Structural controls on epidosite formation and timing of hydrothermal alteration, Mitsero graben, Troodos ophiolite

Cari Johnson
Department of Geology, Carleton College, Northfield, MN 55057
Faculty sponsor: Julie Maxson, Carleton College

INTRODUCTION

Massive sulfide deposits on Cyprus are the products of hydrothermal circulation during the ophiolite's formation in the Late Cretaceous. The discovery of smoker vent fragments by Oudin and Constantinou (1984) indicates that these sulfides formed by processes analogous to those forming black smoker vents at modern spreading ridges. Despite numerous studies of the Troodos ophiolite over the last 25 years, many aspects of the hydrothermal systems are still poorly understood. In particular, the importance and effect of structural controls on upwelling zones has yet to be determined. This project investigates past hydrothermal processes of the Troodos ophiolite by studying the relationships between alteration and structural features such as faults or joints in the root zones of the sheeted dike complex.

Models for ore formation at spreading ridges generally begin with circulation of sea water down into the oceanic crust where it is heated by degassing magma plutons. Through water-rock interaction, these fluids become metal-enriched as they return to the ocean-seafloor interface via upflow zones. Eventually, sulfide-rich exhalative deposits are formed primarily in the pillow lava volcanics. This general model for ore formation is limited by a lack of understanding of the diverse geochemical and physical processes associated with these complex systems.

On Cyprus, the well-exposed sheeted dike section provides an unique opportunity to study the roots of a formerly active hydrothermal system. Many of the dikes are diabase altered to greenschist facies with a characteristic mineralogy of albite, actinolite, quartz and chlorite, and a relict igneous texture. In some areas, however, zones of intense hydrothermal alteration appear in the form of 'epidosite-altered' dikes. Epidosites consist of granular quartz-chlorite-epidote-sphene assemblages and are believed to represent upwelling zones of circulating hydrothermal fluids (Schiffman *et al.*, 1987).

The importance of structural controls on these alteration zones has yet to be determined. Several authors have suggested that epidosite formation is strongly controlled by earlier extensional faults or fractures, and that previous brittle deformation provides the permeability necessary for the development of a large hydrothermal system (Bettison-Varga *et al.*, 1992). Others have argued that epidotization occurred in association with dike intrusion at the spreading axis (Richardson *et al.*, 1987), and that tectonic extension is not a prerequisite for epidosite formation. Distinction between these two models is critical to our understanding of hydrothermal systems in modern spreading environments and in other ophiolites, since they imply significantly different scenarios for alteration.

For the Troodos ophiolite, the question of structural control on epidosite formation is inherently related to the timing of alteration and the location of hydrothermal activity with respect to the spreading axis. Three grabens on Cyprus are defined by listric detachment fault zones underlying rotated dikes, which dip towards the axis on either side of a graben. These grabens are believed to represent fossil spreading axes (Varga and Moores, 1990). Observations of the Troodos spreading structure have constrained most of the extensional faulting and dike rotation to association with graben formation, during either on-axis or off-axis crustal thinning. Faulting as a structural control on hydrothermal alteration is therefore related to timing of alteration with respect to tectonic extension and graben formation.

The main goals of this study are to determine the timing of epidosite formation with respect to dike rotation and to describe the role of structural features in focusing fluid flow. Paleomagnetic analysis complements field observations to address these questions. In addition, the presence of a reversal component in the magnetic signatures of the dikes demands reconsideration of models of the ophiolite's structural evolution and of the currently accepted age for the Troodos.

FIELD OBSERVATIONS

The Mitsero graben is the central of three grabens on Cyprus. A zone of intense alteration of dikes from diabase to epidosite is exposed in the Phterykhoudhi River canyon, located west of the Mitsero graben axis. The epidosite zone is narrow (500-600 m) and elongated northward parallel to the graben axis for approximately 2 km. The zone is defined by areas in which up to 80% of dikes in a given outcrop are altered to epidosites. It is bounded to the south by a sulfide-rich brecciated zone (in non-epidotized dikes) and to the north by a narrow transition zone (<40% altered dikes in a given outcrop) into greenschist-altered diabase dikes.

