

Palaeomagnetic insights into the evolution of Neotethyan oceanic crust in the eastern Mediterranean

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Abstract: A synopsis of palaeomagnetic data from three Late Cretaceous eastern Mediterranean Tethyan ophiolites (Troodos, Hatay and Baër–Bassit) and their sedimentary cover sequences is presented. These data provide valuable insights into the role of regional- and local-scale tectonic rotations in the geodynamic evolution of Neotethyan oceanic crust. The geologically earliest phases of tectonic rotation are documented in the Troodos ophiolite, where rotations around both subvertical and subhorizontal axes are readily related to the development of the spreading fabrics and structures during crustal genesis. Subsequent *c.* 74° anticlockwise intra-oceanic rotation of a ‘Troodos microplate’ has been quantified through analysis of the *in situ* sedimentary cover of the Troodos ophiolite. Results indicate that bulk anticlockwise rotation began soon after the cessation of spreading and ended by the end of the Eocene, with *c.* 50–60° of microplate rotation being over by the Maastrichtian, the time at which ophiolite thrust sheets were emplaced onto the Arabian continental margin to the east of Troodos. Recent results from the emplaced, structurally dismembered Baër–Bassit ophiolite indicate extreme anticlockwise rotations of ophiolitic thrust sheets varying on a kilometre scale. New data from the post-emplacment sedimentary cover confirm that only a small component of these rotations is due to post-emplacment tectonism. Baër–Bassit represents the leading edge of the emplaced ophiolitic sheet. New data from the more coherent section preserved in the Hatay ophiolite to the north demonstrate significant anticlockwise rotation. This is equivalent to the rotation of the most northerly part of the Baër–Bassit units to the south, and is of the same sense and magnitude as the pre-Maastrichtian phase of microplate rotation documented in the Troodos. This suggests a common, intra-oceanic origin for the majority of the Troodos and Hatay rotations, and a significant component of the more variable rotations observed in Baër–Bassit. Overall, therefore, the data support a model involving: (1) intra-oceanic rotation of a coherent region of crust within the southern Neotethyan basin; this rotated unit is more areally extensive than has previously been inferred from consideration of data from the Troodos ophiolite alone; (2) emplacement of part of the rotated unit onto the Arabian platform; (3) subsequent localized post-emplacment modification, related to the development of the current plate configuration.

Ophiolitic terranes provide unique opportunities for investigating the structure and kinematics of constructive plate margins, transform faults and oceanic suture zones. The eastern Mediterranean–Middle East segment of the Tethyan orogenic belt is marked by several chains of ophiolites, the most prominent of which are the Troodos (Cyprus), Baër–Bassit (Syria), Hatay (Turkey), Kermanshah and Neyriz (Iran), and Semail (Oman) ophiolites (Fig. 1). These are interpreted as fragments of ocean lithosphere formed in a southern Neotethyan basin during the Late Cretaceous (e.g. Robertson 1998).

The aim of this paper is to present a synopsis of the major palaeomagnetic results obtained

from the Troodos, Hatay and Baër–Bassit ophiolites (Fig. 2) over the last 20 years. The Troodos ophiolite of Cyprus, in particular, has played a key role in developing and testing concepts of plate tectonics (Gass 1968, 1980; Moores & Vine 1971; Robertson & Xenophontos 1993; Robertson *et al.* 1996), because primary sea-floor geometries are preserved owing to an absence of large-scale thrust faulting. Fundamental insights have been provided through a series of palaeomagnetic and structural studies (e.g. Clube 1985; Clube & Robertson 1986; Allerton & Vine 1987, 1990, 1991; Allerton 1988; Bonhommet *et al.* 1988; MacLeod *et al.* 1990; Morris *et al.* 1990, 1998; Hurst *et al.* 1992) that have highlighted

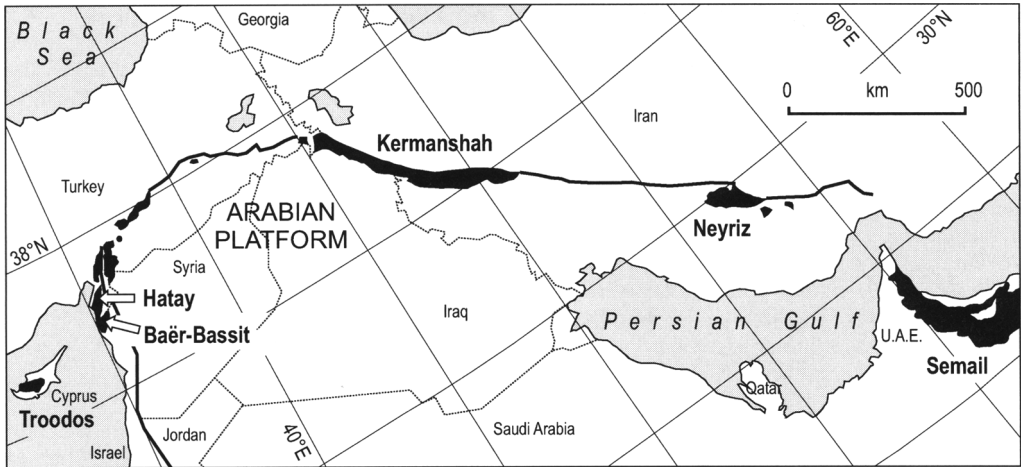


Fig. 1. Major ophiolites of the easternmost Mediterranean and Middle East region. The Troodos ophiolite remains in a pre-emplacment setting, in contrast to ophiolites to the east that were tectonically emplaced onto the Arabian continental margin during the Late Cretaceous.

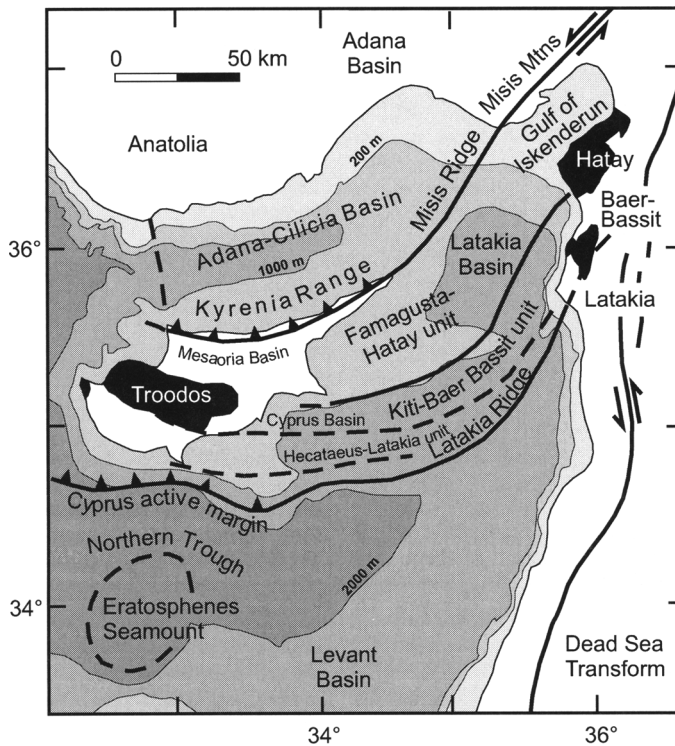


Fig. 2. Outline tectonic map of the eastern Mediterranean, showing the distribution of Late Cretaceous ophiolites (black) and major structural features.

the role of tectonic rotations in oceanic crustal construction and transform tectonism. The importance of such rotations is now firmly established, following their identification in modern spreading systems (e.g. Hurst *et al.* 1994).

More recently, Morris *et al.* (2002), Inwood *et al.* (2003) and Inwood (2005) have provided the first palaeomagnetic data from the Baër–Bassit and Hatay ophiolites, which, in contrast to the Troodos ophiolite, were emplaced tectonically onto the Arabian continental margin as a series of thrust sheets. These investigations have discovered ubiquitous large tectonic rotations, only part of which may be attributed to post-emplacement deformation.

We show that the combined palaeomagnetic database from all three ophiolites is now sufficiently extensive to provide insights into the range of styles of tectonic rotations that have affected the Neotethyan oceanic crust during formation and later deformation, and to discuss the regional-scale significance of these rotations.

