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CHARACTERIZATION OF HYALOCLASTITE DERIVED FROM A BASALTIC PARENT MAGMA, LOCATED AT LEIRHNJÚKUR, NE ICELAND

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INTRODUCTION

This study focuses on a kīpuka surrounded by younger basaltic lavas from the Krafla Fires of 1975-84 near Lake Myvatn in northeast Iceland, referred to as Leirhnjúkur. This ridge contains characteristics which strongly suggest a method of formation similar to that associated with hyaloclastite ridges, which are also commonly referred to as tuyas or tindars in the literature. Although several papers refer to Leirhnjúkur as a hyaloclastite ridge (Bemmelen and Rutten, 1955; Nicholson and Latin, 1991), there is no empirical evidence in the literature to support this claim, as Leirhnjúkur itself has not previously been the subject of any specific study. Accordingly, no data has been presented on the petrological composition of the hyaloclastite deposits at Leirhnjúkur. Thus, the main question addressed here is whether the material that produced the hyaloclastite ridge found at Leirhnjúkur formed from a basaltic magma. Through the use of scanning electron microscopy and x-ray fluorescence analysis, the bulk composition of the material shows that the parent magma was a basaltic andesitic. For the purposes of the whole rock analysis performed, only the glassy clasts were analyzed. In addition to determination of the whole rock composition, samples were characterized based on physical characteristics, such as clast size and abundance, based on observations made in situ at Leirhnjúkur. This study also aims to determine the relationship between the palagonite, or altered volcanic glass (Jakobsson and Gudmundsson, 2008), and clasts of volcanic glass, or sideromelane, that were the basis of the whole rock composition analysis. Although there are several variations in palagonite composition, this study suggests that all derive from similar basaltic glass sources. With material from outcrops positioned around the hyaloclastite ridge Leirhnjúkur, I will create a history of formation based on the formations found at each outcrop and their position relative to one another.

GEOLOGIC BACKGROUND

Volcanism in Iceland is unique in that an active spreading axis is observable on land on the island (McBirney, 1984), which has resulted in its status as a highly volcanically active area since Tertiary times due to the coincidence of a hotspot plume with the Mid-Atlantic Ridge.

The interaction between the Mid-Atlantic Ridge and the plume center of Iceland's hotspot is dominated by the westward movement of the plate boundary responsible for the Mid-Atlantic Ridge and the resulting eastward relocation of the spreading axis. (Hardarson, et al., 1997).

The intense volcanic activity that is a hallmark of Iceland geology, combined with the waxing and waning of ice sheets over time, led to the development of an abundance of landforms developed by subglacial and intraglacial eruptions, such as mobergs, moberg sheets, tindars, and tuyas (Jakobsson and Gudmundsson, 2008), as well as landforms developed by subaerial eruptions, such as scoria cones and subaerial lava flows (Mattson and Hoskuldsson, 2002). Hyaloclastite ridges form as the result of subglacial to intraglacial volcanic eruptions, specifically fissure eruptions (Jakobsson and Gudmundsson, 2008). They are assumed to have formed during successive Pleistocene glaciations (Schopka et al., 2005), (Jakobsson and Gudmundsson, 2008). Tuyas and tindars differ in terms of topographic shape: tindars are linear, serrated ridges (Jones, 1969) and tuyas are subrectangular to circular, flat-topped mountains (Mathews, 1947). There is, however, some overlap in the stratigraphic units that compose them. Schopka, et al. (2005) identifies these units as: 1) pillow lavas that formed under high hydrostatic pressure; 2) tephra cones that formed from the explosive fragmentation attributed to decreased hydrostatic pressure; 3) subaerially erupted lava caps resulting from the sustained volcanic activity melting through the overlying glacial ice; and 4) foreset breccias produced by sustained growth of lava cap. The transition from tindar to tuya is marked by the presence or absence of facies 3 and 4, where a formation is characterized as a tindar if it lacks facies 3 and 4, and as a tuya if facies 3 and/or 4 are present (Fig. 1).