Field observations from the Phterykhoudhi River epidosite zone are similar to observations in previous studies of the Solea graben (Bettison-Varga *et al.*, 1992). Alteration is extremely variable at the outcrop scale, as epidosites are often bounded by relatively unaltered dikes. The most striking alteration feature is epidosite banding, in which 'stripes' of green, resistant epidote-quartz bands alternate with softer, blue chlorite-quartz bands. Most of these stripes are dike-parallel, though the banding does not necessarily follow chilled margins. Another common epidosite pattern in the area are 'pods' of epidosite elongated along microfractures which demonstrates fracture control of this feature.

In some areas, shallowly dipping dikes cut more steeply dipping dikes. These cross-cutting dikes were found to be both altered and unaltered, suggesting that at least some alteration happened after a later intrusion period. Faults are generally dike-parallel. In some areas, alteration is concentrated along fault planes, implying structural control of alteration. In other cases, epidotized fault zones do not show a clear timing relationship between deformation and alteration. Whereas field relations between structural features and epidosites remain ambiguous, paleomagnetic analysis provides an additional method of determining the timing of alteration.

PALEOMAGNETIC ANALYSIS

In this study, paleomagnetism is used to constrain a specific event: the timing of hydrothermal alteration with respect to rotation of the dikes. This method requires comparison of natural remanent magnetization (NRM) vectors of epidosites and diabase dikes from the same graben. The NRM vectors of dikes must also be compared to the Troodos mean direction, which is determined by structurally corrected magnetic vectors in sediments and pillow lavas (Clube *et al.*, 1985). The Troodos mean indicates the direction of the paleomagnetic north pole at the time of the ophiolite's formation. One of the assumptions involved with this technique is that the period of epidotization is recorded in the magnetic signatures of the dikes. Secondary (low TiO_2) magnetite has been reported in altered dikes from the Troodos, and is associated with hydrothermal alteration (Hall and Fisher, 1987). Similarly, magnetic intensities of epidotized cores are 2 orders of magnitude smaller than the intensities in greenschist-diabase dikes, suggesting that high temperature alteration has influenced the magnetic properties of dikes. Assuming that magnetization is recorded in the epidosites, two different timing scenarios are possible (figure 1). Either epidotization occured prior to dike rotation, in which case vectors from all dikes should be similarly rotated away from the Troodos mean, or else the epidosites formed after dike rotation. In the second model, only the unaltered dikes should be rotated away from the Troodos mean direction.

Cores from epidotized, transitional, and greenschist-diabase dikes were analyzed using thermal demagnetization at U.C. Davis. This data will be published with my senior thesis paper and is available through the Carleton College science library. Once corrected for the field orientation of the cores, these results of the demagnetization were plotted using vector component (Zijderveld) diagrams. From the Zijderveld plots, a vector component analysis was performed to obtain the direction of characteristic remanent magnetization. The characteristic vector directions were then plotted on a stereonet to determine a mean vector for each site. As shown in figure 2, all dikes sampled have been rotated away from the Troodos mean vector, which represents the unrotated characteristic vector direction for the ophiolite. Finally, the site means are rotated around a reasonable graben-parallel axis to restore the vector directions to the Troodos mean. Rotating the dike poles around the same axis results in near-vertical orientations for the dike planes prior to graben formation.

Vector component diagrams also show a possible reversal component removed between 300°C and 400°C. The reverse-direction vectors occur in approximately half of the dikes sampled, and appear in both epidotized and greenschist dikes at each of the three drill sites. Principal component analysis of the reversal components shows that their declinations are approximately 173° from the characteristic remanent magnetization (ChRM) directions of the dikes (figure 3). The association of a reverse component antipodal to the ChRMs which are rotated away from the Troodos mean suggests that both signatures were acquired prior to extension and dike rotation.

DISCUSSION

Alteration appears to predate structural rotation of dikes during graben formation and tectonic extension. This is interesting since several authors have suggested that crustal attenuation is necessary to provide the permeability to drive large Troodos-type hydrothermal systems (Bettison-Varga *et al.*, 1992; Schiffman *et al.*, 1987).

Other possible sources of increased permeability in the sheeted dike section must be considered. Bettison-Varga *et al.*, (1995) show that epidosite formation may result in the creation of secondary porosity, perhaps by dissolution of primary chlorite and albite. Thus, hydrothermal systems could maintain fluid circulation through the creation of secondary permeability. We might also question the 'necessity' of extensional deformation to sustain hydrothermal systems. The Semail ophiolite (Oman) also has epidosites associated with sulfide deposits. The absence of fracturing and extensive veining may indicate that epidosite formation does not require previous crustal thinning (Nehlig *et al.*, 1994).