Geological summary of the ophiolites

The Troodos ophiolite

The Troodos Complex ophiolite formed during the Late Cretaceous (Cenomanian–Turonian, U–Pb age 90–92 Ma; Mukasa & Ludden 1987) in a suprasubduction-zone (SSZ) setting (Pearce 1975, 1980). It consists of a complete Penrose pseudostratigraphy disposed in a domal structure as a result of Late Pliocene–Recent uplift, giving rise to a broadly concentric outcrop pattern. Mantle and lower crustal (gabbroic) sequences are exposed around the central structural and topographic high. The plutonic section includes layered cumulates cut by gabbroic intrusions, providing clear evidence for the presence of small, multiple magma chambers beneath the Troodos spreading axis (Robinson & Malpas 1990). The contact between the isotropic gabbros and overlying sheeted dykes is commonly a low-angle extensional detachment fault zone (Varga & Moores 1985), providing evidence for amagmatic stretching during crustal formation. The sheeted dyke complex is exposed over an 80 km wide swath and consists of generally north–south-striking dykes (present coordinates) that at some localities (e.g. Lemithou) are rotated to low angles and occasionally cut by later dykes (Dietrich & Spencer 1993). Spreading took place either by steady-state processes (Allerton & Vine 1987), or by formation of discrete, ephemeral, sea-floor grabens (Varga & Moores 1985). The best documented and most distinctive graben runs through the Solea area to the north of

the plutonic complex, above the ‘Kakopetria Detachment’ fault (Verosub & Moores 1981). This graben is interpreted as a fossil spreading axis (the ‘Solea axis’; see Fig. 4). Magnetic fabric and dyke surface lineation data (Staudigel *et al.* 1992; Varga *et al.* 1998) reveal both upward and lateral magma emplacement through the dyke complex, supporting a model of magma transport along the length of the spreading axis away from isolated magmatic centres beneath axial volcanoes spaced along the ridge crest. The overlying extrusive sequence is best exposed along the northern and SW margins of the ophiolite, providing classic sections where the interplay between magmatic, tectonic and hydrothermal processes during construction of the oceanic crust may be established (Schmincke *et al.* 1983; Schmincke & Rautenschlein 1987).

The southern margin of the main outcrop of the Troodos ophiolite is marked by the east–west-trending Arakapas Fault Belt, a strike-slip fault system that is interpreted as a fossil oceanic transform fault (Moores & Vine 1971; Simonian & Gass 1978). An anomalous ophiolitic sequence is exposed to the south of this structure within the Limassol Forest Complex. Here, mantle sequence and lower crustal rocks are exposed at high structural levels and are cut by numerous east–west-trending shear zones (Murton 1986; MacLeod 1990). The majority of the Limassol Forest Complex is interpreted to have formed within a leaky (transtensional) ‘South Troodos Transform Fault Zone’ (STTFZ) whose principal displacement zone is represented by the Arakapas Fault Belt (MacLeod & Murton 1993). A progressive change in orientation of dykes within the Sheeted Dyke Complex is observed as the STTFZ is approached from the north, suggestive of either primary variation in the orientation of the Late Cretaceous stress field adjacent to a sinistrally slipping transform or post-emplacement clockwise tectonic rotations of dykes resulting from dextral shear along the transform. Palaeomagnetic data (described herein) strongly support this latter model. A small area of normal Troodos-type crust exposed in the SE corner of the Limassol Forest Complex is believed to represent a fragment of crust formed at an ‘Anti-Troodos’ spreading axis located to the south of the transform domain (MacLeod 1988, 1990). Together these various structures and ophiolitic regions provide a unique exposure of the Late Cretaceous Neotethyan spreading system that is well preserved because of a lack of large-scale thrust tectonics during emplacement of the Troodos Complex.

In the Late Cretaceous, shortly after genesis at the Neotethyan spreading axis, the Troodos

oceanic crust became tectonically juxtaposed along its SW margin (present coordinates) with an allochthonous, highly deformed sequence of Upper Triassic to middle Cretaceous deep-sea sedimentary and Upper Triassic volcanic rocks known as the Mamonia Complex. This is interpreted to represent remnants of a passive continental margin and marginal oceanic crust (Robertson & Woodcock 1979; Swarbrick 1979, 1980, 1993). The mode of juxtaposition of the Troodos and Mamonia Complex terranes is under debate, with models invoking either strike-slip-dominated (e.g. Clube & Robertson 1986; Swarbrick 1993) or thrust-dominated (e.g. Malpas *et al.* 1993) emplacement, or a complex multiphase history of deformation (involving successive strike-slip, transtensional and contractional events; Bailey *et al.* 2000). Within the suture zone, high crustal level rocks (extrusive rocks 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 volcanoclastic sandstones, indistinguishable from the sedimentary cover found overlying the ophiolitic basement of the main Troodos Complex (Robertson 1977; Clube & Robertson 1986). The highly depleted geochemistry of the extrusive rocks (Murton 1990) is distinctly different from the alkaline within-plate basalt (WPB) to tholeiitic mid-ocean ridge basalt (MORB) compositions of the Triassic extrusive rocks of the Mamonia Complex (Malpas *et al.* 1993). Stratigraphic and petrographic data, therefore, support correlation of these ophiolitic outcrops with the Troodos Complex and its transform fault-related southern margin. This interpretation is also supported by palaeomagnetic data obtained from these slivers by Morris *et al.* (1998), as discussed below.

The Hatay (Kızıl Dağ) and Baër–Bassit ophiolites

In contrast to the Troodos Complex, coeval ophiolites to the east have been structurally modified during Late Cretaceous thrust-dominated emplacement onto the Arabian continental margin during progressive closure of the southern Neotethyan basin. The most westerly of these emplaced units are the Baër–Bassit and Hatay ophiolites. These are closely related spatially (Fig. 2) and represent parts of a single unit emplaced during the Maastrichtian. The Hatay ophiolite to the north forms a relatively

intact sheet (Delaloye *et al.* 1980), whereas the Baër–Bassit ophiolite to the south (Kazmin & Kulakov 1968; Parrot 1980) represents the leading edge of the emplaced sheet and is highly deformed by thrust faulting (Al-Riyami *et al.* 2000). The radiometric age of these ophiolites is poorly constrained, with ophiolitic dykes yielding K–Ar ages in the range 73–99 Ma (Delaloye & Wagner 1984).

The Hatay ophiolite is split into a large southwestern massif and a smaller northeastern massif by a high-angle fault (Tahtaköprü Fault). The ophiolite is separated from the underlying Arabian platform by only a thin mélangé and no metamorphic sole is preserved (Robertson 2002). The succession in the main Kızıl Dağ massif (Delaloye & Wagner 1984) begins with serpentinitized harzburgite tectonite with local intercalations of dunite, wehrlites, lherzolite and feldspathic peridotites. The ultramafic rocks are separated from the overlying gabbros by a 50–100 m thick shear zone that extends upwards into the base of the layered gabbros (Dilek & Thy 1998). The layered gabbros, in turn, pass into isotropic gabbros, intruded by small bodies of plagiogranites, leucocratic gabbro and dolerite. Diabase dykes increase in abundance towards the top of the gabbros, which pass upwards into a sheeted dyke complex. Locally, the gabbro–dyke contact is a low-angle shear zone marked by hydrothermal alteration. In the NE, sheeted dykes are unconformably overlain by Maastrichtian non-marine to shallow-marine sediments, presumably after erosion of ophiolitic extrusive rocks (Erendil 1984; Pişkin *et al.* 1986).

The succession in the northeasterly massif (NE of the Tahtaköprü Fault) is exposed at several localities. At one, serpentinitized peridotites are tectonically overlain by gabbro, rotated dykes and lavas (Dilek & Thy 1998). Elsewhere, serpentinitized peridotites are overlain, above a gently dipping normal fault, by massive and pillow lavas that are rarely interbedded with or overlain by metalliferous sediments (Erendil 1984; Robertson 1986). Pillow flows are steeply dipping to subvertical. Further south (south of Antakya), gabbros or serpentinites are in low-angle faulted contact with overlying pillow lavas. These extrusive rocks include highly magnesian, boninite-type lavas ('sakalavite'; Delaloye & Wagner 1984).

