USING ANISOTROPY OF MAGNETIC SUSCEPTIBILITY TO DETERMINE FLOW DIRECTIONS OF THE DEVIL TRACK AND KIMBALL CREEK RHYOLITES

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INTRODUCTION

Extrusive rocks of the North Shore Volcanic Group (NSVG) make up a significant part of the 1.1Ga Midcontinent Rift System (MRS) of northeastern Minnesota. Although primarily basalt, the NSVG also consists of approximately 10–25% of felsic flows (rhyolites and icelandites) which is unusual for such settings (Green & Fitz, 1993). Several of the rhyolite flows in fact, have been interpreted by Green and Fitz (1993) to be rheomorphic ignimbrites due to their vast expanse and presence of tridymite paramorphs.

The purpose of this study is to determine flow directions of two rhyolite bodies (the Kimball Creek rhyolite and Devil Track rhyolite) using anisotropy of magnetic susceptibility (AMS). Magnetic susceptibility (K) is the measure of magnetic response of a material to an external magnetic field. Anisotropy of magnetic susceptibility arises from the orientation of the crystallographic axes of minerals, which often control shapes of grains (Rochette et al., 1992). Studies by Khan (1962) have shown that crystallographic axes correspond to the principal axes of the AMS ellipsoid. Although AMS has been widely used as a proxy for emplacement direction of dikes, basaltic and granitic bodies, there have been no published studies that apply AMS to determine flow directions in rhyolite flows.

GEOLOGIC SETTING

Vervoort and Green (1997) concluded two processes responsible for the generation of felsic magma within the bimodal NSVG. Assimilation and fractional crystallization of basaltic magmas in the upper crust resulted in the extrusion small amounts of felsic magma. Larger amounts felsic magmas are attributed to crustal melting by basaltic magma. The Devil Track and Kimball Creek rhyolites are the two largest felsic flows of the NSVG, located in the northeast limb (Fig. 1). Both bodies appear to be massive in hand sample with only few exposures displaying lineations, laminations or flow banding (Green & Fitz, 1993).

The eruptive style of the Devil Track rhyolite could not be determined due to lack of field evidence. It overlies the distinctly different Maple Hill rhyolite flow. The upper parts are not exposed, and the first overlying exposure is a basalt flow. The Kimball Creek rhyolite is the second largest felsic body of the NSVG, and is described as a rheomorphic ignimbrite. It is bounded by icelandite and andesite flows below, and basalts above (Green & Fitz, 1993).

METHODS

Oriented samples from six different sites within each flow were collected, representing the upper, middle and lower parts of each flow. Samples were then cut into oriented 1-inch cubes (n=17 to n=22 per site) to be analysed using an alternating current (AC) susceptibility bridge, housed at the Institute for Rock

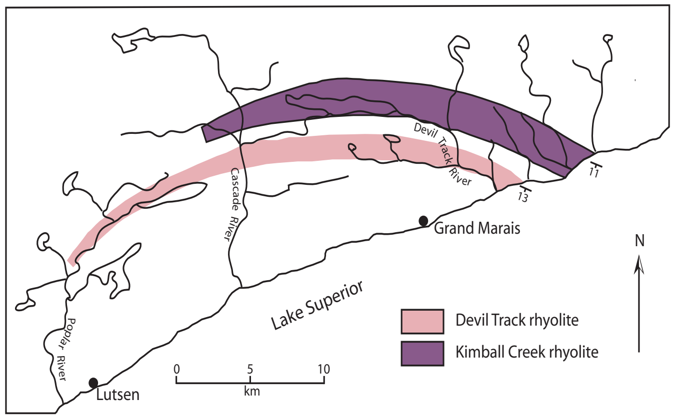

Figure 1. Generalized geologic map showing the of the Devil Track and Kimball Creek rhyolites in south-central Cook county, MN (modified from Green & Fitz, 1993).

