Ridge-forming, ice-bounded lava flows at Mount Rainier, Washington

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ABSTRACT

Large (0.3–4 km^3) andesite and dacite lava flows at Mount Rainier, Washington, sit atop or are perched along the sides of high ridges separating deep valleys. Early researchers proposed that these ridge-forming lavas flowed into paleovalleys and displaced rivers to their margins; entrenchment of the rivers then left the lavas atop ridges. On the basis of exceptional flow thickness, ice-contact features, and eruption age measurements, we propose that the lavas flowed beside and between valley glaciers that filled the adjacent valleys in the Pleistocene. When the glaciers retreated, the flows were left high on the adjacent ridges. These lavas were never situated at valley floors and do not represent products of reversed topography. Instead, ridge-forming and perched lava flows at Mount Rainier and at many other high stratovolcanoes illustrate the ability of ice to dam, deflect, and confine flowing lava.

INTRODUCTION

Mount Rainier is a 4392-m-high andesite-dacite stratovolcano located 65 km southeast of the city of Tacoma, Washington, in the Cascade volcanic arc. Present-day Mount Rainier began to form about 500000 yr ago (Sisson and Lanphere, 1997) in the middle Pleistocene atop Tertiary granitic and metamorphic basement rocks and the extensively eroded remains of an early Pleistocene volcanic edifice[1] (Crandell, 1963; Fiske et al., 1963). The volcano is covered with 4.4 km^3 of glacial ice (Driedger and Kennard, 1986) that currently reaches elevations as low as 1050 m. The valleys radiating from the volcano were filled with ice during much of the Pleistocene, as is shown by their U-shaped cross sections, glacial scour on bedrock outcrops, and extensive till deposits in the surrounding region (Crandell and Miller, 1974).

About 90% of Mount Rainier consists of lava flows, and the remainder is primarily welded and nonwelded block- and ash-flow tuffs. Lava flow thicknesses increase from about 15–20 m on the steep (~25°) upper slopes of the volcano to as much as 450 m on the lower (~4°–8°) gentler slopes. The flows form steep-sided ridges separated by valleys cut into Tertiary basement rocks. The ridge-forming flows radiate from the volcano to distances as great as 25 km from the summit (Fig. 1). Fiske et al. (1963) noted that these low-elevation lava flows have exceptional thickness and appear to have been emplaced on topographic highs rather than in depressions. They attributed the flow morphology and inverted topography to lava flow emplacement within ancestral river valleys followed by reentrenchment of the rivers along flow margins. Such reentrenchment would require significant time, causing Fiske et al. (1963) to suggest that the ridge-forming lavas were emplaced early in the volcano's history.

An examination of high-latitude stratovolcanoes worldwide reveals that similar thick, steep-sided lava flows are common. We present evidence indicating that ice-lava interaction, rather than a rare event, was the dominant control producing these thick lava flows situated high above valley floors.

DEPOSIT FEATURES

Mount Rainier has produced more than 23 ridge-forming lava flows. The great similarity between flow dimensions, paleoslopes, chemical compositions, and outcrop appearance has allowed us to combine field observations from many exposures to construct the following idealized description. Ridge-forming lava flows contain four components shown in Figure 2: base, interior, margins (side and front), and top.

Flow bases have broad (30–40 cm in diameter) polygonal joints that form columns oriented normal to the basal contact. Flow banding can be conspicuous in the basal zone and parallels the underlying flow base. Basal breccias are generally thinner than 5 cm. A sharp transition to flow interior occurs some 2–5 m above the basal contact.

The flow interior is massive and well crystallized, and has platy joints spaced 1–5 cm apart. Unlike the polygonal joints, the platy joints break around rather than through phenocrysts. The platy joints are predominantly parallel to the flow base (subhorizontal), but are more irregularly oriented near flow margins. Poorly defined megacolumns, 50–80 cm in diameter, are common in the flow interiors but are not easily distinguished except from a distance.