The highly dismembered Baër–Bassit ophiolite is underlain by a well-developed inverted amphibolite or greenschist-facies metamorphic sole (Whitechurch 1977; Al-Riyami *et al.* 2002), that has a K–Ar age of 86–93 Ma (Thuizat *et al.* 1981; Delaloye & Wagner 1984). The ophiolitic outcrop is dominated by two massifs,

Baër in the NE (inland) and Bassit in the NW (near the coast), together with smaller masses of highly dismembered ophiolitic rocks further SE. The Baër massif is subdivided into several large thrust sheets, dominated by harzburgites overlain by cumulate ultramafic rocks (Al-Riyami *et al.* 2000). Layered gabbros (<1 km thick) are locally cut by dolerite dykes. The Bassit massif comprises a lower sequence of harzburgites and gabbros, which are overthrust by a slice of mélange and then by thin (<100 m thick) imbricate thrust sheets of gabbro, sheeted dykes and pillow lavas. Geochemical analysis of extrusive rocks reveals strongly depleted, highly magnesian boninite types (Al-Riyami *et al.* 2000). The ophiolite and its metamorphic sole are underlain by the extensive 'Baër–Bassit Mélange' (Al-Riyami *et al.* 2000; Al-Riyami & Robertson 2002), which consists of a Late Triassic to mid-Cretaceous deep-water, passive margin succession (Delaune-Mayère 1984; Al-Riyami *et al.* 2000). All three units (Baër–Bassit ophiolite, metamorphic sole and Baër–Bassit Mélange) were thrust onto the Arabian carbonate platform in the mid-Maastrichtian (*c.* 70 Ma), based on the biostratigraphic ages of the youngest sequences of the Arabian platform beneath the allochthon and the oldest sedimentary rocks of the post-emplacement cover sequences (Kazmin & Kulakov 1968). Lineations in the metamorphic sole, defined by elongation of amphibole porphyroblasts, together with fold facing and vergence directions within the underlying Baër–Bassit Mélange, indicate that thrust sheets were emplaced towards the SE (Al-Riyami *et al.* 2002; Al-Riyami & Robertson 2002).

The disrupted Baër–Bassit allochthon was later unconformably overlain by a sedimentary sequence of late Maastrichtian to Pliocene age (Boulton *et al.* 2006). The sedimentary successions are cut by mainly ENE–WSW-trending strike-slip faults that extend offshore (Figs 2 and 7). This fault system represents part of the extension of the plate boundary zone between the African plate and the Turkish microplate, which runs eastwards from south of Cyprus as a zone of distributed deformation and then comes onshore, passing through the Baër–Bassit region to link with the Dead Sea transform fault system to the east (Al-Riyami *et al.* 2002; Fig. 2).

The palaeomagnetic database

Sources, data selection and reporting

Discussion is restricted to a synopsis of the major palaeomagnetic results obtained to date, and

no attempt is made to summarize the growing literature on magnetic fabric (anisotropy of magnetic susceptibility) results from the Troodos ophiolite (e.g. Staudigel *et al.* 1992; Varga *et al.* 1998; Abelson *et al.* 2001; Borradaile & Lagroix 2001). The majority of ophiolite data used in this synopsis were collated from published sources by Morris (2003) for the purpose of assessing the palaeolatitude of the Neotethyan spreading axis. This compilation consisted of results from: (1) 100 palaeomagnetic sampling sites in the Troodos ophiolite, drawn from Clube (1985), Clube *et al.* (1985) Bonhommet *et al.* (1988), Allerton (1989a), Morris *et al.* (1990, 1998) and Hurst *et al.* (1992); (2) 19 sites in the Baër–Bassit ophiolite presented by Morris *et al.* (2002). Additional data from six sites in the Mandria area of the Troodos ophiolite from MacLeod *et al.* (1990) are included here. New palaeomagnetic data from 18 sites of the Hatay ophiolite are included from Inwood *et al.* (2003) and Inwood (2005). Finally, to assess the timing of post-crustal genesis rotations in the ophiolites, data are also drawn from: (1) 26 sites distributed through the *in situ* Upper Cretaceous to Miocene sedimentary cover sequences of the Troodos ophiolite, reported by Clube (1985), Abrahamsen & Schönharting (1987) and Morris *et al.* (1990); (2) 15 sites within the Tertiary post-emplacement sedimentary cover of the Baër–Bassit ophiolite, reported by Morris *et al.* (2006); (3) 17 sites within the post-emplacement sedimentary sequences overlying the Hatay ophiolite, reported by Inwood *et al.* (2003), Kissel *et al.* (2003) and Inwood (2005).

The following criteria were used in the selection of data from the source publications: (1) site-level data are based on laboratory cleaned sample remanences with the stability of remanences investigated at each site by using either demagnetization of pilot samples or, preferably, full demagnetization of each sample; (2) structural corrections are reported in the source paper or may be recovered from reported *in situ* and tilt-corrected remanence data; (3) data fulfil the following statistical constraints: number of samples included in the site mean, $n \geq 5$; cone of confidence, $\alpha_{95} < 20^\circ$; and Fisherian precision parameter, $k > 10$.

The reader is referred to the source papers for details of sampling procedures and site locations. Stereographic projections of site-mean remanence data and the associated cones of confidence are included therein. Primary tables of data may be found in the source papers, or have been given by Morris (2003) in the case of data from the Troodos and Baër–Bassit ophiolitic sites.

Data correction and interpretation techniques

Standard palaeomagnetic practice involves structurally correcting *in situ* (geographical coordinates) remanence data by applying a simple tilt around a strike-parallel axis to restore a palaeohorizontal or palaeovertical surface to the present-day horizontal or vertical. Tilt-corrected vectors may then be compared with an appropriate coeval reference vector, with differences in declination (azimuth) being interpreted in terms of vertical axis rotations, and differences in inclination (dip) being attributed to either palaeolatitudinal movements or to inclination shallowing as a result of compaction (in the case of sedimentary rocks). This tilt correction approach decomposes the total deformation at a site into components of rotation around horizontal and vertical axes. Declination errors may be introduced artificially if deformation involved tilting around inclined axes, if more than one phase of tilting has occurred, or if fold axes are plunging (MacDonald 1980). In the last case, however, declination errors are $<10^\circ$ for fold plunges of up to 50° if the palaeohorizontal dips at $<40^\circ$, and are $<10^\circ$ even for vertical beds if the fold plunge is $<10^\circ$. The most severe source of error in adopting standard tilt corrections in ophiolitic terranes, however, arises from restoration of sheeted dykes to the vertical, as components of tilt around dyke-normal axes are impossible to resolve in the absence of palaeohorizontal markers (Borradaile 2001; Morris & Anderson 2002). Such unresolved tilts may potentially introduce both declination and inclination anomalies.

An alternative net tectonic rotation approach that has been widely adopted in these ophiolites (Allerton & Vine 1987; Allerton 1989a; Morris *et al.* 1990, 1998, 2002; Hurst *et al.* 1992) is to describe the deformation at a site in terms of a single rotation about an inclined axis, which restores both the palaeohorizontal and palaeovertical to their initial orientation and the site mean magnetization vector to the appropriate palaeomagnetic reference direction. This single rotation may then be decomposed into any number of component rotations on the basis of additional structural data, and/or net tectonic rotation axes may be interpreted directly in terms of structural history. The key assumptions in this method (Allerton & Vine 1987) are that: (1) pre-deformational remanences are preserved; (2) an appropriate (coeval) reference magnetization direction may be found; (3) dyke margins or palaeohorizontal surfaces should be restored to as close to vertical or horizontal as possible;

(4) no internal deformation of sampled units has occurred.

Useful insights into the tectonic evolution of the ophiolites under consideration here have been obtained using either one or both of these interpretation methods. For the purposes of this synopsis, however, data are displayed following simple tilt correction only, for the following reasons: (1) this unifies the palaeomagnetic database; (2) primary, detailed interpretations are available in the source papers, where issues related to choice of methods are discussed in detail; (3) the tectonic significance of tilt corrected data is easier to understand intuitively; (4) application of the net tectonic rotation approach requires use of standard or inclination-only tilt tests based on the simple tilt correction approach in order to properly assess the timing of magnetization acquisition relative to deformation, unless magnetizations are merely assumed to be pre-deformational in age; (5) the tectonic significance of the data in terms of rotation patterns and styles is largely unaffected by the choice of technique. Reference is made to the results of net tectonic rotation analyses where appropriate.

