MAGMA FLOW DIRECTION OF THE SHIP ROCK RADIAL DIKE SWARM, NEW MEXICO

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INTRODUCTION

Dike swarms are commonly studied to gain a better understanding of the implications for the source and propagation direction of magma flow during past volcanic activity. Techniques involved in petrofabric studies are utilized to determine magma flow direction within volcanic structures (Rubin, 1995). Flow direction can be identified by external and internal indicators. Field indicators of flow include lineation patterns in the form of stretched vesicles, phenocrysts, grooves, and folds (Smith, 1987). Anisotropy of magnetic susceptibility is a technique used to determine internal flow from magnetic grains. AMS is a measure of the susceptibility and alignment of crystallized magnetic minerals incorporated within a network of phenocrysts (Rubin, 1995). Studies of magma flow fabrics and magnetization characteristics of dikes include work conducted at Spanish Peaks in Colorado and the Troodos Ophiolite in Cyprus.

Spanish Peaks is a volcanic remanant that contains radial dike scores positioned near two separate intrusive points (Smith, 1987). According to Smith (1987), the radial dikes of Spanish Peaks contain five types of magma flow indicators: elongate and aligned vesicles, scour marks, cataclastic elongation of phenocrysts, asymmetric folds, and aligned phenocrysts. Elongate vesicles are the most common type of flow lineation and indicate a steady direction of magma transport. They are found on the dike in areas where the magma has been extended creating a marked lineation. Dikes that contain an intermediate or felsic composition generally acquire scour marks. Scour marks appear as small folds or depressions as a result of contact with cooled magma. These marks are an indication of weak spots in the dike, which cause it to break off into fragments that lie parallel to the dike contact. Dikes displaying both elongate vesicles and scour marks produce flow lineations that remain parallel, which provides further support as evidence of magma flow direction (Smith, 1987).

Varga et al. (1998) studied the sheeted dike complex of the Troodos Ophiolite for the purpose of testing the validity of dike surface lineaments as field indicators of flow. The dike surface lineations, including slickenlines and elongate vesicles, were compared to the internal flow direction produced by AMS analysis. The surface flow indicators showed a close correlation with the internal mesoscopic flow direction therefore demonstrating that external indicators are an adequate substitute for flow direction. In certain cases, unlike the Troodos dikes, deviations between surface indicators and their internal counterparts can be significant because magma flow can abruptly change positioning, thus altering the alignment of the internal grains (Varga et al., 1998).

Volcanism in the Navajo volcanic field is composed of maar-diatreme volcanoes formed by hydrovolcanic eruptions. The most prominent of these eruptions is Ship Rock, a volcanic neck composed of tuff-breccia containing dikes that branch out from its central stock located on the Navajo reservation near the four corners region in Shiprock, New Mexico (Semken, 2003). The goal of this geologic study is to determine the magma flow direction of the Ship Rock radial dike swarm so as to develop a better understanding of the magma chamber at depth and its role in the formation of Ship Rock 30 mya.

METHODS

Field work was completed during the summer of July 2006 at the Ship Rock radial dike swarm. Block samples were collected along five vertical dikes at approximately 1 km spacing. At each site, the orientation and GPS location of the sample was recorded before being collected from along the dike margin. Other field observations that were noted include magma flow indicators such as slickenlines and elongate vesicles (Fig. 1).   Slickenlines are linear grooves formed along dike margins that result from the deterioration of chilled magma due to contact with internal liquid magma (Smith, 1987). The structural fabric along dike margins shows implications of preliminary magma propagation and flow direction (Staudigel et al., 1992).

Figure 1. Slickenlines observed along an area of the south dike margin. The grooves show a surface lineation indicative of horizontal magma flow.

Approximately 4-7 cores were drilled into each rock sample, which was then reoriented by measuring the azimuth and hade to replicate the original positioning of the block sample (Butler, 1992). Next, the rock cores were taken to Scripps Institution of Oceanography to conduct an AMS study of Ship Rock for the purpose of determining flow direction from the internal alignment of magnetic grains within the rock fabric. A magnetic susceptibility tensor was used to measure the axes representing the maximum, intermediate, and minimum susceptibility for each core (Tauxe et al., 1998).

