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Paleomagnetic vectors and tilted dikes

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Abstract

Where tectonic deformation reorients rocks without penetrative strain, their paleomagnetic vectors may be restored to their original attitudes by untilting. For strata, paleomagnetic inclination is readily restored but the tilt axis must be precisely known if paleodeclination is required. For dikes, without the knowledge of the rotation(s), neither declination nor inclination of the paleomagnetic vector can be uniquely defined. Furthermore, back-rotating dike orientations to an upright attitude assumes primary verticality whereas primary dike dips are bimodal across the spreading axes (e.g. Troodos ophiolite, Cyprus). In the Cyprus ophiolite, the dikes of the Limassol Forest Transform Zone are tilted due to uplift of the mantle-sequence rocks and deflected against the Arakapas Fault. Their paleomagnetic vectors may be restored rotating about the two axes defined by the strike and the vertical, or about a net axis that is possibly the actual tectonic rotation axis. This net axis is determined from the tectonic regional dispersion of the dike orientations. In this test case, the results of the restorations differ slightly but underline the difficulty in selecting the best restoration procedure and the greater difficulty of restoring the paleomagnetic data from dikes vis à vis strata. For dikes, it is recommended that the paleomagnetic vectors are restored using average dike orientations to minimize the inaccuracies due to the large primary variation in dike orientation. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: untilting; dike; paleomagnetic restoration; tectonic restoration

1. Introduction

We wish to investigate the limitations of the structural restorations of dikes in order to examine their potential in paleomagnetic studies. For this purpose, the well-exposed, late Cretaceous ophiolite complex in Cyprus provides an excellent testing ground (Fig. 1). The central part of the terrain, around Mount Troodos, exposes a mantle sequence of harzburgites, lherzolites and dunites in the center of a dome. The domal uplift is attributed by different authors, in varying degrees, to the regional N–S compression above a northward-descending subduction zone and to dilational serpentinization.

Mantle sequence harzburgites, lherzolites and dunites crop out in the center of the dome, surrounded by sheeted dikes that form approximately 60% of the total ophiolite outcrop. The dike swarm is relatively undisturbed, showing mainly only local fracturing and serpentinization. Penetrative deformation is absent from the swarm. However, in the Limassol Forest, the dikes' trends and dips are considerably modified by regional-scale dextral shearing adjacent to a fossil transform fault. Cataclasis increases towards the Arakapas Fault but the fracture separation is much wider than the hand samples so that it is normally possible to extract the oriented samples.

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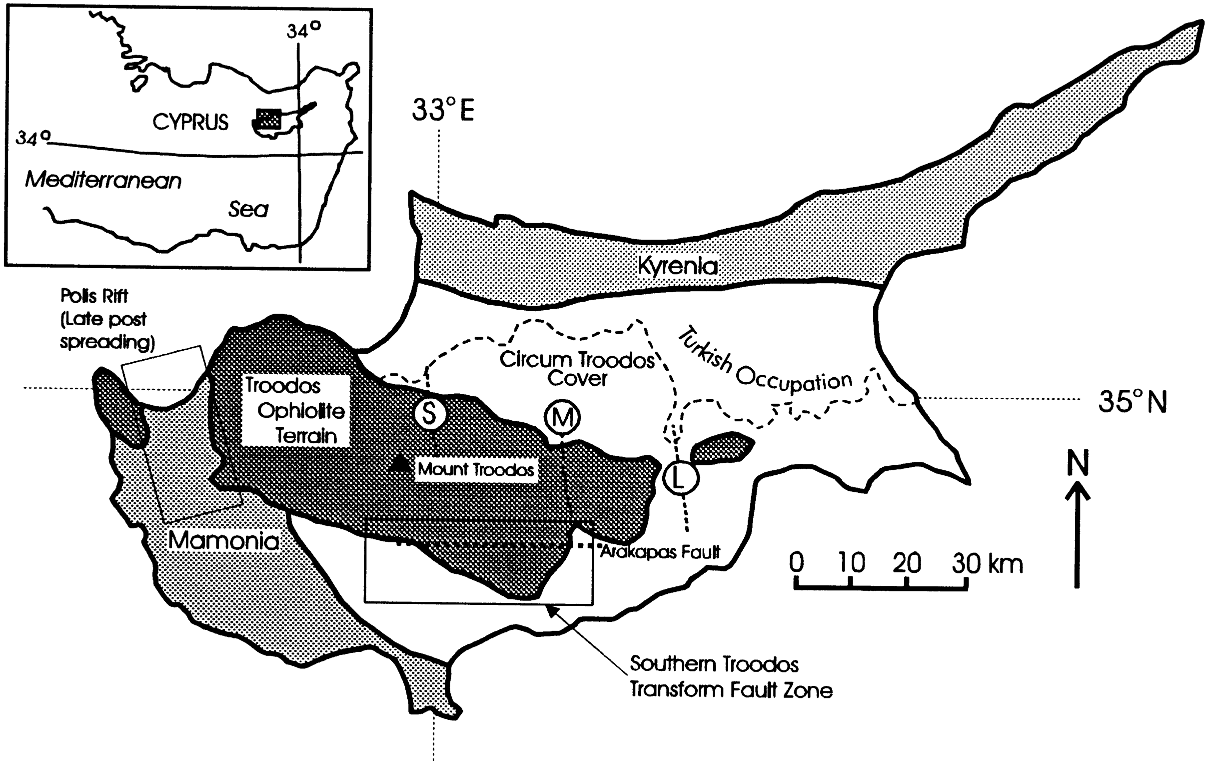

