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INTERACTION OF BASALTIC LAVA FLOWS WITH PATTERNED GROUND: FIELD AND ANALOG STUDIES

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INTRODUCTION

One of the critical factors in hazards mitigation of effusive eruptions is the capacity to predict lava emplacement behavior, particularly lava flow paths. Basaltic flows, such as those produced in Iceland, Hawaii, or other ocean island settings, can not only damage property but can isolate entire areas. In the case of the town of Pahoa, Hawaii, for instance, authorities have had to make repeated predictions about the path of lava from the ongoing Kilauea eruption to prevent loss of personal and municipal property; the lava flows have even threatened to block the only road into town, among other hazards (Miner, 2015).

In order to strengthen future hazard mitigation strategies, it is imperative to improve our understanding of basaltic lava flow emplacement processes. Model predictions of lava flow paths generally take into account major topographic features (e.g., Walker, 1991; Hon et al., 1994), but not smaller-scale variations in terrain (e.g., Gregg and Keszthelyi, 2004). These predictions become important where, for example, lava flows come in contact with the bases of houses and other human-made structures. Understanding flow features associated with such interactions is especially important around the relatively thin margins of flows, where structures are less likely to be completely buried or crushed (Hazlett, pers. comm., 2015).

In Iceland and other northerly regions, the cold winter temperatures produce a distinctive terrain known as patterned ground. This hummocky terrain provides a natural laboratory to examine the interaction of basaltic lava with complex, small-scale topographic variations. In this study, basaltic lava erupted over patterned ground is examined to provide insight into flow paths over complex, variable ground, as well as morphological characteristics that result from the emplacement process.

GEOLOGIC BACKGROUND

Iceland

Iceland is the result of constructional volcanic processes due to the combined activity of the Mid-Atlantic Ridge and a mantle plume (Trønnes, 2002). Currently, the Icelandic mantle plume reaches the lithosphere under the Vatnajökull glacier (Trønnes, 2002). Because of the active mid-ocean ridge system, over the last twenty million years Iceland's landscape has been dominated by a series of rift zones and transform fault zones (e.g., Trønnes, 2002).

One of the most active sections of the Northern Rift Zone is the Krafla volcanic system, which encompasses the areas of Mývatn and Leirhnjukur, located near Krafla (Thordarson and Larsen, 2007; Thorarinsson, 1979; Figure 1). The Krafla volcanic system has experienced fourteen historical eruptions (Thordarson and Larsen, 2007). The two most significant events were the Mývatn Fires from 1724-1729 and the Krafla Fires from1975-1984 (Thordarson and Larsen, 2007).

The 1975-1984 Krafla Fires consisted of nine effusive fissure eruptions, which produced less than 0.2 km^3 of material each (Thordarson and Larsen, 2007). At the outset of the eruption, the earthquake activity was

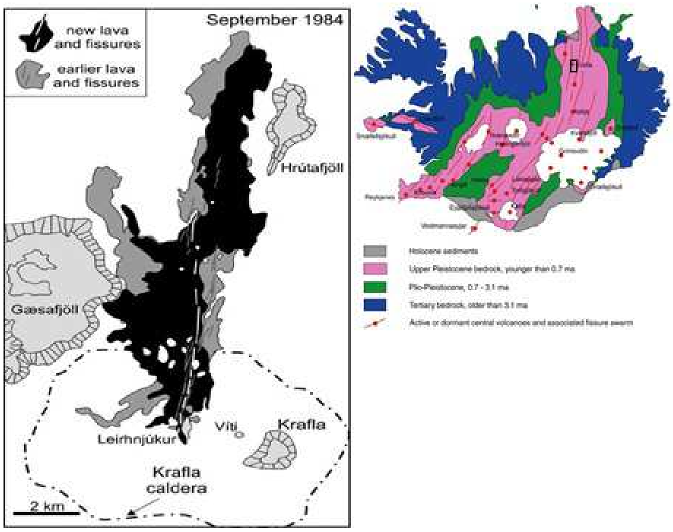

Figure 1. LEFT: Location of Krafla's lava flows during the Krafla Fires 1975-1984. The Leirhnjkur and other light-colored centers are not older lava. Note: This description does not completely detail the lower site. RIGHT: Geological map of Iceland. The area in the box signifies the location of this study's field area. Modified from Thordarson & Larsen (2007) and from http://tobias-weisenberger.de/6Iceland/Introduction/Abb2.5.jpg (accessed 3/1/2016).