At the College of Wooster's paleomagnetics laboratory the natural remanent magnetization of cores from each collection site was measured using a spinner magnetometer. Following the initial NRM measurements, the core samples were demagnetized using alternating field and thermal demagnetization (Butler, 1992).

ANISOTROPY OF MAGNETIC SUSCEPTIBILITY

The application of AMS is used to study the magnetic grain alignment along chilled dike margins that indicates initial flow direction of magma. During magma propagation stretched particles are imbricated along the dike margin, which can reveal the principal direction of magma flow (Fig. 2) (Tauxe et al., 1998). Three axes of magnetic susceptibility perpendicular to one another are measured in AMS: K1 (maximum), K2 (intermediate), and K3 (minimum) (Butler, 1992).

The susceptibility values are used to determine the ellipse shape of the magnetic grains of the petrofabric. Shapes include spherical (K1=K2=K3), oblate (K1=K2>K3), prolate (K1>K2=K3), and triaxial (K1>K2>K3) (Tauxe et al., 1998).

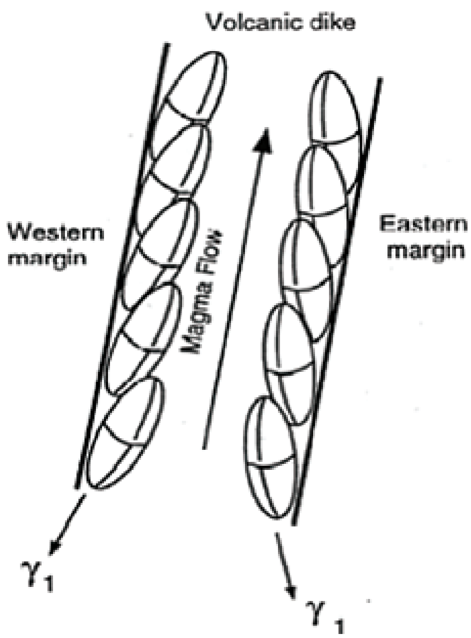

Figure 2. During magma flow, magnetic grains become imbricated along chilled margins. Anisotropy of magnetic susceptibility measures three axes of susceptibility (K1, K2, K3) to determine flow direction. The longest susceptibility axis (K1) represents the principle magma flow direction. The shortest susceptibility axis is positioned perpendicular with respect to the long axis (from Tauxe et al., 1998).

In order to conduct an AMS study of the dikes surrounding Ship Rock, block samples were taken from along one side of the dike margin so as to collect the most accurate data for initial flow direction. The AMS data from the Ship Rock samples indicated that the maximum percent anisotropy was greater than 2%. To determine the ellipse shape a Flinn diagram was constructed, which compares the ratios of K1/K2 (y-axis) and K2/K3 (x-axis) (Tarling & Hrouda, 1993). The ellipse shape for dike samples did not produce one definite shape. Ellipses were mostly oblate and spherical, but produced prolate and triaxial shapes as well (Fig. 3).

