Field Guides

A field guide to Newberry Volcano, Oregon

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Notes

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A field guide to Newberry Volcano, Oregon

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ABSTRACT

Newberry Volcano is located in central Oregon at the intersection of the Cascade Range and the High Lava Plains. Its lavas range in age from ca. 0.5 Ma to late Holocene. Erupted products range in composition from basalt through rhyolite and cover ~3000 km^2. The most recent caldera-forming eruption occurred ~80,000 years ago. This trip will highlight a revised understanding of the volcano's history based on new detailed geologic work. Stops will also focus on evidence for ice and flooding on the volcano, as well as new studies of Holocene mafic eruptions. Newberry is one of the most accessible U.S. volcanoes, and this trip will visit a range of lava types and compositions including tholeiitic and calc-alkaline basalt flows, cinder cones, and rhyolitic domes and tuffs. Stops will include early distal basalts as well as the youngest intracaldera obsidian flow.

OVERVIEW

Newberry Volcano is a large shield-shaped volcano (Fig. 1), which lies ~60 km east of the crest of the Cascade Range (Fig. 2). The main edifice of Newberry rises ~1 km above the surrounding terrain and encompasses a 7 km by 8 km summit caldera with an area of 45 km^2. Limited argon dating exists, but preliminary $^{40}Ar/^{39}Ar$ dating (A. Calvert, 2008, personal commun.) suggests that the oldest lavas may be less than half a million years old. The summit caldera formed ~80,000 years ago when a compositionally zoned rhyolitic to andesitic ash-flow tuff was erupted. At least two previous ash-flow tuffs with significant volumes erupted at ca. 300 ka (Donnelly-Nolan et al., 2004) and may represent earlier caldera-forming eruptions.

Total volume of erupted lavas probably exceeds 500 km^3. Total area is ~3000 km^2, including basaltic lavas that extend well beyond the main edifice. The edifice itself covers ~1300 km^2. Its north and south flanks are covered mainly by basalt and basaltic andesite lavas of late Pleistocene and Holocene age. More than 400 cinder cones and fissure vents have been identified on the flanks of Newberry. In contrast, silicic volcanism mostly occurs on the upper central parts of the volcano. Lavas of intermediate composition are relatively uncommon. Pyroclastic flow deposits are most widely exposed on the east and west flanks of the volcano, where tephras and sediments dominate.

The volcano last erupted in late Holocene time, when initial explosive activity produced rhyolitic tephra that reached Idaho and ended with emplacement of the Big Obsidian Flow in the

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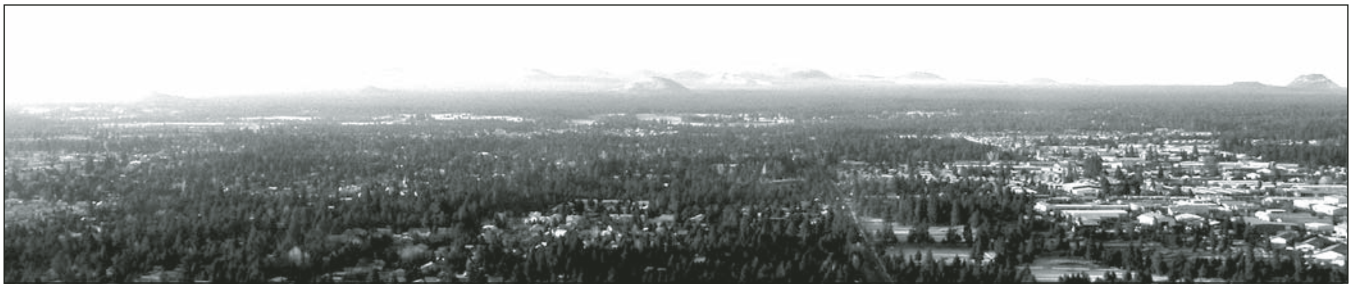

Figure 1. Photo looking south from Pilot Butte (Stop 3-5) across the southern part of the city of Bend toward the broad shield-shaped edifice of Newberry Volcano. Field of view spans ~20 km. Cinder cone on far right is Lava Butte (Stop 1-2). Photo by R. Jensen.

caldera. Early Holocene postglacial eruptions were dominantly mafic. As many as a dozen such eruptions occurred in postglacial time prior to the eruption of Mount Mazama ~7700 years ago (Hallett et al., 1997) to form Crater Lake caldera. Ice on Newberry Volcano extended down the flanks to elevations at least as low as 1735 m and deposited erratics up to 7 km outboard from the caldera rim (Donnelly-Nolan and Jensen, this volume).

There has been considerable debate about how to categorize Newberry Volcano. Its position behind the main arc, together with its broad shield form, large volume, and abundance of both tholeiitic basalt and rhyolite, all set it apart from typical Cascade volcanoes. Only Medicine Lake volcano to the south in northern California is similar in size and range of magma types. Donnelly-Nolan (2008) and Donnelly-Nolan et al. (2008) compare and contrast these two volcanoes and argue that they are subduction-related, rear-arc Cascade volcanoes located in extensional tectonic environments.

A variety of studies about the volcano, including geophysical studies (Achauer et al., 1988; Catchings and Mooney, 1988; Fitterman et al., 1988; Gettings and Griscom, 1988; Stauber et al., 1988) were published in a special issue of the *Journal of Geophysical Research*. See overview article (Fitterman, 1988) and other 1988 citations in reference list.

Newberry Volcano has long been known to the geologic community for its great diversity of rock types and wide range of volcanic landforms (Russell, 1905; Williams, 1935; Nichols and Stearns, 1938; MacLeod and Sherrod, 1988). Parts of Newberry were proposed as a National Park at least twice (1920 and 1940). In November 1990, President George H.W. Bush signed a bill establishing Newberry National Volcanic Monument, which includes the caldera and much of the post-Mazama mafic fissure eruption of the informally named northwest rift zone that extends from the northwest base of the edifice to the caldera and the upper southwest side of the volcano.

ROAD LOG

The road log and all road-related distances are given in miles in deference to car odometers, and elevations are given in feet as they are shown on topographic maps. However, measured heights, lengths, thicknesses, and areas are given in metric units of measure.

Where mileposts exist along highways and roads a tie is made to the mileposts in the road log, for example: [Hwy. 26 M.P. 71.45].

Informal names are in quotes, for example "Hixon Draw" or basalt of "Lunabess Hill."

Day 1: Portland to Bend, with Introduction to Newberry

This day involves ~200 miles (310 km) of travel from Portland to Bend via Government Camp, with three stops (see Figs. 2 and 3).

Cumulative mileage	*Description*
0.00	[I-84 M.P. 3.40][Elev. = 200 ft] Field trip begins in Portland, on I-84 at the Exit 3 offramp.
9.85	[I-84 M.P. 15.60] The route takes Exit 16 to Wood Village and Mount Hood. At the first traffic light turn right on 238th and follow it (and 242nd) south to the seventh traffic light at Burnside and 242nd.
12.95	The route turns left at traffic light at Burnside and 242nd. Follow Burnside (U.S. Hwy. 26) southeast.
24.10	[Hwy. 26 M.P. 24.60] Junction of Hwy. 211 (right) in Sandy. Continue on straight on Hwy. 26.
48.50	[Hwy. 26 M.P. 49.75] View of Mount Hood ahead. Summit Elevation: 11,239 ft Area: 210 km^2 Volume: 50–70 km^3 (Hildreth, 2007) Last Eruption: 1790s (Scott et al., 1997)
49.65	[Hwy. 26 M.P. 50.90] Oregon History Sign—Laurel Hill: "The Pioneer Road here detoured the Columbia River rapids and Mount Hood to the Willamette Valley. The road at first followed an old Indian trail; the later name was Barlow Road. Travel was difficult; wagons were snubbed to trees by ropes or held back by drags of cut trees. Early travelers named the hill from the resemblance of native leaves to Laurel."
52.75	[Hwy. 26 M.P. 54.00] The route turns left to Government Camp Rest Area.

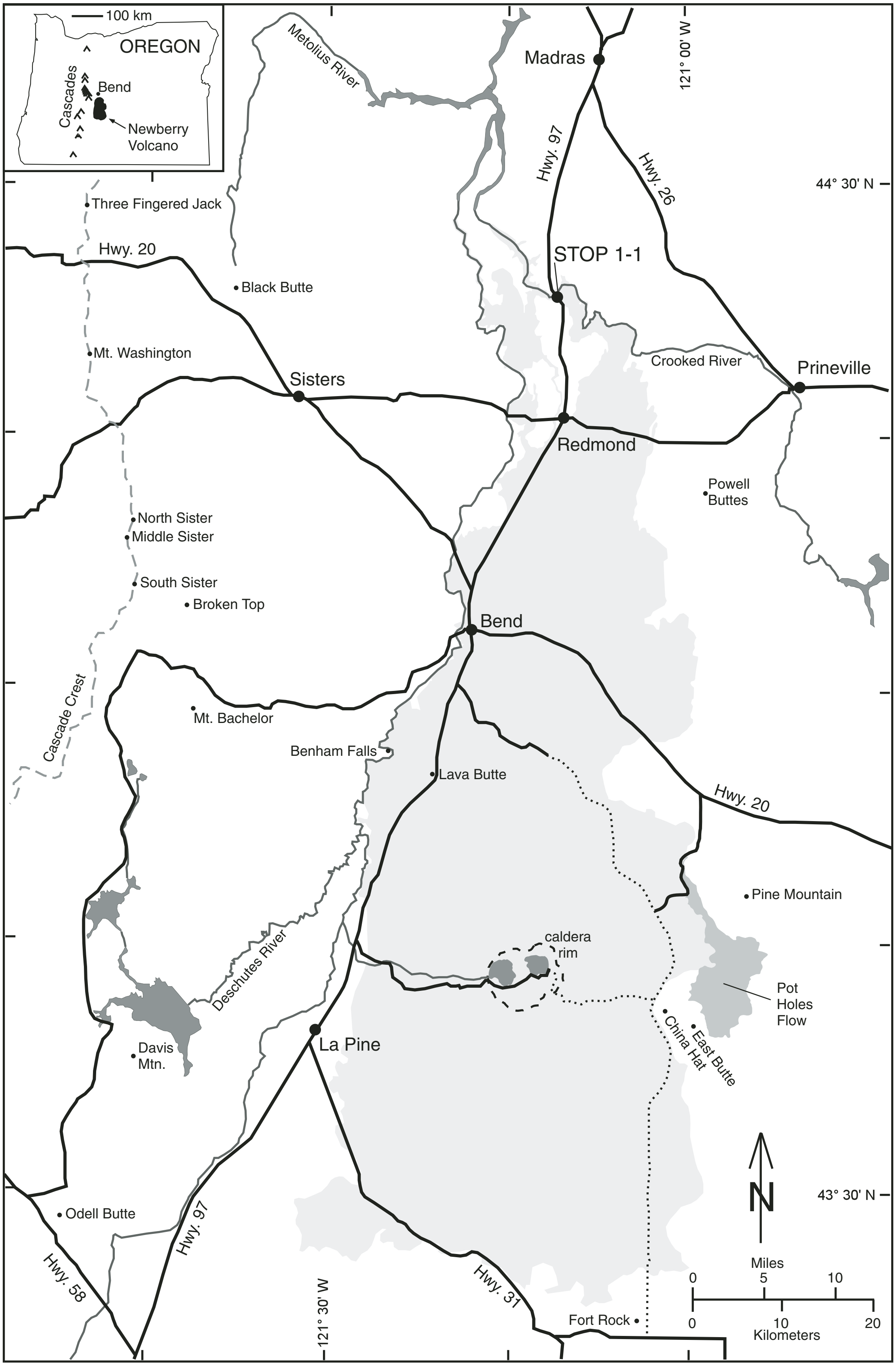

Figure 2. Location map. Light-gray area shows approximate distribution of lavas from Newberry Volcano. Dotted lines are major unpaved roads. Stop 1-1 is shown; see Figure 3 for additional stop locations.

52.85 Rest stop at Government Camp Rest Area. [Elev. = 4000 ft]

52.95 [Hwy. 26 M.P. 54.00] The route turns left on Hwy. 26.

53.20 [Hwy. 26 M.P. 54.25 = 55.25] Road (left) leads to the historic Timberline Lodge. Continue straight on Hwy. 26.

55.15 [Hwy. 26 M.P. 57.20] Junction of Ore. Hwy. 35 (right). The route continues on Hwy. 26.

61.35 [Hwy. 26 M.P. 63.40] Summit of Blue Box Pass – 4024 ft.

69.40 [Hwy. 26 M.P. 71.45] Junction of Oregon Hwy. 216 (left). The route continues on Hwy. 26.

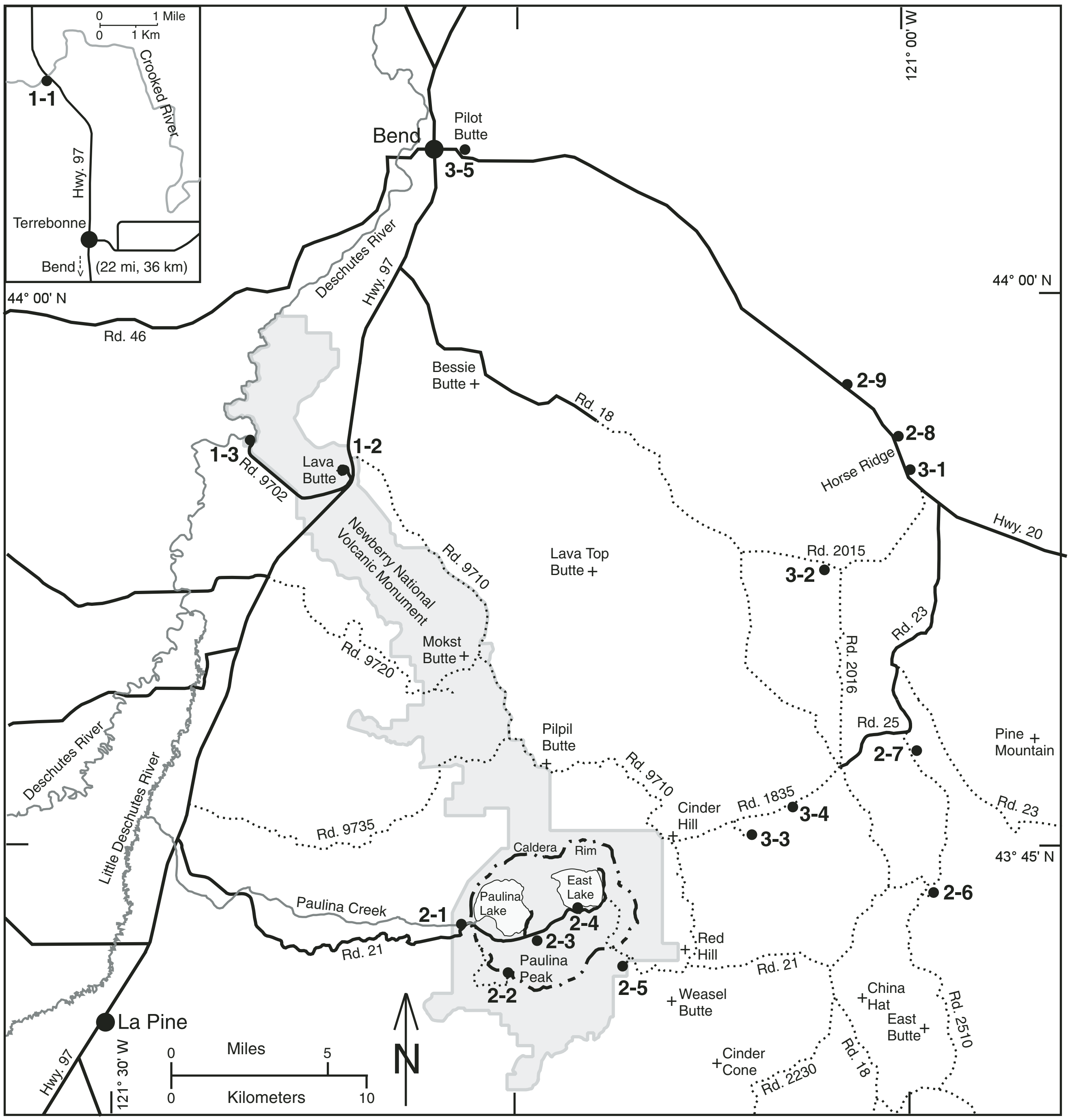

Figure 3. Location map showing field trip stops. The area encompassed by the Newberry National Volcanic Monument is shown in gray. Paved roads are shown as solid lines; major unpaved roads are shown as dotted lines. Inset figure shows location of Stop 1-1.

