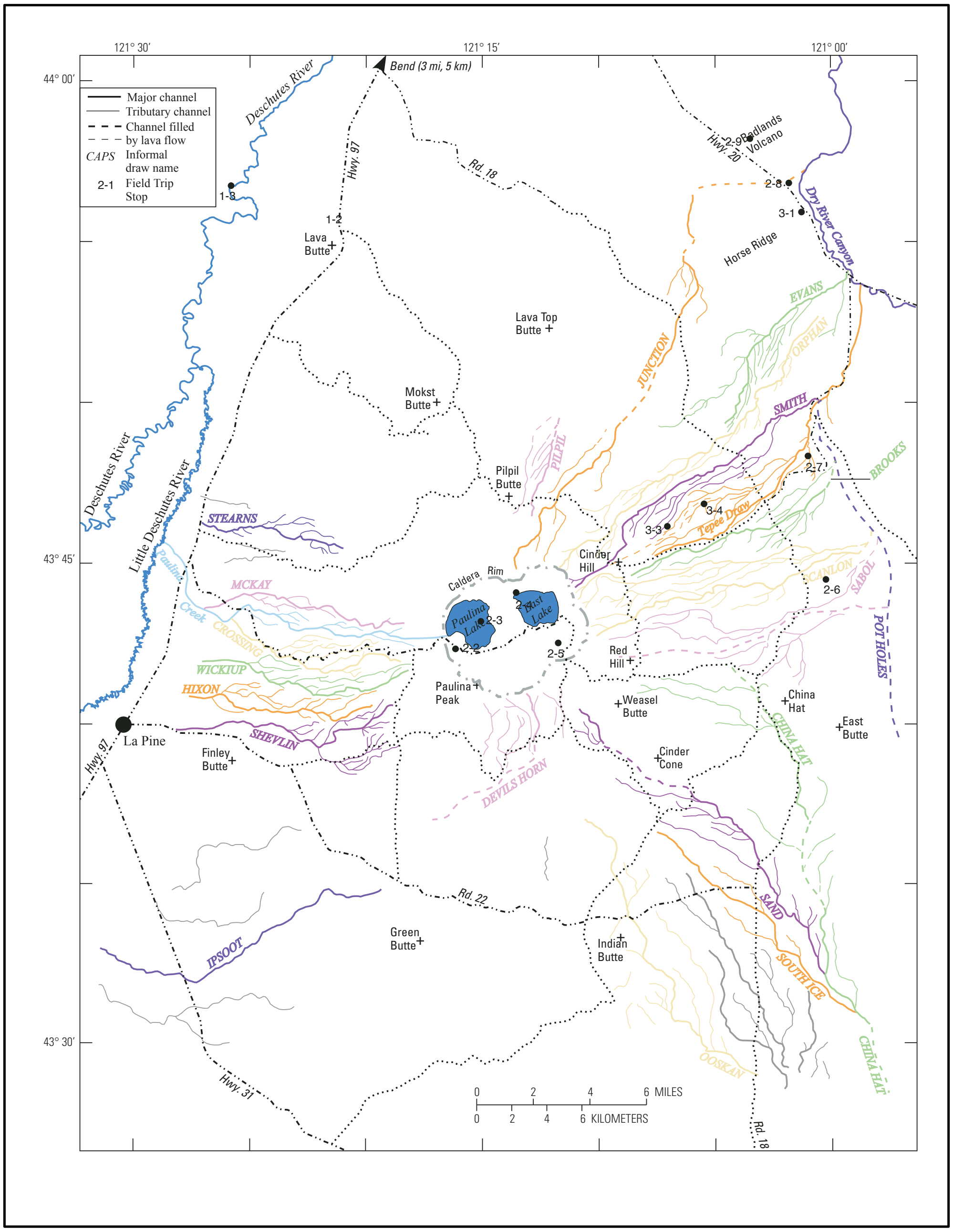
2017 Bretz Club Field Trip

The Backside of Newberry Volcano: Glaciers? Lakes? Floods?

Leaders: Daniele McKay (OSU-Cascades); Jim O’Connor (USGS); and Robert A. Jensen (US Forest Service, retired)

29 April 2017



The backside of Newberry Volcano has tantalizing evidence of glaciation, a pluvial lake, and outburst floods. Could all this be true? Could Dry River Canyon have been incised all at once? If you want certain answers to these questions, DON'T COME on this Bretz Club field trip! But if you want to see and discuss some of the perplexing features indicating a vigorous hydrologic system, please do attend.

This trip will start at Pilot Butte in Bend, with an overview of Newberry Volcano and regional drainage systems. We will proceed from there to the northeast flank of the volcano where we will examine dry waterfalls, lake shorelines, and dry canyons, pondering as we go the story of water and ice on Newberry.

As for all Bretzian field-trip guides, it derives from a hodgepodge of reputable and disreputable sources, has not undergone any kind of review, and is not a citable document.

Newberry Volcano

From Jensen and Donnelly-Nolan (2017)

Newberry Volcano and its surrounding lavas cover about 3,000 km^2 in central Oregon (fig. 1 and 2). This massive, shield-shaped (fig. 3) volcano is located in the rear of the Cascades volcanic arc, ~60 km east of the Cascade Range crest. The volcano overlaps the northwestern corner of the Basin and Range tectonic province, known locally as the High Lava Plains, and is strongly influenced by the east-west extensional environment. Lava compositions range from basalt to rhyolite. Eruptions began about half a million years ago and built a broad composite edifice that has generated more than one caldera collapse event. At the center of the volcano is the 6- by 8- km caldera, created ~75,000 years ago when a major explosive eruption of compositionally zoned tephra led to caldera collapse. The volcano hosts Newberry National Volcanic Monument, which encompasses the caldera and much of the northwest flank of the volcano (fig. 2) where mafic eruptions occurred about 7,000 years ago (the "northwest rift zone;" an informal name first used by Peterson and Groh, 1965). These young lava flows erupted after the volcano was mantled by the Mazama tephra, a blanket of volcanic ash generated by the eruption that created Crater Lake about 7,700 years ago (Bacon and Wright, 2017).

Newberry’s most recent eruption took place about 1,300 years ago in the center of the caldera and produced tephra and lava of rhyolitic composition. Prior to that, a significant mafic eruptive event occurred (Mckay and others, 2009) about 7,000 years ago along the northwest rift zone and produced lavas ranging in composition from basalt to andesite that erupted over a distance of 35 km from south of the caldera to Lava Butte, where erupted lava flowed west to temporarily block the Deschutes River (fig. 4). Because of its proximity to populated areas, the presence of hot springs within the caldera, and the long and recent history of eruptive activity including explosive activity, the U.S. Geological Survey has installed monitoring equipment on the volcano

