Using paleomagnetism to determine magma flow direction within the sheeted dike complex of the Troodos ophiolite, Cyprus

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INTRODUCTION

Purpose. The purpose of this project is to determine the magma flow direction of selected dikes within the Troodos ophiolite. It long has been assumed that magma flows vertically upward in the formation of oceanic crust, but recently there have been studies that show lateral flow may also be an important component of magma movement. In earlier studies, vesicle elongation and surface lineations have been used to determine an approximate direction of dike propagation. This project will determine if there is the possibility of vertical or lateral flow using paleomagnetic data.

Study area. The area of study focused on a 120 m section of road cut approximately two kilometers from the town of Palekhori, which is located on Cyprus, an island in the eastern Mediterranean Sea. The project area is located in the lower section of the sheeted dike complex of the 90 Ma Troodos ophiolite (Staudigel et al., 1992).

METHODS

Field work. Ken Veit and I mapped the 120 m section near Palekhori, where he was observing the geochemcial aspects of the sheeted dikes. The process of mapping included marking chilled margins, dike widths, dike attitudes, faults, veins, and descriptions of rock samples. Of the 66 dikes that were mapped, 14 were sampled due to their apparent chilled margins. Dike widths ranged between 10 cm and 3.1 m. Most of the dikes sampled were trending northeast and dipping relative steeply in a northwesterly direction. Cores were drilled using a portable gasoline-powered drill with a diamond drill bit. An average of five cores were extracted from within five centimeters of the chilled margin of each dike. The initial magma flow direction has been inferred at the quenched margins, since the dike margins are the first to solidify (Knight and Walker, 1988). These samples were then oriented using a Brunton and sun compass, where azimuth, hade (angle from vertical), sun-angle and time were noted. This orientation procedure is done in order to obtain an accurate geographic orientation of each sample (Butler, 1992). The sun-angle and time are recorded as a check because of possible magnetic disturbances that might affect the Brunton readings.

Laboratory work. The cores were then cut and taken to Scripps Institute of Oceanography where the susceptibility tensors were measured on a Kappabridge KLY-2 (Staudigel et al., 1992). Each core was measured in fifteen different directions. The orientation of the cores was then corrected from the sun compass data. The cores also went through a step demagnetization process at the institute.

Software. The bootstrap method of Constable and Tauxe was used to determine mean eigenvector and confidence regions (Staudigel et al., 1992). The program MacPaleomag was used to generate many of the plots.

AMS DATA

Knight and Walker define anisotropy of magnetic susceptibility (AMS) as a description of the variation of magnetic susceptibility with direction within a material (1988). Butler expresses AMS by comparing magnetic susceptibility values in three perpendicular directions: K_1 = maximum susceptibility; K_2 = intermediate susceptibility; K_3 = minimum susceptibility. These three values describe the magnetic susceptibility ellipsoid. If $K_1=K_2=K_3$, the ellipsoid is spherical; if $K_1 \approx K_2$ but $K_2 > K_3$, the ellipsoid is oblate (flattened); if $K_1 > K_2$ and $K_2 \approx K_3$, the ellipsoid is prolate (cigar-shaped) (1992). The ellipsoids that are created are interpreted as implying statistical alignment of elongate magnetic grains. For oblate ellipsoids, K_3 is perpendicular to flow surfaces. For prolate ellipsoids, K_1 parallel to lines of flow (Butler, 1992). Basically, the sum of all individual magnetic grains is represented by the susceptibility ellipsoid (Knight and Walker, 1988). Examples of these ellipsoids are found in Figures 1 and 2. Figure 1A shows the geographical position of the cores with respect to the plane of the dike. Figure 1B shows the ellipsoid and its relative position in the plane of the dike.

The direction of remnant magnetism may be influenced by an anisotropy of more than 10% (Butler, 1992). Remnant magnetism is the recording of past magnetic fields that may have acted on the material. Percent anisotropy is denoted by $(100)(K_1\text{-}K_3)/(K_1+K_2+K_3)$ (Staudigel et al., 1992). Only one sample had an anisotropy greater than 10%. This sample had a percent anisotropy of approximately 20%, which may be due to the presence of a fairly magnetic material. Percent anisotropy values ranged from .5% to 5.0%.