Fig. 1. Principal geological regions of Cyprus. S, M and L show the positions of the Solea, Mitsero and Larnaca spreading axes to which the ophiolite dike swarms are parallel. On the north side of the Arakapas Fault, the normally NS dikes swing SW due to dextral shear as shown by Bonhommet et al. (1988) from the deflection of the dikes' remanences.

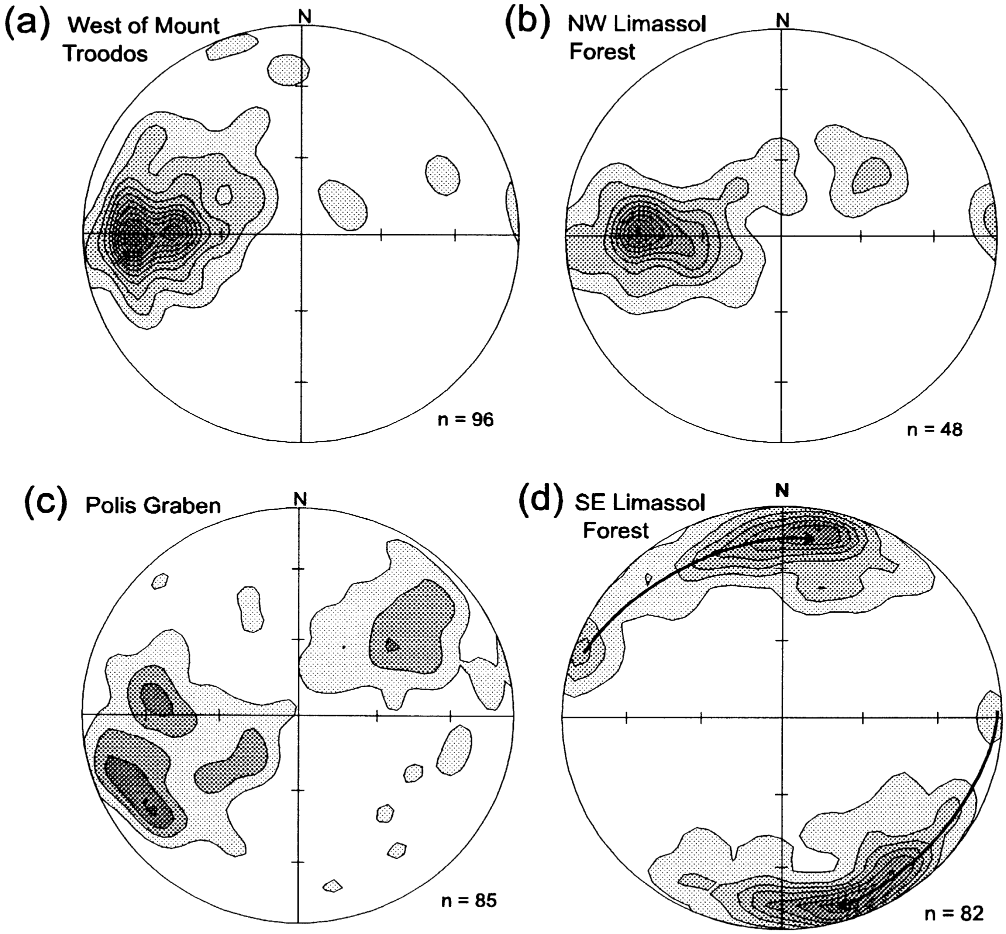

Fig. 2. Lower hemisphere stereonets of poles to dikes in the Troodos Ophiolite complex. (a), (b) and (c) are believed to show primary bimodality of dike dips, especially enhanced by normal faulting in (c). (d) shows the curving dike swarm due to dextral shear as the dikes approach the Southern Troodos Transform Fault Zone. The skewness of the distribution matches the inferred swing in orientation recorded in field maps (e.g. Gass et al., 1994) and its locus, marked by an arrow, fixes the true single rotation experienced by the dike swarm. The axis of the rotation is the normal to that great-circle distribution (175/75).

In general, the dikes strike north–south and their dips are partly due to tilting caused by the doming centered near Mount Troodos (e.g. Fig. 2a and b). However, the dikes also show some bimodality of their pole-clusters, with the modes of two subclusters separated by <20° (especially in Fig. 2a). This is because the dikes are formed on the flanks of a spreading axis and show steep dips toward that axis from either side (Moores et al., 1990; Varga and Moors, 1990). As the local spreading axes shift and migrate, dikes from opposed flanks, and of opposed steep dips, combine to form the population. Thus, individual dikes show a greater variation in primary dip than the separation shown by the modes. Also, pillow lavas dip gently away from the active spreading axes, for which there is evidence in Cyprus (e.g. Gass et al., 1994, p. 166) but the stratification-roughness of pillowed sequences is too great to permit paleomagnetic-tilt corrections.

In some areas, crustal attenuation by steep, normal listric faults enhances the bimodality of dike orientations (e.g. the rift-faulting near Polis, Fig. 2c).

However, within any small subarea, 95% of the dikes are subparallel, with dihedral angles $<15°$, and for the purposes of a paleomagnetic study may be considered synchronous. Thus, it is reasonable to restore the dikes' dips to the vertical to reconstruct the orientations of their initial paleomagnetic vectors. However, restoring the dikes' mean orientation in a subarea to the vertical avoids the inevitable departure of individual dikes from the vertical.

There is no reason to assume that the back rotation of the dikes in a subarea should be performed about a horizontal axis, i.e. the dikes' mean strike, nor need the rotation axis be parallel to the dike at all. In fact, only the restoration about the rotation axis, or axes, utilized by natural deformation will produce the correct restoration of both the dike orientations and the paleomagnetic vectors. Of course, the assumptions involved considerably degrade the precision of such restored paleomagnetic results in comparison with the more routine paleomagnetic work in non-deformed rocks. The uncertainties involved in paleomagnetic restorations of penetratively deformed rocks, such as slates, schists and folded sedimentary rocks, may be greater still and their restored paleomagnetic results should be treated with great caution (Borradaile, 1997). The distortion affecting the Troodos Dikes provides an interesting test of the structural restoration procedures because the dikes possess some intrinsic bimodality of dips, and because they have been subsequently tilted and sheared in an unknown sequence of events that changed their strikes and dips with a net rotation axis that was not vertical.

