalt of Bend and Lava Butte flow. *A*, View from pre-Newberry terrain looking south-southeast across the Deschutes River and the bridge to Benham Falls toward the eroded margin of the ~75,000-yr-old basalt of Bend. At the left end of the wall of basalt, mostly hidden by trees, the ~7,000-yr-old Lava Butte flow flowed over and around the front of the older flow. Parking for Stop 9 is to the right of the photograph on the far side of the river. *B*, View west from the bicycle and pedestrian bridge to Benham Falls toward the rocky edge of the ~7,000-yr-old Lava Butte flow.

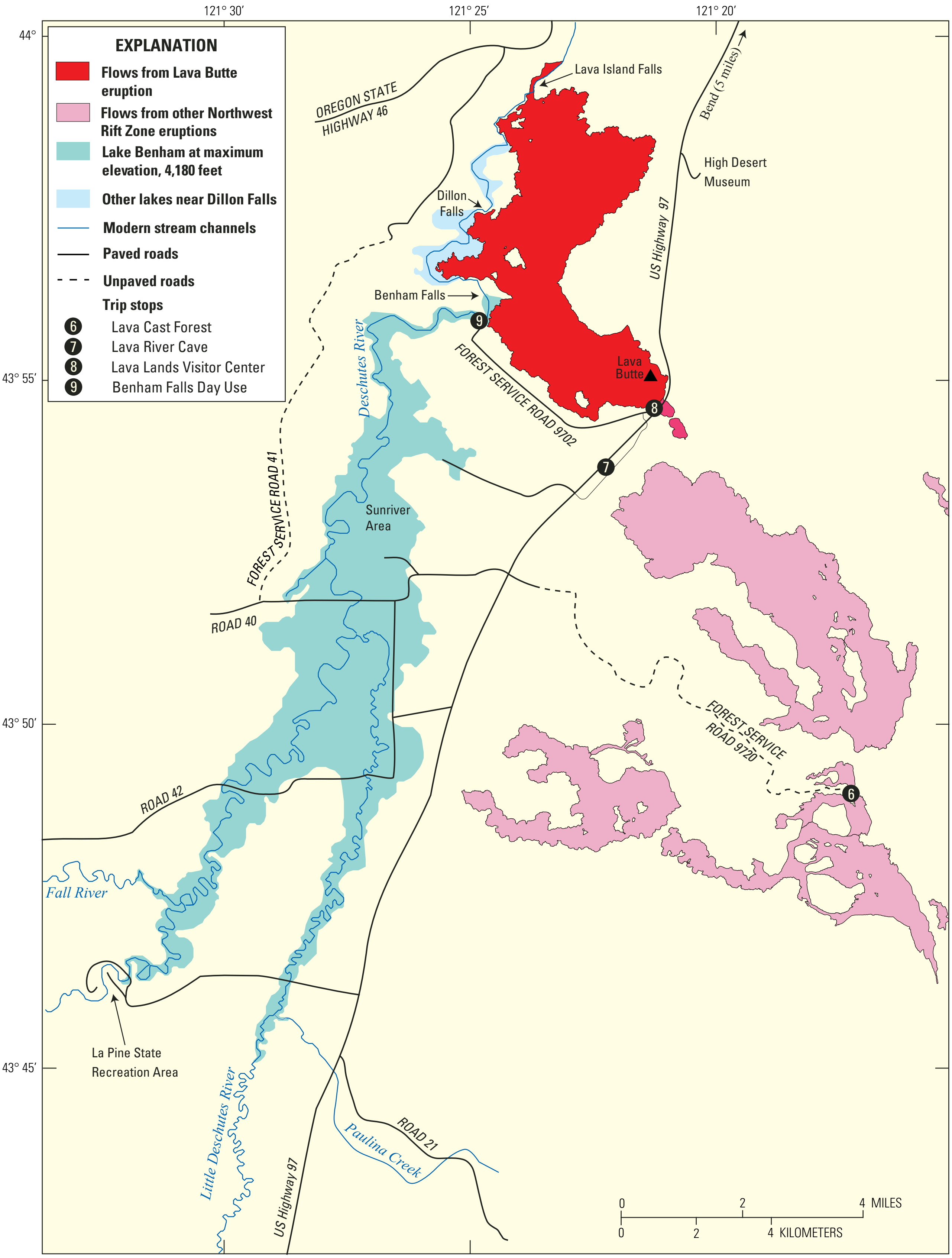


Figure 24. Map showing the temporary lake created when the Lava Butte flow blocked the Deschutes River ~7,000 years ago. Modified from Jensen and Donnelly-Nolan (2009, their fig. 9).

