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Ice and water on Newberry Volcano, central Oregon

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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,

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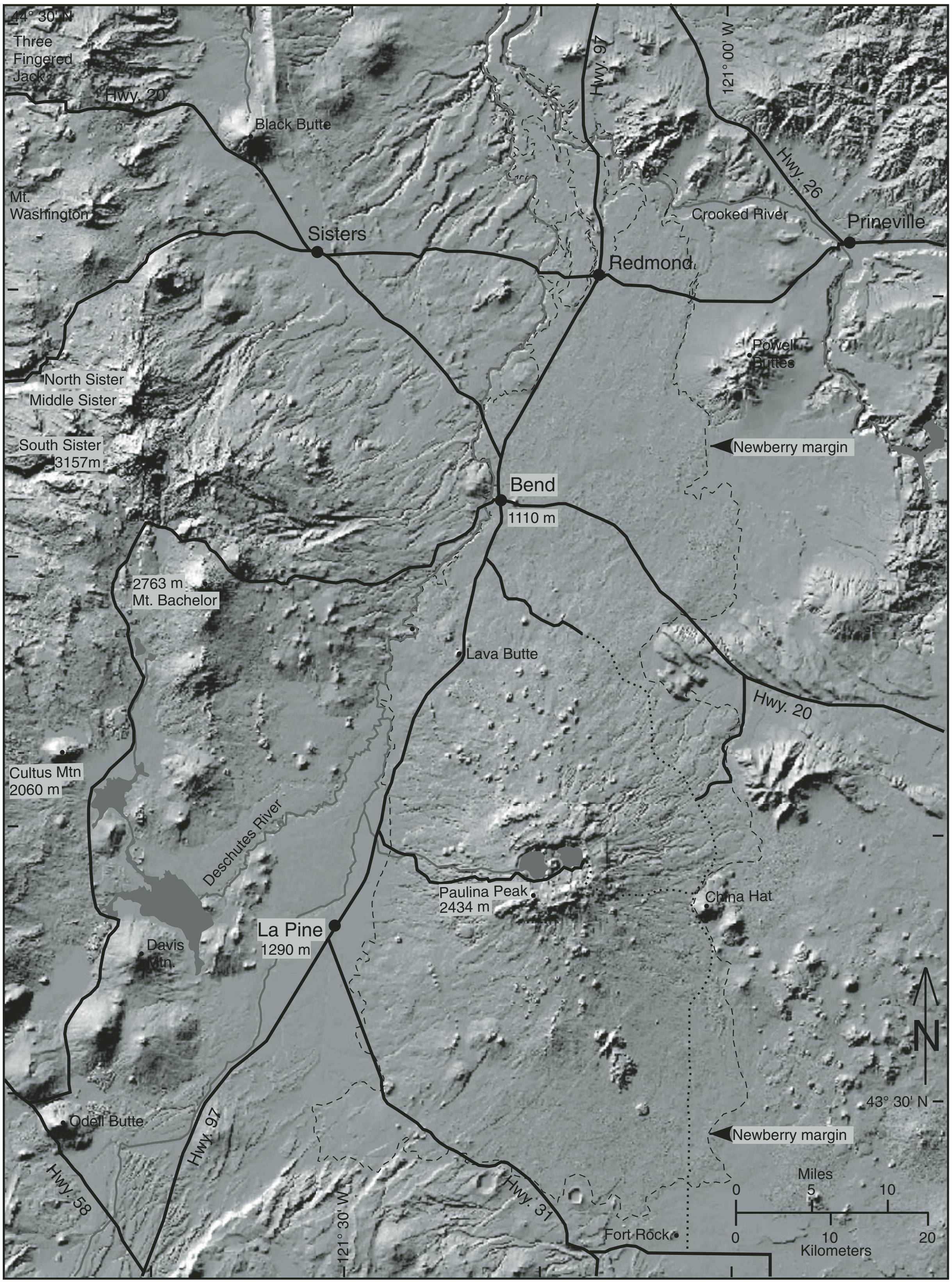

Figure 1. Location map. The approximate extent of lavas from Newberry Volcano is shown by the dashed line. Solid dark lines are paved roads; dotted lines are major unpaved roads. Base is shaded relief derived from 30 m digital elevation model.