Some of the epidosite alteration observed in the Mitsero graben does appear to be fracture controlled. We may consider the possibility that epidosite formation is influenced by fractures that initially accommodate crustal extension prior to faulting and dike rotation. Compared to other typical extensional systems, sheeted dike sections have a strong vertical anisotropy parallel to dike chilled margins. This structural feature may facilitate vertical fracturing and epidosite formation prior to dike rotation.

The presence of a rotated reversal component is an interesting result considering that the currently accepted age for the Troodos ophiolite is 88-91 Ma (Mukasa and Ludden, 1987), during the Cretaceous Long Normal period (83-118Ma). One possible explanation, suggested by Gee *et al.*, (1993) is that the event during which the reversal was recorded occurred during the next reversal period (79-83 Ma). This would require that dikes remained unrotated for at least 5 million years, as the ophiolite moved off-axis. Furthermore, late Campanian (~75 Ma) rotation of the Troodos microplate (Clube *et al.*, 1985) would confine dike rotation to a short time period in the early Campanian (~80 Ma). Another possible explanation is that the Troodos ophiolite is younger than the currently accepted age, and formed closer to the end of the Cretaceous long normal period. Additional radiometric and biostratigraphic dating may help constrain the age of the ophiolite.

Finally, the timing of epidotization within the framework of the Troodos ophiolite's formation depends on when the grabens formed relative to the spreading axis. It is possible that the grabens formed on axis, during a period of amagmatic extension (Varga and Moores, 1990). On the other hand, Van Everdingen and Cawood (1995) suggest that the Mitsero graben may not have formed until well off-axis. A further step in the study of Troodos hydrothermal systems is a better understanding of how the three exposed fossil spreading axes formed during the ophiolite's evolution.

REFERENCES CITED

Bettison-Varga, L., Varga, R.J., and Schiffman, P., 1992, Relation between ore-forming hydrothermal systems and extensional deformation in the Solea graben spreading center, Troodos ophiolite, Cyprus: Geology, v.20, p.987-990.

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.

Hall, J.M., and Fisher, B.E., 1987, The characteristics and significance of secondary magnetite in a profile through the dike component of the Troodos, Cyprus, ophiolite: Canadian Journal of Earth Science, v.24, p. 2141-2159.

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.

Nehlig, P., Juteau, T., Bendel, V., Cotten, J., 1994, The root zones of oceanic hydrothermal systems: Constraints from the Samail ophiolite (Oman): Journal of Geophysical Research, v.99(B3), p.4703-4713.

Oudin, E., and Constantinou, G., 1984, Black smoker chimney fragments in Cyprus sulfide deposits: Nature, v.308, p.349-353.

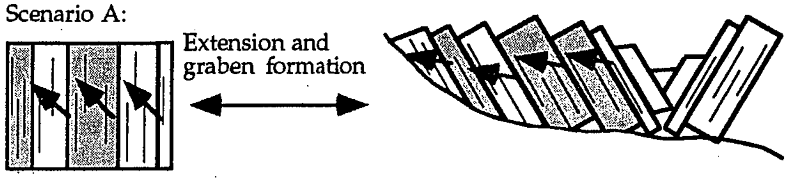
Schiffman, P., Smith, B.S., Varga, R.J., and Moores, E.M., 1987, Geometry, conditions and timing of off-axis hydrothermal metamorphism and ore-deposition in the Solea graben: Nature, v.325, p.423-425.

Richardson, C.J., Cann, J.R., Richards, H.G., and Cowan, J.G., 1987, Metal-depleted root zones of the Troodos ore-forming hydrothermal systems, Cyprus: Earth and Planetary Science Letters, v.84, p.243-253.

Van Everdingen, D.A., and Cawood, P.A., 1995, Dyke domains in the Mitsero graben, Troodos ophiolite, Cyprus: an off-axis model for graben formation at a spreading centre, *Journal of the Geological Society*, London, v.152, p.923-932.

