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Evidence for Ice and Water on Newberry Volcano, Oregon

By J. Donnelly-Nolan and R. Jensen

Introduction

Donnelly-Nolan and Jensen (2009) published a paper entitled "Ice and water on Newberry Volcano, central Oregon." We argued for glaciation at the volcano to explain the lithic blocks found on cinder cones located high on the slopes of the volcano. Previous workers (MacLeod et al., 1995) noted the lack of polish and striations, moraines, and well-formed cirques and concluded that the volcano had not been glaciated. The interpretation of Donnelly-Nolan and Jensen continues to be controversial, so this document is an attempt to summarize the evidence and arguments pro (and con), and offer possible explanations for widespread heterolithic diamictons on the east flank of the volcano that were not recognized in 2009 prior to the availability of lidar imagery.

Background: Medicine Lake volcano

Similar in shape, height, elevation, and high desert location east of the Cascade Range, MLV lies 250 km south of Newberry, but displays unequivocal evidence of glaciation (Anderson, 1941; Donnelly-Nolan 2010). Glacial polish and striations on dense rim andesites (Fig. 1), morainal deposits and till, scraped cinder cones and modified topography all testify to the presence of ice. Donnelly-Nolan found deposits and terrain modification indicating that ice extended as low as 6,000 ft. Fluid inclusion data from drill cores also provide evidence for ice on the volcano (Bargar, 2001). Anomalous fluid inclusion homogenization temperatures determined from minerals in a caldera drill hole suggest that ice thicknesses may have exceeded 150 m. Despite the clear evidence for ice, only limited evidence for runoff of water is present in the form of channels and gravel.

Newberry Volcano

As noted by MacLeod et al. (1995), glacial polish and striations are absent on the caldera rim at Newberry. However, hard dense rocks that might preserve such evidence are also absent. The rim consists of pumice and tuffs, rhyolite flows, and cinder cones. A few small morainal ridges have been found high on the east flank, but the dominant geomorphic features of the east and west sides of the volcano are the abundant water-cut channels. Also present on the east flank are relatively extensive sedimentary deposits (diamictons) containing unsorted heterolithic assemblages of subangular to subrounded clasts in a finer-grained matrix.

Prior to the caldera-forming eruption about 75,000-80,000 years ago, lavas rich in TiO_2 and FeO erupted from vents high over the present basin. The broad distribution of these lavas to the east, north, west, and southwest requires that the vents were located higher than the current height of the volcano -- perhaps 500 ft to as much as 1,000 ft higher. The age of these lavas is uncertain -- 5 argon plateau ages by A. Calvert range from 76-97 ka. Stratigraphically above these lavas, and erupted prior to caldera formation, is the rhyolite of Paulina Peak, for which 3 argon ages (A. Calvert, M. Lanphere) range from 77-85 ka. Post-dating caldera formation are two large basaltic eruptions on the north flank, the basalt of Bend (78±9 ka; M. Lanphere) and the overlying and paleomagnetically-transitional (D. Champion data) basalt of Lava Top Butte, thought to be the age of the Norwegian Sea Event (72? ka).

Cinder cone evidence for ice

Eight cones within 7 km of the caldera rim (shown on Fig. 2 location map) display foreign lithic blocks as large as 2.5 m. Seven of the eight cones are within 5.1 km of the rim. The cones vary in elevation from a high of 6760 ft to a low of 5760 ft, and in azimuth from north around to east, southeast, and southwest. Two of the cinder cones are discussed below. Appendix 1 includes information on the other six. For each cone, information documented by Jensen is provided, including locations of the lithic blocks shown on enlarged lidar images, descriptions of the cone and the lithics, and photographs of some of the lithics. All cones have at least one lithic measuring 0.7 meters in maximum dimension.

1. No evidence exists for human intervention in distribution of the lithics.
2. Another theory, that the lithics were erupted by the cones, is unlikely. Donnelly-Nolan has been to the top of at least 300 cinder cones at Newberry and yet only a very limited number of cones, and only high on the slopes, have large foreign lithic blocks sitting atop them. No such lithics are found on any of the numerous cinder cones at Newberry that are located farther than 7 km from the caldera rim. Lack of adhering spatter also argues against eruption of the blocks by the cones on which they sit. The more than 35 cinder cone quarries at Newberry reveal that few if any lithics are present within the cones and none larger than 0.3 m have been seen.
3. Another suggested origin for the lithics is as ballistic blocks tossed out by a powerful eruption from the caldera, but the lack of any continuous deposit of ballistics indicates that this explanation is highly unlikely. The varied composition of the blocks and lack of apparently juvenile material also argues against this explanation.
4. In the absence of an eruptive process to put the foreign blocks onto the cinder cones, and together with the modifications of cone shape, we conclude that only ice could have transported the blocks. Thus, we interpret them as glacial erratics.

Evidence from post-caldera Lowullo Butte (Fig. 3)

One of the cinder cones that exhibits a variety of lithic blocks at the top and a sculpted shape on the caldera-facing side definitely post-dates caldera formation -- Lowullo Butte erupted about 65 ka and its lavas overlie pyroclastic flows erupted during caldera formation.

Confusing deposits on Washed Butte (Fig. 4)

An older cone on the east side, informally named Washed Butte, displays a range of lithic types among erratics on its 5782' summit, including rhyolite and both coarsely porphyritic and aphyric basaltic andesites. During a field trip visit to this cone about a decade ago, J. Vallance showed that the surface of the cone has a mantle of porphyritic scoria. Subsequent visits to this cone by the authors indicated that there is no need to break open scoria fragments to find the porphyritic ones – they are noticeably heavier than scoria that make up the cinder cone. No cinder cone source for these heavy scoria exists on the east flank of Newberry. In a recent visit to the northern arm of the cone, we found bombs as large as 0.7 m across of the same porphyritic material and briefly considered the possibility that they might make up that arm of the cone. However, that is not the case. The porphyritic bombs and scoria are all deposited on top of the cone. No obvious source exists for the porphyritic material. We conclude that the material was most likely transported by ice – perhaps on top of an ice sheet from a now-buried source.

Channels and water evidence

Abundant dry channels, including many that are 10's of meters deep, traverse the east and west sides of Newberry Volcano. They incise sedimentary and tuffaceous deposits and in places water has polished resistant bedrock creating what are now dry waterfalls. At distances of 10-20 km, some gravel fans have been deposited, and subsequently incised. Multiple generations of incision can also be documented on the eastern slope of Newberry where channels have been carved into ash-flow tuffs, then occupied by narrow tongues of lava, and subsequently the adjacent walls of tuff have been removed by more channeling. Donnelly-Nolan and Jensen (2009) include a map of the drainage network. More recently, hillshade images created from lidar coverage show enhanced details of the drainage network (partially shown on Fig. 2). In a few channels, minor evidence exists for modern water movement, most likely during heavy thunderstorm events. However, so little water transport occurs that one of the primary roads around the volcano, Road 18 (the China Hat road), which was built for railroad logging, was constructed across deep channels without provision for drainage under the road -- and decades later there's no evidence that any culverts were needed.

The evidence is clear that large volumes of water capable of cutting channels and carrying significant volumes of sediment flowed off of Newberry Volcano at multiple times in the geologic past. Potential sources of water include overflow of a caldera-ponded lake, a lake perched on an ice cap, rapid melting of large volumes of snow, e.g. with warm rain across frozen ground, and rapid melting of ice.

On the west flank of the volcano, a smooth surface exists for ~2 km across welded tuff of the ~75-80-ka caldera-forming eruption at the lowest point on the caldera rim. Beyond that, a dense drainage network has formed across poorly-welded to non-welded areas of the tuff.