The route turns left to take the paved ~1-mi-long road to the summit of Pilot Butte (the road is closed during the winter season and may be closed before 10:00 a.m.). This nearly 500-ft-high cinder cone (fig. 25) is preserved as a State Scenic Viewpoint and is located within the city limits of Bend. It is a popular destination for the 360° view from the summit and as a hiking destination.

Below is an alternate route if you wish to park at the picnic area and walk to the summit.

0.00 Junction to Pilot Butte, continue east on Hwy 20.

0.40 Traffic light at 15th Street.

0.80 Turn left on Azure Drive.

0.90 Turn left on Savannah Drive.

1.00 Turn left on Linnea Drive.

1.20 Parking lot for Pilot Butte Trailhead (44°03.503′ N, 121°16.688′ W). There are two trails to the summit. The primary, unpaved trail mainly follows the road to the summit, while the other is a nature trail that follows a lower route.

98.5 **STOP 10: Pilot Butte Summit (44°03.637′ N, 121°16.992′ W, Elev. ~4,138 ft)** Pilot Butte is a large Pleistocene cinder cone and its porphyritic basaltic andesite lava flow to the north are surrounded by the younger basalt of Bend. The view from the top of the cone encompasses the city of Bend, and to the west the high peaks of the Cascade Range (fig. 26). To the south is the broad edifice of Newberry Volcano, which extends in this view (see fig. 3) from Horse Ridge on the east (left) to Lava Butte on the west (right). The north flank of the volcano is dotted with cinder cones; more than 400 occur on the whole volcano. Visible peaks from the summit include from south to north, Mount Bachelor, Broken Top, South Sister, Middle Sister, North Sister, Mount Washington, Three Fingered Jack, Mount Jefferson, Mount Hood, and on a clear day Mount Adams in Washington State (fig. 27).

To the northeast are the Ochoco Mountains, which form the western end of the Blue Mountain Range that extends to the Wallowa Mountains in northeast Oregon. The youngest rocks in the Blue Mountains are about 15 million years old and the oldest are at least 300 million years old.

Return to the base of the cinder cone and Greenwood Avenue. **1.1**

99.6 At base of the cone turn right (west) on Greenwood Avenue. **0.7**

100.3 Traffic light at Third Street and Greenwood Avenue; turn right (north). **1.1**

101.4 Just beyond the railroad overpass take the off ramp to join U.S. Hwy 97 to Redmond and Portland. **2.5**

103.9 Traffic light at Cooley Road, last traffic light in Bend. Between Bend and Redmond the highway passes through many cuts in the basalt of Bend. **11.4**

115.3 Traffic light at Odem Road, first traffic light in Redmond. Redmond's Dry Canyon begins ~1 km north-northwest

Figure 25. Pilot Butte is preserved as a State Scenic Viewpoint within the city of Bend. This Pleistocene cinder cone and lava flow may represent an early and distal eruption of the Newberry Volcano magmatic system. The nearly 500-feet-high cinder cone has a paved road to the top and provides both vehicle and pedestrian access to this must-see stop for visitors (Stop 10). In this view looking west-northwest, the snow-covered peaks of the Three Sisters on the Cascades crest ~40 kilometers away can be seen on the horizon to the left of Pilot Butte.

