Structural interpretation of the gabbro in the Solea graben, Troodos ophiolite, Cyprus

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INTRODUCTION

Located on the northern flank of the Troodos ophiolite, Cyprus, the Solea graben represents a fossil spreading center which was active during late Cretaceous time. This study examines the brittle deformation of gabbro within the graben. Previous structural studies in the Troodos ophiolite have addressed the sheeted dike complex, but until now there has been no comprehensive evaluation of the plutonic complex.

FAULTING CHARACTER

The gabbro is a highly brecciated and faulted unit, nearly penetratively fractured on the scale of tens of centimeters to meters: all outcrops within the study area contain at least 40% fault breccia. Unbrecciated gabbro occurs as fault-bounded blocks of less than a meter in size. A data set of 104 fault orientations (figure 2) collected over a 15 square kilometer area suggests that fault orientations are not systematically distributed. Many fault planes exhibit slickenside lineations which indicate the sense of shear. The sense of shear was unequivocally determined on 86 out of the 104 faults. Rakes of slickenside lineations vary nearly evenly from 0° to 90°, an indication that a significant portion of the faults had oblique-slip motion.

Cross-cutting fault planes are common, and overprinting slickenside marks exist in several locations. These observations suggest that brittle deformation was not restricted to a single phase of faulting.

The results of two different methods of fault phase separation and fault inversion, that of Angelier (1984) and that of Hardcastle (1991), concur that the complex deformational history of the gabbro included at least two definable episodes of faulting: one in which σ_1 was subvertical and σ_3 was subhorizontal oriented NW-SE, and a second, more dominant phase in which σ_1 was NW-SE and σ_3 was subvertical (figure 4). These tensors are in present coordinates, uncorrected for any possible movement during a later deformational period wherein fault blocks and slickenside lineations rotated as a unit. These two tensors account for only approximately 55% of the measured faults.

PALEOMAGNETIC INVESTIGATION

This study analyses five paleomagnetic sites, the locations of which are shown on figure 3. Each site consists of six to ten drilled cores; one or two specimens were cut from each core. Two specimens from each site were demagnetized in an alternating field using twelve steps from 2.5 mT to 80 mT, and two were demagnetized thermally using five steps from 200°C to 580°C. In all cases a stable magnetization was observed early in the demagnetization process. Both demagnetization methods revealed similar primary components. The remaining specimens were demagnetized in successive peak alternating fields of 20, 40, 60, and 80 mT. J/Jo and IRM curves are consistent with magnetite as the magnetic carrier. Petrographic and electron microprobe analyses confirmed the presence of fine grained (<5 μm) magnetite. The magnetite grains exist as exsolution lamellae in clinopyroxene which has partially altered to actinolite. It is likely that the magnetite grains exsolved and acquired a thermoremnant magnetization during cooling of the gabbro from a melt. Such an acquisition would most likely precede brittle deformation.

The stable magnetization components of all specimens are discordant with the Troodos mean vector (TMV) of 274°/36°. Additionally, each of the sites clusters independently, suggesting that the stable magnetization direction of each site is discordant with that of the four other investigated sites. The within-site clusters of stable components are paleomagnetically statistically significant: α_{95} values range from 3.1° to 7.3°; κ values range from 71 to 250. The site mean directions are 148°/57°, 120°/68°, 186°/40°, 252°/40°, and 296°/85° (figure 5). These directions are not significantly clustered to suggest that they represent statistical scatter around a single mean direction for the gabbro complex; each site is independent.

It is possible to restore four of the five site mean vectors to within uncertainty of the TMV by a single rotation about an axis of 230°/63°. The fifth site mean vector may be restored in a single rotation the TMV by a similarly plunging but more westerly trending rotation axis.

Deformation in the gabbro is extreme, and multiple rotational events rather than a single event may better describe the history of the fault block motion in the gabbro.

FOLIATION

Throughout the study area, gabbro outcrops exhibit a magmatic foliation defined by alternating pyroxene-rich and plagioclase-rich layers, most commonly on a mesoscopic scale. Although generally steeply dipping, the foliation varies significantly in orientation (figure 3) and degree of development. The foliation is not evident at all locations within the study area. In places the gabbro is layered, exhibiting mineral banding on a centimeter scale.

An igneous foliation is present at four out of five paleomagnetic sites. The average angle between each site mean paleomagnetic vector and the associated mean pole to foliation is 52° ± 10°, within uncertainty of 54°, the angle between the TMV and the pole to a horizontal plane.