2. The Limassol Forest Transform Fault Zone

Southeast of Mount Troodos, in the Limassol Forest, the N–S dikes veer SSW in the proximity of the E–W-striking Southern Troodos Transform Fault (Fig. 1), first recognized by Moores and Vine (1971). The contact between the dike swarm and the transform zone is marked by the Arakapas Fault. Metamorphism is restricted to sea-floor hydrothermal greenschist facies with localized late-stage brownschist hydrothermal submarine alteration. There is no evidence of ductile deformation or large finite strains at the outcrop scale. However, it is clear from the field observations that the dike complex was sheared cataclastically at all scales. Simonian and Gass (1978) suggested that the swing of dikes' strikes toward parallelism with the transform fault zone was either a primary feature due to the intrusion along curved stress trajectories or due to shear against the active portion of a transform fault. Either mechanism could account for the change in dike trends along the dextral, active portion of the transform now exposed in the Limassol Forest (Gass et al., 1994, p. 145). However, Bonhommet et al. (1988) resolved this problem by examining the paleomagnetic vectors in the dikes. They showed beyond doubt that the primary paleomagnetic vectors deflect in concert with the curvature of the dike swarm. Thus, the dikes rotated after being magnetized, so that their swing in strike must be a secondary tectonic feature. The magnetization of dikes near a spreading axis is considerably delayed after intrusion, because the remanence-carrying mineral is titanomagnetite which has a relatively low Curie point (~175°C; Dunlop and Özdemir, 1997, p. 392). High geothermal gradients would postpone magnetization perhaps by 1 Ma, depending on the local spreading-rate. Dike centers were sampled to provide samples of a uniform texture; the cooling variation effects across dikes are not suspected since the paleomagnetic signatures have been reset by sea-floor metamorphism. For our purposes the remanences can be considered as synchronous, 'late' primary vectors that accompanied sea-floor alteration and subsequently rotated together with the dikes. Our field observations corroborate the view that the dikes were cataclastically sheared by dextral displacement against the transform zone and that the cataclastic deformation increases southwards toward the Arakapas Fault (Fig. 1). Dextral shear is now generally accepted (Gass et al., 1994, pp. 144 et seq.), contradicting an erroneous interpretation of sinistral shear from serpentinite schistosity in small-scale shear zones (Murton, 1990, p. 92, fig. 6 cf. fig. 7).

The effects of different restoration procedures can be tested using the paleomagnetic data of Bonhommet et al. (1988). They were cautious in their interpretation and did not use the paleomagnetic data in a traditional sense for plate tectonic or paleopole purposes. They restricted the interpretation to the local structural problem concerning the origin of the dike swarms' curvature. Others had considered that the curvature of the dike swarm adjacent to the Arakapas

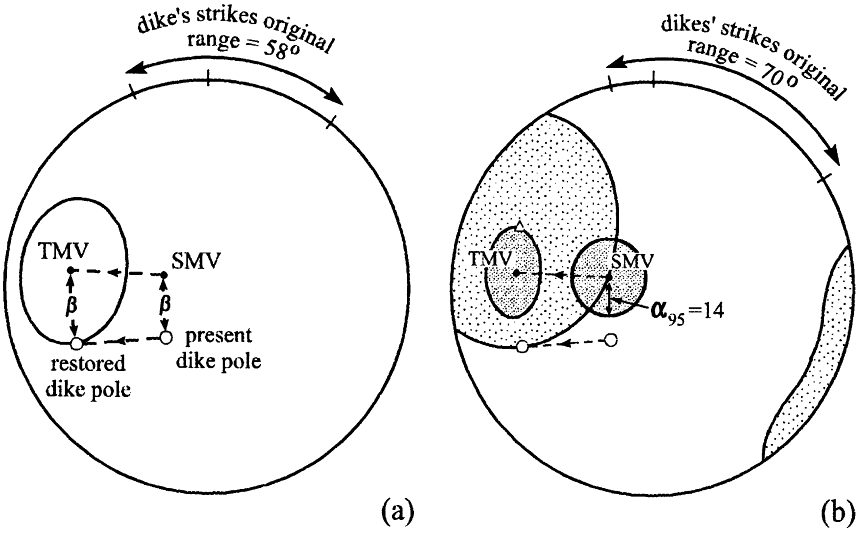

Fig. 3. (a) Allerton and Vine (1987) showed that restoration of a site-mean vector for a dike (SMV) to the regionally predicted direction (TMV) permitted a range of possible original dike orientations to be fixed. The original dike pole must lie along a small circle of radius β, where β is the unchanged angle between the remanence-vector and the dike pole in the outcrop. The most probable dike-pole orientation is that corresponding to the steepest possible dike. (b) When we consider the dispersion of the SMV, here with a conservative confidence limit $\alpha_{95} = 14°$, the small-circle range of possibilities for the restored dike pole becomes a broad girdle. Consequently, the range of possible strikes for the restored dike increases from 58 to 70°. The precision of this procedure becomes further degraded when one introduces the dispersion of the regional magnetic vector (TMV).