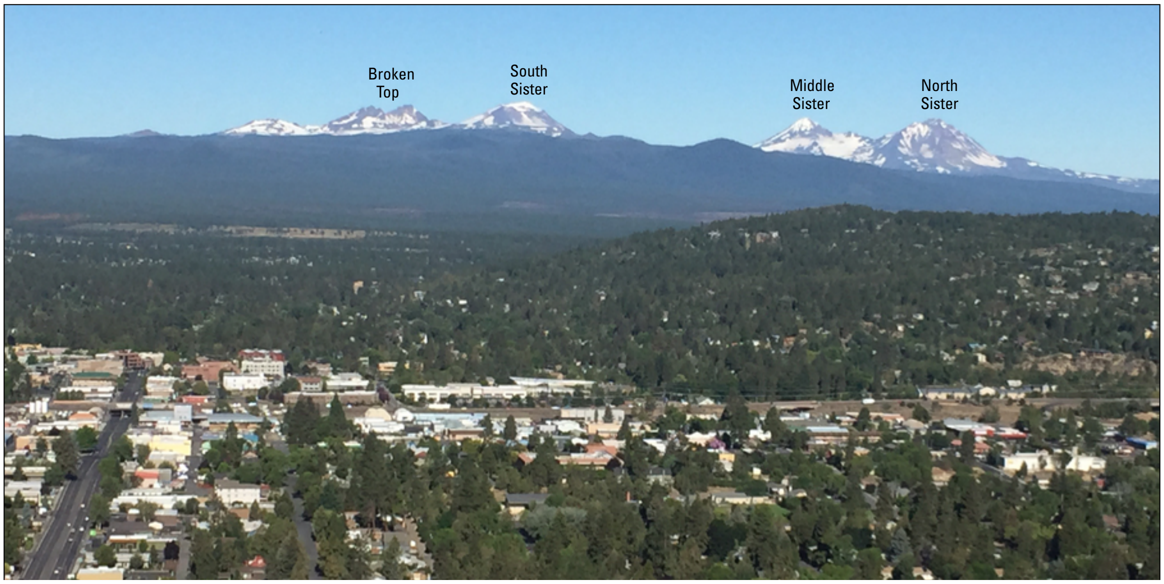


Figure 26. The view west from the top of Pilot Butte toward the Cascade crest highlights the snow-capped peaks overlooking the city of Bend.

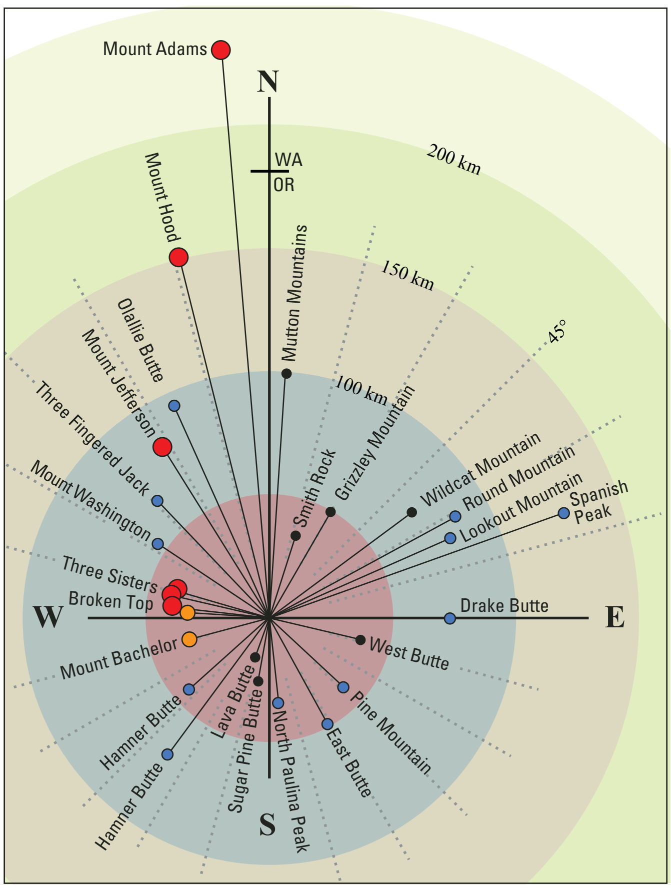


Figure 27. Plot showing azimuths and distances of high points visible from the top of Pilot Butte. Circles are 50 kilometers wide and colored dots indicate approximate height range of peaks with large red dots indicating peaks higher than 10,000 feet (ft), orange dots 8,000 to 10,000 ft, blue dots 6,000 to 8,000 ft, and black dots notable high points less than 6,000 ft in elevation. McKay Butte and North Paulina Peak are two high points on the broad Newberry Volcano shield to the south (fig. 3).