Flow sides are marked by a zone of glassy columns 8–20 cm in diameter. The outermost columns are subhorizontal and perpendicular to the present day near-vertical cliff exposures (Figs. 2 and 3) that face adjacent valleys. The subhorizontal columns extend 2–4 m into the flow where they end abruptly at a 2–4 m wide zone of subvertical columns or, less commonly, at the massive flow interior (Fig. 3). The termination of the subhorizontal columns is commonly marked by an open fracture or gap in the lava flow. Flow fronts have thicker glassy zones (up to 12 m thick) than flow sides and subhorizontal columns span the entire distance to the flow interior (Figs. 2 and 4).

Flow tops are rarely preserved on ridge-forming lavas at Mount Rainier due to glacial erosion and

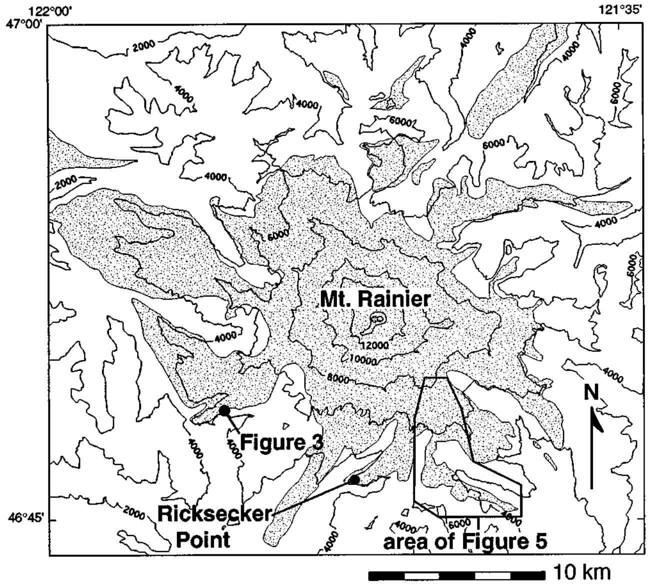

Figure 1. Map modified after Fiske et al. (1963) showing Quaternary volcanic rocks (shaded) of Mount Rainier, Washington; glaciers are omitted; contour interval is 2000 ft (610 m).

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[1] GSA Data Repository item 9840, K-Ar ages of selected Mount Rainier lava flows, is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301. E-mail: editing@geosociety.org.

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Data Repository item 9840 contains additional material related to this article.

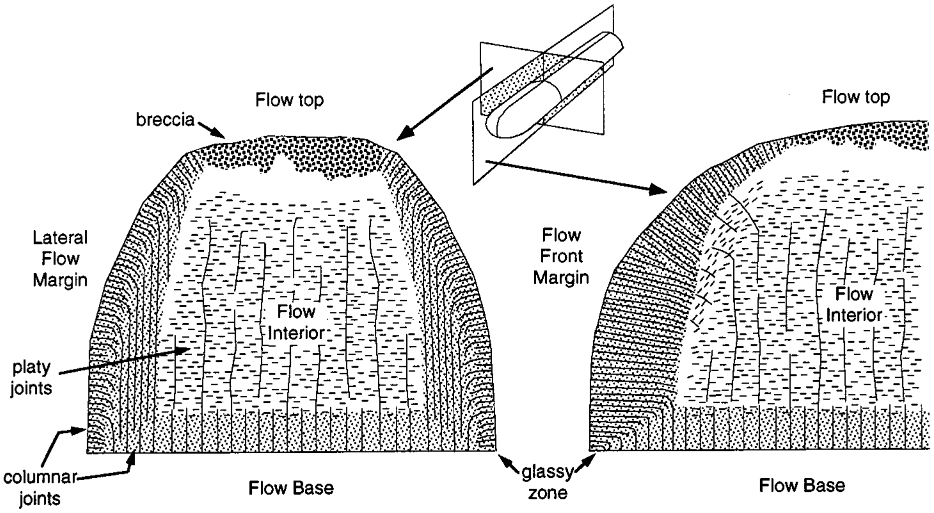

Figure 2. Idealized cross sections of ice-marginal lava flow. Vertical exaggeration ~5×. Note that in the case of perched flows, only one side of flow shows ice-contact features.

