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Discussion

Comment on: "Tectonics of the Akamas and Mamonia ophiolites, Western Cyprus: magnetic petrofabrics and paleomagnetism" by G.J. Borradaile and K. Lucas[☆]

A. Morris[a,*], M.W. Anderson[a], A.H.F. Robertson[b]

[a]School of Earth, Ocean and Environmental Sciences, University of Plymouth, Drake Circus, Plymouth PL4 8AA, UK
[b]School of Geosciences, University of Edinburgh, West Mains Road, Edinburgh EH9 3JW, UK

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Borradaile and Lucas (2003) present valuable new palaeomagnetic and magnetic fabric data that shed further light on the relationship between the main outcrop of the well-known Troodos ophiolite of Cyprus and the outlier of the Akamas Peninsula to the west. The focus of this comment, however, is Borradaile and Lucas' re-interpretation of palaeomagnetic data previously reported from Cyprus. We show that: (i) the paper misinterprets our earlier research (Morris et al., 1998), leading to an erroneous apparent polar wander path (APWP) for the Mamonia Complex of SW Cyprus; and (ii) the proposed equatorial palaeolatitude for the Troodos ophiolite in the Late Cretaceous results from inappropriate use of existing palaeomagnetic data and is incompatible with the relative motion history of the African and Eurasian plates.

The geology of SW Cyprus is dominated by Late Triassic–Late Cretaceous rocks of the Mamonia Complex. This consists of tectonically disrupted sequences of deep-sea sedimentary and volcanic rocks, interpreted as remnants of a passive continental margin and marginal oceanic crust formed in a small Mesozoic Neotethyan basin (Robertson and Woodcock, 1979). In contrast to the Troodos ophiolite, no proper ophiolite sequence is present in the Mamonia Complex. The tectonic contacts with the Troodos ophiolite are sealed by overlap sequences of Late Cretaceous age. To the SW of the main Troodos outcrop, high crustal level rocks (extrusives and cross-cutting dykes) are exposed in fault-bounded slivers, with faulted contacts marked by discontinuous, steeply dipping strands of serpentinite. These slivers are overlain by an in situ sedimentary cover of Campanian umbers and radiolarites (Perapedhi Formation), and by thick, largely undeformed, successions of bentonitic clays and volcaniclastic sandstones, indistinguishable from the Kannaviou Formation found overlying the ophiolitic basement of the main Troodos massif (Robertson, 1977; Clube and Robertson, 1986). The geochemistry of the extrusives (Murton, 1990) is distinctly different from the WPB alkaline to MORB tholeiitic compositions of the Triassic extrusives of the Mamonia Complex (Malpas et al., 1993). Palaeomagnetic analyses within these slivers (Morris et al., 1998) demonstrate differences in remanence directions between cross-cutting units at several localities, a characteristic of syn-magmatic rotation during transform tectonism. Stratigraphic, petro-graphic and palaeomagnetic data, therefore, all support correlation of these ophiolitic outcrops with the Troodos ophiolite and its transform fault-related southern margin.

Our palaeomagnetic data from these Late Cretaceous ophiolitic rocks of SW Cyprus are erroneously used by Borradaile and Lucas to define the first APWP for the Mamonia Complex terrane. Their compilation map (Fig. 10c) clearly ascribes poles derived from our data to the "Mamonia ophiolite" (sic), and the APWP track is then

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[*] Corresponding author. Tel.: +44-1752-233100; fax: +44-1752-233117

E-mail address: amorris@plymouth.ac.uk (A. Morris).

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described as extending "the APWP for the Troodos microplate, along the same locus" (p. 2073). They assert that the age of the rocks from which these poles are obtained is irrelevant since they "record the paleomagnetic position since the rocks were penetratively deformed" (p. 2073). There is, however, no evidence for penetrative deformation in the rocks sampled by Morris et al. (1998). Deformation is accommodated almost exclusively along the bounding serpentinite shear zones, with only minor brittle faulting within the slivers. Moreover, we provided unequivocal evidence that these rocks preserve pre-deformational remanences (Morris et al., 1998; and discussion below). This is acknowledged by Borradaile and Lucas (p. 2067), and yet on the basis of unsubstantiated assumptions of the degree of penetrative deformation and its effects on the magnetic history, they interpret our remanence vectors as post-deformational markers providing information on "Mamonia-terrane rotation" (p. 2069). Since the data in question are derived from Late Cretaceous ophiolitic rocks that demonstrably carry pre-deformational remanences and lack penetrative deformation, and not from Mamonia Complex rocks, the "Mamonia" APWP presented by Borradaile and Lucas must be discounted from consideration in future syntheses. As yet, insufficient palaeomagnetic data are available from the Mamonia Complex (Clube, 1985; Clube and Robertson, 1986) to allow any tectonic interpretation.