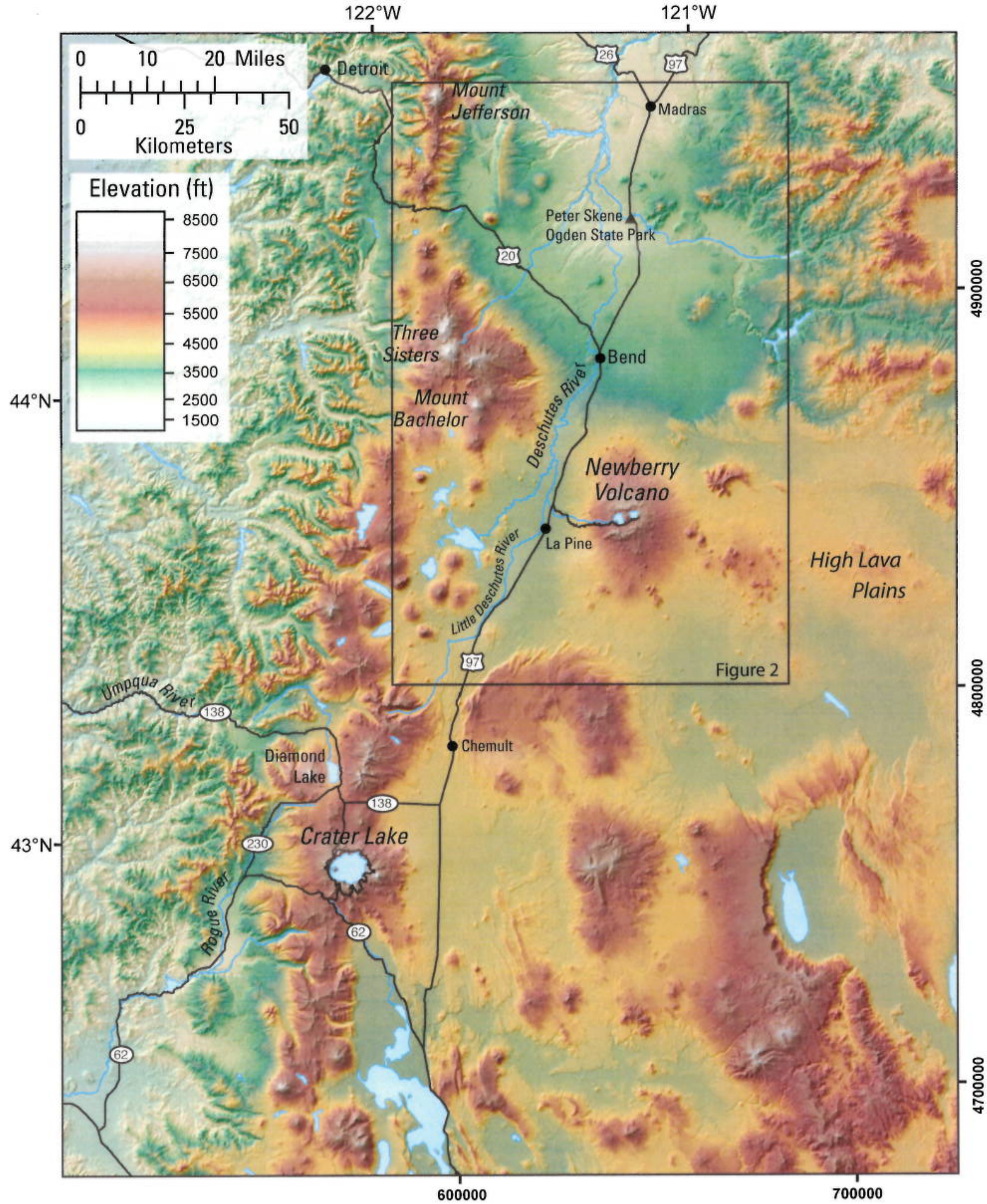
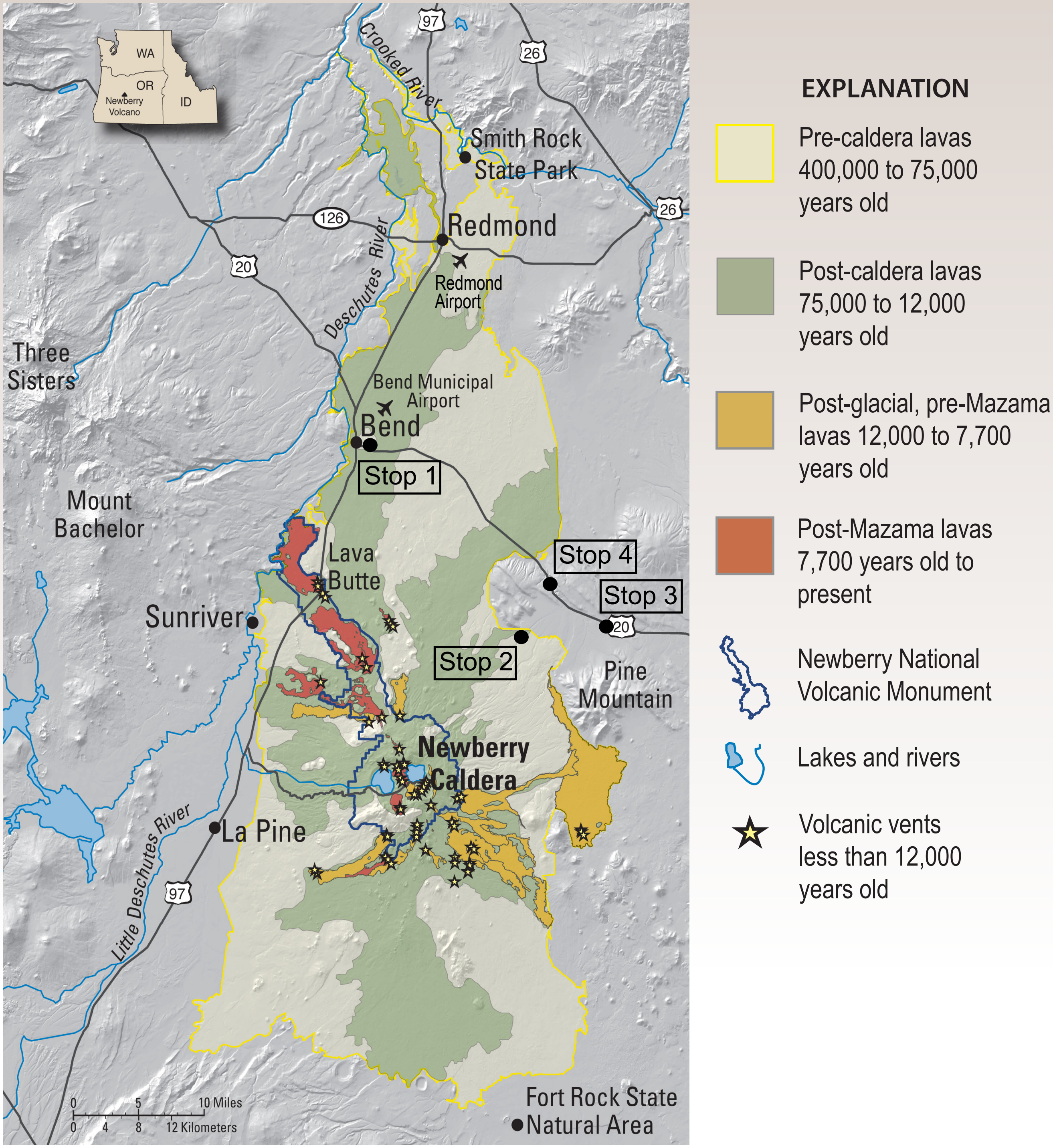


Figure 1. Location map of central Oregon. Box indicates area of Figure 2. Colored digital elevation map is modified from Figure 1 of Bacon and Wright (2017).