82.80 [Hwy. 26 M.P. 84.85] Junction of road to Kah-Nee-Ta (left). The route continues on Hwy. 26, and shortly crosses the Warm Spring River.

86.20 [Hwy. 26 M.P. 88.25] The Mutton Mountains, Clarno and John Day age rocks form the skyline at 9:00. The Ochoco Mountains dominate the skyline from 10:00–12:00. The two most prominent peaks ahead are Grizzly Mountain (5635 ft) and Gray Butte (5108 ft), post-caldera domes along the northeast margin of the (ca. 29.5 Ma) Crooked River caldera (McClaughry et al., 2008).

86.95 [Hwy. 26 M.P. 89.00 to Hwy. 26 M.P. 99.00] Mount Jefferson is visible to right for the next 10 miles.
Summit Elevation: 10,497 ft
Area: 65 km^2
Volume: 20 km^3 (Hildreth, 2007)
Last Eruption: ca. 20 ka (Hildreth, 2007)

90.65 [Hwy. 26 M.P. 92.60] Cross Mill Creek Canyon. This 70-m-deep canyon exposes five units of diktytaxitic olivine basalt. Total thickness of diktytaxitic basalts in this area is over 120 m. These basalts form the rimrocks of the northwest portion of the Deschutes basin and were erupted from unknown vents on the east flank of the High Cascades (Smith and Priest, 1983).

90.70 [Hwy. 26 M.P. 92.65] Oregon History Sign (right): "From Ancient Days trails made by the first Indians of the Region crossed this plain. Over them passed Peter Skene Ogden, in 1825 & 1826, with his trapping parties bound south for the Crooked and John Day Rivers, the Harney and Klamath Basins. Nathaniel J. Wyeth, fur trader, went south in 1834 and returned in 1835. Captain John C. Fremont used the trails on his southward exploration into Nevada and California in 1843. And Lt. Henry L. Abbot heading up a Pacific Railroad Survey followed them in 1855."

97.45 [Hwy. 26 M.P. 99.30][Elev. = 2440 ft] Begin down grade into Deschutes River canyon. Roadcuts for first mile of the grade are in Deschutes Formation and expose a capping basalt flow, two ash-flow tuffs, numerous ashfall and pumice lapilli beds, and interbedded sediments. After the first mile, cuts are in the John Day Formation, Pleistocene terrace gravels, and landslide deposits (Smith and Priest, 1983).

101.40 [Hwy. 26 M.P. 103.25] Junction of road to Kah-Nee-Ta (left) in Warm Springs. Continue on Hwy. 26.

103.45 [Hwy. 26 M.P. 105.30] Cross Deschutes River. [Elev. = 1370 ft]

108.15 [Hwy. 26 M.P. 110.00] Base of the 5 Ma basalt of Tetherow Butte (Sherrod et al., 2004) that was erupted from Tetherow Butte, ~44 km to the south. This flow covers at least 180 km^2 on the east side of the Deschutes River and at this location is ~45-m thick where it filled and overflowed an ancestral Deschutes River channel (Smith and Priest, 1983).

108.90 [Hwy. 26 M.P. 100.75] Top of grade out of Deschutes River canyon. [Elev. = 2330 ft]

114.95 [Hwy. 26 M.P. 116.80] Begin grade down to Madras.

115.90 [Hwy. 26 M.P. 100.75 to Hwy. 97 M.P. 94.90] North Madras Junction of U.S. 97 and U.S. 26. The route continues south on Hwy. 97.

118.25 [Hwy. 97 M.P. 97.25] South Madras Junction of U.S. 97 and U.S. 26. The route continues south on Hwy. 97. For the next 8 miles, roadcuts expose various units in the Deschutes Formation.

126.40 [Hwy. 97 M.P. 105.40] For the next 2 miles, the highway climbs up and over the saddle between Juniper Butte to west and Haystack Butte to east. Juniper Butte is a rhyolite dome, which formed as an outlier along the peripheral fault zone that defines the ca. 29.5 Ma Crooked River caldera (McClaughry et al., 2008).

126.80 [Hwy. 97 M.P. 105.80 = 105.65] Road (right) to Culver and Cove Palisades State Park. Continue south on Hwy. 97.

127.85 [Hwy. 97 M.P. 106.70] Summit of Juniper Butte grade. [Elev. = 3140 ft]

128.00 [Hwy. 97 M.P. 106.85 = 107.00] View of Three Sisters ahead on Cascade crest.
South Sister Summit elevation: 10,358 ft
Middle Sister Summit elevation: 10,047 ft
North Sister Summit elevation: 10,085 ft
Total area: 160 km^2
Total volume: 47 km^3 (Hildreth, 2007)
Last eruption: 2 ka (Scott, 1987)

129.00 [Hwy. 97 M.P. 108.00] The broad shield-shaped edifice of Newberry Volcano is visible on the skyline ahead.

132.30 [Hwy. 97 M.P. 111.30] To the left are Gray Butte (28.8 Ma rhyolite dome) and Smith Rock area (ca. 29.5 Ma intracaldera tuff) related to the (ca. 29.5 Ma) Crooked River caldera (McClaughry et al., 2008).

133.45 [Hwy. 97 M.P. 112.45] The route is now on intracanyon flow from Newberry Volcano, the old north canyon rim is the high to the left, formed by the basalt of Tetherow Butte (Sherrod et al., 2004).

133.60 [Hwy. 97 M.P. 112.60] Cross Crooked River Gorge. This concrete arch span is 90 m above the river, 125 m long and was completed in September 2000. The old Conde B. McCullough steel arch bridge was built in 1926 and is now a pedestrian bridge. The nearby railroad bridge was built in 1911.

133.80 [Hwy. 97 M.P. 112.80] The route turns right to Peter Skene Ogden Scenic Wayside.

133.95 Parking for Stop 1-1 [Elev. = 2700 ft]

Stop 1-1 at Peter Skene Ogden Scenic Wayside

From the parking lot walk to the old 1926 bridge for a view of Crooked River Gorge (Fig. 4).

Peter Skene Ogden Scenic Wayside is located near the northwest margin of the ca. 29.5 Ma Crooked River caldera (McClaughry et al., 2008). The 36 km × 24 km caldera formed a northwest-southeast elongate depression. Since the caldera-forming eruption, the Crooked, Deschutes, and Dry River drainages have maintained channels across and largely filled the depression. At ca. 5 Ma, the basalt of Tetherow Butte (Sherrod et al., 2004) was erupted and flowed northward to beyond Madras filling and blocking all drainage from the depression. A new outlet for the drainage from the caldera basin was established in this area. At ca. 3.5 Ma, the basalt of Redmond (Sherrod et al., 2004) again blocked northward drainage and a new channel was established along the northern margin of the basalt of Redmond. About 400 ka (unpublished argon dating, M. Lanphere and A. Calvert, 2008, personal commun.) 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 Deschutes River channel northward to the vicinity of Smith Rock (Figs. 5A and 5B). Here at the wayside, the old Deschutes River channel was nearly filled (old canyon rims are visible to the north and south). The Deschutes River was forced to the west and established a new channel (Dry Canyon) through the site of the City of Redmond (see log mile 144.30). The Crooked River, which formerly joined the Deschutes upstream near Smith Rock, reestablished a channel along the northern edge of the basalt of Crooked River Gorge and cut a deep gorge upstream, e.g., at Smith Rock State Park. At this bridge, the river has down cut through 90 m of basalt of the Crooked River Gorge, which filled the old river channel. Upstream, downcutting exposed sediments and tuffs of the Deschutes Formation beneath the capping basalt of Tetherow Butte.

After viewing the gorge, continue across the bridge to view an outcrop of the basalt of Crooked River Gorge. It is an aphyric, diktytaxitic basalt containing ~49% SiO_2 (Table 1).

Lunch stop.

Cumulative mileage	*Description*
134.15	[Hwy. 97 M.P. 112.80] The route turns right on Hwy. 97.
135.30	[Hwy. 97 M.P. 113.95] Railroad overpass, approximate south edge of old river canyon, formed by the basalt of Redmond (Sherrod et al., 2004). Rim is visible to right rear.
137.15	[Hwy. 97 M.P. 115.80] Junction in Terrebonne of road to Smith Rock State Park (left), where basalt of Crooked River Gorge flowed up against fill of the Crooked River caldera (McClaughry et al., 2008) and the Crooked River subsequently excavated the contact.
138.35	[Hwy. 97 M.P. 117.00] Series of cinder cones to right and ahead. These low hills are collectively known as Tetherow Butte. Basalt flows from these vents covered much of the eastern Deschutes basin to a distance of 60 km to the north (Smith, 1986). In

Figure 4. Photo taken at Stop 1-1 from old highway bridge looking west toward railroad bridge that spans Crooked River Gorge. Walls of canyon consist of basalt of Crooked River Gorge, erupted ca. 400 ka from buried vents on the north flank of Newberry Volcano. Photo by R. Jensen.

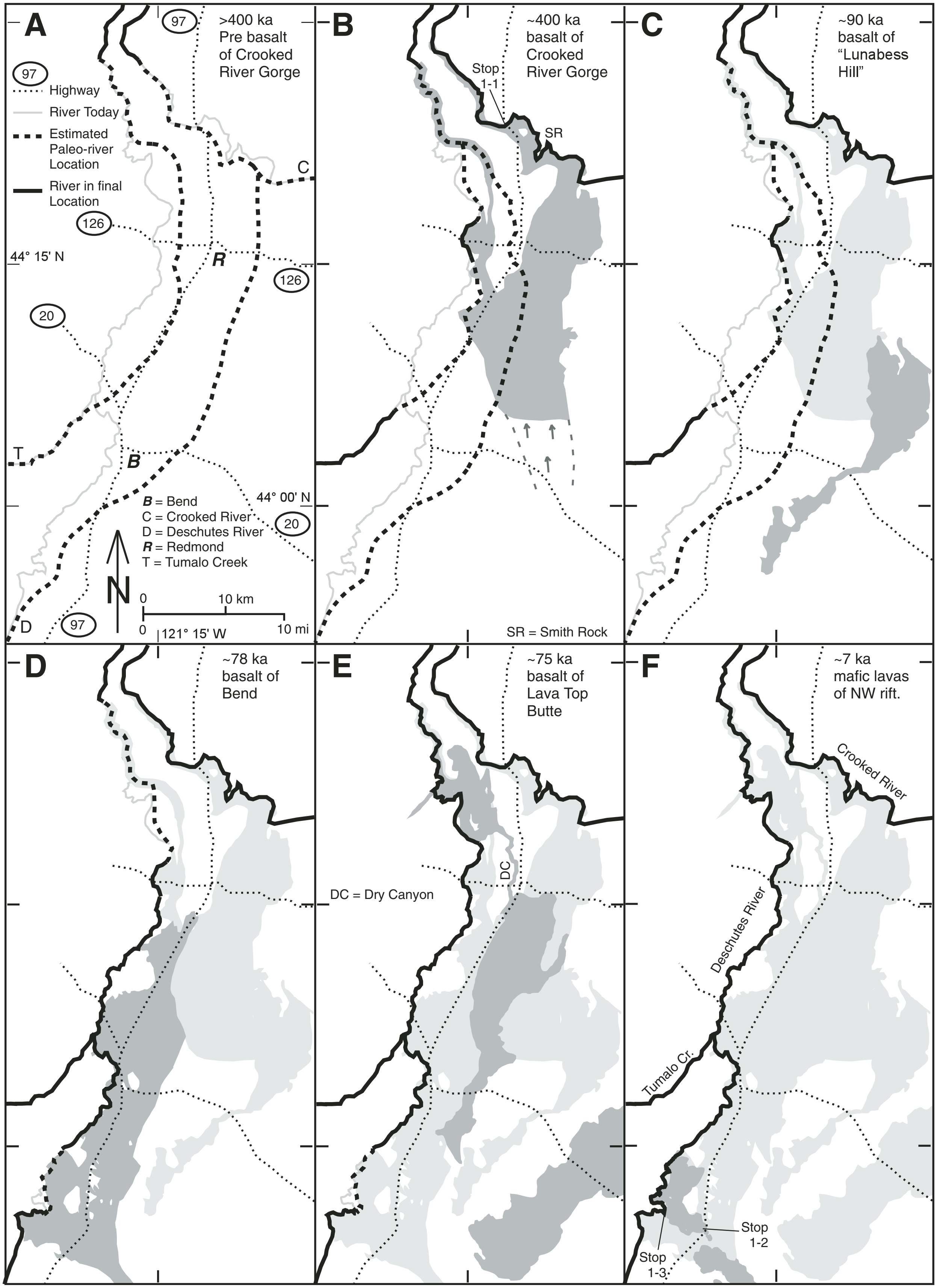

Figure 5. Panels A through F show evolution of major rivers in central Oregon in response to interaction with lava flows from Newberry Volcano. Dark gray is flow described by that panel, light gray are flows from previous panels.

TABLE 1. CHEMICAL ANALYSES OF SELECTED ROCKS FROM NEWBERRY VOLCANO

Sample no.:	1465J	70J	674J	204J-a	737J-b	1174J	1090J	741J	77J	868J	50J	202J	282J	870J
Unit:	Basalt of Crooked River Gorge	Basalt of Bend (near Benham Falls)	Tuff of Paulina Creek Falls (was Qbt)	Tuff of Paulina Creek Falls (was Qat)	Tuff of Paulina Creek Falls	Rhyolite of Paulina Peak	Big Obsidian Flow	Basaltic andesite of north caldera wall	The Dome (at cinder pit)	Basalt of Red Hill (at Groundhog Quarry)	Basalt of the Pot Holes	Tuff of Tepee Draw (was Qtp)	Basalt of Lava Top Butte (at the Bad-lands)	Tuff of "Brooks Draw" (was Qdt)
wt%														
SiO_2	49.5	49.0	55.2	66.4	69.9	71.5	73.0	53.4	55.8	50.0	49.2	71.3	51.0	66.1
Al_2O_3	17.4	17.5	16.4	15.8	14.9	14.8	14.2	15.6	16.7	18.3	17.4	14.3	17.7	15.7
FeO*	9.29	9.44	9.80	4.62	3.76	2.76	2.05	11.26	7.96	7.21	9.22	3.32	8.43	4.62
MgO	8.58	8.27	3.34	1.12	0.30	0.28	0.19	3.75	4.38	8.30	8.78	0.54	7.86	1.32
CaO	9.79	10.85	6.82	2.61	1.59	1.18	0.88	7.65	7.89	11.21	10.17	1.78	9.44	3.40
Na_2O	3.18	2.86	4.66	6.24	5.89	6.21	5.28	4.36	4.04	2.71	2.98	4.78	3.31	4.89
K_2O	0.42	0.36	0.90	1.84	3.03	2.81	4.07	0.91	1.31	0.78	0.53	3.34	0.56	2.55
TiO_2	1.43	1.40	2.23	0.90	0.41	0.29	0.23	2.42	1.43	0.91	1.26	0.38	1.23	0.88
P_2O_5	0.29	0.24	0.51	0.31	0.10	0.04	0.03	0.50	0.43	0.37	0.37	0.20	0.32	0.34
MnO	0.16	0.16	0.19	0.16	0.13	0.09	0.06	0.20	0.15	0.13	0.16	0.10	0.15	0.12
ppm														
Rb	5	6	14	26	58	74	113	14	32	11	8	66	9	62
Sr	386	316	428	269	132	103	53	397	502	937	326	123	468	267
Y	26	21	39	45	58	46	44	42	26	12	22	50	22	36
Zr	132	100	167	271	383	364	339	182	179	101	111	344	104	265
Nb	6.2	13	12	14	21	17	19.8	14	15	4	14	18	9	12
Ba	173	110	348	648	766	924	861	312	475	518	173	915	258	828
Ni	188	121	10		8		0	14	25	120	161		122	
Cu	62	92	11	14	6	2	5	47	78	80	74	25	73	4
Zn	85	81	109	103	104	76	55	107	85	60	76	83	67	71

Note: Major elements are normalized to 100% with all iron calculated as FeO. X-ray fluorescence spectrometry analyses were performed at U.S. Geological Survey, Denver, Colorado, except for 1465J and 1090J, which were analyzed at Washington State University, Pullman Washington. Qbt, Qat, Qtp, and Qdt are previous unit designations by MacLeod et al. (1995).

the railroad cut to the left are exposures of silicified tuffs that are thought to represent the western margin of the Crooked River Caldera.