Fault was original, due to emplacement along the curved stress trajectories (e.g. Allerton and Vine, 1990, p. 109), but the congruent deflection of the paleomagnetic vectors shows that the dikes' deflections is a secondary tectonic feature (Bonhommet et al., 1988). Although the data set lacks the high definition required for more traditional paleomagnetic goals concerned with the site-paleolatitude and paleopole position, the quality is very suitable to illustrate the potential difficulties of rotational restorations. Some aspects of this problem were discussed with reference to other localities in Cyprus (Moores et al., 1990, p. 32). The restorations of Troodos dikes attempted by others and in this paper assume no penetrative strain of the dikes, which could change the angle between the dike's pole and the remanence in the dike (e.g. Borradaile, 1997). Cataclastic deformation can be sufficiently penetrative to cause such penetrative strain at the sample-scale, comparable to plastic deformation in the regional metamorphic rocks; however, that is not the case in these rocks as samples can always be found in which the fracture frequency exceeds the standard paleomagnetic core diameter (25 mm). Microscopic observations confirm this.

The *regional* restoration procedure used here differs from that of Allerton and Vine (1987). They considered each dike individually. They rotated its remanence (site-remanence vector (SMV)) back to the expected regional value (Troodos mean vector (TMV)). Since the dike-pole^SMV angle (β) was unchanged by tectonic tilting, a small circle of radius β about the TMV offers all possible solutions to the original position of the dike pole (Fig. 3a). Normally, the steepest possible solution would be the correct value since the dikes intrude close to the vertical. This ingenious method is particularly useful in situations where individual dikes are investigated, and the rotations are large and the regional strain heterogenous (Allerton, 1989). However, it is less valuable when one considers the dispersion of the SMV and small tectonic rotations. For a modest $\alpha_{95} = 14°$ for the SMV, the small circle of possibilities for the restored dike pole becomes a broad small-circle girdle and the range of possible dike strikes increases from 58 to 70° (Fig. 3b).

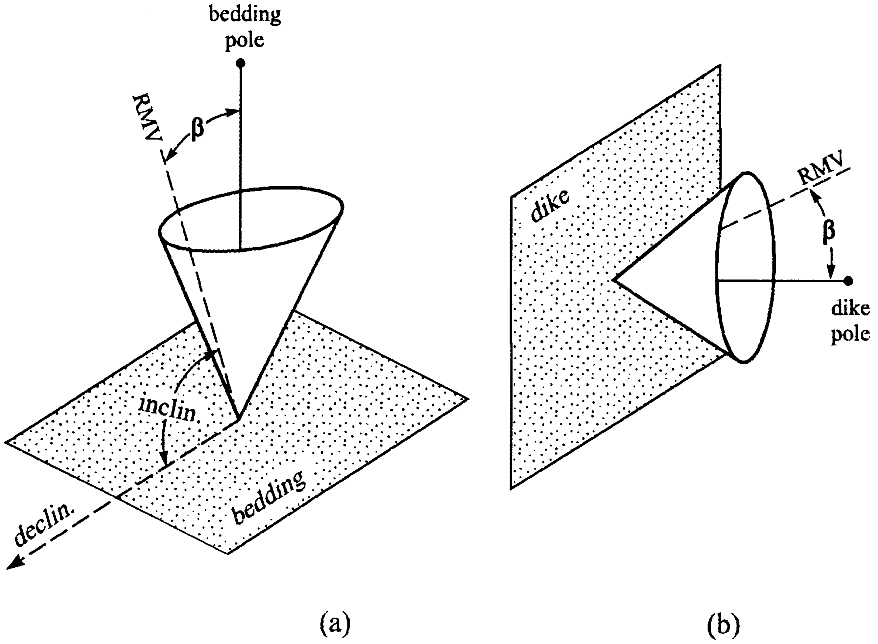

Fig. 4. (a) Restoration of tilted beds to the horizontal correctly indicates paleomagnetic inclination. However, the paleomagnetic declination is open to question if the tilt axis is not precisely known (MacDonald, 1980). This is commonly the case. (b) Where a dike is restored to the vertical, without precise knowledge of the rotation axis, both paleomagnetic declination and inclination are indeterminate. (Moreover, the initial verticality of a dike is more questionable than the primary horizontality of most beds.)