Table 4 of Borradaile and Lucas presents a compilation of published palaeomagnetic vectors from the Troodos ophiolite. We identify the following weaknesses in this table: (i) the authors reject the use of palaeomagnetic tilt corrections in their analyses (see below), yet Table 4 mixes in situ and tilt-corrected data without indicating which data are in which reference frame. It is necessary to go back to the original sources to identify whether a particular vector has been tilt corrected or not; (ii) the mean vectors listed in Table 4 are frequently those calculated by Borradaile and Lucas by combining published site mean vectors, with no indication of which data are taken directly from the source articles. This is of fundamental importance because in several instances the mean vectors listed in Table 4 incorporate data from sites that have experienced large relative intra-site tectonic rotations, as demonstrated by the original authors. Mean vectors calculated in this way have no tectonic value; (iii) several instances where data are repeated. Most notable are the five mean vectors calculated by Borradaile and Lucas from the original data of Allerton and Vine (1990) (reference 6 in Table 4), which are then averaged again (but in a different combination) to produce two of the mean vectors attributed to Allerton (1989) (reference 11 in Table 4). Likewise, the "limestone" data of Morris et al. (1990) listed in the table, which actually come from radiolarian mudstones, are also incorporated in the mean vector calculated by Borradaile and Lucas from the full data set presented by Morris et al. (1990); (iv) several entries that indicate a larger number of sites used to calculate mean vectors than are actually reported in the original source articles; and (v) some significant transcription errors from the original sources. Taken together, these weaknesses undermine confidence in subsequent analyses in the paper, and indeed there is a danger that errors may be propagated in future syntheses that may not consult the original published datasets.

Borradaile and Lucas reject the use of palaeomagnetic tilt corrections on the grounds that it is impossible to determine precisely the original tilt axes or the sequence of rotations, potentially leading to the introduction of significant declination errors. We agree that this is a consideration that is often overlooked, although in situations where the tilt of a palaeohorizontal surface is less than 30° such errors are minimal ($<5^{\circ}$). The magnitude of *inclination error* that is introduced by not tilt correcting data from rocks that preserve pre-deformational remanences, however, is potentially far more severe. This is especially relevant where data sets are subsequently used to determine palaeolatitude. The critical consideration when deciding whether data require tilt correction is the timing of magnetization acquisition relative to deformation (determined using fold tests). In the Troodos ophiolite, however, standard fold tests are difficult to employ since individual sites usually display uniform tilts and large intra-site relative tectonic rotations are common. These difficulties may be overcome by using inclination-only 'tilt-tests' that make no assumptions over the sequence of rotations and tilts that have affected a rock sequence. Instead, the angle between the remanent magnetization and the pole to the primary structure at a site is assumed to remain constant during rigid body deformation. Significant improvement in clustering of inclinations upon tilt correction is expected if pre-deformational magnetizations have been identified (Enkin and Watson, 1996). This approach allowed us to demonstrate that pre-deformational remanences are carried by Troodos-type rocks exposed in SW Cyprus (Morris et al., 1998).

Morris (2003) recently compiled palaeomagnetic data from the extrusive series (41 sites) and the sheeted dyke complex (59 sites) of the Troodos ophiolite. The "block-rotation Fisher" technique of Enkin and Watson (1996) was then used to assess the age of magnetization for each of these pseudostratigraphic units. An increase in the maximum likelihood estimate of the Fisher precision parameter ($\hat{\kappa}$) upon untilting is observed for the extrusive sequence (Fig. 1a). These data constitute a positive inclination-only tilt test (Enkin and Watson, 1996), unequivocally indicating acquisition of remanence prior to tectonic disruption of the extrusive series of the Troodos ophiolite. The maximum likelihood estimate of the true mean tilt corrected inclination is $\hat{I}=35.5^{\circ+3.6^{\circ}}_{-3.5^{\circ}}$.