Age of magnetization

Detailed discussion of the palaeomagnetic characteristics of the ophiolites is beyond the scope of this paper. In summary, demagnetization of natural remanent magnetizations generally reveals characteristic magnetizations carried by a range of ferrimagnetic phases that can be readily related to assemblages observed within *in situ* oceanic crust and other ophiolites (Dunlop & Özdemir 1997). Of prime concern, however, is consideration of the age of magnetization within the sampled ophiolitic lithologies, as this is critical to the tectonic interpretation of the palaeomagnetic data. This is determined with respect to tectonic disruption of sampled units using field tests of palaeomagnetic stability, the most common of which is the palaeomagnetic fold or tilt test (McElhinny 1964; McFadden & Jones 1981). Differential vertical axis rotations, however, invalidate use of area-wide tilt tests based on full remanence vectors (declination and inclination). An alternative approach that is not affected by such rotations is to determine the effect of untilting on the distribution of inclinations only. The angle between the inclination and the palaeohorizontal at a site may be assumed to remain constant during rigid body rotation, regardless of the axis of rotation. Significant improvement in clustering of inclinations upon tilt correction of mean directions from sites

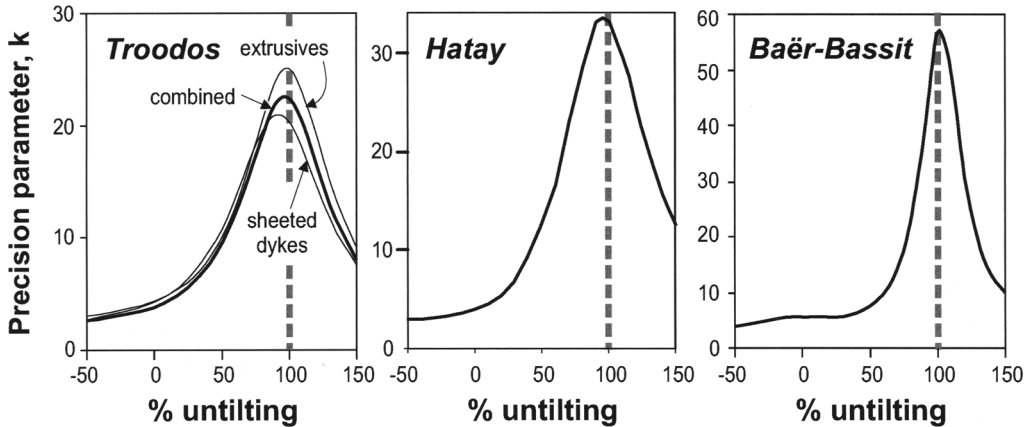


Fig. 3. Variation in the Fisher precision parameter with progressive untilting of palaeomagnetic data from sites within the Troodos, Hatay and Baër–Bassit ophiolites. These data indicate positive inclination-only tilt tests (Enkin & Watson 1996) in all three cases, with peaked distributions centred on 100% untilting. This demonstrates unequivocally that pre-deformational magnetizations are recorded by the sampled units, and that palaeomagnetic data should therefore be interpreted in tilt-corrected coordinates.

with different structural orientations therefore suggests that a pre-tilt magnetization has been identified (Enkin & Watson 1996). Figure 3 shows the variation of the maximum likelihood estimates of the Fisher precision parameter, k , with degree of untilting for each of the three ophiolites. Strongly peaked distributions with maximum k values at 100% untilting demonstrate unequivocally that pre-deformational remanences are identified within each terrane. The extensive database available for the Troodos ophiolite allows separate consideration of the age of magnetization of the extrusive sequences and sheeted dyke complex. Positive tilt tests are observed in both cases. Close agreement between the tilt-corrected mean inclinations of both units suggest that the sheeted dyke dataset is sufficiently large to ensure that any components of tilting around dyke-normal axes (Borradaile 2001; Morris & Anderson 2002) at individual sites produces little bias in the overall mean inclination for this unit.

Tectonic significance of the data

On the basis of the tilt test results described above, palaeomagnetic data from the ophiolites are hereafter described and interpreted in tilt-corrected (stratigraphic) coordinates. Stereographic projections of site-mean remanence data are given in Figure 4 (Troodos) and Figure 7 (Hatay and Baër–Bassit). Data from the sedimentary

cover sequences are presented in Figure 6 (Troodos) and Figure 7 (Hatay and Baër–Bassit). Results are discussed by individual ophiolite below, prior to regional synthesis.

Troodos ophiolite

There is a clear distinction within the Troodos palaeomagnetic database (Fig. 4) between regions with magnetization vectors that cluster around westerly declinations and regions where declinations are widely variable from WSW, through northerly to easterly declinations. The former regions (stereonet 1–4 with unshaded α_{95} ellipses in Fig. 4) are the northern margin of the main ophiolite (Clube 1985), the Solea region (Allerton & Vine 1987; Allerton 1989a; Hurst *et al.* 1992), the Akamas peninsula (Clube 1985; Morris *et al.* 1998) and the western margin of the ophiolite (Morris *et al.* 1998). These regions are remote from the STTFZ and its inferred westerly along-strike extension, and provide the evidence for the ophiolite-wide bulk anticlockwise rotation of the Troodos microplate first identified from natural remanent magnetization data by Vine & Moores (1969) and Moores & Vine (1971). The mean direction of magnetization of these 29 sites is declination (D) = 272.5°, inclination (I) = 38.4°, α_{95} = 6.5°, k = 17.7. This westerly-directed magnetization is also observed at sites (Morris *et al.* 1990) within the SE part of the Eastern Limassol Forest Complex to the immediate south of the STTFZ (stereonet 5, Fig. 4), providing palaeomagnetic support for the presence of a fragment

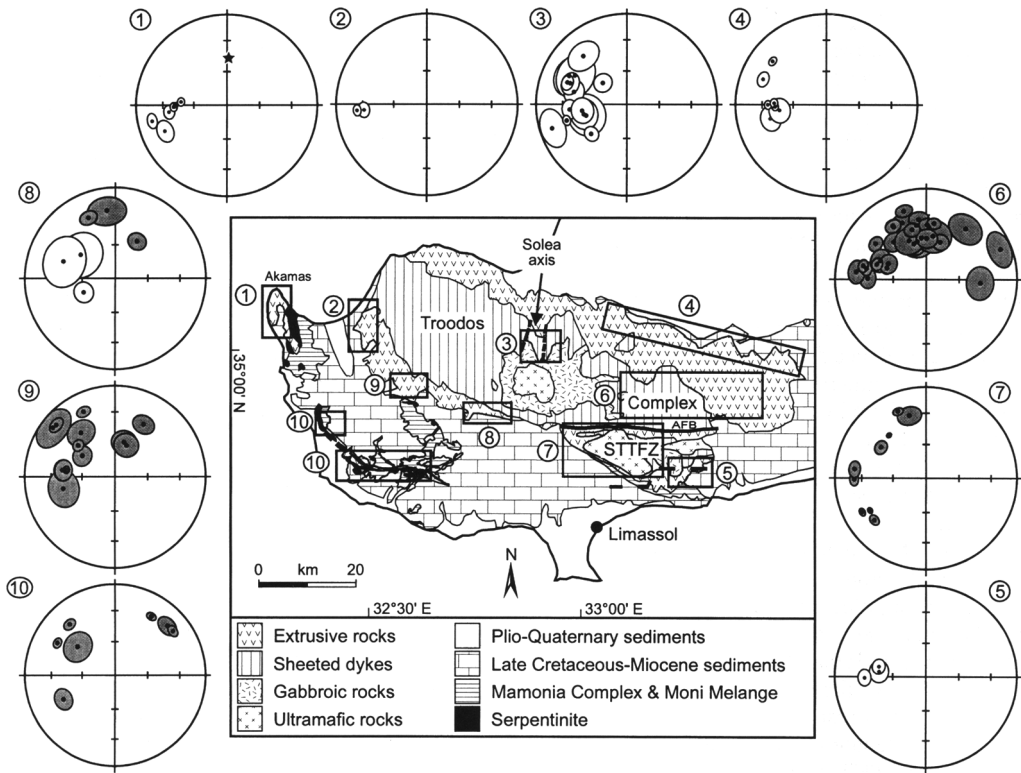


Fig. 4. Outline geological map of Cyprus, showing the location of major structural features and the locations of areas that have been investigated palaeomagnetically. Lower hemisphere stereographic projections show tilt-corrected site-level palaeomagnetic directions and associated α_{95} cones of confidence from each area. Shaded α_{95} ellipses indicate data obtained from ophiolitic crust that is inferred to have experienced significant transform tectonism, whereas unshaded α_{95} ellipses indicate data obtained from localities outside the transform tectonized zone. Black star in stereographic projection 1 indicates the direction of the present-day geomagnetic field. STTFZ, South Troodos Transform Fault Zone; AFB, Arakapas Fault Belt. Data sources: Clube (1985); Bonhommet *et al.* (1988); Allerton (1989a); Morris *et al.* (1990, 1998); Hurst *et al.* (1992).

of an Anti-Troodos plate in this area, as originally deduced by MacLeod (1988, 1990) from field geological observations.