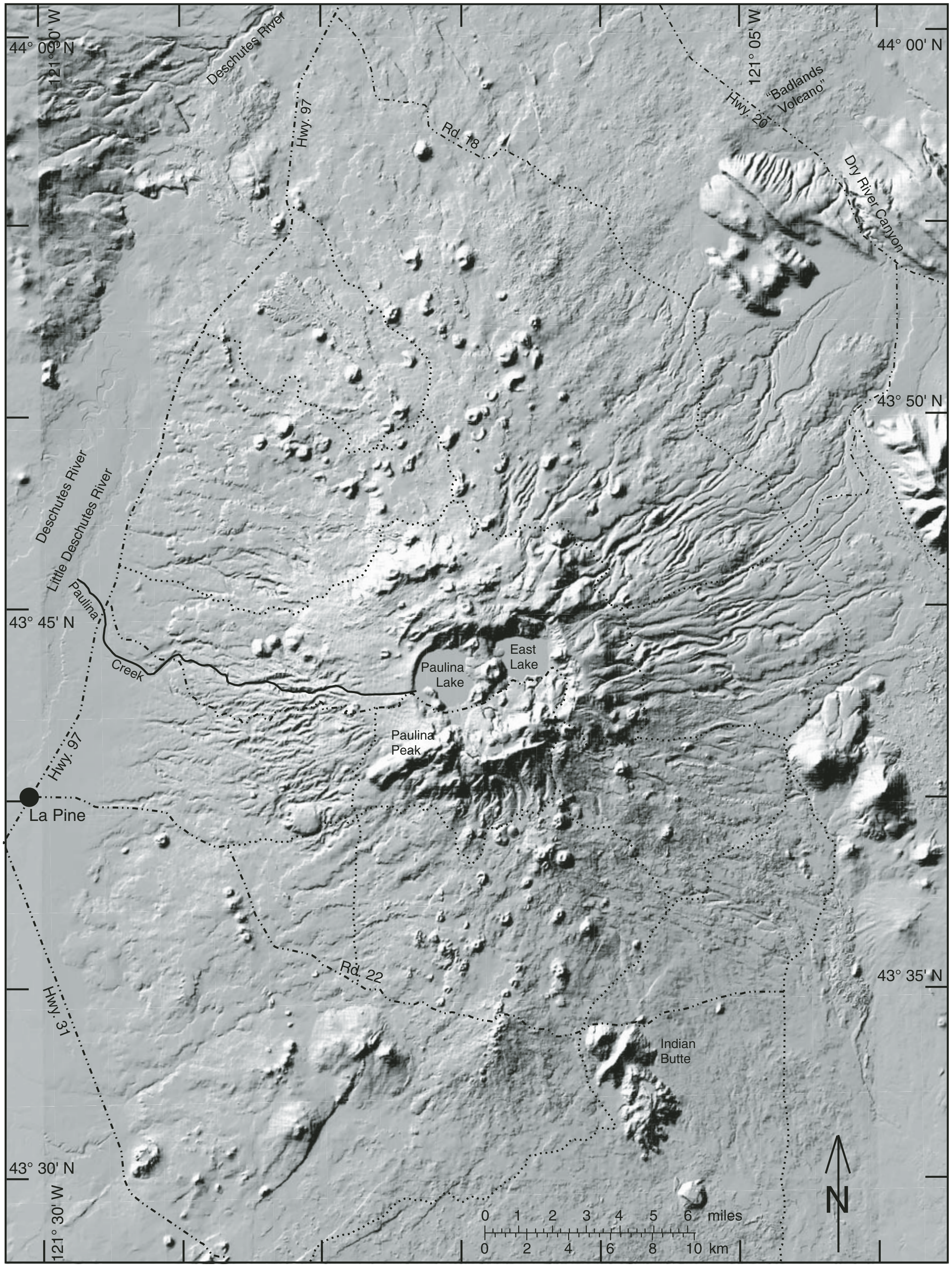

Figure 2. Shaded relief image (from 10 m digital elevation model) of the main edifice of Newberry Volcano shows obvious drainage networks on west, northeast, and east sides. South and north sides are mostly covered by late Pleistocene and postglacial lava flows and vents.