139.85 [Hwy. 97 M.P. 118.50] O'Neil Junction near north edge of Redmond. The mouth of Redmond's Dry Canyon is ~0.8 miles west of here.

140.45 [Hwy. 97 M.P. 119.10] Exit 119 to downtown Redmond. The route stays left on bypass.

142.80 [Hwy. 97 M.P. 120.85] Traffic light at Evergreen Avenue. Hwy. 126 Junction. Route continues straight ahead.

144.30 [Hwy. 97 M.P. 122.80] Traffic light at Odem Road [Elev. = 3000 ft]. Northwest of here is Redmond's Dry Canyon (Fig. 6), where the Deschutes River flowed (Fig. 5C) until the eruption of the basalt of Bend at 78 ± 9 ka (Champion et al., 2004). The basalt erupted ~50 km to the south, from now-buried vent(s) midway up the north slope of Newberry Volcano. The lava forced the river into a new channel farther west along the western edge of the basalt of Bend (Fig. 5D). Subsequently, ca. 75–80 ka (Champion et al., 2004), the Horse Cave lobe of the basalt of Lava Top Butte (previously called "basalt of the Badlands") flowed down the old channel, partially filling it to form the present-day floor of the canyon. Continue south on Hwy. 97.

144.90 [Hwy. 97 M.P. 123.40] Southbound Yew Avenue Exit [do not take]. To the left are roadcuts in the basalt of Crooked River Gorge. Ahead the highway crosses onto the basalt of Bend, which the highway traverses all the way to Bend, and is exposed in a number of roadcuts.

155.60 [Hwy. 97 M.P. 134.10] Traffic light at Cooley Road. Continue straight ahead.

156.40 [Hwy. 97 M.P. 134.90] The route goes left onto Bend Parkway.

158.60 [Hwy. 97 M.P. 137.10] The view ahead to Newberry shows the shield-shaped profile of the volcano.

162.35 [Hwy. 97 M.P. 140.85] South Third Street traffic light at south end of Bend Parkway. [Elev. = 3810 ft]

165.85 [Hwy. 97 M.P. 145.05] High Desert Museum Entrance (left). Shevlin Park Tuff exposed at entrance. Prior to the ca. 78 ka basalt of Bend, the Deschutes River channel was most likely about a kilometer west of here (Fig. 5C). Today the channel is ~5 km to the west along the western margin of the basalt of Bend.

170.30 [Hwy. 97 M.P. 149.50] The route turns right to Lava Lands. [Current (2009–2011) road construction will change access to Lava Butte (Stop 1-2) and Benham Falls (Stop 1-3). Future access will be from Exit 151.]

170.40 Entrance Station, turn right and drive to summit of Lava Butte.

172.15 Summit Parking Area. Walk up trail to summit for Stop 1-2. NOTE: This stop is in Newberry National Volcanic Monument, and a research permit is required to collect samples.

Stop 1-2 at Lava Butte Summit (5020 ft)

Lava Lands Visitor Center and the road to the summit of Lava Butte are typically open from mid-May through mid-October. From Memorial Day weekend through Labor Day weekend it is open 7 days a week from 9:00 a.m. to 5:00 p.m. The remainder of the season it is open Wednesday to Sunday from 9:00 a.m. to 5:00 p.m. There is a use fee at selected sites in Newberry National Volcanic Monument; the Lava Lands area is one of those sites.

From the summit of the Lava Butte cinder cone (Fig. 7) there is a view of the Cascades from Mount Scott in Crater Lake National Park to Mount Adams in Washington State (see Fig. 8).

Lava Butte is the northernmost vent along the Holocene "northwest rift zone" (an informal name first used by Peterson and Groh, 1965) a nearly continuous zone of mafic vents and flows extending

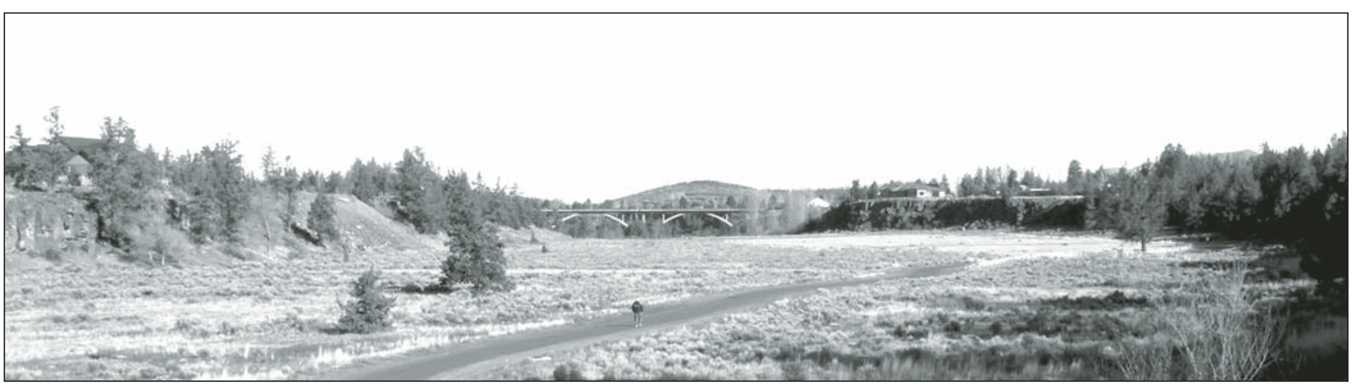

Figure 6. View north looking down Redmond Dry Canyon toward Tetherow Butte. Bridge in middle distance crosses canyon and is anchored on the west side in basalt of Redmond and on the east side in basalt of Dry River, both ca. 3.5 Ma (Sherrod et al., 2004). These two basalts formed the walls of the paleo Deschutes River channel before the river was diverted by the basalt of Bend. Later the Horse Caves lobe of the basalt of Lava Top Butte entered the canyon and now forms the floor of the canyon. The Horse Cave lobe was erupted ~35 km to the south on the north flank of Newberry Volcano ~75,000–80,000 years ago. Photo by R. Jensen.

from Lava Island on the Deschutes River to the north wall of Newberry caldera. Included in this fissure eruption is the Surveyor Flow on the upper southwest flank of the volcano (32 km to south). Erupted lavas range in composition from 51.3 to 58.4 wt% SiO_2 (see accompanying article by Mckay et al., this volume).

The eruption postdated deposition of the Mazama Ash when Mount Mazama erupted to form Crater Lake ~7650 years ago (Hallett et al., 1997). MacLeod et al. (1995) listed 11 radiocarbon dates from 8 flows along the rift zone as reported by 5 different sources. Calibrated radiocarbon ages range from 6610 to 7240 yr B.P. with an average of 6927 calendar years B.P. We use an even 7000 calendar yr B.P. as an estimate of the 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 150-m high cinder cone, several spatter ramparts, and lava flows covering over 23 km^2. Chemical analyses of Lava Butte and its lavas yield silica contents of 55.3–56.2 wt% (Mckay et al., this volume).

Vents along the "northwest rift zone" provide examples of the types of mafic eruptions that have occurred on the flanks of Newberry Volcano. Individual vents in this zone have produced spatter ramparts, cinder cones of various sizes, both ‘a‘a and pahoehoe lava flows, and tephra blankets. Physical characteristics of these erupted materials demonstrate that not all cinder cone eruptions are the same. Vents for some flows produced low spatter ramparts and lava flows dominated by pahoehoe, products typical of Hawaiian-style eruptions. Other vents produced small cinder cones and lava flows dominated by ‘a‘a, products typical of low energy Strombolian-style eruptions. Lava Butte and Mokst Butte are large cinder cones that produced extensive ‘a‘a lava flows, and tephra blankets, products indicative of energetic Strombolian or perhaps violent Strombolian-style activity. See accompanying paper by Mckay et al. (this volume) for discussion of the classification of cinder cone eruptions and physical and chemical data from vents along the "northwest rift zone."

The route returns to base of the butte and through Lava Lands Visitor Center parking lots.

Cumulative mileage	*Description*
174.00	The route turns right on Road 9702 at exit from Lava Lands Visitor Center parking.
177.20	Cross the Burlington Northern Santa Fe Railroad.
177.70	Cross old canyon rim.
177.80	Park in Benham Falls Day Use Area for Stop 1-3 [Elev. = 4150 ft]. Walk back up road to the old canyon rim and then eastward along rim to a view overlooking the river. NOTE: This stop is in Newberry National Volcanic Monument, and a permit is required to collect samples.

Stop 1-3 at River Overlook near Benham Falls Day Use Area

Circa 78 ka, the eruption of the basalt of Bend filled the channel of the Deschutes River for more than 45 km (Fig. 5D). This primitive (see Table 1) basalt flow underlies downtown Bend and extends nearly to Redmond (see log mile 144.90). The river reestablished a channel along the western edge of the flow and here, near Benham Falls; the river proceeded to cut a channel at least

Figure 7. Photo of Lava Butte and a portion of the Lava Butte basaltic andesite lava flow. Stop 1-2 is at the top of the cinder cone. Photo by R. Jensen.

30 m deep. From this point the old channel went around the easternmost portion of the Benham Buttes dome and then northward to the location of Dillon Falls.

The ca. 7 ka eruption of Lava Butte buried almost 8 km of the Deschutes River channel (Fig. 5F) and dammed the river. The resulting lake at its maximum stage extended upstream for over 22 km and covered ~48 km^2 (Fig. 9). The river found an outlet across a low saddle on Benham Buttes and formed Benham Falls. Sediments filled the old channel and the new base level resulted in a meandering new section of channel over 50 km long. According to Sherrod et al. (2002), the Deschutes River gradient steepens dramatically north of Benham Falls from 0.48 m/km to 8.7 m/km along the 18.5 km reach to Bend.

The Benham Falls Day Use Area is located ~9 m below the top of the old canyon wall. Test drilling for a proposed dam site near the bridge in 1913 showed that the sediments under the day use area extend to a depth of 20 m and overlie what is interpreted as the lava flow from Lava Butte. The flow is 3.6 m thick and overlies additional sediments (Cooperative Officers of the State of Oregon and the Reclamation Service Office, 1914).

Below Benham Falls, the river follows the flow margin until it spills back into the old channel at Dillon Falls. Below Dillon Falls the old channel is blocked by the flow in two other locations before the end of the flow is reached below Lava Island Falls.

The route returns to Hwy. 97.

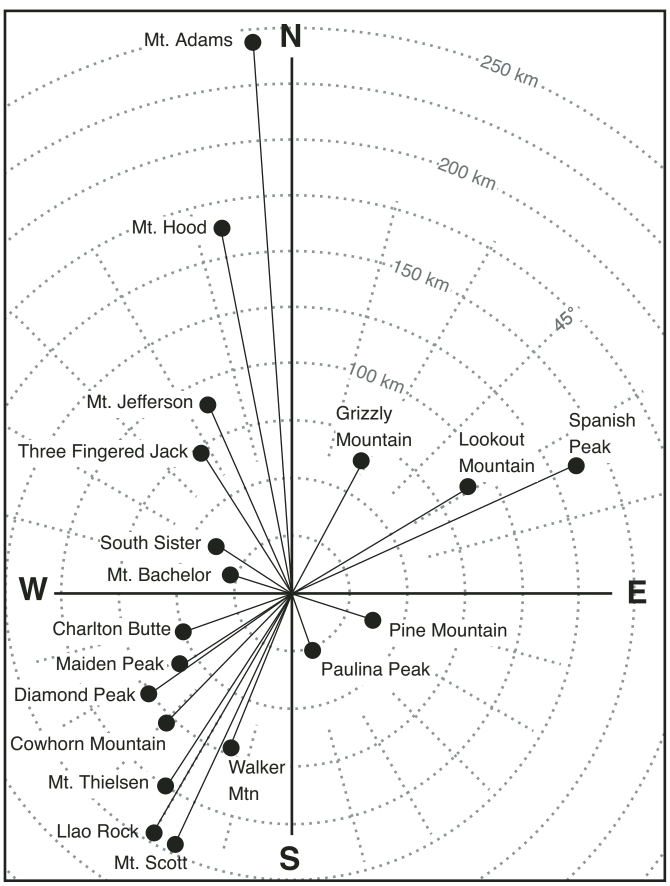

Figure 8. Azimuths and distance to prominent points that can be seen from the top of Lava Butte (Stop 1-2).

Cumulative mileage	*Description*
181.75	[Hwy. 97 M.P. 149.50] The route turns left on Hwy. 97.
189.55	[Hwy. 97 M.P. 141.00] The route goes left on to Bend Parkway.
192.35	[Hwy. 97 M.P. 138.20] The route takes Exit 138 to Colorado Avenue.
192.55	The route turns right on Colorado Avenue.
193.10	Traffic light at Colorado Avenue and Bond Street. The route turns right on Bond Street.
193.50	Traffic light at Bond Street and Franklin Avenue. [Elev. = 3630 ft]

DAY 2: LOOP TRIP THROUGH NEWBERRY CALDERA

This day involves about a 100 mile (160 km) loop across Newberry Volcano and through the caldera with a total of nine stops (see Fig. 3).

Cumulative mileage	*Description*
0.00	Traffic light at Franklin Avenue and Bond Street. [Elev. = 3630 ft] The route goes north on Bond Street.
0.15	Traffic light at Bond Street and Oregon Avenue. The route turns right on Oregon Avenue.
0.45	[Hwy. 97 M.P. 137.80] The route turns right on Hwy. 97 (Bend Parkway).
3.50	[Hwy. 97 M.P. 140.85] South Third traffic light at south end of Bend Parkway. Continue south on Hwy. 97.
7.00	[Hwy. 97 M.P. 145.05] High Desert Museum Entrance (left). The Shevlin Park Tuff is exposed at the entrance. Conrey et al. (2002) suggest a source in the Bend Highland ~25 km west of Bend, based on the spatial distribution of the tuff.
7.80	[Hwy. 97 M.P. 145.85 to Hwy. 97 M.P. 151.95] For the next 6 miles the route crosses the ca. 78 ka basalt of Bend. The vent for the basalt of Bend has not been found, but possible near-vent coarse spatter has been identified just northwest of Mokst Butte (a cinder cone of the ca. 7 ka "northwest rift zone" eruption) at an elevation of ~5600 ft.
11.45	[Hwy. 97 M.P. 149.50] Lava Lands entrance (right).
12.65	[Hwy. 97 M.P. 150.70] Lava River Cave entrance (left). This large lava tube was a major feeder tube for the basalt of Bend. The main northwestern portion of the tube is 1880 m long and the southeastern (closed