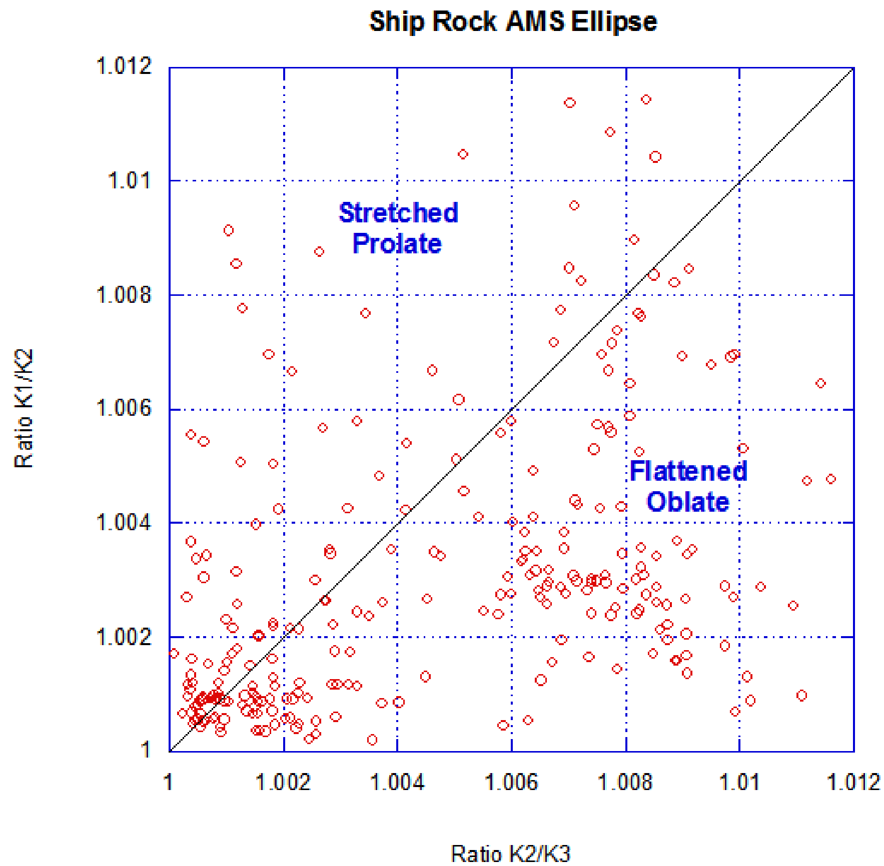

Figure 3. Flinn diagram comparing the ratios of the maximum and intermediate susceptibility values (K1/K2) to the intermediate and minimum susceptibility values (K2/K3) to determine ellipse shape of Ship Rock samples analyzed by AMS. The graph points show some scatter, but clustering indicates oblate and spherical ellipse shape.

Equal area projections of the sample sites were created to show the susceptibility measurements of the three axes with respect to the dike margin (Fig. 4). The susceptibility axes are represented by three different symbols: squares (maximum), triangles (intermediate), and circles (minimum).

Several of the samples produced nicely clustered AMS measurements that indicated horizontal and vertical magma flow patterns in the south and west dike along with the central diatreme. Other sample sites (i.e. northeast dike area) produced AMS readings that were too scattered to reveal any conclusive evidence of flow direction.

formation. This information was gathered to aid in the geophysical projects involving magnetic and gravity surveying conducted by other students participating in the New Mexico Keck project. Paleomagnetic data does not provide any correlation to magma flow direction.

