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Millimeter-scale modal layering and the nature of the upper solidification zone in thick flood-basalt flows and other sheets of magma

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Abstract

Water flooding the surface of the Holyoke flood-basalt flow of Connecticut and Massachusetts was probably responsible for its entablature developing quench textures to depths of 80 m beneath the flow's surface. Despite the rapid cooling from above, the entablature–colonnade boundary is displaced above the center of the flow, which can only mean that crystal mush sank from the roof zone to the floor of the flow during solidification.

The entablature of the Holyoke flow exhibits a subtle, quasi-horizontal, millimeter-scale modal layering, with sheets of ophitic pyroxene–plagioclase clusters alternating with discontinuous sheets of residual liquid. The layering is believed to have formed by repeated nucleation of pyroxene–plagioclase clusters in a rapidly advancing thermal boundary layer. The alternating layers of crystals and residual liquid produced a mush with planes of weakness along which the dense crystal mush could separate from the roof. The layering parallels the cuspate entablature–colonnade boundary, which must therefore be a primary magmatic feature rather than simply where downward and upward propagating fractures met.

The modal layering has been found in other flood-basalt flows, but also in the roof zone of the Palisades sill. This texture may therefore be common in the roof zones of many sheet-like bodies of magma.

Keywords: Flood-basalt flow; Crystal mush; Entablature

1. Introduction

Many thick flood-basalt flows are divided into an upper and lower part by a prominent cuspate boundary separating regular columnar joints below — the *colonnade* — from more irregular or splaying joints above — the *entablature* (Tomkeieff, 1940). In many of these flows, this boundary also separates two distinct textural types of basalt, the one above characterized by more elongate and skeletal crystals and the one below by more equant crystals (Philpotts and Doyle, 1983; Long and Wood, 1986; Lyle, 2000). The texture of the entablature in these flows is interpreted to result from rapid crystallization, probably brought about by heat lost to water that flooded across the surface of the flow soon after eruption (Saemundsson, 1970; Long and Wood, 1986; Lyle, 2000).

This scenario certainly fits the cooling of the thick Holyoke flood-basalt flow of the Mesozoic Hartford basin of Connecticut and Massachusetts, because it is covered by fluvial and lacustrine sediments and its entablature has quench textures throughout (Philpotts and Doyle, 1983; Philpotts, 1998). But its entablature also exhibits another feature — a subtle, quasi-horizontal, millimeter-scale modal layering with sheets of intergrown plagioclase and pyroxene crystals alternating with discontinuous sheets of residual liquid, which was quenched to a mesostasis. This type of layering occurs not only in the upper part of thick flood-basalt flows but has also been found in the roof zones of thick sills, as will be described below. Despite the pervasive nature of the layering, it went unrecognized until the rock was examined in detailed scanned images of entire thin sections. The field of view of a typical petrographic microscope's low-powered objective is not large enough to make the structure readily apparent.

We will show that this modal layering is formed by rhythmic nucleation and growth of pyroxene–plagioclase clusters in a rapidly advancing thermal boundary layer. The layering is important for two reasons. First, its distribution and orientation proves that the cuspate entablature–colonnade boundary in thick flood-basalt flows is a primary magmatic feature reflecting the shape of the downward-solidifying roof and is not simply a post-solidification feature separating upward- and downward-propagating