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

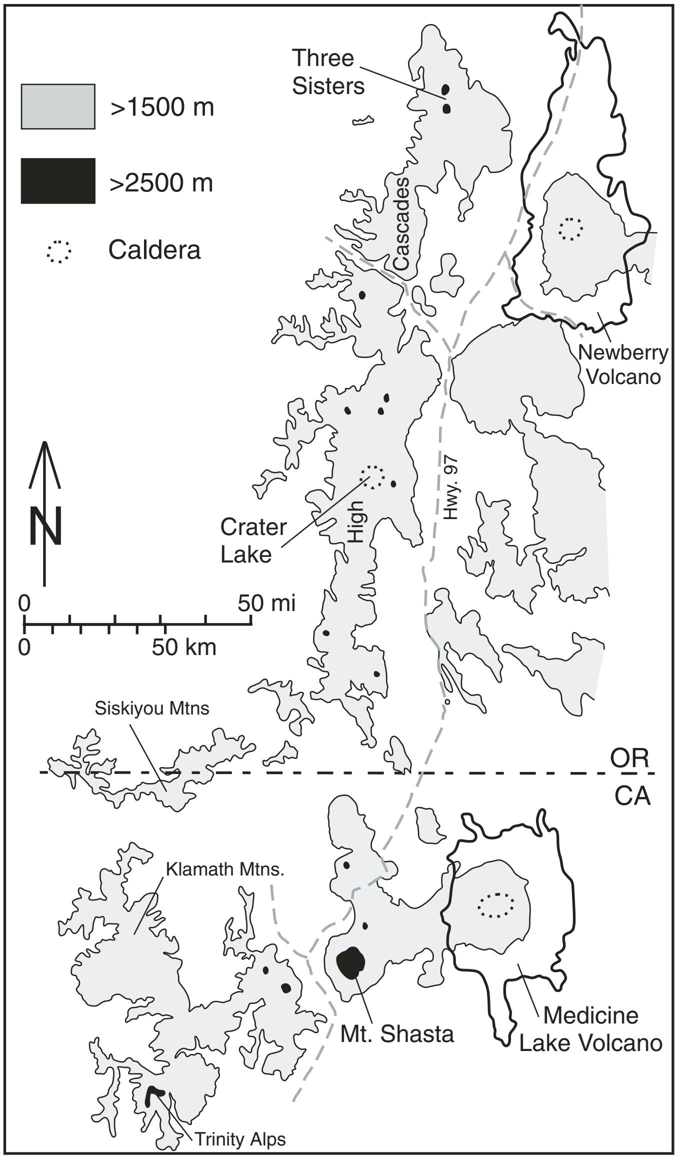

Figure 3. Regional map showing positions of Newberry Volcano and Medicine Lake volcano with respect to each other and relative to high terrain to the west.