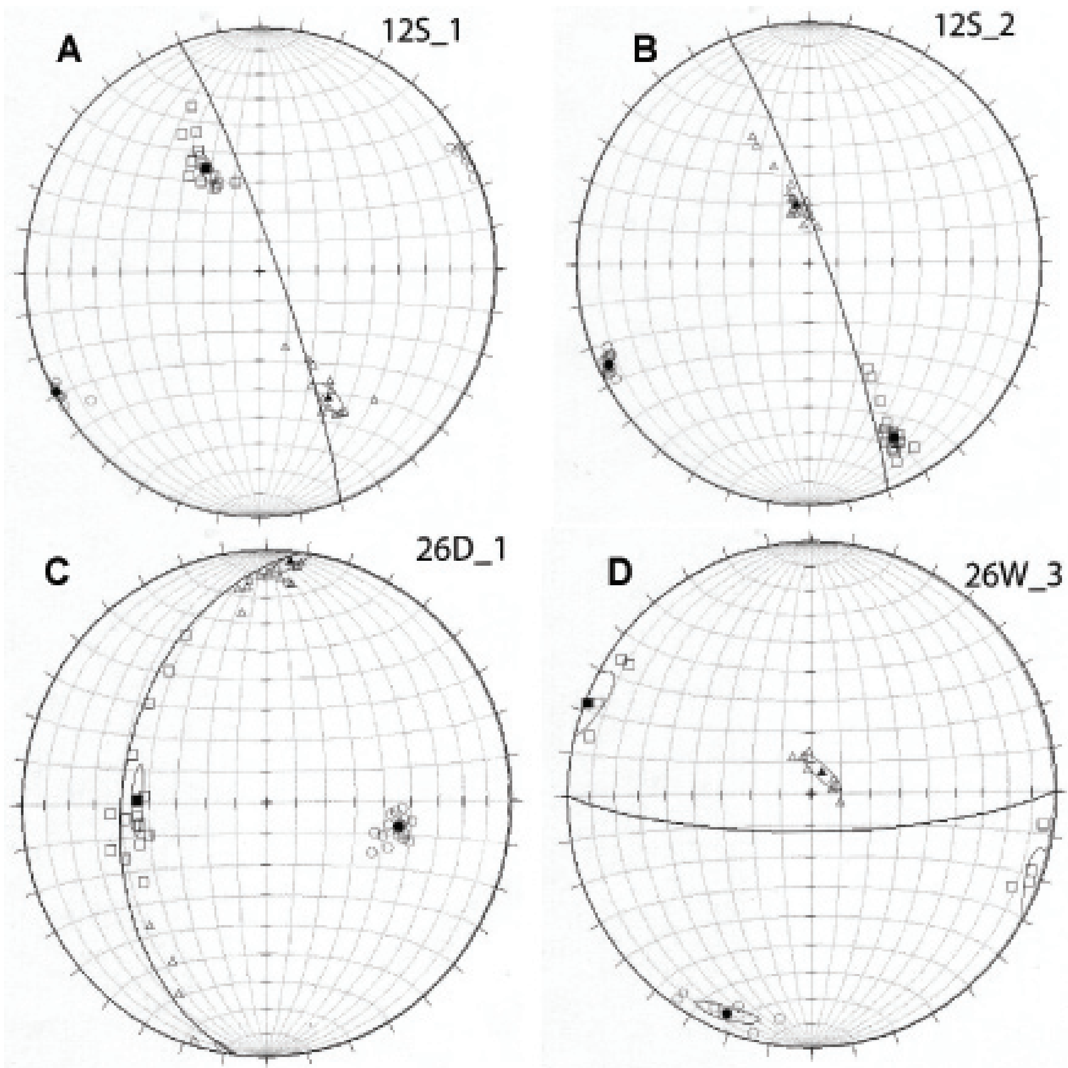

Figure 4. AMS data plotted on a equal area projections. A) Sample collected from the south dike along a margin trending to the northwest. Square points indicate the maximum susceptibility axis showing near horizontal principle flow direction. B) Another south dike sample from a northwest trending margin taken from a different site that displays horizontal flow pattern. C) Block sample collected from the central stock of the volcanic intrusive showing vertical magma propagation. D) West dike sample showing some deviance from the dike margin, but presumed to be indicative of horizontal magma flow

PALEOMAGNETICS

Paleomagnetic analysis was conducted for the Ship Rock samples to determine the orientation of the geomagnetic field during initial

The natural remanent magnetization for the samples was measured using a spinner magnetometer. The Ship Rock area has a magnetic inclination of 62º. Equal area projections of the NRM vectors from the core samples produced very scattered results and thus were determined to be relatively unstable (Fig. 5). Unstable NRM values were evident from NRM values decreasing significantly during low demagnetization treatments.

the Ship Rock samples display the K3 value perpendicular to the K1 value, which represents principal horizontal flow along the dike margin. The AMS results speculate that there was initial vertical magma migration through the