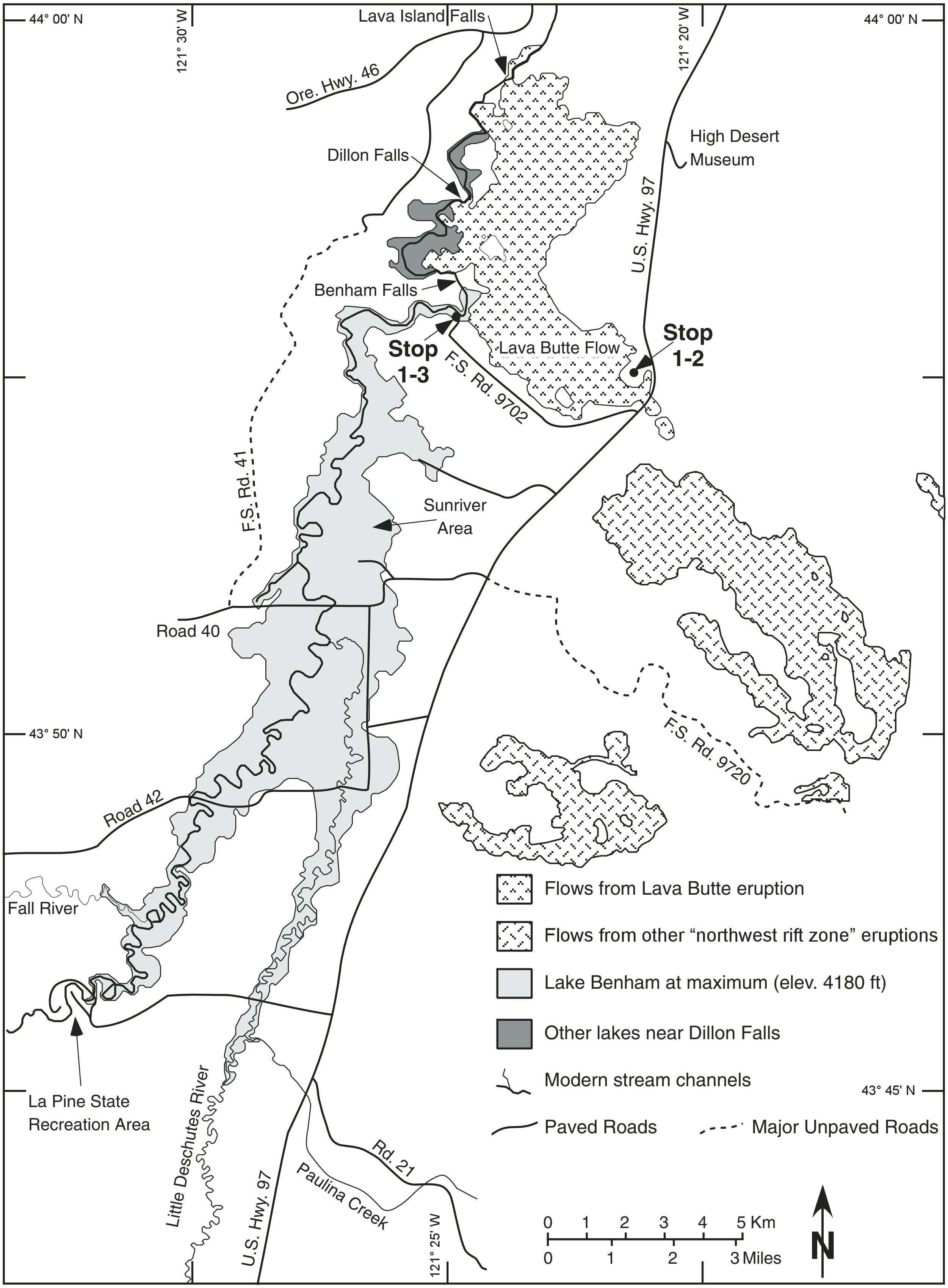

Figure 9. Map shows areas of upstream flooding that followed damming of the Deschutes River by the Lava Butte flow ~7000 years ago when the informally named "northwest rift zone" eruption took place at multiple vents on the northwest flank, in the caldera, and on the upper southwest flank of Newberry Volcano.

to public) portion is 490 m long. [Current (2009–2011) road construction will change access to Lava River Cave. Future access will be from Exit 151.]

14.00 [Hwy. 97 M.P. 152.15 to Hwy. 97 M.P. 154.30] For the next 2.15 miles the route crosses the basalt of "Camp Abbot Buttes."

14.70 [Hwy. 97 M.P. 152.85] Southbound Exit 153 offramp to Sunriver and Lava Cast Forest. The Lava Cast Forest area includes parts of three Holocene lava flows (Forest Road Flow, Lava Cast Forest Flow, and Lava Cascade Flow) that are part of the "northwest rift zone" (see Mckay et al., this volume, for map). These flows were erupted ca. 7 ka from a 6.4-km-long fissure along the rift zone and are well known for the many tree molds they contain. A paved pathway has been constructed across the lava flow for viewing the tree molds, some of which are a meter across.

16.15 [Hwy. 97 M.P. 154.30 to Hwy. 97 M.P. 159.25] For the next 4.95 miles the route crosses flows from four different sources.

17.35 [Hwy. 97 M.P. 155.50] Fall River Junction (right) and U.S. Forest Service (USFS) Road 9724 (left). USFS Road 9724 provides access to Sugar Pine Butte and the Sugarpine Flows. North Sugarpine and South Sugarpine Flows were erupted from a 1.6-km-long fissure, which cuts across the west flank of pre-Mazama Sugarpine Butte. These flows are part of the ca. 7 ka "northwest rift zone" eruption and also contain tree molds.

21.10 [Hwy. 97 M.P. 159.25 to Road 21 M.P. 3.00] For the next 3.5 miles, the route crosses sediments of the La Pine Basin. Along the route of the field trip, the upper part of the La Pine Basin sediments is largely reworked ash-flow deposits erupted during the most recent Newberry caldera collapse ca. 80 ka.

22.35 [Hwy. 97 M.P. 160.50] USFS Road 9735 (right) provides the highest road access to the "northwest rift zone" and crosses the vent area for the Lava Cascade Flows.

23.55 [Hwy. 97 M.P. 161.70 = Road 21 M.P. 0.00] At Newberry Caldera junction, the route turns left on paved Road 21 toward the caldera. [Elev. = 4205 ft]

25.70 [Road 21 M.P. 2.15] Cross "McKay Draw." The west flank of Newberry is drained by six main drainages of which "McKay Draw" is one (Fig. 10). Today only Paulina Creek has flowing water because it is fed by Paulina Lake. The other five drainages all head high on Newberry at an elevation of ~6000 ft. The west flank drainages are all post-caldera in age and cut deeply into ash-flow deposits emplaced during caldera collapse, which beheaded the rhyolite of Paulina Peak, dated at 83 ± 5 ka (Donnelly-Nolan et al., 2004). Erosion has cut deeply enough in places to expose the underlying lava flows.

26.35 [Road 21 M.P. 2.80] Cross Paulina Creek, the only flowing water on Newberry Volcano. For the next 7 miles the route primarily crosses non-welded ash-flow tuff of the caldera-forming eruption. This poorly exposed deposit, mapped by MacLeod et al. (1995) as unit Qbt (Quaternary basaltic andesite lapilli tuff), covers much of the western flank of Newberry Volcano. The deposit has been deeply channeled, exposing underlying lava flows.

An interesting feature of the Paulina Creek drainage is the lack of Mazama Ash at most locations on the valley floor up to 3–5 m above the current stream level. In addition to the missing Mazama Ash there are gravel terraces, scoured bedrock surfaces, waterfalls, and boulder trains. These features indicate that since the ashfall ~7650 years ago there was a large flood down Paulina Creek, which

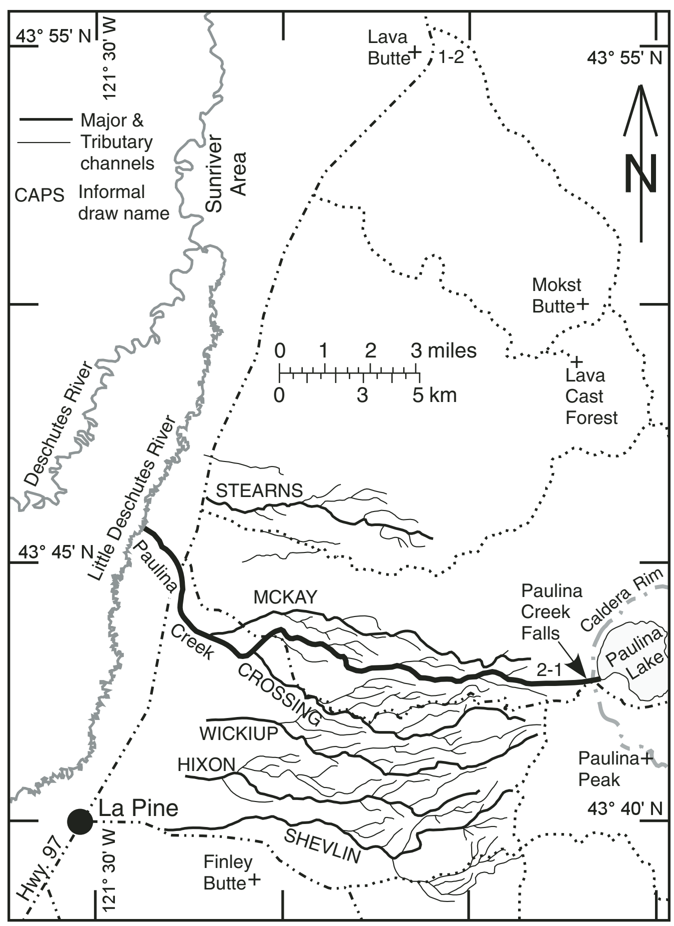

Figure 10. Map of west flank drainages. Names in all capital letter identify major dry channels. Dash-dot lines are paved roads; dotted lines are major unpaved roads. Locations of Stops 1-2 and 2-1 are indicated.

removed the ash in all but a few sheltered locations (Jensen and Chitwood, 1996).

33.10 [Road 21 M.P. 9.55] 10-Mile Sno-Park on left has among the best exposures of the ca. 80 ka non-welded ash-flow tuff.

34.80 [Road 21 M.P. 11.25] Newberry National Volcanic Monument Entrance Station. No collecting in monument without a research collecting permit. The Newberry Caldera area is typically accessible from late May through the end of October. Snow may limit access to some areas of the caldera, especially Paulina Peak, until late June. There is a fee for parking at most day use sites in Newberry National Volcanic Monument.

35.85 [Road 21 M.P. 12.30] The route turns left to Paulina Creek Falls.

35.95 Parking for Stop 2-1. [Elev. = 6270 ft] NOTE: This stop is in Newberry National Volcanic Monument, and a research permit is required to collect samples.

Stop 2-1 at Paulina Creek Falls

At the falls, Paulina Creek drops ~30 m over a vertical cliff face in welded ash-flow tuff (Fig. 11). Mapped by MacLeod et al. (1995) as unit Qat (Quaternary andesitic tuff), it was interpreted as overlying unit Qbt, the Quaternary basaltic andesite lapilli tuff. Donnelly-Nolan et al. (2004) recognized that Qat and Qbt are parts of the same compositionally zoned ash-flow tuff (see Table 1 for chemical analyses). However, unit Qat is here reinterpreted based on new mapping and tephra studies as the lower part of the tuff, and Qat and Qbt combined are here named the tuff of Paulina Creek Falls. Based on chemical analyses, we correlate the tuff of Paulina Creek Falls with the Pumice Flat tephra of Kuehn and Preppernau (2005), a 3.4-m-thick compositionally zoned deposit found east of Newberry. The deposit grades upward from coarse white pumice up into mixed black and white pumice, accretionary lapilli, and black scoria. A sample of the black scoria matches the distinctive chemical composition of Qbt lapilli. The Pumice Flat tephra may be just one lobe of tephra generated by the caldera-forming event. Donnelly-Nolan et al. (2004) suggested that the widespread Olema ash bed may represent another lobe. Caldera formation postdates the rhyolite of Paulina Peak (83 ± 5 ka, Donnelly-Nolan et al., 2004) but predates the basalt of Bend and the ca. 75–80 ka basalt of Lava Top Butte (previously called basalt of Badlands by Champion et al., 2004). Poorly exposed ash-flow deposits blanket much of the west flank of Newberry.

As mentioned at mile 26.35, abundant evidence exists for a large flood down Paulina Creek. Paulina Creek Falls is the uppermost of a series of waterfalls ("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 that the lake's outlet failed as the result of upstream migration of a 1.5–2.4 m knickpoint (waterfall) that reached the lake. The andesitic tuff at the lake's outlet is irregularly stratified

Figure 11. Photo of Paulina Creek Falls (Stop 2-1) where Paulina Creek divides and flows over the welded lower portion of the tuff of Paulina Creek Falls. The tuff was emplaced during the eruption that produced the present caldera ca. 75–80 ka. Photo by R. Jensen.

with variable degrees 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 deposits associated with the flood indicates that the flood probably occurred between ca. 1700 and 4900 calendar yr B.P. (Jensen and Chitwood, 1996).

Return to Road 21.

Cumulative mileage	*Description*
36.05	[Road 21 M.P. 12.30] The route turns left on Road 21.
36.35	[Road 21 M.P. 12.60] Cross over the low western rim of Newberry Caldera at the Paulina Lake Lodge Road (left). The road to the lodge crosses the dam at the outlet for Paulina Lake. The first dam was built across the outlet in 1899. [Elev. = 6340 ft] This junction of paved roads covers the site of the oldest dwelling in the western United States, dated at ~9500 years ago. The date of earliest site use goes back to 11,000 years ago (Connolly, 1991, 1999).
36.40	[Road 21 M.P. 12.65] Paulina Lake Day Use Area (left). Paulina Lake covers an area of ~6 km^2 and has an average depth of 50 m with a maximum depth of 76 m. The late Holocene failure of the lake outlet, which resulted in the flood down Paulina Creek, also lowered the lake level by nearly 2 m, resulting in 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 5.5 m above the natural lake level (Jensen and Chitwood, 2000). At the northeast corner of Paulina Lake there is an area of hot springs along the shoreline with temperatures as high as 57 °C. Offshore along the northeast perimeter of the lake, there is a large area of above normal temperatures and rising gas bubbles that extends southward to the north end of Little Crater Campground.
36.65	[Road 21 M.P. 12.90] The route turns right to Paulina Peak. This gravel road is not suitable for trailers and motorhomes. The road is single lane with passing turnouts. It winds up the steep exposed southwest and west sides of Paulina Peak. The road cuts through exposures of rhyolite and provides views to the west of the Cascade crest and south across the cinder cone dotted south flank of Newberry.
40.55	Parking for Stop 2-2. [Elev. = 7984 ft] NOTE: This stop is in Newberry National Volcanic Monument, and a permit is required to collect samples.

Stop 2-2 at Paulina Peak

From Paulina Peak there is a 360° view, which on a clear day includes the Cascade peaks from Mount Adams (270 km) in Washington to Mount Shasta (265 km) in California and eastward to Steens Mountain (248 km) (Fig. 12). In addition there is a spectacular view down into the caldera (Fig. 13).

Paulina Peak at nearly 8000 ft is the highest point on the rim of Newberry Crater, a 45 km^2 caldera. The floor of the caldera includes East and Paulina Lakes and a wide variety of late Pleistocene and Holocene volcanic features. Between Paulina and East Lake are Little Crater (basaltic tuff cone) and the Central Pumice Cone (rhyolitic tuff cone). Also visible just southeast of East Lake are the 3.5 ka (Friedman, 1977) East Lake obsidian flows (Fig. 14).

Caldera collapse beheaded the 83 ± 5 ka rhyolite of Paulina Peak (Donnelly-Nolan et al., 2004), which vented from somewhere within the area of subsequent collapse. Prior to caldera collapse, glacial ice removed the glassy carapace of the rhyolite flow (see accompanying article by Donnelly-Nolan and Jensen, this volume). A chemical analysis of the rhyolite is given in Table 1.

The large size of Newberry Volcano and the significant travel times involved in driving around the volcano preclude any stops on its south flank, but views from this location show the many cinder cones that dot the south side as well as the post-Mazama Surveyors Lava Flow of the "northwest rift zone" eruption. South flank distal basalts are similar in composition to those on the north flank, but do not extend as far away from the central part of the edifice because they were contained by topography.

A 1981 U.S. Geological Survey drill hole in the center of the caldera encountered a temperature of 265 °C at 930 m (Sammel et al., 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 et al. (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, thus precluding additional geothermal drilling within the caldera. Subsequent exploratory drill holes have been sited outside of the monument, most recently (fall of 2008) on the upper west side of the volcano.

Return to Road 21.