Assuming a constant angle between the site mean vector and the respective pole to foliation during deformation, it is possible to simultaneously restore the site mean vector to the Troodos mean and the pole to foliation to subvertical. If the foliation at all four paleomagnetic sites is so restored, the mean pole to foliation plunges 88° with an α_{95} of 8.5°, within uncertainty of vertical. The axes which simultaneously restore the poles to foliation to vertical and the respective site mean vectors (figure 5) to the TMV plunge moderately to the southwest. The minimum amount of rotation required to restore any site mean vector to the TMV while restoring foliation to subhorizontal is 83°. The rotation axes which accomplish such a restoration are similar to the axis which restore several site mean vectors to the TMV in a single rotation.

These observations suggest that magmatic foliation of the gabbro was originally subhorizontal.

COMPARISON TO THE SHEETED DIKE COMPLEX

A current model of the Solea graben proposes that a listric normal faults in the sheeted dike complex sole into a low-angle normal fault, the Kakopetria detachment, at the contact between the sheeted dike complex and the gabbro (Hurst et al. 1994). This fault geometry would accommodate fault block rotation within the sheeted dike complex about an axis subparallel to the axis of the Solea graben. The model does not suggest fault block rotation within the gabbro.

Several features structurally distinguish the gabbro in the footwall of the Kakopetria detachment from the overlying sheeted dike complex which makes up the hanging wall of that detachment zone. The gabbro is significantly more fractured and suffered more extensive brittle deformation than the sheeted dike complex. Both units experienced fault block rotations, but whereas dikes can normally be restored to their original subvertical orientations by a single rotation about a NNW trending subhorizontal axis, the axes which restore gabbro blocks in a single rotation trend southwest and plunge moderately. A fault inversion analysis reveals two similar episodes of faulting for both units.

This study concludes that significant brittle deformation occurred below the Kakopetria detachment. If the extensive brittle deformation in the gabbro is related to the formation of the Solea graben and not to the emplacement of the ophiolite, the Kakopetria detachment cannot have functioned as a simple decollement during graben formation. The Kakopetria detachment seems to be a zone of structural transition within the Solea graben of the Troodos ophiolite; its function as a major detachment fault, however, is open to question.

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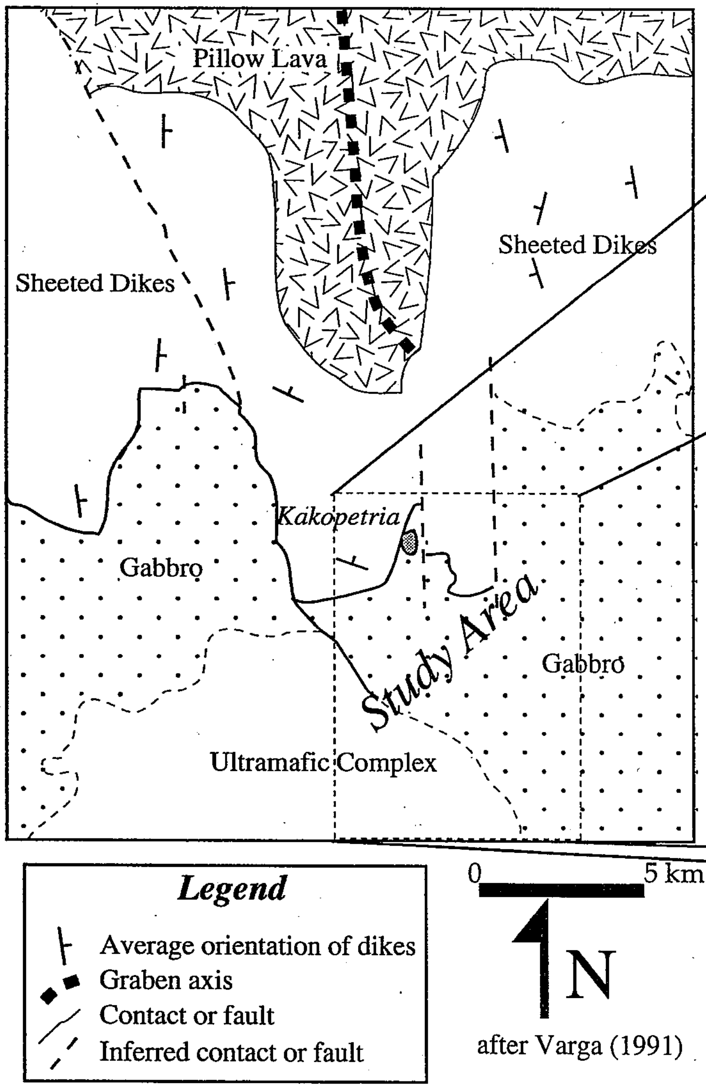


Figure 1. Map showing study area within the Solea graben.

