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WM Project 10, 11, 16
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Dr. D. J. Brooks
Geotechnical Branch
Office of Nuclear Material
Safety and Safeguards
Room 623-SS
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Washington, D.C. 20555

Dear Dave:

Please find enclosed the letter report referenced in the November monthly progress report for B0287, "Technical Assistance in Geochemistry."

Sincerely,

Gary K Jacobs

Gary K. Jacobs
Manager, NRC Waste Programs
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GKJ/

Enclosures: Letter Report LR-287-65

cc w/o enclosure:

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LR-287-65
12/08/86

LETTER REPORT

Title: Review and Evaluation of Structures, Textures, and Cooling Histories of Columbia River Basalt Flows, Geol. Soc. Amer. Bull., v. 97, pp. 1144-1155, Sept., 1986, by Philip E. Long and Bernard J. Wood

AUTHOR: J. G. Blencoe
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PROJECT TITLE: Technical Assistance in Geochemistry

PROJECT MANAGER: G. K. Jacobs

ACTIVITY NUMBER: ORNL #41 88 54 92 4 (FIN No. B0287)
NRC #50 19 03 01

OVERVIEW

This article discusses the origin of colonnade and entablature zones in subaerial basalt flows. The evidence weighed in theorizing an origin for these structures includes: (1) the macroscopic characteristics of subaerial basalt flows – and particularly the nature of fracturing (columnar jointing) in these flows; (2) the petrographic characteristics of rock samples from intraflow structures in subaerial basalts; and (3) the results obtained from mathematical modeling of the cooling of a subaerial basalt flow. It is concluded that colonnade zones in subaerial basalt flows form by slow conductive cooling, while entablature zones form by relatively fast, "convective" cooling induced by downward-ingressing meteoric water that enters the flow after its base and top have solidified.

REVIEW

Petrologic and Petrographic Characteristics of Colonnade and Entablature Zones in Subaerial Basalts

In numerous localities worldwide, subaerial basalt flows are characterized by laterally persistent, intraflow structures known as "colonnade" and "entablature." (Hereinafter, these structures will be referred to as "colonnade zones" and "entablature zones.") Colonnade zones commonly occur in the lower and upper third of a subaerial basalt flow, and consist of relatively well-formed ~0.3-2 m basalt columns which are typically oriented perpendicular to the base of the flow. The lower (basal) colonnade zone commonly grades upward into an entablature zone which occupies the interior one-third or upper one-half of the flow. The entablature zone exhibits small (0.2- to 0.5-m-diameter), irregular to hackly columns, which may form radiating patterns, or otherwise deviate from an orientation perpendicular to the base of the flow. Finally, in many subaerial basalt flows, entablature grades upward into an upper colonnade zone, which in turn is overlain by a vesicular flow top.

In most subaerial basalts there is a close relationship between intraflow structures and petrographic textures. Samples of basalt from colonnade zones typically exhibit intersertal to intergranular textures. By contrast, samples from entablature zones are characterized by subhyalophitic textures, dendritic opaque oxide minerals, and an inclusion-charged glassy mesostasis.

Long and Wood stress that the petrographic characteristics of colonnade and entablature basalt can be highly variable. For example, both the quantities and the textures of mesostasis in entablature basalt can vary significantly from one flow to the next. In particular, the quantities and morphologies of opaque oxide grains in the mesostasis are highly variable from one flow to another. In some flows it is observed that opaque oxide phases are virtually absent in the entablature, whereas in other flows the textures of opaque grains differ only slightly across the entablature-colonnade contact(s). Despite these variations, however, two features of colonnade and entablature zones are consistent from one flow to the next: (1) the quantities of mesostasis are always markedly greater in entablature zones than in colonnade zones, and (2) the quantities of inclusions (blebs) in entablature mesostasis are always much greater than the quantities of inclusions in colonnade mesostasis.

Internal Structures and Textures of Grande Ronde Basalt Flows

In attempting to explain the origin of colonnade and entablature zones in subaerial basalts, Long and Wood focus attention on the basalt flows of the Grande Ronde Basalt formation in the Columbia Plateau of Washington state. The authors believe that this formation merits special attention because an unusually high proportion (~60%) of Grande Ronde flows exposed in the central part of the Columbia Plateau exhibit well-defined entablature zones.

