Magma propagation direction and the timing of dike tilting in mid-level sheeted dikes, Troodos Ophiolite, Cyprus

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Introduction

Vertical propagation of magma through the sheeted dike section (seismic layer 3) of the ocean crust has long been the model for magmatism at spreading centers (Gudmundsson, 1990). In recent years however, studies have not been able to locate any large magma reservoirs along slow-spreading ridges, such as the mid-Atlantic ridge (Detrick et al., 1990). Axial magma chambers have, however, been well-documented along fast spreading centers (Macdonald, 1982; Sinton and Detrick, 1992). The lack of magma chambers at slow spreading ridges has been explained by the possibility of ephemeral magma chambers which occasionally pond and supply temporary magmatic events along the ridge (Macdonald, 1982, 1986). In the sheeted dikes of the Troodos ophiolite, Cyprus, looked at in this study, field and paleomagnetic studies show evidence for horizontal propagation of magma along the paleo-ridge axis (Staudigel et. al, 1992; Varga et. al, in review). This opens up the possibility that magma could be supplied from several isolated sources flowing laterally from these points along the length of the ridge. This may change current view points on how spreading zones receive magma without a major axial magma chamber located directly beneath and has implications for study of the mantle souce areas deduced from samples colleceted along spreading centers.

Anisotropy of magnetic susceptibility (AMS) was used to determine flow direction within the sampled dikes. It has been observed that a magnetic field passes most easily through the long direction of magnetite grains or along preferentially aligned groups of grains (Hargraves et. al, 1991). In theory, these grains have been aligned with the flow direction of the magma and thus yield an indirect measure of flow direction (Hargraves et. al, 1991; Staudigel et. al, 1992).

There is controversy surrounding the processes which led to the formation of the grabens that are observed in the Troodos ophiolite. Competing theories suggest that the tilting occurred either while still close to the spreading center, or as a result of obduction (Van-Everdingen and Cawood, 1995). The paleomagnetic remnance of cross cutting dikes were studied in an attempt to constrain the tilting of the dikes to an on or near axis location. In these situations, shallowly dipping dikes were cut by later, more steeply dipping dikes. These dikes were analyzed for distinct paleomagnetic signatures which would indicate that the crosscutting dikes were emplaced diachronously after some sort of rotation and still near a magma source.

Geologic Setting

The field sites were all located within the Mitsero graben of the Troodos ophiolite. After surveying several kilometers of Phterykhoudhi canyon, four sampling sites were chosen in addition to a final site at a roadcut above nearby Peristerona Canyon. All of these sites were constrained to the middle region of the Troodos ophiolite's sheeted dike zone.

Methods

Each core was collected from within 5 cm of the margin of the dike in the hopes of finding an imbricated AMS fabric. An orientation stage was used to accurately record the inclination and declination of the cores as they were drilled. A sun compass was used when possible to correct for possible brunton errors caused by magnetic interference from the dike itself.

Thermal demagnetization was carried out at the Scripps Institute of Oceanographic Research labs in La Jolla Ca with the help of Dr. Jeff Gee. A cryogenic magnetometer was used for the measurement of all of the samples. After initial NRM directions were measured, the samples were heated to 100°C for 45 minutes and remeasured. Temperature steps of 50°C were used up to 500°C. 25° steps were used for the final two steps to a final temperature of 550°C.

The AMS of each core was recorded before magnetic cleaning using a Kappabridge magnetic susceptibility meter. This was done by measuring the magnetic susceptibility of each core in 15 orientations. A three dimensional susceptibility tensor was generated from the maximum, intermediate, and minimum eigenvectors (K_1, K_2, K_3 respectively) of the core sample. The long vector of this ellipsoid is associated with average elongation