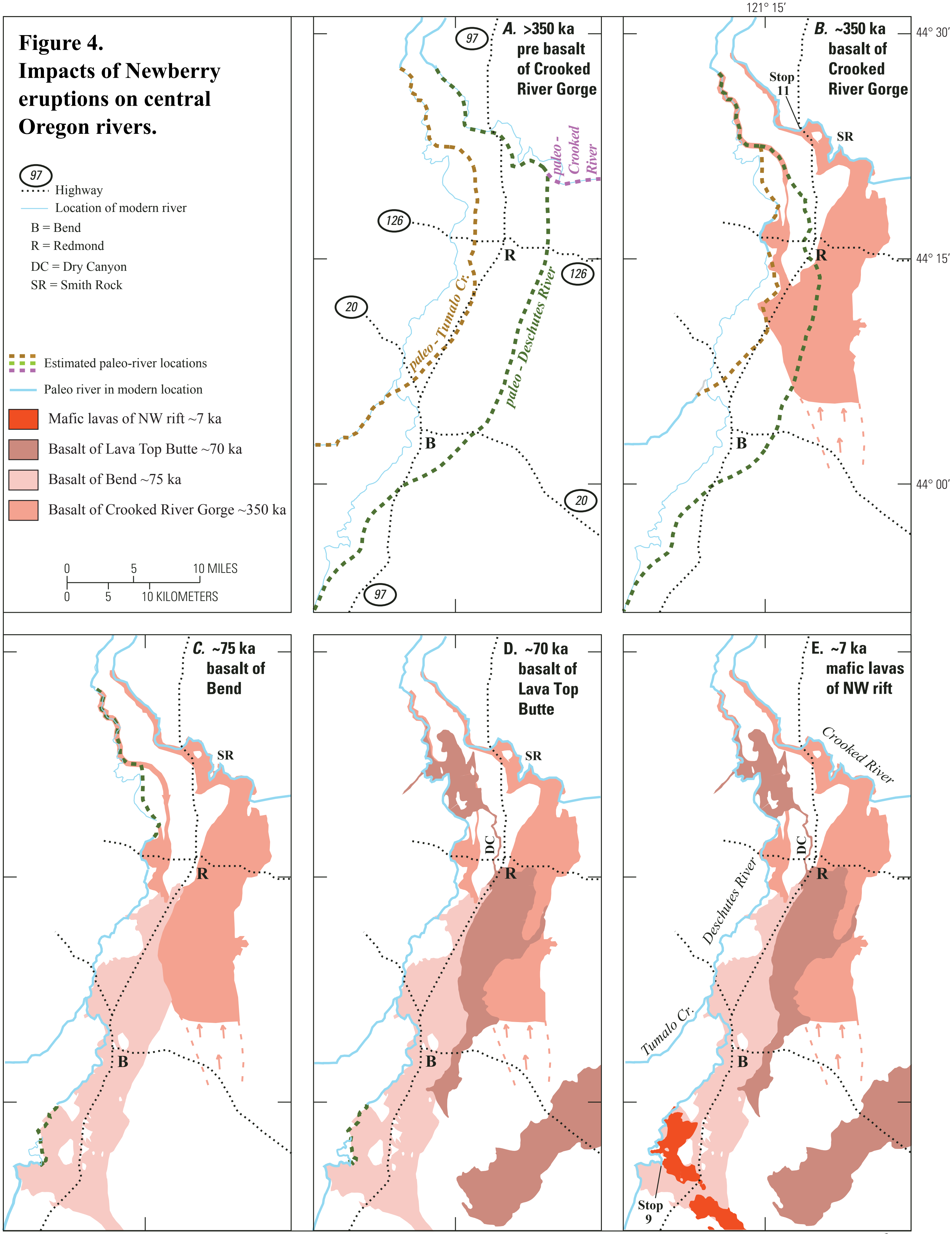
Figure 2. Map showing extent and ages of lavas from Newberry Volcano. (From Donnelly-Nolan and others, 2011).



This map shows the region surrounding Newberry Volcano, Oregon, which first began to erupt about 400,000 years ago. Extending about 75 miles north to south and 27 miles east to west, the volcano and its broad apron of lavas (outlined in yellow) cover a total area of almost 1,200 square miles, making it the largest volcano of the Cascades volcanic chain. Colors show the extent of lavas erupted before the caldera formed about 75,000 years ago; after caldera formation; after glaciation but before the catastrophic eruption about 7,700 years ago that destroyed ancient "Mount Mazama" and formed Crater Lake, an event that deposited a thick volcanic ash layer over Newberry Volcano; and after deposition of Mazama ash. The Deschutes River, which lies on the volcano's western flank, has at times been shifted to the west by Newberry lavas. At other times, eruptions from volcanoes on the Cascades crest to the west have shifted the river channel eastward.

Figure 3. Panoramic photograph of Newberry Volcano. View south is from Pilot Butte (Stop 1) in the city of Bend.

Figure 4. Impacts of Newberry eruptions on central Oregon rivers.



(Donnelly-Nolan and others, 2011). A recent geophysical study by Heath and others (2015) indicates the presence of magma at 3 to 5 km depth beneath the caldera.

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

Ice and Water on Newberry Volcano

From Donnelly-Nolan and Jensen (2009)

Nestled within the scenic caldera at the top of Newberry Volcano (figs. 1 and 2) are two beautiful lakes – Paulina Lake and East Lake – both are popular destinations for fishing, boating, swimming, and camping. Paulina Lake covers ~6 km^2 whereas the smaller East Lake covers only ~4 km^2. East Lake, which has no surface outlet, is ~15 m higher than Paulina Lake, which has a surface elevation of 1930 m. The latter drains across a small dam sited on the low western caldera rim into Paulina Creek, and the creek is augmented just below the dam by a small cold spring. No surface springs or creeks feed either lake. Both are fed by snowmelt and by groundwater, including thermal water. Paulina Creek flows at a rate of ~0.5 m^3/sec (Morgan and others, 1997) west for ~15 km to Paulina Prairie at the edge of Newberry Volcano. Here the flow is considerably diminished because of losses into permeable lavas of Newberry.

The image of Newberry Volcano as host to lakes and a rushing stream that cascades over several waterfalls on its way to the Deschutes River belies the truth. Aside from the caldera and the immediate vicinity of Paulina Creek, the volcano is a dry, dusty place for most of the year. Winter snow and summer thunderstorms soak into the permeable volcanic rocks and add to groundwater. Runoff of surface water is rarely seen except on hard surfaces such as roads, even during the heaviest thundershowers. Annual total precipitation ranges from ~25 cm on the lower flanks to >75 cm over the highest

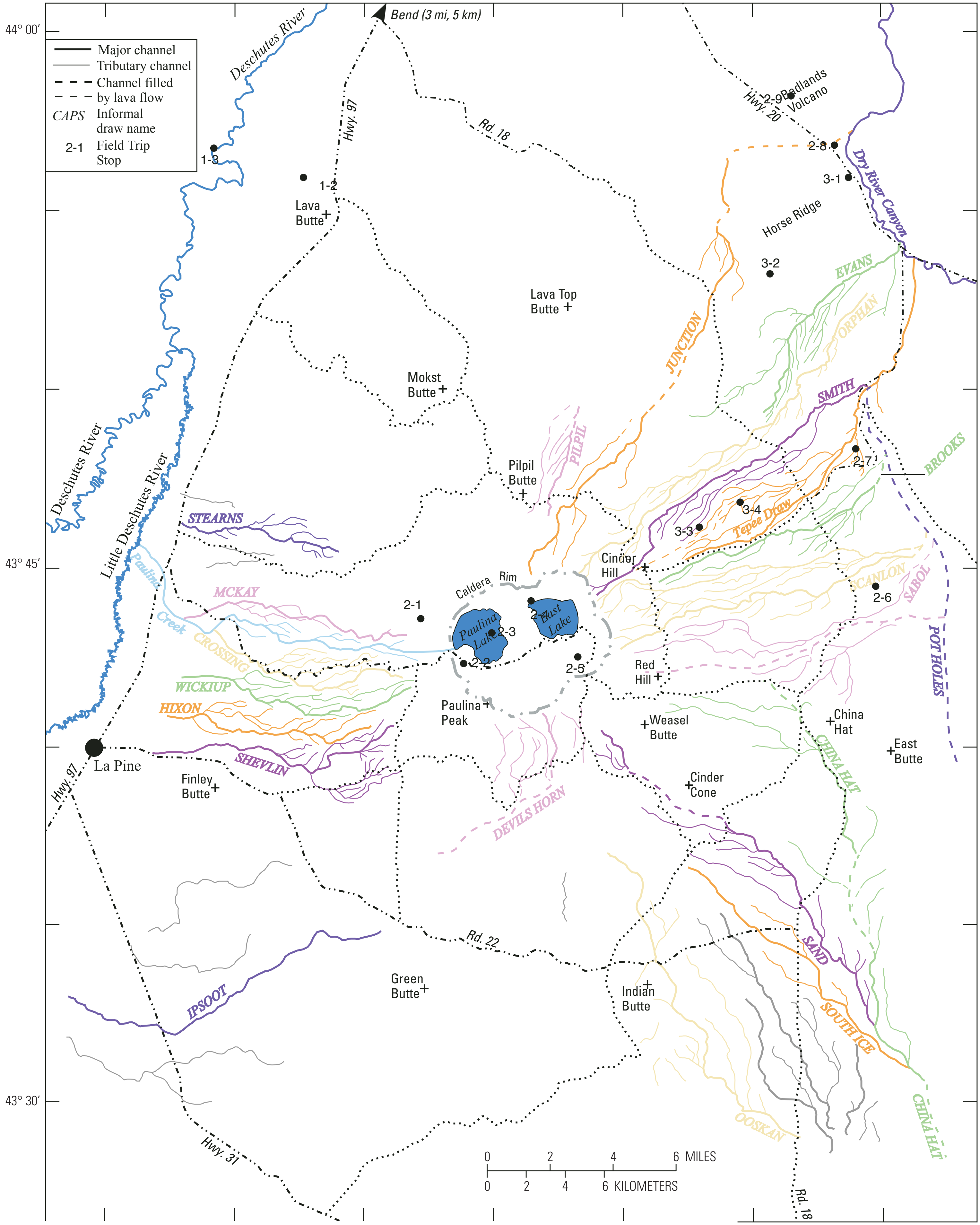


Figure 5. Map showing drainages on Newberry edifice. All paleo drainages are presently dry channels, except Paulina Creek, which drains west from Paulina Lake. Dash-dot lines are paved roads; dotted lines are major unpaved roads.