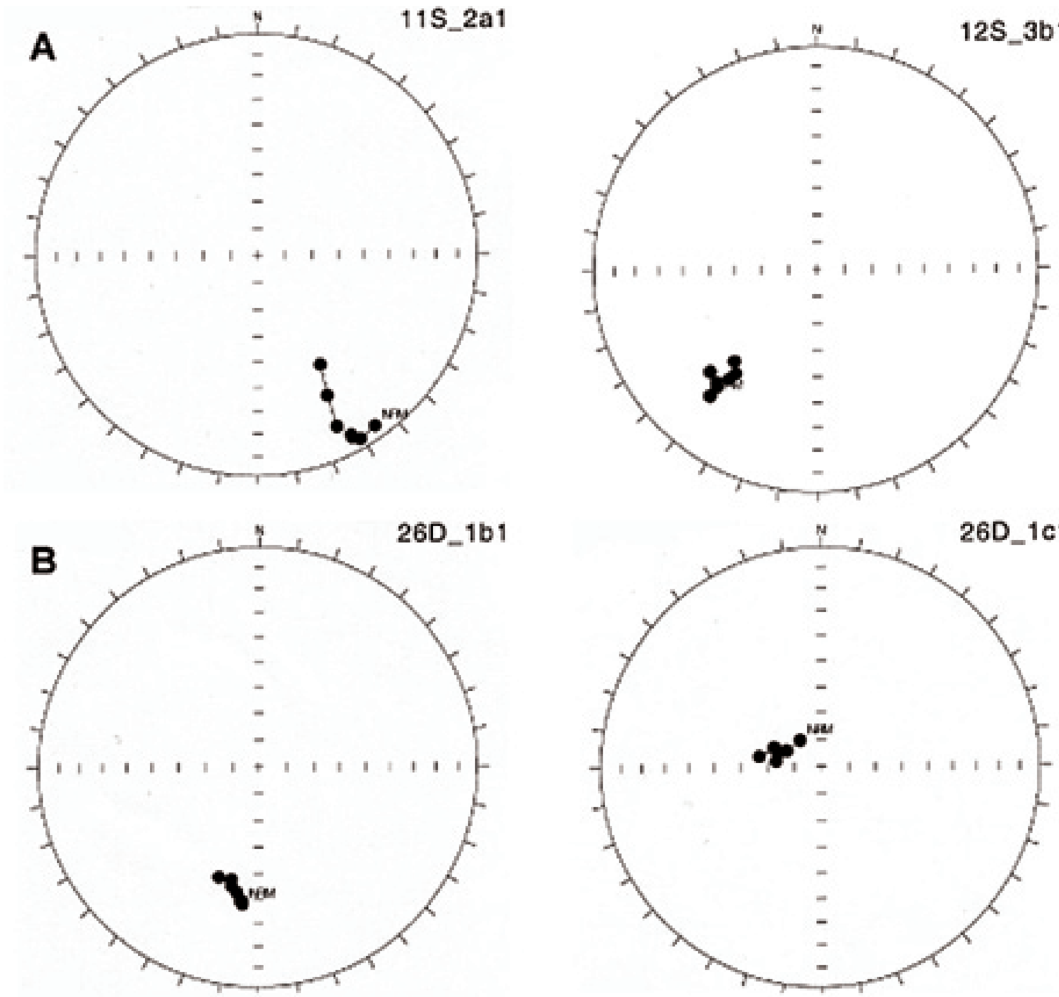

Figure 5. Natural remanent magnetization for select samples from the Ship Rock radial dike swarm. Ship Rock has a magnetic inclination of 62 degrees, but NRM results show significant variance from this value. A) Samples collected from the south dike display remanence values that are scattered and thus considered unstable. B) Remanence values taken from diatreme sample show significantly different values further indicating instability

CONCLUSION

AMS data for the Ship Rock radial dike swarm indicates a trend in horizontal flow from the central stock. Oblate ellipsoids are oftentimes recorded in volcanic rocks containing petrofabric flow indicators where the minimum axis is perpendicular to the maximum susceptibility axis (Butler, 1992). Many of

central stock, which upon eruption spread out horizontally during initial dike propagation. It is concluded that magma transport was initiated in a centralized magma chamber from the subsurface as opposed to a more expansive magma chamber that would produce complex flow patterns and vertical magma flows with respect to the surface.

There were several disadvantages involving the procedures used to conduct this field study that may have altered the accuracy of the data collection and interpretation. The collection of block samples results in the possibly of error with respect to orientation measurements in the field that can later affect the core orientation values used for AMS investigation. When collecting samples for paleomagnetic analysis, it is important to collect unweathered specimens because weathering can potentially alter the NRM measurements. Lightning strikes may also induce an alteration in the NRM that can create instability in the recorded geomagnetic field (Butler, 1992).

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