

Characterization and evolution of fractures in low-volume pahoehoe lava flows, eastern Snake River Plain, Idaho

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ABSTRACT

We characterize fracture evolution in pahoehoe lava flows of the eastern Snake River Plain, Idaho, and highlight significant differences to flood-basalt sheet flows and implications for hydrologic models. There are four distinct fracture types in eastern Snake River Plain flows: (1) column-bounding; (2) column-normal; (3) entablature; and (4) inflation fractures. Types 1–3 are driven by thermal stress, whereas type 4 is induced by lava pressure from within the flow. Thermal stress distribution in a flow is dictated by its aspect ratio (width/height), which controls the shape of isotherms. Isotherms control column-bounding fracture orientations, resulting in increasingly radial fracture patterns as the aspect ratio approaches unity. Column-normal fractures form in response to thermal stress and fracture-induced stress within basalt columns. Overlap in the timing of column-bounding and column-normal fracture growth has resulted in complex fracture relationships. Column-normal fracture growth is strongly influenced by vesicular layers, which act as mechanical heterogeneities, creating preferential pathways for fracture growth as well as causing jogs or terminations along column-bounding fractures. Eastern Snake River Plain entablatures, which preserve the shape of the central lava core during the final stages of cooling, have distinctly different origins and fracture styles compared to sheet flows. Entablatures formed by penetration of the edges of pressurized lava cores by inflation fractures, causing rapid convective cooling. In addition, inflation fractures significantly perturb isotherm shapes in lava flows, af-

fecting flow-scale fracture patterns and densities. The overall effect of all these processes is a complex pattern of fracturing that attests to a strong impact by each fracture type on the growth behavior of all other fracture types.

Keywords: basalt, fracture, lava flow, pahoehoe, inflation entablature.

INTRODUCTION

Cooling fractures in igneous rocks have been a focus of geologic research since the late 1600s, producing a wealth of literature that both characterizes and attempts to explain their origin (Aydin and DeGraff, 1988; Budkewitsch and Robin, 1994; Dance et al., 2001; DeGraff and Aydin, 1987, 1993; DeGraff et al., 1989; Geikie, 1893; Grossenbacher and McDuffie, 1995; James, 1920; Lachenbruch, 1961, 1962, 1966; Lister, 1974; Long and Wood, 1986; Lore, 1997; Lore et al., 2000, 2001; Mallet, 1875; Peck and Minakami, 1968; Pollard and Aydin, 1988; Preston, 1930; Reiter et al., 1987; Ryan and Sammis, 1978, 1981; Saemundsson, 1970; Spry, 1961; Tomkeieff, 1940).

Most of the existing knowledge on cooling fractures stems from the analysis of flood-basalt flows, such as those of the Columbia River Basalt Group of the northwest United States. Flood-basalt flows are typically much wider and longer than they are thick and are thus referred to as sheet flows. However, sheet-flow fracture characteristics, and the fracture-evolution models developed to explain them, are inconsistent with the fracture patterns we observe in pahoehoe basalt flows of the eastern Snake River Plain in southeast Idaho. Eastern Snake River Plain flows are relatively low-volume (0.005–7 km³) flows that erupted from small shield volcanoes (Hughes and Thackray, 1999; Kuntz, 1992;

Kuntz et al., 1986, 1988, 1994) and thus differ from the high-volume sheet flows that typify the Columbia River Basalt Group. Although some of the fracture types are similar, the overall fracture geometries are more complex in the Snake River Plain flows, which contain abundant inflation fractures and have entablature geometries and formation mechanisms distinctly different from those of the Columbia River Basalt Group. The Snake River Plain basalts host one of the largest aquifers in the United States (Johannesen, 2001; Welhan et al., 2002) and are the medium for potential vadose-zone contaminant migration from the Idaho National Engineering and Environmental Laboratory (INEEL) (Faybishenko et al., 2000). Fracture characterization and fracture prediction models for the Snake River Plain lava flows thus should not be based on flood-basalt models. We therefore have developed a fracture evolution model that is not only applicable to eastern Snake River Plain-style pahoehoe flows, but may serve as a useful analog for fracture development in similar low-volume flows elsewhere, such as in Hawaii and Iceland, as well as for flows of other compositions but having comparable aspect ratios.

In this paper, we present detailed field observations of fractures in cooled basaltic lava flows of the eastern Snake River Plain (Fig. 1) and develop a theory for the origin of the fracture types. We identify four fracture types in a typical cooled basalt flow: (1) column-bounding fractures; (2) column-normal fractures; (3) entablature fractures; and (4) inflation fractures. Column-bounding fractures occur in basalt flows worldwide, defining the columns ordinarily associated with flood basalts. Column-normal fractures form perpendicular to column-bounding fractures and segment columns along their lengths. Entablatures are approximately elliptical, highly fractured zones located slightly below

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Figure 1. The Snake River Plain, shown in gray, is divided into three geographic regions (western, central, and eastern). Lava-flow field sites mapped in this study are on the eastern Snake River Plain and are indicated by open circles.

the flow center. Thermal stress produced during cooling causes column-bounding, column-normal, and entablature fractures to form and propagate. In contrast, inflation fractures, which have up to meter-scale apertures and can be hundreds of meters in length, form as pressure within a lava flow induces circumferential stress and resultant failure of the brittle crust.

We demonstrate that the distribution of these fractures is predominantly controlled by the aspect ratio (width/height) of the lava flow and the effects of thermal perturbations during the cooling history. We focus on describing the fracture types and their distribution, fracture interactions, the effect of vesicular layers on fracture distribution, and the influence of inflation fractures on the cooling history of lava flows.

FRACTURE GROWTH IN COOLING LAVA

Much of the physics of fracture growth in cooling lava flows has already been determined through analyses of fracture-surface morphology (DeGraff and Aydin, 1987; DeGraff et al., 1989; Ryan and Sammis, 1978), thermal stress-related fracture propagation (Budkewitsch and Robin, 1994; DeGraff and Aydin, 1993; Grossenbacher and McDuffie, 1995; Lister, 1974; Long and

Wood, 1986; Lore et al., 2000; Reiter et al., 1987; Ryan and Sammis, 1981), petrographic textures (DeGraff et al., 1989; Long and Wood, 1986; Saemundsson, 1970), and flow-emplacement processes (Chitwood, 1994; Hon et al., 1994).

The surface of a newly erupted lava flow exposed to the atmosphere cools by convection and radiation. The surface of the flow in contact with the Earth undergoes conductive cooling. The rate of convective heat loss to the atmosphere is greater than the rate of conductive heat loss to the underlying substrate. Hence, where a basalt flow cools by convective cooling, the flow solidifies more quickly. Actual rates of cooling vary depending on flow volume and thermal properties, but are typically <1 °C/h for conductive cooling and as much as 10 °C/h or more for convective cooling (Long and Wood, 1986). Cooling produces thermal stress that causes contraction of the basalt and resultant fracturing. Fractures are initiated at the outer boundary of a newly emplaced lava flow minutes after the brittle crust begins to form (Peck and Minakami, 1968). As fractures propagate inward away from the flow boundaries, they facilitate the transfer of heat from the flow interior to the surrounding environment. Those fractures that are initiated at the upper surface of the flow serve as convection pathways from the flow interior, further increasing the contrast in cooling rates between the flow top and flow bottom.

Cooling fronts or solidification fronts represent the transition from elastic basalt to viscoelastic basalt and the boundary between fractured and unfractured basalt. Although flows are often idealized as having an upper and a lower cooling front, in actuality there is only one cooling front that migrates inward from the flow periphery. References to upper and lower cooling fronts were developed for flood-basalt sheet flows having widths much greater than their thickness, producing approximately planar, parallel flow boundaries (Long and Wood, 1986; Reiter et al., 1987). In eastern Snake River Plain flows and analogous pahoehoe basalt flows having much lower aspect ratios than flood-basalt sheet flows, the shape of the flow periphery has a greater impact on the shape of the cooling front so that it can no longer be idealized as consisting of parallel upper and lower cooling surfaces.

Fracturing of a basalt flow occurs behind the advancing cooling front. Cooling fractures typically propagate parallel to the maximum thermal gradient, perpendicular to both the isotherms and the cooling front. Stress is produced by thermal gradients and induces con-

tractional strain that varies as a function of position within a lava flow. Fracture growth begins when thermal stress is equal to the tensile strength of the basalt and results in relief of thermal stress perpendicular to the fracture plane (Lachenbruch, 1961, 1962, 1966). Continued propagation occurs whenever the stress concentration at the fracture tip is greater than or equal to the tensile strength of the basalt. Fracture growth ceases when insufficient thermal stress exists for propagation or when the strain rate is too low to overcome viscous relaxation of stress when the fracture tip is close to the cooling-front boundary.

Cooled basalt flows typically consist of two generic parts, termed "colonnade" and "entablature" (Tomkeieff, 1940). The term "colonnade" is assigned to a set of well-developed columns formed by fractures having the same growth direction. Entablatures are typically more intensely fractured zones within a flow. Sheet flows of the Columbia River Basalt Group commonly exhibit multiple tiers of colonnades and entablatures (Long and Wood, 1986). Eastern Snake River Plain basalt flows have an upper and a lower colonnade distinguished by opposite growth directions, as indicated by fracture-surface plumose structures. A single entablature separates the two colonnades and characteristically occurs below the center of the flow because the convectively cooled upper zone of cooling migrates faster than the conductively cooled lower zone (DeGraff et al., 1989; James, 1920; Long and Wood, 1986; Reiter et al., 1987).

Stress produced during cooling of a basalt flow is released through two types of strain: elastic strain, expressed as fracture growth, and viscous strain, expressed as viscous flow ahead of fracture tips. The percentage of total strain that is viscous strain increases with decreasing cooling rates (Lore et al., 2000). Viscous blunting of fracture tips occurs when ductile flow near a highly stressed joint tip deforms the tip from an atomically sharp (i.e., crack-opening at the tip is at the scale of individual atoms) form to a smooth curved form (DeGraff and Aydin, 1993). Fracture-tip blunting increases the radius of curvature and thus decreases the stress concentration at the fracture tip (DeGraff and Aydin, 1993). In response, a greater driving stress is necessary for the stress-intensity factor at the blunt tip to equal the critical stress-intensity factor for fracture growth and allow a new growth increment to begin (DeGraff and Aydin, 1993).

