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USING ANISOTROPY OF MAGNETIC SUSCEPTIBILITY TO DETERMINE THE SHEARING HISTORY OF A CHANNELIZED PAHOEHOE LAVA FLOW

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INTRODUCTION

Understanding lava flow morphology and developing the tools to accomplish this task have been complex problems for much of the last century (Cañón-Tapia, et al., 1997). Hazards associated with volcanic eruptions make it difficult to observe active lava flow processes leaving geologists to rely on techniques such as petrography to determine the shearing history (e.g. the formation of fabrics such as stretching lineations) of lava flows in the rock record (Loock, et al., 2008).

The purpose of this study is to evaluate the utility of anisotropy of magnetic susceptibility (AMS) to examine the deformational history of a channelized pahoehoe flow from its core to its margins. We hypothesize that the AMS signature of a flow increases in value from its core to its margins reflecting a greater amount of shearing at the margins (Jackson and Tauxe, 1991). Results from an experimental flow on a natural scale are compared to AMS measurements obtained from samples of a channelized pahoehoe lava flow at Krafla, Iceland to evaluate the utility of the experimental analog.

BACKGROUND

AMS is a useful technique for detecting petrofabrics within lava and other deformed rock types, and the technique can be useful for evaluating flow directions in ancient lava flows where other structural data are lacking (Glen, et al., 1997). The property reflects the preferred orientations of magnetic minerals within a rock and can depict weak deformation fabrics that cannot be examined macroscopically. When a specimen's magnetic signature varies with respect to an induced magnetic field, the specimen is said to be anisotropic (Tauxe, 2010). The intensity of this anisotropy varies depending on the preferred orientation of the magnetic minerals producing the AMS signature. In lavas, AMS is the result of the preferred orientation of magnetic minerals resulting from shearing during viscous flow.

Previous AMS studies conducted on lava flows have examined various flow aspects such as flow direction and shearing history (Cañón-Tapia, et al., 1997, Glen, et al., 1997, Loock, et al., 2008). These studies have focused primarily on natural samples collected in the field, due to the difficulty of replicating lava flows in the laboratory. Only one study (Cañón-Tapia and Pinkerton, 2000) has examined AMS in experimental lava flows and only with limited amounts of lava (on the order of cubic centimeters per flow). In contrast, this study will examine AMS in an experimental flow at a natural scale (on the order of cubic meters per flow).

LAVA FLOWS AND METHODS

The Krafla eruptive fissure zone in Northeast Iceland lies about 20 km NE of Lake Myvatn in the Northern Rift Zone of Iceland. The most recent eruptions took place in 1974-1989, and are termed the "Krafla Fires." Lavas erupted mostly north of Krafla caldera spread in the east-west direction from the central fissure system (Einarsson, 2008).

Samples for this study were collected from a channelized pahoehoe lava flow that appears to have broken out of an a'a flow 20 m upslope (Fig. 1). The flow appears to have a collapsed roof exposing

Figure 1. Channelized pahoehoe flow near the Krafla caldera, northern Iceland. Both the core and margins were sampled.