According to Long and Wood, Grande Ronde Basalt flows are typically stratified from top to bottom as follows: (1) a ropy to brecciated, vesicular flow top; (2) upper colonnade with relatively large, irregular columns (0.7 to 2.2 m in diameter) — with or without vesicles; (3) entablature, consisting of relatively small, hackly to regular columns (0.2 to 0.9 m in diameter); (4) lower colonnade, consisting of well-formed to wavy, large columns (0.5 to 1.5 m in diameter); and (5) a glassy basal zone that varies greatly in thickness and may be highly fractured, vesicular, or pillowed with hyaloclasite. However, the authors also stress that, in a given flow, these structures may vary greatly in thickness, be entirely absent, or occur repeatedly.

Long (1978) has documented the relationships between the petrologic and petrographic features of Grande Ronde Basalt flows. He classified the flows into three general types: Type I, Type II, and Type III. Long and Wood stress that these flow types should be regarded as hypothetical end members, among which there can be continuous gradation of petrologic and petrographic characteristics.

Type I Flows

Type I flows are composed mainly of highly irregular colonnade basalt. Type I flows are comparitively thin (10-30 m thick), they contain irregular, tapering columns 1-2 m in diameter, they always lack a distinct entablature, and they have a poorly developed vesicular flow top. Also, Type I flows exhibit little variation in petrographic texture throughout the main body of the flow. Specifically, with the exception of the glassy basalt in the upper 5% of the flow (this basalt is believed to be formed by rapid cooling of surficial and near-surface lava shortly after eruption), Type I flows exhibit intersertal to intergranular textures throughout their thicknesses. Moreover, the quantities and textures of mesostasis glass, as well as the morphologies of opaque grains, are similar in all parts of the flow beneath the flow top.

Type II Flows

Type II flows exhibit repeated colonnade and entablature tiers. An upper colonnade zone may or may not be present. Type II flows are comparatively thick flows (45-76 m thick) and exhibit columnar tiers of alternating entablature and colonnade-type columns in the lower half of the flow, which grade upward into a hackly entablature. In the upper one-third of some tiered flows, layers are defined by thin zones of abundant vesicles. In the entablature zones, fanning of columns is sometimes observed. Finally, Type II flows commonly possess a clinkery flow top.

Type II flows also exhibit petrographic characteristics that vary in accordance with macroscopic intraflow structures. Samples of basalt from the lower colonnade typically display intersertal to intergranular textures that are finer grained but otherwise similar to basalt samples from Type I flows. In contrast, basalt samples from entablature zones typically exhibit subhyalophitic textures, dendritic opaque oxide minerals, and an inclusion-charged glassy mesostasis. Another important observation is that glassy mesostasis is much more abundant in entablature zones than in colonnade zones. Colonnade zones typically contain 15 to 25 volume % mesostasis, whereas entablature zones contain from 35 to 65 volume % mesostasis.

Type III Flows

Type III flows are typically thick flows (30-80 m) that possess a distinct lower colonnade zone and a single, well-defined entablature zone. Therefore, unlike Type II flows, the colonnade and entablature sequence is not repeated. A crude upper colonnade caps the entablature of most Type III flows. Basal pillow basalt, while observed in all types of Grande Ronde Basalt flows, is most common in Type III flows. The columns in the colonnade zones frequently exhibit pinch-and-swell structure. The entablature zone is typically a complex pattern of small, radiating columns. The textures of colonnade and entablature basalt samples from Type III flows are similar to those in Type II flows.

In Type III flows, the boundary between colonnade and entablature is marked by an abrupt change in fracture abundance and column size. This single, sharp entablature-colonnade contact commonly occurs approximately one-third of the way up from the base of the flow. Samples ~1 m apart on either side of this contact show the characteristic textures of colonnade and entablature. In the few flows where the entablature-colonnade contact is gradational, the textures of basalt samples are also gradational across the contact. Therefore, in type III flows, petrographic textures consistently reflect macroscopic features.

Origin of Colonnade and Entablature Zones in Grande Ronde Basalt Flows

The petrographic characteristics of colonnade and entablature zones in Grande Ronde Basalt flows – specifically, the quantities and textures of the mesostasis in entablature zones, along with the quantities and morphologies of opaque grains in these zones relative to colonnade zones – suggest strongly that entablature zones formed during periods of comparatively rapid cooling of a flow. Therefore, Long and Wood propose that entablature zones form when comparatively slow rates of cooling (which produce zones of colonnade basalt) are suddenly interrupted or replaced – spatially or temporally – by rates of much faster cooling. This hypothesis accounts for the greater quantities of mesostasis observed in entablature samples. Long and Wood emphasize, however, that rates of cooling during the formation of entablature zones were not so rapid that crystallization was arrested completely. Instead, the accelerated cooling typically gave rise to higher rates of crystal nucleation that produced a higher density of both crystalline and glassy inclusions (rounded blebs) in the mesostasis.