Magnetism at the University of Minnesota, Twin Cities. The AC susceptibility bridge is used to determine anisotropy of low-field magnetic susceptibility. An alternating current in the external "drive" coils produces an alternating magnetic field in the sample space with a frequency of 680 Hz and amplitude of up to 1 mT. The induced magnetization of a sample is detected by a pair of "pickup" coils, with a sensitivity of $1.2*10^{-6}$ SI volume units. For anisotropy determination, a sample is rotated about three orthogonal axes, and susceptibility is measured at 1.8° intervals in each of the three measurement planes. The susceptibility tensor is computed by least squares from the resulting 600 directional measurements. The output is a trend and plunge for each of the principal susceptibility tensors (i.e. K_{max}, K_{int}, K_{min}), mean susceptibility, and three axial ratios $L=K_{max}/K_{int}$, $F=K_{int}/K_{min}$, and $P=K_{max}/K_{min}$ (lineation, foliation, and degree of anisotropy respectively). Principal tensors are plotted on lower hemisphere stereonet projections using the "Stereonet" software developed by Richard W. Allmendinger (2002).

RESULTS

The ideal result of AMS measurements would be an orthorhombic ellipsoid represented by orthogonal clusters of the principal tensors on a stereonet plot. Lower hemisphere projections for K_{max} and K_{min} for lower, middle and upper parts of the Devil Track rhyolite are shown in Figures 2(a), 2(b), and 2(c) respectively. All three parts consist of varying amounts of scatter in orientation of tensors. The lower and upper parts of the flow exhibit noticeably separate clusters of K_{max} and K_{min} tensors. The lower part of the flow (Fig. 2(a)) has an approximate E-W trend for most K_{max} with an N-S trend for the rest. The plunge of the K_{max} axes is relatively similar (between 0˚ and 20˚) for all but four samples. K_{min} axes have greater variation in trend but most samples have a plunge between 70˚ and 90˚. A more uniform trend (E-W) of K_{max} is seen in the upper part of the flow (Fig.

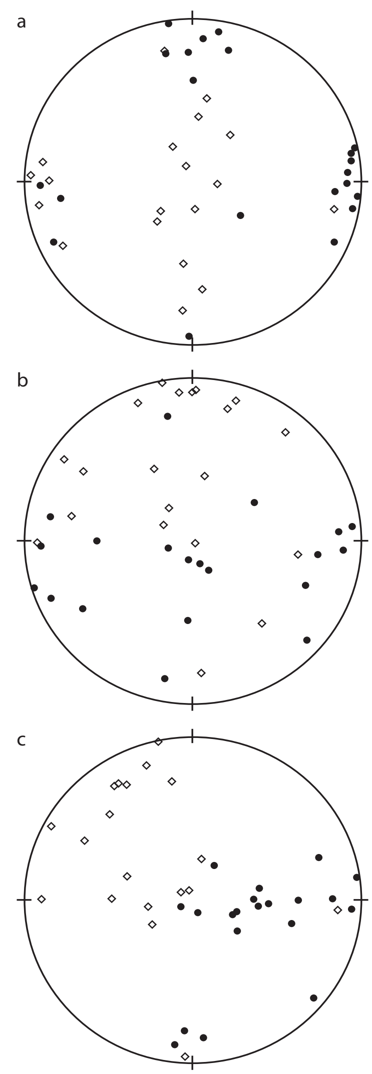

Figure 2. Lower hemisphere stereonet projections of Kmax (filled circles) and Kmin (hollow diamonds) tensor orientations, for the (a) lower, (b) middle, and (c) upper parts of the Devil Track rhyolite.

2(c)) with large variance in the plunge. K_{min} for these samples is also variable. The middle part of the flow (Fig. 2(b)) shows no significant clusters of either tensor.