Column-bounding fracture growth is thus a cyclical process involving repeated hesitation and incremental growth. Resultant fracture planes are composites of multiple growth in-

crements (DeGraff and Aydin, 1987), or striations (Ryan and Sammis, 1978), each representing a discrete, finite advance of the fracture. As the cooling front or solidification front continues to advance ahead of a fracture tip, a new elastic layer is produced. Thermal stress accumulates in this layer, eventually inducing a new fracture-growth increment.

At high cooling rates, fracture repropagation proceeds relatively quickly after hesitation occurs, and the thickness of the elastic layer ahead of the fracture tips is small. This effect results in small growth increments and fracture spacings (DeGraff and Aydin, 1993; Spry, 1961). At slow cooling rates, a greater amount of stress is relieved through viscous strain. Fracture tips are thus more likely to be blunted, and thicker elastic layers develop ahead of the crack tip before repropagation occurs. Growth-increment dimensions therefore increase as the rate of cooling decreases (DeGraff and Aydin, 1993; Grossenbacher and McDuffie, 1995; Reiter et al., 1987; Ryan and Sammis, 1978).

FIELD LOCATIONS

Several studies have examined fracture distributions in Snake River Plain basalt flows (Beard, 1959; DeGraff and Aydin, 1987, 1993; DeGraff et al., 1989; Lore, 1997; Lore et al., 2000, 2001). These studies were predominantly concerned with characterizing the development of column-bounding fractures and determining controls on the spacing of these fractures. The current work augments these previous studies by developing a rigorous fracture-evolution model to describe and explain all of the fracture types present in the low-volume basalt flows of the eastern Snake River Plain.

The Snake River Plain (Fig. 1) is a volcanic province associated with the passing of the North American plate over the Yellowstone hot spot. The eastern Snake River Plain is a basaltic plains terrain (Greeley, 1982) composed of late Tertiary to Quaternary olivine tholeiite basalt flows interlayered with fluvial, lacustrine, and eolian sedimentary deposits. The basalt flows exhibit inflated pahoehoe flow morphologies such as pressure plateaus, plateau pits, tumuli, and inflation fractures (Anderson et al., 1999; Chitwood, 1994; Hon et al., 1994; Johannesen, 2001). Inflation involves a volumetric increase of a flow resulting in the uplift of the brittle crust encasing the molten core and occurs when lava pressure within the flow overcomes the combined weight and strength of the overlying brittle shell and viscoelastic transition zone.

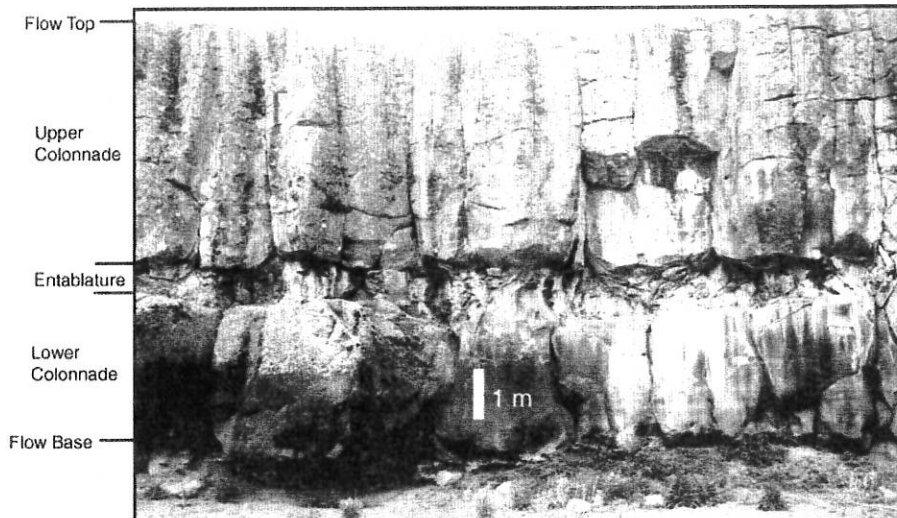


Figure 2. Internal morphology of a typical pahoehoe basalt flow. An upper colonnade and a lower colonnade are separated by a more intensely fractured entablature. Upper colonnades contain column-bounding and column-normal fractures, whereas lower colonnades are almost exclusively composed of column-bounding fractures. Entablatures were not observed in all of the eastern Snake River Plain basalt flows. The flow shown here is the central part of flow A in Figure 3.

Our field observations of inflated pahoehoe flows are predominantly from Box Canyon, along the Big Lost River, south of Arco, Idaho (Fig. 1). Box Canyon is an incised river channel offering exceptional cross-sectional exposures of fractured basalts estimated to have erupted between 730 and 400 ka (Kuntz et al., 1994). Fractured flows were also mapped at the relatively younger Hells Half Acre, Cerro Grande, and Craters of the Moon National Monument lava fields (Fig. 1).

FRACTURE TYPES IN EASTERN SNAKE RIVER PLAIN FLOWS

Column-Bounding Fractures

Colonnade-forming, column-bounding fractures exhibit characteristic cyclic growth increments and are the most prevalent fracture type in eastern Snake River Plain basalt flows. In Box Canyon, basalt flows contain one upper colonnade and one lower colonnade, typically separated by a single central entablature (Fig. 2). In flows lacking an entablature, the upper and lower colonnades can be distinguished by using fracture-growth direction indicators such as growth increments and plumose structures (DeGraff and Aydin, 1987). Of the three cooling-fracture types in the Snake River Plain basalt flows, column-bounding fractures appear to have the greatest apertures.

Column-bounding fractures form a three-dimensional network of interconnected cooling fractures, producing polygonal basalt columns in plan view. In cross-section view, column-bounding fractures typically show an increasing fracture spacing with increasing distance from the flow periphery, although this phenomenon is less pronounced as flow aspect ratio decreases (Fig. 3). Column-bounding fracture lengths are variable; some fractures extend from the flow periphery to the central entablature, but others terminate against cross fractures, vesicular layers, or at an identifiable fracture tip (Fig. 3). Accordingly, despite the presence of a single cooling front during lava cooling, column-bounding fractures generate a nonuniform fracture front consisting of leading (longer) and trailing (shorter) fractures (Fig. 4 inset).

Column-bounding fracture patterns become increasingly radial toward the flow center with decreasing flow aspect ratio (Fig. 3). Large-aspect-ratio flows (Fig. 3A) more closely approximate a conceptual planar body with parallel upper and lower surfaces. Away from lateral flow peripheries, column-bounding fractures in large-aspect-ratio flows appear vertical and are perpendicular to flow boundaries (Figs. 2 and 3A). Near lateral peripheries of flows, column-bounding fractures rotate from a vertical orientation to remain perpendicular to the curved flow boundary and are commonly horizontal (Figs. 3B–3D). The ori-

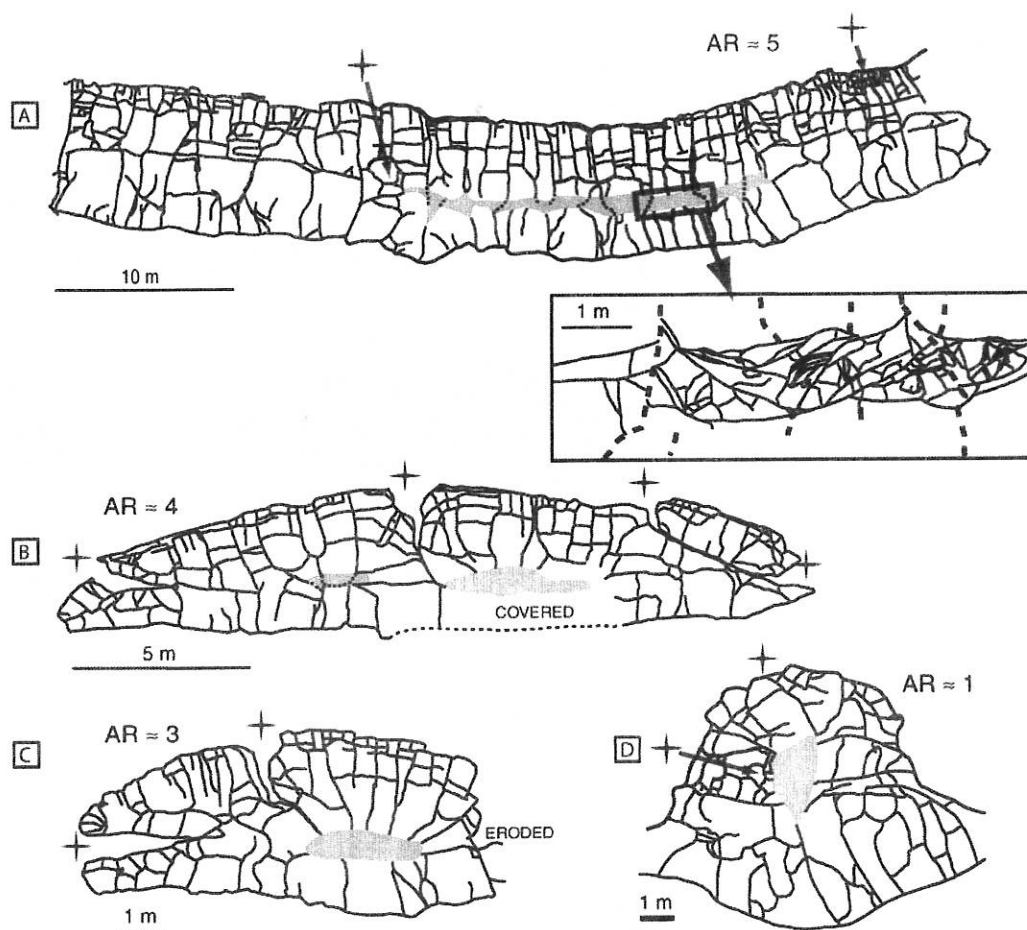


Figure 3. Cross-section fracture maps of four Box Canyon flows having different aspect ratios ($AR = \text{width/height}$). Approximate aspect ratios for flows A–D are respectively 5, 4, 3, and 1. AR affects entablature shape (gray regions), inflation-fracture locations (crosses), and the flow-scale pattern of fracturing. As AR tends toward 1 (A to D), the cooling-fracture distribution becomes more radial about the central entablature. A fracture map of part of the entablature of flow A is shown in the inset box; column-bounding fractures crossing the entablature are shown as dashed lines. Both lateral edges of flow A and the right edge of flow C were obscured. The curvature of the flow A fracture map reflects a curvature in the canyon wall. Inflation fractures indicated by crosses and arrows have fracture walls in the plane of the cross section.

entation of column-bounding fractures can change along the planar middle section of the flow if a thermal perturbation, such as that caused by an inflation fracture (e.g., top center of Fig. 3B), occurred during cooling.