Palaeomagnetic data from the Solea area provide important insights into tectonic processes at slow- to intermediate-spreading axes. The Solea graben is a 15–20 km wide asymmetrical structure defined principally by variations in dyke attitude in the Sheeted Dyke Complex (Varga & Moores 1985), which in this area is separated from the underlying plutonic complex by the low-angle Kakopetria detachment fault zone. An oceanic environment for formation of the graben is demonstrated by the horizontal disposition of the overlying sedimentary sequences (MacLeod *et al.* 1990). To the east of the inferred spreading axis, dykes are generally steeply dipping to subvertical and trend NNW except for several

small areas where dykes dip more gently (Hurst *et al.* 1992). The wider western flank is distinctly different, with north–south-trending dykes dipping at low angles of 25–45° to the east. The low-angle orientations of these dykes were attributed by Verosub & Moores (1981) to listric normal faulting associated with the Kakopetria detachment, above a magma chamber at the active spreading axis. In this model, plate separation was at least partly accommodated by tectonic thinning of the upper crust during periods of amagmatic stretching. Palaeomagnetic analysis of these dykes (Allerton & Vine 1987; Allerton 1989a; Hurst *et al.* 1992) confirms that they were originally intruded in (sub)vertical orientations. Tilt-corrected vectors (stereographic projection 3, Fig. 4) generally cluster around the mean inclination observed at other localities far

from the STTFZ, in contrast to *in situ* inclinations (not shown) that vary widely from -25° to 75° . The data are most informatively analysed using the net tectonic rotation approach (Allerton & Vine 1987). This reveals rotation axes for dykes in the western portion that are subhorizontal and subparallel to the original dyke strikes (Allerton & Vine 1987; Allerton 1989a; Hurst *et al.* 1992), consistent with rotation (tilting) of dykes by faults above the detachment surface. For the eastern Solea graben, marked by steeper and more variable dyke orientations, structural evidence does not support the existence of a throughgoing detachment fault. Net tectonic rotation analysis here indicates that some dykes appear to have been tilted towards the Solea axis, but the majority show minor to significant rotation about vertical axes. This was attributed by Hurst *et al.* (1992) to local variations in the amount of extension, related to late-stage episodic intrusions.

Extensive palaeomagnetic data (Clube 1985; Bonhommet *et al.* 1988; Allerton 1989a; MacLeod *et al.* 1990; Morris *et al.* 1990) from the southern half of the main Troodos ophiolite and the Limassol Forest Complex have been used to address the debate on the sense of displacement along the STTFZ and its relationship with the Solea axis. A progressive change in dyke trend is observed within the Sheeted Dyke Complex as the transform zone is approached from the north, from a predominant north–south orientation into eventual alignment with the transform lineament (Fig. 5a). This has been interpreted as the result of either dyke injection into a sigmoidal stress field, implying that dykes are in their original orientations relative to the sinistrally slipping transform (Fig. 5b), or clockwise vertical-axis fault block rotations in response to dextral slip (Simonian & Gass 1978; Fig. 5c). Discrimination between these alternative models can be achieved palaeomagnetically, as systematic tectonic rotations would result in systematic variations in magnetization vectors away from the westerly directed vectors observed outside the transform-influenced zone. Data from the region to the north and NE of the Arakapas Fault Belt (Bonhommet *et al.* 1988; Allerton 1989a; stereonet 6, Fig. 4) show a broad spread of directions that are clearly rotated in a clockwise sense relative to this westerly vector, supporting a dextral shear sense along the transform between sinistrally offset spreading axes. The most unequivocal analysis was presented by Bonhommet *et al.* (1988), who showed that magnetizations in sampled dykes cluster tightly with

westerly declinations after correction of dykes back to the predominant north–south trend, thereby ruling out initial NE–SW trends. Further palaeomagnetic support for dextral shear along the transform zone is provided by data from the STTFZ itself (Morris *et al.* 1990; stereonet 7, Fig. 4), the majority of which are also rotated clockwise away from the general Troodos vector. Net tectonic rotation analysis of data from sets of cross-cutting dykes (Allerton & Vine 1990; Morris *et al.* 1990) demonstrates that clockwise block rotations were actively occurring during crustal genesis, rather than resulting from later reactivation of the fault zone.

Analysis of upper crustal rocks of Troodos-type exposed in fault-bounded slivers along the suture zone with the Mamonia Complex in SW Cyprus (stereonet 10, Fig. 4) reveals significant rotations in a generally clockwise sense away from the Troodos vector (Morris *et al.* 1998). In particular, differences in remanence directions between cross-cutting units are observed at several localities, interpreted elsewhere as a characteristic of synmagmatic rotation during transform tectonism. Net tectonic rotation analyses allow decomposition of the total rotation at these sites into early and late components. Early rotations are consistently clockwise, in agreement with studies of rotations associated with the STTFZ further to the east. These data, therefore, suggest that transform-tectonized crust is preserved in SW Cyprus, an interpretation supported by stratigraphic and geochemical similarities between these units and the main Troodos ophiolite and its transform fault-related southern margin.

The overwhelming palaeomagnetic evidence for clockwise fault block rotations associated with dextral slip along the Southern Troodos transform contrasts with sinistral kinematic data reported by Murton (1986) within the western Limassol Forest Complex (i.e. within the transform zone). This apparent paradox was resolved by MacLeod & Murton (1995), who proposed a model in which sinistral shear developed locally at block boundaries within an overall dextral shear zone.

Detailed palaeomagnetic and structural analyses (MacLeod *et al.* 1990) have identified a limit to the zone of transform-related rotations along the STTFZ (within area 8, Fig. 4; Fig. 5d). The changeover from rotated to unrotated dykes occurs across a complex zone about 2–5 km wide to the west of the village of Mandria. This zone was interpreted by MacLeod *et al.* (1990) as a fossilized intersection between

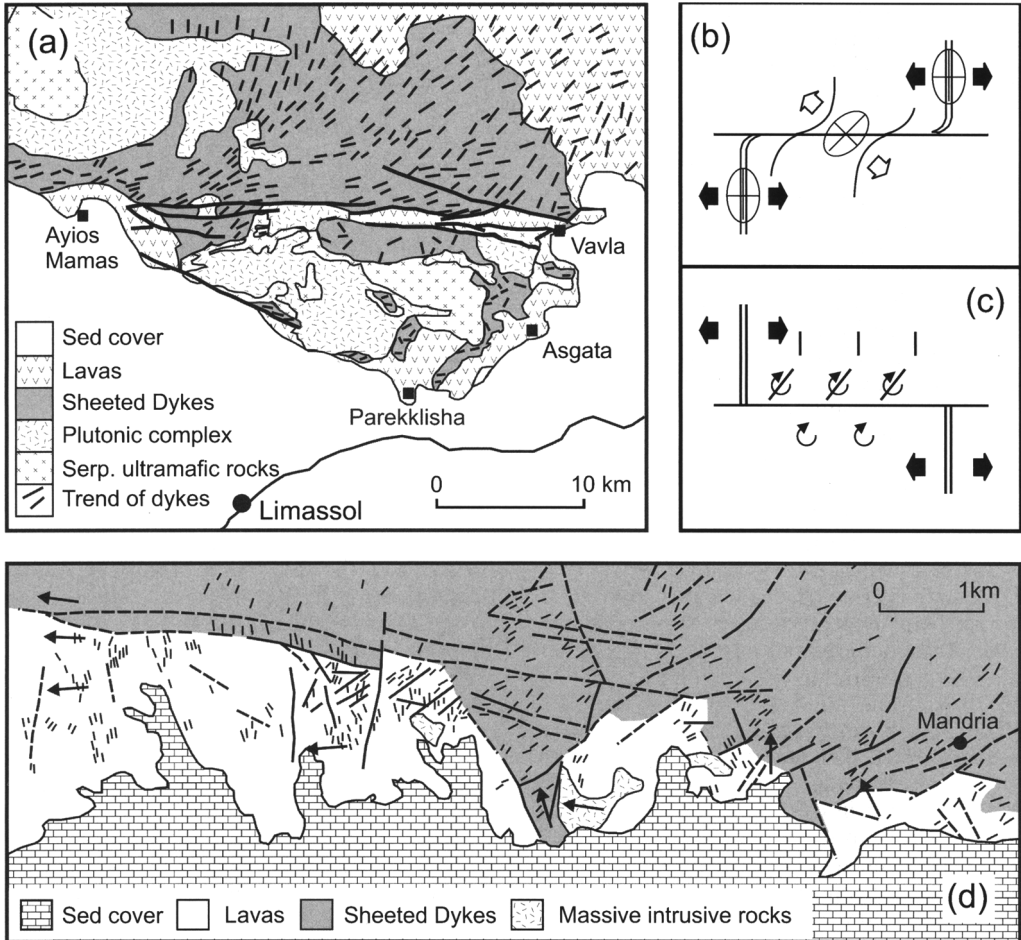


Fig. 5. (a) Simplified geological map of the southern margin of the main Troodos ophiolite and the Limassol Forest Complex (after Simonian & Gass 1978), showing the progressive change in dyke trend into near parallelism to the Southern Troodos transform zone over a distance of 10–15 km (from Morris *et al.* 1990). (b) and (c) show possible alternative settings in which deviations in dyke trend could occur close to the Southern Troodos Transform Fault Zone (from Morris *et al.* 1990): (b) dyke injection into a sigmoidal stress field operating across a sinistrally slipping transform between dextrally offset spreading axes; (c) rotation of fault blocks related to dextral slip along the active transform domain between sinistrally offset spreading axes. (d) Geological map of the Mandria area (modified from MacLeod *et al.* 1990), with palaeomagnetic sites shown (*in situ* declinations indicated by arrows). Dykes in the west have an average north–south trend in contrast to highly rotated dykes to the east. The boundary between these domains represents a fossil ridge–transform intersection.