Diamictons

Gently eastward-sloping, broad ridges of heterolithic unsorted sedimentary material cover significant areas of the mid- to upper east flank of the volcano. Mapped as "Qsp" (Quaternary sediments and pyroclastic material – MacLeod et al., 1995), the ridges are mantled with tephra and give little evidence of the primary internal material. However, lidar images have revealed locations otherwise hidden by thick vegetation where ridges have been incised by erosion. Two photographs of the deposit at 1940J (see Fig. 2 for map location) are shown in Figure 5. Clasts larger than 10 cm range from a few angular platey rhyolites to the more common subangular to the predominant subrounded lithics that are up to 1 meter in size. The clasts are in a matrix-supported, finer-grained loose matrix that contains some clay.

Possible interpretations of these deposits include:

1. glacial till

   <u>Argument against till</u>: The primary argument against till seems to be that the elevation is too low (5900 ft at site 1940J). Also, it's argued that Newberry is situated in the High Cascades rain shadow, which would have deprived it of moisture to make ice. This latter argument seems contradicted by the abundant water-cut channels.

   <u>Argument in favor of till</u>: The deposits look like till, and till makes sense given the erratics on the cinder cones. Incorporated within the deposits are lithics ranging in composition from rhyolite to basalt, some of which are not known in outcrop; others are intrusive in texture suggesting that they were erupted from deep within the roots of the volcano. We suggest that these materials were deposited explosively (e.g. as a lithic breccia) on the high rim/slopes of the volcano where they were available for ice to transport. Glacial till would be consistent with ice transporting the lithic blocks onto the tops of the cinder cones. Figure 6 shows a shaped and polished erratic on Lithic Butte. Regarding the rain shadow argument, Medicine Lake volcano lies to the east of higher -- and more extensive -- high terrain some 250 km <u>south</u> of Newberry and yet its upper slopes and caldera display clear evidence of glaciation. Also, contrary to the evidence at Newberry, there is no evidence that MLV was higher than present. Thus it would seem that Newberry –

both higher (prior to caldera formation) and farther north – should have been glaciated.

2. debris flow deposits
   The matrix of the deposits is not indurated although although some clay is present. Instead, the deposit can be dug out relatively easily. There's no apparent channelization. Large volumes of water would have been required. Trenching of the deposit may expose internal structure and should give a better view of the diamicton matrix. One possibility would be eruption of hot material onto thick snow or caldera-adjacent ice that melted quickly, forming a slurry that moved downhill.

3. lithic pyroclastic flow
   It's not obvious that the clasts were heated. There's no prismatic jointing on the outsides of clasts, nor is there an obvious juvenile pumice component. Trenching to expose the matrix will be useful to look for any such evidence.

Caldera eruption

When the caldera-forming eruption occurred about 75,000 to 80,000 years ago, approximately 50 cubic km of material was erupted explosively (based on a simple calculation: ~50 square km by ~1 km deep). Juvenile magma ranging in composition from basaltic andesite (~53% SiO_2) through rhyolite (~73% SiO_2) erupted as ash flows and ash falls. [Judy Fierstein is currently engaged in a detailed study of the deposits and the eruptive sequence.] There is some limited evidence in the form of mafic palagonite tuffs exposed in the east caldera wall that water might have played a role in the caldera eruption.

Included in the caldera deposits are lithic fragments ranging from granitic to dioritic intrusive rocks, porphyritic basaltic andesites, older rhyolites, and aphyric mafic lavas. Preliminary evidence suggests that a very similar range of lithic types is present within the eastern diamictons and among lithic blocks found on some of the cinder cones that ring the upper flanks of the volcano suggesting the possibility that the erratics and the diamictons were emplaced in post-caldera time.

Some diamicton ridges on the volcano's east side seem to be capped by deposits of the caldera-forming eruption, whereas other ridges lack such a cap and their stratigraphic position suggests that the diamicton was emplaced post-caldera.

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LIST OF FIGURES

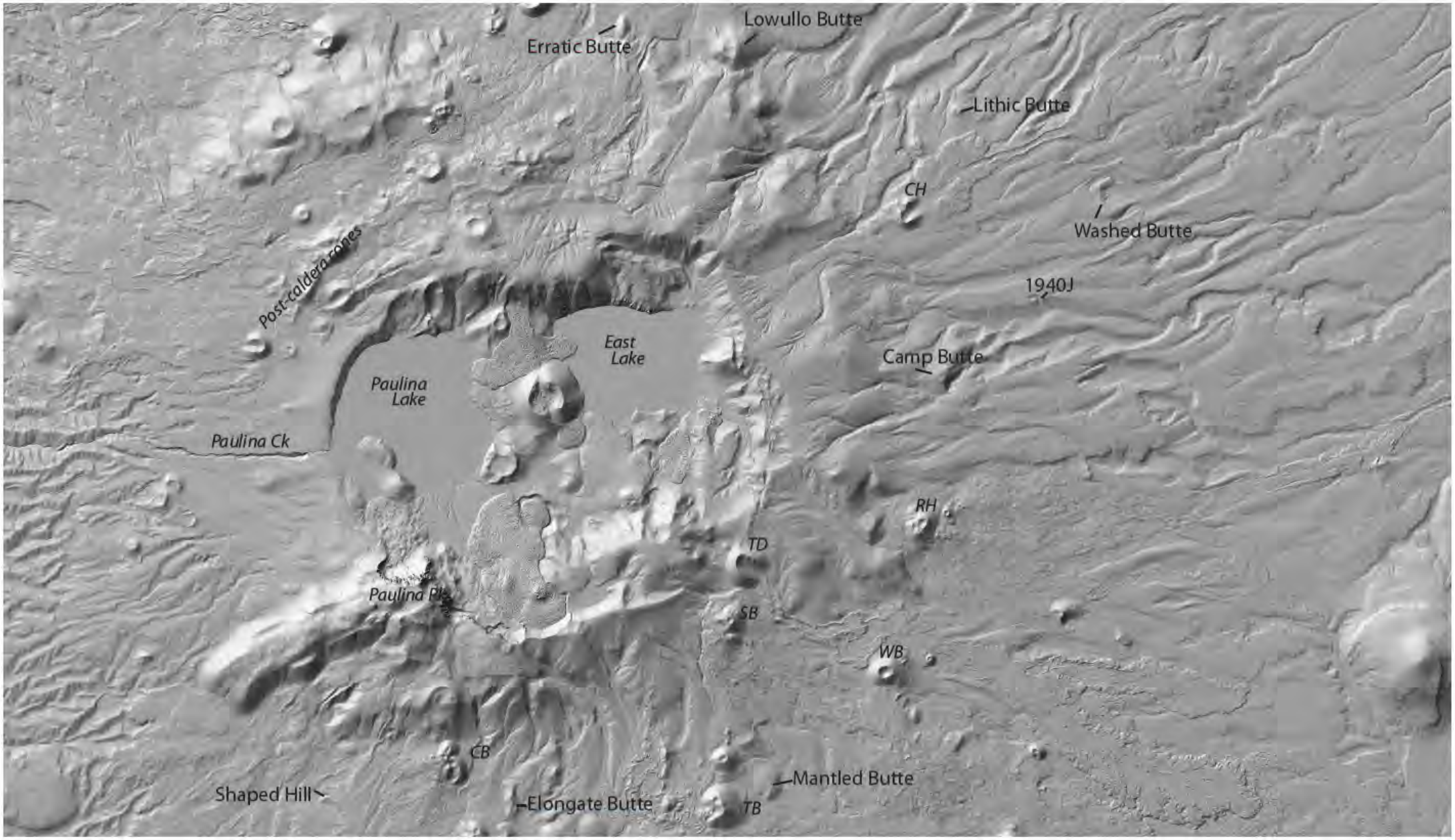
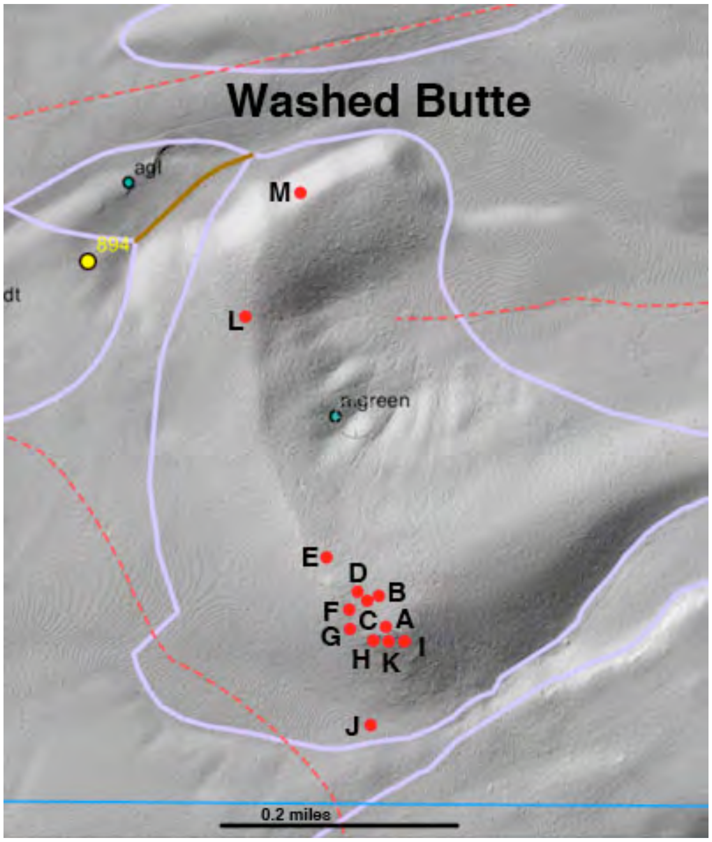