Cumulative mileage	*Description*
44.45	[Road 21 M.P. 12.90] The route turns right on Road 21.
44.90	[Road 21 M.P. 13.35 to Road 21 M.P. 13.85] For the next half-mile the route passes over the low south flank of "Lakeshore Dome."
45.40	[Road 21 M.P. 13.85 to Road 21 M.P. 14.85] For the next mile the route crosses the Paulina Lake ash-flow deposit. During reconstruction of the road charcoal stumps (13) and log segments (35) were exposed along this road section.
46.00	[Road 21 M.P. 14.45] Road left to Little Crater Campground. The campground is located on lake terraces cut into the slope of the Little Crater tuff

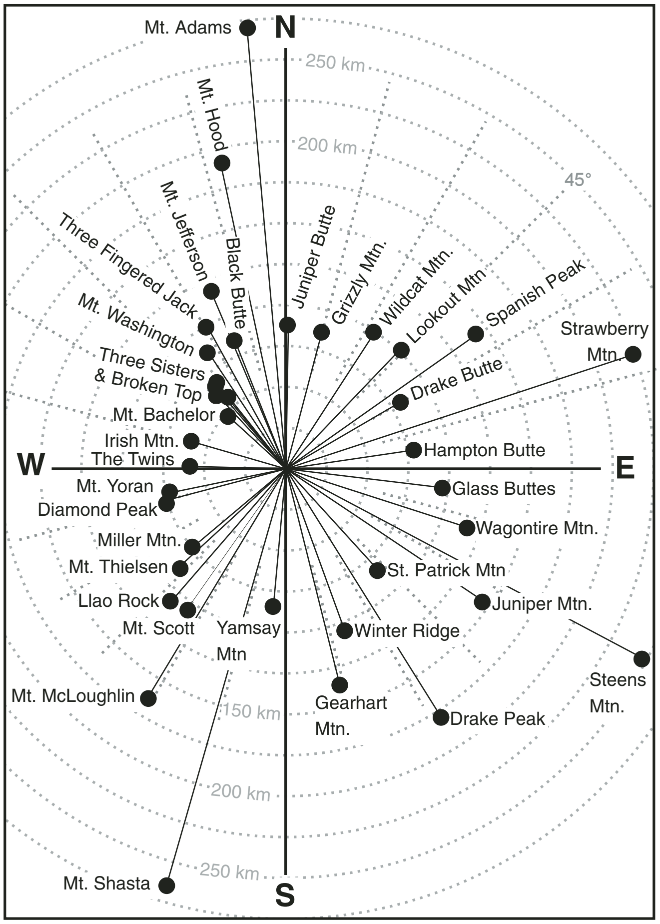

Figure 12. Azimuths and distances to prominent points that can be seen from the top of Paulina Peak (Stop 2-2).

cone. Similar terraces occur along much of the east and southwest shores of Paulina Lake. The variable elevations of terraces indicate that the floor of the caldera has in places undergone as much as 3 m of differential uplift. (Jensen and Chitwood, 2000).

46.40 [Road 21 M.P. 14.85] The route turns right to Big Obsidian Flow.

46.50 Parking for Stop 2-3. [Elev. = 6400 ft] We will walk up a paved trail and climb the stairs to the first viewpoint on the obsidian flow. A chemical analysis of the lava is in Table 1.

NOTE: This stop is in Newberry National Volcanic Monument, and a research permit is required to collect samples.

Stop 2-3 at Big 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 tuff, which has been dated at ~1300 years old (1310 ^{14}C yr B.P.) (See summary and calibrated age in Jensen, 2006, table II). The ash-flow tuff and the lava flow are parts of the same eruptive event, as is the Newberry Pumice that forms a strongly east-directed (Fig. 15) narrow deposit (MacLeod et al., 1995) extending eastward into Idaho (Kuehn, 2002; Kuehn and Foit, 2006).

Return to Road 21.

Cumulative mileage	*Description*
46.60	[Road 21 M.P. 14.85] The route turns right on Road 21.
47.55	[Road 21 M.P. 15.80 to Road 21 M.P. 16.55] For the next 0.75 miles the route climbs up and over the

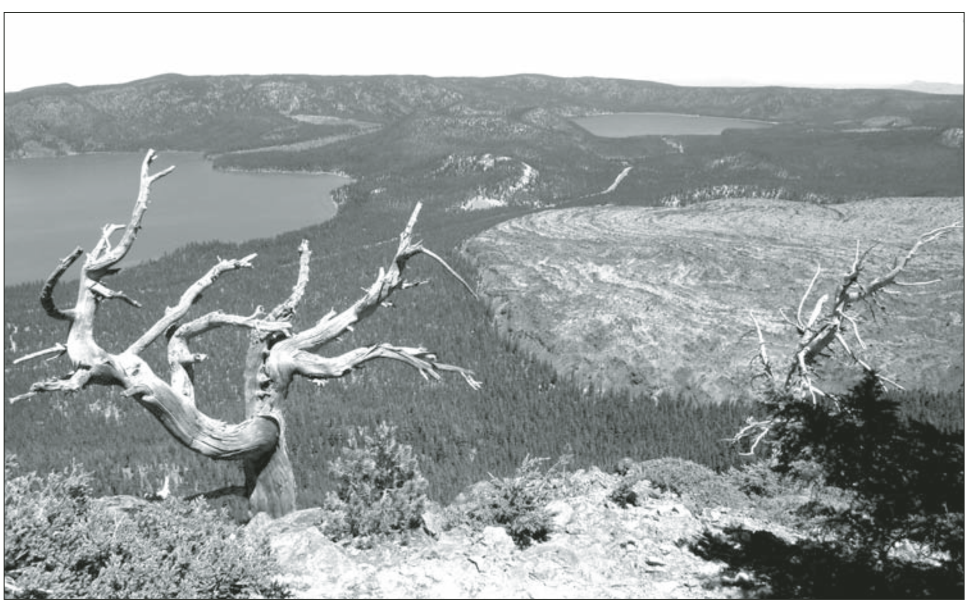

Figure 13. Photo of Newberry caldera as seen from near the top of Paulina Peak (Stop 2-2). Big Obsidian Flow in right middle ground erupted ~1300 years ago and is youngest lava at Newberry Volcano. Paulina Lake is on left, East Lake on right of Central Pumice Cone. Photo by R. Jensen.

buried obsidian flow from "South Dome." This flow is likely postglacial in age, but has been buried by the late Holocene Newberry Pumice.

48.35 [Road 21 M.P. 16.60] The route turns left to East Lake Campground on the south shore of East Lake.

48.45 Parking for Stop 2-4. [Elev. = 6390]
NOTE: This stop is in Newberry National Volcanic Monument, and a research permit is required to collect samples.

Lunch stop.

Stop 2-4 at East Lake Campground

East Lake covers an area of ~4 km^2 and has an average depth of 20 m with a maximum depth of 55 m. The lake has a typical surface elevation between 6375 and 6380 feet, ~40 feet higher than Paulina Lake. The lake has no outlet; instead, water drains westward underground.

The view from this locality at the south shore of East Lake encompasses lava flows and tuffs of a variety of compositions and ages. The south shore to our left (west) is bounded by the postglacial rhyolite of "South Dome," which is poorly exposed because of burial by the Newberry Pumice. Continuing clockwise around the lakeshore, we see the White Pumice Slide on the east side of the Central Pumice Cone. This steep unvegetated 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 portion of the post-Mazama central caldera rhyolite fissure that extends from the paved caldera road north-northwest to the base of the north caldera wall. A very small rhyolite dome at the base of the south caldera wall may also be part of this eruptive event. The east end of the Inter Lake Flow, which erupted farther north along the fissure, can be seen just to the right (north) of the Central Pumice Cone. Tephra correlated to the central caldera rhyolite fissure has been dated by radiocarbon and yields a calibrated age of ca. 7300 calendar yr B.P. (see summary and calibrated age in Jensen, 2006, table II).

Above the end of the rhyolite flow on the north wall of the caldera is The Spire, a precaldera rhyolite flow. Still higher on the caldera wall (above the older rhyolite) is a pair of precaldera aphyric basaltic andesite flows of a distinctive composition

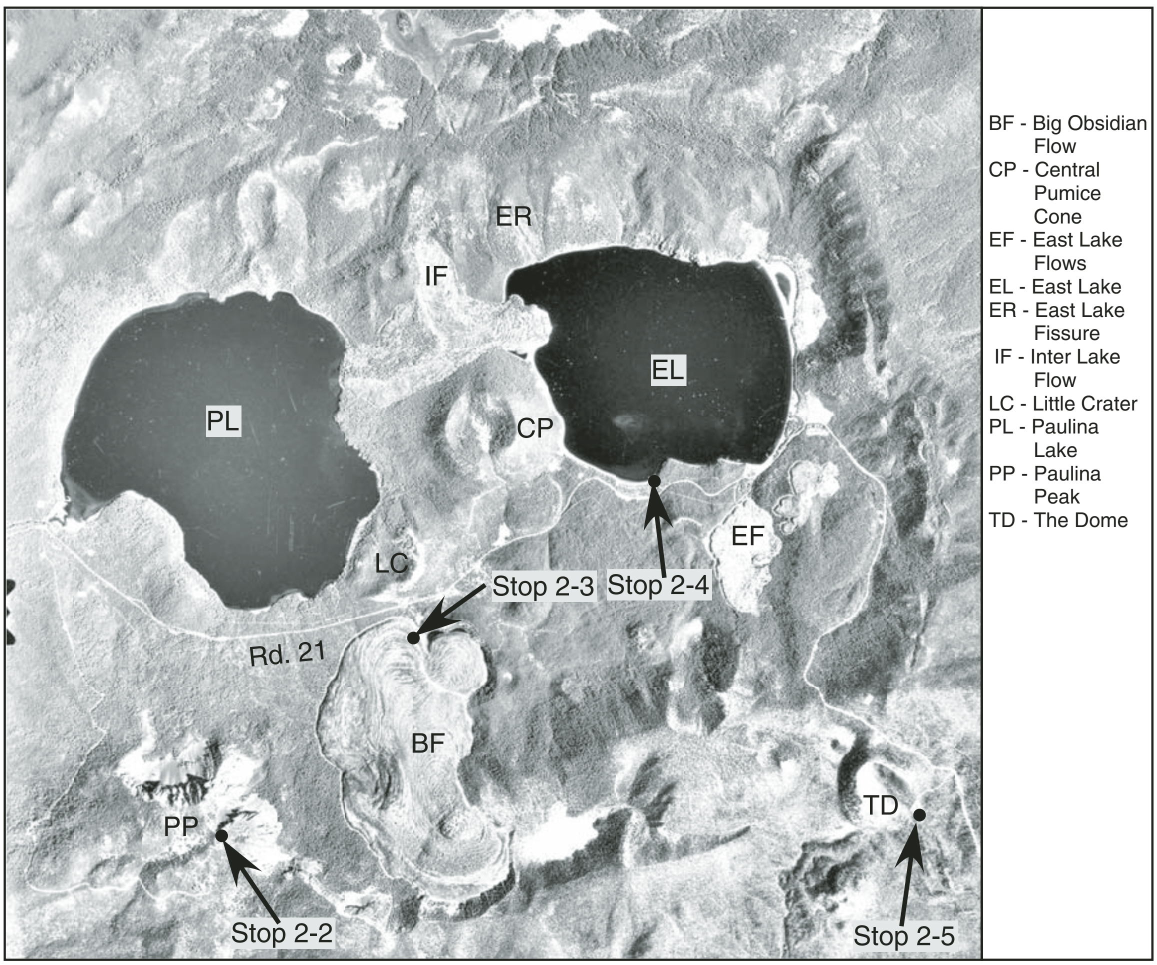

Figure 14. Aerial photograph of caldera showing important named features and locations of Stops 2-2 through 2-5. Width of view is ~9 km.

having high FeO and TiO_2 (see Table 1 for a chemical analysis). Higgins (1973) recognized that these lavas are present in the north, east, and south caldera walls. We here refer to these lavas as the basaltic andesite of the north caldera wall. We have subsequently mapped lavas of this composition to the east of the caldera nearly to Road 18, southwest to Road 22 (the paved road across the south flank of the volcano), and west down Paulina Creek to "McKay" falls. They apparently erupted from vents located over the present caldera.

At the northwest corner of the lake is the East Lake Fissure, part of the post-Mazama ca. 7 ka northwest rift zone. The fissure eruption postdates the central caldera rhyolite fissure eruption. The lava of the fissure is andesitic in composition (see Mckay et al., this volume) and contains multiple inclusions of rhyolite. On the north-northeast side of the lake is a postcaldera rhyolite flow whose upper part has been stripped of obsidian, presumably by ice.

To our right (east) on the south shore are exposures of basaltic palagonite tuff. If there is time, we'll walk out to examine the tuff. Only a portion of the tuff ring is preserved, but it presumably represents postcaldera mafic eruptive activity.

Return to Road 21.

Cumulative mileage	*Description*
48.55	[Road 21 M.P. 16.60] The route turns left on Road 21 and proceeds around the southeastern edge of the lake. Warm springs with temperatures as high as 46 °C emerge along the south shore of the lake. The East Lake Health Resort used water from these springs from 1913 to 1941.
49.55	[Road 21 M.P. 17.60] At the East Lake Resort, the route turns right on the continuation of Road 21,which in 0.15 miles becomes unpaved. For the next 2 miles the route climbs to the east rim of Newberry Caldera.
51.50	[Road 21] Summit of road at east rim of Newberry Caldera. [Elev. = 7010 ft] At this location (7.9 km from vent) the pumice fall (Newberry Pumice) from the Big Obsidian Flow vent is ~250 cm thick (MacLeod et al., 1995).
52.25	[Road 21] The route turns right on Road 2100 800.
52.60	Parking for Stop 2-5. [Elev. = 6720 ft]

Stop 2-5 at The Dome Cinder Pit

The Dome is a large breached cinder cone. Previous work (MacLeod et al., 1995) ascribed this cone and a small area of mapped lava flow to the post-Mazama ca. 7 ka "northwest rift zone" eruption. The apparent lack of Mazama tephra combined with extensive coverage by the late Holocene Newberry Pumice made it difficult to assign a correct age. However, new mapping and chemical analyses now place the flow terminus nearly 10 km to the east where the Mazama tephra clearly overlies the flow. Here in the cinder pit no Mazama tephra has been found between the cinders and the Newberry Pumice, presumably having been removed by the wind. The basaltic andesite of The Dome (see Table 1 for a chemical analysis) is one of as many as a dozen postglacial, pre-Mazama mafic eruptions.

The large number of Holocene age cinder cones on the flanks of Newberry Volcano indicate that future cinder cone eruptions are likely and that hazards posed by this type of

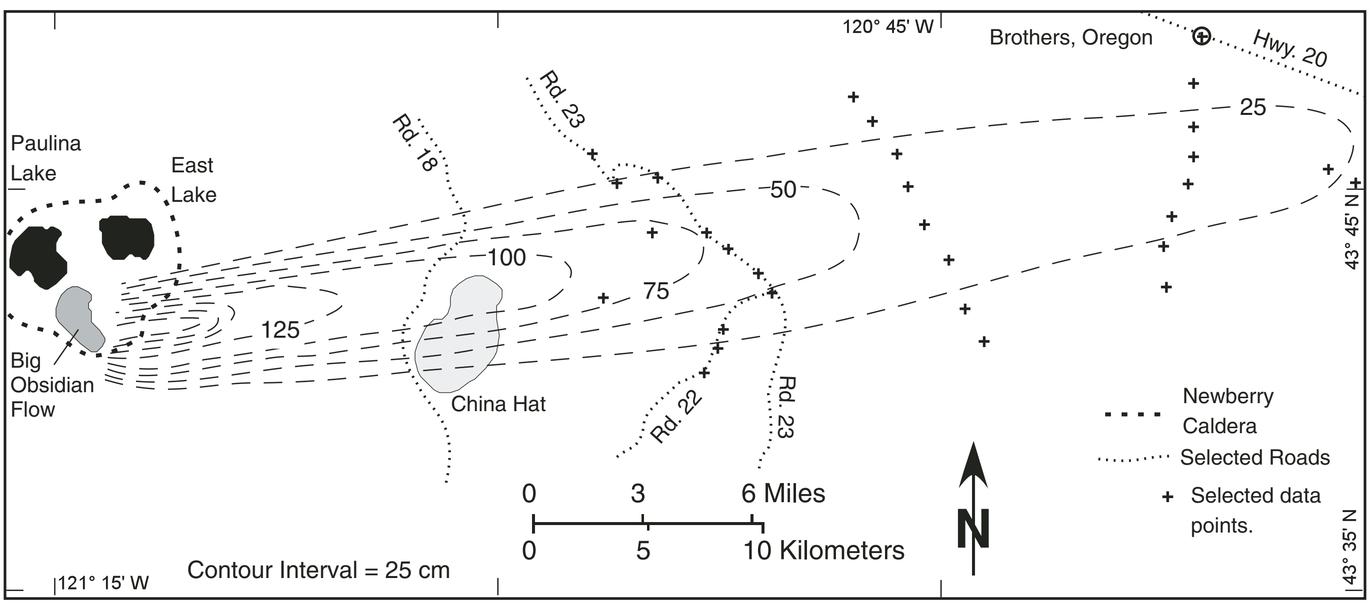

Figure 15. Map showing thickness contours on the Newberry Pumice, the initial tephra plume of the eruption that took place ~1300 years ago and resulted in emplacement of the Big Obsidian Flow. Isopachs based on data from MacLeod et al. (1995) and from D. Sherrod (1987, personal commun.).

activity need to be assessed. Typical cinder cone eruptions at Newberry have produced cones, lava flows, and tephra blankets. Each of these erupted products is associated with specific hazards. Some of the hazards posed by cone formation and lava flows have been addressed (e.g., Sherrod et al., 1997), but hazards associated with the production of tephra blankets are often overlooked. Since cinder cone eruptions can continue for years to decades (e.g., Fries, 1953), the production of even very limited tephra blankets can pose significant hazards in developed areas (e.g., Hill et al., 1998). Refer to the accompanying paper by Mckay et al. (this volume) for discussion of hazards posed by cinder cone eruptions.