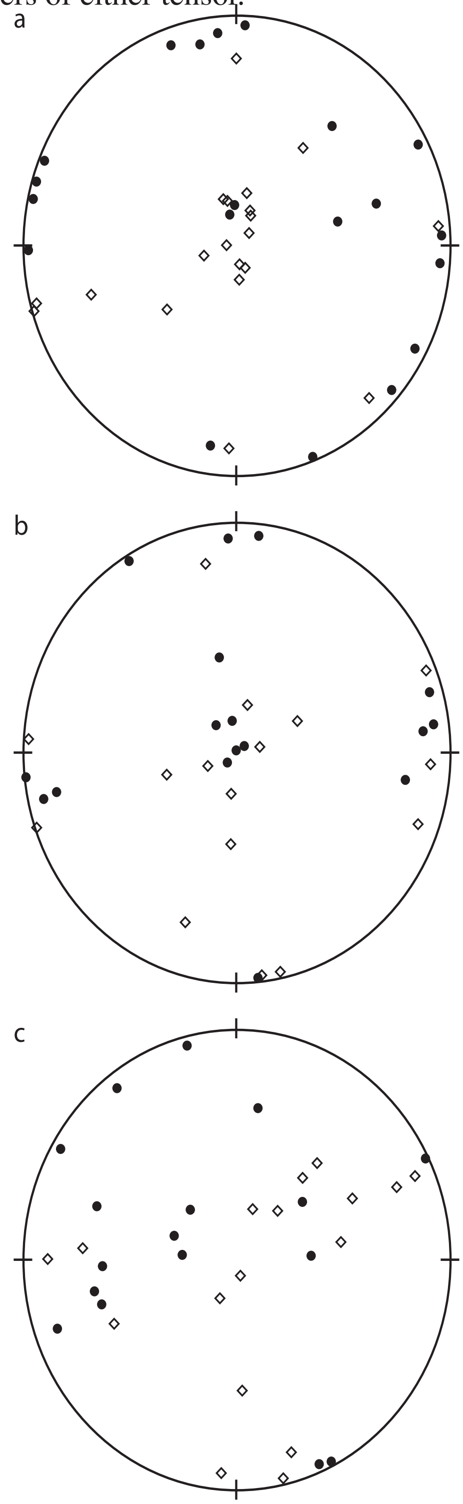

Figure 3. Lower hemisphere stereonet projections of Kmax (filled circles) and Kmin (hollow diamonds) tensor orientations, for the (a) lower, (b) middle, and (c) upper parts of the Kimball Creek rhyolite.

Figures 3(a), 3(b), and 3(c) respectively show the orientation of K_{max} tensors for the lower, middle and upper parts of the Kimball Creek rhyolite. Only the middle part of the flow yielded significant clusters of principal tensors. Majority of K_{max} tensors trend between 070˚ and 090˚ with either sub-parallel or sub-vertical plunges. K_{min} tensors are more scattered.

To more accurately define a specific direction of the principal axes, Le Pennec et al. (1998) analyzed samples dependent on their anisotropy. The magnetic lineation (K_{int}/K_{max}) of each sample is compared to the mean magnetic lineation of all the samples from their specific site. Samples with anisotropies greater than the mean were selected for the analyses. Application of this method only yielded significant results from the lower and upper parts of the Devil Track rhyolite. The lower part of the flow (Fig. 4) reveals an approximate K_{max} trending 085˚ and plunging about 8˚E. K_{min} for the lower part, on average trends 080˚ with an approximate plunge of 80˚W. The upper part of the flow (Fig. 5) yields a K_{max} which trends 100˚ and plunges 60˚E. The K_{min} trends 300˚ and plunges about 60˚NW.

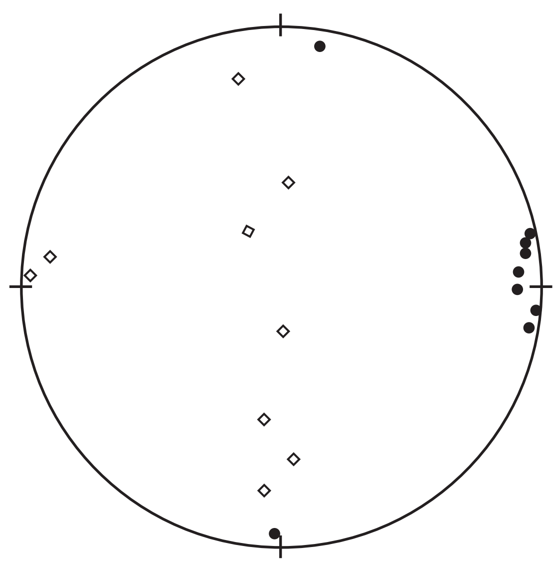

Figure 4. Lower hemisphere stereonet projections of Kmax (filled circles) and Kmin (hollow diamonds) tensor orientations for samples, from the lower part of the Devil Track rhyolite, with high values of anisotropy.