Figure 2. Lidar image of Newberry Caldera and adjacent terrain. East-west dimension of the caldera is slightly less than 8 km. Cinder cones with erratics (see Fig. 2-4) are labeled by name. Lowullo Butte is known to be post-caldera in age. Some other postcaldera cinder cones are labeled by initials: CB (Corner Butte), TB (Topso Butte), SB (Sand Butte), TD (The Dome), WB (Weasel Butte), RH (Red Hill), and CH (Cinder Hill). 1940J is the site of the diamicton shown in Fig. 5.

View west-northwest from upper south side of Erratic Butte toward Three Sisters on far horizon. Early Holocene Pilpil Butte is on near horizon at left. Age of Erratic Butte (informal name) is unknown. Block in foreground is Erratic B, sample 1956J.

Washed Butte

Cone Size: About 0.75 by 0.55 kilometers, 85 meters high (280 ft)
Cone Chem: Sample 891J, 54.6% SiO_2, poorly phyric
Cone Location: 6.9 kilometers east of caldera rim, elevation of 5782 feet
Cone Description: Butte varies in height from 15 (W) to 85 (E) meters (50 to 280 ft). Cone is breached to the east.
Cone Age: older than Qdt, ~300 ka
Area Description: Cone is a vent for unit "mgreen". Diamictons surround cone and reach rim level over much of the area between E & L.



Erratic Descriptions:

A group of two dozen plus, multiple types
0.3 meters - nearly aphyric ba - 1957J-A
0.2 meters - very porph bomb - 1957J-B
B 0.15 meters - part of porph bomb
C 0.2 meters - porph bomb
D up to 0.3 meters - group of three porphs
E 0.4 meters - porph bomb
F up to 0.3 meters - group of five porphs
G 1 meter - porph bomb
H 0.2 meters - porph
I 1 & 0.5 meters - angular porph blocks
J 1.2 x 1 meters - grubby porph
0.5 x 0.7 meters - gray slightly porph
K four samples out of A area
A - 0.15 x 0.4 x 0.5 meters - bluish ryholite - 2074J-A
B - 0.15 x 0.3 x 0.4 meters - gray coarse porph - 2074J-B
C - 0.25 meters - dark gray ba - 2074J-C
D - 0.25 meters - light gray, fine grained ba - 2074J-D
L 0.4 meters - dacitic
M 0.7 meters - porph bomb - 2073J

<u>Washed Butte Erratics</u>

Erratic from Group A

Erratic from Group A

Erratic from Group A

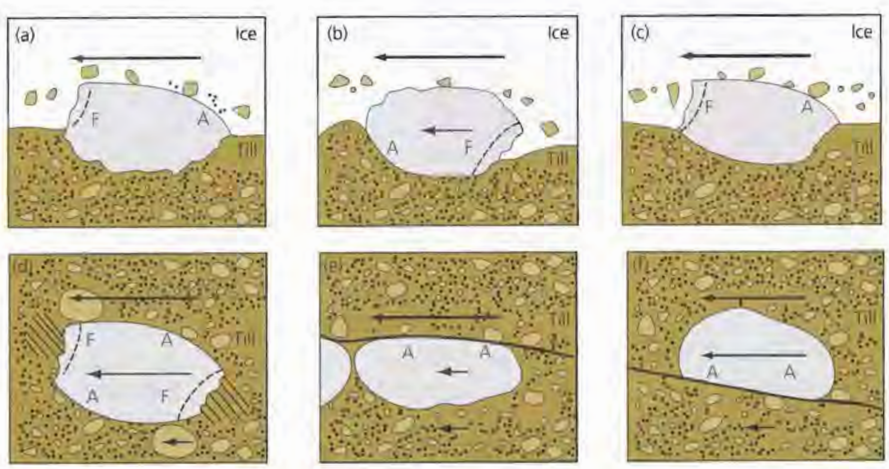
Erratic C - porph bomb

Erratic Group I

Erratic Group I closeup

Figure 5. Two views of the diamicton at site 1940J (see Fig. 1 map for location). Subangular to subrounded clasts up to 1 m across include fine-grained basaltic andesite, very crystalline basalt, platey rhyolite, welded rhyolite tuff, coarse-grained probable shallow intrusive mafic rocks, and very porphyritic basaltic andesites. Fine-grained uncompacted matrix contains some clay.

Figure 6. Erratic "C" on Lithic Butte (see Fig. 2). Block is polished and has a shape much like the one shown below on p. 362 of Benn, D.I., and Evans, D.J.A., 2010, Glaciers & Glaciation, Second Edition, Hodder Education, 802 p.



362 GLACIERS AND GLACIATION

Figure 9.45 Development of asymmetric clast wear patterns beneath sliding ice and within deforming till, showing principal locations of abrasion (A) and fracture (F). Arrow lengths show relative velocities. (a) Lodged clast with stoss-lee form owing to stoss-side abrasion and lee-side fracture below sliding ice. (b, c) Double stoss-lee morphology resulting from a two-stage process of ploughing and lodgement. (d) Double stoss-lee clast resulting from a single-stage process within a deforming layer. Low pressure zones are shaded. (e, f) Flat, polished facets eroded on the upper and lower surfaces of clasts, where there is significant slip between the clast and the adjacent shear plane (Modified from Krüger, 1984, and Benn and Evans, 1996).