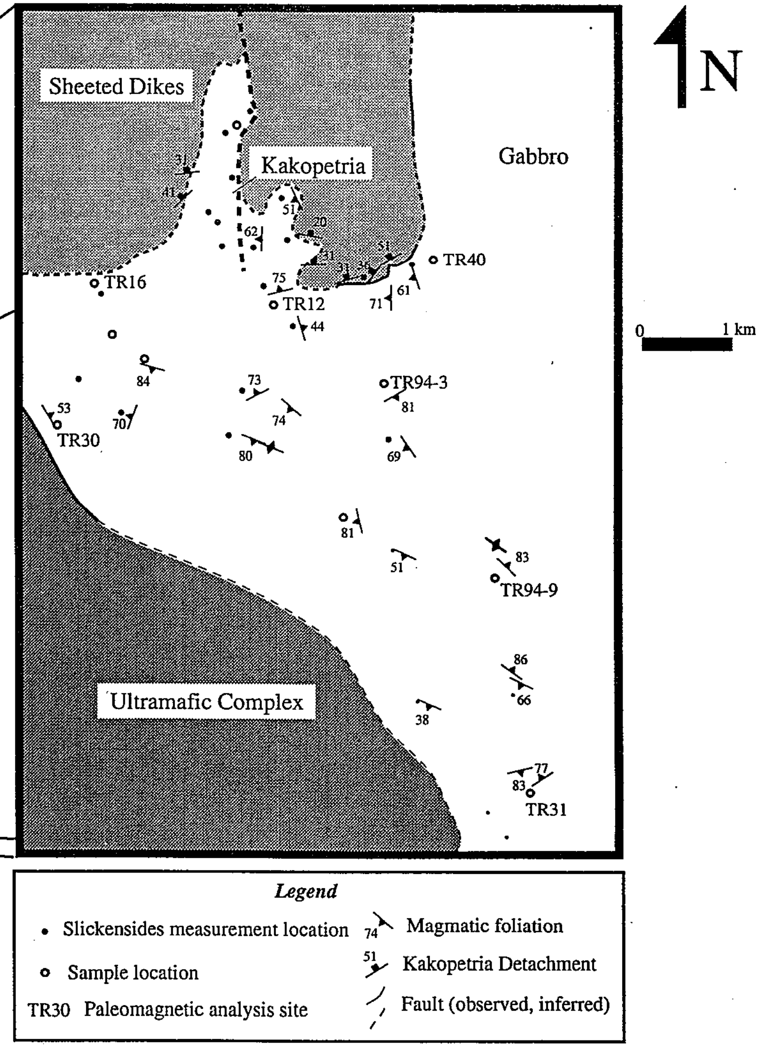


Figure 3. Map of study area showing sampling and measurement locations and magmatic foliation. Measurements were made at all levels of the gabbro complex. All lithologic contacts are faulted.

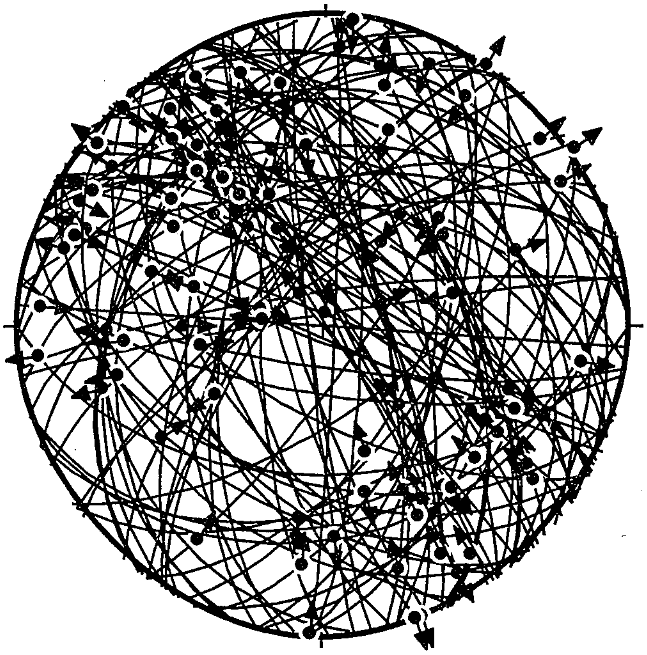
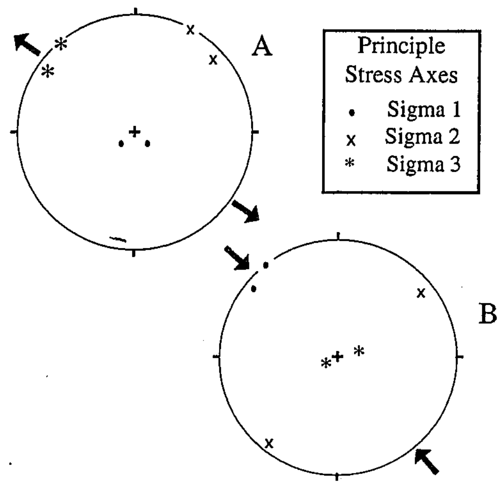