3. Paleomagnetic restorations and the Limassol Forest Transform Fault Zone

Most paleomagnetic restorations of dipping structures are restricted to stratified rocks in which there is no penetrative deformation or folding. For such unstrained rocks, the bedding may be assumed to be a tilted paleohorizontal. However, untilting requires knowledge of the tilt axis during tectonic deformation and if there are multiple tilts, their order must be known also because rotations, like strains, are non-commutative processes (Borradaile, 1997).

MacDonald (1980) emphasized that simple restorations about strike were simplistic as the rotation axes are more likely to be inclined, even in the absence of folding. Furthermore, to restore multiple rotations one must know the order in which they were applied because rotations are non-commutative processes, like strains. The effect of such ‘rigid body rotations’ (Ramsay, 1967; Ramsay and Huber, 1983) is that the angle between the bedding and the magnetic vector is unchanged. Thus, when the dip is removed, the inclination of the paleomagnetic vector is successfully recognized. Unfortunately, without knowing the actual rotation axis, the declination is indeterminate (MacDonald, 1980, p. 3661). The unsatisfactory corollary is that when a dike is untilted to a vertical position, both the inclination and the declination of the restored paleomagnetic vector are open to question (Fig. 4a and b) because, even if the rotation axis were horizontal, it need not be parallel to the dike.

In this study, the dikes’ original verticality is much more open to question than the horizontality of most stratified rocks. Furthermore, in the case of the Troodos ophiolite, the dikes have some original bimodality of dips as explained above. Notwithstanding these primary uncertainties, one hopes to restore the tilting due to Troodos uplift and shearing against the Arakapas Fault. The complexities introduced by these factors degrade the restoration to a level that is probably unacceptable for conventional paleomagnetic purposes, e.g. paleopole and perhaps even paleolatitude determinations.

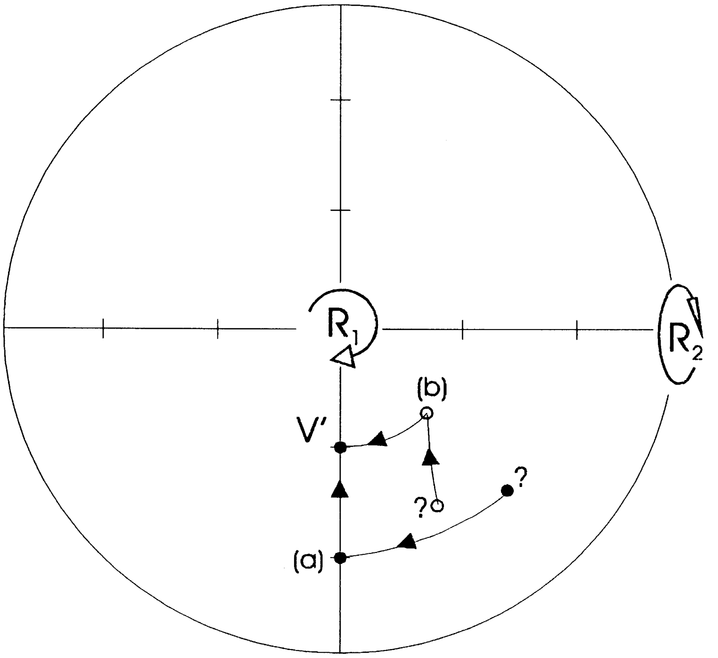

Fig. 5. Finite angular rotations are non-commutative. (a) A paleomagnetic vector (or any other line) may be rotated successively about R_1 and then about R_2 to bring it to V' from its initial position V_0, the two possibilities for which are shown by '?'. (b) If the sequence of rotations had been reversed, first R_2 and then R_1, a different initial position would have been required for V'. The actual difference between the possible restored solutions '?' greatly depends on the fortuitous nature of the angular relationships.

The first step in minimizing the errors introduced by these uncertainties is to restore the *mean orientation of dikes in a small subarea* to the vertical, thus averaging out the effects of the individual, dike-dip variability. This problem is hardly encountered in untilting strata because one can choose sedimentary facies that have paleohorizontal strata and minimum bedding-plane roughness at most sites.