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Ice and water on Newberry Volcano, central Oregon

Julie M. Donnelly-Nolan*
U.S. Geological Survey, MS 910, 345 Middlefield Rd., Menlo Park, California 94025, USA

Robert A. Jensen*
U.S. Forest Service (retired), Bend, Oregon 97701, USA

ABSTRACT

Newberry Volcano in central Oregon is dry over much of its vast area, except for the lakes in the caldera and the single creek that drains them. 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. 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. The evidence suggests that Newberry Volcano has been subjected to multiple glaciations.

INTRODUCTION

Nestled within the scenic 45 km^2 Newberry caldera at the top of Newberry Volcano (Fig. 1) are two beautiful lakes—Paulina Lake and East Lake—that 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 et al., 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 (Figs. 1 and 2) 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 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,

*jdnolan@usgs.gov bjensen@bendnet.com

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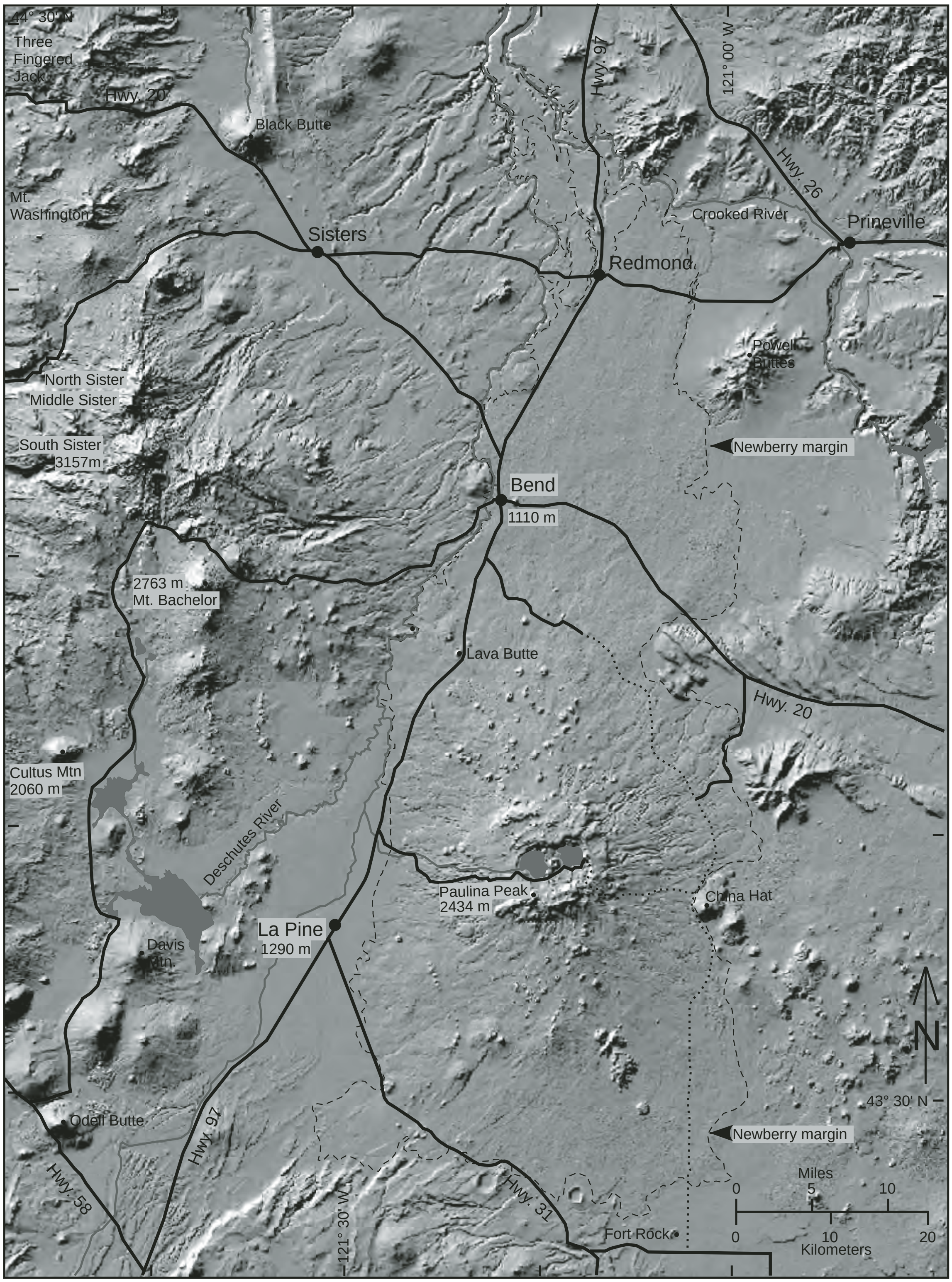

Figure 1. Location map. The approximate extent of lavas from Newberry Volcano is shown by the dashed line. Solid dark lines are paved roads; dotted lines are major unpaved roads. Base is shaded relief derived from 30 m digital elevation model.