Clube, T.M.M., Creer, K.M. and Robertson, A.H.F., 1985, Paleorotation of the Troodos microplate, Cyprus: Nature, v. 317, p. 522-525.
Constantinou, G. and Grovett, G.J.S., 1973, Geology, geochemistry and genesis of Cyprus sulphide deposits: Economic Geology, v. 68, p. 843-858.
Gass, I.D., 1990, Ophiolites and oceanic lithosphere, *in* Malpas, J.G. and Moores, E.M., eds., Ophiolites and Oceanic Crustal Analogues, Proceedings of the Symposium "Troodos 1987": Nicosia, Geological Survey Department, p. 1-10.
Hurst, S.D., Moores, E.M. and Varga, R.J., 1994, Structural and geophysical expression of the Solea graben, Troodos ophiolite, Cyprus: Tectonics, v. 13, n. 1, p. 139-156.
Livicari, R.F., Geissman, J.W. and Reynolds, S.J., 1993, Palaeomagnetic evidence for large-magnitude, low-angle normal faulting in a metamorphic core complex: Nature, v. 361, p. 56-59.
Miyashiro, A., 1973, The Troodos ophiolite was probably formed in an island arc: Earth and Planetary Science Letters, v. 19, p. 218-224.
Moores, E.M., Varga, R.J., Verosub, K.L. and Ramsden, T., 1990, Regional structure of the Troodos dike complex, *in* Malpas, J.G., Moores, E.M., Panayiotou, A. and Xenophontos, C., eds., Ophiolites and Oceanic Crustal Analogues, Proceedings of the Symposium "Troodos 1987": Nicosia, Geological Survey Department, p. 27-35.
Moores, E.M. and Vine, F.J., 1971, Troodos massif, Cyprus and other ophiolites as ocean crust: evaluations and implications: Philosophical Transactions of the Royal Society of London Serial A., v. 268, p. 443-466.
Mukasa, S. and Ludden, J.N., 1987, Uranium-lead isotopic ages of plagiogranites from the Troodos Ophiolite, Cyprus, and their tectonic significance: Geology, v. 15, p. 825-828.
Mutter, J.C. and Karson, J.A., 1992, Structural processes at slow-spreading ridges: Science, v. 257, p. 627-634.
Nicolas, A., 1988, Structure of Ophiolites and Dynamics of Oceanic Lithosphere: Dordrecht, Kluwer Academic Publishers, 367 pp..
Rautenschlein, M., Jenner, G., Hertogen, J., Hofmann, A.W., Kerrich, J., Schmincke, H.-U. and White, W.E.M., 1985, Isotopic and trace element composition of volcanic glass from the Akaki Canyon, Cyprus: Earth and Planetary Science Letters, v. 75, p. 369-383.
Schiffman, P., Bettison, L.A. and Smith, B.M., 1990, Mineralogy and geochemistry of epidosites from the Solea graben, Troodos ophiolite, Cyprus, *in* Malpas, J.G., Moores, E.M., Panayiotou, A. and Xenophontos, C., eds., Ophiolites and Oceanic Crustal Analogues, Proceedings of the Symposium "Troodos 1987": Nicosia, Geological Survey Department, p. 673-683.
Schiffman, P. and Smith, B.M., 1988, Petrology and O-isotope geochemistry of a fossil seawater hydrothermal system within the Solea graben, northern Troodos ophiolite, Cyprus: Journal of Geophysical Research, v. 93, p. 4612-4624.
Schiffman, P., Smith, B.M., Varga, R.J. and Moores, E.M., 1987, Geometry, conditions and timing of off-axis hydrothermal metamorphism and ore deposition in the Solea graben, Troodos ophiolite, Cyprus: Nature, v. 325, p. 423-425.
Sigurdsson, H., 1987, Dyke injection in Iceland: a review, *in* Halls, H.C. and Fahrig, W.F., eds., Mafic dyke swarms: Geological Association of Canada, p. 55-64.
Simonian, D.O. and Gass, I.G., 1978, Arakapas fault belt, Cyprus: a fossil transform fault: Geological Society of America Bulletin, v. 89, p. 1220-1230.
Staudigel, H., Gee, J., Tauxe, L. and Varga, R.J., 1992, Shallow intrusive directions of sheeted dikes in the Troodos ophiolite: Anisotropy of magnetic susceptibility and structural data: Geology, v. 20, p. 841-844.
Varga, R.J., 1991, Modes of extension at oceanic spreading centers: evidence from the Solea graben, Troodos ophiolite, Cyprus: Journal of Structural Geology, v. 13, p. 517-537.
Varga, R.J. and Gee, J., 1995, Paleomagnetic evaluation of the detachment model for crustal extension within the Troodos ophiolite, Cyprus: EOS, Transactions of the American Geophysical Union, v.
Varga, R.J. and Moores, E.M., 1985, Spreading structure of the Troodos ophiolite, Cyprus: Geology, v. 13, n. 12, p. 846-850.
Varga, R.J. and Moores, E.M., 1990, Intermittent magmatic spreading and tectonic extension in the Troodos ophiolite: implications for exploration for black smoker-type ore deposits, *in* Malpas, J.G., Moores, E.M., Panayiotou, A. and Xenophontos, C., eds., Ophiolites and Oceanic Crustal Analogues, Proceedings of the Symposium "Troodos 1987": Nicosia, Geological Survey Department, p. 53-64.
Whitechurch, H., Juteau, T. and Montigny, 1984, Role of the eastern Mediterranean ophiolites (Turkey, Syria, Cyprus) in the history of the Neo-Tethys, *in* Dixon, J.E. and Robertson, A.H.F., eds., The Geological Evolution of the Eastern Mediterranean: Geological Society of London Special Publication, v. 17, p. 301-317.

direction of the magnetite within the rock. A preferred orientation direction is associated with flow direction of the magma.