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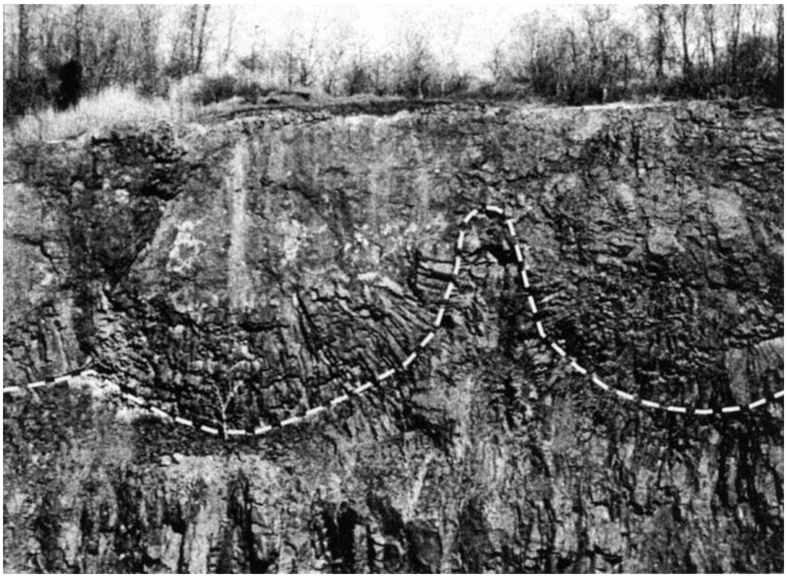

Fig. 1. Cuspate boundary (dashed line) separating radiating joints in entablature from vertical columnar joints in colonnade of the Holyoke flood-basalt flow in the North Branford Quarry, Connecticut. The boundary is approximately 120 m above the base of this 200-m-thick section through the flow. Centers of the two cusps are 15 m apart.

fractures. Second, the layering shows that crystal mush in the upper solidification zone of these magma sheets has distinct quasi-horizontal planes of weakness (the residual liquid layers) along which dense crystal mush can detach from the roof and sink to the floor.

2. Description of layering

The Holyoke flood basalt forms a massive flow up to 200 m thick in the Mesozoic Hartford, Pomperaug, and Deerfield basins of Connecticut and Massachusetts (Philpotts, 1998). The internal structure of the flow indicates that it solidified as a single ponded body of magma, with vesicles rising and collecting in the upper 10–20 m and crystal mush compacting in the lower third of the flow, with the expelled residual liquid segregating to form sheets of coarse-grained ferrodiorite near the center of the flow (Philpotts et al., 1996, 1999). A prominent, cuspate boundary separates the entablature from the colonnade (Fig. 1). Where the flow is thick (>100 m), this boundary occurs above the center of the flow, which indicates that crystal mush must have sunk to the floor of the magma sheet during solidification (Philpotts and Dickson, 2000).

The Holyoke basalt is a quartz tholeiite with approximately 5% plagioclase phenocrysts in a groundmass of plagioclase, augite, pigeonite and minor magnetite, quartz, and alkali feldspar. In the entablature, the pyroxene is ophitically intergrown with plagioclase, whereas in the colonnade, it occurs in granular patches that are surrounded by plagioclase crystals clustered together into chains that form a three-dimensional network (Philpotts et al., 1999). In the entablature, the late-crystallizing constituents are quenched to intersertal patches of extremely fine-grained dark mesostasis containing dendritic magnetite crystals and in some places immiscible droplets of iron- and silica-rich glass, whereas in the colonnade, slower cooling resulted in formation of patches of granophyre and equant-shaped magnetite crystals. Similar textural differences between the entablature and colonnade have been described from other thick flood-basalt flows (Long and Wood, 1986; Lyle, 2000) and attributed to more rapid crystallization in the entablature. Philpotts and Dickson (2000) showed that the rock texture in the colonnade is in fact inherited from crystal mush that formed in the upper solidification zone and then, on sinking to the floor of the magma sheet, underwent recrystallization.

In the entablature, plagioclase has three modes of occurrence. Some crystals are ophitically intergrown with pyroxene, others occur as separate intersertal crystals between the ophitic clusters, and a small number occur as phenocrysts. The ophitic clusters are approximately spherical with a diameter of ~1 mm (Fig. 2). They consist of several differently oriented pyroxene crystals. The intergrown plagioclase forms tapered laths that broaden as they radiate from the center of each cluster. In contrast, the intersertal plagioclase laths, which tend to be slightly larger, are rectangular and are commonly tangential to the ophitic clusters. Small olivine grains (now totally altered) occur near the center of many ophitic clusters and may have acted as nucleation centers for the pyroxene crystals. Such ophitic 'spherulitic' clusters are common in basalt (e.g. Fig. 86 in MacKenzie et al., 1982).