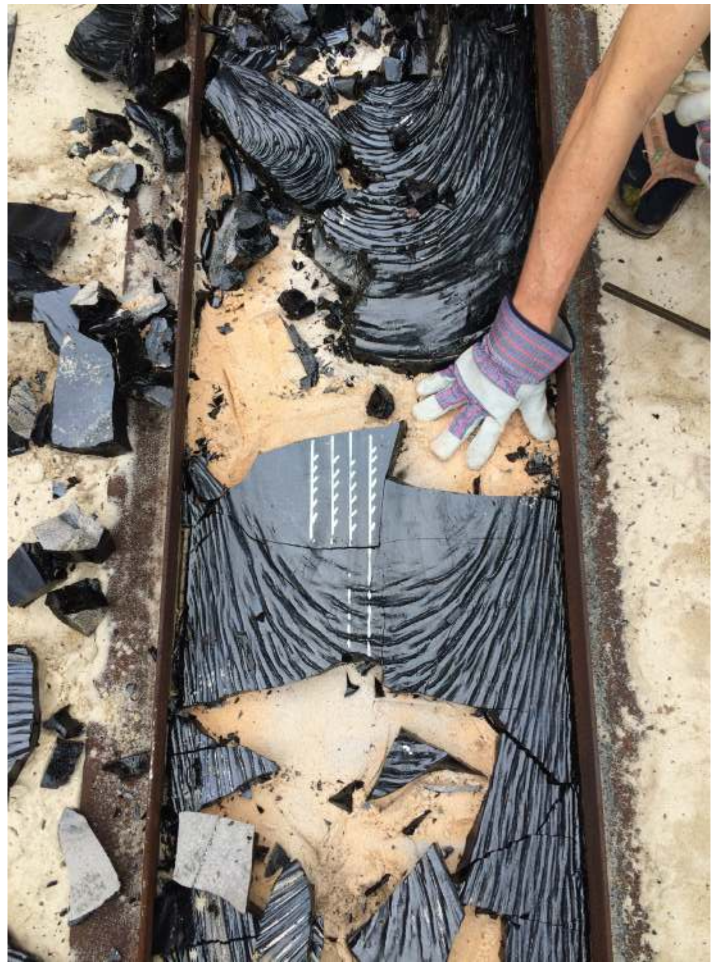

Figure 2. Channelized experimental flow from Syracuse University, New York. Both the core and margins were sampled.

“bathtub ring” structures on the inner levee walls. Due to the lack of exposure it is impossible to determine the depth of the flow, but the exposed ring structures imply it was probably at least 0.5 m thick. The channel has an approximate 2° slope, is 2.5 m wide, and 65 m long. Apart from this discrete flow the surrounding area is characterized by an abundance of a’a flows. The source of the lavas in the area appears to be a lava lake upslope from the channel.

Samples were collected along two transects perpendicular to the flow, a site proximal to the source and one more distal. At each site care was taken to collect samples from both edges of the flow and one from the middle for comparison between sheared and non-sheared portions. Based on the convex-downslope fabric on the flow surface it is inferred that shearing was minimal near the flow center and much greater toward the margins. Oriented samples were removed at the best available sections using a rock hammer. Before removal, sample surfaces were marked with arrows marking north, the strike and dip of the samples were recorded, and horizontal lines were marked on the exposed sides of each sample for spatial orientation. Location of each sample within the flow was recorded for future reference.

For comparison with the Krafla lava flow, an experimental basaltic flow was produced and sampled for AMS. The flow was created under the auspices of the Syracuse Lava Project (Karson and Wysocki, 2012; http://lavaproject.syr.edu). The flow was on a 5° slope, poured at a temperature of 1200 °C and had dimensions of 3 m long x 0.5 m wide. The flow was 5 cm thick. The folded surface of the flow was similar to that of the Krafla flow with a convex-downslope form with the most intense shearing at the margins. The flow was marked with north arrows, and strike and dip