the Solea axis and the SSTFZ. They noted that the radius of curvature of dyke swing remains approximately constant across the entire exposed width of the Troodos massif to the east of the ridge–transform intersection (see Fig. 5a). MacLeod *et al.* (1990) concluded that transform-related rotations occurred within the active inside corner of the intersection itself rather than being accommodated progressively with increasing strike-slip displacement along the

transform. This supports a theoretical model (Allerton 1989b) for distortions within weak crust at ridge–transform intersections. Distributed rotational deformation is, therefore, considered to be largely confined to the inside corner of the intersection itself (MacLeod *et al.* 1990), and subsequent strain is taken up by strike-slip faulting concentrated almost exclusively in the principal transform displacement zone within the transform valley (Arakapas Fault Belt).

The debate over the tectonic interpretation of the STTFZ has recently been reopened by Cann *et al.* (2001). They noted the presence in the Limassol Forest area of outcrops of deeper mantle or crustal lithologies in low-angle extensional tectonic contact with a range of shallower crustal lithologies, as mapped by B. J. Murton and C. J. MacLeod (in Gass *et al.* 1991, 1994). In the eastern Limassol Forest Complex these extensional structures were attributed by MacLeod (1988, 1990) to a sustained period of post-volcanic extensional reactivation of the STTFZ in the Late Cretaceous, related to the initiation of palaeorotation of the 'Troodos microplate'. By contrast, Cann *et al.* (2001) compared these outcrop patterns and structures with the characteristics of extensional oceanic core complexes developed at inside corners of ridge-transform intersections in modern slow-spreading systems (e.g. those associated with the Atlantis Transform Fault, Mid-Atlantic Ridge at 30°N; Blackman *et al.* 1998). In this alternative interpretation (Fig. 6a), the Limassol Forest Complex represents a remnant of a strip of inside-corner crust formed to the present-day south of a sinistrally slipping active transform, with the zone of curved dyke trajectories (described above) lying in crust formed at the outside corner. This model, however, provides no geologically realistic explanation for the progressive change in dyke strike as the STTFZ is approached from the north (Fig. 5a), a pattern that has been unequivocally shown to result from differential vertical-axis tectonic rotations. It is also inconsistent with the dominance of clockwise rotations within the transform zone itself (that demonstrably were synchronous with active magmatism), and finally cannot be reconciled with the evidence for the presence of a ridge-transform intersection in the Mandria area (Fig. 5d), which indicates that inside-corner crust lies to the present-day east of the Solea axis (Fig. 6b).

The large anticlockwise rotation of the 'Troodos microplate' is a regionally significant event within the Neotethys ocean. Initial estimates of the size of the rotated unit (Clube 1985; Clube & Robertson 1986) suggested that rotation was restricted to an oceanic microplate of approximately the same area as the Troodos ophiolite itself, although this now requires re-evaluation in the light of new data from the emplaced ophiolites exposed further east (summarized below). The timing of the rotation may be determined by palaeomagnetic analysis of the continuous upper Cretaceous to Recent *in situ* sedimentary cover to the ophiolite, on the basis that magnetic declinations within the sediments record rotation

of the underlying ophiolitic basement. Several attempts at such analyses have been made, the earliest of which (Shelton & Gass 1980) was hindered by difficulties in measuring the very weak magnetizations of the predominantly carbonate lithologies and a lack of appropriate demagnetization experiments. Subsequent investigations by Clube (1985) and Abrahamsen & Schönharting (1987) yielded data distributed through the succession, and further constraints on the early rotation history were provided by Morris *et al.* (1990). Site-level data from these studies that meet the quality criteria outlined above are shown in Figure 7a. Hydrothermal sediments (umbers) of the Perapedhi Formation share a common direction with the underlying extrusive sequence. The overlying Campanian radiolarian mudstones (Perapedhi Formation) and Maastrichtian–Oligocene chalks (Lefkara Formation) show a general progression from WNW to northerly declinations upwards through the stratigraphy. Data for some time intervals show significant scatter, most notably in the inclination of the Maastrichtian sites and in both inclination and declination of the Paleocene sites. This may reflect the influence of compaction-related inclination shallowing and/or potential contamination of site-level remanence vectors by residual normal polarity overprints. This latter effect is the most likely explanation of the inclination difference between the two Maastrichtian sites with the shallowest inclinations (representing inverted reversed polarity sites) and the remaining three (normal polarity) sites of this age. Late Oligocene to Miocene sites exhibit exclusively northerly declinations (within error). Figure 7b shows the variation of rotation angles through time, derived from a comparison of mean remanence data for time periods represented by three or more site mean directions in Figure 7a with expected directions calculated from the African master apparent polar wander path of Besse & Courtillot (2002). These data clearly indicate the progressive and prolonged nature of the rotation of the Troodos microplate during the Campanian–Eocene interval. However, interpretation in terms of variations in rotation rate through time is made difficult by palaeomagnetic uncertainties relating to limited site numbers and lack of more precise dating of sampled units.

Hatay and Baër–Bassit ophiolites

Morris & Anderson (2002), Morris *et al.* (2002), Inwood *et al.* (2003) and Inwood (2005) have recently provided the first palaeomagnetic data from the emplaced ophiolites directly to the east of Troodos. Layered gabbros, and massive and pillowed lava flows of the Hatay ophiolite

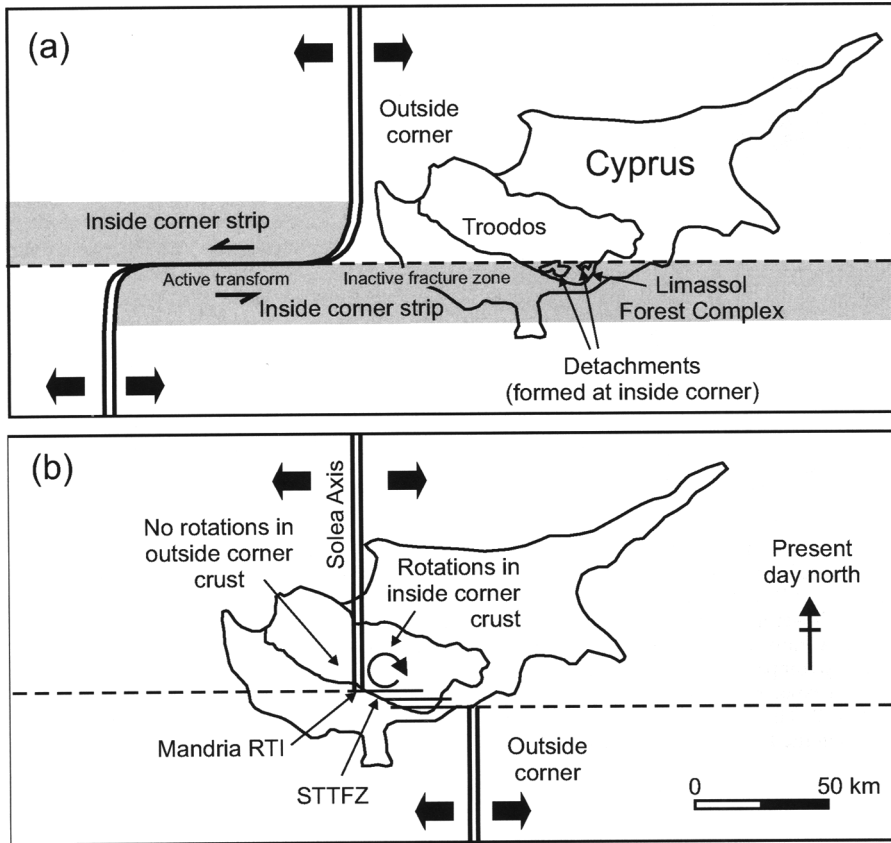


Fig. 6. (a) Summary of the Cann *et al.* (2001) model for the origin of the Limassol Forest Complex. This model invokes a sinistral slipping transform between dextrally offset spreading axes to account for an inferred inside-corner setting for the development of extensional structures observed in the Limassol Forest area (modified from Cann *et al.* 2001). (b) The geometry of the alternative model that is consistent with field and palaeomagnetic evidence for clockwise transform-related rotations and their distribution relative to the Solea spreading axis (as discussed in the text). In this model, extensional structures in the Limassol Forest Complex result from post-volcanic reactivation of the STTFZ during the early stages of microplate rotation, rather than the development of synspreading oceanic core complexes. RTI, ridge-transform intersection; STTFZ, South Troodos Transform Fault Zone.