Column-Normal Fractures

Column-normal fractures form perpendicular to column-bounding fractures. Column-normal fractures terminate against leading column-bounding fractures; however, trailing column-bounding fractures typically terminate against column-normal fractures, resulting in a complex fracture sequence (Fig. 4). There are no growth increments or plumose structures apparent on exposed column-normal

fracture surfaces; therefore, we were unable to determine which column-bounding fracture a particular column-normal fracture was initiated at, or even if it was initiated at a column-bounding fracture at all.

The most significant characteristic of column-normal fractures is that they typically propagate along vesicular layers. As a result, the column-normal fractures in the eastern Snake River Plain flows tend to be very planar, unlike the sheet flows of the Columbia River Basalt Group, which commonly show concave column-normal fractures; hence their original description as “ball and socket joints” (Preston, 1930). Column-normal fracture density in eastern Snake River Plain flows is therefore closely related to vesicular-layer

density, which is greatest near flow tops. Fracture propagation utilizes stress concentrations at the corners of vesicles within the vesicular layers (Fig. 5), as well as planes of weakness produced by crystal boundaries and cleavage planes. There are four distinct styles of vesicular layers (Schaefer, 2002) that differ in vesicle shape and layer geometry. Each style focuses column-normal fracture propagation in a specific manner, as well as influencing the propagation of column-bounding fractures by changing their direction of growth, terminating growth, or initiating growth.

Adjacent to inflation fractures, vesicular layers are commonly at an oblique angle to column-bounding fractures, causing column-normal fractures to deviate away from the ve-

sicular layers in order to remain perpendicular to the column axis. Column-normal fractures are thus typically horizontal, except near lateral peripheries of flows (Fig. 3) or in flows with low aspect ratios, where column-normal fractures can become vertical.

Entablature Fractures

Flow aspect ratio determines cooling-front migration and hence the shape of the internal lava core, which in turn influences entablature dimensions (Fig. 3). Larger-aspect-ratio flows have larger entablatures. A detailed fracture map of a part of the entablature in flow A is shown in Figure 3. Entablature-fracture surfaces of the eastern Snake River Plain display continuous plumose structures indicating single-event, rather than cyclic, fracture growth. Unlike column-bounding and column-normal fractures, entablature fractures are regularly arcuate in three dimensions. Some, but not all, column-bounding fractures pass through the entablature (dashed lines in Fig. 3), displaying growth increments up to 1 m in size (but typically less) and directly connecting fractures of the upper colonnade to fractures of the lower colonnade. In some entablatures, the column-bounding fractures appear to have spanned the thickness of the entablature in one increment of growth.

Crosscutting relationships indicate that the first cooling fractures to propagate through an entablature in a large-aspect-ratio flow are column-bounding fractures (Fig. 6). Plumose structures indicate that subsequent entablature fractures were initiated at these entablature-penetrating column-bounding fractures and propagated laterally into the surrounding basalt. Each subsequent generation of entablature fractures began propagating at the previous generation and further subdivided the entablature. The early generations of entablature fractures thus typically have greater lengths than later generations of fractures, and the orientation of each generation is controlled by the orientation of the preceding generation of entablature fractures.

In most flows with entablatures, particularly large-aspect-ratio flows, some column-bounding fractures were initiated at the lower entablature boundary and propagated downward into the underlying lower colonnade (Fig. 3A). Some downward-propagating, column-bounding fractures intersect upward-growing fractures of the lower colonnade; others terminate at an identifiable tip. Column-bounding fractures also grew upward from the upper entablature boundary, ultimately intersecting column-normal fractures.

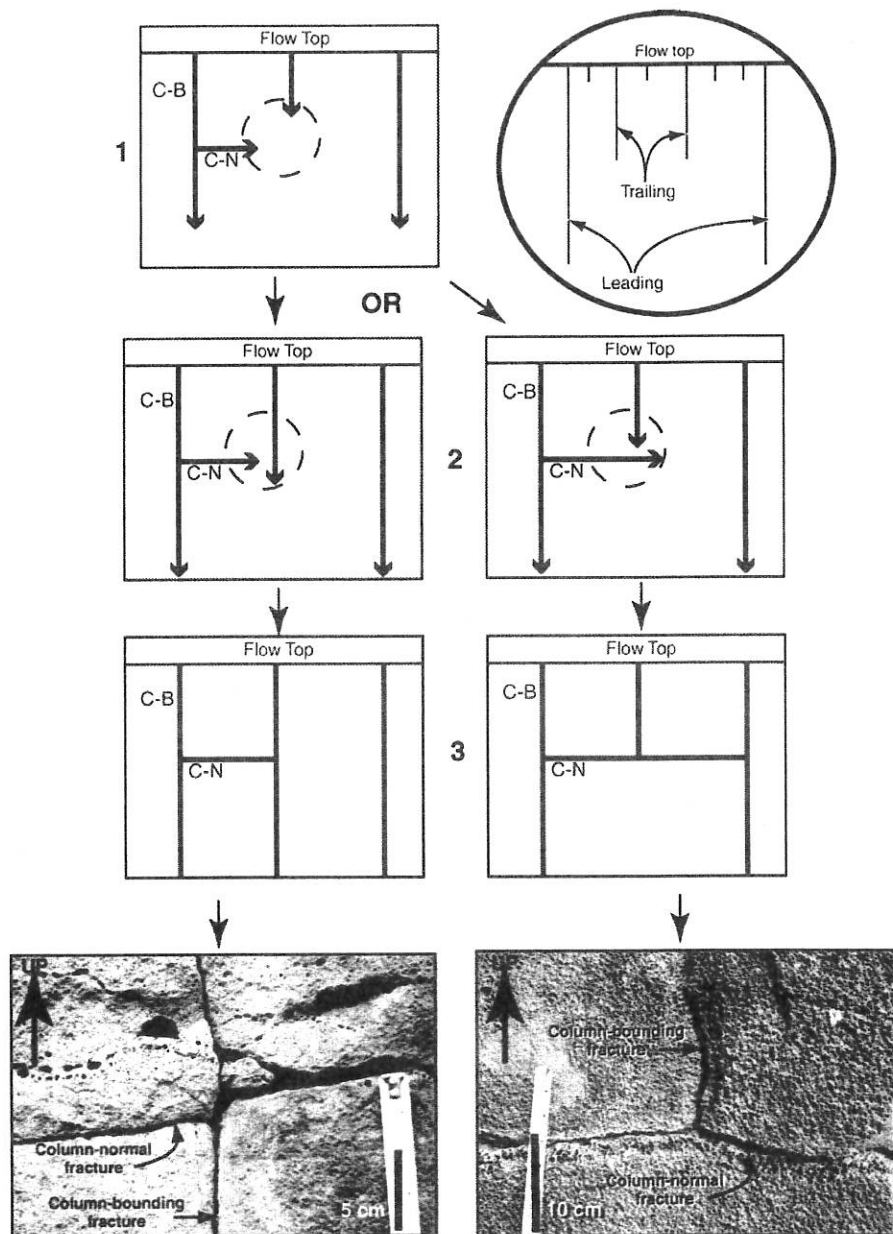


Figure 4. Schematic illustration of two potential fracture patterns that may result from the interaction of column-bounding (C-B) and column-normal (C-N) fractures. A column-normal fracture is initiated at a leading column-bounding fracture in step 1 and propagates toward the circled region simultaneously with a trailing column-bounding fracture. The concept of leading and trailing column-bounding fractures is shown in the circled inset (top right). The final fracture pattern in step 3 is dependent on which fracture propagates through the circled region first in step 2. If the trailing C-B fracture is faster, C-N fractures terminate at the C-B fracture (bottom left). If the C-N fracture is faster, the trailing C-B fracture terminates at the C-N fracture (bottom right).

Nearly all entablatures in Box Canyon are either visibly connected to an inflation fracture or an inflation fracture is present within close proximity to the entablature. Each of the four flow-scale fracture maps presented here (Fig.

3) have an inflation fracture and an entablature associated with them; however, not all flows exposed in the walls of Box Canyon exhibit entablatures. This lack of entablature is sometimes the result of the positioning of the sec-

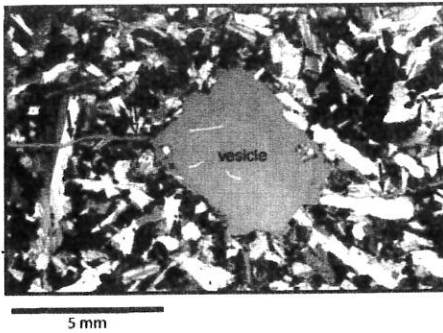


Figure 5. Photomicrograph of a column-normal fracture (shown by arrows) within a vesicular layer. Fractures propagate through vesicular layers by utilizing stress concentrations at the corners of vesicles like the one in the center, then propagating along crystal boundaries and cleavage planes. The vesicle and fracture both appear gray because of the epoxy of the thin section.

tion view through the flow with regard to the flow axis, but may also be an indication that entablatures are limited in their three-dimensional extent within a flow.