Figure 2. A. The 'lower site' of the study at Krafla. This lava flow is likely the result an earlier, discrete eruption during the 1975-1984 Krafla Fires. The lava overlies patterned ground. The dimension of pattern ground can be seen more clearly toward the bottom of the image (the polygon outlined in yellow). The walkway mentioned is not included in the image. It would be approximately 200 m to the right. The white marks are approximately 10 meters apart; B. The 'upper site' of the study with approximately the same scale as A. This flow also overlies patterned ground, visible near the bottom left of the image. The area where patterned ground is not present shows evidence of water erosion. The lava lake mentioned is not included in the image. It would be to the right.

confined to the area below the caldera (Thordarson and Larsen, 2007). The seismic activity began to spread to the fissure swarm near the north coast and towards the south (Thordarson and Larsen, 2007). During these eruptions, the area experienced periodic rifting and exhibited a pattern of gradual inflation, followed by abrupt deflation of the caldera floor (Buck et al., 2006). The morphology of the lava is primarily pahoehoe with significant areas of a'a lava, although there were a few instances of explosive activity. Krafla Fire lava flows constitute the field sites in this study.

Patterned Ground

The lavas of the Krafla Fires were deposited primarily over terrain distinct to northern climates known as patterned ground. Patterned ground features in Iceland can include turf hummock, frost mounds, and many other forms (Priesnitz and Schunke, 1983). The dimensions of the patterned ground can vary from 0.1 m to 3 m in diameter due to the difference in debris cover thickness, which is the determining factor for hummock size (Priesnitz and Schunke, 1983). The patterned ground features dominant in the Krafla area are turf hummocks known as thufurs (Priesnitz and Schunke, 1983), which vary from 0.5 m to 3 meters in diameter. These turf hummocks are one of the most common periglacial features across Iceland when the debris cover requirement is met (Priesnitz and Schunke, 1983).

There is no clear consensus about the mechanism responsible for patterned ground (e.g., Priesnitz and Schunke, 1983; Scotter and Zoltai, 1982). The dominant hypothesis holds that patterned ground features are associated with permafrost, requiring periodic freeze-thaw cycles (Priesnitz and Schunke, 1983). Other researchers believe that the turf hummocks are instead the result of water saturation (Troll, 1943; Scotter & Zoltal 1982). According to this hypothesis, highly absorptive, water-saturated soil with closed vegetation cover is required to form turf hummocks (Schunke, 1975). Regardless of the formation mechanism, patterned ground is a dominant feature on Icelandic landscapes. Consequently, it is likely that patterned ground features were present during the emplacement of the Krafla Fires lavas.

METHODS

Over the course of two weeks in Iceland (2015), the Keck Geology Consortium–Lava Project team examined the 1975 Krafla eruption deposits. The dimensions and extents of several lava flows from the main fissure at Krafla were documented, to investigate the effect of patterned ground on emplacement and morphology of basaltic flows. Subsequently, a series of analog experiments was performed at the Syracuse Lava Project facilities at Syracuse University, New York, to study the emplacement process in more detail.

Field Setting

At Krafla, the field sites are located close to the 1975 fissure system along the walking trail ("upper site"), approximately one hundred meters southeast of the Leirhnjúkur lava lake complex (Figure 2A). The second site is south of the wooden walkway ("lower site"), approximately 200 m east of Leirhnjúkur Hill, location of the initial breakout in 1975 (Hazlett, pers. comm., 2015). The lava at the upper site was emplaced when a lava lake overflowed (Hazlett, pers. comm., 2015), covering a swath of patterned ground (Hazlett, pers. comm., 2015). The precise vent that produced the lower site's lava is unknown, but it must have ultimately been erupted from the fissure system (Figure 2B).

Field Measurements

A variety of measurements of lava flow morphology and terrain dimensions were made at Krafla. For the patterned ground, the width and depth of the troughs and the length and width of the hummocks were recorded. Other measurements include the ground slope at each site and the lava toe dimensions that overlie the hummocks. Toe measurements include their length, width, and thickness. The widths and thicknesses of the lava toes were measured at the half-length of the toe. The lava along the margin of the flow seems to travel into the troughs and up the side of the mounds while the lava near the center of the flow covers the patterned ground completely.

Syracuse Analog Flows

Two experiments were performed at the Syracuse Lava Project facility (http://lavaproject.syr.edu/Research/Lava_Facilities-Research_SE.html) to reproduce the interaction of lava with patterned ground. The Lava Project facilities use a tilt furnace powered by natural gas to melt samples of Keweenaw basalt, simulating freshly erupted Icelandic mafic lava (Karson and Wysocki, 2012). In the first experiments, brick "hummocks" were arranged to examine the path lava would travel through them (Figures 3B & 3C). The bricks were spaced 19.7 cm apart in a row in order to roughly match half the trough widths documented at the lower site (Figure 3A). For the first experiment, the slope was 5˚. For the second experiment, all of the parameters were the same, except the slope was 10˚.