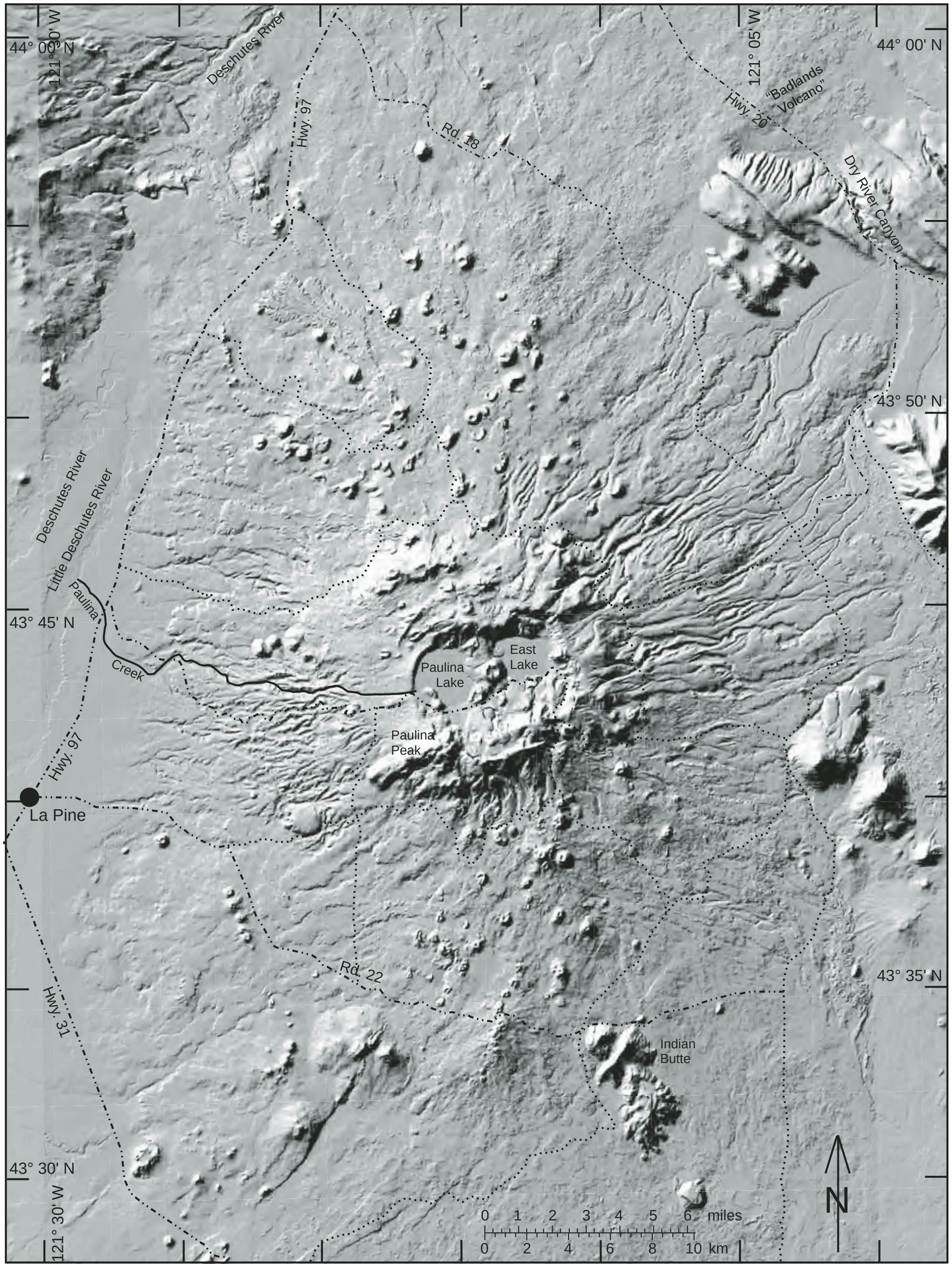

Figure 2. Shaded relief image (from 10 m digital elevation model) of the main edifice of Newberry Volcano shows obvious drainage networks on west, northeast, and east sides. South and north sides are mostly covered by late Pleistocene and postglacial lava flows and vents.

are prominent features of the eastern and western sides of the volcano (Fig. 2). 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 et al. (1995) concluded that Newberry was not glaciated, with the exception of localized ice on the north-facing intracaldera wall of Paulina Peak (Fig. 2), 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 et al. (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 in the Cascade Range to the west. MacLeod et al. (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, 240 km farther south, 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 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 (Fig. 3). In the Mountain Lakes Wilderness of southern Oregon, ~170 km southwest of Newberry caldera, ice extended as low as 1700 m (Rosenbaum and Reynolds, 2004) from a maximum elevation of 2500 m. 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 et al., 2004) and a continuing search for evidence indicating the extent of ice.

EVIDENCE FOR ICE AND WATER

A variety of glacial erratics have been identified at elevations as low as 1735 m and possibly lower. Figure 4 shows the locations where the erratics have been found. Most erratics sit on tops or backs of cinder cones as solid blocks of non-matching rock types, with no adhering spatter and typically with smoothed surfaces. Figure 5 shows photographs of three different erratics on the upper caldera-facing slope of a cinder cone with an elevation of 1833 m, located 5 km from the northeastern caldera rim that has an elevation ranging from ~2150 to 2225 m.

Small moraines have also been recognized, as well as polished outcrops and poorly developed cirques. Elongated cinder cones without summit craters but surmounted by erratics indicate that glaciers over topped and modified some terrain. The lack of obvious glacial striations is probably the result of rocks on the upper part of the volcano being either soft (cinder cones, tuff, rhyolite) or buried by tephra. This is in sharp contrast to the situation at Medicine Lake volcano, where the caldera rim is constructed mostly of dense, hard andesite that accepts polish and striations. Despite the undeniable evidence for ice at Medicine Lake volcano, as recorded in glacial polish and striations in rim andesites, only limited areas of moraine are present. Thus, the rarity of constructional moraines at Newberry Volcano does not preclude the existence of ice on the volcano. The abundance of

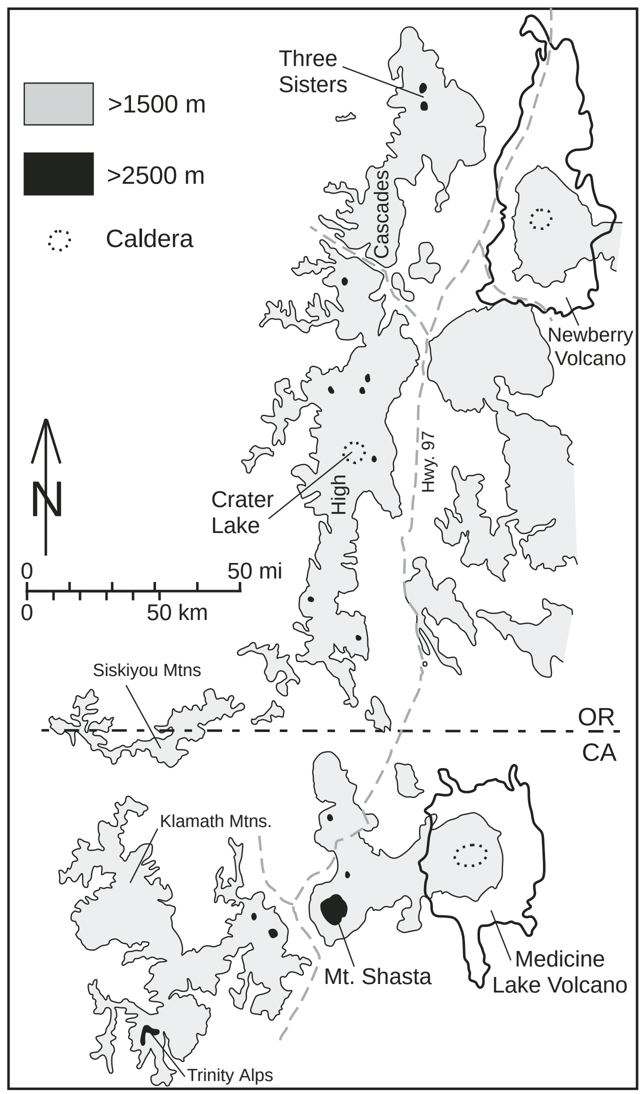

Figure 3. Regional map showing positions of Newberry Volcano and Medicine Lake volcano with respect to each other and relative to high terrain to the west.