of here and extends for 8 km to the north. The Deschutes River occupied the Dry Canyon channel for about 275,000 years until the eruption of the basalt of Bend soon after the eruption forming Newberry caldera about 75,000 years ago. Eruption of the basalt of Bend from now-buried vents about 50 km to the south located midway up the north slope of Newberry Volcano, forced the river into a new channel along the west edge of the lava flow. Subsequently, ~70 ka the Horse Cave lobe of the basalt of Lava Top Butte (Jensen and others, 2009), also called basalt of the Badlands (Champion and others, 2004), flowed into the old Dry River Canyon channel, partly filling it to form the present-day flat-floored canyon. The sequence of basalt-river interactions is shown in figure 28.

Continue north on U.S. Hwy 97 around downtown Redmond. **4.6**

119.9 Flashing yellow light at north edge of Redmond-O'Neil Highway to right. About 2 km west-northwest of here is the northern end of Dry Canyon, where the basalt of Lava Top Butte spread out and then blocked and diverted the Deschutes River in the Lower Bridge area. **2.7**

122.6 Junction of Smith Rock Way in Terrebonne. For an optional side trip, turn right (east) to access Smith Rock State Park. **1.9**

124.5 Railroad overpass. This overpass is located at the approximate south edge of an old river canyon cut in the basalt of Redmond (Sherrod and others, 2004). The old rim is visible ahead on the left. To the right are Gray Butte (28.8 Ma rhyolite dome) and Smith Rock area (~29.5 Ma intracaldera tuff) related to the ~29.5 Ma Crooked River caldera (McClaughry and others, 2009). **1.1**