Inflation Fractures

Inflation fractures present in surface flows are open at their upper extent but are partly filled with loess (Fig. 7A). Inflation fractures are as wide as 4 m and as deep as 8 m. They occur along flow boundaries, tumuli, pressure plateaus, pressure ridges, and plateau pits (Chitwood, 1994). Inflation fractures in subsurface flows exposed in Box Canyon are typically filled with basalt from overlying flows (Fig. 7B). Although no loess filling was observed within inflation fractures at Box Canyon, Johannesen (2001) cited locations where loess-filled inflation fractures are observed in the subsurface.

Eastern Snake River Plain inflation-fracture walls display zones equivalent to those of inflation fractures in Hawaiian lava flows described by Anderson et al. (1999) (Fig. 8). The

upper zone (zone 1) has a columnar appearance. The middle zone (zone 2) has a smooth, planar, non-columnar appearance. The basal zone (zone 3) is a planar, texturally banded surface providing evidence of both brittle deformation (smooth fracture surface) and ductile deformation (rough fracture surface containing tear fractures with large fracture apertures in comparison to fracture lengths). These zones record successive stages of inflation fracture-growth history.

Subhorizontal surfaces displaying lineations, thus resembling slickensides, intersect the walls of inflation fractures of the Cerro Grande and Hells Half Acre lava flows. The lineations trend parallel to the azimuth of the vector of inflation-fracture opening. These surfaces consistently form along vesicular layers intersecting zone 3 of inflation-fracture walls, producing centimeter-scale jogs and horizontal ledges. Each ledge on one wall of an inflation fracture has a corresponding small roof on the opposing wall, indicative of where the opposing fracture walls had previously been in contact.

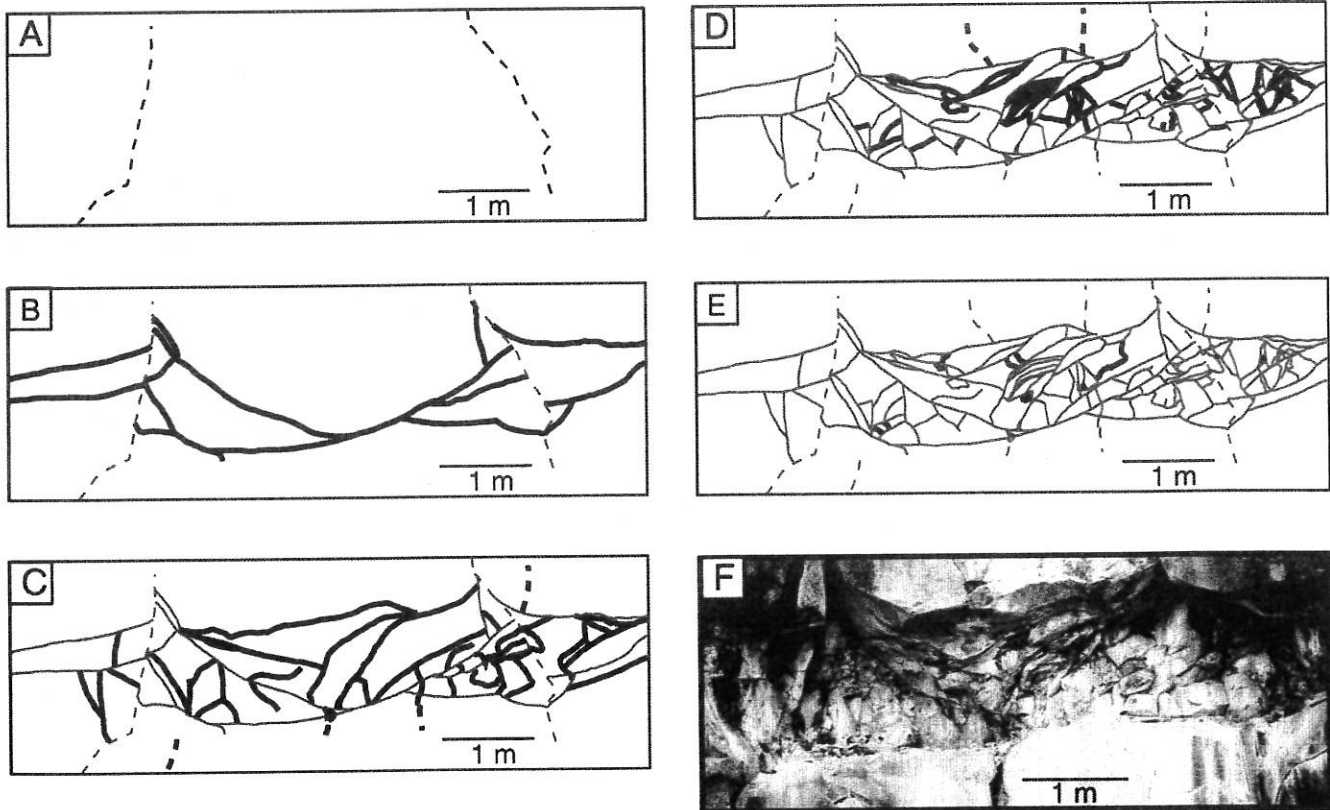


Figure 6. Entablature-fracture evolution. (A) Column-bounding fractures (dashed lines) are the first fractures to propagate through an entablature. (B–E) Successive generations of fractures (thick black lines) then dissect the blocks of basalt delineated by preceding generations (gray lines). (F) The final geometry in the photograph represents the same area as the box in flow A in Figure 3.

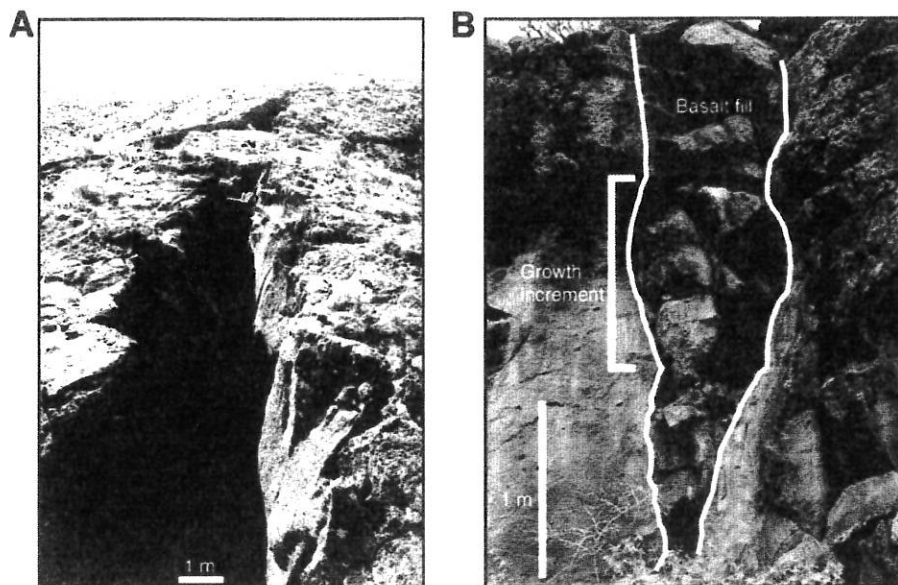


Figure 7. (A) Surface view of a Cerro Grande lava-flow inflation fracture. (B) An inflation fracture in Box Canyon filled by basalt from an overlying flow. Inflation fractures display meter-scale growth increments analogous to centimeter-scale growth increments on column-bounding fractures.

A significant characteristic of inflation fractures in most flows within Box Canyon is that they curve toward and intersect the lateral tips of entablatures (Fig. 3). This phenomenon has apparently not been previously described, probably because basalt-filled inflation fractures are often extremely difficult to identify in exposed subsurface flows. Although open inflation fractures in young, surface flows are typically partly filled with loess, they also commonly appear to curve downward, presumably toward unexposed entablatures within the flows.

Inflation fractures influence the development of the three other fracture types (column-bounding, column-normal, and entablature). This influence is manifested as three distinct fracture patterns within cooled lava flows: (1) rectangular and triangular columns formed by column-bounding fractures adjacent to inflation-fracture walls (Fig. 9A); (2) column-bounding fractures radiating away from inflation fractures and reorienting to vertical with increasing distance (Fig. 9B); and (3) entablature fractures (Fig. 3). The first pattern is visible in plan view in basalt flows along the Big Lost River. The second and third patterns are visible in cross section along the walls of Box Canyon. Identification of these inflation fracture-related effects is extremely important when interpreting fracture patterns in cross sections of basalt flows because inflation-fracture surfaces may be in the plane of the

cross section, rather than at a high angle to it. For example, at the left edge of the entablature in Figure 3A, a polygonal fracture pattern implies a cross-section view of columns radiating away from an inflation fracture that connects to the entablature. Inflation-fracture effects can also be identified in the top right corner of the same flow (Fig. 3A), as well as along the three inflation fractures in Figure 3B and to the left of the entablature in Figure 3D.

Column-bounding fractures that propagated away from an inflation-fracture wall can be distinguished from regular column-bounding fractures that formed at an equivalent distance below the flow top because the growth increments are smaller on fractures related to an inflation fracture. This, along with the presence of rectangular or triangular columns, is an effective means of identifying proximity to an inflation fracture that is either not physically exposed or difficult to identify because of being filled with basalt from a younger flow (Fig. 7B).

ANALYSIS OF FRACTURE TYPES

Column-Bounding Fractures

Column-bounding fractures are the first fractures to form in the crust of the lava flow. These fractures relieve the thermal stress induced by cooling; they grow toward the flow center as a single cooling front advances away

from the flow periphery. The mechanics of growth of individual column-bounding fractures has been described in detail by other authors (e.g., DeGraff and Aydin, 1987, 1993) and so will not be elaborated upon here.