DEMAGNETIZATION DATA

Each sample was demagnetized at several different levels, each being higher than the one before. At each level the natural remnant magnetization was measured (Butler, 1992). The equal area plot (Figure 3) shows the magnetization remaining after each step. Filled circles are lower hemisphere projections, and open circles are for upper hemisphere projections. Below the equal area plot is a plot of the remnant intensity (J) and susceptibility (K) versus temperature. This merely monitors mineralogical changes.

The Zijderveld diagram is a vector endpoint diagram which shows horizontal (filled circles) and vertical (open circles) projections of the vector at each step (Figure 4). Since the magnetization direction, declination, inclination, and intensity can be decomposed into North, East, and down components, the North versus East and East versus down is plotted on the same diagram. The final stable direction of magnetization shows up as a straight line heading towards the origin. Both Figures 3 and 4 represent data taken from Dike 56.

The final direction was chosen by principal component analysis or a least squares sense. All data points plotted in the northwest quadrant and were well grouped. This is shown in Figure 5 (the equal area plot). The mean direction and 95% confidence region are shown as well as the approximate expected direction for the Troodos ophiolite. The Troodos mean is the open circle with the "x" in the center. The grouped data points have not yet been rotated to the average Troodos mean.

DISCUSSION

The AMS data given illustrates the direction of magma flow. The 14 dikes sampled resulted in both prolate and oblate susceptibility ellipsoids. In Figures 1A and 2A, the small squares represent the orientation direction of each core taken from the dike in the upper hemisphere. The small circles show the core orientations in the lower hemisphere. The ellipsoids are plotted on both the upper and lower hemispheres, hence the second ellipsoid in each figure.The lines represent the attitudes of the dike at different locations, usually where the cores were extracted. Only the K_1 direction is shown on the diagram. The ellipsoid in Figure 1A is dipping at approximately 45° and flow is upward. The ellipsoid in Figure 2A is dipping 80° and flow is also upward.

When the magnetic component changes in any way, the AMS ellipsoid also varies (Knight and Walker, 1988). As these components change, the ellipsoid is affected, which may account for variances in the ellipsoid shapes of the 14 samples. In this study, most of the ellipsoids were found near the plane of the dike and flowed vertically through the dikes. The dike attitudes and ellipsoids will not represent true flow direction until they are rotated to the Troodos mean which was the location of the ophiolite at the time of emplacement; this rotation will not change the fact that the magma flow was vertical.

CONCLUSIONS

It has been shown that using paleomagnetism is an applicable method of determining magma flow direction; although, this study indicated that there was only one basic direction of flow. The majority of the dikes sampled appeared to display predominantly vertical upward movement along the attitude of the dike. The susceptibility ellipsoids clearly show that magma propagation remained vertical.

It should be noted that the magma composition and magma chamber placement may have an effect on the direction of magma movement. In this study, the dikes had similar compositions, but magma flow may be directed differently for those dikes which have contrasting compositions.

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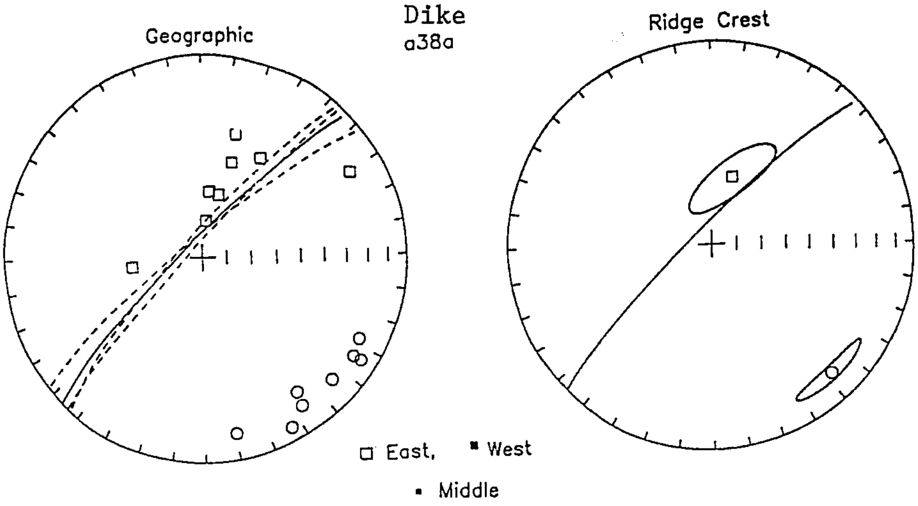