Electron microprobe analyses show that the pyroxene crystals are strongly zoned from magnesium-rich augite and pigeonite at the core of each cluster through sub-calcic

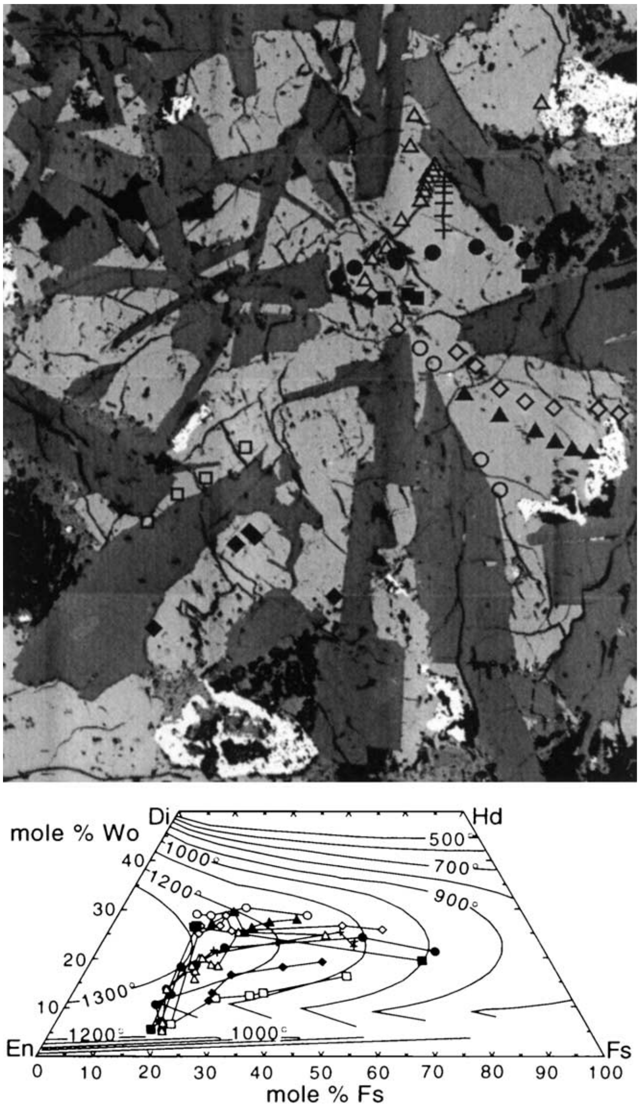

Fig. 2. Polished section of ophitic pyroxene–plagioclase cluster from near base of the entablature, 79 m beneath surface of flow (reflected light, width of field is 0.7 mm). Location of electron microprobe analyses of pyroxene (light gray) on the photomicrograph and in the pyroxene quadrilateral are shown with various symbols. The pyroxene is zoned from a Mg-rich core to Fe-rich rim through compositions lying within the pyroxene solvus (Lindsley, 1983). Note increasing width of plagioclase laths (dark gray) from center to rim of cluster.

augite to iron-rich compositions on the rim (Fig. 2). The pyroxenes crystallized with a complete disregard for the pyroxene solvus (Lindsley, 1983), indicating that they grew rapidly and far from equilibrium. The plagioclase laths in the ophitic clusters are normally zoned from An_{58} at the core of the clusters to An_{35} in contact with the surrounding mesostasis. The intersertal plagioclase crystals consistently show a slightly higher anorthite content at the core, being zoned from cores of An_{60} to rims of An_{35}.