Figure 2. Equal area lower hemisphere projection showing great circle trace of all (n=104) measured fault planes and direction of movement of the hanging wall in that plane (arrow). Note no clearly systematic distribution of fault planes or slip directions.



	Inversion method	Hardcastle (1991)	Angelier (1984)
A	No. of faults fit	32	26
	Sigma 1	227/78	133/78
	Sigma 2	47/12	28/3
	Sigma 3	317/0	298/12
	Phi	0.3	0.1
B	No. of faults fit	34	32
	Sigma 1	309/10	322/2
	Sigma 2	218/6	52/14
	Sigma 3	97/78	225/76
	Phi	0.1	0.25

Figure 4. Results of phase separation and fault inversion using two different methods and equal area lower hemisphere projection of principle stress axes. Arrows represent direction of compression or extension. Both phase separation and fault inversion methods suggest that there were at least two phases of brittle deformation. In this case, in Phase A, $\sigma 1$ is subvertical and $\sigma 3$ is subhorizontal oriented NW-SE; in Phase B, $\sigma 1$ is oriented NW-SE and subhorizontal and $\sigma 3$ is subvertical.

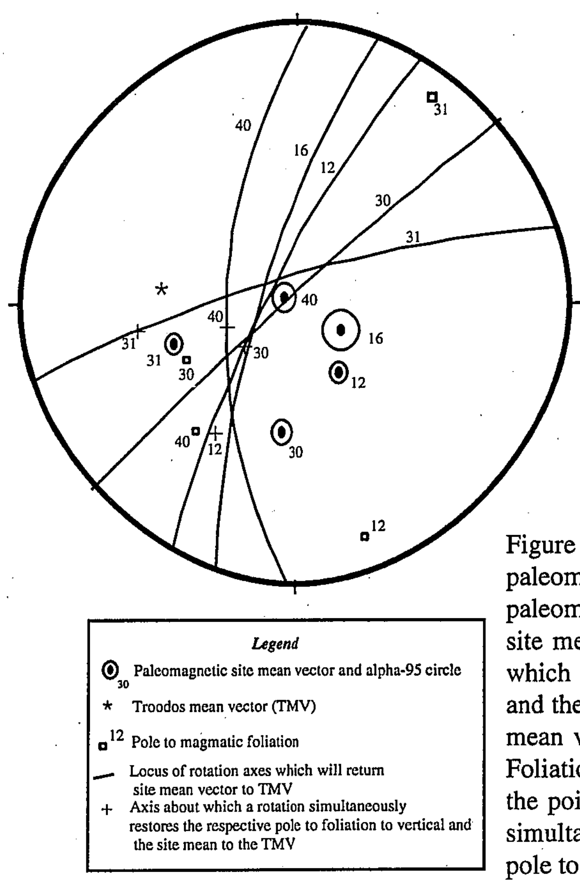


Figure 5. Equal angle lower hemisphere projection of site mean paleomagnetic vectors, poles to magmatic foliation at each paleomagnetic sampling site, loci of rotation axes which restore site mean vectors to the Troodos mean vector (TMV), and axes which simultaneously restore each site mean vector to the TMV and the respective pole to foliation to vertical. Paleomagnetic site mean vectors are discordant with the TMV and with each other. Foliation is moderately to steeply dipping. Note the proximity of the point of great circle intersection and the rotation axes which simultaneously restore the site mean vector and the respective pole to foliation.