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., Moores, E.M., Panayiotou, A., and Xenophontos, C., eds., Proceedings of the Symposium "Troodos 1987": Geol. Surv. Dept., Nicosia, Cyprus, p.37-52.

Scenario A:



Alteration occurs with dike injection. After graben formation, all dike vectors are rotated away from the Troodos mean.

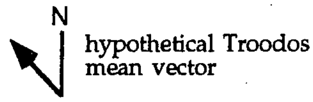
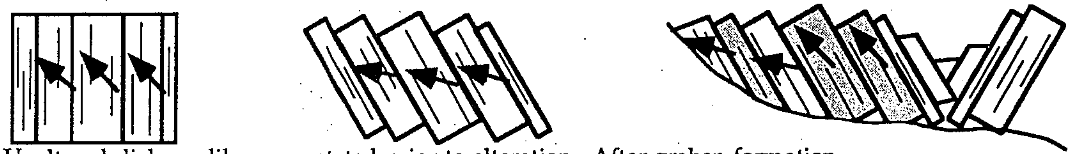


Figure 1: Schematic portrayal of vector orientations in dikes with respect to alteration and extensional deformation.

Scenario B:



Unaltered diabase dikes are rotated prior to alteration. After graben formation, alteration resets magnetic vectors in epidosites, so that these vectors do not appear to be rotated.

Key

- + site 15 (epidosite zone) vector means: (D) 310°, (I) 61°; ∝95= 2.5°
- • site 16 (epidosite zone) vector means: (D) 289°, (I) 60°; ∝95= 4.6°
- ▲ site 27 (greenschist-diabase zone) vector means: (D)285°, (I)67°; ∝95= 10.7°
- ◻ Troodos mean direction (from Clube *et al.*, 1985): (D)274°, (I)36°; ∝95= 12.3°
- ✕ Mean dike-pole orientation after rotation: (tr)276°, (pl)6°; ∝95= 4.7°

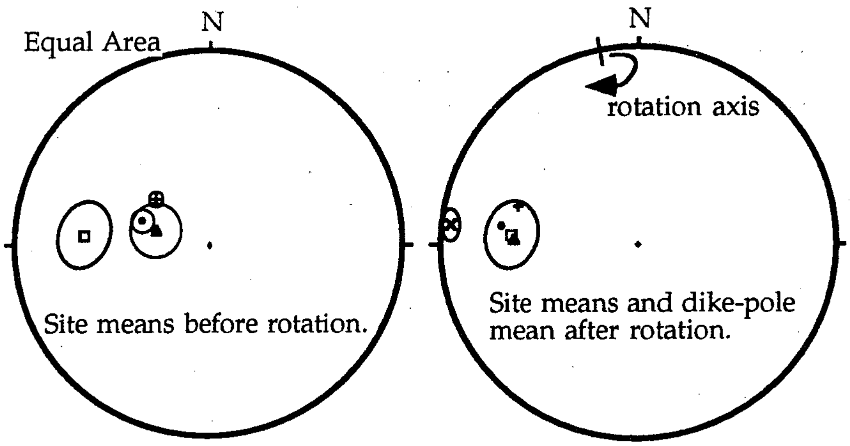


Figure 2: Equal area projection of mean characteristic components of natural remanent magnetization (ChRM) by drill site. Alpha-95 ellipses, determined by Fisher distribution, represent areas projected onto the stereonet in which the 'true' mean direction is 95% likely to plot within the distance of ∝95 from the calculated mean. Site means are then rotated 30° around a graben-parallel axis (trend 350°, plunge 0°). Note that dike poles after rotation are near horizontal, thus restoring a near-vertical orientation for the dikes prior to graben formation.

Figure 3: (A) Zijderveld plot from an epidotized core, showing reversal components. (B) Stereonet plot of mean reversed and characteristic vector components. Reversed vectors plot 173° away from the characteristic vector directions.

Figure 3 (A)

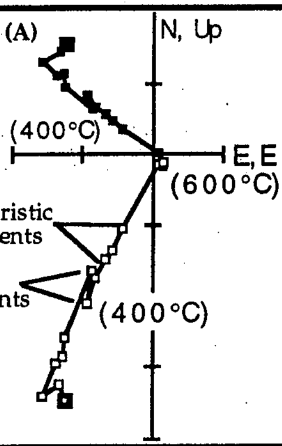


Figure 3 (B)