The modal layering is present everywhere in the entablature beneath the vesicular crustal layer. However, it is subtle and normally visible only in scanned images of an entire thin section (Fig. 3). First, a thin section is cut from an oriented sample in a plane parallel to the original vertical, which in a flood-basalt flow is defined by the colonnade jointing. A high-resolution image is then obtained by placing the petrographic thin section in a 35-mm-film scanner. An 11-Mbyte image provides enough detail for the entire thin section to be viewed at the same magnification as provided by a typical low-power objective on a petrographic microscope (see, for example, De Keyser, 1999). In these large, detailed images, faint large-scale features are apparent.

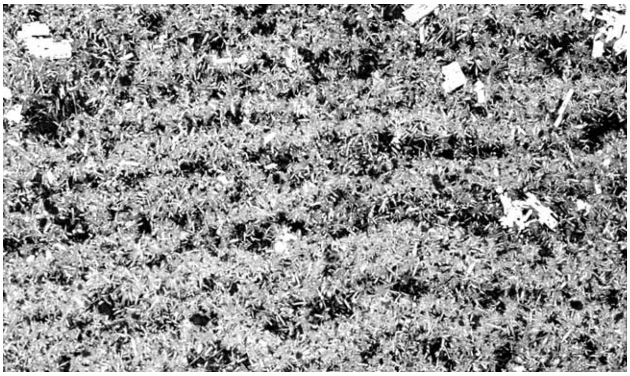

Fig. 3. Horizontal modal layering in the entablature 122 m above the base of the 200-m-thick flow. Light colored layers consist of ophitic pyroxene–plagioclase clusters, whereas intervening dark zones consist of patches of mesostasis containing dendritic magnetite crystals and glassy droplets of iron- and silica-rich immiscible liquids. The image was obtained by scanning the thin section in a 35-mm-film scanner. Width of field is 22 mm.

Throughout the entablature, most ophitic pyroxene–plagioclase clusters are linked together to form roughly horizontal layers that are separated from each other by patches of mesostasis (Fig. 3). The layers are typically one ophitic cluster thick and repeat approximately every 1–2 mm. They range in length from only a few clusters to ones that have been traced on polished glaciated surfaces for over a meter. Although most are sub-parallel, some tend to sag away from the overlying layer to produce lenses of mesostasis between the layers (top center of Fig. 4). In thin section, these cuspate layers of linked pyroxene crystals with their radiating laths of plagioclase resemble the pattern of tinsel hung on a Christmas tree or a boa draped across the shoulders. For this reason we propose that this type of layering be referred to as the *boa texture*.

Because the layers are normally visible only in thin section, the precise orientation of the layers in most of the entablature is uncertain. Based on the orientation seen in more than 80 thin sections from the entablature, the layers are approximately horizontal. However, in a series of samples collected immediately above the cuspate boundary separating the colonnade from the entablature (Fig. 1), the layers parallel the boundary and are normal to the radiating joints in the entablature. This simple observation is of great importance because the layers were clearly formed from minerals that crystallized from the magma, and thus the layering must predate the fractures, which form during

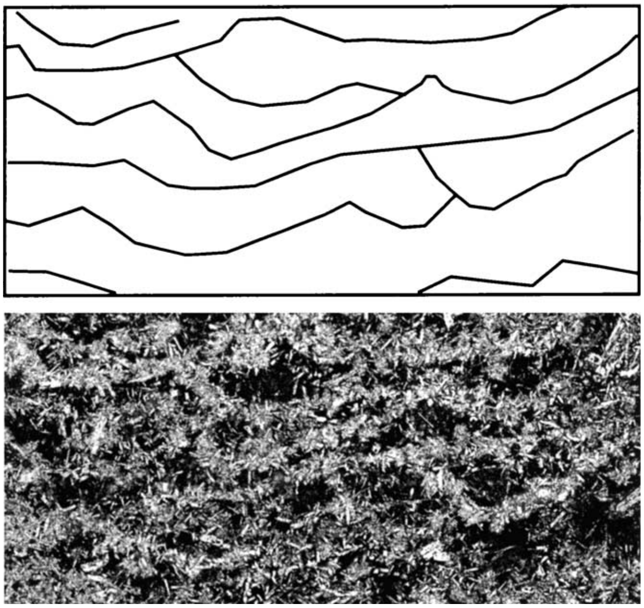

Fig. 4. Detail of layers of pyroxene–plagioclase clusters (light) and intervening patches of mesostasis (dark). Note sags in some layers producing the lower bounds of larger patches of mesostasis. Plane light. A tracing of the layers is shown above. Width of field is 12.5 mm.

