Magma flow directions and spreading structures within the upper part of the sheeted dike complex of the Troodos ophiolite, Cyprus

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INTRODUCTION

The Troodos ophiolite in the eastern Mediterranean contains three grabens within its sheeted dike complex. The Solea, Mitsero and Larnaca grabens are defined by west-dipping dikes on their eastern flanks and east-dipping dikes on their western flanks (Varga and Moores, 1985). There is some dispute as to origin of the grabens. Moores and Varga (1984) suggest they are abandoned axial valleys of fossil spreading centers. Citing the absence of cross-cutting dikes, Allertine and Vine (1987) argue the Solea graben formed by antithetic faulting on the west flank of the spreading axis. Field observations and paleomagnetic analysis from this study will be used to try to ascertain which model is a more likely explanation for the formation of the grabens.

Independent of their association with spreading structures, the sheeted dikes in the ophiolite provide insight into the flow of magma. Two families of geochemically different dikes were simultaneously injected within a small region of the dike complex (Baragar et al., 1990). Early models of spreading ridges employing vertical flow of intrusions from elongated axial magma chambers do not offer a plausible mechanism for these contemporaneous injections. Work in Iceland by Sigurdsson (1987) and in Hawaii by Knight and Walker (1988) indicate that horizontal propagation within vertical dikes is common. This new data suggests a model in which magma horizontally propagates from centralized chambers to magma-starved sections of the spreading ridge. The variety of flow directions found in the dike complex of the Troodos ophiolite by Staudigel et al. (1992) indicates the centralized chamber model is a more likely explanation of the geochemically different intrusions. Flow directions indicated by field-observations of slickensides and elongated vesicles along with anisotropy of magnetic susceptibility of the dikes sampled should show if there was any horizontal flow in the upper section of the dike complex.

Along the Peristerona River in the Mitsero Graben, the study area is a 78m exposure. The section is composed of gabbro dikes that vary in width from 0.1m to 2.5m. The focus of this study on the upper part of the sheeted dike complex is two-fold: 1) to determine the origin of the structural graben and; 2) determine the flow directions of the dikes. Both aspects of the study will integrate data from field observations, paleomagnetization, and anisotropy of magnetic susceptibility.

METHODS

Four sites along the Peristerona River were mapped, but the largest and southernmost one is the focus of this study. The chilled margins of the younger dikes were mapped along with volcanic screens and hydrothermally altered breccias. Once mapping was completed the quenched margins were examined for flow indicators, principally slickensides and elongated vesicles. Slickensides are parallel grooves and ridges thought to result from scouring of the intruding magma by the bedrock or from collapse of highly elongated vesicles along the quenched margins (Staudigel et al., 1992).

At the site it was observed that there are two distinct groups of dike orientation. One group of dikes dipped about 60° to the North. The other group of dikes were nearly vertical and cross-cut the inclined dikes. The largest vertical dike also cut hydrothermally altered breccia. Cores were drilled in both the vertical dikes and the tilted dikes. The five to seven centimeter cores were drilled within five centimeters of the quenched margins of the dikes. The orientations of the dikes and the cores were taken using a Brunton compass and a sun compass.

The cores were transported to Scripps Institute of Oceanography to be cut and analyzed. A minimum of two cores from each sampled dike were thermally demagnetized using eleven steps from 100°C to 550°C. After each step the natural remnant magnetization of each core was measured (Butler, 1992). The susceptibility tensors of the remaining cores were measured on a Kappabridge KLY-2 in fifteen different directions (Staudigel et al., 1992).

PALEOMAGNETIC ANALYSIS

Paleomagnetism is employed in this study to determine the original orientations of the dikes at their time of emplacement. The results of the thermal demagnetization were plotted in Zijderveld vector component diagrams (figure 1). The direction of characteristic remnant magnetization (ChRM) for each core was derived from vector component analysis of the diagrams. The ChRM of each core was rotated to correct for the 10° dip of the northern section of the ophiolite. The core data was separated into two groups according to the orientations of their source dike: north tilting or almost vertical. In figure 2 the mean ChRM of each dike group from the site is compared to the Troodos mean direction (TMD) which was determined from magnetic vectors in sediment and pillow lavas that were structurally corrected by Clube, et al. (1985). The ellipses around each vector mean (a95 ellipses) represent areas in which there is 95% confidence of the true mean direction (Butler, 1992).