During this set of analog experiments, flow thicknesses were recorded using a ruler once the flows had cooled. The experiments were documented using two video cameras (one from an oblique angle and the other from

Figure 3. The images depict display all of the experiments done at the Syracuse Lava Project Facility. A. The set-up for the first experiments using bricks for hummocks (11 cm high brick piles). B. The results of the first experiment's lava pour. C. The results of the second brick experiment, where obstacles were <6 cm high. D. The control for the first set of experiments. E. The setup for the second set of experiments using mortar mounds as hummocks. F. The results of the second set of experiments.

an aerial view) and a thermal infrared (FLIR) camera; pictures were also taken throughout the pours. The initial temperature for both flows was over 1000˚C (measured by thermocouple).

In the fall of 2015, a second set of experiments was performed, designed to reproduce more closely the spatial relationship of a basaltic flow and patterned ground hummocks, as documented at Krafla (Figures 3E & 3F). To replicate the patterned ground, mounds were created from tile mortar, at approximately 1/7th the average dimensions of the ground at Krafla. This scale was chosen because the lava flows at Syracuse are about 1/7th the thickness of typical Krafla flows. The mounds were about 10 x 10 x 3.5 cm. The mounds were placed on a sand-covered metal ramp (10° slope), with two metal rails to prevent overflow. The mounds were arranged in front of the lava trough, about 3.5 cm apart in an irregular pattern. We also performed a control pour, which used the same ramp without any mounds. We performed a control pour in order to establish the morphology of the flow without significant terrain variations.

RESULTS

Field Measurements of Krafla Flows

The field measurements from Krafla mentioned below are the result of six different measurements (e.g. length, width, etc.) taken from ten toes in the lower site. The lava toes in the two Krafla field areas vary from 350 cm to over 1000 cm long (Figures 2A & 2B). The width of the toes ranges from 75 to 375 cm. The toe thickness varies from approximately 35 cm to 170 cm. The mean values for the field measurements for basaltic toes in the Krafla study area are: 605 cm long, 192 cm wide, and 107 cm thick.

Basaltic Toe Dimensions at Krafla

Compared to results from a morphological study of pahoehoe flows at Mauna Ulu, Hawaii (Crown and Baloga, 1999), Krafla lava toes are considerably larger (Figure 4; insert Figure 4); the majority of the toe lengths from the Crown and Baloga (1999) study are shorter than 200 cm, with a maximum of <600 cm. The narrowest toe documented in Hawaii (Crown and Baloga, 1999) is <25 cm, reaching a maximum of over 300 cm, significantly wider than those observed at Krafla. The majority of the toe thicknesses at Mauna Ulu are 30 cm or thinner (Crown and Baloga, 1999), almost 6 times less than the maximum thickness documented at Krafla.

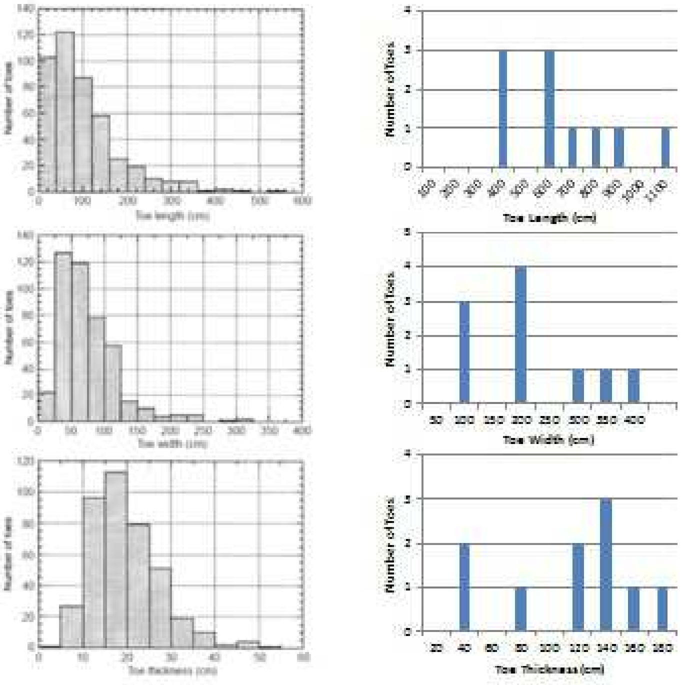

Figure 4. On left: Lava toe dimension histograms from Mauna Ulu study by Crown and Baloga (1999). On right: Lava toe dimensions histograms for Krafla [this study].

