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

As a secondary goal, Borradaile and Lucas (2003) conservatively examined previous paleomagnetic data from Cyprus. From published declinations and inclinations of paleomagnetic vectors, we calculated paleopoles not previously available, from which we verified post-deformation and post-metamorphic terrane-integrity and relative microplate rotations for the Troodos, Akamas and Mamonia Terranes. (Formation, massif, complex, ophiolite and series have been used interchangeably for 'Terrane' in previous works.) If magnetic anisotropy is weak (*not obviously considered in the cited works*) a rock's characteristic remanence vector (ChRM) *may* be parallel to a paleofield. Typical anisotropies may deflect ChRMs by as much as $<5°$ from the paleofield orientation; troublesome in itself. The combined inclination and declination of ChRM specify the apparent position of the contemporary paleopole, in the rock's *present-day* coordinate frame. Our critics use the declinations (Morris, 1996) or the inclinations (Morris, 2003) but they appear to object to their combined use, and the definition of an apparent paleopole, following standard paleomagnetic practice (Tarling, 1983; Butler, 1992). Three issues arise, which pose essentially structural problems of interest to readers of this journal.

1. Is a ChRM identified, and is it primary?

Direct remanence-measurement yields the natural remanent magnetization (NRM), the sum of many vector components of different orientations and different ages. From the NRM, a ChRM vector may be isolated by progressively demagnetizing the specimen to determine a concatenation of similarly oriented vector components. Only 11.7% of the previously published available data were fully demagnetized, and some were not demagnetized at all, albeit for valid reasons in the original context (e.g. Allerton and Vine, 1987).

Valid paleogeographic reconstructions require a *primary* ChRM, usually validated by fold, conglomerate, reversal, or baked-contact 'field' tests. In Cyprus, local conditions conspire to limit their use. The traditional *fold test* uses differently inclined parts of a continuous stratum in the same site; if ChRM vectors from different fold-limbs align when the layer is de-folded, the remanence may be primary (strain is ignored!). Morris et al. over-interpret a 'tilt' test in this context; they un-tilt disconnected tilt-blocks (not contiguous fold limbs) to the horizontal from different sites. Without the constraint of a common original strike, effectively ignoring ChRM declinations, it will always be possible to find some improved clustering of *inclinations* from such independent fault blocks.

Furthermore, in ophiolite igneous rocks, re-magnetization accompanies ocean-floor spreading and metamorphism differently at different levels, with progressive oxidation or with serpentinization. Each new remanence-bearing mineral blocks in a new ChRM vector at a different post-petrogenetic age, depending non-systematically with stratigraphic level and more systematically with axis-distance. Recent rock-magnetic research (Dunlop and Özdemir, 1997) vindicates the original concerns of Moores and Vine (1971) in this regard.

2. Secondary disturbance of ChRM?

2.1. The frame of reference: concerns

Ideally, ChRM *declination* points to the paleopole and its *inclination* fixes the site-paleolatitude in contemporary specimen coordinates. Those coordinates must be restored to a syn-magnetization reference frame, defined (*only in part*) by determining a marker for the paleohorizontal ($\sim$stratification) or for the paleovertical ($\sim$dikes). Stratification is a reasonably accurate paleohorizontal in many sedimentary rocks but this assumption is questionable for pillow lava (42% of the database).

For the dike complex, ($\sim$40% of the database), the site-mean dike orientation is generally assumed to be a paleovertical. However, dikes are not planar, vary widely from the vertical, with a typical dip-range $>20°$ at any site. Also, it is implicit from earlier studies that dikes were not necessarily vertical when finally re-magnetized (e.g. Varga, 1991).

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2.2. Geological re-orientation of ChRM: concerns

In most sedimentary rocks (~18% of the data), compaction causes inclination-shallowing (Butler, 1992), not obviously considered in the database. Morris (1996, his fig. 1) refers to the sedimentary rocks covering the Troodos ophiolite as non-deformed *sediments.* On the contrary, the rocks possess ubiquitous penetrative tectonic magnetic-grain alignments revealed by anisotropy of magnetic susceptibility and of anhysteretic remanent magnetization (Lagroix and Borradaile, 2001). Their magnetic vector-components either rotated with them or were acquired after strain. Macroscopically, the sedimentary cover shows pressure-solution cleavage that aligns grains penetratively on the scale of the standard rock-magnetism specimen (Fig. 1). The tectonized sedimentary rocks and the underlying dikes and lavas of the Troodos Terrane are not simply affected by tilting about strike, nor about any other combination of simple horizontal axes. Listric fault rotation about inclined axes is usual (e.g. Allerton and Vine, 1987), with rotations and cataclastic flow on all scales (Murton and Gass, 1986; MacLeod, 1990; Varga, 1991; Dietrich and Spencer, 1993; MacLeod and Murton, 1995). Strain, penetrative grain-alignment, cataclastic flow, and block-rotation have re-oriented ChRM on all scales, in all terranes.