The ChRM of each group is statistically different because the a95 ellipses do not overlap (Butler, 1992). Dike group 1B, the sub-vertical dikes, has ChRM which is closer to the Troodos mean. This implies that they are less rotated than the other dike group 1A and are thus younger. After a two step rotation correction the mean vector for group 1B plots within the TMD ellipse and the mean vector for group 1A is closer to the ellipse (figure 3). Applying the same correction to the dike orientations shows that group 1A was dipping about 30° SE when dike group 1B intruded them at a dip of about 60° W (figure 4). Further rotation corrections were applied to dike group 1A to determine the orientation of the dikes at the time that they intruded. Unlike group 1B, these dikes are shown to have been nearly vertical at the time of intrusion.

ANISOTROPY OF MAGNETIC SUSCEPTIBILITY

Anisotropy of magnetic susceptibility (AMS) is often used as a flow indicator in intrusive volcanics (Staudigel et. al., 1992; Knight and Walker, 1988). AMS describes the variation of magnetic susceptibility in different directions as an ellipsoid. Kmax is the longest axis of the ellipsoid and indicates the direction of elongation of magnetite crystals in the dike (Butler, 1992). Along the quenched margins of the dike, these crystals record the original flow direction of the magma as it intruded the bedrock and immediately cooled.

Several cores for each dike were measured for magnetic susceptibility. The orientations of the Kmax and Kmin of the AMS ellipsoids were plotted on equal area stereonets along with the orientations of their corresponding dike. A great variety of flow directions are represented within the upper section of the dike complex. Dike 141 displays a Kmax that is very near vertical and a Kmin that is perpendicular to the orientation of the dike (figure 6). This indicates a vertical flow. Measurements were taken from both chill margins for dike 148. The margins have different variation in flow directions due to the imbrication of the magnetite crystals along the edge of each dike (figure 7 and figure 8).

CONCLUSIONS

Cross-cutting dikes, paleomagnetism and AMS in this study suggest a complex history of horizontal to vertical intrusion and extensional faulting within the Mitsero graben. The older group of dikes intruded vertically with strikes parallel to the axis of the graben. These dikes cooled and contracted, forming joints perpendicular to the chill margins. Magma intrusion ceased for a time and was followed by a period of extension along the spreading axis, forming listric normal faults that tilted the dikes to sub vertical orientations. The vertical dikes at the site cross-cut other dikes as well as fault-related hydrothermally altered breccia. The intrusion of these younger dikes through both tilted dikes and fault breccia indicates that the graben is an abandoned axial valley of the spreading ridge. Unlike the older dikes, the later intrusions were sub-vertical. The intrusions followed the path of least resistance to the surface, which for the younger dikes was along the older dike margins and joints (figure 5).

AMS flow vectors and slickensides observed in the field have similar flow directions, indicating that AMS is an accurate measure of flow. The AMS analysis of flow directions indicates that the magma propagated both vertically and horizontally. This suggests that there were a variety of centralized magma sources along the spreading ridge. With multiple sources for intrusions, the magmas have the potential to mix and produce geochemically complex, if intruded contemporaneously.

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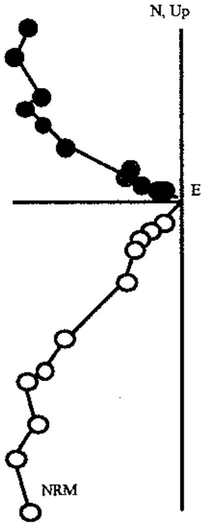


Figure 1. Zijderveld plot from dike 148 for thermal demagnetization. Circles represent projections onto vertical plane, squares onto horizontal plane. NRM is natural remanent magnetization.

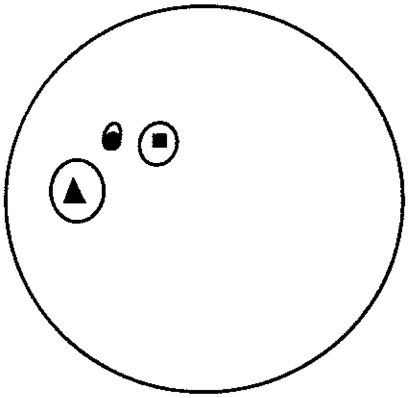


Figure 2. Equal area projection of mean characteristic components of natural remnant magnetization by dike group.