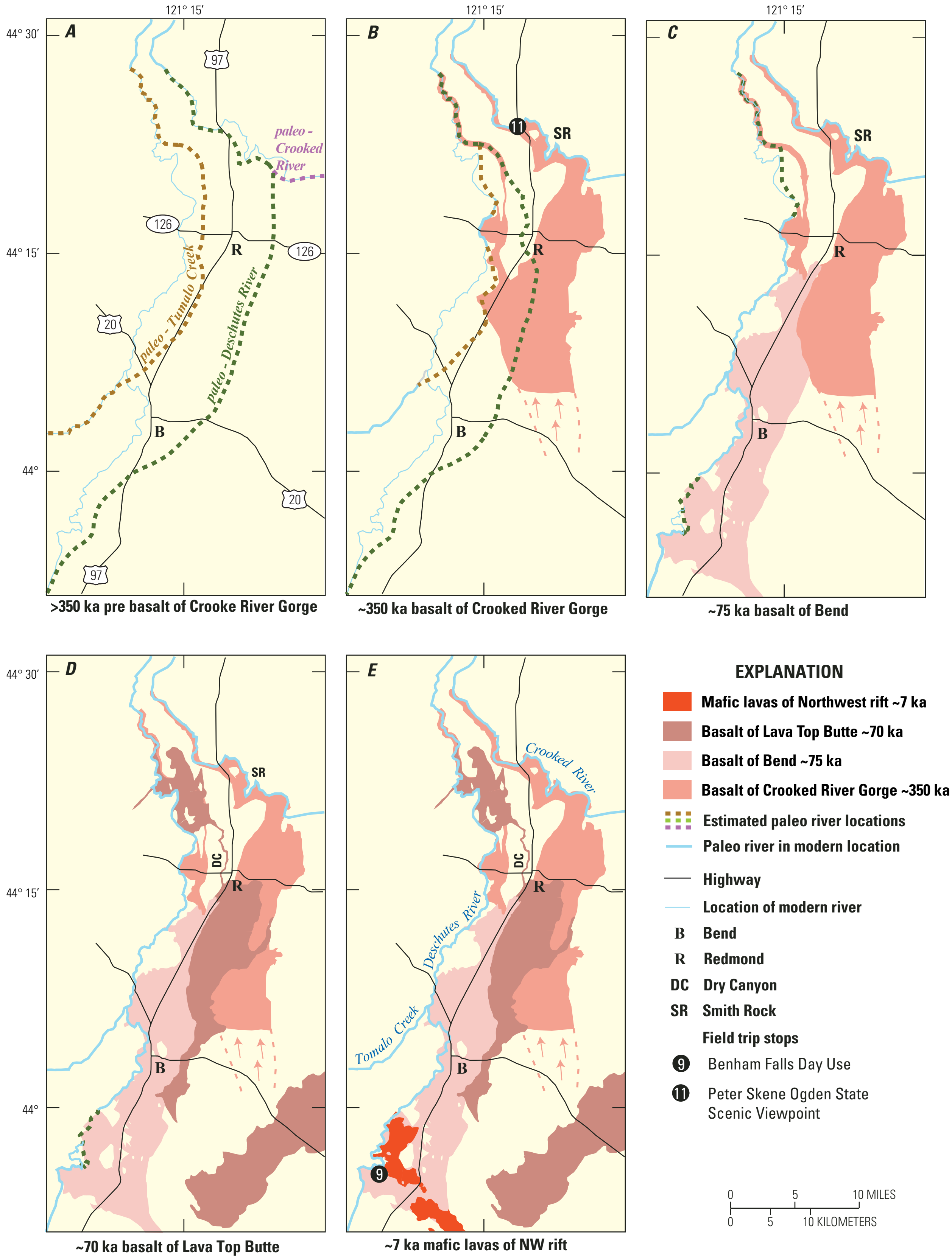


Figure 28. Panels *B* through *E* depict the the generalized history of central Oregon rivers and the changes that resulted from eruptions at distant Newberry Volcano. All of the source vents are located south of Highway 20. Note the locations of Stops 11 (shown on Panel *B*) and 9 (on Panel *E*). Figure is modified from Jensen and Donnelly-Nolan (2009, their fig. 5).

125.6 Junction to Peter Skene Ogden Scenic Wayside; turn left (west). **0.1**

125.7 **STOP 11: Peter Skene Ogden Scenic Wayside Parking Lot (44°23.442' N, 121°11.553' W, Elev. ~2,765 ft)** Follow the short trail behind the restrooms and walk to the old Conde B. McCullough steel arch bridge (built in 1926) spanning the Crooked River Gorge. This pedestrian bridge (44°23.565' N, 121°11.633' W) provides a spectacular view into the gorge downstream to the west (fig. 29*A*) and upstream to the east (fig. 29*B*) along the Crooked River. To the east is the new Rex T. Barber Veterans Memorial Bridge, which is a concrete arch span about 300 ft (~90 m) above the river. The bridge is 410 ft (125 m) long, and was completed in September 2000. To the west is the railroad bridge which was built in 1911.

The Peter Skene Ogden Scenic Wayside is located near the northwest margin of the ~29.5 Ma Crooked River caldera (McClaughry and others, 2009). The 36-by-24 km caldera formed a northwest-southeast elongate depression. Since that caldera-forming eruption, the Crooked, Deschutes, and Dry River drainages have maintained channels across the deposits and largely filled the depression. At ~5 Ma, the basalt of Tetherow Butte (Sherrod and others, 2004) was erupted and flowed northward to beyond Madras, Oregon, filling and blocking all drainage from the depression. A new outlet for the drainage from the caldera basin was established in this area. At ~3.5 Ma, the basalt of Redmond (Sherrod and others, 2004) again blocked northward drainage and a new channel was established along the northern margin of the unit. About 350,000 years ago (Donnelly-Nolan and others, 2011), the basalt of Crooked River Gorge was erupted from now buried vents on the north flank of Newberry Volcano ~50 km to the south. It entered and followed the paleo-Deschutes River channel northward to the vicinity of Smith Rock, where today it forms the parking area for Smith Rock State Park. Here at the Ogden Wayside, the old Deschutes River channel was nearly filled (old canyon rims are visible to the north and south) by the basalt from Newberry Volcano. The Deschutes River was forced to the west and established a new channel (Dry Canyon) through the present site of the city of Redmond. The Crooked River, which formerly joined the Deschutes River upstream near Smith Rock, reestablished a channel along the north edge of the basalt of Crooked River Gorge, cutting a deep gorge and joining the Deschutes River ~29 km downstream. At this bridge, the river has cut down through >90 m of the basalt of the Crooked River Gorge, which had filled the old river channel. Upstream, downcutting has exposed sediments and tuffs of the Deschutes Formation.