The orientation of column-bounding fracture planes is normal to the isothermal surfaces (Ryan and Sammis, 1978). The shapes of the isothermal surfaces are determined by the aspect ratio of the flow and the presence of thermal perturbations, such as those induced by inflation fractures, vesicular layers, other cooling fractures, and water and steam convection in fractures. Thus, any changes in the distribution of isotherms during the cooling history of a lava flow are recorded by the column-bounding fracture patterns. For example, in low-aspect-ratio (AR) flows in Box Canyon (Figs. 3B–3D), the propagation of column-bounding fractures toward the central entablature results in fractures curving away from vertical; the fracture's orientation becomes radial to a central entablature for the case of $AR = 1$ (owing to circular isotherms). We can thus infer that the entablature represents the last remnant of lava (i.e., the lava core) during the cooling process and the last part of the flow to solidify. Second to aspect ratio in controlling fracture patterns is the coincident evolution of column-normal fractures and column-bounding fractures. Because these two fracture types are the most common in all flows, fracture patterns throughout the flow are dependent on their mutual interactions (Fig. 4).

Column-Bounding Fracture Spacing

A fracture-spacing analysis was performed for flow A (Fig. 3A) by using a scan-line technique (Fig. 10). Only the column-bounding fractures were included in the spacing measurements; in actuality, the high degree of fracturing within the entablature would skew the spacing to very small values in that part of the flow. However, column-bounding fractures have greater lengths, apertures, and flow-scale connectivity than entablature fractures and are probably of greater significance for determining characteristics such as hydraulic conductivity. Supporting this notion is the fact that column-bounding fractures commonly show evidence of mineral precipitates on exposed fracture surfaces, whereas entablature fractures do not.

The average fracture spacing was determined for several depths within the 8-m-thick flow A in order to compare the variation of spacing as a function of depth (Fig. 10). The spacing data show close agreement to an analysis of a flow of similar dimensions by Lore

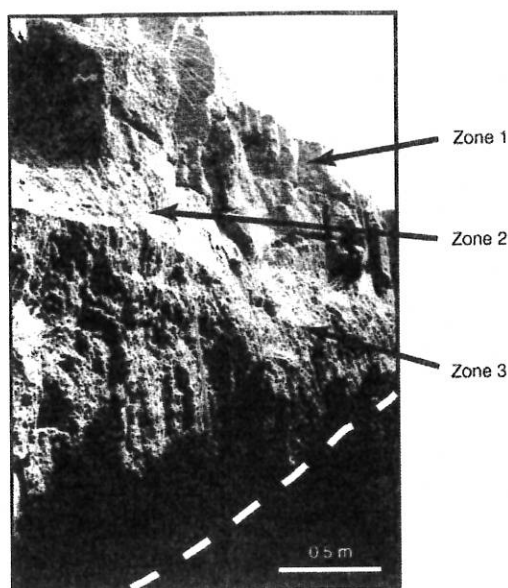


Figure 8. Three zones on an inflation-fracture wall in the Cerro Grande lava field. Zone 1 is columnar in appearance and records opening of the inflation fracture along pre-existing column-bounding fractures. Zone 2 has a smooth, planar appearance representing growth of the inflation fracture through elastic basalt ahead of the zone 1 column-bounding fractures. Zone 3 has a rough surface texture and indicates growth through viscoelastic basalt. The white dashed line indicates a rib mark produced by a change in propagation direction after a period of hesitation.

et al. (2001). The average spacing—found by dividing the summed spacing values by the number of fractures—thus averages out lateral variations in spacing at any particular depth within the flow. Standard deviations about the mean spacings (Fig. 10) indicate a moderate variability in fracture spacing in this flow, particularly where average fracture spacing is highest, possibly owing to the effects of fracture concentrations around inflation fractures. Nonetheless, an identifiable trend exists in average fracture spacing, which increases from the top surface to a maximum of 1.83 m (or 23% of the flow thickness) at ~3 m from the flow base. The larger fracture spacing near the flow center reflects a slow cooling rate at this level (DeGraff and Aydin, 1993; DeGraff et al., 1989; Grossenbacher and McDuffie, 1995; Reiter et al., 1987) and the absence of trailing column-bounding fractures.

The maximum spacing occurs at the level of the entablature and is an average for all column-bounding fractures beyond the lateral ends of the entablature in addition to column-bounding fractures that cut through the entablature. The average spacing of the column-bounding fractures that cut through the entablature is greater still (2.66 m) because entablatures inhibit the connection of column-bounding fractures of the upper and lower col-

onnades. Average fracture spacing at the top surface of the flow (0.5 m) is smaller than at the bottom surface of the flow (0.79 m); this result reflects more rapid convective cooling against the atmosphere at the flow top compared to slower, conductive cooling against the underlying substrate at the flow bottom.

Contoured relative-fracture-density plots (Fig. 11) of the four studied flows that have different aspect ratios (Fig. 3) illustrate the variation of fracture density as a function of depth and aspect ratio. A 1 m grid was overlain on each map, and the number of fractures either partly or fully contained within each grid block was counted. All fractures except entablature fractures are included in the fracture count. This choice was predicated by the fact that extremely small fracture spacings in entablatures would dominate a fracture-density plot, yet entablatures are of limited lateral extent within a flow and do not appear to be a major control on fluid-flow pathways. Density values in all flows have been normalized to the greatest fracture-density value among the four flows—13 fractures per square meter—which occurs in the AR = 3 flow (Figs. 3C and 11C).

A region of low fracture density occurs at the entablature depth in each contour map; this region probably inhibits the fluid-flow

connectivity between colonnade and entablature fractures. The highest fracture density typically occurs near the upper surface of a flow, which was subjected to high cooling rates and a resultant dense network of column-bounding and column-normal fractures. Nonetheless, the highest fracture density in flow A (Fig. 11A) occurs at the upper right-hand corner of the map, which corresponds with the location of an inflation-fracture wall. Inflation fractures allow convective cooling within a flow, and this increases the cooling rate, causing increased fracturing adjacent to them. Low-aspect-ratio, more elliptical flows appear to have higher fracture densities than sheet flows (Fig. 11). Coincident with this characteristic is a tendency for low-aspect-ratio flows to contain a greater number of inflation fractures. Where multiple low-aspect-ratio basalt flows overlap in the subsurface, the combination of high cooling-fracture densities and abundant inflation fractures may result in a greater hydraulic conductivity than occurs in sheet flows having an equivalent total volume.

Despite the prevalence of higher fracture densities in low-aspect-ratio flows, it is likely that the overall cooling-fracture density of a flow is related more to the ratio of flow volume to flow surface area (i.e., area of convective heat loss), rather than the simple geometric parameter—aspect ratio—which has no explicit heat-transfer basis.

Column-Normal Fractures

Column-normal fractures have consistently been described as postdating column-bounding fractures in cooled basalt flows (Geikie, 1893; James, 1920; Mallet, 1875; Preston, 1930; Tomkeieff, 1940). This description is only partly true in eastern Snake River Plain basalts in which leading and trailing column-bounding fractures generate a nonuniform fracture front (Fig. 4 inset). Column-normal fractures are initiated after leading column-bounding fractures have propagated through solidified basalt, but evolve contemporaneously with, and ahead of, trailing column-bounding fractures. In response, column-normal fractures truncate trailing column-bounding fractures but are themselves truncated by the leading column-bounding fractures (Fig. 4).

Previous thermal-mechanical analyses of column-normal fracture development in a cooling basalt flow have led to hypotheses of likely isotherm and stress-contour distributions within columns of basalt (Geikie, 1893; James, 1920; Mallet, 1875; Preston, 1930; Tomkeieff, 1940). These conceptual models sug-

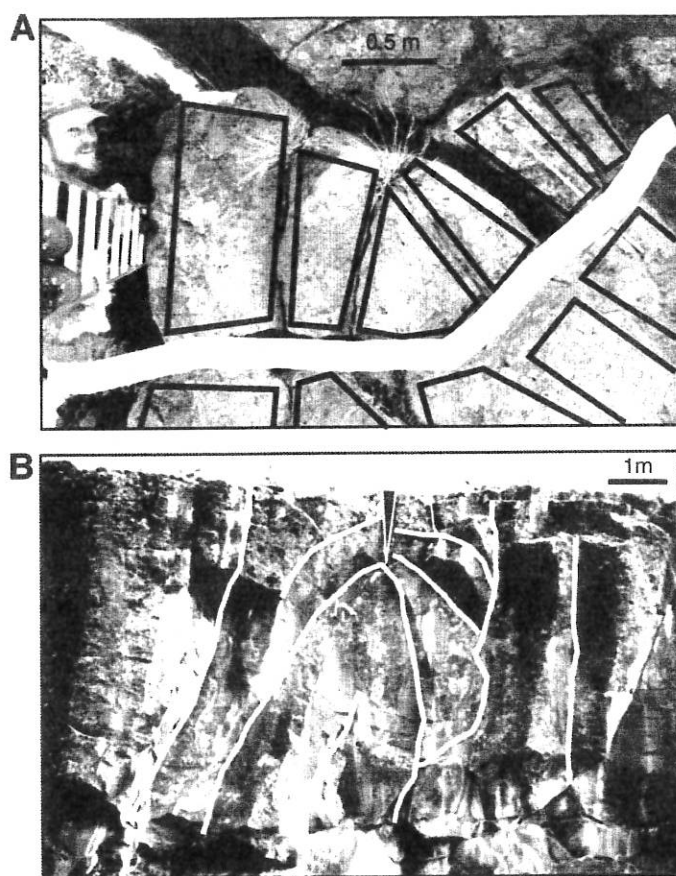


Figure 9. (A) Triangular and rectangular columns (shapes outlined with black lines) are formed by column-bounding fractures responding to perturbed isotherms alongside an inflation fracture (thick white line). Along the planar inflation-fracture wall (perpendicular to the plane of view), column-bounding fractures appear as vertical, parallel fractures. (B) The pattern of column-bounding fractures (white) near an inflation fracture (black V-shape, top center) records the shape of perturbed isotherms. With increasing distance from the inflation fracture, the column-bounding fractures reorient in accordance with the shape of the flow-scale isotherms.

gest that column-normal fractures result from the thermal-stress distribution within a column cooling by convection along the column-bounding fractures, which results in components of heat transfer both parallel and perpendicular to the column axis. The overall effect is for column-bounding fractures to induce axis-parallel contraction, causing column-normal fracture growth.