Return to Road 21.

Cumulative mileage	*Description*
52.95	[Road 21] The route turns right on Road 21.
55.30	[Road 21] Road 9710 (left). At this location (7.2 km from vent) the Newberry Pumice is ~230 cm thick (MacLeod et al., 1995). The main axis of the deposit is 0.95 km to the north. To the north is Red Hill. The only seismograph on Newberry Volcano is located on "Little Red Hill," a subsidiary vent below the main cone. The postglacial basalt of Red Hill flowed east ~15 km. At our next stop, we will visit a quarry in the lava flow.
57.50	[Road 21] Road 2239 (right). At this location (10.9 km from vent) the Newberry Pumice is ~165 cm thick (MacLeod et al., 1995). The main axis of the deposit is ~0.8 km to the north.
59.85	[Road 18 M.P. 31.40] The route turns left on Road 18. [Elev. = 5250 ft] At this location (14.5 km from vent) the Newberry Pumice is ~100 cm thick (MacLeod et al., 1995). The main axis of the deposit is 2.2 km to the north.
62.40	[Road 18 M.P. 28.85] The route cuts through marginal levees and crosses large gutter in basalt of Red Hill.
62.95	[Road 18 M.P. 28.30] The route leaves the basalt of Red Hill and crosses "Sabol Draw" The "Sabol Draw" drainage (Fig. 16) has been significantly modified by the eruption of Red Hill. The basalt of Red Hill filled the full length of the former channel, whereas much of today's "Sabol Draw" follows the northern edge of the flow from Red Hill as it does at this location.
63.15	[Road 18 M.P. 28.10] The route turns right on Road 2510 450.
63.30	The route follows north edge (on right) of basalt of Red Hill for next 0.35 miles.
64.35	The route turns right on Road 2510 500.
64.70	The route turns right on Road 2510 and is now on basalt of Red Hill again. At this location the Newberry Pumice is ~76 cm thick.
65.10	The route turns left on Road 2510 569.
65.40	Parking at former rock quarry now used as vehicle "Rock Crawl" play area. [Elev. = 4880 ft]

Stop 2-6 at Groundhog Quarry

Quarry is in basalt of Red Hill, a high-strontium calc-alkaline basalt that erupted from Red Hill, a postglacial vent located ~15 km to the west, high on the east flank of Newberry Volcano. Just to the east of the quarry, this basalt is overlain by the basalt of the Pot Holes, which we will visit at our next stop. See Table 1 for a chemical analysis of the basalt of Red Hill. In addition to having over 900 ppm Sr at ~50 wt% SiO_2, the lava has Mg#'s of 66–67, among the highest at Newberry, despite having K_2O contents of ~0.8 wt%. Ba contents are around 500 ppm, with Nb <10 ppm, yielding Ba/Nb ratios >60. Such high ratios indicate a significant slab fluid contribution at Newberry (Carlson et al., 2008). By contrast, the overlying Pot Holes flow (Fig. 2; see Table 1 for a chemical analysis) is a tholeiitic basalt with somewhat lower SiO_2 contents (~49 wt%) and Mg#'s (62–63), significantly lower Sr (~300 ppm) and Ba/Nb (<20), but still having a relatively high K_2O content around 0.5 wt%.

In addition to providing the opportunity to look at and collect an interesting rock, this extensive quarry displays a variety of interesting internal flow features.

Turn around and return to Road 2510.

Cumulative mileage	*Description*
65.70	[Road 2510] The route turns right on Road 2510.
66.80	[Road 2510] The route drops down off basalt of Red Hill.
67.05	[Road 2510] The route begins descent down into the present "Sabol Draw." The basalt of Red Hill fills the former channel of "Sabol Draw."
67.80	[Road 2510] The route begins following the Pot Holes flow to the right. At this location the Newberry Pumice is ~25 cm thick.
68.20	[Road 2510] The route crosses mouth of "Scanlon Draw." The draw heads high on Newberry near the caldera rim. One of the main tributaries shares the beheaded glacial valley in which "Orphan Draw" heads.
69.05	[Road 2510] Cattle guard. This is the approximate northern edge of the Newberry Pumice.
71.15	Parking for Stop 2-7. [Elev. = 4710 ft]

Stop 2-7 at "Brooks Draw."

"Brooks Draw" (Fig. 16) is one of about a dozen major dry channels that drain the east flank of Newberry. Inception of most of these drainages appears to predate formation of the ca. 80 ka caldera. Seven of the draws head high on Newberry (above 6800 ft). Postcaldera lavas have occupied large portions of the northern channels. The four southern channels are buried by postglacial lava flows. For additional discussion about the

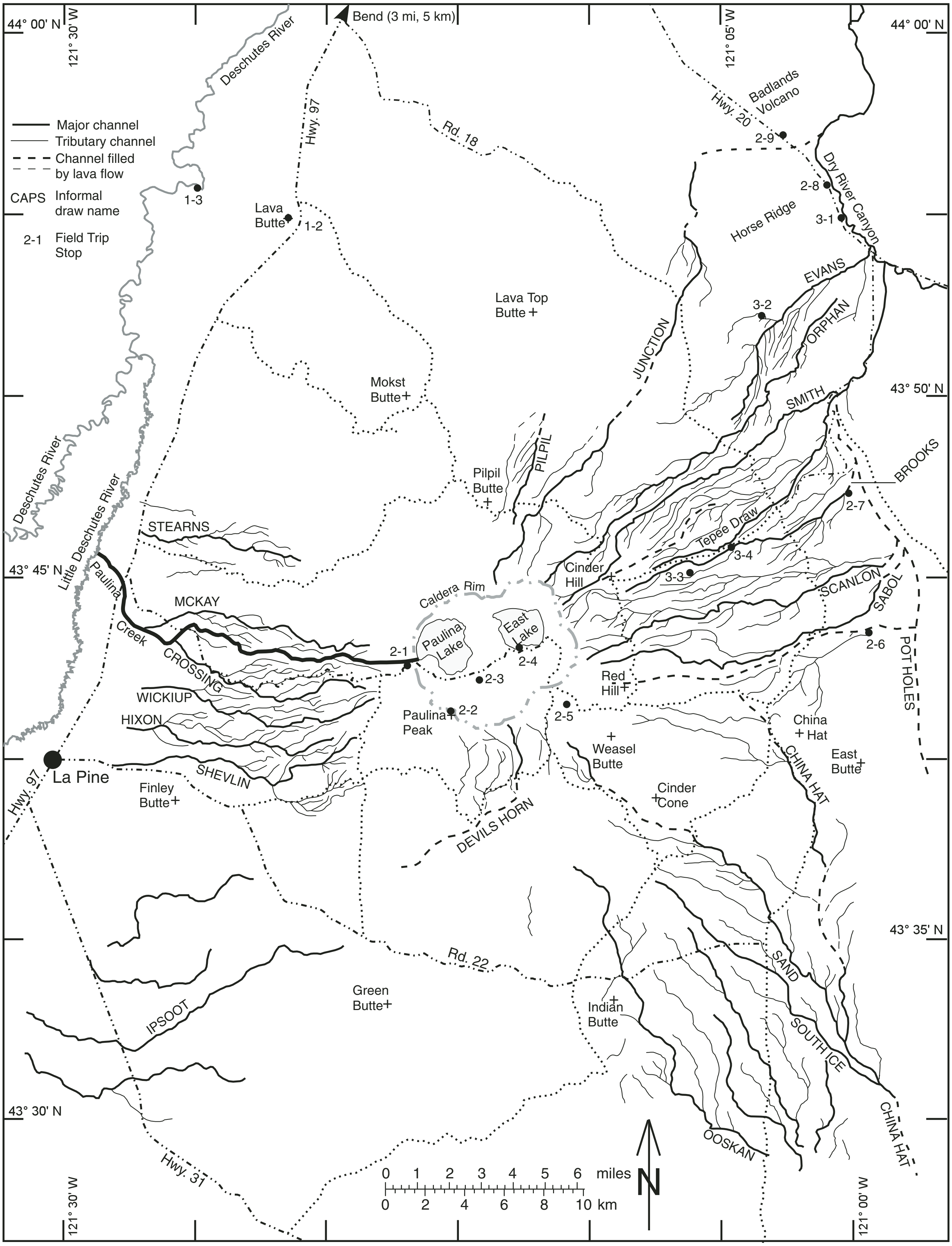

Figure 16. Map showing drainages on Newberry edifice. All paleo drainages are presently dry channels, except Paulina Creek, which drains west from Paulina Lake. Dash-dot lines are paved roads; dotted lines are major unpaved roads.

channels, see the accompanying paper by Donnelly-Nolan and Jensen (this volume).

At this location, we can see two very different rock types, the basalt of the Pot Holes, and the tuff of Tepee Draw.

The vents for the Pot Holes flow are a group of small cinder and spatter cones located 10 km south of here and east of the Newberry edifice. The flow continues another 8 km to the north along a major tributary of the Dry River drainage basin. The flow is younger than the basalt of Red Hill, which it overlies. The southern part of the Pot Holes flow is heavily mantled by Newberry Pumice, but farther north this diktytaxitic lava flow has a very youthful appearance with nice pahoehoe flow features and in places a spectacular inflated flow margin up to 18 m high (Chitwood, 1994).

The tuff of Tepee Draw is a rhyodacitic ash-flow tuff, which contains pumices ranging in composition from ~69–72 wt% SiO_2. See Table 1 for a chemical analysis. The tuff covers a large area on the lower east flank and was emplaced during an early caldera forming eruption.

Cumulative mileage	*Description*
71.85	[Road 25] The route turns right on paved Road 25.
73.25	[Road 25] Good exposures of Tepee Draw tuff to left in Tepee Draw.
74.00	[Road 23 M.P. 5.85] The route turns left on Road 23. The Pot Holes Flow comes down small draw just east of this junction.
74.20	[Road 23 M.P. 5.65] Cross Tepee Draw. Tepee Draw currently heads high on the east side of the volcano in the area below Cinder Hill but prior to the Cinder Hill eruption the draw drained a glaciated valley farther up slope.
74.85	[Road 23 M.P. 5.00] The north end of the Pot Holes flow is visible to the right in bottom of Tepee Draw. The high, lumpy flow to the left is the basaltic andesite of Smith Well, which overlies the Tepee Draw tuff.
76.95	[Road 23 M.P. 2.90] To the left is the end of the basaltic andesite of Smith Well.
79.85	[Road 23 M.P. 0.00 = Hwy. 20 M.P. 22.25] The route turns left on Hwy. 20.
80.40	[Hwy. 20 M.P. 21.00] Start up Horse Ridge
80.85	Hwy. 20 M.P. 20.55] Summit of Horse Ridge. [Elev. = 4292 ft]
81.40	[Hwy. 20 M.P. 20.00] Dry River Viewpoint (right); we'll stop here tomorrow morning.
82.40	[Hwy. 20 M.P. 19.00] Parking for Stop 2-8 in turnout. [Elev. = 3950 ft]

Stop 2-8 at Badlands Viewpoint

View to the northwest of what is locally known as "Badlands Volcano," a small lava shield with a summit pit crater (Fig. 17). However, this small shield is actually a large rootless vent (MacLeod et al., 1995), which was fed by the Arnold Lava Tube system from the vent at Lava Top Butte located southwest of here on the north flank of the Newberry edifice. The lava flowed ~16 km through the tube system and then the tube was apparently blocked and lava came to the surface to create the broad (~8 km) rootless shield. This eastern lobe of the unit, previously referred to as the basalt of the Badlands (Champion et al., 2004) and here named basalt of Lava Top Butte, covers ~150 km^2 (Fig. 5E). That is approximately the same area covered by the separate western part of the unit, which was fed through the Horse Cave lava tube system from spatter vents located ~3 km south of the Knott landfill near the south edge of the City of Bend. The Horse Cave lava overlies sediments in the landfill that contain lapilli of the tuff of Paulina Creek Falls, and thus the basalt eruption postdates caldera collapse. The western flow skirts the east side of Bend and extends north under the Bend Airport, under the Redmond Airport, then west into what is now Redmond Dry Canyon, where it forms the floor of the canyon that was formerly occupied by the Deschutes River. To the north, the lava spread out into the Crooked River Ranch area, farther north than yesterday's Stop 1-1, but stopped just short of entering the Crooked River. This aphyric diktytaxitic basalt is not a distinctive rock, but the unit has a distinctive transitional paleomagnetic direction and has been correlated to a time of anomalous magnetic directions recorded by ca. 80 ka sediments in the Norwegian Sea and elsewhere (Champion et al., 2004). One chemical analysis is given

Figure 17. Photo looking west toward Cascade Range shows broad, gentle shield shape of "Badlands Volcano" (in middle distance), which is actually a large tube-fed rootless vent of the basalt of Lava Top Butte. U.S. Hwy. 20 crosses just south of the highest point. View is from Stop 2-8. On a clear day, panoramic view extends from South Sister to Mount Hood and Powell Buttes. See Figure 18 for azimuths and distances to prominent points. Photo by R. Jensen.

in Table 1, but there is some compositional variation in the unit, with SiO_2 ranging from 49 to 51.5 wt%.

Also visible from here are Powell Buttes (30 km) and Gray Butte (55 km) on the southeast and northern margins respectably of the ca. 29.5 Ma Crooked River caldera (McClaughry et al., 2008). Smith Rock near Stop 1-1 is also visible along with the Cascade crest from the South Sister (64 km) to Mount Hood (170 km) (see Fig. 18).

Cumulative mileage	*Description*
83.50	[Hwy. 20 M.P. 17.45] Base of Horse Ridge. [Hwy. 20 M.P. 17.45 to Hwy. 20 M.P. 12.60] For the next 4.85 miles the route climbs up and over the Badlands, a rootless vent of the basalt of Lava Top Butte (Fig. 5E).
84.65	[Hwy. 20 M.P. 16.30] Parking for Stop 2-9. [Elev. = 3720 ft]

Stop 2-9 at Badlands Roadcut

Brief stop to allow for collecting a sample of the basalt.

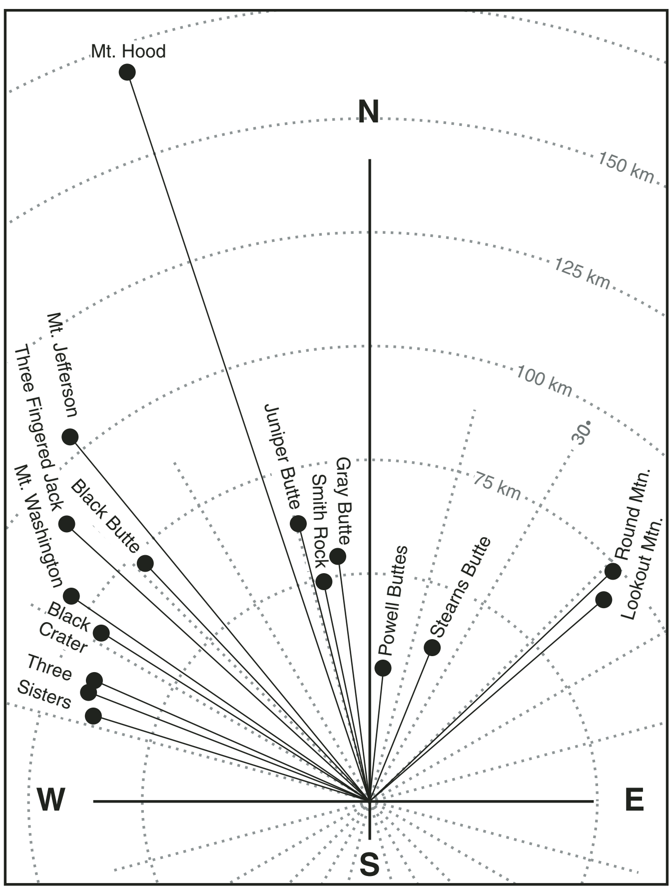

Figure 18. Azimuths and distances to prominent points that can be seen from Stop 2-8.