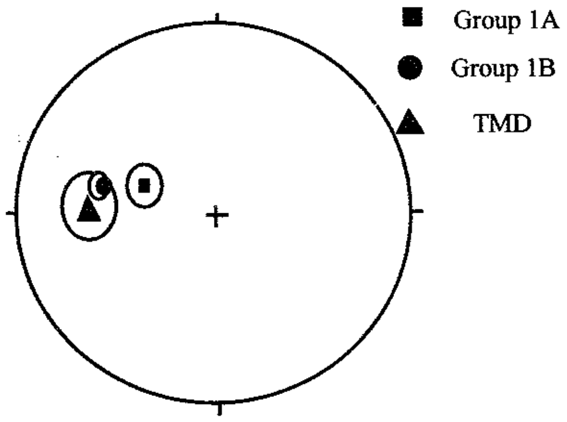


Figure 3. Group ChRM means rotated. Note that group 1B plots within the TMD a95 ellipse.

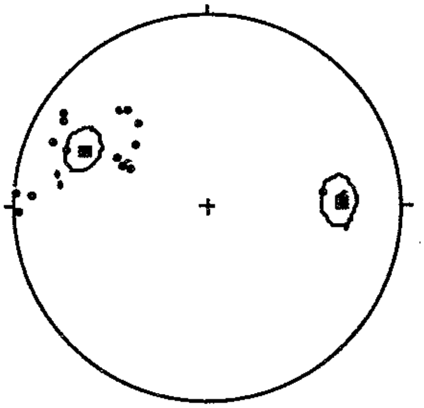
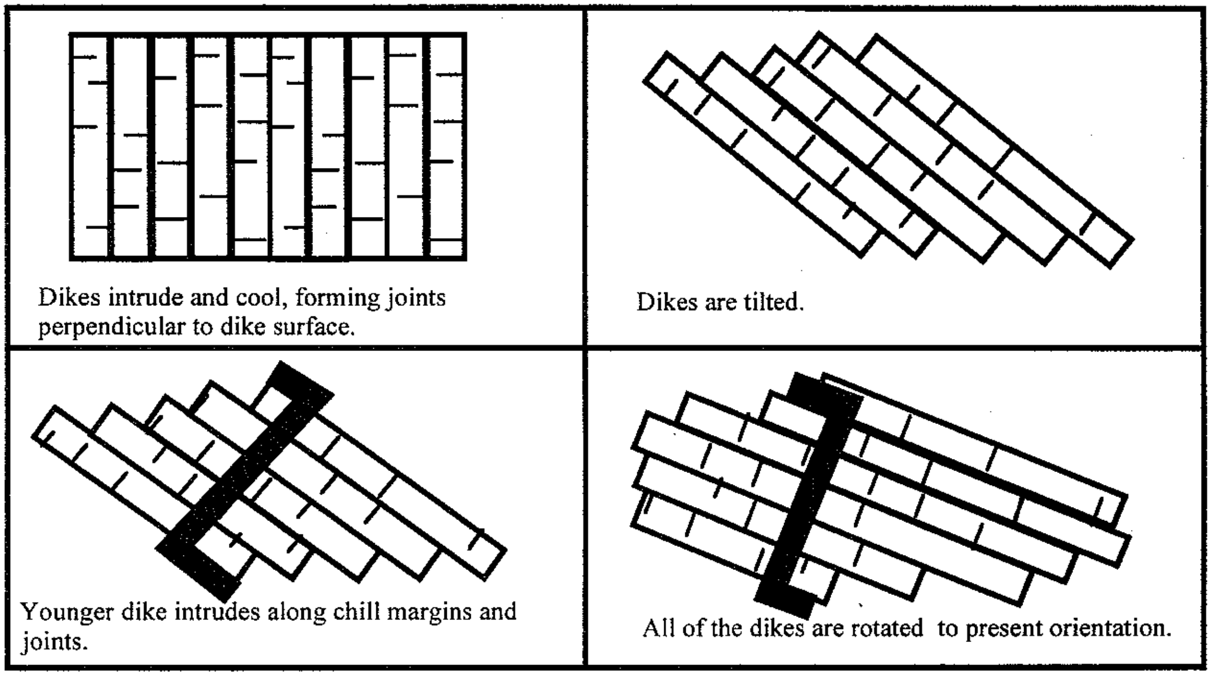


Figure 4. Poles to dikes plotted on equal area stereonet. Dikes have been rotated to position at time of intrustion of 1B.