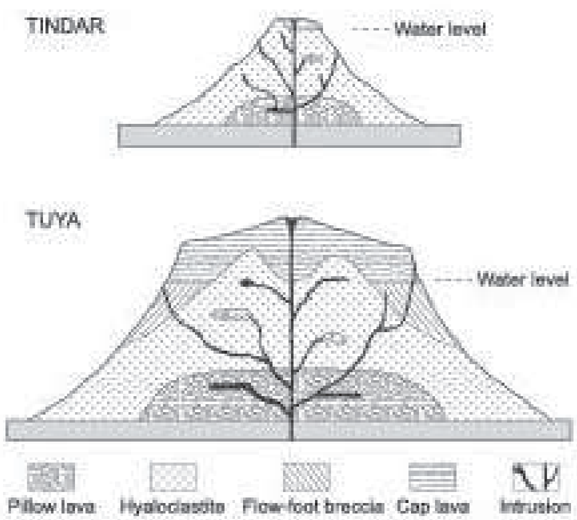

Figure 1. Schematic representation of the components comprising tindars and tuyas. Taken from Jackson & Grundmundsson, 2008.

Hyaloclastite is the dominant material comprising these subglacial and intraglacial landforms. Hyaloclastite is a type of volcaniclastic deposit formed when magma explosively interacts with water, as well as when glassy lava rims become granulated through non-explosive processes. In both cases, hyaloclastite can be used to refer to both consolidated and unconsolidated deposits (Jakobsson and Gudmundsson, 2008). The explosive magma-

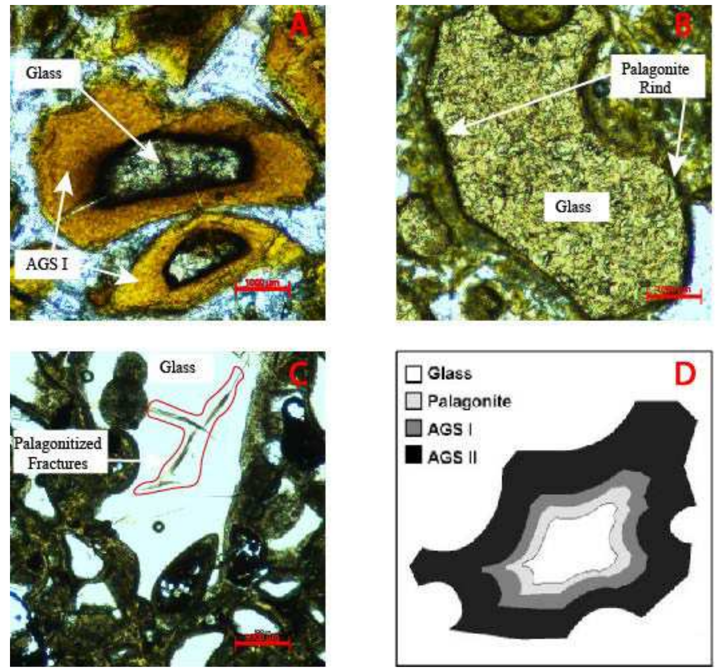

Figure 2. Thin section photomicrographs of three different samples showing variations in degree of palagonitization: (A) thoroughly palagonitized glass shard showing palagonite and aging stage I material (Stroncik & Schminke, 2001) from sample K3E-05. (B) glass shard with palagonite rind from sample K1M-04. (C) Fractured glass chard (factures outlined in red) from sample K2Hyalo-03 showing development of palagonite along exposed fracture surfaces. Slight development of palagonite rinds is evident. (D) Sketch showing ideally zoned palagonite, following the classification scheme presented in Stroncik & Schminke, 2001.

water interactions form angular fragments of glassy material, and can include whole or partial fragments of pillow basalts. Banik et al. (2013) describe hyaloclastite breccia as a massive volcaniclastic rock composed of angular fragments of sideromelane and fragments of crystalline lava, such as pillow basalts incorporated from previous eruptions. The term bedded hyaloclastite is used to describe a fine-grained volcaniclastic rock composed of angular sideromelane in which bedding features are evident (Banik et al., 2013).