This roadcut in the basalt of Lava Top Butte displays a typical exposure through a primitive diktytaxitic basalt. Farther west as we proceed along Highway 20 toward Bend, we will cross through half a dozen similar basalt flows. Paleomagnetic drilling (D.E. Champion, 2008, personal commun.) combined with chemical analyses, topographic expression, and minor petrographic variations enabled the flows to be distinguished and mapped.

Cumulative mileage	*Description*
88.35	[Hwy. 20 M.P. 12.60 to Hwy. 20 M.P. 8.95] For the next 3.65 miles the route crosses older basalts from Newberry.
92.00	[Hwy. 20 M.P. 8.95 to Hwy. 20 M.P. 8.70] For the next 0.25 miles the route crosses the narrow tube-fed lobe of basalt of "Lunabess Hill" (Fig. 5C).
92.25	[Hwy. 20 M.P. 8.70 to Hwy. 20 M.P. 3.95] For the next 4.75 miles the route crosses older basalts from Newberry.
97.00	[Hwy. 20 M.P. 3.95 to Hwy. 20 M.P. 3.10] For the next 0.85 miles the route crosses the western lobe of the basalt of Lava Top Butte (Fig. 5E).
97.85	[Hwy. 20 M.P. 3.10 to Hwy. 20 M.P. 1.70] For the next 1.4 miles the route crosses the basalt of Bend (Fig. 5D).
98.40	[Hwy. 20 M.P. 2.55] Traffic light at 27th Street and Hwy. 20. Continue straight ahead past Safeway grocery store and other services.
99.25	[Hwy. 20 M.P. 1.70 to Hwy. 20 M.P. 1.00] For the next 0.70 miles the route crosses the low flank of Pilot Butte.
100.45	[Hwy. 20 M.P. 0.50] Traffic light at Greenwood Avenue and Third Street. The route turns left on Greenwood Avenue.
100.70	Traffic light at Third Street and Franklin Avenue. The route turns right on Franklin Avenue.
101.30	Traffic light at Franklin and Bond.

DAY 3: EMPHASIS ON GLACIAL AND FLUVIAL FEATURES, AND THEN RETURN TO PORTLAND

This day involves ~250 miles (400 km) of travel. The morning will be spent at three stops (see Fig. 3) related to glacial and fluvial features on the northeast flank, followed by a lunch stop at an ash-flow tuff cut by one of the east side channels, then a final overview stop before returning to Portland via the Santiam Pass.

Donnelly-Nolan et al. (2004) described the occurrence of glacial erratics on cinder cones, which provided evidence that ice extended far down the flanks of the volcano during glacial times. They also ascribed the abundant sediments and the carving of the multiple east flank dry channels (Fig. 16) to periodic outburst floods related to melting of ice, perhaps linked to under-ice volcanic activity. Donnelly-Nolan and Jensen (this volume) expand on these ideas.

Cumulative mileage	*Description*
0.00	Traffic light at Franklin Avenue and Bond Street. The route goes north on Bond Street.
0.25	Traffic light at Bond Street and Greenwood Avenue. The route turns right on Greenwood Avenue.
0.70	[Hwy. 20 M.P. 0.50] Traffic light at Third and Greenwood. The route continues east on Hwy. 20 (Greenwood Avenue.)
19.75	[Hwy. 20 M.P. 19.00] Parking for Stop 3-1. [Elev. = 4210 ft]

Stop 3-1 at Dry River Canyon

To the east, upstream from the canyon of Dry River, shallow channels of the Dry River extend east to Hampton Butte (60 km), but the highest area within the ~1350 km^2 Dry River drainage system is the northeast flank of Newberry Volcano. The 5-km-long canyon of Dry River deepens from ~6 m at its upper end to ~60 m deep in less than a kilometer, and continues northwest for another 3 km at depths of 90–120 m before it rapidly becomes shallower, having dropped 150 m in elevation along this reach. To the west, after having cut through Pliocene and Miocene lavas, the channel disappears under the basalt of Lava Top Butte. No water flows in the canyon today. Donnelly-Nolan et al. (2004) suggest that multiple large floods originating primarily from Newberry Volcano may have carved the canyon. The lower Tepee Draw, "Orphan Draw," and "Evans Draw" drainages meet near the head of the canyon (See Fig. 16).

Cumulative mileage	*Description*
20.75	[Hwy. 20 M.P. 21.00] Base of Horse Ridge. The route turns right on Road 2015.
24.60	Junction in Evans Draw. Road 2016 to left. The route stays to right on Road 2015.
25.35	Park along Road 2015 for Stop 3-2. [Elev. = 4360 ft]

Stop 3-2 near Evans Well

From the parking location, hike south to a dry channel that is tributary to "Evans Draw" (see map Fig. 16). We will inspect an apparent dry waterfall that shows clear evidence of polishing by water flow, with no evidence of any present drainage.

"Evans Draw" is a large channel along the western edge of the Evans Well alluvial fan. Much of the fan is precaldera in age and consists of materials derived from the upper "Orphan Draw" drainage. The lower "Orphan Draw" channel forms the eastern edge of the fan. Interbedded in the upper part of the fan sediments is ~1 m of the Evans Well tephra (Kuehn, 2002) that we interpret as part of the 80 ka caldera forming eruption (see Jensen, 2006). "Evans Draw" heads near the upper end of the Evans Well fan and was likely carved by high flows from upper "Orphan Draw."

From here we have an unimpeded view of the northeast side of Newberry and the profile of the north flank with its abundant cinder cones. One 7.5′ quadrangle, Fuzztail Butte, which encompasses the upper north-northeast flank includes more than 50 cinder cones.

Turn around and return east on Road 2015.

Cumulative mileage	*Description*
25.70	The route turns right toward Road 2016.
25.95	The route turns right on Road 2016. Junction is in Evans Draw. For the next 1.80 miles the route crosses the Evans Well alluvial fan.
27.75	[Road 2016] The route turns right on Road 2016. Junction is in "Orphan Draw," which heads high on Newberry near the caldera rim. For the next 2.80 miles the route crosses the basalt of Smith Well.
29.35	[Road 2016] Cross "Smith Draw" (Fig. 16) "Smith Draw" seems to have a complicated history. The upper portion of this drainage (above 6400 ft) appears to occupy a beheaded glacial valley that terminates at the caldera rim. Because of the thick deposit of Newberry Pumice there are very limited exposures in this portion of the drainage. Prior to the postcaldera eruption of Cinder Hill high on the east side of the volcano, this drainage flowed into the Tepee Draw system.
30.70	[Road 2016] For the next 1.65 miles the route crosses the Tepee Draw tuff.
31.80	[Road 2016] Cross Tepee Draw, which heads at ~5900 ft on mid flank.
31.95	The route turns left on Road 18.
32.00	The route turns right on Road 1835.
35.75	The route turns left on Road 1835 300.
35.85	Cross "Brooks Draw." (Yesterday we visited lower "Brooks Draw" at Stop 2-7.)
36.00	The route turns left on Road 1835 315.
36.45	Parking for Stop 3-3. [Elev. = 5700 ft]

Stop 3-3 East Flank and Glaciation

From the parking area hike to the summit of an older cinder cone of nearly aphyric basaltic andesite on the east flank of Newberry Volcano. On the summit and uphill side are glacial erratics of several lithologies including solid blocks to 0.8 m across of porphyritic basalt, as well as smaller platey pieces of rhyolite and a covering of small, subrounded, dense scoria fragments that mantle the uphill side and top of the cone. Summit elevation of this cone is 5782 ft. It is located ~7 km east of the caldera rim and ~180 m lower than the level of East Lake in the caldera. For a discussion of ice and water on Newberry Volcano, see accompanying article by Donnelly-Nolan and Jensen (this volume). It is unclear when the ice dropped these erratics on the cone, which is older than the dacitic ash-flow tuff that was erupted ca. 300 ka (Donnelly-Nolan et al., 2004); we will visit the tuff at our next stop.

Return to Road 1835.

Cumulative mileage	*Description*
37.15	The route turns right on Road 1835.
39.00	The route turns right to Stop 3-3.
39.10	Parking for Stop 3-4. [Elev. = 5200 ft]

Stop 3-4 Dacitic Ash-Flow Tuff

This location is along "Brooks Draw," one of many dry channels on the northeast flank of Newberry (Fig. 16). These draws cut through and expose a wide variety of deposits including lava flows, ash flow tuffs, and sedimentary deposits. The draws (and segments of them) vary in age. Some have acted as channels for younger lava flows, resulting in still younger channel segments along the margins of the lava flows or cut into deposits of the nonwelded caldera-forming tuff of Paulina Creek Falls.

At this location, the dacitic tuff was mapped by MacLeod et al. (1995) as unit Qdt. Chemical analyses indicate that their other mapped east-side dacitic tuff, unit Qto (tuff of Orphan Butte), is part of the same ash-flow tuff, which we here informally name the tuff of "Brooks Draw" (tbd). Large black pumices are abundant in the well-exposed tuff at this location (see Table 1 for a chemical analysis). The age relation of this tuff to the tuff of Tepee Draw is uncertain because they have never been found in contact. However, the physical relationships and the distribution of the two tuffs suggest that the Tepee Draw tuff is the younger. Preliminary $^{40}Ar/^{39}Ar$ dating (A. Calvert and M. Lanphere, 2008, personal commun.) supports this conclusion.

Lunch stop.

Return to Road 1835.

Cumulative mileage	*Description*
39.20	The route turns right on Road 1835.
41.10	The route crosses Road 18 (also known as China Hat Road) and continues straight onto paved Road 25.
45.90	[Road 23 M.P. 5.85] The route turns left on Road 23.
51.75	[Road 23 M.P. 0.00 = Hwy. 20 M.P. 22.25] The route turns left on U.S. 20.
70.30	[Hwy. 20 M.P. 2.55] Traffic light at 27th and Hwy. 20.
71.65	[Hwy. 20 M.P. 1.20] The route turns right onto road to Pilot Butte summit. This road is heavily used by walkers so drive with care. The gate opens at 8 a.m. and closes mid-evening during much of the year, but the road is typically closed to vehicles from early November to early April due to icy conditions.
72.80	Parking for Stop 3-5. [Elev. = 4140 ft]

Stop 3-5 at Pilot Butte Summit

Pilot Butte, a Pleistocene cinder cone (188 ± 42 ka, Donnelly-Nolan et al., 2000), and its basaltic andesite lava flow are surrounded by the ca. 78 ka basalt of Bend.

To the south is the edifice of Newberry Volcano, which extends in this view from Horse Ridge on the east to Lava Butte on the west (site of Stop 1-2). The north flank of the volcano is dotted with cinder cones. See Figure 1 for a photo.

To the west are the Cascades (Fig. 19). Visible peaks 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 (Fig. 20). Hildreth (2007) contains many useful summary tables and vent location maps for the Cascades.

To the northeast are the Ochoco Mountains, which form the western end of the Blue Mountain Range, which extends to the Wallowa Mountains in northeast Oregon.

Return to Hwy. 20.

Figure 19. View west from top of Pilot Butte (Stop 3-5) toward the snow-covered Three Sisters on the Cascade crest. South Sister is on left; Middle Sister and North Sister on right. Photo by R. Jensen.

Cumulative mileage	*Description*
73.95	[Hwy. 20 M.P. 1.20] The route turns right on Hwy. 20.
74.65	[Hwy. 20 M.P. 0.50] Traffic light at Third and Greenwood. The route turns right on Third Street.
75.70	The route takes exit to Hwy. 97 and Redmond.
77.25	The route takes Exit 135A to Hwy. 20 and Sisters.
80.35	[Hwy. 20 M.P. 15.60] Western edge of the basalt of Bend. The Deschutes River has been forced westward to its present course along the west margin of the basalt of Bend. The highway cuts from here to the river expose coarse stream gravels, as well as Tumalo Tuff and Bend Pumice, which erupted ca. 440 ka (Lanphere et al., 1999) from vent(s) at or near the Cascade crest under lavas of The Three Sisters.
80.85	[Hwy. 20 M.P. 15.10] Cross Deschutes River. The Desert Springs Tuff is exposed at river level. From here to the town of Sisters the highway climbs through the Bend Pumice/Tumalo Tuff section and then crosses a surface largely covered by glacial outwash sediments with windows of older units.
95.95	[Hwy. 20 M.P. 0.00 = Hwy. 20 M.P. 101.15] OR 126 Jct. (right). The route continues on Hwy. 20 through Sisters.
96.05	[Hwy. 20 M.P. 101.05] Cross Whychus Creek (formerly Squaw Creek), which heads in the saddle between the South and Middle Sister.
97.00	[Hwy. 20 M.P. 100.10] Junction Hwy. 242 (left). For about the next 12 miles the route passes over mainly glacial outwash gravels and a couple of highs of older rock.
110.00	[Hwy. 20 M.P. 87.10] Cross Lake Creek, which drains Suttle Lake through gap in terminal moraine, which dams the lake. The moraines are covered by ~20 cm of fine ash from the Sand Mountain chain of cinder cones and by ~30 cm of younger cinders from Blue Lake Crater.
112.40	[Hwy. 20 M.P. 84.70] Mount Washington Viewpoint (left). View of Mount Washington and Cache Mountain to the south. Also a limited view of Blue Lake, which occupies a Holocene crater and erupted ~1300 years ago (Sherrod et al., 2004). The eruption was quite violent as the crater was blasted out of solid bedrock and large fragments were scattered in all directions to elevations as much as a thousand feet above the lake. The landscape is blanketed with cinders for 5 km to the east and southeast.
116.30	[Hwy. 20 M.P. 80.80] Summit of Santiam Pass. [Elev. = 4817 ft]
117.55	[Hwy. 20 M.P. 79.55] Start broad right-hand curve around western margin of Hogg Rock. Hogg Rock and Hayrick Butte to the south are both flat topped, steep sided features with glassy margins. They are probably tuyas, which erupted under a thick ice sheet. Hogg Rock is named for Colonel T. Egenton Hogg who was the head of the Oregon Pacific Railroad, which was proposed to extend from Newport to Boise. In 1890 they completed a railroad grade eastward across Santiam Pass for a few miles. Construction funds ran out when the completed railroad reached Idanha (log mile 149.60 ahead), some 50 km northwest of here. To secure the route across the pass Hogg had his construction crews haul a boxcar and enough rails to lay a couple hundred feet of track up to the top of Santiam Pass, where they built a short stretch of track on which they reportedly pulled the boxcar back and forth a few times with a mule. Financing failed and the railroad was never completed.
120.45	[Hwy. 20 M.P. 76.65] View west to Lost Lake group of cinder cones. Approximately 2000 years ago (Sherrod et al., 2004) a north-south alignment of four basaltic cinder cones and associated lava flows was formed across a glacial canyon and the resulting ridge dammed Lost Creek to form Lost Lake.

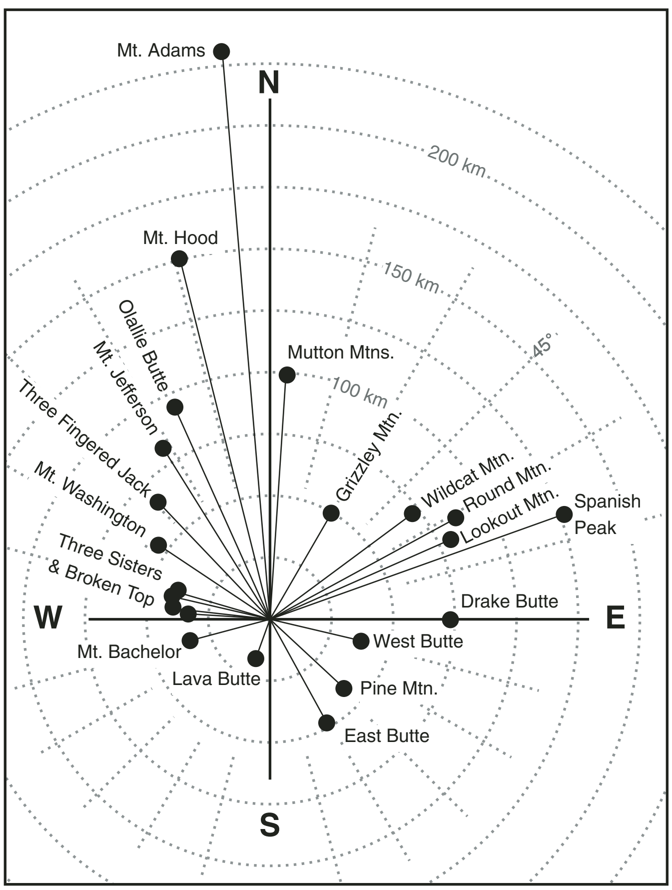

Figure 20. Shows azimuths and distances to prominent points that can be seen from the top of Pilot Butte (Stop 3-5).