part (http://nationalatlas.gov, map of Oregon precipitation), but springs and streams are absent on the flanks and distal lava flows of this nearly 3000 km^2 volcano. Dry channels, however, are prominent features of the eastern and western sides of the volcano (fig. 5). The obvious explanation for the channels is that they were cut by water, but no source exists under current climatic conditions to provide the volumes of water necessary to carve channels, in some cases more than 60 m deep. The major channels commonly have depths of 20–30 m.

Russell (1905) proposed that Newberry had been glaciated, although "no polished or striated surfaces were seen" (p. 104). MacLeod and others (1995) concluded that Newberry was not glaciated, with the exception of localized ice on the north-facing intracaldera wall of Paulina Peak, which forms the highest point on the caldera rim at 2434 m. Other than morainal deposits at the caldera-facing base of Paulina Peak, no other moraines were recognized by MacLeod and others (1995). Their apparent absence, along with the lack of glacial polish or striations, scarcity of apparent lava-flow ice-contact features, and the lack of well-formed cirques seemed to confirm the ice-free history of the volcano, despite widespread evidence for ice as low as 1370 m [4500 ft] in the Cascade Range to the west. MacLeod and others (1995) cited the location of Newberry in the rain shadow of the High Cascades as the reason for the lack of glaciation.

Medicine Lake volcano in northern California, 240 km south of Newberry, displays ample evidence for ice (Anderson, 1941). It is an edifice of similar height, size, and elevation, also with a central caldera, and located in a similar high desert environment. There, ice extended at least as low as 1800 m [5900 ft] in elevation (Donnelly- Nolan, 2009), and the ice may have accumulated to thicknesses of 150 m (Anderson, 1941). Elevations of mountains to the west of Medicine Lake volcano, including the Klamath Mountains, Trinity Alps, and Mount Shasta, are as high as and higher than those of the High Cascade peaks west of Newberry Volcano. In the Mountain Lakes Wilderness of southern Oregon, ~170 km southwest of Newberry caldera, ice extended as low as 1700 m [5600 ft] (Rosenbaum and Reynolds, 2004) from a maximum elevation of 2500 m [8200 ft]. Thus, the apparent lack of ice on Newberry seems anomalous. This discrepancy, combined with new geologic mapping at Newberry by the authors, led to a reevaluation of Newberry's ice-free status (Donnelly-Nolan and others, 2004) and a continuing search for evidence indicating the extent of ice.

Directions from Bend to Stop 1

Travel east on NW Newport Avenue / NE Greenwood Avenue / Highway 20 ***PAST*** the brown Oregon State Parks sign for Pilot Butte Summit Drive. Turn left (north) on NE Azure Drive. The turn is marked with a brown Oregon State Parks sign for the Pilot Butte Trailhead. Continue on NE Azure Drive for about 0.1 miles; turn left (north) onto NE Savannah Drive. Continue for about 350 feet on NE Savannah Drive; turn left (east) onto NE Linnea Drive. Continue for about 0.2 miles to the parking area for the Pilot Butte Trailhead. The group will meet in the parking lot and then proceed to the summit of Pilot Butte.

Stop 1. Top of Pilot Butte
From Deligne and others (2017)

Pilot Butte is a Pleistocene cinder cone (188 ± 42 ka, Donnelly-Nolan and others, 2000), with a basaltic andesite lava flow exposed to the north of the cone. The cone and associated lava flow are surrounded by ~78 ka basalt flows from the north slope of Newberry Volcano (Jensen and others, 2009). The summit of Pilot Butte offers splendid views of the entire Bend area. Most of the southern skyline is dominated by Newberry Volcano and the many cinder cones dotting its flanks (fig. 3). To the west are hundreds of cinder cones, domes, large and small shield volcanoes, and stratocones of the Cascade Range. To the northeast are the Ochoco Mountains and, in the middle distance, post-caldera domes of the ~29.5 Ma Crooked River Caldera (McClaughry and others, 2008). A simplified compass wheel shows the declination and distance to many features visible from the summit of Pilot Butte on a clear day (fig. 6).

This paragraph from Donnelly-Nolan and Jensen (2009)

Newberry Volcano is dry over much of its vast area, except for the lakes in the caldera and Paulina Creek (figs. 1 and 2). Despite the lack of obvious glacial striations and well-formed glacial moraines, evidence indicates that Newberry was glaciated. Meter-sized foreign blocks, commonly with smoothed shapes, are found on cinder cones as far as 7 km from the caldera rim. These cones also show evidence of shaping by flowing ice. In addition, multiple dry channels likely cut by glacial meltwater are common features of the eastern and western flanks of the volcano (fig. 5). On the older eastern flank of the volcano, a complex depositional and erosional history is recorded by lava flows, some of which flowed down channels, and interbedded sediments of probable glacial origin. Postglacial lava flows have subsequently filled some of the channels cut into the sediments.

An argument that is frequently made against glaciation of Newberry is that the volcano is located in the rain shadow of the Cascades, which would limit precipitation and glacier development. However, Newberry is higher in elevation than most of the Cascade crest to the west (fig. 7). Paulina Peak is nearly 8,000 feet high and most of the caldera rim is over 7,000 feet. Medicine Lake volcano in northern California also sits in the rain shadow of the Cascades, yet it displays ample evidence for ice (Anderson, 1941)

Eruptions at Newberry have impacted central Oregon rivers multiple times over the life of the volcano (fig 4). The first major event was the eruption of the basalt of Crooked River Gorge about 350,000 years ago, which filled the paleo-channel of the Deschutes River and diverted the river to the west where it cut a new channel through the Redmond area to join the paleo-channel of Tumalo Creek. The next major change occurred about 75,000 years ago when the basalt of Bend again filled the Deschutes channel and again diverted the river to the west. About 70,000 years ago the basalt of Lava Top Butte flowed northward and entered the former Deschutes channel through Redmond to form Redmond's flat-floored Dry Canyon. The most recent change to the