cooling of the rock. The shape of the boundary between the entablature and colonnade must therefore reflect a primary magmatic feature and is not simply the position where downward and upward propagating fractures met.

3. Other occurrences

Although we do not have oriented samples from the entablature of other thick flood-basalt flows, examination of randomly oriented samples in the petrographic collection at the University of Connecticut reveal clear examples of the boa texture in the Picture Gorge basalt of Oregon, and in the Deccan traps of India (Fig. 5A and B, respectively).

A similar texture has also been found in oriented samples from the roof zone of the Palisades sill of New Jersey (Fig. 5C). Here, sheets of darker colored diabase separate light-colored quasi-horizontal layers of ophitic pyroxene–plagioclase clusters. The darker rock clearly contains later-crystallizing minerals, including magnetite, biotite, and hydrous alteration products of the ferromagnesian minerals; it also contains patches of granophyre and apatite crystals. This darker fraction corresponds to the mesostasis that separates the pyroxene–plagioclase layers in the Holyoke basalt. An interesting feature of this layering in the Palisades sill is that it is commonly disrupted; the crystal mush appears to have been caught in the act of falling from the roof zone (Fig. 5C). Steiner et al. (1992) in describing the chilled margin of the Palisades sill at Upper Nyack illustrates (his Fig. 3) a similar texture of pyroxene–plagioclase clusters strung together.

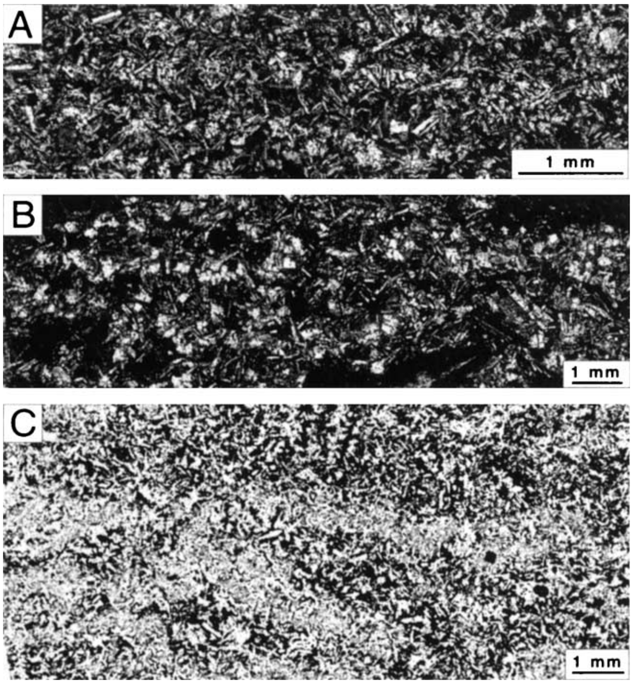

Fig. 5. Layers of ophitic pyroxene–plagioclases clusters in (A) the Picture Gorge flood basalt of Oregon (crossed polars, width of field is 6 mm), (B) in Deccan trap of India (crossed polars, width of field is 12 mm), and (C) in the roof zone of the Palisades sill (plane light, width of field is 12 mm).

Fig. 63 in the *Atlas of Igneous Rocks and their Textures* by MacKenzie et al. (1982) while illustrating intersertal, intergranular, and subophitic textures, serendipitously provides a beautiful example of the boa texture in the Whin sill of northern England. Although the orientation of this sample is not indicated, the linkage between the clusters is clear. These few examples lead us to believe that the texture may be common not only in flood-basalt flows but also in the roof zones of shallow intrusions.