Borradaile and Lucas, and also Borradaile (2001), highlight a difficulty of applying structural corrections within ophiolites, whereby components of rotation around dyke-normal axes in sheeted dykes may give rise to both declination and inclination errors upon tilt correction. This

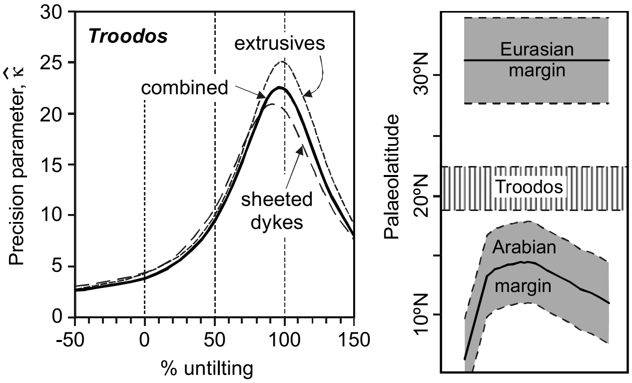

Fig. 1. (a) Variation in maximum likelihood estimates of the Fisher precision parameter with progressive untilting, indicating positive block-rotation Fisher inclination-only tilt tests (Enkin and Watson, 1996) for the Troodos extrusive series and sheeted dyke complex (from Morris, 2003). (b) Palaeolatitudinal constraints on the relative positions of the Eurasian and Arabian continental margins and their 95% confidence limits, derived from the APWPs of Besse and Courtillot (1991), and that for the Troodos ophiolite based on tilt corrected palaeomagnetic vectors. Note that there is no palaeolongitudinal control in this diagram (after Morris, 2003).

important potential source of error is rarely considered in the literature, although an example of this phenomenon has been reported recently (Morris and Anderson, 2002). It is informative, then, to consider the data available from the sheeted dyke complex of the Troodos ophiolite. Again, an increase in $\hat{\kappa}$ upon tilt correction (Fig. 1a), indicates that pre-deformational magnetizations are preserved, with a maximum likelihood estimate of the true mean tilt corrected inclination of $\hat{I}=38.0°^{+3.4°}_{-3.3°}$. The tilt corrected mean inclinations for the sheeted dyke complex and extrusive series are statistically indistinguishable. This suggests that the sheeted dyke data-set is sufficiently large to ensure that any components of tilting around dyke-normal axes at individual sites produces little bias in the overall mean inclination. It is appropriate, therefore, to combine these data-sets in the tilt test formulation, resulting in statistics that again indicate a pre-deformational age for the remanent magnetization (Fig. 1a). This analysis demonstrates, therefore, that palaeomagnetic data from the upper levels of the ophiolite should be tilt corrected prior to tectonic interpretation.

The overall maximum likelihood estimate of the true mean tilt corrected inclination is $\hat{I}=37.0°\pm2.6°$. Assuming a geocentric axial dipole field, this $\hat{I}$ value indicates a Late Cretaceous palaeolatitude of 20.6°N ± 1.8° for the Troodos ophiolite. This is consistent with a palaeogeographic position between the African/Arabian and Eurasian continental margins (Fig. 1b), in agreement with reconstructions of the eastern Mediterranean Neotethys based on regional geological considerations (e.g. Robertson, 1998). This contrasts with the equatorial palaeolatitude determined by Borradaile and Lucas based on the distribution of non-tilt corrected palaeopoles (their Fig. 10). Although some uncertainty in the Mesozoic apparent polar wander path for Africa remains, there is good agreement between reported Late Cretaceous palaeopoles. These place the north African/Arabian continental margin north of the equator, precluding an equatorial position for the Troodos ophiolite unless large-scale palaeolongitudinal displacement around the Arabian margin is invoked. There is no geological support for such large displacement of the Troodos terrane. This plate-scale palaeogeographic constraint is not considered by Borradaile and Lucas and we conclude that their equatorial Late Cretaceous palaeolatitude for Troodos should be discounted.

Finally, two unintentional minor errors in the paper that may confuse those not familiar with the literature on Cyprus are: (i) the Solea Graben is the most westerly of the Troodos spreading axes, not the most easterly (p. 2054); and (ii) the Troodos microplate rotated over a protracted ~40 Ma period, ending in the Eocene, not “in the interval from 92 to 88 Ma” (p. 2054).

In summary, we welcome the new data presented by Borradaile and Lucas, but their interpretation of existing data in terms of a “Mamonia Complex” APWP and the inferred equatorial Late Cretaceous palaeolatitude for the Troodos ophiolite are both flawed.

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