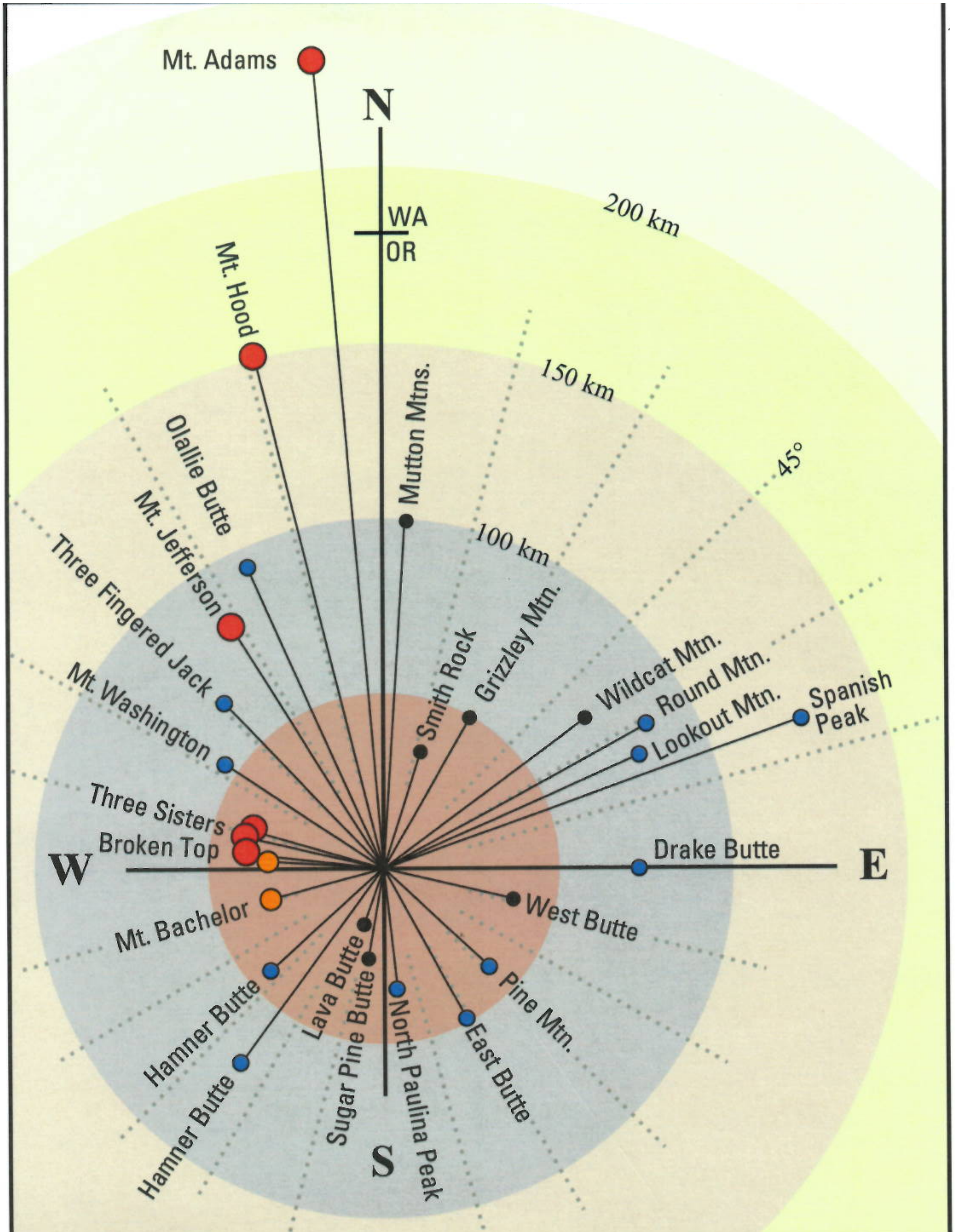
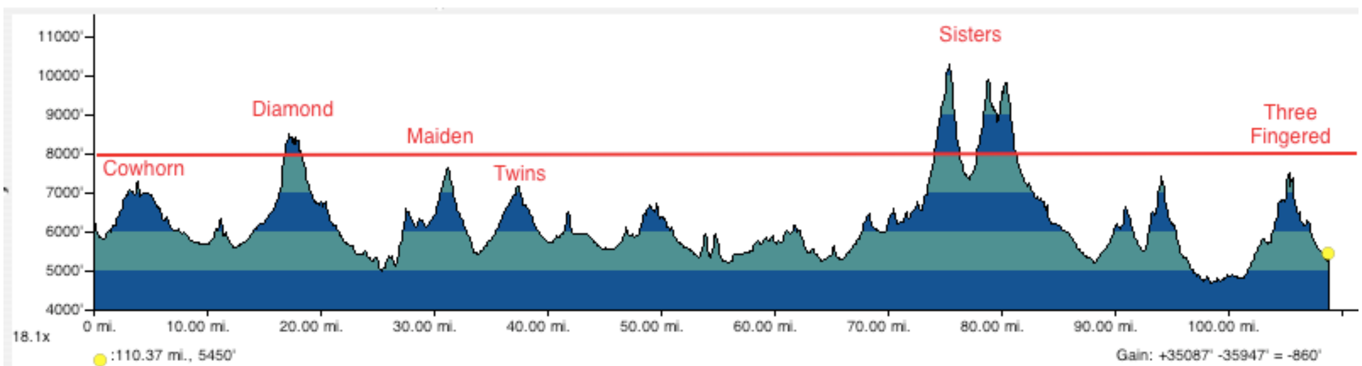


Figure 6. Plot showing azimuths and distances of points visible from the top of Pilot Butte. Circles are 50 km wide; colored dots indicate approximate height range of peaks (red dots >10,000 feet, orange dots 8,000 to 10,000 feet, blue dots 6,000 to 8,000 feet, and black dots <6,000 feet in elevation).

Figure 7. Profile along the Cascade crest from Cowhorn Mountain (7664 feet) to Three Fingered Jack (7841 feet). Red line is the elevation of Paulina Peak at Newberry Volcano; Paulina Peak is due east of The Twins.



Deschutes River occurred about 7,000 years ago when the eruption of the Lava Butte flow again filled a portion of the channel between Benham Falls and Lava Island Falls.

Since the eruption of the basalt of Crooked River Gorge, the Crooked River has cut a 300-foot deep gorge through the basalt. The Deschutes River has cut a channel up to 150 feet deep since the eruption of the basalt of Bend. Along the Deschutes there are deposits of meter-plus size boulders downstream from deep canyon sections.

Overall, the distribution of lava flows (mainly from other sources) show that the northern Deschutes Basin was little incised 5-3 Ma, with extensive basalt flows such as the basalt of Juniper Flat near Maupin (2.8 Ma) and the Agency Plains basalt flow north of Madras (5.3 Ma) covering vast upland surfaces, indicating an unincised landscape. At Round Butte, a 4 Ma flow invaded Deschutes River gravel about 275 m above present river level (O'Connor and others, 2003). But by 1.2 Ma, Basalt of The Island (Sherrod and others, 2004) filled a paleocanyon of the Crooked River to nearly its modern depth, indicating an incised landscape. This Pliocene/Quaternary incision of ~0.1 mm/yr between 4 and 1 Ma is consistent with less precise observations of regional incision of the interior Columbia Basin. Nevertheless, these values have been exceeded by much higher rates of incision through the later Quaternary canyon filling basalts derived from Newberry.

Directions to Stop 2

From the top of Pilot Butte, return to NE Greenwood Avenue / Highway 20. Our goal is to travel east on NE Greenwood Avenue / Highway 20, but a left turn (east) is not permitted from Pilot Butte. Instead you will turn right (west) and find a location to turn around. Once you are successfully traveling east on NE Greenwood Avenue / Highway 20, continue east for about 20 miles to Milepost 21; turn right (south) on Road 2015 / Ft. Rock Road. Continue on Road 2015 for about 3.6 miles to the junction with Road 2016 to the left. Stay right (west) on Road 2015 and continue for about 0.75 miles. Park on the side of Road 2015.