weathering. One locality, at Ricksecker Point (Fig. 1), exposes unconsolidated flow breccia and lava spines in a 25 m thick zone, consistent with subaerial exposure during emplacement. The preservation of this flow-top breccia may result from the relative youth of the flow, 40 ± 9 ka (Lanphere and Sisson, 1995).

At Mount Rainier, many ridge-forming flows are little eroded, excepting the loss of flow-top breccias. Most flows retain portions of their thin (4–8 m wide) side margins, demonstrating minimal erosion and confirming that the vertical sides of the flows are products of emplacement and not of subsequent erosion. In most areas one or both flow sides face deep U-shaped valleys, which suggests that those valleys existed and were ice-filled when the lavas were emplaced (Fig. 3).

GENERAL MODEL FOR ICE-MARGINAL VOLCANISM

Features of the lava flows, summarized previously and illustrated in Figure 2, show that the flows were not emplaced in a simple subaerial setting. The thick, glassy flow sides and fronts indicate rapid quenching and probable cooling by meltwater. Steep flow sides with subhorizontal columns suggest extensive near-vertical cooling surfaces of more than 50 m height, which are unlikely within river valleys. The abrupt transition from glassy margin to crystalline flow interior and the lack of basal or marginal breccia suggest that the moving flows consisted of a solid sheath-like shell and a molten interior, similar to basaltic lava tubes.

Fiske et al. (1963) and others (Lescinsky and Fink, 1996) recognized that these features result from interaction between lava and ice. During such interaction, lava is confined by the near-vertical walls of canyons melted into the glacial ice and is quenched by melt water. Confinement of lava by ice was proposed by Mathews (1952) to explain unusually thick lava flow scarps at Garibaldi, British Columbia. He noted that during the 1945 eruption at Okmok volcano, Alaska (Byers et al., 1947), lava flowed against a glacier and was diverted by it, demonstrating that ice can resist thermal erosion by lava and is capable of directing the course of lava flows. This has been substantiated by observations of lava flowing on top of snow and ice during eruptions at a variety

Figure 3. Horizontal columns forming near-vertical side of dacite flow (on left) capping Emerald Ridge (Fig. 1). Formerly ice-filled valley of Tahoma Creek lies on right. Horizontal columns are 2–3 m in length. Base of dacite flow is within 2 m of bottom of photographed exposure, and bed of Tahoma Creek lies another 250 m lower and to right.

Figure 4. Terminus of dacite of Mazama Ridge in lower Stevens Canyon (Fig. 5), showing ice-contact features (highly glassy columns at base, top, and right side of outcrop). Outcrop is ~120 m high.

of volcanoes worldwide, including Hekla, Iceland, and Villarrica and Hudson, Chile (Major and Newhall, 1989; Smithsonian Institution/SEAN, 1989; Naranjo et al., 1993). Growth of a solidifying skin on a lava flow dramatically slows the rate of heat transfer (Allen, 1980), causing ice to melt more slowly than lava flow advance and enabling ice to confine and deflect lava.

The development of a ridge-forming lava flow begins with eruption high on the volcano. Lava that flows over large, steep headwalls fragments and cascades onto the ice at the foot of the headwalls where the cooled debris is carried away or forms lava talus deposits. Lava flowing down a shallower slope or down the side of a ridge is deflected where it contacts thick ice, and the lava then flows along the margin of the glacier, possibly within a steep-walled meltwater channel that precedes the lava.