A defining feature of these subglacial volcanic eruptions is the alteration of the volcanic material, known as hyaloclastite, into a variety of clay minerals, which are collectively referred to as palagonite. Palagonite was coined as a term to describe the products of altered sideromelane by Vonwaltershausen in 1845 (Stroncik, et al., 2001). The first detailed analysis of palagonite was presented by Peacock and Fuller in 1928 (Stroncik, et al. 2001), in which two common varieties of palagonite are identified. 'Gel palagonite' is isotropic, yellow, clear, and concentrically banded, whereas 'fibro-palagonite' is slightly anisotropic, translucent, yellow-brown, and slightly to strongly birefringent (Stroncik, et al., 2001). This classification of palagonite has stood uncontested since its presentation, until Stroncik and Schminke presented a new classification scheme in 2001 (Fig. 2).

METHODS

Field Methods

I identified six outcrops at Leirhnjúkur near the site of initial outbreak of the Krafla eruption. I identified facies in these outcrops based on texture and structure of the rock that show development of the ridge. For each sampling site, a minimum of one fist-sized matrix specimen was collected from each facies, as well as several clasts of less fresh material where present.

Experimental Methods

I designed this study's experimental portion, conducted at Syracuse University as a part of the Syracuse Lava Project (SLP – http://lavaproject.syr.edu), to replicate the fabric and composition of the hyaloclastic material that was collected in the field. For each pour, the melt material was derived from basalts of the Dresser Trap Rock unit of the Precambrian Keweenawan Rift. The first experiment poured 30-40 pounds of melt into a 700 liter volume of water. During this pour, pressure was physically applied to a small section of the lava after it came into contact with the water to mimic compaction experienced in naturally occurring hyaloclastite deposits. The second experiment poured 30-40 pounds of melt into 70 liters of water. The purpose of the second pour was to more closely model the phreatomagmatic environment in which hyaloclastite forms by increasing the lava to water ratio in order to increase the explosivity of the lava. For each experiment, two separate video recordings were taken, one from an aerial viewpoint approximately 4 meters above the flow's surface and one from a landscape view. A FLIR camera was also used to record the temperature of the flow's surface and data on the temperature of the inner portion of the flow was gathered using thermocouples attached to a data logger. These thermocouples recorded the initial temperature of the lava as it came out of the furnace and the water temperature for the duration of the flow (Fig. 3).

Analytical Methods

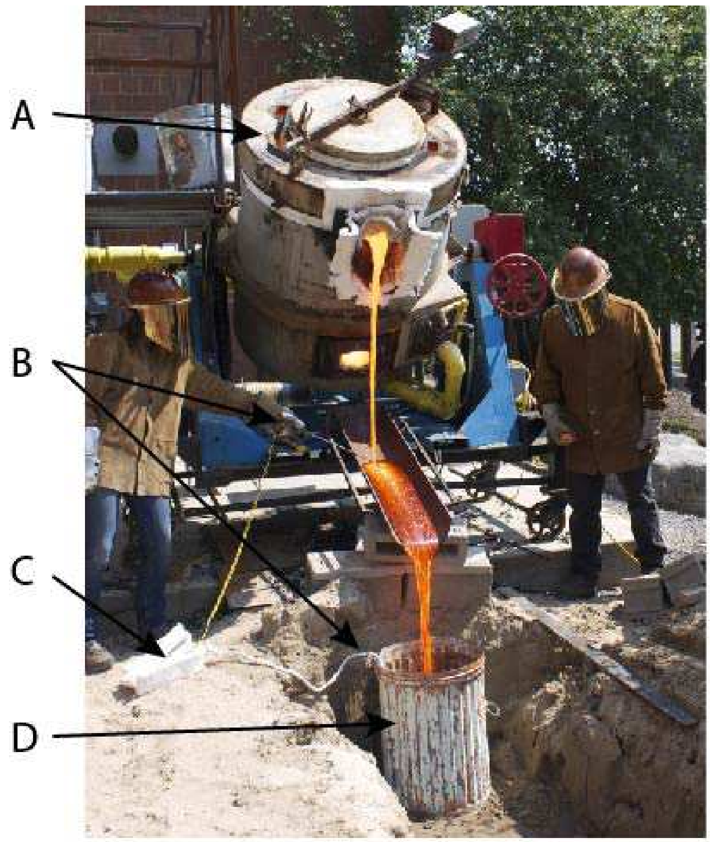

Figure 3. Photograph of experimental setup while at Syracuse University. (A) Large gas-fired tilt-furnance used to produce the lava used in the experiment. The furnance has a silicon carbide crucible that can hold approximately 800 lbs of molten lava (SLP - Http://lavaproject.syr.edu). (B) Thermocouples used to measure the initial temperature of the lava after exiting the furnace and the temperature of the lava throughout the experiment. (C) Datalogger used to record the temperature values obtained from the thermocouples. (D) Receptacle used in second experiment filled with 70 liters of water. Several bricks were placed in the bottom of the receptacle to prevent the molten lava form melting through the metal.