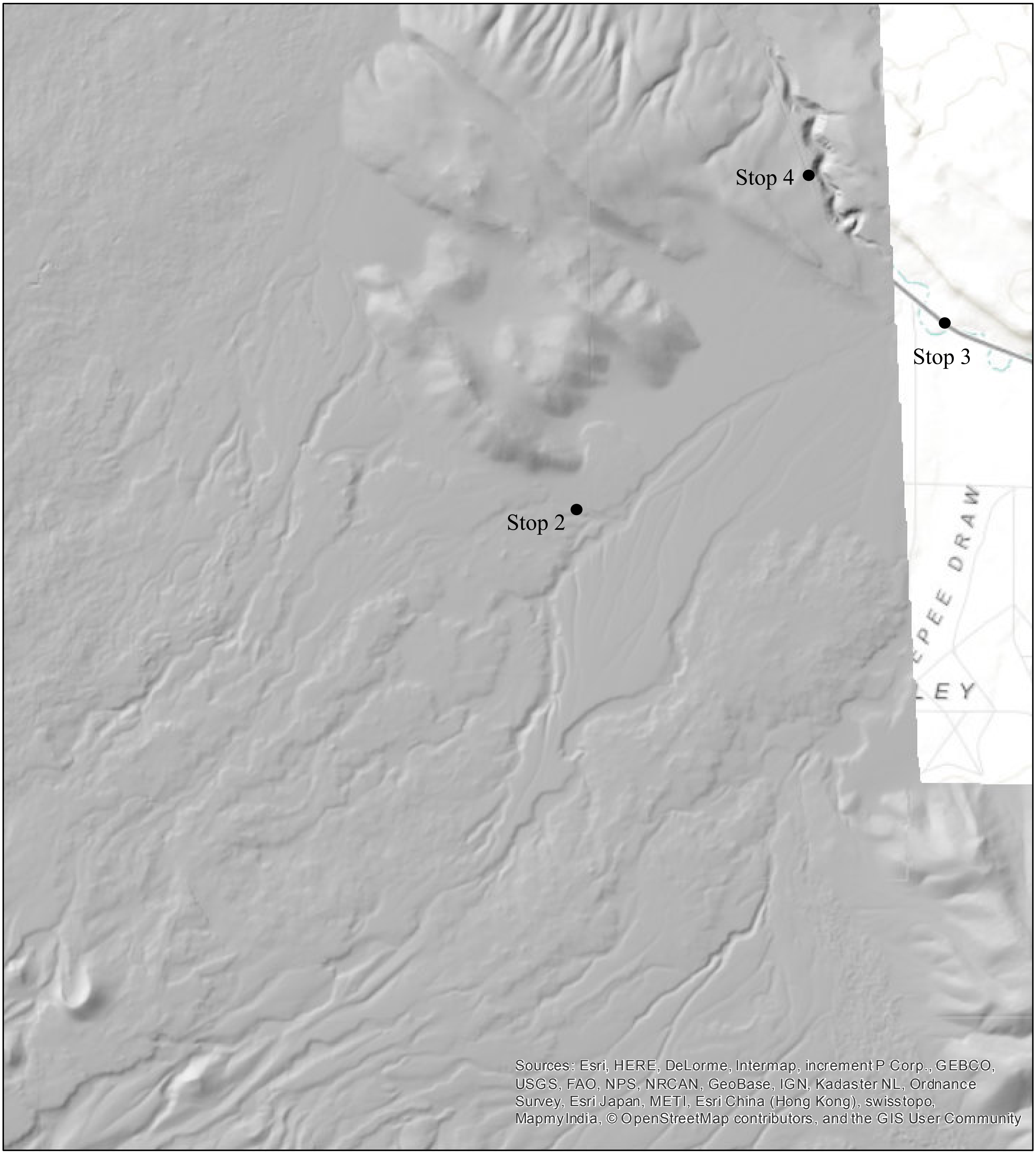
Stop 2. Dry waterfall NW of Evans Well

From Jensen and others (2009), as modified April 2017 by JND

From the parking location, hike south to a dry channel that is tributary to "Evans Draw" (figs. 5 and 8). 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. At this stop 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. Some of the fan is precaldera in age and consists of materials derived from

Figure 8. Map of the northeast flank of Newberry Volcano showing field trip Stops 2-4.



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the upper "Orphan Draw" drainage (fig. 5). The lower "Orphan Draw" channel forms the eastern edge of the fan. Interbedded in the upper part of the fan sediments is about 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" in post-caldera time.

Directions to Stop 3

Return to Highway 20 and turn right (east); continue on Highway 20 for about 1 mile. Park on the south side of Highway 20 (use caution and be aware of highway traffic).

Stop 3. Pleistocene History of Lake Millican

See attached Pleistocene history of Lake Millican, central Oregon, extracted from Vanaman and others, 2006 and Vanaman, 2007.

Directions to Stop 4

Turn around and travel west towards Bend on Highway 20 for about 2 miles to a pullout on the right (north) side of the road. The pullout is marked with a brown Oregon geology sign.

Stop 4. Dry River Canyon Overlook

From Jensen and others (2009)

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 about 1350 km^2 Dry River drainage system is the northeast flank of Newberry Volcano. The 5-km-long canyon of Dry River deepens from about 6 m at its upper end to about 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 post-caldera basalt of Lava Top Butte. Water rarely flows in the canyon today. Donnelly-Nolan and others (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 (fig. 5).

Alternatively, canyon cutting may owe to outburst of pluvial Lake Millican, which occupied the basin to the east to a maximum elevation of 1310 m [4300 ft] (Vanaman and others, 2006; Vanaman, 2007). At it’s maximum, this lake covered about 50 km^2 with about 7 km^3 of water. This lake could not of existed with the canyon in its present form.

Pleistocene history of Lake Millican, central Oregon

Extracted from:

Vanaman, K.M., O'Connor, J.E., and Riggs, N., 2006, Pleistocene history of Lake Millican, central Oregon, Geological Society of America Abstracts with Programs, v. 38, no. 7, p. 71.

and

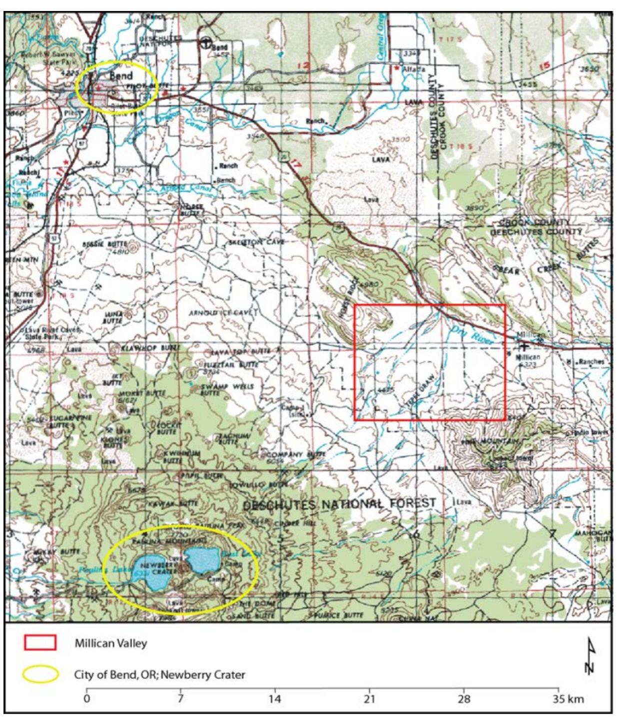
Karen M Vanaman, 2007, The Pleistocene history of Millican Valey, Central Oregon, M.S. Thesis, Northern Arizona University

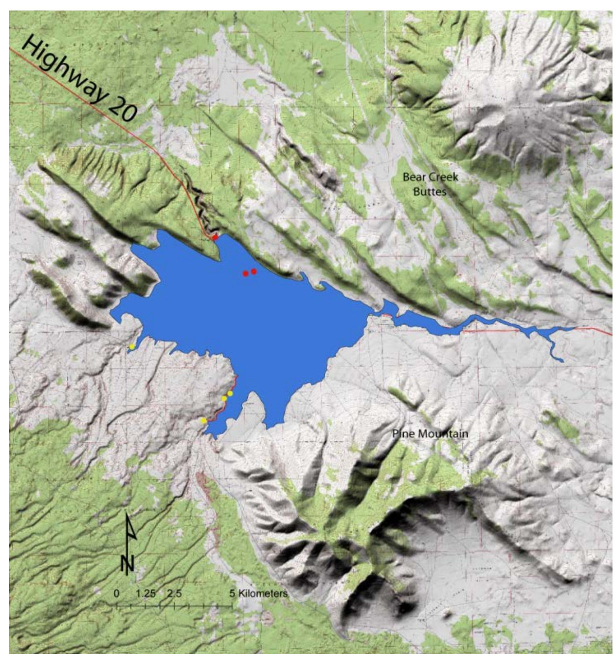
Abstract

Millican Valley is presently a dry, high-desert perched basin in central Oregon, bounded to the north by lava flows and volcaniclastic ridges uplifted by the Brothers Fault Zone, a series of predominantly northwest-trending faults spanning ~300 km through central Oregon. The basin is bounded to the south and west by Quaternary lava flows and alluvial fans shed from Newberry Volcano, and to the east by a ~22 Ma lava dome. During the Quaternary, the basin has partly filled with basaltic-andesite flows as well as alluvial fans consisting of unconsolidated gravels and tuffaceous deposits from Newberry Volcano. Millican Valley is also host to laminated sediments from a brief lacustrine occupation, and extensive dune-fields made up of tephra from the ~6.9 ka eruption of Mt. Mazama. Both alluvial/fluvial and lacustrine systems were active throughout the Pleistocene and were coevally active in Millican Valley during at least one point in time, perhaps forming the northernmost body of water in the Pleistocene Great Basin pluvial system. Eventual linkage to the Columbia River basin via the Crooked and Deschutes Rivers was established in the late Pleistocene by breaching of a shallow divide at the northern margin of the basin, leading to an outburst flood and nearly complete draining of Lake Millican through the present-day Dry River Canyon.