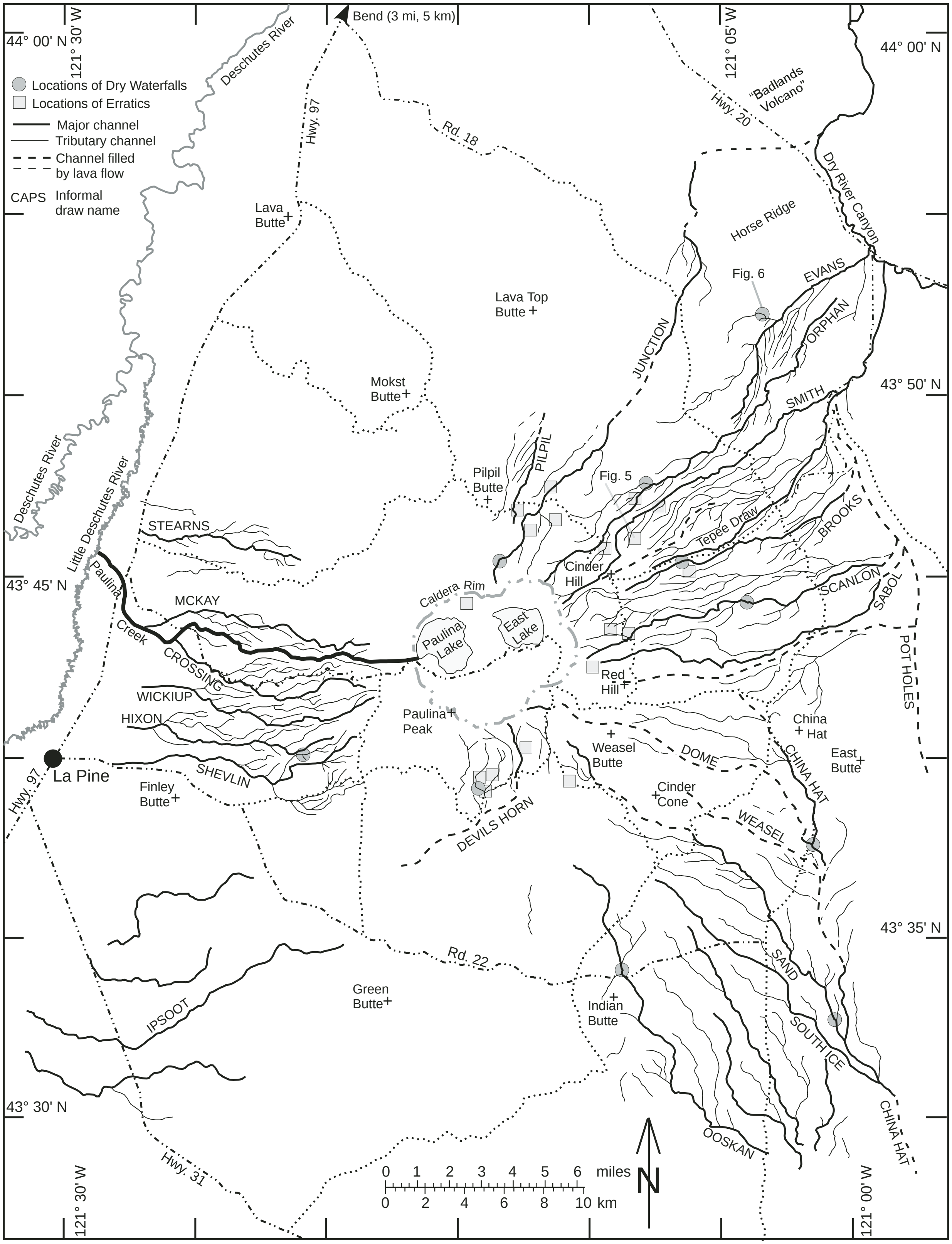

Figure 4. Map shows drainage network, erratics, and dry waterfalls on Newberry Volcano. Informal draw names of major dry channels are shown in capital letters.

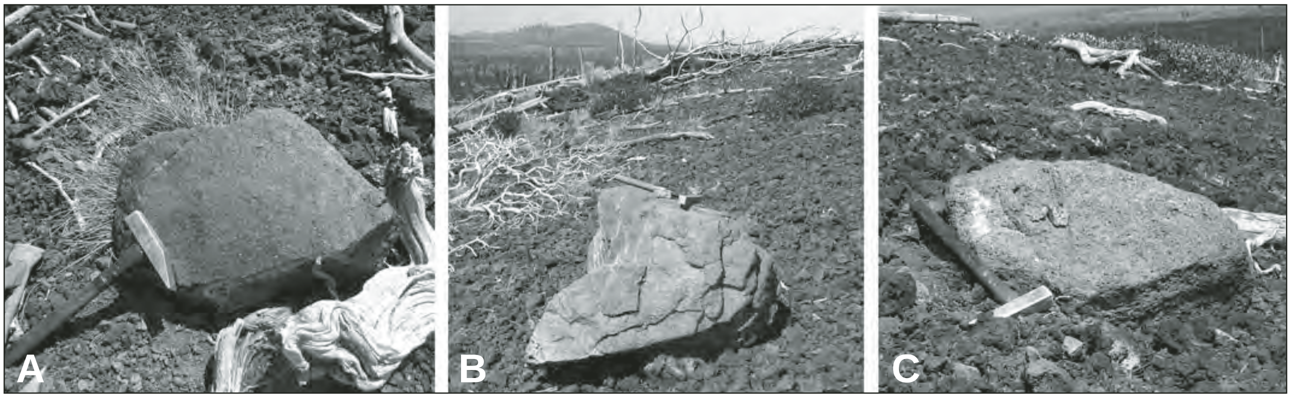

Figure 5. Photographs of erratics of three different rock types found on cinder cone located ~5 km northeast of the caldera rim (see Figure 4 for location). Hammer is 39 cm long.

gravel on the volcano's upper flanks may be evidence for dispersed and reworked ground moraine.

Evidence for large volumes of water is more compelling. In addition to the multiple large channels (Fig. 2 and 4), scattered dry waterfalls have been identified (Fig. 4) showing clear evidence of polish by high flows of water cascading over a break in slope or through a narrow slot (Fig. 6). The catchment areas for these waterfalls are poorly defined, suggesting broad overland flow. In addition, extensive blankets of Qsp (Quaternary sedimentary and pyroclastic deposits) were mapped at Newberry by MacLeod et al. (1995). These deposits include gravel as well as "abundant cobbles and boulders at higher elevations on flanks of volcano" (MacLeod et al., 1995, map explanation). The distribution of the deposits overlaps the distribution of the drainages.

Figure 6. Photograph looking down water-smoothed slot in basalt (see Figure 4 for location). This dry waterfall location has no obvious upstream feeder channel. Channel, slot, and surfaces are dry and show no evidence of recent water flow.

West Flank

The west side of the volcano is mostly mantled by ash-flow tuff that erupted ~80,000 years ago when the caldera formed subsequent to emplacement of the rhyolite of Paulina Peak at 83 ± 5 ka (Donnelly-Nolan et al., 2004; Jensen et al., this volume). The compositionally zoned tuff of Paulina Creek Falls was previously mapped (MacLeod et al., 1995) as two deposits, Qat (Quaternary andesitic tuff) and Qbt (Quaternary basaltic andesite lapilli tuff). On the basis of chemical analyses of samples in mixed outcrops, we correlate the two, and we correlate both to the Pumice Flat tephra of Kuehn and Preppernau (2005), which we consider as part of the caldera-forming eruption. Kuehn and Preppernau (2005) document that the more silicic tephra erupted first, followed by a more mafic tephra. A sample of black scoria from high in the tephra deposit matches the composition of Qbt. The early partially welded to welded rhyodacitic to andesitic Qat is found mainly on the upper west side of the volcano, but also high on the east rim. The subsequent andesite to basaltic andesite Qbt, which is almost entirely non-welded, is exposed mainly on the mid-lower west side, although it is also seen in smaller patches on the northeast and east sides of the volcano.

The lowest point on the caldera rim is on the west side where Paulina Creek emerges at an elevation of ~1930 m from Paulina Lake and flows over welded Qat. The upper nonwelded portion of the tuff has been removed, and the remaining Qbt, which is exposed farther to the west and lower on the flank, has been extensively channeled and rilled (see Fig. 2). We interpret the removal of Qbt on the upper west side to have resulted from scraping by ice, whereas the channeling and rilling of Qbt at lower elevations are the result of glacial meltwater from the wide glacial front. Evidence of any precaldera channeling has been obscured by the mantle of ca. 80 ka tuff deposited during caldera formation.

North Flank

The northern caldera rim at ~2225–2300 m is higher than the eastern or western rims. Evidence of scraping by ice is seen near the north rim where cinder cones have been substantially reshaped and meter-sized erratics were deposited on an elongate crater-less cinder cone ~5 km north of the rim at an elevation of 1980 m. Also, some areas of Qsp have been mapped high on the northeast side, coincident with channels. The presence of Qbt lapilli in the Knott Road landfill in southern Bend, some 30 km north of the caldera rim, indicates that some of the caldera-forming tuff must have been deposited on the north flank, but younger lavas have subsequently covered it. Postcaldera lavas, including large areas of postglacial lavas, cover much of the north flank of Newberry.