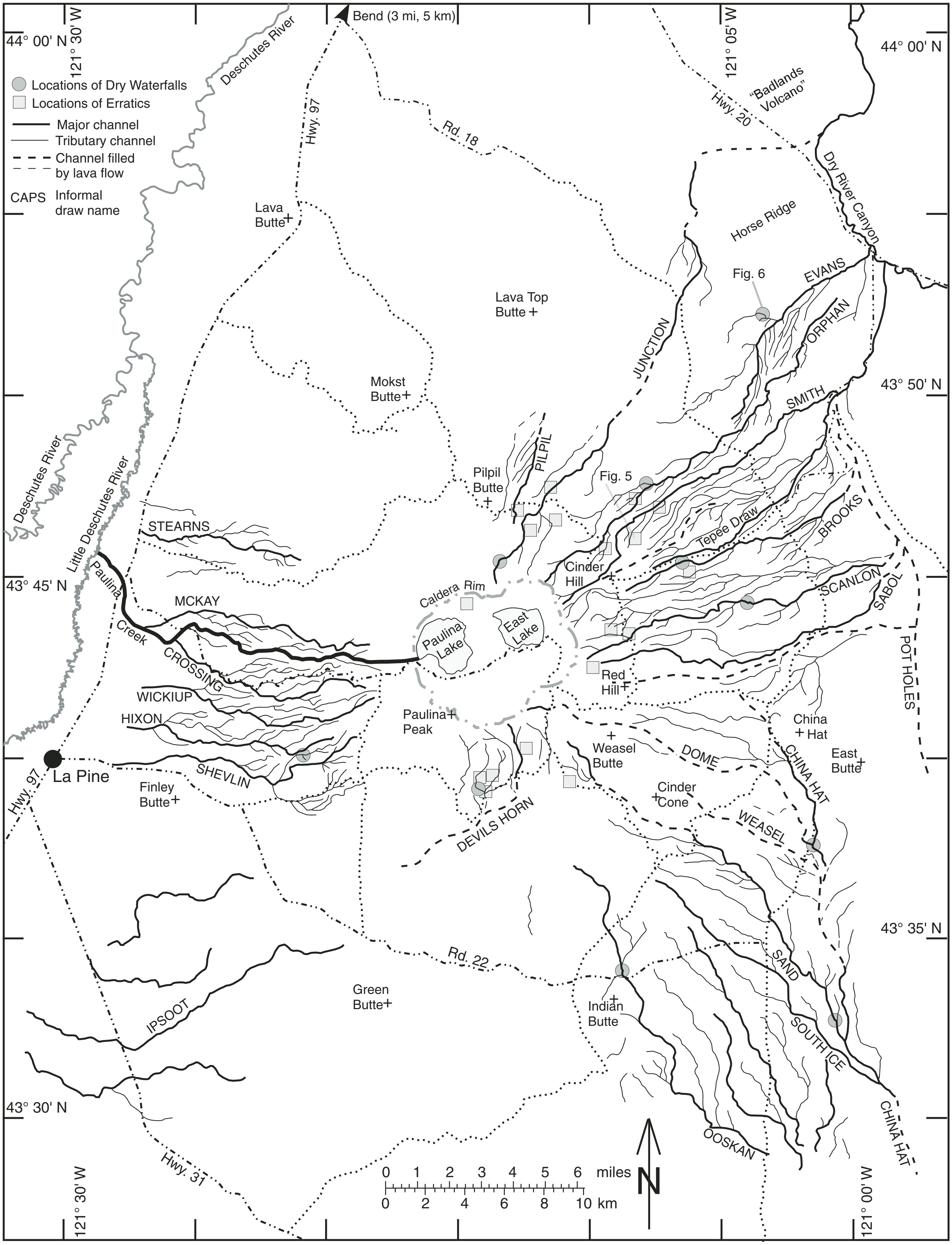

Figure 4. Map shows drainage network, erratics, and dry waterfalls on Newberry Volcano. Informal draw names of major dry channels are shown in capital letters.