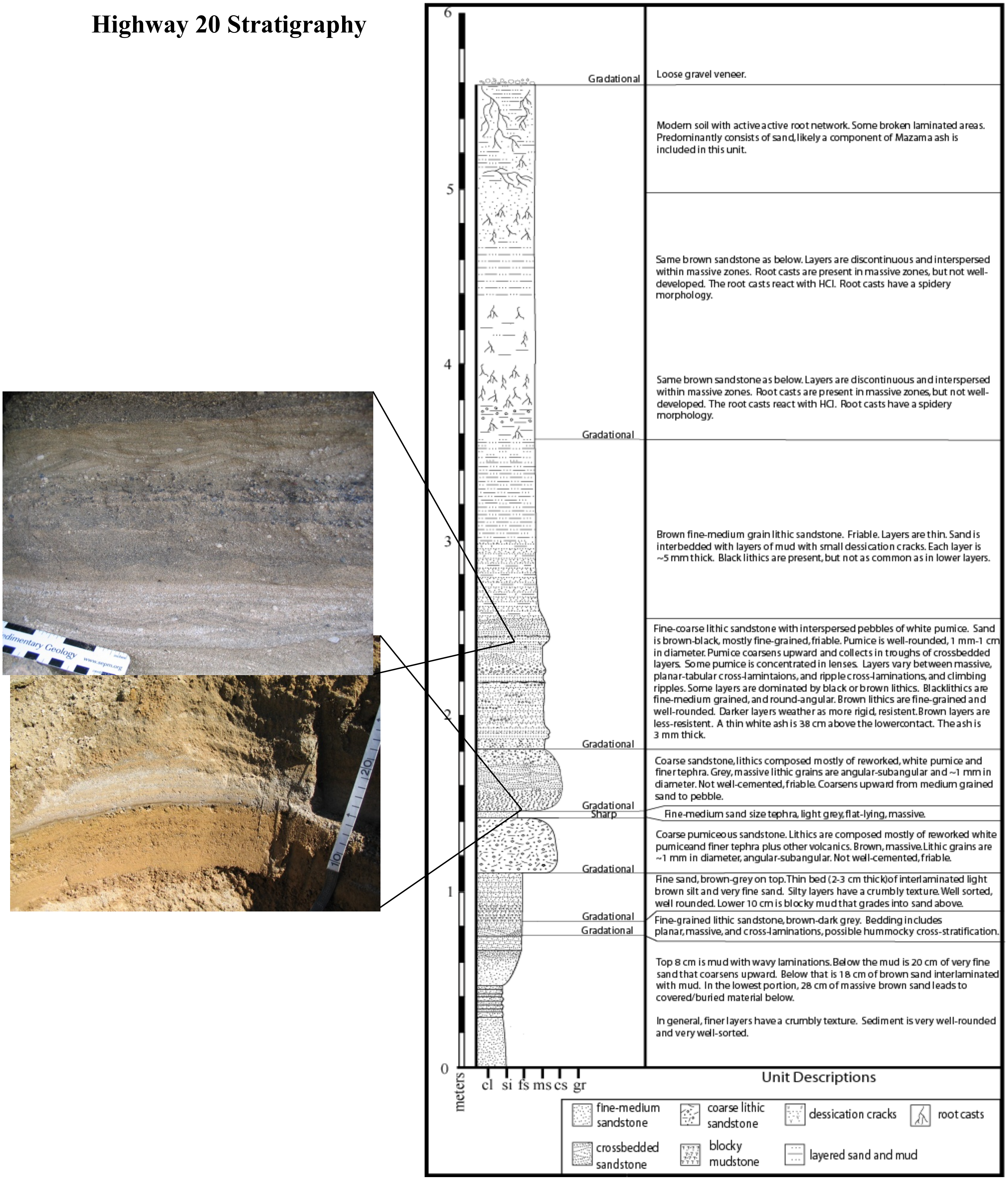
Pluvial Lake Millican boundaries were defined from a 1310 m elevation paleoshoreline locally identified by beveled ledges of equal elevation littered with gravel along the southeastern edge of the Smith Well lava flow in Millican Valley and from the elevation of a gravel spit near the western lake margin. At this elevation, the lake inundated an area of ~ 48 km2. The presence of freshwater diatoms in lake deposits in conjunction with a reworked tephra tentatively identified as the 27.3 ka Wono tephra (0.97 similarity coefficient) suggests that the lake was full and draining at that time but had not yet breached its outlet [*O'Connor doubts this tephra correlation, and thinks the lake is older, but the lake does apparently post-dates ~200 ka Smith Well flow to south; possibly making it OIS 6 or 4?*]. Final linkage with the Colombia River basin, which persists to present time, therefore occurred in latest Pleistocene time.