The July 2015 flows at Syracuse University

The control flow in July 2015 at Syracuse University produced one large toe and a single breakout (Figures 3A). The toe was approximately 320 cm long, 110 cm wide, and 5 cm thick. The length of the breakout was about 25 cm, with a width of 15 cm and a thickness of about 7 cm.

The first experimental flow used bricks that were stacked 11 cm high to simulate rough patterned ground (Figure 3B). In this pour, the flow was not thick enough to exceed the height of the bricks, resulting in toes whose movement was controlled strongly by the locations of the bricks. The flows were effectively channelized between the rows of bricks, with flow thicknesses between 4 and 5 cm, 1/20th of the average thickness of Krafla toes. The widths of the two toes for this experiment were 17 cm and 27 cm, 1/11th and 1/7th of the average width of the Icelandic toes, respectively. The two toes were approximately 170 cm and 85 cm long, which was 1/3rd and 1/7th of the average length for the Icelandic toes.

In a second patterned ground simulation, the height of the bricks was less than 6 cm. Here, the lava overrode the tops of the bricks, resulting in a flow whose morphology was not as strongly controlled by the locations of the obstacles (Figures 3C & 3D). This experiment produced two elongated toes, ranging from 7-12 cm thick, 105-150 cm long, and 40-50 cm wide.

The October 2015 Flows at Syracuse University

In the simulation of patterned ground, the lava interacted in variable ways with the mortar mounds. Toward the center of the flow, where the basalt was thickest, initial flow direction was dictated by the locations of the mortar hummocks. The basalt pooled at the uphill side of the mound, until its thickness exceeded the height of the mortar barrier. Once this happened, the basalt flowed over the mound, unimpeded. The flow was approximately 135 cm high, 45 cm wide, and 3-7 cm thick.

At the periphery of the pour, however, where flow volume was lower, the mortar mounds provided a strong control on the migration path of the lava, similar to the behavior observed in the July experiments (Figures 3E & 3F) and at Krafla, where peripheral lava had moved around hummocks. Toes along the periphery varied from 6 to 22 cm in width, 3 to 8 cm in height, and 13 to 22 cm in length.

DISCUSSION

Results indicate that the dimensions of lava toes emplaced over older pahoehoe flows (i.e., Mauna Ulu; Crown and Baloga, 1999) are significantly smaller than those erupted over patterned ground at Krafla (Figure 4). The dimensions of the lava toes at Krafla closely resemble the sizes of the patterned ground hummocks. Similarly, the smaller Mauna Ulu toes reflect the magnitudes of underlying pahoehoe flows (Crown and Baloga, 1999). These observations suggest that meso-scale terrain variations such as patterned ground have a profound effect on lava flow emplacement processes, and can drastically alter the morphology of a basaltic flow.

An important additional finding of this study is related to the role of effusion rate in flow emplacement (e.g., Gregg and Keszthelyi, 2004; Harris et al., 2007). It appears as though the influence of terrain on lava flow migration paths is only significant when the effusion rate and volume are sufficiently low that the topography is not completely buried by the lava. Where effusion rates are low enough, lava will be confined between topographic highs (e.g., Figure 4F), as is observed at the margins of flows (e.g., Gregg and Keszthelyi, 2004). Once buried by lava, however, topographic barriers no longer have an influence on lava flow paths (e.g., Figure 3F). This reversal of topography phenomenon has been described by Hon et al. (1994). Once a flow has filled a topographic low area that becomes a topographic high, and subsequent flows will be directed along alternative paths (Hon et al., 1994).

The implications for hazard mitigation are significant if the properties found for lava and topography interaction are consistent when scaled up. Under certain circumstances, newly formed barriers (resulting from pre-existing topographic highs) could direct the flow toward populated areas, posing a challenge for predictive models that might be based on original topography.

CONCLUSIONS

Field and analog studies of basaltic lavas suggest several conclusions. First, even meso-scale terrain features, such as hummocks in patterned ground or underlying lava flow toes (e.g., Crown and Baloga, 1999), can have a strong influence on the morphology and migration paths of lava flows. Second, the topographic control from these meso-scale features is limited to conditions in which the effusion rate of pahoehoe flows is relatively low, such as along the margins of flows; where effusion rate is high enough to overrun the topographic features, they no longer exert a strong influence on the lava's path.

An additional aspect of this study is that in areas that have been covered by low effusion rate basaltic eruptions, lava flow dimensions will reflect the characteristics of the underlying topography. This provides a potentially useful tool for identifying the terrain prior to lava emplacement, which could be useful in remote sensing studies of extra-terrestrial surfaces, such as those of Mars if the users of the tool take into account the factors from this study.

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