With increased distance from the volcano, some emergent ridge crests descend beneath the ice of the flanking glaciers. If the eruption is sufficiently voluminous, lava will continue to flow along the crest of the submerged rock ridge where the ice is thinnest and therefore provides the least barrier to continued advancement of the lava. Consistent with this interpretation, ridge-forming lava flow deposits at Mount Rainier attain their maximum thickness at the confluences of major valleys where large ice streams joined and ice depth increased greatly. The increase in ice depth from thin atop the buried ridge crests to thick at the glacial confluences served to dam the lava streams.

Formation of a meltwater trench ahead of the advancing lava also contributes to keeping a lava flow along the margin of the glacier or atop the ice-buried ridge. Surficial glacial runoff is greatest along topographic lows between the central bulges of valley glaciers because these areas are low and because they have few open crevasses that would otherwise drain water to the glacier's bed. The increase in runoff volume and temperature during an eruption can rapidly cut a meltwater trench along the supraglacial topographic low that extends down to bedrock (Clarke, 1982; Björnsson, 1992; Vinogradov and Murav'ev, 1988). When the glaciers retreat, the lava flow deposits are left either capping ridges or perched on the side of ridges.

REVERSED TOPOGRAPHY VERSUS ICE-MARGINAL VOLCANISM: AN EXAMPLE

Fiske et al. (1963) identified the Stevens Canyon–Mazama Ridge locality (Fig. 5) as a prime example of inverted topography resulting from valley-filling lava emplacement and subsequent large scale erosion. They inferred that the ridge-capping lava flow on Mazama Ridge and the two adjacent lava benches (levels I and II on Fig. 5) were emplaced early in the volcano's history. Following erosion and the formation of Stevens Canyon, a much younger lava flow (level III on Fig. 5), was emplaced on the valley floor along the margin of a glacier.

New geologic mapping, chemical analyses, and radiometric dating show that the ridge-capping, bench-forming, and valley floor lava of the Mazama Ridge–Stevens Canyon region are all the same flow. Each of the geomorphic portions of the flow consist of petrographically indistinguishable phenocryst-rich dacite containing abundant inclusions of quenched andesite and rare inclusions of gabbro-norite. Whole-rock major and trace element concentrations form tightly coherent trends, with SiO_2 ranging from 61.3 to 64.1 wt%. Eruption ages were measured on four widely separated samples by high-precision (Hildreth and Lanphere, 1994) whole-rock K-Ar techniques, yielding 87 ± 5 ka, 91 ± 6 ka, 93 ± 7 ka, and 105 ± 9 ka, and giving a weighted mean eruption age of 91.5 ± 3.2 ka (see footnote 1) (1σ uncertainties; Lanphere and Sisson, 1995). The age measurements preclude any appreciable period of erosion between eruption of the upper and lower portions of the dacite and rule out the reversed topography interpretation for this locality.

Development of the different geomorphic portions of the flow is explicable through lava-ice interaction processes. During a period of extensive glaciation, lava erupted high on the volcano and flowed down the crest of Mazama Ridge, bounded on the east and west margins by ice fill-