Results and Discussion

The cross-cutting dikes within my sites were not statistically different paleomagnetically from the surrounding dikes at the sites. The paleomagnetic results were used, however, to rotate the dikes back to their unrotated positions. Through successive steps, the stratigraphic tilt of the ophiolite was first corrected for. The dikes were then rotated back towards vertical, and subsequently around a vertical axis of rotation until their paleomagnetic vectors were statistically indistinguishable with the Troodos mean paleomagnetic direction.

A well-developed imbrication was found in most of the dikes in which both margins were sampled from (Fig. 1). The flow fabric implied by these AMS ellipsoids indicates a mostly vertical flow direction with a partial horizontal component. In the lower sections of the sheeted dike regions studied by Ken Viet and Amy Huskey (Huskey, 1996), the predominant flow direction was shown to be strongly vertical. With the addition of the data from Helen Rance and Nancy Adams (this volume) who worked in the upper section of the sheeted dikes, I will attempt to define a horizon of neutral buoyancy (Ryan, 199within the sheeted dikes. The data does indicate that such a horizon probably exists and it is likely to be located between the upper and mid regions of the sheeted dike section.

References Cited

Detrick, Robert S., Mutter, John, C., Buhl, Peter, Kim Issac I. Kim, 1990, No evidence from multichannel reflection data for a crustal magma chamber in the MARK area on the Mid-Atlantic Ridge: Nature, v. 347, p. 61-64.

Gudmundsson, A., 1990. Emplacement of dikes, sills and crustal magma chambers at divergent plate boundaries. Tectonophysics, v. 176 p. 257-275.

Hargraves, R.B., Johnson, D., Chan C.Y., 1991, Distribution anisotropy: the cause of AMS in igneous rocks?, Geophysical Research Letters, v.18 n.12 p.2193-2196.

Huskey, A., 1996, Using paleomagnetism to determine magma flow direction within the sheeted dike comlpex of the Troodos ophiolite, Cyprus: *in* The Ninth KECK Research Symposium in Geology p.233-236.

Macdonald, K. C., 1986, The crest of the Mid-Atlantic Ridge: Models for crustal generation processes and tectonics; in Vogt, P.R., and Tucholke, B.E., eds., The Geology of North America, Volume M, The Western North Atlantic Region: Geological Society of America.

Macdonald, K. C., 1982, Mid-Ocean Ridges: Fine Scale Tectonic, Volcanic and Hydrothermal Processes Within the Plate Boundary Zone: Ann. Rev. Earth Planet. Sci. 1982 v. 10, p.155-90.

Ryan, M.P., 1987, Neutral bouyancy and the mechanical evolution of magmatic systems, *in* Mysen, B.O. (ed.), The Geochemical Society, Special Publication n.1 p.259-287.

Sinton J.M., and Detrick R.S., 1992, Mid Ocean Ridge Magma Chambers: Journal of Geophysical Research, v. 97, n. B1, p. 197-216.

Staudigel, H., Gee, J., Tauxe, L. & Varga R.J., 1992, Shallow intrusive directions of sheeted dikes in the Troodos ophiolite: Anisotropy of magnetic susceptibility and structural data: Geology. v. 20 p. 841-844.

Van Everdingen D.A., Cawood P.A., 1995, Dyke domains in the Mitsero graben, Troodos ophiolite, Cyprus: an off-axis model for graben formation at a spreading center: Philosophical Transactions of the Geological Society of London p.923-931.

Varga R.J., Gee, J.S., Staudigel H., Tauxe, L., in review, Dike surface lineations as magma flow indicators within the sheeted dike complex of the Troodos ophiolite Cyprus.

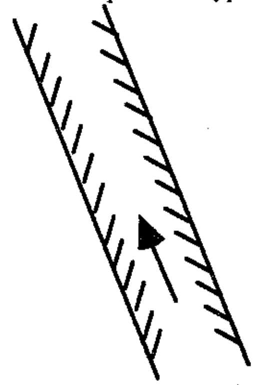

Figure 1b. Illustration of how imbrication can imply a propagation direction. Note shallowly raking AMS directions on right margin and more steeply raking AMS on the left.