In addition to thermal stress within a column, there is also an elastic stress perturbation induced by the presence of column-bounding fractures (cf. Bai and Pollard, 2000; Bai et al., 2000; Lachenbruch, 1961, 1962, 1966; Pollard and Segall, 1987). In response to the opening motion of the fracture walls, a component of compressive normal stress, equal in magnitude to the tensile driving stress, develops both perpendicular and parallel to the fracture plane

(Pollard and Segall, 1987). With increasing distance from the fracture, a mechanical stress-shadow effect around the column-bounding fractures results in a gradually increasing (i.e., more tensile) differential stress (fracture-parallel minus fracture-perpendicular) (Bai and Pollard, 2000; Bai et al., 2000). We hypothesize that in response to this phenomenon, the column-parallel normal-stress component may reach a value sufficient to promote column-normal fracture growth near the center of columns, producing radial plumose structures on column-normal fracture surfaces, as has been documented in sheet flows of the Columbia River Basalt Group (e.g., Pollard and Aydin, 1988; Spry, 1961; Tomkeieff, 1940).

In basalt flows containing abundant heterogeneities, such as vesicles, the location of the

maximum differential stress within a column may be a less important control on column-normal fracture initiation location than mechanical stress concentrations around heterogeneities. Unlike the Columbia River Basalt Group, the high concentration of vesicular layers within eastern Snake River Plain basalts needs to be considered when evaluating the origin of column-normal fractures, which typically propagate along the vesicular layers. The combined increase of column-axis-parallel extension and mechanical stress perturbations at vesicle corners within vesicular layers produces conditions favorable for the initiation and propagation of a fracture (Fig. 5).

Resultant column-normal fracture surfaces along the vesicular layers are very rough, obscuring subtle features such as growth increments and plumose structures, if they exist. Thus, column-normal fractures could admittedly be initiated at any location within a vesicular layer and propagate laterally through the layer until encountering and terminating against another fracture. However, if convective cooling occurs within column-bounding fractures, the highest thermal gradients may occur at the column boundaries. Thus, the intersection of a column-bounding fracture and a vesicular layer may be where the greatest stress values occur within a column, causing column-normal fractures to be initiated there. Hesitation rib marks produced along column-bounding fracture surfaces by overlap of adjacent growth increments (DeGraff and Aydin, 1987) may also concentrate stress and become the initiation locations for column-normal fractures.

In response to the high vesicularity of eastern Snake River Plain basalts, column-normal fractures do not form with a regular spacing. The fracture spacing is controlled by the spacing and location of vesicular layers, suggesting that vesicularity may be used as a proxy for fracture-density estimates in the subsurface. Furthermore, because vesicular layers are approximately planar, tabular bands a few centimeters wide, column-normal fractures that propagate through them are also planar. In contrast, column-normal fractures in sheet flows of the Columbia River Basalt Group do not propagate along vesicular layers and thus grow in accordance with isotherms within individual columns, which promote concave fracture surfaces.

Entablature Fractures

Entablatures were first defined by Tomkeieff (1940) as an "upper zone composed

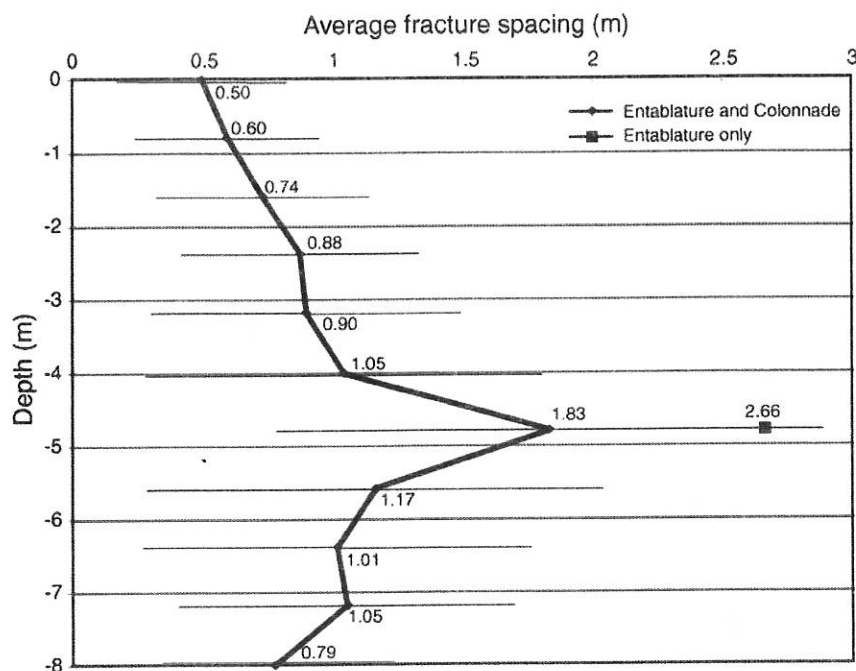


Figure 10. Average column-bounding fracture spacing within flow A (Fig. 3A). Spacing is least at the top surface of the flow and increases from both the upper and lower boundaries toward the central entablature. Entablatures prevent trailing column-bounding fractures of the upper and lower colonnades from connecting; thus the spacing of those leading column-bounding fractures that pass through the entablature increases. The entablature does not extend across the entire width of the flow; hence there is a separate spacing measurement for the entablature itself (black square) in addition to the average spacing across the entire width of the flow at the level of the entablature. Standard deviations about the average spacing at each point are shown with horizontal black lines and reflect a moderate variability in fracture spacing, particularly near the entablature.

of closely spaced wavy columns or of thick vertical columns (pseudo-columnar jointing), or both." Since its definition, the term "entablature" has primarily been associated with the Columbia River Basalt Group, where entablature formation is probably related to intense water and steam convection within column-bounding fractures, which produced rapid cooling and fracturing (DeGraff et al., 1989; Long and Wood, 1986). The term has most recently been applied to eastern Snake River Plain basalts by Lore et al. (2001); however, their entablature fractures are not columnar and show no evidence of having resulted from water inundation of the flows.

The primary distinction between entablature fractures in the Columbia River Basalt Group and those in the eastern Snake River Plain basalts is the manner in which the fracture propagation occurs. Entablature-fracture growth in the Columbia River Basalt Group involves growth rates much higher than occur in column-bounding fractures. Columbia River entablature fractures are, nonetheless,

column-bounding fractures and form according to the same fracture-growth mechanisms involving cyclic fracture propagation (DeGraff and Aydin, 1987, 1993; Lore et al., 2000; Pollard and Aydin, 1988; Ryan and Sammis, 1978), with growth increments on the order of millimeters to centimeters in scale.

On the basis of our observations of the interaction between entablatures and inflation fractures within Box Canyon flows, we hypothesize that individual eastern Snake River Plain entablatures formed from a sudden and rapid increase in cooling rate induced by penetration of a pressurized lava core by an inflation fracture. This interpretation is supported by the fact that inflation fractures typically curve toward the lateral corners or tips of entablatures, corresponding to expected locations of stress concentration at the tips of elliptical pressurized cavities (Pollard, 1987; Pollard and Aydin, 1988). Our model for entablature formation implies that Snake River Plain entablatures are not simply the result of the upper and lower colonnades' cooling

fronts slowly coalescing. In fact, an entablature cannot form in the absence of inflation-fracture penetration, explaining why some lava flows do not contain entablatures at the level where the fractures of the upper and lower colonnades meet.

If entablature formation represents rapid chilling of the lava core, then at the time of entablature formation, leading fractures in the upper and lower colonnades would be located at the boundaries of the lava core and would therefore have blunt tips. Upon penetration of the lava core by an inflation fracture, and resultant rapid solidification of the entire thickness of the near-solidus liquid contained therein, colonnade fractures propagated through the brittle core in a single growth increment as soon as the stress concentration at the fracture tip exceeded the fracture toughness of the newly solid entablature.

Primary entablature fractures were then initiated at the column-bounding fractures (Fig. 6), and subsequent generations of entablature fractures successively dissected the entablature. Rapid entablature cooling also superimposed a reversal in thermal gradient at the entablature boundary, causing column-bounding-like fractures to propagate away from the entablature into both the upper and lower colonnades. Primary entablature fractures were initiated at column-bounding fractures because they were the locations of the highest thermal gradients and resultant thermal stress. Such fracturing may have been facilitated by the connection of the upper and lower colonnades through the entablature, initiating a convection system from the thermally isolated lower colonnade up through the entablature and upper colonnade to the atmosphere. Both column-bounding and entablature fractures were thus heat-transfer pathways creating thermal gradients perpendicular to their walls. These gradients drove the formation of subsequent generations of entablature fractures, producing the continually subdividing nature of entablature-fracture evolution. Entablatures do not contain vesicular layers that concentrate fracture growth; therefore, the first generation of entablature fractures is concave (Fig. 6B), implying that the isotherms in the newly solidified entablature were also concave. This geometry would be expected if the isotherms were governed by the first column-bounding fractures to cut through the entablature (Fig. 6A), producing an effect similar to that of the concave column-normal fractures typical of sheet flows of the Columbia River Basalt Group.