4. Origin of layering

In flood-basalt flows, the layering is restricted to the entablature and is not found in the colonnade. The layering must therefore result from conditions that are peculiar to that part of the flow. We believe that rapid cooling and crystallization are key to the formation of the layers. Long and Wood (1986) first argued that the textural differences between the entablature and colonnade in many thick Columbia River flood-basalt flows resulted from water flooding the surface of the flow and circulating down through fractures in the crust where it brought about quenching in the upper solidification zone. Lyle (2000) has examined numerous flood-basalt flows, including those of the Giant's Causeway in Northern Ireland, and has come to the same conclusion. The textures and the compositions of the pyroxenes in the entablature of the Holyoke basalt (Philpotts and Dickson, 2000) indicate that

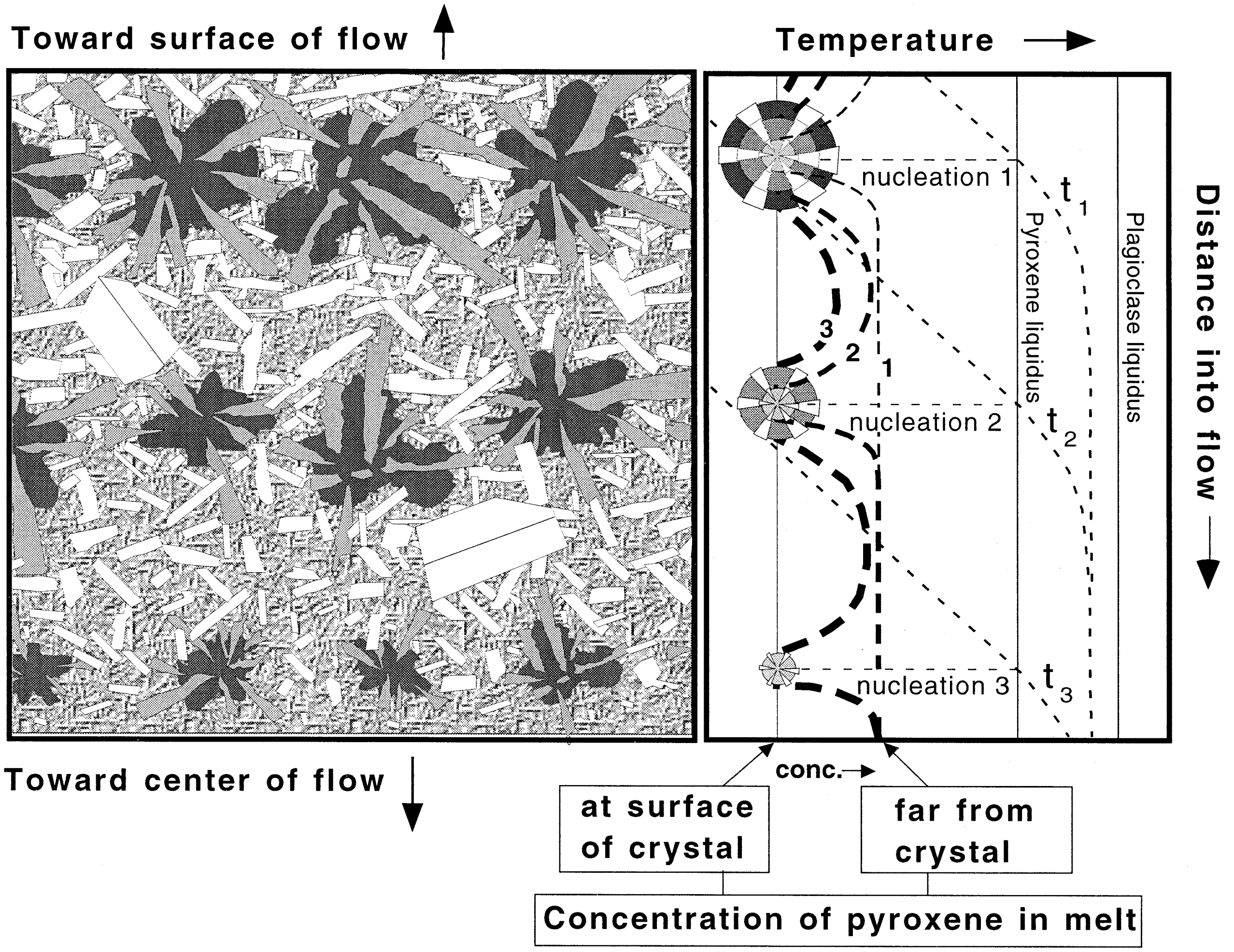

Fig. 6. Schematic model showing the formation of three layers of pyroxene–plagioclase clusters in the upper solidification zone of the Holyoke basalt. The position of the thermal boundary layer is shown at three successive times (t_1, t_2, t_3). Nucleation of pyroxene–plagioclase clusters occurred as the thermal boundary layer advanced, and the temperature fell below the pyroxene liquidus. Although the growth of any one pyroxene–plagioclase cluster is continuous, we have divided the growth into three stages for illustrative purposes. By the time the third-nucleating cluster reached its first growth stage, the first-nucleating cluster reached its third stage. The growth of the pyroxene in the clusters depleted the surrounding melt in pyroxene components to produce compositional gradients (1, 2, 3), which are shown for the three successive growth periods. See text for details. In the schematic drawing of the rock, plagioclase external to the pyroxene–plagioclase clusters is white, whereas plagioclase intergrown with pyroxene is light gray and the pyroxene is dark gray.

this part of the flow did indeed crystallize rapidly. The flux of water through the fractures, which would have depended on the density and width of the fractures, would have determined the upper solidification zone's rate of advance.

Although the Holyoke basalt contains phenocrysts only of plagioclase (i.e. the original basalt was already on the plagioclase liquidus), experiments reveal that pyroxene appeared on the liquidus following only a few degrees of cooling (Philpotts and Reichenbach, 1985). The basalt was therefore multiply saturated during most of its crystallization, and the pyroxene–plagioclase clusters that form the boa texture would have started forming in the upper solidification zone almost as soon as cooling began.