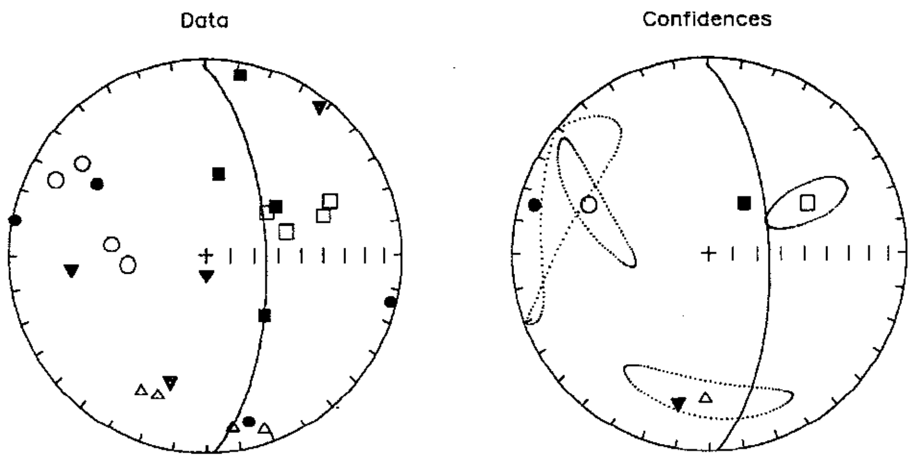

Figure 1a. Plot of dike and principle AMS direction with confidence ellipsoids. The maximum, intermediate, and minimum axes are represented by squares, triangles, and circles respectively. Samples taken from the western margin are indicated by filled symbols while samples from the eastern margin are open. Note imbricated sense with western ellipsoids raking more steeply than the dike and eastern ellipsoids raking more shallowly.

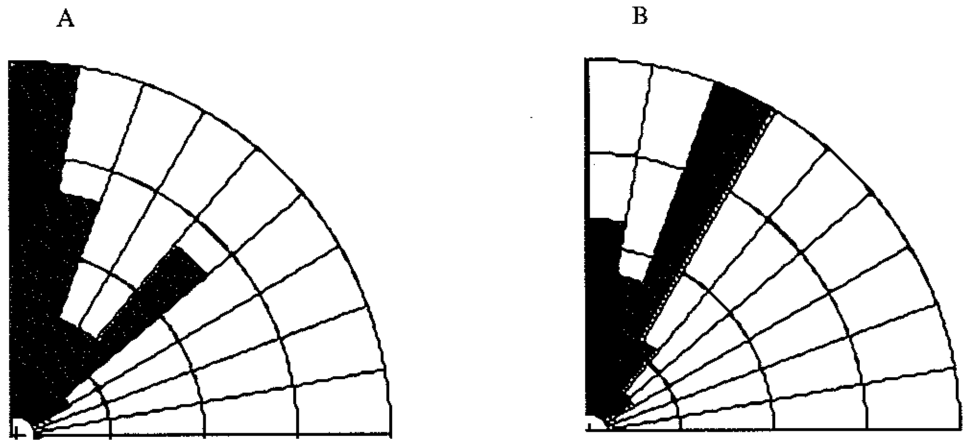

Figure 2 Rose diagrams showing the direction of the maximum elongation directions of AMS ellipsoids. (a) AMS flow directions through dikes prior to any tilt corrections. (b) AMS after tilt corrections for extentional and stratal tilt have been performed.

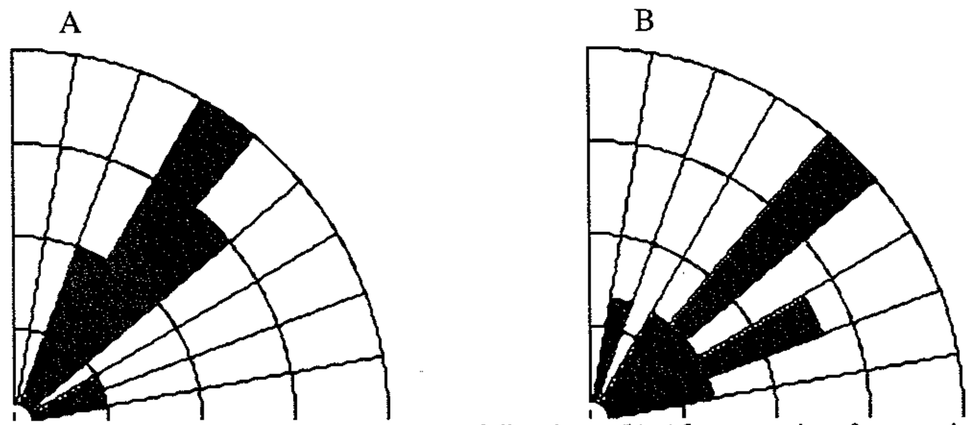

Figure 3. Rose diagrams of HSL directions. (a) Unrotated directions. (b) After corrections for extentional and stratal tilt have been performed