South Flank

Much of the south rim of the caldera has an elevation higher than 2300 m. Rocks are poorly exposed on the upper south flank, where MacLeod et al. (1995) mapped much of the area as covered by Qsp, but streamlined cinder cones capped by meter-sized erratics are found at elevations of ~1850 m and lateral distances of 3–4 km from the rim. Farther south, early Holocene and late Pleistocene lavas cover much of the south flank. One probable drainage ("Devils Horn Draw," Fig. 4) was filled by a postglacial lava flow.

East Flank

In contrast with the west flank of Newberry, the east flank displays both undated precaldera lavas and sediments. Qbt is present and has been cut by channels, although it covers only a small area, contrasting with its wide coverage of the west flank. Two older ash-flow tuffs ca 300 ka in age (Donnelly-Nolan et al., 2004) are exposed. One tuff is dacitic (mapped by MacLeod et al., 1995, as units Qdt and Qto) and covers relatively small areas, whereas the other is rhyolitic (unit Qtp of MacLeod et al., 1995) and covers large areas of the lower slopes. Kuehn (2002) also found significant thicknesses of tephra on this flank of the volcano. The sediments and pyroclastic deposits were mapped as a single poorly exposed unit, Qsp, by MacLeod et al. (1995). Most of the dry channels are found on this side of the volcano (Figs. 2 and 4).

Unconformities and sedimentary deposits record four significant episodes of erosion and sedimentation on the east flank of Newberry. The earliest lava flows on this side are mostly buried by the two ca. 300 ka ash-flow tuffs and by sediments. No obvious sediments lie between the early lava flows and the tuffs. The distribution of these two tuffs, which are exposed almost exclusively on this flank of the volcano, suggests that the lowest rim of a presumed early caldera was on the east side. A single outcrop of the rhyolitic tuff on the south wall of the caldera at ~2200 m elevation indicates that some of the tuff went to the south, but also indicates that an edifice of significant height had grown by ca. 300 ka. Subsequent to these two tuffs and prior to the ca. 80 ka caldera-forming eruption, a handful of mafic lava flows descended the east flank. One late precaldera lava flow followed a narrow path down the east flank where it occupied a prior branch of "Brooks Draw" (Fig. 4), forcing that main channel northward. Sediments, including definitive ground moraine deposits, subsequently covered the upper part of the lava flow. The upper parts of all the precaldera lava flows are buried by sediments.

Before formation of the present caldera at ca. 80 ka, the Newberry edifice was higher. By 83 ± 5 ka, when the rhyolite of Paulina Peak erupted (Donnelly-Nolan et al., 2004) from vent(s) located high over the present caldera, the highest parts of the edifice were probably at least 100 m higher than the present caldera rim. There is little evidence to indicate the existence of a large summit basin on the highland, although a lake likely existed over the eastern part because precaldera palagonite tuff deposits are found today high on the caldera walls north and east of East Lake.

When the present caldera formed at ca. 80 ka, water was apparently available such that the upper (Qbt) portion of the tuff of Paulina Creek Falls is characterized by small cauliflower bombs, typically considered to result from interaction with water. The tuff was deposited on the east side of the volcano, filling former channels where it was preserved and subsequently excavated by postcaldera water flow. Sediments were also deposited on top of the tuff in postcaldera time, along with a few lava flows.

On the northeast side of the volcano, a postcaldera lava flow erupted high on the northeast flank at Lowullo Butte (Fig. 4) and flowed northeastward as a narrow lobe, probably filling a preexisting channel that may represent the upstream end of a channel that is tributary to "Evans Draw" (Fig. 4). The southeast side of this flow has apparently been plucked, whether by ice or water is unknown, and small erratics were deposited on top of the Lowullo Butte cinder cone, the back of which has been scraped off. High on the east side, the basaltic andesite of Cinder Hill erupted near the mouth of a large amphitheater-like basin that heads at the caldera rim. We interpret this basin as a beheaded glacial valley with poorly exposed morainal deposits nearly closing the lower end. The Cinder Hill lavas initially spread out over sediments, then found a channel in the Qbt and flowed east ~7 km as a narrow tongue. The lava flow filled an older channel of Tepee Draw and forced it northward, diverting the valley's drainage into "Orphan Draw" to the north and "Scanlon Draw" to the south (Fig. 4 or 7). Subsequent channeling has exposed the north edge of the Cinder Hill flow. Cinder Hill itself was also glaciated, and although it is speculative, there is evidence that ice may have extended down the channel on the north side of the flow.

High on the southeast side of Newberry, two postglacial cinder cones sent lavas eastward down channels cut into the sediments. One, Red Hill (Fig. 4), appears to sit within an alcove of a poorly defined cirque at ~1950 m elevation. Its lava flows extend as far as 15 km down the east side of the volcano. The other, the Dome, sits even higher at ~2100 m. Its lavas extend some 10 km to the southeast. Neither cone shows any evidence of interaction with ice. These are two of as many as a dozen postglacial mafic lava flows that erupted high on the volcano prior to deposition of Mazama ash when Mount Mazama erupted to form Crater Lake ~7650 years ago (Hallett et al., 1997). Several of these lava flows clearly follow preexisting channels in sedimentary deposits. Some of these postglacial lava flows went south toward Fort Rock Lake. The southernmost tongue of one extended down "China Hat Draw" (Fig. 4) to just south of 43° 35′ N. latitude. Another postglacial lava, the Pot Holes basalt flow, erupted at the base of the east flank and filled the drainage that previously collected water from the east side draws and funneled it into Tepee Draw and then into the Dry Driver canyon. No gravel has been found deposited against the margin of the Pot Holes flow or on top of the flow, indicating that since the lava flow was emplaced, little or no water has flowed down the draws that terminate against the lava flow.

ICE TIMES, ICE EXTENTS, AND SOURCES OF WATER

The timing of glacial periods in Oregon is not well known from direct evidence. Periods of global cooling as defined by marine oxygen isotope stages (MIS) are correlated with glaciations (e.g., Martinson et al., 1987; Bassinot et al., 1994). Times of maximum ice volume based on the MIS and sea surface temperatures have been estimated at ca. 250 ka, ca. 130 ka, and ca. 20 ka (e.g., Whitlock et al., 2000; Herbert et al., 2001). Ice probably melted off by the beginning of Holocene time ca. 11.5 ka (U.S. Geological Survey Geologic Names Committee, 2007), but perhaps as early as 14 ka (e.g., Rosenbaum and Reynolds, 2004). Possible sources of water might include a lake or lakes at various times on the top of the volcano. Also, rapid melting of large volumes of snow or ice could accompany volcanic eruptions, which could generate jokuhlhaups (glacial outburst floods) from under-ice eruptions. Each scenario would permit large volumes of water to be stored high on the volcano in one form or other.

Pierce and Scott (1982) describe factors that they considered important as generating increased discharges of late Pleistocene streams in southeastern Idaho. They concluded that even without increased precipitation, cooler temperatures would result in a snowpack that would build up earlier and melt later, holding more moisture when snowmelt began in late spring or summer at a time when the sun's rays were more nearly vertical and the days were longer. Thus, melting would happen more quickly, producing higher sustained peak discharges. Pierce and Scott (1982) also suggest that runoff would increase if infiltration were impeded by either seasonally or permanently frozen ground. At Newberry, the rocks are extremely permeable, and it is unclear whether water could be stored effectively in the near surface as ice. However, an ice cap could perhaps provide a relatively impermeable surface during melting of an annual overburden of snow, resulting in high discharges and downcutting focused at the margins of the ice. Downcutting would be especially efficient in the relative soft rocks of the three ash-flow tuffs that are widespread on the east side of the volcano.