Each pyroxene–plagioclase cluster is strongly zoned from magnesium-rich pyroxene and calcic plagioclase at the core to iron-rich pyroxene and more sodic plagioclase at the rim where it comes in contact with patches of mesostasis formed from iron-rich residual liquid. Although the pyroxenes have compositions far from equilibrium (Fig. 2), their strong zoning indicates that they crystallized over a considerable temperature range from liquid that must have developed strong compositional gradients around the crystals as they grew. Such gradients are to be expected in a rapidly advancing thermal boundary layer because heat diffuses so very much faster than do ions.

Fig. 6 illustrates how we believe the boa texture formed. Cooling from above lowered the temperature in the upper solidification zone below the pyroxene liquidus, and after sufficient undercooling, a layer of pyroxene crystals nucleated along an isothermal plane. This is designated nucleation event 1 in Fig. 6. Cotectic crystallization of plagioclase and pyroxene resulted in many of the plagioclase crystals growing in a radial manner around the center of each pyroxene cluster. As each cluster grew, however, the melt immediately below it became depleted in pyroxene and plagioclase components and enriched in excluded elements such as iron and titanium. Because the thermal gradient advanced more rapidly than did the diffusional gradients, melt in front of the diffusional boundary layer soon fell below the pyroxene liquidus and a new zone of pyroxene–plagioclase clusters nucleated (nucleation 2 in Fig. 6). These clusters grew from components in the melt both in front of the zone of nucleation and from the melt trapped between the two layers of pyroxene–plagioclase clusters. Although this trapped liquid was enriched in iron, the rapidly falling temperature soon allowed for progressively more iron-rich pyroxene and more albitic plagioclase to crystallize onto the rims of the clusters. In front of the newly nucleated pyroxene–plagioclase clusters, however, the thermal gradient again got ahead of the diffusional boundary layer and a third layer of clusters nucleated (nucleation 3 in Fig. 6). The process continued with successive nucleation and growth of layers of pyroxene–plagioclase clusters between which was trapped the residual liquid, some of which crystallized onto the rims of the clusters and the remainder split into iron-rich and silica-rich immiscible liquids or crystallized to fine-grained skeletal magnetite and felsic phases. Although the layering results from the interaction of diffusional processes, the spacing between the layers does not vary with depth in the flow. This is because the temperature gradient and the rate of advance of the solidification front remain relatively constant and are controlled by the rate of advance of fractures in which water can flash to steam.