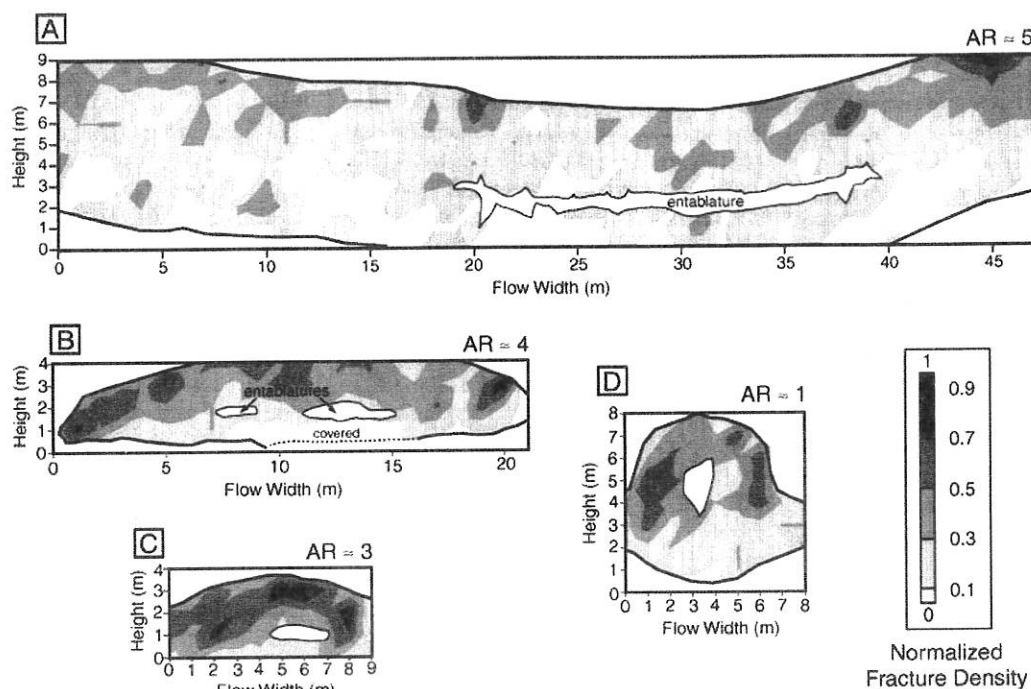


Figure 11. Relative-fracture-density plots for the four fracture maps in this study (Figs. 3A–3D). All plots are normalized to the maximum measured fracture density of 13 fractures per square meter (the flow in C). Flows having a lower aspect ratio appear to possess higher fracture densities than flows having a higher aspect ratio. Flow tops and inflation-fracture locations also show high fracture densities. Entablature locations are shown in white with black borders. Entablature-fracture densities are not included in this analysis.

Inflation Fractures

Previous inflation-fracture studies were undertaken predominantly to develop an understanding of physical volcanological processes and flow mechanics (Anderson et al., 1999; Chitwood, 1994; Hon et al., 1994; Rossi and Gudmundsson, 1996; Walker, 1991). More recently, Johannesen (2001) and Welhan et al. (2002) explored the contribution of inflation fractures to subsurface porosity in the eastern Snake River Plain aquifer. Inflation fracturing begins when the circumferential stress produced by inflation equals the strength of the overlying carapace of brittle basalt. Inflation fractures have been referred to as fissures, tension fractures (Hughes et al., 1999; Johannesen, 2001), and lava-inflation clefts (Walker, 1991). We adopt the term “inflation fracture” in this study as it encompasses their genetic origin, and we use our observations of the surface morphologies of eastern Snake River Plain inflation fractures to develop a comprehensive explanation for their growth behavior.

Surface morphologies of inflation fractures indicate a pulsed inflation history. Just as plume structures and growth increments can be used to interpret column-bounding fracture growth, so too can textural features on

inflation-fracture walls indicate the growth history of inflation fractures. The three zones of inflation-fracture walls (Fig. 8) respectively represent (1) the initial accommodation of circumferential tension within the brittle crust via opening along existing column-bounding fractures; (2) propagation of the inflation fracture into unfractured basalt ahead of column-bounding fracture tips; and (3) cyclic inflation-fracture growth after the fracture enters viscoelastic basalt. Variations in surface texture indicate cessation and later repropagation of the inflation fracture. For example, within zone 3 of Cerro Grande lava flow inflation fractures, rib marks on fracture surfaces indicate either extreme blunting of the fracture tip or a change in propagation direction. Either possibility indicates stages of growth related to a change in the internal pressure along one or more internal lava channels.

The smooth morphology of zone 2 is produced as column-bounding fractures of zone 1 coalesce into a single, planar inflation fracture driven forward by inflation stress. Using the atomically sharp fracture tips of the existing zone 1 column-bounding fractures, the inflation fracture propagates until it enters viscoelastic basalt, at which point the fracture tip blunts. Zone 2 of inflation fractures thus rep-

resents a transition zone between elastic basalt fractured by cooling fractures and unfractured viscoelastic basalt below. This zone is critical to understanding the propagation of inflation fractures. Of particular importance, if zone 1 corresponds with the maximum depth to which elastic basalt exists and the maximum depth to which thermal fractures can propagate, how is an inflation fracture able to propagate ahead of this zone into viscoelastic basalt to create zone 2?

Two parameters that may help answer the above question are the effective glass-transition temperature of basalt and the driving stress that causes inflation-fracture growth. The effective glass-transition temperature is the highest temperature at which elastic deformation can occur in basalt (Ryan and Sammis, 1981). Lore et al. (2000) showed that the glass-transition temperature of basalt is dependent on the cooling rate and strain rate. Higher cooling and strain rates correspond with higher effective glass-transition temperatures at which elastic/brittle deformation can occur. Inflation produces higher tensile stress in the brittle carapace than is produced by cooling (Anderson and Fink, 1992; Anderson et al., 1999) and is associated with higher strain rates. For example, Hon et al. (1994) de-

scribed a period of Hawaiian pahoehoe flow inflation involving a 0.5 m increase of flow thickness in 1 h. They noted that ~40% to 50% of the total flow thickness may be attained during the first 5 to 10 h of emplacement.

We interpret the smooth texture in zone 2 to reflect where the inflation fracture underwent high-strain-rate propagation through an elastic layer to the depth of the effective glass-transition temperature, where viscous flow resulted in fracture-tip blunting. The combined effects of the high strain rates of inflation and the stress concentration at the atomically sharp fracture tips of column-bounding fractures in zone 1 likely resulted in an increase of the effective glass-transition temperature in the basalt ahead of inflation fractures in zone 2. Because the strain rate is much higher for inflation than for cooling, no viscous relaxation occurs around the inflation-fracture tip, which thus remains atomically sharp like the cooling fractures it originated from. However, as increasingly hotter basalt is entered, the high strain rate cannot sustain fracture growth, and the inflation-fracture tip blunts, resulting in a decrease in the effective glass-transition temperature. However, because the inflation-related driving stress is not relieved by blunting of the fracture tip, as occurs with thermal stress during cooling-fracture growth, the inflation fracture continues to rip through viscoelastic basalt, resulting in the rough surface texture of zone 3.

Fracture-tip blunting will ultimately arrest inflation-fracture propagation in zone 3, allowing an increase in fracture aperture without a concomitant increase in fracture length. In this way, inflation fractures are able to attain apertures several meters wide at the upper surface of the flow. An increase in fracture aperture would allow greater convective cooling to occur, generating elastic basalt ahead of the blunted inflation-fracture tip. Eventually, when a critical stress intensity is reached at the blunted fracture tip, repropagation occurs through the elastic basalt layer to the new glass-transition temperature boundary, producing the banded texture typical of zone 3. The quicker the basalt is cooled by convection in the inflation fracture, the faster it nears the effective glass-transition temperature and the less time to repropagation. In this manner the increments of growth may decrease in size downward until inflation-fracture propagation approaches continuous growth. This model for eastern Snake River Plain inflation-fracture

growth is in good agreement with a model developed by Anderson et al. (1999) to explain

inflation fracture-growth behavior in Hawaiian inflated pahoehoe flows.

Because wider-aperture inflation fractures allow more heat loss through convection and radiation than do narrow inflation fractures, columns are less perturbed near narrow inflation fractures and form at smaller angles to the inflation-fracture walls than they do along wide-aperture inflation fractures. Inflation fractures also affect the morphology of vesicular layers and, hence, column-normal fractures. Vesicular-layer locations depend on the shape of the viscoelastic ceiling, which may be perturbed during inflation-fracture growth depending on the stage in the cooling history when the inflation fracture began propagating inward. At depths within a flow at which the basalt had solidified before the perturbation influenced the shape of the cooling front, the vesicular layers are parallel with the flow boundaries. Thus, after the arrival of the inflation fracture, the vesicular layers are perpendicular to the inflation-fracture wall; however, with increasing depth, a deflection of the solidification front ahead of the inflation fracture is evidenced by downward-deflected vesicular layers in the basalt, formed by exsolved gases rising to rest against a downward-deflected viscoelastic ceiling during cooling.

The conditions for inflation-fracture propagation are dependent on the availability of driving stress, provided by internal pressure within discrete lava channels. Inflation fractures do not appear to be driven by thermal gradients around the lava core, but rather result in a perturbation of the cooling-related isotherms, as is reflected by column-bounding and column-normal fracture patterns adjacent to inflation fractures. Lava channels may start out as a broad liquid interior that inflates the entire upper surface of a flow (e.g., Hon et al., 1994); however, the association of inflation fractures with discrete and sometimes multiple entablatures in a single flow supports a model of inflation around finger-like lava pathways beneath the surface of a single flow (e.g., Anderson et al., 1999). These pressurized cavities concentrate stress at their lateral edges, causing nearby inflation fractures to curve toward the corners of the lava cores, which ultimately become entablatures. When a pressurized lava core is not directly underneath an inflation fracture, shear stress is resolved onto the inflation-fracture plane. This shear stress causes an inflation fracture to change the direction of growth in order to reorient with the maximum tensile stress. Changes in the curvature of inflation fractures during increments of growth indicate that inflation and deflation processes influence fracture growth. The infla-

tion history will vary along the width and length of an individual flow, and inflation fractures should therefore reflect the local inflation history.

Inflation-fracture geometries are thus clearly influenced by lava core location and shape, and eventual piercing of the lava core results in the development of an entablature through rapid cooling, an increase in the glass-transition temperature, and resultant fracturing. Correspondingly, inflation fractures thermally influence lava-channel shape and location by perturbing the thermal field within a flow. This effect, in turn, changes the distribution of cooling fractures growing toward the lava core. For example, we know from field observations that the entablature shape mimics the shape of the flow, which controls the isotherms during the cooling process. Given this, the shape of flow B (Fig. 3B) would be expected to have generated a more centralized, single entablature such as occurs in flow C (Fig. 3C). Instead, two entablatures occur on either side of the central inflation fracture. These entablatures probably represent the division of a single internal lava channel by the thermal perturbation ahead of the central inflation fracture as it propagated downward, clearly demonstrating inflation-fracture control on entablature-shape evolution.