After viewing the gorge, walk north across the bridge to view an outcrop of the basalt of Crooked River Gorge. It is an aphyric, diktytaxitic basalt containing ~49 weight percent SiO_2.

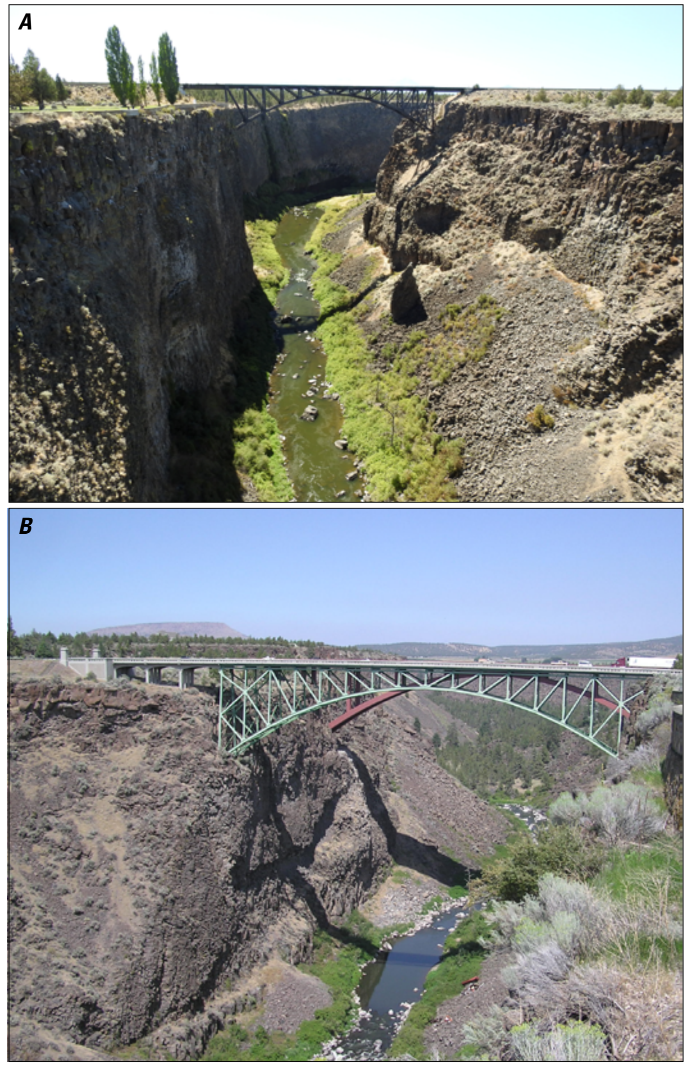


Figure 29. Photographs of Crooked River Gorge taken at Stop 11, the Peter Skene Ogden State Scenic Viewpoint and rest area. *A*, Photograph taken from the old highway bridge across the Crooked River shows the view downstream of this ~300-feet-deep canyon. Lawn and trees on upper left are within the Ogden rest area; immediately beyond is the railroad bridge. About 350,000 years ago, this channel was filled with basalt from Newberry Volcano. *B*, View east from Ogden rest area upstream toward the old highway bridge (green supports) and just beyond to the new bridge (dark red supports). In addition to the basaltic lava from Newberry Volcano that can be seen on the walls of the Crooked River Gorge, older tuffs are exposed about 0.5 kilometers upstream.

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