Figure 5. Scenerio for later dike intrusion.



Dikes intrude and cool, forming joints perpendicular to dike surface.

Dikes are tilted.

Younger dike intrudes along chill margins and joints.

All of the dikes are rotated to present orientation.

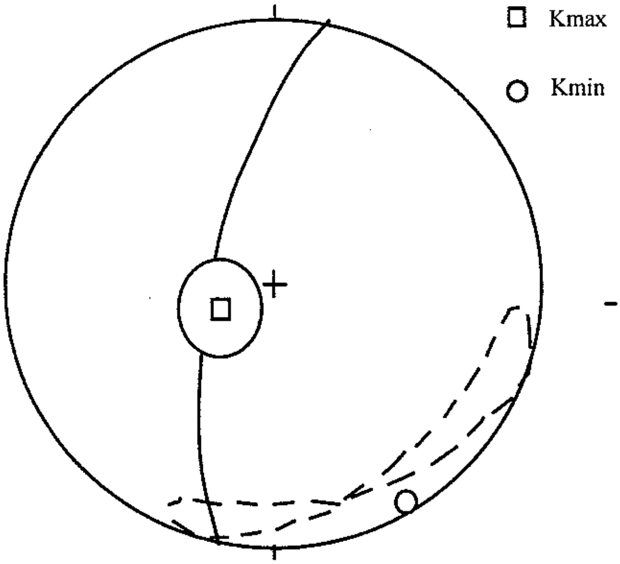


Figure 6. Equal area stereonet of dike 141. Kmax is near vertical.

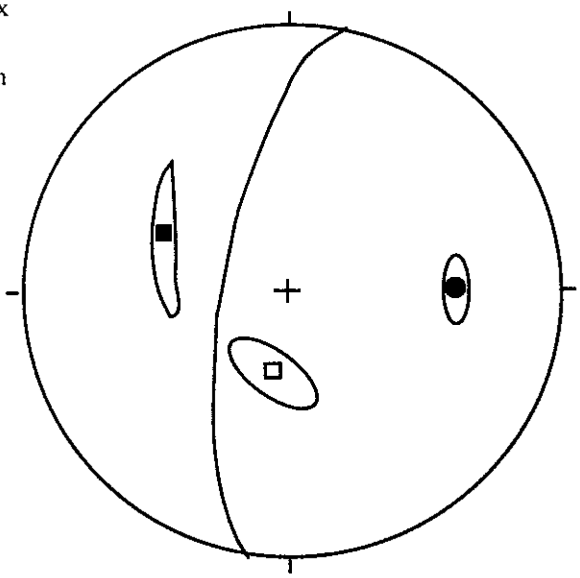


Figure 7. Equal area projection of Kmax and Kmin for dike 148. Solid shapes indicate western margin and hollow shapes are eastern margins.

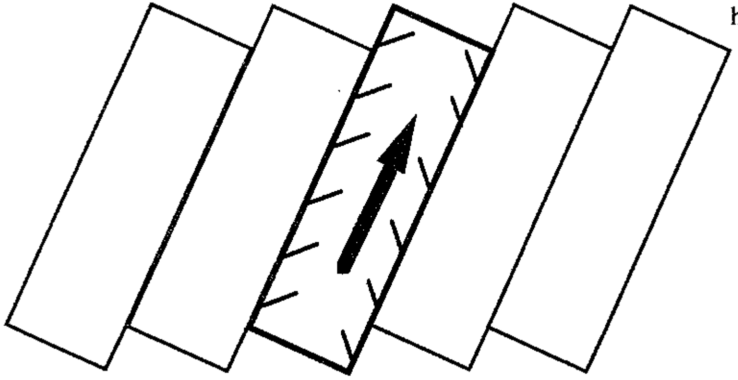


Figure 8. Imbrication of elongated cyrstals along dike margins.