(Fig. 8a) share a common tilt-corrected inclination with declinations strung out along a partial small circle through this inclination. The mean direction of $D=274^\circ$, $I=34^\circ$ is indistinguishable from that commonly reported for non-transform tectonized parts of the Troodos ophiolite ($D=273^\circ$, $I=38^\circ$ (this paper); $D=276^\circ$, $I=32^\circ$ (Vine & Moores 1969); or $D=274^\circ$, $I=36^\circ$ (Clube & Robertson 1986)), and indicates a mean anticlockwise rotation of 73° when compared with an expected direction derived from the apparent polar wander path for Africa (Besse & Courtillot 2002). The distribution of vectors is comparable with that observed in the Solea area

of Troodos (stereonet 3, Fig. 4). The spread of declinations may result from relatively minor vertical-axis rotations during crustal accretion and/or the cumulative effects of minor tilting or rotation during phases of post-emplacement faulting (Inwood 2005). Finally, a contribution to the spread of declinations from transform-tectonism cannot be excluded (although cross-cutting units, characteristic of such deformation within the STTFZ in Cyprus, were not observed in the field).

Data for the post-emplacement sedimentary cover of the Hatay ophiolite, reported by Kissel *et al.* (2003) and Inwood (2005), include sites of

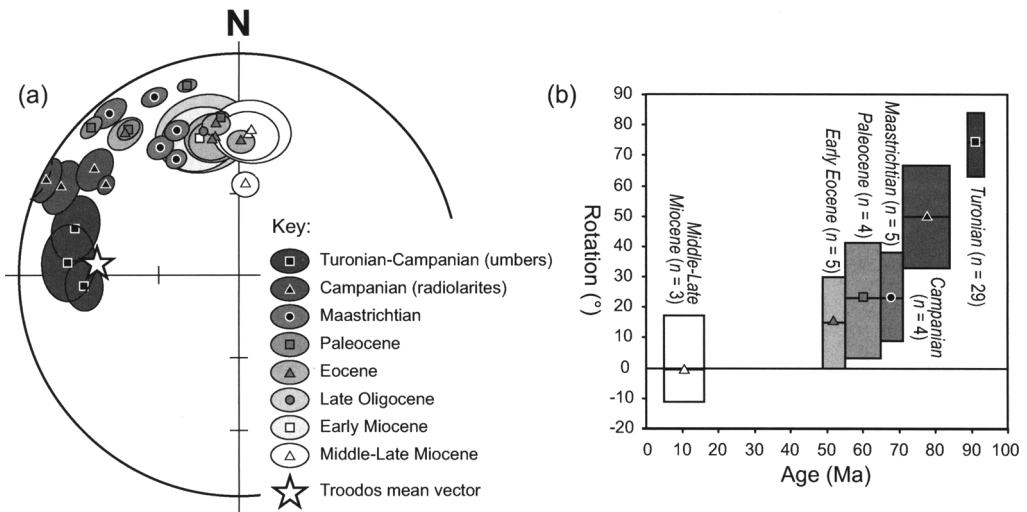


Fig. 7. (a) Lower hemisphere stereographic projection of tilt-corrected site-level palaeomagnetic data obtained from the *in situ* sedimentary cover of the Troodos ophiolite. Data from Campanian radiolarites and Maastrichtian and Paleocene carbonates include both normal and reversely magnetized sites, with the latter inverted to the lower hemisphere in this plot. Eocene to Miocene data are all of normal polarity. Data sources: Clube (1985); Abrahamsen & Schönharting (1987); Morris *et al.* (1990). (b) Variation of rotation angle through time derived by comparing mean data for stratigraphic intervals with three or more palaeomagnetic site mean directions with expected directions calculated from the African apparent polar wander path of Besse & Courtillot (2002). These data clearly demonstrate the progressive anticlockwise rotation of the underlying ophiolite during the Late Cretaceous and Palaeogene.

both normal and reverse polarity (Fig. 8c) that pass reversal and tilt tests (Inwood 2005) suggesting that pre-deformational remanences are preserved. These data, including those for the oldest (Palaeocene) sequences, indicate only minor anticlockwise rotation (Fig. 8c). This contrasts with the large anticlockwise rotations observed in the underlying ophiolite, and confirms that most (*c.* 62°) of the rotation of the ophiolite occurred in an intra-oceanic setting and/or during tectonic emplacement in the Maastrichtian.

Results from the highly dismembered Baër–Bassit ophiolite (Morris *et al.* 2002), representing the leading edge of the emplaced ophiolite sheet (Robertson 2002), indicate extreme relative rotations between sampled localities (Fig. 8b), with rotations varying on a kilometre scale. The eastern, Baër massif is dominated by mantle sequence rocks and data are available from only one locality, in the sheeted dyke complex. This is dominated by tilting with only moderate components of anticlockwise rotation about a vertical axis (NW directions, Fig. 8b). Within the Bassit massif, anticlockwise net tectonic rotations increase from *c.* 90° in the north (westerly directions, Fig. 8b) to in excess of 200° in the south (SE

directions, Fig. 8b), and rotation axes determined using the net tectonic rotation approach are steeply plunging to subvertical. The possibility that the largest rotations occurred in a clockwise sense cannot be excluded, but anticlockwise solutions were preferred by Morris *et al.* (2002), as this results in a systematic pattern of rotations across the Bassit massif. Data from another eight sites at a fifth locality (in the Bassit massif) where subvertical remanence directions resulted from rotation around shallow- to moderately plunging dyke-normal axes are not shown in Figure 8b but were discussed in detail by Morris & Anderson (2002).

The increase in rotation angles southwards through the Bassit sheet is most readily explained by increasing proximity to a major strike-slip fault zone that traverses the southern half of the ophiolite, representing the expression of the present-day plate boundary system in this region (Al-Riyami *et al.* 2000). Palaeomagnetic data for the Palaeogene post-emplacement sedimentary cover sequences within and adjacent to this fault zone (Morris *et al.* 2006) reveal widely different rotation angles and senses in different fault blocks (Fig. 8d), confirming that significant