The dendritic morphologies of the opaque oxide grains in samples of entablature basalt are also consistent with a significant degree of undercooling that would result from rapid cooling. In some flows, titaniferous magnetites are completely absent in entablature zones, and this observation suggests that, in these flows, rates of cooling were sufficiently rapid to completely suppress the nucleation and growth of magnetite. These same samples of entablature basalt typically exhibit mesostasis with the finest grain size. This observation, too, is consistent with a high rate of cooling.

Thus, for Type II and Type III basalt flows, it is evident that there were significant differences in the rates of cooling across entablature-colonnade contacts. Significantly, however, the thermal properties of silicate rocks and mathematical models of conductive cooling indicate that abrupt changes in rates of cooling of a basalt flow cannot occur if cooling is attributable entirely to conductive heat loss (Jaeger, 1961; Spry, 1962). In other words, the apparent "quenching" of the center of a subaerial basalt flow cannot occur if the flow cools in an undisturbed conductive manner.

Because undisturbed conductive cooling cannot explain "quenching" of the interior of a subaerial basalt flow, Long and Wood suggest that a special event must occur during the cooling history that induces more rapid cooling. They suggest that the most likely means of rapid cooling is for liquid water to invade the solidified top of the cooling lava flow along propagating cooling joints. Water has a high heat capacity and latent heat of vaporization and, therefore, combined with its low viscosity, it provides a viable medium for removal of heat via convective circulation. The ability of water to induce relatively high cooling rates has been amply demonstrated in modern extrusive basalts such as the Haemiey basalt flow (Bjornsson et al., 1982) and Kilauea Iki Lava Lake (Hardee, 1980).

Cooling of Grande Ronde Basalt Flows via Water Ingress

Laterally extensive pillow structures that occur locally at the bases of Grande Ronde Basalt flows (Long and Davidson, 1981) reflect the lacustrine environment into which these lavas were erupted. Paleoclimatic evidence indicates that the environment during the main Grande Ronde eruptive phase (16.5-14.5 m.y. B.P.) was subtropical with a relatively high rainfall (Newman, 1970; McKee et al., 1977). Under such conditions, there would have been considerable runoff of meteoric water and a potential for the development of both long- and short-lived lakes. Accordingly, Long and Wood propose that, as thick Grande Ronde Basalt flows invaded stream valleys and lakes, they caused temporary damming and disruption of local drainage systems. This eruptive phase was followed by a period of subaerial cooling that established a quenched flow top, a glassy basal zone, a basal colonnade zone and, in some cases, an upper colonnade zone in each lava flow. However, in this climatic and physiographic setting, it is also to be expected that, within a brief period of time – perhaps a few months to a year – water would overflow the tops of cooling flows. Influx of water into the solidified tops of flows along columnar joints and cracks would have increased the rates of cooling in the interiors of the flows. Alternatively, widespread flooding might have occurred as subsequent basalt flows rapidly displaced ponded water.

Mathematical Models for the Cooling of Grande Ronde Basalt Flows

To test the idea that flood waters affected the cooling histories of many Grande Ronde Basalt flows, Long and Wood developed a simple one-dimensional thermal model that mimics convective removal of heat by water. Specifically, two simple hypothetical cases of basalt-flow cooling and solidification were investigated mathematically to explore the possibility that water ingress can explain the development of entablature zones in Grande Ronde Basalt flows.

Case 1

In Case 1, water penetrates the solidified top of the flow and cools it to ambient temperature down to a depth "x." The flow above depth "x" remains fixed at ambient temperature (0°C). Cooling below depth "x" proceeds by pure conduction.

Case 2

In Case 2, water also penetrates the solidified top of the flow and cools it to ambient temperature down to a depth "x." However, unlike

Case 1, as soon as the solidus is reached at a particular depth, the basalt is instantaneously quenched to 0°C. Therefore, as the lava below depth x cools through the solidus, the cold boundary – representing the depth of water penetration – follows the solidus down through the flow, extending the zone of quenching through the flow interior.

Results for Case 1

Results for Case 1 indicate that a fixed cold boundary within a subaerial basalt flow cannot quench more than a small fraction of the liquid beneath it. Therefore, Case 1 is a poor model for subaerial basalt flows with thick entablatures.