For the Mamonia terrain, which is most deformed, Morris et al. state there is “no evidence for penetrative deformation in the rocks sampled by Morris et al. (1998)”. However, structural geologists are of the following opinions on the Mamonia Complex: “intensely faulted inliers with volcanic rocks” and “a continuous section was not observed, since the beds have been subject to violent deformation” (Henson et al., 1949, p. 6); “Fortement tectonisée et plissée” (Lapierre, 1968, p. 32); “because of its broken up and sometimes chaotic appearance” (Ealy and Knox, 1975, p. 85). These workers recognize mylonitized rocks, sheared serpentinites and garnet-bearing amphibolite facies schists, and mapped extensive tectonic mélange intercalated with Troodos-type ophiolite. Moreover, Robertson and Woodcock (1979, p. 651) agree with Lapierre “about the relatively disorganized state of the Mamonia rocks”. Recent structural mapping reports amphibolite facies metamorphism, penetrative tectonite fabrics, thrusting, intercalated fault slices, and serpentinite extrusion (Swarbrick, 1993; Bailey et al., 2000). Morris et al. claim to have sampled *non-deformed* specimens from this terrain. Why then do they state that “insufficient data are available from the Mamonia Complex to allow any tectonic interpretation”, when they have already done so (Morris, 1996; Morris et al., 1998)?

3. ChRM-restoration to paleo-coordinates

Deformation comprises *translation, strain, dilation* and *rigid-body rotation*. ChRMs were primarily disorientated by the last three in Cyprus. Morris et al. restore only the effects of the latter process (‘tilting’). Robertson et al. (1991) imply that tilting of the sedimentary cover-rocks is uniform over large areas, witnessed by stratigraphic breaks. However, the breaks are regional, not local to Cyprus; Kähler and Stow (1998) attribute them to sea-floor erosion driven by global climate change. Instead, ‘tilting’ is much more local and mostly affects *consolidated* sedimentary rock due to listric faulting from the kilometric-scale downward, with inclined net rotation-axes. Tilting becomes progressively more complex in Troodos igneous rocks and in the Mamonia terrain.

ChRM may be un-tilted to its original attitude and be of precise paleomagnetic value *if and only if*: there is no other aspect to the deformation, the tilt axis or axes are known, the amount(s) and sense(s) of rotation are known and the order of rotations is known (MacDonald, 1980; Borradaile, 1997). Even if all geometrical parameters are known, ChRM declinations are still ambiguous when strata are un-tilted to the horizontal. Morris et al. appear not to accept the generality of MacDonald’s proof, claiming this error is minimal, yet elsewhere they recognize “this procedure can cause serious declination errors” (Morris et al., 1998, p. 238). Still worse, when *dikes* are un-tilted to the vertical, *both the original declination and inclination of the ChRM* are ambiguous (Borradaile, 2001). Of deeper concern is a procedure advocated by Morris et al. (1998, 2002) and Morris (1996) in which rotation parameters are estimated by back-rotating a dike to vertical and simultaneously restoring its ChRM *to a pre-conceived reference direction*. This circular reasoning subjectively re-enforces the assumption.

Our use of the database differs from Morris et al. in three main ways. (1) We do not advocate unverifiable tilt corrections to complexly deformed rocks; this introduces more error into the ChRM restoration. Restored directions were included only where deformation was minimal or where original data were obscured. (2) We combine inclination and declination to determine the apparent position of the paleopole [Morris et al. object to this though they do not hesitate to use the declinations (Morris et al., 1990; Morris, 1996) and inclinations (Morris, 2003) in separate papers]. (3) We determine the paleopole using reported, in situ ChRM declination *and* inclination since it was mostly acquired after deformation or metamorphism. Is this use of the existing database justified? The results spoke for themselves.

Apparent pole positions for each of the 35 site-groups lie along a locus of constant site-co-latitude (Borradaile and Lucas, fig. 10), Mamonia and Troodos terranes being approximately 90° from the palaeopoles from ~88 Ma until ~45 Ma. The terranes then move poleward (to site-colatitudes ~55°). Thirty-five diverse site-groups, from 2532 measurements at 338 sites, yield paleopoles distributed in approximate chronological order along a single path. This confirms the terranes’ *early post-deformational integrity* at sub-equatorial paleolatitudes. Counter-clockwise microplate rotation about a nearby axis (90–45 Ma)

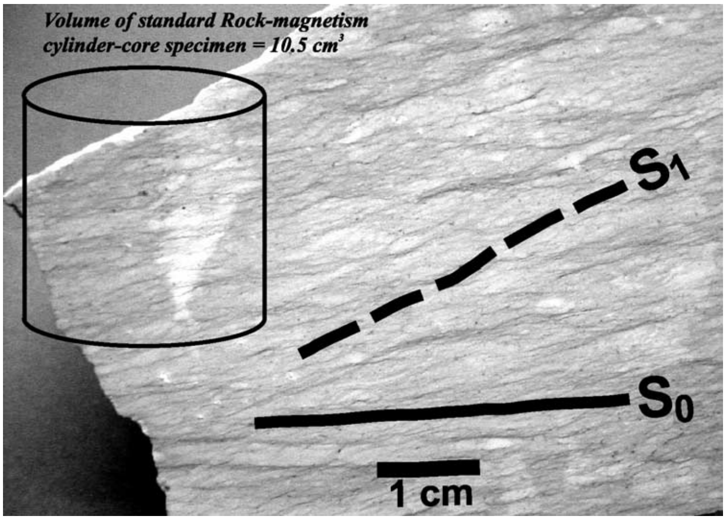

Fig. 1. Polished surface of a typical limestone specimen from the sedimentary rocks of the Troodos ophiolilte terrane. The typical cylindrical core sample (outlined, 10.5 cm^3) includes mineral-orientation distributions from both bedding (S_0) and stylolitic-cleavage (S_1) subfabrics; both penetrative at the scale of specimens used in magnetic measurement. Paleomagnetic vector-components may be rotated during deformation or postdate the S_1 subfabric.

and then about a more distant axis is evident from a structured paleopole-locus that did not arrive without geological cause.

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