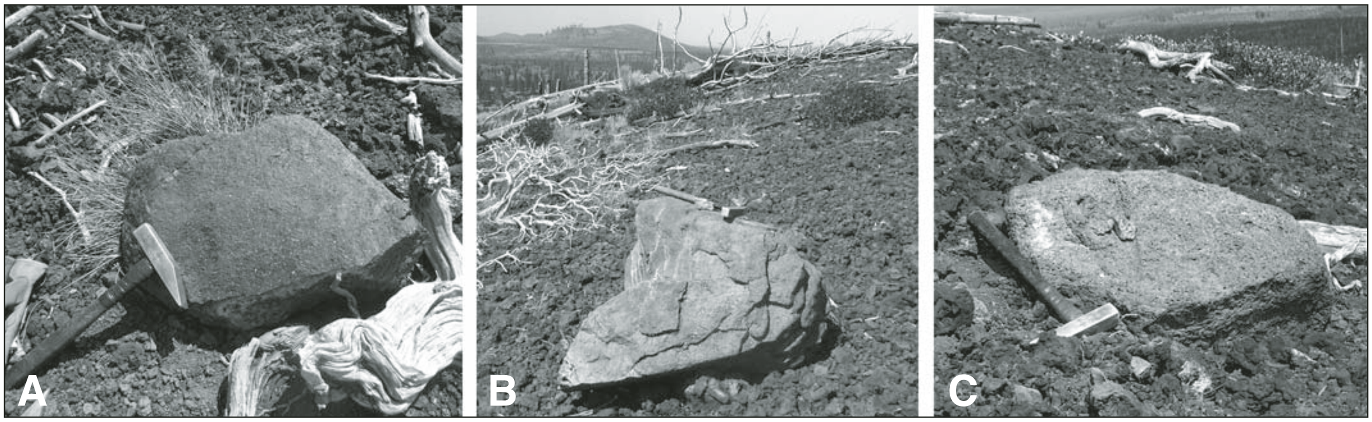

Figure 5. Photographs of erratics of three different rock types found on cinder cone located ~5 km northeast of the caldera rim (see Figure 4 for location). Hammer is 39 cm long.

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.

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,

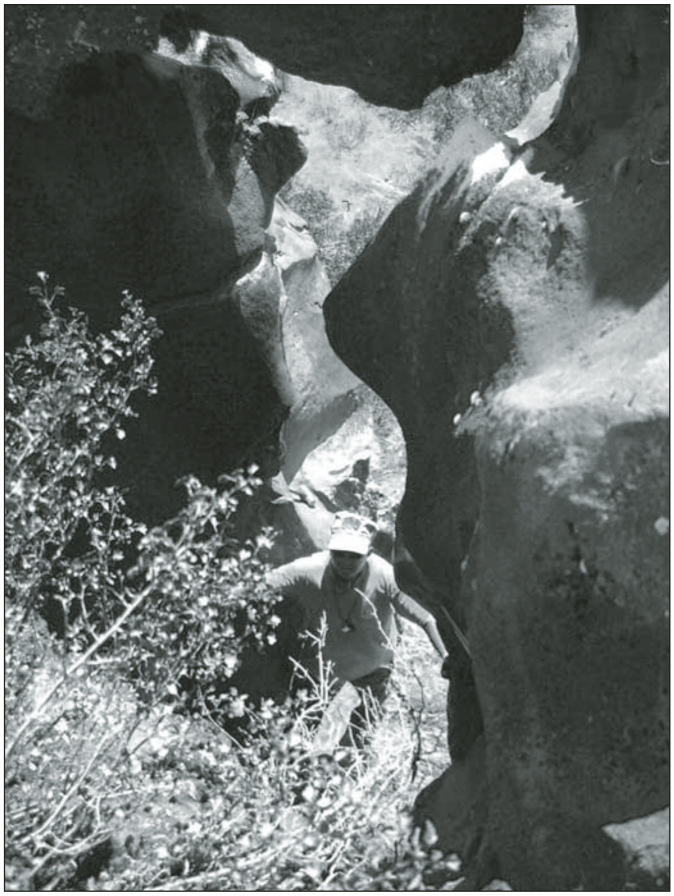

Figure 6. Photograph looking down water-smoothed slot in basalt (see Figure 4 for location). This dry waterfall location has no obvious upstream feeder channel. Channel, slot, and surfaces are dry and show no evidence of recent water flow.

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.