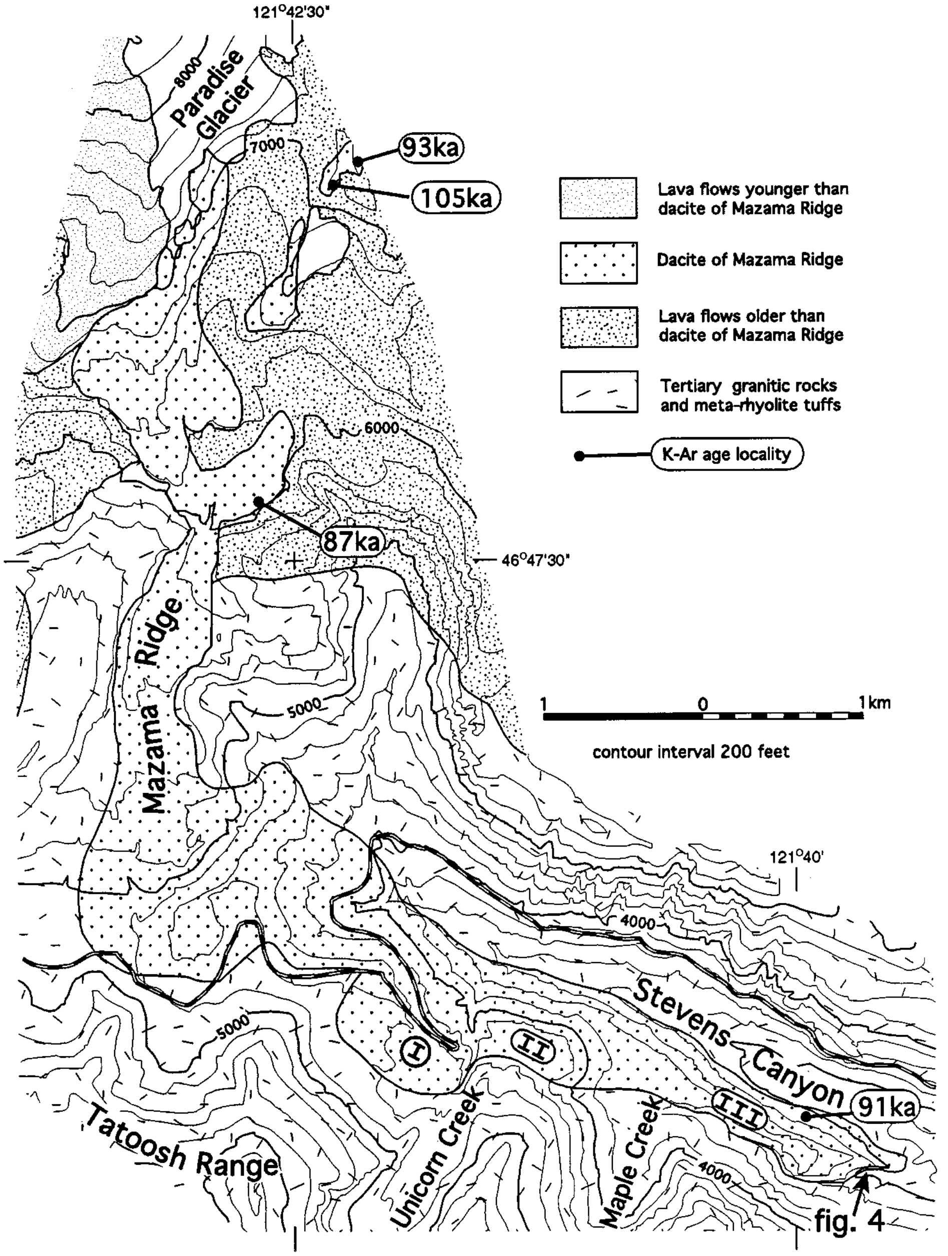

Figure 5. Map of dacite of Mazama Ridge showing K-Ar age localities and lava benches (I, II, III) formed by temporary damming of lava by ice streams.