5. Significance of layering

Recognition of the layering produced by the linkage of pyroxene–plagioclase clusters in the entablature of the Holyoke flood-basalt flow has two important consequences. First, the layering tells us about the shape of the upper solidification zone as it advanced down into the flow, and second, it tells us about the texture and consequently the physical properties of the crystal mush in the upper solidification zone.

The layering was clearly developed in the magmatic state. The layers appear to have formed parallel to the downward-growing crystallization front. Because the layering parallels the cuspate boundary separating the entablature and colonnade, this cuspate boundary must indicate the shape of the final position of the downward solidifying roof of the magma sheet; it is not simply where downward and upward propagating fractures met. When we look at this cuspate boundary (Fig. 1), we are actually seeing the shape of the roof of this magma sheet.

As pointed out by DeGraff and Aydin (1987), the downward protruding lobes of radiating fractures in the entablature (Fig. 1) are commonly centered on a prominent fracture through the crust of the flow. Such fractures provide access for water, which on boiling removes the heat that promotes rapid crystallization in the upper solidification zone. These fractures in the Holyoke would have behaved as cold fingers that extended down into the magma sheet and produced the lobate shape of the upper solidification zone.

The fact that the crystal mush in the upper solidification zone was layered rather than homogeneous made it weaker than would be predicted for a given degree of crystallization (see, for example, the Roscoe–Einstein equation in Marsh, 1981). Indeed, the discontinuous sheets of liquid between the layers of pyroxene–plagioclase clusters would have remained liquid until late in the crystallization and provided planes of weakness along which the mush could have separated from the roof zone. The bulk density of the crystal mush was greater than that of the initial magma away from the crystallization front, so the mush in the roof zone was always gravitationally unstable. Moreover, Philpotts and Dickson (2000) have shown that the texture of the rock in the Holyoke's colonnade is most easily interpreted as having formed by recrystallization of mush that sank from the upper solidification zone of this flow. The melt zones between the pyroxene–plagioclase layers are therefore the most likely zones along which the mush detached from the roof. The disruption of the layering illustrated in Fig. 5C in the sample from the Palisades sill may actually record the breaking away of crystal mush from the roof of this sill along the liquid layers separating the pyroxene–plagioclase clusters.

If the cusps on the entablature–colonnade boundary (Fig. 1) give a measure of the relief on the upper solidification zone of the flow, and if the layering parallels this boundary, crystal mush sinking from the upper solidification zone would almost certainly have sunk from the lowest points on the cusps. The return flow of hot magma from within the flow would then most likely have occurred in the narrow high points between the lobes (Fig. 1). The wavelength of 10–15 m on the entablature–colonnade boundary would therefore provide a length scale for this convective process.

The layering produced by ophitic clusters in the roof zone of the Palisade sill appears essentially identical to that in the entablature of the Holyoke basalt. It is expected, therefore, that the boa texture will be found to be common in the roof zones of other thick sills (e.g. the Whin sill) where its presence will be equally important in revealing the nature of the crystal mush that may have sunk from the roof zones of these sills.

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