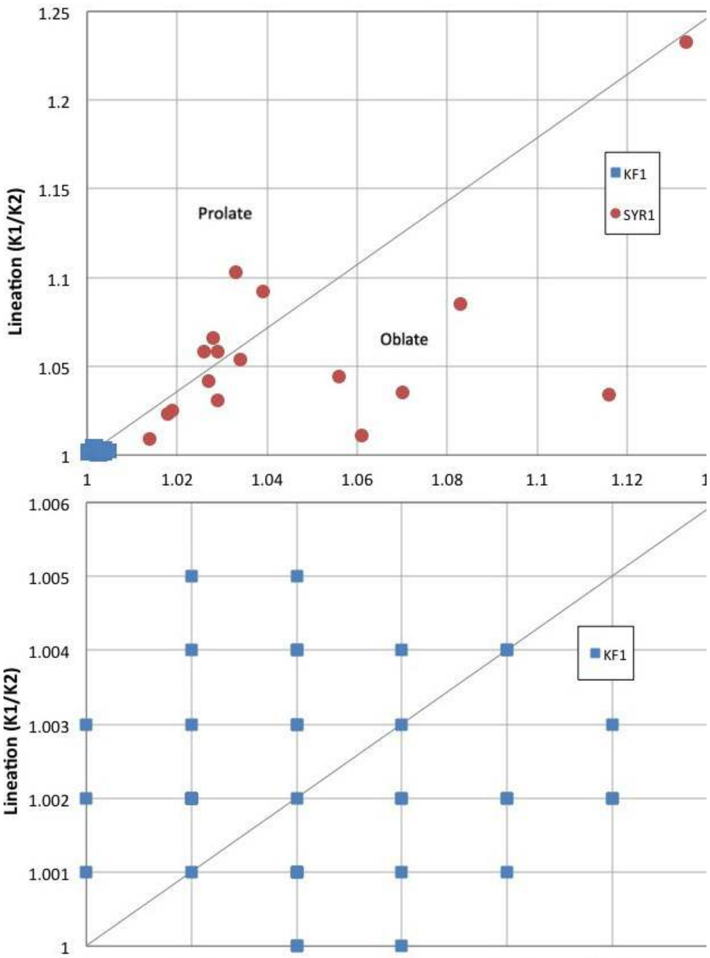

Figure 3. a) Flinn diagram for the Krafla flow (KF1) and Syracuse flow (S1). b) Smaller scale Flinn diagram for the Krafla flow. The Krafla flow specimens have very low anisotropy and variation resulting in tight clustering around the origin. Syracuse flow specimens display oblate, prolate, and spherical ellipsoid shapes.

symbols, and sampled across its width to acquire both sheared and non-sheared portions.

Both natural and experimental samples were prepared at Macalester College by re-orienting the samples using their strike and dip information. Cores were then obtained from each sample using a drill core with a 2 cm diameter. Samples were cut into 2x2 cm cylinders and their orientations were marked again.

AMS measurements on the oriented core samples were obtained with a MFK1-FA Susceptibility Bridge using the spinning specimen method (Jelinek, 1997) at the Institute for Rock Magnetism at the University of Minnesota.

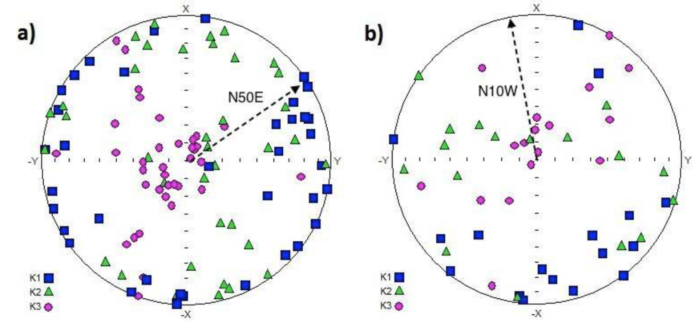

Figure 4. Equal area stereographic projections for the a) Krafla flow and b) Syracuse flow, with flow directions indicated. Data are plotted with the flow surface as horizontal. K3 axes show clustering near the middle in both flows indicating a degree of flattening.

RESULTS

Specimens from the Krafla flow display an average bulk susceptibility of 5.8×10^{-2} with a standard deviation of 8.1×10^{-3} showing that there is not a significant difference in bulk susceptibility values from the flow core to margins. Bulk susceptibility is a parameter that relates the magnetization induced in a material (M_1) with an external magnetic field (H), because M_1 and H always have the same units, bulk susceptibility is dimensionless. The average bulk susceptibility for the specimens from the experimental flow is 1.6×10^{-2}. The average Hext F statistic for all specimens is over the critical value of 3 and therefore the data show statistical significance. Hext F statistics are used to calculate uncertainty ellipses for the orientations of the principal susceptibility axes (K_1, K_2, K_3) (Tauxe, 2010).

AMS data are typically reported in terms of three major axes of an ellipsoid which can be plotted on a Flinn diagram (Tauxe, 2010) (Fig. 3). AMS data from both flows show the natural flow data have very little range in both foliation and lineation, while the experimental data display greater variation in the shape of their AMS ellipsoids. Moreover, the data for the natural flow show little to no variation between the average maximum susceptibility axis (K_1) and the average minimum susceptibility axis (K_3), 1.001 and 0.999, respectively. In contrast, the experimental flow data have slightly greater variation with an average K_1 value of 1.030 and an average K_3 value of 0.981.

Overall, the low variation between the susceptibility axes in both flows results in the majority of samples having a spherical ellipsoid shape. Equal area projections of the principal susceptibility axes show samples from various parts of the flow all display a high degree of scatter between individual specimens (Fig. 4). Therefore, there appears to be no correlation between AMS values and sample location across the channelized flow.

DISCUSSION

Although the AMS data show that K_1- K_3 axial orientations are highly scattered, there are some weak trends in the data. K_2 orientations in specimens from both flows display the most amount of scatter, while K_1 orientations display a weak magnetic lineation (more apparent in the experimental flow) (Fig. 4). In contrast, the K_3 orientations are more uniform throughout both flows and tend to cluster in the middle of the equal area projections (Fig. 4). Because equal area projections were plotted with flow surface as horizontal, the clustering of K_3 orientations normal to the flow surface implies some degree of flattening. Previous studies have shown that K_3 orientations tend to be perpendicular to flow surfaces (Cañón-Tapia, 2005), as in the Krafla and experimental flows in this study.