DISCUSSION

Despite numerous investigations into the origins of cooling fractures in basaltic lava flows, the central focus of previous studies tended to be the development of column-bounding fractures in sheet-like lava flows. These investigations provided detailed descriptions of fracture patterns, variations in column spacing, and the incremental-growth process of the fractures in the context of the thermal-mechanical behavior of cooling basalt. There have been significant advances in both analytical and numerical heat-transfer modeling of cooling sheet flows that allow the determination of cooling times as a function of sheet-flow thickness (DeGraff and Aydin, 1993; DeGraff et al., 1989; Grossenbacher and McDuffie, 1995; Lore et al., 2000, 2001; Reiter et al., 1987). Hypotheses have been developed to explain the increase in column-bounding fracture spacing with depth into a flow (due to stress shadows alongside leading fractures) and the reason for the development of multiple tiers of entablatures in sheet flows (due to inundations by surface water). These developments in fracture interpretation for basaltic sheet flows have been very useful for advancing a conceptual understanding of

sheet-flow cooling and the resultant fracture distribution that may be important for fluid-flow modeling and for contaminant-migration concerns at facilities built on basaltic sheet flows, such as the Hanford Site nuclear laboratory in southern Washington State.

However, as demonstrated by the field observations described here, previous work on basalt fractures cannot be applied directly to the characterization, or to the thermal-mechanically based interpretation, of fracture development in low-volume, inflated pahoehoe basalt flows. Where such flows are common, such as on the eastern Snake River Plain, Hawaii, and Iceland, a different fracture classification scheme is needed to account for differences in genetic origin between different fracture types within individual flows, as well as the significant differences between the low-volume flows and the high-volume sheet flows. Such an independent classification scheme is vital for the development of predictive models of fracture distributions to address fluid-flow and contaminant-migration issues in low-aspect-ratio inflated pahoehoe flows. The importance of this predictive ability is amply demonstrated on the eastern Snake River Plain, which contains a major aquifer in southern Idaho as well as being the location of the Idaho National Engineering and Environmental Laboratory.

One of the most significant aspects of our model for fracture-growth and lava-cooling history in eastern Snake River Plain basalts is the identification and description of major differences in entablature characteristics and formation mechanism between sheet flows and the low-volume, inflated pahoehoe flows. Entablatures are more densely fractured zones than the adjacent colonnades in both sheet flows of the Columbia River Basalt Group and the low-volume flows of the eastern Snake River Plain; however, the similarity ends there. For example, Columbia River Basalt Group sheet flows can have multiple entablatures at different depths within a flow (Long and Wood, 1986), whereas Snake River Plain flows only have one entablature level, which in some flows is laterally subdivided in response to thermal-perturbation effects by an overlying inflation fracture (Fig. 3B). Columbia River basalt entablature fractures are essentially very closely spaced column-bounding fractures intensely dissected by column-normal fractures that together give the entablature a rubbly appearance. In contrast, eastern Snake River Plain entablatures have a greater amount of internal fracture heterogeneity and are not column-bounding fractures. Columbia River basalt entablatures are not obviously associ-

ated with any type of inflationary process or feature, whereas Snake River Plain basalt entablatures are almost invariably visibly associated with an inflation fracture.

This study elucidates the impact of inflation fractures on cooling-fracture patterns, lava core location and shape, entablature formation, and the accelerated time to complete solidification of a flow in response to convective cooling within inflation fractures. The potential impact of inflation fractures on subsurface fluid flow is significant, considering their abundance, wide apertures, and association with high fracture densities in the adjacent basalt; therefore, it is important to attempt to be predictive about their most likely locations within subsurface flows, as well as how they may be manifested. For example, loess-filled inflation fractures in the subsurface could be mistaken in borehole core for sedimentary interbeds, which could affect the interpretation of subsurface stratigraphy. In addition, loess filling may influence fluid and contaminant migration in the subsurface.

Along Box Canyon, vertical parallel fractures of uniform spacing on planar, noncolumnar walls are useful for detecting the location of an inflation-fracture wall. By using this characteristic in conjunction with the triangular and rectangular plan-view appearance of columns adjacent to inflation-fracture walls, two previously overlooked inflation fractures were discovered in a basalt-flow featured in Faybishenko et al. (2000), Lore et al. (2000), and Lore et al. (2001). In their fracture map, we interpret a central, shallow inflation fracture evidenced by radiating, column-bounding fractures. Inflation fractures are commonly difficult to detect, as demonstrated by this example, but with the perturbed cooling-fracture patterns and inflation-fracture geometries outlined in this paper, detection of inflation fractures should become easier and can be incorporated into hydrological models.

The dominant mechanism controlling fracture distributions in flow bottoms is stress relief by adjacent fractures. Thus, column-bounding fracture distributions in flow bottoms evolve in accordance with thermal stress and stress shadows. This fracture growth behavior results in more dead-end fractures and subsequently less fracture connectivity in flow bottoms in comparison to the upper-colonnade region. Correspondingly, the fracture spacing and hence the fracture density in flow bottoms is less than in flow tops (Faybishenko et al., 2000; Lore, 1997; Lore et al., 2000) (Figs. 10 and 11). The fracture-distribution variation between flow tops and bottoms elucidates the importance of vesicular

layers to fracture distribution, density, and hydraulic connectivity in eastern Snake River Plain flows. In addition, the fact that inflation fractures and adjacent highly fractured zones are restricted to the upper-colonnade regions indicates that flow tops are likely to be conductive to fluids over greater lateral distances than both flow bottoms and laterally restricted entablatures. Vertical connectivity between flows is limited where entablatures prevented trailing column-bounding fractures from linking the upper colonnade to the lower colonnade.

CONCLUSIONS

There are four fracture types in eastern Snake River Plain basalt flows: column-bounding, column-normal, entablature, and inflation fractures. The first three of these are cooling fractures, whereas inflation fractures form in response to fluid pressure within the lava flow that causes the flow to inflate from within. Our observations of eastern Snake River Plain basalt flows highlight the disparity between fracturing processes in flood-basalt sheet flows and low-volume inflated pahoehoe flows. Principles of thermal fracturing that were developed through the analysis of sheet flows should not be applied to eastern Snake River Plain or analogous-style flows without modification. This conclusion is supported by the fact that the Snake River Plain flows differ from sheet flows in aspect ratio, thermal history, vesicularity, column-normal fracture formation, column-normal and column-bounding fracture patterns and interactions, entablature formation, entablature dimension, entablature location within the flow, entablature-fracture geometry, and inflation-fracture formation, morphology, evolution, and contribution to the thermal evolution of a flow.

An important characteristic of low-volume, inflated pahoehoe flows is that all fracture types mechanically interact and directly influence the evolution of the other fracture types. The most prevalent expression of fracture interactions involves column-bounding fractures and column-normal fractures, each of which affects the growth of the other throughout a flow (Fig. 4). Flow shape or aspect ratio is the main parameter controlling fracture patterns in the eastern Snake River Plain flows. Aspect ratio controls the shape of the flow-scale isotherms that, in turn, dictate column-bounding fracture-growth patterns and the shape of the lava core that cooling fractures propagate toward. The lava core location and shape determines the initiation locations, and subsequent growth behavior, of inflation fractures. Infla-

tion fractures utilize column-bounding fractures to begin propagating inward; hence the zigzag, columnar appearance of inflation-fracture surfaces in zone 1. Continued opening produces a planar fracture front below the column-bounding fractures, allowing the inflation fracture to propagate downward through viscoelastic basalt by effectively lowering the glass-transition temperature in the vicinity of the fracture tip. Eventual blunting of the fracture tip in viscoelastic basalt arrests growth of the inflation fracture, which then advances in cycles through successive bands of elastic basalt that form ahead of the fracture tip in response to convective cooling within the inflation fracture.

As inflation fractures propagate deeper into a flow, they perturb the flow-scale isotherms. This process creates highly fractured zones adjacent to inflation-fracture walls as well as controlling the ultimate lava core location. Inflation fractures propagate toward the lateral ends of lava cores, where stresses are concentrated in response to the lava pressure. Once the lava core is pierced by an inflation fracture, inducing rapid cooling of the entablature, the entablature then influences column-bounding fracture growth by preventing the connection of most column-bounding fractures in the upper colonnade with fractures in the lower colonnade. Entablatures may also induce a reversal in the thermal gradient that causes column-bounding fractures to be initiated at the entablature boundary and to propagate outward into the surrounding colonnades. Leading column-bounding fractures that propagate through a rapidly solidified entablature govern the locations of the concave primary entablature fractures and hence all subsequent generations of entablature fractures that subdivide blocks of entablature basalt bounded by earlier generations of entablature fractures (Fig. 6).

Most of this fracture evolutionary history is heavily influenced by the location and orientation of vesicular layers. Vesicular layers are numerous near the tops of eastern Snake River Plain flows, where they concentrate column-normal fractures, cause column-bounding fractures to either jog or terminate at a column-normal fracture, and create layer-parallel shear offsets in inflation-fracture walls. Vesicular layers thus play a major role in controlling fracture patterns and the fracture-growth sequence and ultimately cause an increase in the hydraulic conductivity of a flow. Rarely, vesicular layers are present below the entablature of a flow, resulting in fewer column-normal fractures than occurs in upper colonnades and causing lower-colonnade column-bounding

fractures to terminate at identifiable tips. Mechanical inhibitors to growth created by vesicular layers and early column-normal fractures distinguish eastern Snake River Plain basalt flows from more homogeneous flows such as those of the Columbia River Basalt Group, where mechanical inhibitors to fracture growth are not as prevalent.

High fracture densities at inflation-fracture walls emphasize the role of inflation fractures as significant pathways for fluid and contaminant migration. An additional consideration is the apparent increase in fracture density in lower-aspect-ratio flows, which may be important for assessing relative hydraulic conductivities of basalt flows having various aspect ratios in the eastern Snake River Plain.

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