Next, we consider the choice of rotation axes and the order in which they occurred. Since rotations are non-commutative, the order in which they occur and, for our purposes, the order in which they are reversed greatly affects the outcome. A hypothetical example is illustrated in Fig. 5.

Bonhommet et al. (1988) untilted their dikes to the vertical assuming a rotation axis parallel to strike and then rotated them about a vertical axis to bring them into parallelism with the unsheared N–S-striking dikes to the north of their area of study. This assumes that doming tilted the rocks after the transform sheared them; the restoration then reverses the non-commutative sequence in what appears to be the correct order. This sequence is reproduced using the local mean dike orientation, rather than that of the sampled dike as in Bonhommet et al. (1988). This restoration suggests that the corrected paleomagnetic data should be as shown in Fig. 4a, and hardly differs from that of Bonhommet et al. (1988).

Normally, if one reversed the sequence of rotations, the result would be quite different. Thus, back rotating first about a vertical axis to correct for fault shear and then untilting the effects of Troodos uplift should produce a very different result. However, in this case, the results of this procedure are insignificantly different (Fig. 6b) although, in general, greater differences may be expected (Fig. 5). The special reason for this is that six of the thirteen paleomagnetic data come from vertical dikes for which only one correction was needed and the fortuitous combination of back-rotation axes and angles produced minor differences for the other paleomagnetic vectors.