While data overall lack distinct trends, specimens (n=5) from the middle of the experimental flow display a prolate ellipsoid shape approximately parallel to the flow direction (Fig. 5). This is what might be expected as stretching lineations commonly occur parallel to the flow direction in both natural and experimental flows. A larger number of samples from the experimental flow might help to constrain overall flow direction.

It is puzzling that the anisotropy values do not show systematic variation across the flows. The movement of lava flows can be highly complex and there are various uncertainties concerning the behavior the lava flows in this study such as the movement and distribution of particles within the flows.

Specimens taken from the Krafla flow tend to be highly vesicular, which is one possible explanation for the lack of variation in anisotropy. Thin sections of this flow show a weak lineation defined by elongated magnetite parallel to the direction of the flow that would be expected to influence the AMS signature.

In contrast, specimens from the experimental flow have higher values of anisotropy. The samples from the flow are glassy, and have only very small amounts of vesicles (<10%). Previous studies have shown that flows that cool quickly tend to have greater values of anisotropy (Cañón-Tapia, and Pinkerton, 2000), which might explain the observed difference in anisotropy between the experimental and natural samples studied.

One potential source of error is that samples were removed from sections of the collapsed roof of the channelized Krafla flow. Ideally, samples should be gathered in areas where the flow is laminar, but limited exposure led to the collection of samples only at the flow surface; an area exposed to high amounts of strain that can lead to highly variable results (Cañón-Tapia, 2005). Moreover, sampling was limited to a small section of the overall flow. Flows commonly have local variations, which may have been a factor. Previous studies have been able to constrain flow direction by systematically sampling over a much larger area than in this study (Callot, et al., 2004). Further sources of potential error include inaccurate orientations measured in the field and reorienting in the lab.

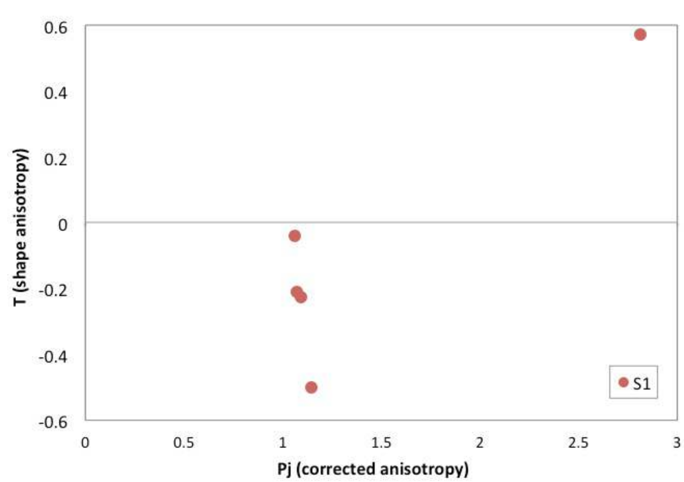

Figure 5. Jelinek (1997) diagram for specimens from the core of the Syracuse flow. Specimens display prolate ellipsoid shapes approximately parallel to flow direction.

Further research examining the relationship between cooling time and AMS data may help to constrain the factors that affect AMS. It is possible that the flow we sampled was cooled over a long period of time leading to variable AMS data. Future work should include a more comprehensive sampling approach, making sure to sample the entirety of a flow rather than a local section. Moreover, drilling cores *in situ* may help to provide more accurate AMS measurements in the future. Until further research is conducted it is impossible to say what factors control AMS data within lava flows and how they are connected.

CONCLUSION

Overall, the lack of significant clustering in the AMS data from the Krafla flow suggests low strain regardless of position across the flow. The AMS values indicate horizontal flattening of the flows but they do not increase from the flow core to margins. Thus, the AMS fabric does not appear to correlate with the strain implied by surface flow fabrics. The large scatter in susceptibility axes across the flow suggest a complex flow pattern within the lava flow. Specimens from the core of the experimental flow tend to have prolate ellipsoid shapes as expected from a channelized flow core. While previous studies have used AMS to constrain flow direction (e.g., Callot, et al., 2004), high scatter in the data prohibit accurately constraining the flow direction in either the natural or experimental flows studied.

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