XRF Analysis

Samples selected for analysis by XRF techniques were chosen based upon the abundance of glassy clasts in the sample: samples with a high percentage of large, glassy clasts were selected for XRF analysis, and XRF analysis was foregone on samples that had higher clay compositions and lower percentages of glassy clasts due to the time intensive nature of collecting glassy clasts. XRF analysis was conducted following the methods of Vervoort, et al (2007) at Macalaster College in St. Paul, MN.

SEM Analysis

In order to address the question of parental magma composition for the hyaloclastite deposits found at Leirhnjukur, clasts of fresh, glassy material were selected for SEM analysis. Five to ten glassy clasts were collected from samples in which glassy material was more abundant. Grain mounts were made of these clasts, with clasts from two samples in each grain mount. Chemical compositions of the clasts were obtained on the Carleton College Hitachi S-3000N Scanning Electron Microscope equipped with an Oxford INCA microanalysis system. An acceleration voltage of 20 kV was used for all analyses. Anhydrous phases were normalized to 100 weight percent (wt. %).

RESULTS

Field Descriptions

While conducting field work, each sample that was collected was described in terms of size and relative abundance of glassy clasts present, size and relative abundance of older clasts, color and abundance of palagonitic clay material, vesicularity of both glassy clasts and older clasts, and any other notable features present in the sample and outcrop, presented in Table 1. Lithofacies were recognized based on these physical characteristics found at each outcrop, resulting in a total of six lithofacies, loosely based on the facies defined by I.P. Skilling in his paper on subglacial to emergent basaltic volcanism at Hlodufell, described in the following section.

XRF Data

X-ray fluorescence analysis was used to collect compositional data on both major and minor elements for two pillow basalts and four samples of hyaloclastite deposits. However, because rare earth element data was obtained for only six total samples, analysis of those data did not yield any meaningful results and they were disregarded. Major element data from the six samples plotted as basaltic on Lebas et al. (1986). Three samples were analyzed using both SEM and XRF techniques. There was a compositional discrepancy between the samples analyzed by SEM and those by XRF. This discrepancy was actually expected, as the material that was analyzed using XRF techniques was hypothesized as older material that was incorporated into a given eruptive event.

SEM Data

The results of SEM analysis showed that the glassy clasts plotted as basaltic andesites on the Lebas et al. (1986) rock type diagram on average. However, there were some variations in the compositional data due to the palagonitization that occurred. Some spectra showed an enrichment in silica, while others showed silica depletion. Averages for unaltered, silica enriched, and silica depleted sideromelane were calculated for each sample using the range in silica for basaltic andesite shown in Lebas et al. (1986). These averages were plotted and are shown in Figure 4.

DISCUSSION

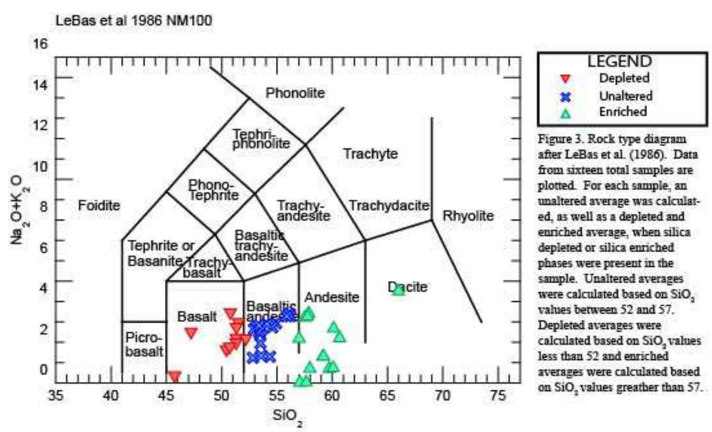

Figure 4. Rock type diagram after LeBas et al. (1986). Data from sixteen total samples are plotted. For each sample, an unaltered average was calculated, as well as a depleted and enriched average, when silica depleted or silica enriched phases were present in the sample. Unaltered averages were calculated based on SiO_2 values between 52 and 57. Depleted averages were calculated based on SiO_2 values less than 52 and enriched averages were calculated based on SiO_2 values greater than 57.