A potentially deeper concern of angular restoration

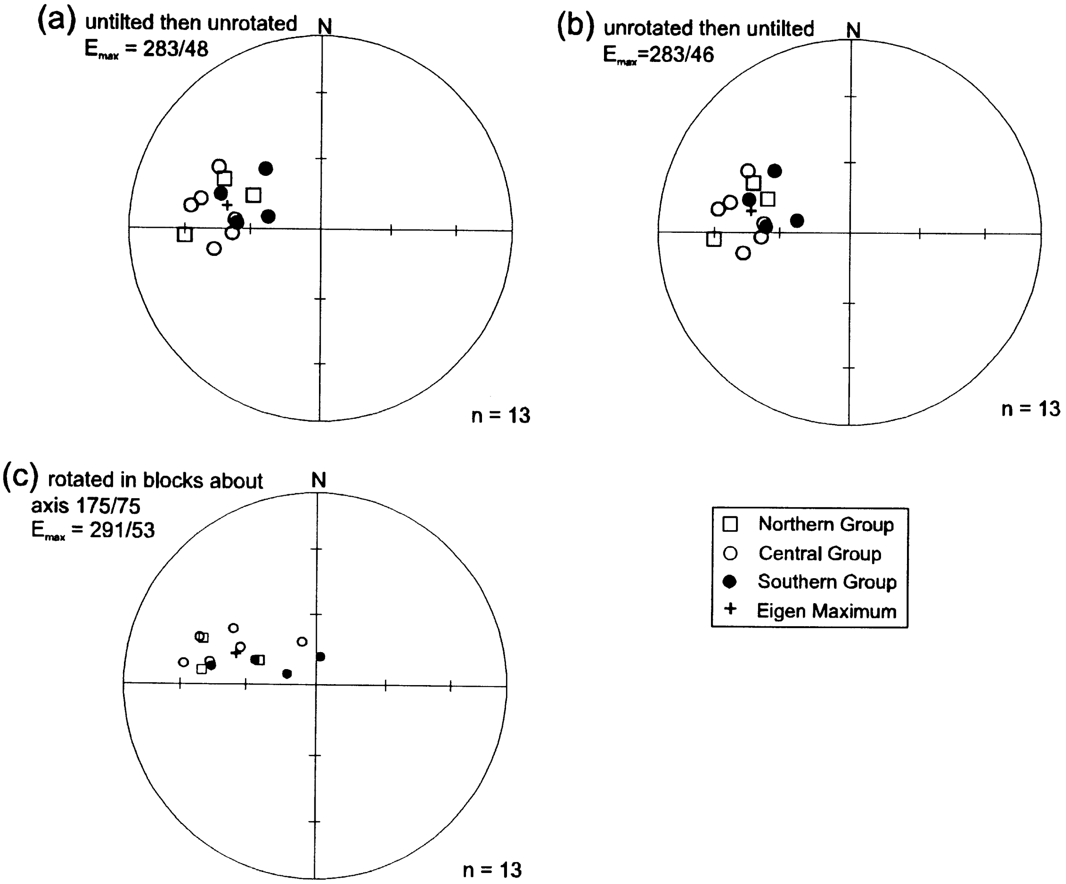

Fig. 6. Different restoration procedures for the remanence vectors of Bonhommet et al. (1988). (a) and (b) assume arbitrarily chosen horizontal and vertical rotation axes in different orders. (c) uses a single rotation axis inferred from structural analysis, perhaps a better approximation to the true geological rotation history.

is whether one should even attempt to define the two component rotations. If there are indeed two separate geological rotational events, then their effects should be undone in the correct order. Alternatively, as MacDonald (1980) notes, the geometrical effects of multiple rotations may always be replaced by a single, artificial *net rotation*. His study emphasized that real tilt axes may be inclined so that single restorations about the inclined axes should be considered.

If, for the sake of argument, the uplift of Troodos and the shearing against the transform at least partly overlapped or even occurred simultaneously, a single inclined rotation axis would be a geological reality, not merely a geometrically convenient description. Evidence for an inclined rotation must be sought from the structural information. This is revealed by the dispersion of dike poles (Fig. 2d). These show a primary, bimodal pole distribution, smearing the dikes' strikes from an original EW trend to almost NS as they approach the Arakapas Fault. The axis of rotation is 175/75. Although this seems to be the most objective choice of net rotation because it is derived directly from the dispersion of the dikes, it does not produce a unimodal, isotropic cluster ('Fisher distribution') of restored paleomagnetic vectors (Fig. 6c). The arcuate dispersion of the magnetic vectors suggests some residual, uncorrected tilting (MacDonald, 1980). Since the correction for the dike's dispersion has been performed directly from the structural data (Fig. 2), the residual dispersion must be pretectonic. The residual dispersion is probably due to the primary bimodality of dike dips revealed elsewhere (e.g. Fig. 2(c)). Its small-circle dispersion in Fig. 6(c) corroborates the view that there was some primary tilting about a N–S rotation axis which would have been parallel to the (now) N–S oceanic spreading axis.

4. Discussion