Figure 1A

Figure 1B

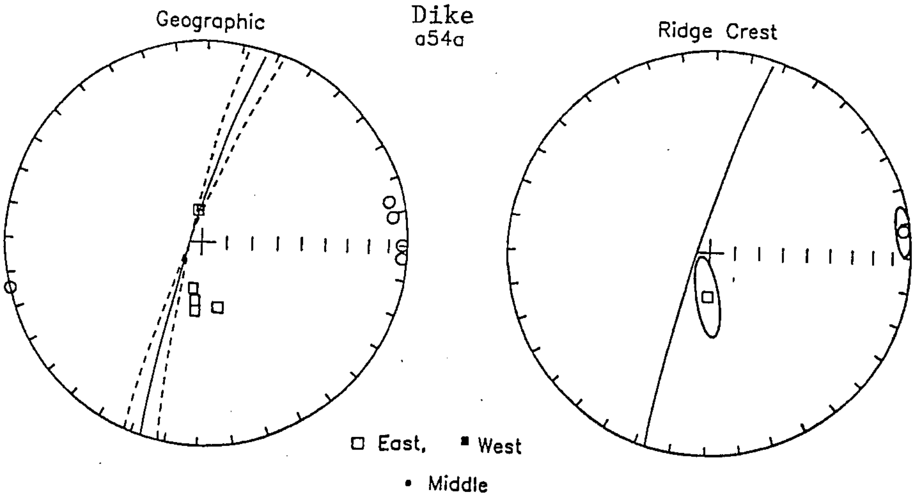

Figure 2A

Figure 2B

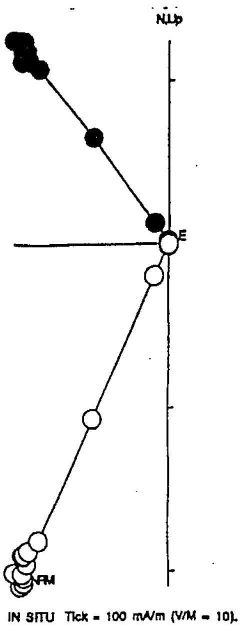

Figure 3: Dike 56

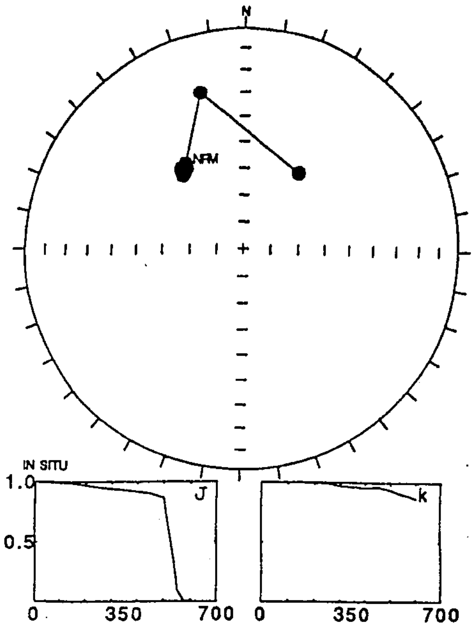

Figure 4: Dike 56

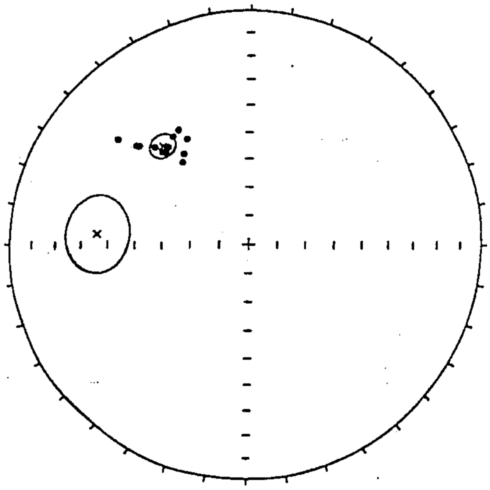

Figure 5