Table 1. Field Descriptions				
Sample	**Matrix (color and porosity)**	**Glassy Clast Size/Vesicularity**	**Older Clast Size/Vesicularity**	**Other Comments**
K2Inter-01	Brown-golden, very fine-grained clay particles (palagonite) and some larger particles	Very fine-grained to approximately 1-3 cm fragments of black, glassy basalt. Small, regular vesicles, with large and/or irregular vesicles present in sparse clasts	Not present	N/A
K2Inter-02	Varies from yellow to light brown to dark brown, very fine-grained clay particles (palagonite) and some larger particles	Black, glassy, and vesiculated basalt fragments with small, regular vesicles	Not present	More proximal to contact between pillow basalt facies and massive hyaloclastite facies than K2Inter-01
K2Contact-02	N/A	No glassy material present or sampled	Material is not glassy, but does not have the same appearance as older material (pillow fragments) found in other hyaloclastite deposits	Sampled from actual contact between this facies (ice contact) and massive hyaloclastite facies.
K2Hyalo-03	Fine-grained, compacted matrix. Brown-grey in color	Vesiculated glassy clasts, approximately 0.5 cm wide on average	Old clasts are approximately 3 cm wide where present	Slightly laminated texture
K2Hyalo-06	Fine-grained, compacted matrix. Brown-grey in color	Glassy clasts are sparse and approximately 0.5 cm on average	Large clasts of older material are absent; approximately 1 cm wide where present	Clay rich band located at base of sample
K2Hyalo-08	Fine-grained, compacted matrix. Brown-grey in color	Abundant, vesiculated glassy clasts with zeolite minerals in vesicles. Average clast size is 0.25-1 cm	Older clasts appear to be slightly oxidized and vary in size from 1.5-3 cm	No signs of lamination as in K2Hyalo-03
K1N-01	Shards of largely unaltered sideromelane, with bands of brown-gold palagonite	Matrix is predominantly composed of fresh looking shards of sideromelane, vesiculated but not glassy	Oxidized older clats, approximately 0.5-1.5 cm on average and very vesiculated	N/A
K1M-02	More palagonitized matrix material. Gold-brown-grey in color with	Very fine-grained sideromelane shards	Clasts of oxidized material approximately 0.5-3 cm wide on average	It is difficult to discern if oxidized clasts were originally older, incorporated material, or

Processes of palgonitization

Based on the compositional data of the palagonitized glass acquired using scanning electron microscopy, presented in Figure 3, several phases appear to be present. Drieff and Schiffman present three possible methods of palagonitization by which these phases could form: 1) congruent dissolution, in which silica is released from the unaltered glass at a constant rate, until the concentration of silica reaches sufficient levels to precipitate a silicate phase. 2) Selective dissolution, in which a lesser amount of silica is released from the unaltered glass, resulting in a residual hydrated layer of glass, or leached layer. 3) Selective dissolution that transitions into congruent dissolution over time. This method of palagonitization results in a leached layer of glass after the transition to congruent dissolution.

Evolutionary history of Leirhnjúkur

Based on the six outcrops that were identified as hyaloclastic deposits on Leirhnjúkur, several