The Troodos dikes show some interesting aspects that should be considered in the restoration of paleomagnetic data from any ophiolitic dike sequence. First, the swarm shows primary bimodal dips so that individual dike orientations should not be restored to the vertical. Mean orientations of local dikes are preferred although this must reduce the precision of the reconstruction. Indeed, at depth, there is no reason to suppose that the stress field is conducive to vertical diking: some consistent deviation might be expected.

Correction for tectonic rotations requires recognition of the actual axes and their sequence of activity. This can be critical although in the fortuitous case of the Limassol Forest dikes, the differences are slight. However, decomposing a natural event into discrete artificial rotations (e.g. about the horizontal and vertical axes) is generally unwise. It is better to identify the natural net rotation axis from the dispersion of some structural feature. In the Limassol Forest, the great-circle dispersion of dike poles clearly reveals the combined contributions of crustal tilting and transform-shearing that may represent a synchronous tectonic event. Back rotating about the axis of great-circle dispersion fails to produce the expected unimodal cluster (Fisher distribution) achieved by either of the two-stage back rotations about the artificial axes (Fig. 6a and b). The small-circle scatter of the restored vectors is, however, compatible with the primary dispersion of dike dips about their N–S strike.

The Limassol Forest dike swarm provides an interesting example of the choice of discrete, rotation axes that may be real or artificial. In general, care must be taken to see that these axes represent the actual rotation of the rock bodies; simply choosing axes defined by strike and the vertical could produce erroneous restorations. The recognition of a true single-axis tectonic rotation is more direct. However, its weakness lies in the imprecise definition of the rotation axis and the angle derived by structural analysis (e.g. Fig. 2d). Compounded with the greater difficulties of working with dikes (inherent inclination and declination anomaly, Fig. 4b), their departure from the original verticality shows that the restoration of paleomagnetic vectors in dikes is far less robust than in sedimentary rocks.

Acknowledgements

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