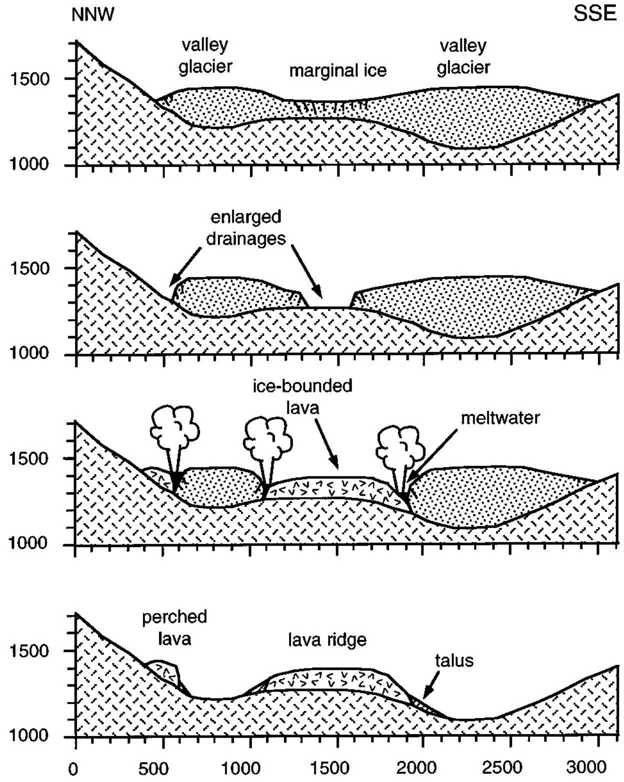

Figure 6. Sequential cross-sectional views (top to bottom) of proposed ice-marginal formation of ridge-forming and perched lava flows. Elevations and horizontal distances in meters.

ing the flanking valleys (Fig. 5). When the lava reached the Tatoosh Range it was deflected to the east and flowed along the southwest margin of the paleo–Paradise Glacier, which occupied Stevens Canyon, until it encountered a tributary glacier occupying the valley of Unicorn Creek. Here, the lava was temporarily dammed and formed the uppermost bench (level I in Fig. 5). Eventually the lava melted through the tributary glacier and continued along the margin of the paleo–Paradise Glacier until it reached a second tributary glacier within the Maple Creek valley. The lava was dammed again and built a second bench 100 m lower than the first (level II in Fig. 5). Once the second tributary glacier was melted through, the lava proceeded down a meltwater channel along the margin of the paleo–Paradise glacier until the eruption ceased (level III in Fig. 5).

IMPLICATIONS

Important aspects of volcanic history are revealed by the lava-ice interaction model. First, since prolonged erosion is not required to create lava ridges, those flows may be as young as the most recent period of extensive glaciation. Age measurements at Mount Rainier show that some ridge-forming lava flows are much younger than previously supposed (Lanphere and Sisson, 1995). Second, estimates of the extent of glacial and stream erosion in the valleys surrounding the volcano are vastly reduced, which also leads to reduced estimates of magmatic productivity. Third, ice-marginal flows indicate periods of extensive glaciation and are measures of previous ice thickness. Mapping and dating ice-marginal flows can directly quantify regional climatic and glacial histories.

CONCLUSIONS

The thick, ridge-forming and perched lava flows at Mount Rainier and many other high-latitude stratovolcanoes have near-vertical glassy margins with well-developed subhorizontal columns that face deep U-shaped valleys. These features result from lava having banked against thick valley ice during lava flow emplacement. The near-vertical sides of the lava flows result from the lava confinement within meltwater trenches incised into ice. The elevated locations of the lavas result from their having flowed along the margins of thick valley glaciers and atop ice-buried ridges between major ice streams (Fig. 6). Confluences of large ice streams terminated lava advancement, leading to lava deposits nearly 500 m thick. Retreat of the glaciers at the end of the Pleistocene has left the lava flows high on the sides of ridges and along ridge crests. The lavas were never situated at valley floors and did not attain their elevated positions by entrenchment of adjacent valleys. Some of the ridge-forming flows at Mount Rainier are much younger than previously thought, and dating of ice-marginal lavas at stratovolcanoes can be useful in reconstructing regional glacial histories.

ACKNOWLEDGMENTS

This research was supported by National Science Foundation grant EAR 9614330 and National Aeronautics and Space Administration grant NAGW 529 to J. H. Fink and by the U.S. Geological Survey's Volcano Hazards Program. We thank Marvin A. Lanphere and James Y. Saburomaru for providing essential K-Ar age determinations, and Jonathan H. Fink, James G. Moore, Judith E. Fierstein, Setsuya Nakada, and Peter T. Bobrowsky for valuable comments and reviews.

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Manuscript received July 15, 1997
Revised manuscript received January 7, 1998
Manuscript accepted January 19, 1998