Table 2. Lithofacies	
Lithofacies	Description
Massive hyaloclastite	Fine-grained, small, sparse to abundant clasts of angular, vesiculated sideromelane characterize this lithofacies. Sparse inclusion of older, incorporated material is also present in certain areas
Ice-contact facies	Regularly jointed/fratured blocks of vesiculated material reminiscent of pillows characterize this lithofacies. There are no clasts of sideromelane present in this lithofacies
Pillow lavas	This lithofacies is dominated by the presence of pillow lavas that vary in size from 0.25 to 1 m in diameter, with variations in vesiculation throughout each pillow. Interstitial material located between pillows is heavily palagonitized and contains sparse clasts of old material. The majority of the sideromelane in this interstitial matrix has been partially of fully palagonitized
Banded hyaloclastite	Located in the uppermost section of the Massive hyaloclastite lithofacies, this lithofacies contains bands of clay-rich material, as well as bands of rounded pebbles and gravel
Porous hyaloclastite	This lithofacies is significantly less compacted than the other hyaloclastic lithofacies. The matrix material varies between heavily palagonitized and not palagonitized at all. Clasts are frequently oxidized in certain areas.
Transported hyaloclastite	Hyaloclastite deposit that experienced epiclastic reworking post eruption, resulting in the rounding of clasts within the palagonitized matrix

lithofacies were distinguished. These lithofacies, which are presented in Table 1 in the results section, were utilized to develop a formative history of Leirhnjúkur, in which three evolutionary stages were defined, namely Stage I (Subglacial Phreatomagmatic-Ice Contact Complex) (Lescinsky, 2000), Stage II (Deep-water Subglacial Complex), and Stage III (Secondary Phreatomagmatic Flow Influenced Deposits).

Stage I

During this stage of Leirhnjúkur's evolution, the massive hyaloclastite lithofacies, the banded hyaloclastite lithofacies, and the ice-contact lithofacies were deposited. This stage is interpreted as the initial eruptive event that began the formation of the hyaloclastite ridge.

Stage II

This stage is interpreted as the second main event in the series of eruptions that formed Leirhnjúkur. Pillow lavas typically form at deeper depths, as a higher hydrostatic pressure is required for their formation. The subglacial body of water in which these eruptive events occurred is interpreted as having experienced an increase in water depth due to the vigorous eruptive activity that occurred in Stage I. These eruptions, particularly the eruptions that formed the ice contact lithofacies, are believed to have been in close enough contact to the overlying glacial body, which caused a significant amount of melting, resulting in an increase in subglacial water depth.

Stage III

This evolutionary stage is dominated by a singular lithofacies, termed sub-rounded hyaloclastite in Table 2. This stage is interpreted as having formed initially as foreset beds on the slope of the hyaloclastite ridge that formed in Stages I and II (Schopka et al., 2005). This is attributed to the presence of some laminar beds that can be seen in the outcrop, as well as the sub-rounded to rounded nature of some of the clasts of older material, which indicates some type of mechanical reworking acted on the clasts post-eruption. These beds do not appear in place, however, which suggests that while the material was not yet fully lithified, it was plastically deformed via slumping of the foreset beds, or flow foot breccias (Schopka et al., 2005).

CONCLUSIONS

The hyaloclastite deposits found at Leirhnjukur was not derived from a basaltic magma, but rather from a magma of basaltic andesitic composition. Furthermore, material from either singular or multiple previoius eruptions was incorporated into hyaloclastite deposits. These clasts of older material do in fact plot as basaltic rocks, rather than basaltic andesites. These angular clasts of sideromelane are seen as large clasts within the hyaloclastite matrix and fine-grained shards composing the matrix material. These clasts were palagonitized via two different mechanisms: selective dissolution and congruent dissolution. Selective dissolution led to the formation of a palagonitic rind on the exposed surfaces of the sideromelane that was depleted in silica. Congruent dissolution led to the formation of a silica rich layer of palagonite.

Finally, comprehensive analysis of the outcrops at Leirhnjukur led to the identification of three distinct evolutionary stages: (1) shallow-water eruption, in which massive hyaloclastite formed in relatively shallow water, (2) deep-water eruption, in which pillow lavas formed and (3) secondary hyaloclastic eruption with associated transport. The second stage is interpreted as a direct consequence of the initial eruptive stage melting the overlying glacial body, increasing the water depth and therefore hydrostatic pressure, which is a requirement for the formation of pillow lavas. The third stage is interpreted as resulting from a decrease in hydrostatic pressure in the subglacial body of water. Material produced in this stage produced foreset beds on the slope of the incipient hyaloclastite ridge, resulting in epiclastic reworking of some of the larger clasts, evidenced by their sub-rounded to rounded shape.

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