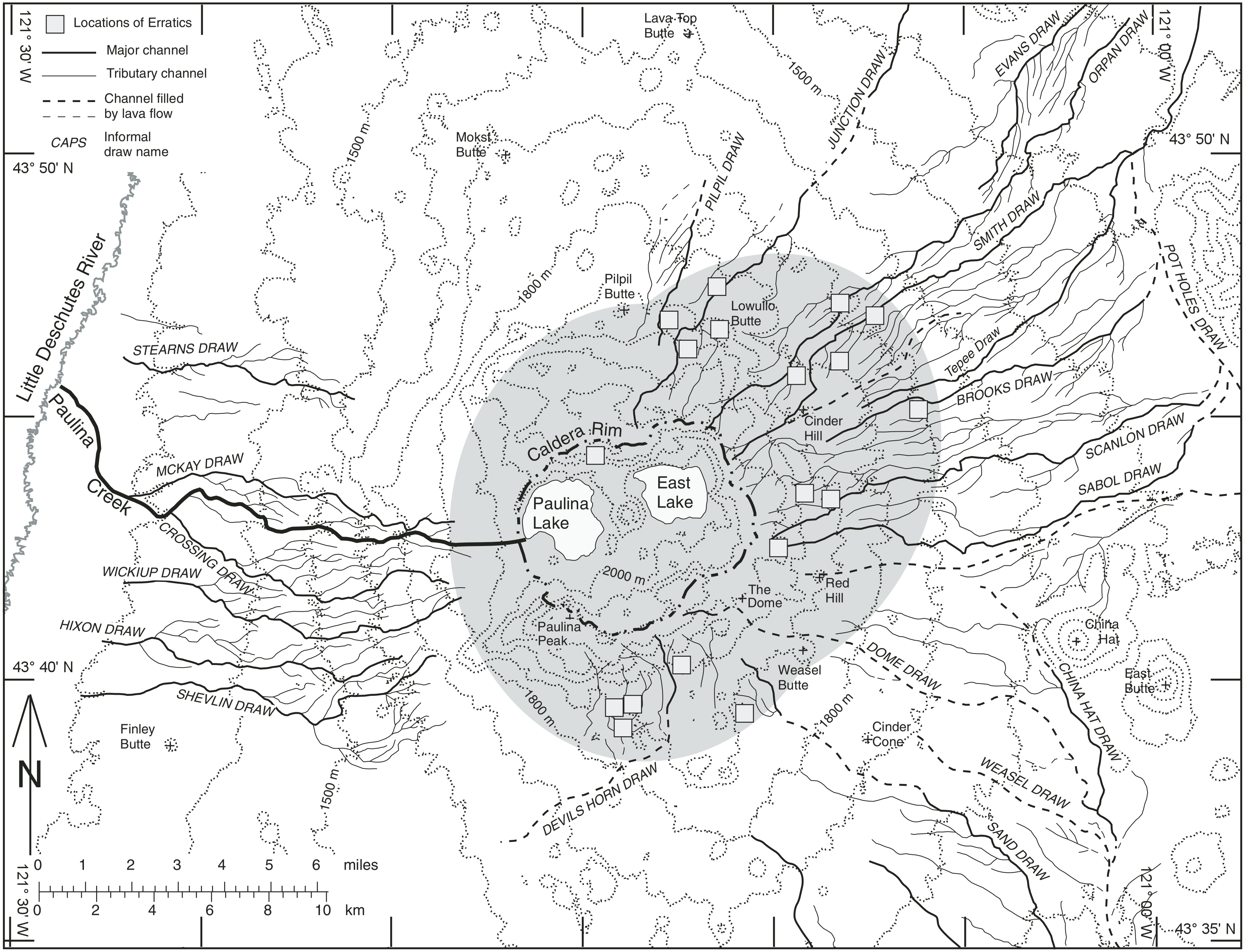

Figure 7. Shaded area indicates possible maximum extent of ice on Newberry Volcano. Contour interval is 100 m.

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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