Highstand = 1310 m; Area = 50 km^2; Volume = 7 km^3



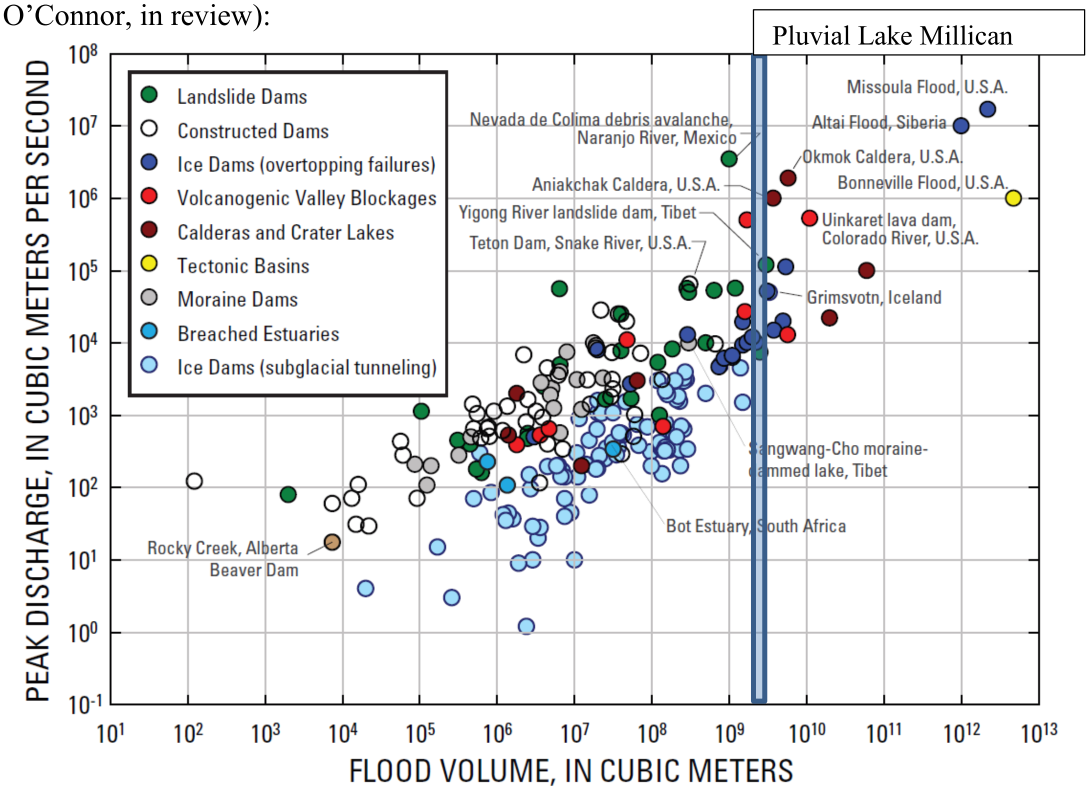


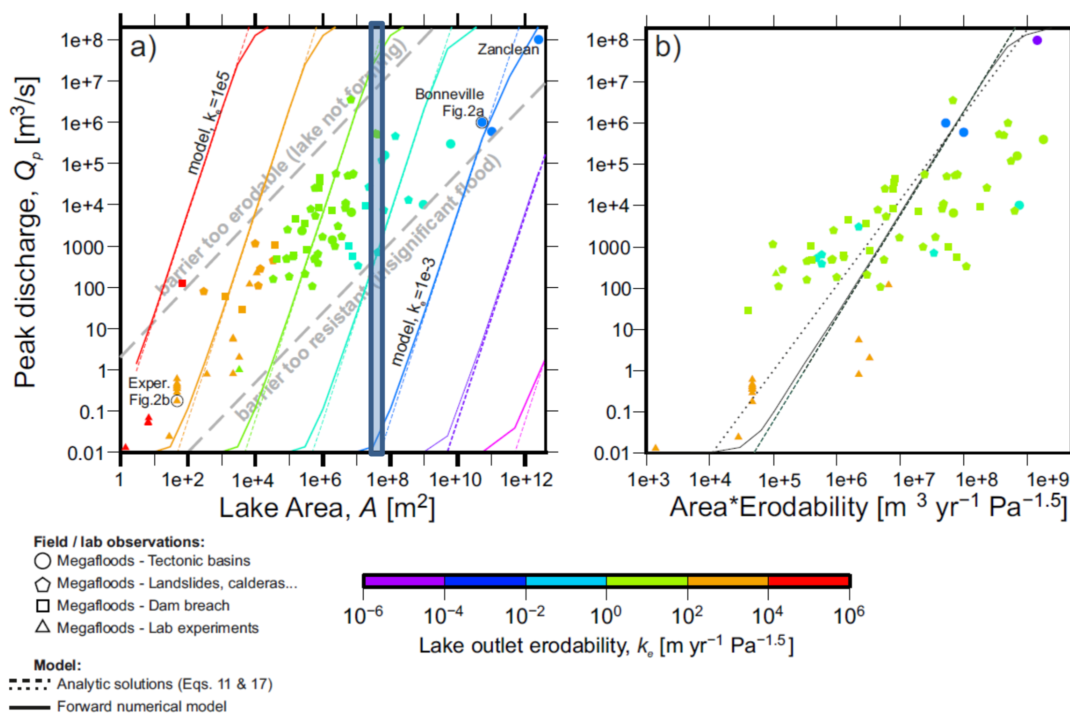
Highway 20 Stratigraphy



Could an outburst flood from Lake Millican carve (all of!!) Dry River Canyon??
Key Observations:
1. Sill area formed of thin lava flow (a few meters thick) over thick (several meters thick) pumice fall deposit.
2. Large 1-m+ rounded boulders at canyon mouth indicate significant flow.
3. The canyon has otherwise minimal drainage area.

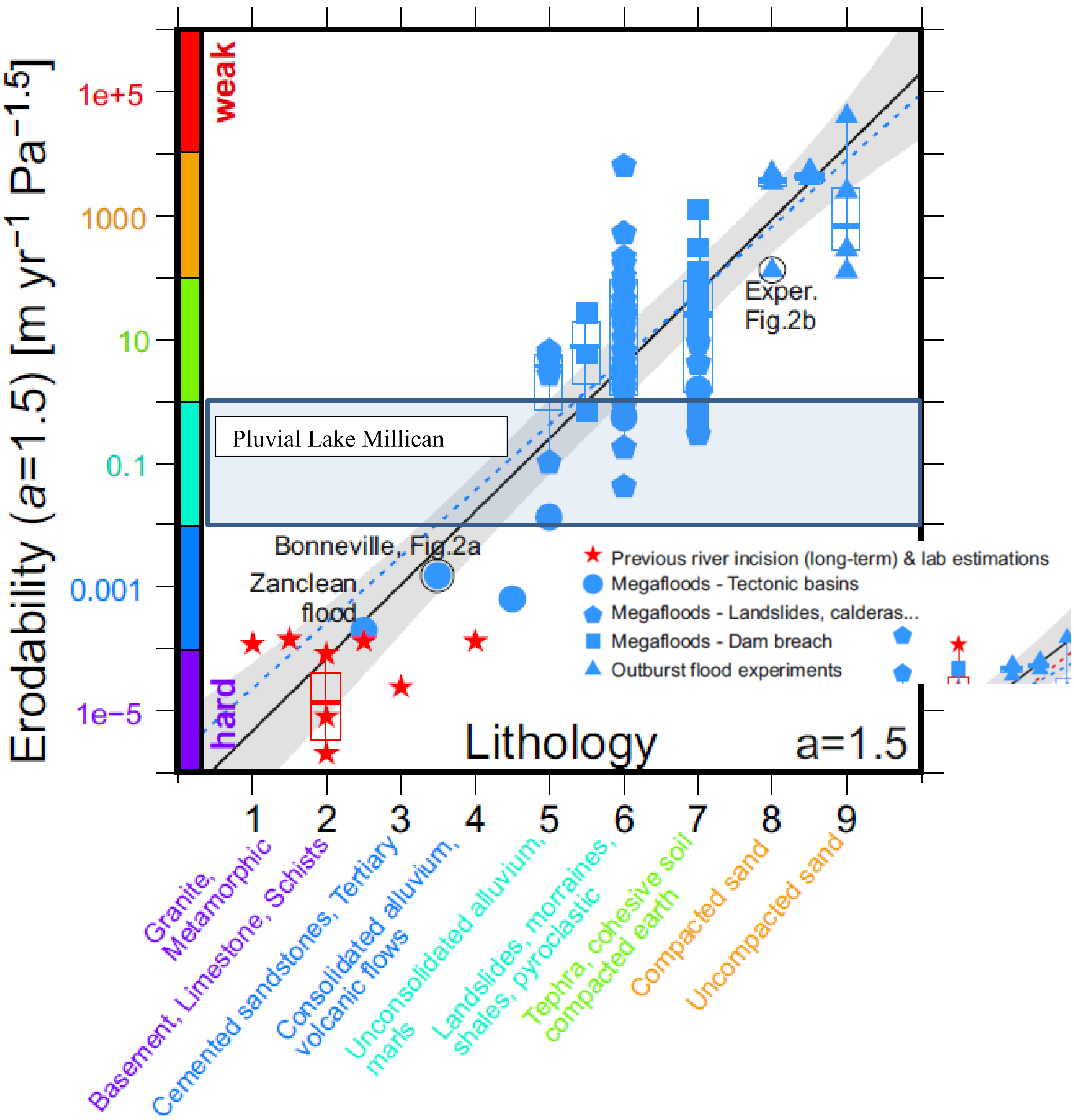
Some outburst flood perspective (from O'Connor et al., 2013, and Garcia-Castellanos and O'Connor, in review):





--Outburst floods from lakes the size of pluvial Lake Millican have discharges of 100-10,000 m^3/s.
--They're typically associated with outlets with erodability values, k_e, of 10^{-2}-10^{0} m yr^{-1} $Pa^{-1.5}$, similar to erodabilities calculated for floods breaching unconsolidated materials in other environments.
--Where k_e is the rock intrinsic parameter relating outlet erosion to shear stress:

$$\frac{dz_s}{dt} = -k_e\,(\tau - \tau_c)^a \quad (\tau > \tau_c)$$



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