122.30 [Hwy. 20 M.P. 74.80 = Hwy. 22 M.P. 81.95] Santiam Junction. The route stays right on OR 22. Ahead is Little Nash Crater and for the next mile the route crosses the tephra blanket from Little Nash Crater. Then the route crosses the flow from Little Nash Crater for a half mile. Then for about the next six miles roadcuts expose glacial moraine and outwash deposits.

128.45 [Hwy. 22 M.P. 75.65] Cross North Santiam River. The North Santiam River heads at Santiam Lake on the west flank of Three Fingered Jack and flows westward to this point where it turns northward along the fault controlled boundary between the High Cascades and the Western Cascades. The river flows northward ~24 km to just beyond Whitewater Creek where it again turns westward to cross the Western Cascades. To the south the McKenzie River flows south along the fault controlled boundary for ~32 km before also turning westward.

137.65 [Hwy. 22 M.P. 66.45] Cross Marion Creek, which heads at Marion Lake near the crest between Three Fingered Jack and Mount Jefferson.

143.30 [Hwy. 22 M.P. 60.80] Cross Whitewater Creek, which heads on the north flank of Mount Jefferson. A Quaternary block-and-ash flow came down Whitewater Creek from Mount Jefferson (Priest, 1983). Road cuts expose it south of the creek for about a third of a mile.

149.60 [Hwy. 22 M.P. 54.50] Idanha Post Office.

154.25 [Hwy. 22 M.P. 49.85] Cross Breitenbush River at Detroit. The Breitenbush River also heads on the north flank of Mount Jefferson.

161.35 [Hwy. 22 M.P. 42.75] Detroit Dam was completed in 1953 and created the 120-m deep Detroit Lake.

169.45 [Hwy. 22 M.P. 34.65] The route turns left to the Maples Rest Area.

169.60 Rest stop at the Maples Rest Area. [Elev. = 970 ft]

169.75 [Hwy. 22 M.P. 34.65] The route turns left on Hwy. 22.

202.80 [Hwy. 22 M.P. 1.60] Traffic light. The route takes the exit right to U.S. I-5 Northbound.

203.25 [I-5 M.P. 254.20] The route continues north on I-5.

232.15 [I-5 M.P. 283.10] Cross Willamette River.

249.45 [I-5 M.P. 300.40] PORTLAND. Cross Willamette River in Portland. End field trip.

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REFERENCES CITED

Achauer, U., Evans, J.R., and Stauber, D.A., 1988, High-resolution seismic tomography of compressional wave velocity structure at Newberry volcano, Oregon Cascade Range: Journal of Geophysical Research, v. 93, no. B9, p. 10135–10147, doi: 10.1029/JB093iB09p10135.

Carlson, R.W., Grove, T.L., and Donnelly-Nolan, J.M., 2008, Concentrating the slab-fluid input to Newberry Volcano, Oregon [abs., Goldschmidt Conference]: Geochimica et Cosmochimica Acta, v. 72, no. 12S, p. 136.

Catchings, R.D., and Mooney, W.D., 1988, Crustal structure of east central Oregon—Relation between Newberry volcano and regional crustal structure: Journal of Geophysical Research, v. 93, no. B9, p. 10,081–10,094, doi: 10.1029/JB093iB09p10081.

Champion, D.E., Donnelly-Nolan, J.M., Lanphere, M.A., and Ramsey, D.W., 2004, Magnetic excursion recorded in basalt at Newberry Volcano, central Oregon: Eos (Transactions, American Geophysical Union), v. 85, no. 47, abstract GP43B-0861.

Chitwood, L.A., 1994, Inflated basaltic lava—Examples of processes and landforms from central and southeast Oregon: Oregon Geology, v. 56, no. 1, p. 11–21.

Chitwood, L.A., and Jensen, R.A., 2000, Large Prehistoric Flood Along Paulina Creek, Newberry Volcano, Oregon, *in* Jensen, R.A., and Chitwood, L.A., eds., What's New at Newberry Volcano, Oregon: Guidebook for the Friends of the Pleistocene Eighth Annual Pacific Northwest Cell Field Trip, p. 31–40.

Connolly, T.J., 1991, Archaeological investigations along the Paulina–East Lake Highway within Newberry Crater, central Oregon: University of Oregon, Oregon State Museum of Anthropology Report 91-6, 130 p.

Connolly, T.J., 1999, Newberry Crater—A Ten-Thousand-Year Record of Human occupation and Environmental Change in the Basin-Plateau Borderlands: Salt Lake City, University of Utah Press, University of Utah Anthropological Papers no. 121, 287 p.

Conrey, R.M., Taylor, E.M., Donnelly-Nolan, J.M., and Sherrod, D.R., 2002, North-central Oregon Cascades: Exploring petrologic and tectonic intimacy in a propagating intra-arc rift: Field Guide to Geologic Processes in Cascadia: Oregon Department of Geology and Mineral Industries Special Paper, v. 36, p. 47–90.

Cooperative Officers of the State of Oregon and the Reclamation Service Office, 1914, Oregon Cooperative Work—Deschutes Project: Portland, Oregon, p. 51–58, 98–101.

Donnelly-Nolan, J.M., 2008, Newberry and Medicine Lake: Two Large Rear-Arc Cascade Volcanoes: IAVCEI General Assembly, Reykjavik, Iceland, 18 August 2008, abstract 2-a P13, http://www.parthen-impact.com/eventure/publicAbstractView.do?id=75189.

Donnelly-Nolan, J.M., and Jensen, R.A., 2009, this volume, Ice and water on Newberry Volcano, central Oregon, *in* O'Connor, J.E., Dorsey, R.J., and Madin, I.P., eds., Volcanoes to Vineyards: Geologic Field Trips through the Dynamic Landscape of the Pacific Northwest: Geological Society of America Field Guide 15, doi: 10.1130/2009.fld015(04).

Donnelly-Nolan, J.M., Champion, D.E., and Lanphere, M.A., 2000, North flank stratigraphy revealed by new work at Newberry volcano, Oregon, *in* Jensen, R.A., and Chitwood, L.A., eds., What's New at Newberry Volcano, Oregon: Guidebook for the Friends of the Pleistocene Eighth Annual Pacific Northwest Cell Field Trip, p. 177–180.

Donnelly-Nolan, J.M., Champion, D.E., Lanphere, M.A., and Ramsey, D.W., 2004, New thoughts about Newberry Volcano, central Oregon USA: Eos (Transactions, American Geophysical Union), v. 85, no. 47, Fall Meeting supplement, abstract V43E-1452.

Donnelly-Nolan, J.M., Grove, T.L., Lanphere, M.A., Champion, C.E., and Ramsey, D.W., 2008, Eruptive history and tectonic setting of Medicine Lake Volcano, a large rear-arc volcano in the southern Cascades: Journal of Volcanology and Geothermal Research, v. 177, p. 313–328, doi: 10.1016/j.jvolgeores.2008.04.023.

Fitterman, D.V., 1988, Overview of the structure and geothermal potential of Newberry Volcano, Oregon: Journal of Geophysical Research, v. 93, no. B9, p. 10,059–10,066, doi: 10.1029/JB093iB09p10059.

Fitterman, D.V., Stanley, W.D., and Bisdort, R.J., 1988, Electrical structure of Newberry volcano, Oregon: Journal of Geophysical Research, v. 93, no. B9, p. 10,119–10,134, doi: 10.1029/JB093iB09p10119.

Friedman, I., 1977, Hydration dating of volcanism at Newberry Crater, Oregon: U.S. Geological Survey Journal of Research, v. 5, no. 3, p. 337–342.

Fries, C., Jr., 1953, Volumes and weights of pyroclastic material, lava, and water erupted by Paricutin volcano, Michoacan, Mexico: American Geophysical Union Transactions, v. 34, p. 603–616.

Gettings, M.E., and Griscom, A., 1988, Gravity model studies of Newberry volcano, Oregon: Journal of Geophysical Research, v. 93, no. B9, p. 10109–10118, doi: 10.1029/JB093iB09p10109.

Hallett, D.J., Hills, L.V., and Clague, J.J., 1997, New accelerator mass spectrometry radiocarbon ages for the Mazama tephra layer from Kootenay National Park, British Columbia, Canada: Canadian Journal of Earth Sciences, v. 34, p. 1202–1209, doi: 10.1139/e17-096.

Higgins, M.W., 1973, Petrology of Newberry Volcano, central Oregon: Geological Society of America Bulletin, v. 84, p. 455–488, doi: 10.1130/0016-7606(1973)84<455:PONVCO>2.0.CO;2.

Hildreth, W., 2007, Quaternary magmatism in the Cascades—Geologic perspectives: U.S. Geological Survey Professional Paper 1744, 125 p., http://pubs.usgs.gov/pp/pp1744/.

Hill, B.E., Connor, C.B., Jarzemba, M.S., La Femina, P.C., Navarro, M., and Strauch, W., 1998, 1995 eruptions of Cerro Negro volcano, Nicaragua, and risk assessment for future eruptions: Geological Society of America Bulletin, v. 110, no. 10, p. 1231–1241, doi: 10.1130/0016-7606(1998)110<1231:EOCNVN>2.3.CO;2.

Jensen, R.A., 2006, Roadside guide to the geology and history of Newberry Volcano, 4th edition: Bend, Oregon, CenOreGeoPub, 182 p.

Jensen, R.A., and Chitwood, L.A., 1996, Evidence for recent uplift of caldera floor, Newberry volcano, Oregon: Eos (Transactions, American Geophysical Union), v. 77, no. 46, p. F792.

Jensen, R.A., and Chitwood, L.A., 2000, Late Holocene Uplift of Caldera Floor, Newberry Volcano, Central Oregon, *in* Jensen, R.A., and Chitwood, L.A., eds., What's New at Newberry Volcano, Oregon: Guidebook for the Friends of the Pleistocene Eighth Annual Pacific Northwest Cell Field Trip, p. 87–96.

Keith, T.E.C., and Bargar, K.E., 1988, Petrology and hydrothermal mineralogy of U.S. Geological Survey Newberry 2 drill core from Newberry caldera, Oregon: Journal of Geophysical Research, v. 93, p. 10174–10190, doi: 10.1029/JB093iB09p10174.

Kuehn, S.C., 2002, Stratigraphy, distribution, and geochemistry of the Newberry volcano tephras [Ph.D. dissertation]: Pullman, Washington State University.

Kuehn, S.C., and Foit, F.F., 2006, Correlations of widespread Holocene and Pleistocene tephra layers from Newberry Volcano, Oregon, USA, using glass compositions and numerical analysis: Quaternary International, v. 148, no. 1, p. 113–137, doi: 10.1016/j.quaint.2005.11.008.

Kuehn, S.C., and Preppernau, C.A., 2005, Pumice Flat tephra of Newberry Volcano, Oregon: Deposit of a mixed-magma Plinian eruption: Geological Society of America Abstracts with Programs, v. 37, no. 4, p. 67.

Lanphere, M.A., Champion, D.E., Christiansen, R.L., Donnelly-Nolan, J.M., Fleck, R.J., Sarna-Wojcicki, A.M., Obradovich, J.D., and Izett, G.A., 1999, Evolution of tephra dating in the western United States: Geological Society of America Abstracts with Programs, v. 31, no. 6, p. A-73.

MacLeod, N.S., and Sherrod, D.R., 1988, Geologic evidence for a magma chamber beneath Newberry volcano, Oregon: Journal of Geophysical Research, v. 93, no. B9, p. 10076–10079.

MacLeod, N.S., Sherrod, D.R., Chitwood, L.A., and Jensen, R.A., 1995, Geologic Map of Newberry volcano, Deschutes, Klamath, and Lake Counties, Oregon: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-2455.

McClaughry, J.D., Ferns, M.L., Gordon, C.L., and Patridge, K.A., 2008, A field guide to the volcanic stratigraphy of the Oligocene Crooked River caldera, Crook Deschutes, and Jefferson Counties, Oregon: DOGAMI Lower Crooked Basin Geology Workshop, 15 p.

Mckay, D., Donnelly-Nolan, J.M., Jensen, R.A., and Champion, D.E., 2009, this volume, The northwest rift zone eruption at Newberry Volcano, Oregon, post-Mazama, *in* O'Connor, J.E., Dorsey, R.J., and Madin, I.P., eds., Volcanoes to Vineyards: Geologic Field Trips through the Dynamic Landscape of the Pacific Northwest: Geological Society of America Field Guide 15, doi: 10.1130/2009.fld015(05).

Nichols, R.L., and Stearns, C.E., 1938, Fissure eruptions near Bend, Oregon [abs.]: Geological Society of America Bulletin, v. 49, no. 12, pt. 2, p. 1894.

Peterson, N.V., and Groh, E.A., eds., 1965, Lunar Geological Field Conference Guide Book: Oregon Department of Geology and Mineral Industries Bulletin, 51 p.

Priest, G.R., 1983, A field trip guide to the central Oregon Cascades: Second Day: Santiam Pass—Belknap Hot Springs—Breitenbush Hot Springs: Oregon Geology, v. 45, no. 11, p. 119–126.

Russell, I.C., 1905, Preliminary report on the geology and water resources of central Oregon: U.S. Geological Survey Bulletin 252, 138 p.

Sammel, E.A., Ingebritsen, S.E., and Mariner, R.H., 1988, The hydrothermal system at Newberry volcano, Oregon: Journal of Geophysical Research, v. 93, no. B9, p. 10149–10162, doi: 10.1029/JB093iB09p10149.

Scott, W.E., 1987, Holocene rhyodacite eruptions on the flanks of South Sister volcano, Oregon, *in* Fink, J.H., The Emplacement of Silicic Domes and Lava Flows: Geological Society of America Special Paper 212, p. 35–53.

Scott, W.E., Pierson, T.C., Schilling, S.P., Costa, J.E., Gardner, C.A., Vallance, J.W., and Major, J.J., 1997, Volcano Hazards in the Mount Hood Region, Oregon: U.S. Geological Survey Open-File Report 97-89, 14 p.

Sherrod, D.R., Gannett, M.W., and Lite, K.E., Jr., 2002, Hydrogeology of the upper Deschutes Basin, central Oregon: A young basin adjacent to the Cascade volcanic arc: Field Guide to Geologic Processes in Cascadia: Oregon Department of Geology and Mineral Industries Special Paper, v. 36, p. 109–144.

Sherrod, D.R., Mastin, L.G., Scott, W.E., and Schilling, S.P., 1997, Volcano Hazards at Newberry Volcano, Oregon: U.S. Geological Survey Open-File Report 97-513.

Sherrod, D.R., Taylor, E.M., Ferns, M.L., Scott, W.E., Conrey, R.M., and Smith, G.A., 2004, Geologic Map of the Bend 30′ × 60′ Minute Quadrangle, Central Oregon: U.S. Geological Survey Geologic Investigations Series Map I-2683, scale 1:100,000.

Smith, G.A., 1986, Stratigraphy, sedimentology, and petrology of Neogene rocks in the Deschutes basin, central Oregon: a record of continental-margin volcanism and its influence on fluvial sedimentation in an arc-adjacent basin [Ph.D. dissertation]: Corvallis, Oregon State University, 467 p.

Smith, G.A., and Priest, G.R., 1983, A field trip guide to the central Oregon Cascades: First Day: Mount Hood–Deschutes basin: Oregon Geology, v. 45, no. 12, p. 133–138.

Stauber, D.A., Green, S.M., and Iyer, H.M., 1988, Three-dimensional P velocity structure of the crust below Newberry volcano, Oregon: Journal of Geophysical Research, v. 93, no. B9, p. 10,095–10,107, doi: 10.1029/JB093iB09p10095.

Swanberg, C.A., Walkey, W.C., and Combs, J., 1988, Core hole drilling and the "Rain Curtain" phenomenon at Newberry volcano, Oregon: Journal of Geophysical Research, v. 93, no. B9, p. 10,163–10,173, doi: 10.1029/JB093iB09p10163.

Williams, H., 1935, Newberry volcano of central Oregon: Geological Society of America Bulletin, v. 46, no. 2, p. 253–304.

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