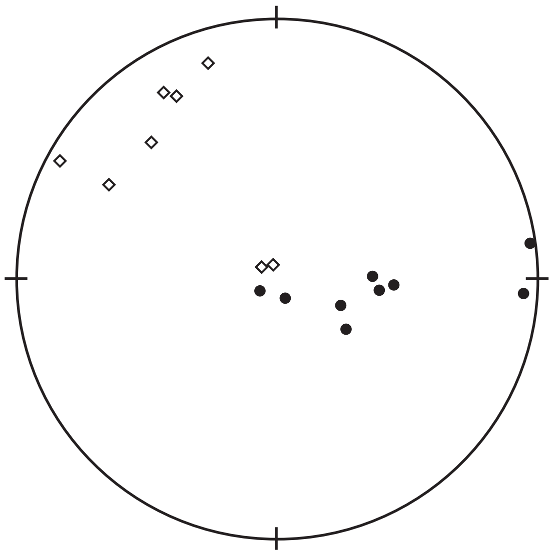

Figure 5. Lower hemisphere stereonet projections of Kmax (filled circles) and Kmin (hollow diamonds) tensor orientations of samples, with high values of anisotropy, from the upper part of the Devil Track rhyolite.

DISCUSSION

Khan (1993) has shown that K_{max} in flows is parallel to direction of flow. Therefore consistency in alignment of K_{max} is a good proxy for determining magmatic flow directions. Large scatter in AMS directions obtained from 4 samples makes it difficult to interpret a primary flow direction. On the other hand significant clusters (Figs. 2(a) & 2(c)) in the two samples from the Devil Track rhyolite (lower and upper part) can be interpreted as alignment due to flow. Exclusion of the samples with smaller magnitudes of anisotropy, enhance the magnetic fabric. Figures 4 and 5, therefore suggest a general eastward, "rift-normal" flow.

There are several factors that could attribute to the large scatter in AMS measurements. The high viscosity of felsic flows is likely to be a major deterrent to grain alignment. Alignment of grains could also change due to growth or realignment in the liquid, once flow has ceased. In addition, degassing and crystallization could contribute to alteration of grain orientations grains. Convection in the lava is also likely to effect alignment once flow has come to an end (Ellwood 1978). Progressive oxidation of magnetic grains could also alter the shape of the grains, therefore randomizing AMS orientations (Watkins and Haggerty, 1967).

The brittle nature of the samples could have also led to scatter, since some samples contained cracks, and chipped edges, formed during sample preparation. It is likely one or a combination of these factors contributed in the large observed scatter. Green and Fitz (1993) recorded flow lineations within the basal part of the Devil Track rhyolite, which concur to the orientation of magnetic fabric obtained in this study (080˚-085˚). This suggests that AMS can be used to interpret flow directions in felsic flows.

CONCLUSION

Analysis of AMS for two samples from the Devil Track rhyolite yield significant data to imply a flow orientation of 080˚-085˚. This agrees with lineations measured by Green and Fitz (1993). Unfortunately the four other sample sites yield data that cannot be interpreted as a fabric. This random alignment could be a result of a number of factors that took place during and/or after flow had ceased. Anisotropy of magnetic susceptibility could be a useful but not always practical tool to determine flow directions in the felsic flows.

ACKNOWLEDGEMENTS

This study would not have been possible without the support of the Beltmann Research Grant and the Keck Geology Consortium. I would also like to thank the project leaders John Craddock, Cameron Davidson, and Karl Wirth, as well as my fellow research students for all their assistance. Thank you also to Jeff Thole for his endless support and guidance.

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