Results for Case 2

Results of calculations for Case 2 indicate that a "front" of downward ingressing water immediately above the liquid/solid interface can produce a thick entablature zone in the interior of a flow. Also, the calculations indicate that the bottom part of a flow will continue to cool slowly through the solidus, thereby allowing the basal colonnade zone to extend upward. Therefore, the contact between the lower colonnade and the entablature represents the position in a flow where the upper and lower solidification fronts meet and where the last magma crystallizes. The upper solidification front moves downward from the top of the flow at a faster rate than the lower solidification front moves upward from the base of the flow and, therefore, the upper solidification front is responsible for cooling most of the flow. (The relatively slow upward movement of the solid/liquid interface near the bottom of the flow – compared to the downward movement of the solid/liquid interface near the top of the flow – may explain the observation that lower colonnades are generally better developed and exhibit more perfect column shapes than do upper colonnades.) Upper colonnades are explained by the Case 2 model if it is assumed that slow cooling prior to flooding continues long enough to crystallize a significant portion of the upper part of the flow.

Origin of Type I, II, and III Basalt Flows in the Grande Ronde Basalt

Type I Flows

In view of the comparatively simple "typical" petrology and petrography of Type I flows, and particularly the absence of a well-defined entablature zone, Long and Wood conclude that these flows solidified by slow conductive cooling. Type I flows are typically thinner than Type II or Type III flows and, therefore, Type I flows were less likely to pond and disrupt local drainage patterns. Consequently, Type I basalts were less susceptible to "quenching" by flood waters.

In some Type I flows, the thickness of the lower colonnade zone varies markedly, even to the extent of being almost completely absent locally. Where the lower colonnade of Type I flows is thin, Long and Wood surmise that conductive cooling must have been very rapid. Correspondingly, where Type I flows exhibit a thick basal colonnade zone, it is logical to conclude that conductive cooling was comparatively slow.

Type II and III flows

In the Case II mathematical model investigated by Long and Wood, progressive downward movement of a quenched zone induced by water ingress generates a thick, rapidly cooled entablature zone in the interior of the flow. This model accurately predicts the principal macroscopic features of Type III Grande Ronde Basalt flows. However, in Type II flows, colonnade and entablature tiers are repeated from the bottom to the top of the flow. In order to simulate conditions that could produce this pattern of intraflow structures, Long and Wood devised a model based on cyclic flooding. Significantly, this model reproduces the cycle of fast and slow cooling that is required to give the appropriate structural and textural variations in Type II flows. Therefore, mathematical modeling indicates that Type II flows can be formed by multiple flooding events with intervening dry periods.

Conclusions

Evidence and analysis presented by Long and Wood imply the following conclusions regarding the origin of colonnade and entablature zones in Grande Ronde Basalt flows.

1. Colonnade zones in Grande Ronde Basalt flows form by slow conductive cooling, while entablature zones form by relatively fast, "convective" cooling induced by downward-ingressing meteoric water that enters the flow after its base and top have congealed.

2. The water content of primary basaltic lava, evolution of volcanic gases, and kinematics of flow emplacement appear to be irrelevant to to the development of colonnade and entablature zones in Grande Ronde Basalt flows.

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EVALUATION

This article discusses the origin of colonnade and entablature zones in subaerial basalt flows. The evidence weighed in theorizing an origin for these structures includes: (1) the macroscopic characteristics of subaerial basalt flows – and particularly the nature of fracturing (columnar jointing) in these flows; (2) the petrographic characteristics of rock samples from intraflow structures in subaerial basalts; and (3) the results obtained from mathematical modeling of the cooling of a subaerial basalt flow. It is concluded that colonnade zones in subaerial basalt flows form by slow conductive cooling, while entablature zones form by relatively fast, "convective" cooling induced by downward-ingressing meteoric water that enters the flow after its base and top have solidified.

The authors' explanation for the origin of colonnade and entablature zones in Grande Ronde Basalt flows is fully consistent with the evidence presented. However, it is also true that additional evidence could have been marshalled to further elucidate the origin of these intraflow structures. In particular, it would be very informative to obtain whole-rock oxygen isotope data for samples of basalt taken from colonnade and entablature zones. If the authors' explanation for the origin of entablature zones is correct, then samples of basalt from the layer of rock immediately above each entablature zone should offer evidence of oxygen isotope exchange between basalt and meteoric water. Further, it is distinctly possible that the Fe^{2+}/Fe^{3+} ratio of mesostasis glass in the rocks immediately above entablature zones will provide evidence of intimate contact with hot, oxidizing meteoric waters.

Finally, in text presented near the end of this article, Long and Wood imply that all of the secondary minerals now found in Grande Ronde basalts formed after burial beneath superjacent rocks. However, no evidence is provided to support this conclusion. Therefore, the reader is left wondering whether some of the secondary minerals observed in entablature-bearing flows might have crystallized contemporaneously with entablature basalt via rock-water interaction in the rocks immediately above the part of the flow where entablature basalt was forming.