The lowest recognized erratics on the east flank of the volcano are found at ~1735 m. elevation. However, an outcrop of one of the ca. 300 ka tuffs is littered with faceted boulders suggesting the possibility, although speculative, that ice may have extended as low as 1585 m.

DISCUSSION

Even the accumulation of a large annual snowpack and rapid melting under summer sun would not explain how the large foreign blocks ended up on the tops of cinder cones several kilometers from the caldera rim. Rolling down snowfields is unlikely, given that some of the largest blocks are angular (e.g., Fig. 5B). Ice is the only plausible agent to have carried solid blocks a meter in diameter at least as far as 7 km from the Newberry caldera rim. Figure 7 shows a possible maximum extent of ice at Newberry, although the timing of maximum ice is uncertain. Modification of topography was limited. No classic U-shaped channels were cut, and obvious constructional moraines are absent, suggesting that the ice blanket was relatively thin. However, an abrupt steepening from gentle lower flanks to steeper upper slopes occurs at ~1800–1900 m elevation (MacLeod and Sherrod, 1988). This puzzling change in slope could be in part the result of glacial action steepening the highest terrain while redepositing material downslope. We interpret much of the sedimentary blanket of the east flank to be redistributed morainal deposits and glacial outwash sediments.

The broad distribution of the Qsp sedimentary and pyroclastic deposits on the east side of the volcano and the interbedding of sediments with lava flows indicates multiple episodes of deposition, presumably correlated with wet and/or ice times at Newberry. During times of global cooling as defined by the marine oxygen isotope stages (Bassinot et al., 1994; Martinson et al., 1987), temperatures must have been distinctly cooler, but it is unclear whether there was more precipitation. Pierce and Scott's 1982 suggestion that longer snowpack accumulation times combined with delayed melting provides one plausible explanation for creating significant runoff.

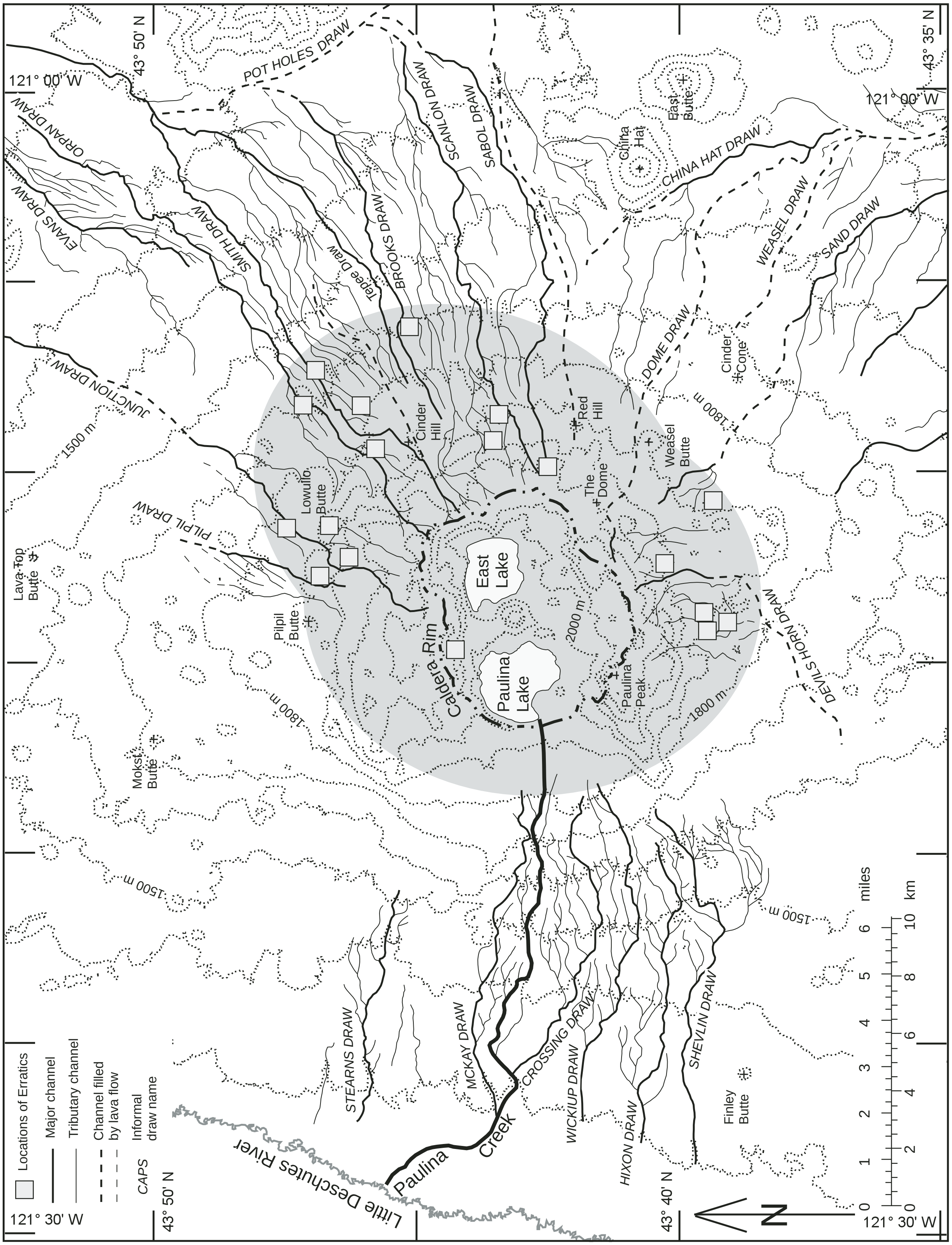

Figure 7. Shaded area indicates possible maximum extent of ice on Newberry Volcano. Contour interval is 100 m.

Under present relatively warm and dry conditions, water does not run off the volcano except down Paulina Creek. Sediments are neither deposited nor eroded because no water runs in the dry channels.

Consequences of the elevated periods of runoff include the cutting of the multiple channels, now dry, and the deposition of large gravel fans at the base of the northeast slope of the volcano. Here the drainages converge at the head of Dry River canyon (Fig. 4), a dry canyon several hundred feet deep. The canyon may have been carved by multiple large floods originating primarily from Newberry as suggested by Donnelly-Nolan et al. (2004).

CONCLUSIONS

Despite the apparent lack of glacial features such as striations and obvious constructional moraines, Newberry Volcano was not spared from glaciation. Diverse meter-sized foreign blocks interpreted as erratics litter cinder cones up to 7 km outboard from the caldera rim. No large U-shaped valleys are present; indicating that modification of topography by ice was limited, probably because of a relatively thin ice cap. However, the multiple dry channels that primarily dissect the western and eastern slopes of the volcano are ample evidence for runoff of water on the now dry slopes of the volcano. Much of the evidence for ice and water on Newberry is on the east side of the volcano, which is heavily mantled with sediments that may represent redistributed morainal material and glacial outwash gravel. Interbedded lava flows and sediments and multiple episodes of channel cutting indicate a complex history of erosion, probably reflecting multiple glaciations. Postglacial lava flows have subsequently filled some of the channels cut into the sediments.

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