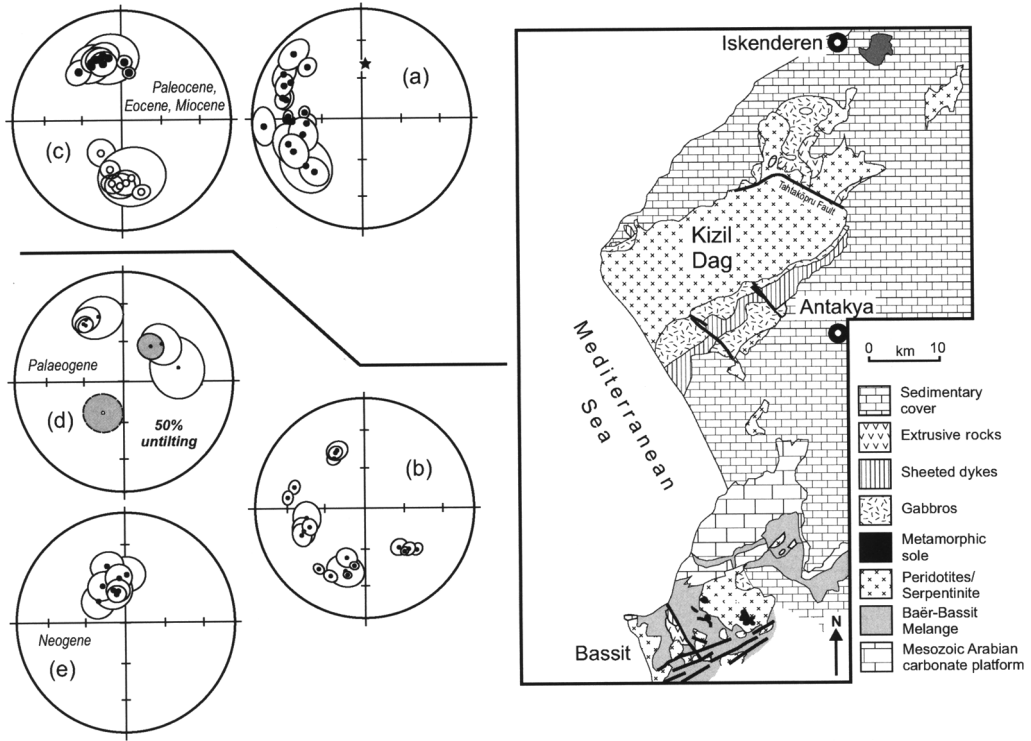


Fig. 8. Outline geological map of the Hatay (Kızıl Dağ) and Baer–Bassit ophiolites, showing the distribution of lithologies and major structures. Lower hemisphere stereographic projections of tilt-corrected site-level palaeomagnetic data from: (a) and (b) the Hatay and Baer–Bassit ophiolites, respectively (data from Inwood *et al.* (2003), Inwood (2005) and Morris *et al.* (2003)); in (b), reversed polarity data (14 out of 19 sites) have been inverted to allow ready comparison with (a); (c) the post-emplacment sedimentary cover of the Hatay ophiolite (data from Inwood *et al.* (2003), Kissel *et al.* (2003) and Inwood (2005)); (d) and (e) the Palaeogene and Neogene post-emplacment sedimentary cover of the Baer–Bassit ophiolite (data from Morris *et al.* (2006)). An inclination-only tilt test performed on data from the Palaeogene sequences indicates maximum clustering of inclinations at 50% untilting. Black star in stereographic projection (a) indicates the direction of the present-day geomagnetic field.

rotational deformation accompanied the development of these neotectonic structures. The weakly magnetized Paleocene carbonates are gently folded, and an inclination-only tilt test suggests that remanences were acquired during folding. Data from Neogene sequences (Fig. 8e) exposed to the NE are inherently more difficult to interpret, as the distinction between northerly directed viscous overprints and unrotated Neogene magnetizations is impossible in these subhorizontal sequences.

Overall, the data obtained to date from the Hatay and Baer–Bassit ophiolites and their post-emplacment sedimentary cover sequences are most consistent with large-scale, bulk rotation of the ophiolitic sheet, either in an intraoceanic setting or during emplacement. The northern, Hatay, part of the emplaced sheet experienced

only moderate post-emplacment tectonic rotation (Inwood *et al.* 2003; Kissel *et al.* 2003; Inwood 2005), in contrast to the more highly deformed southern leading edge in Baer–Bassit, where subsequent amplification of the amount of rotation resulted from neotectonic modification during development of the modern plate boundary configuration.

Discussion of regional implications

Palaeogeographical implications

Palaeolatitudes of *c.* 21–24°N derived from inclination-only statistical analysis of the ophiolite palaeomagnetic database are consistent with a Late Cretaceous position for the Neotethyan

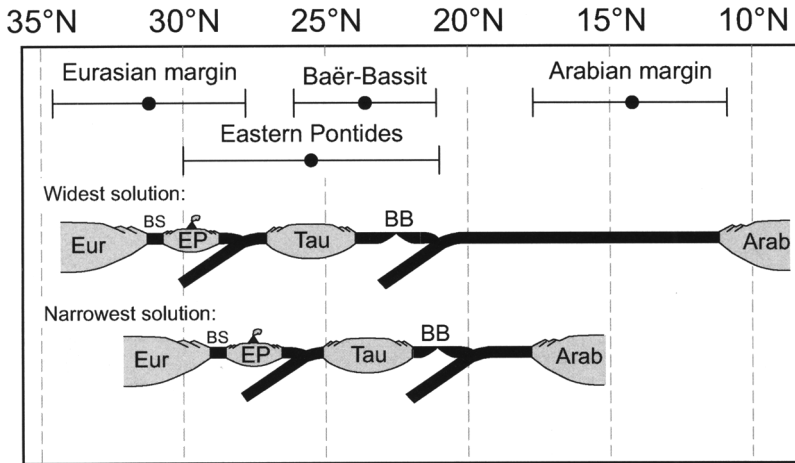


Fig. 9. End-member tectonic cross-sections along a north-south transect (from the Arabian margin, through the Baër-Bassit spreading axis and eastern Pontides to the Eurasian margin) that satisfy the palaeomagnetic constraints on the palaeolatitude of the Eurasian and Arabian continental margins, the Baër-Bassit spreading axis and the eastern Pontide volcanic arc. Upper and lower sections respectively illustrate the solution that yields the widest and narrowest south Neotethyan ocean (Eur, Eurasian margin; EP, eastern Pontides; Tau, Taurides; BB, Baër-Bassit segment of the Neotethyan spreading axis; BS, Black Sea; Arab, Arabian margin).

spreading axis between the Arabian and Eurasian margins (Morris 2003). These data, together with a well-defined palaeolatitude of *c.* 26°N for the eastern Pontides (Channell *et al.* 1996) and palaeolatitudes of the Arabian and Eurasian margins derived from appropriate apparent polar wander paths (e.g. Besse & Courtillot 1991, 2002), provide constraints on potential tectonic reconstructions of the eastern Mediterranean Tethys. Two model reconstructions that involve genesis of the ophiolites in a southerly basin (e.g. Robertson & Dixon 1984; Robertson *et al.* 1991; Robertson 1998) and that satisfy the palaeolatitude data are shown in Figure 9, using the data from the Baër-Bassit ophiolite as an example. The solution giving the widest southerly Neotethys is obtained by placing the Arabian continental margin at its southernmost limit. This produces a 1000 km wide Neotethyan strand to the south of the subduction zone associated with the Baër-Bassit spreading axis. Major arc magmatism would result from subduction of this lithosphere during continued plate convergence. Arc-related products are sparse, although in SE Turkey the Başkil arc (Aktaş & Robertson 1984; Yazgan & Chessex 1991; Rızaoğlu *et al.* 2006) 200 km to the NE of Baër-Bassit provides evidence for Andean-type arc magmatism along the southern Tauride margin during the late Cretaceous (Robertson 2002). The problem of

the scarcity of arc products in the wider region is potentially avoided in the 'narrowest solution' (and near intermediate solutions), which implies an oceanic tract *c.* 300 km wide to the south of the subduction zone (Fig. 9). In both solutions, the northern Neotethyan strand was essentially consumed by subduction beneath the Pontides. This is consistent with geological evidence suggesting that northward subduction beneath the Pontides was active from the Late Mesozoic onwards (Ustaömer & Robertson 1993, 1994), providing sufficient time for the northern Neotethys to have been subducted by the Late Cretaceous. The 'narrowest solution' also implies a restricted width of the southern Neotethyan strand following ophiolite emplacement (Fig. 9). In this respect, intermediate solutions that place the Eurasian margin further to the north (thereby permitting a wider oceanic tract between the Taurides and the Neotethyan spreading axis) are more consistent with geological evidence indicating that a southern Tethyan basin persisted to the north of the Arabian margin well into the Tertiary after partial basin closure associated with ophiolite emplacement (Aktaş & Robertson 1984; Yılmaz 1993; Robertson *et al.* 1996).

Alternative models (e.g. Ricou 1971; Ricou *et al.* 1979, 1984; Dercourt *et al.* 1986, 1993) involve formation of the ophiolites in a northerly Neotethyan basin by spreading at a 'normal'

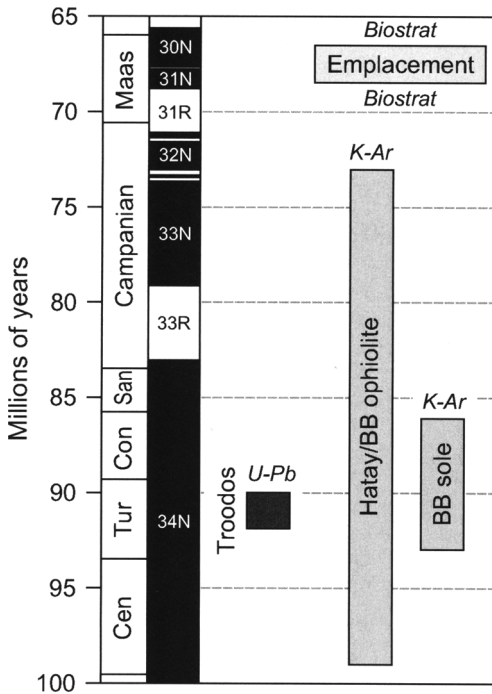


Fig. 10. Summary of available radiometric age constraints for the Troodos, Hatay and Baër-Bassit ophiolites and the Baër-Bassit metamorphic sole (together with biostratigraphic constraints on the timing of emplacement of the Hatay and Baër-Bassit thrust sheets), in relation to the geomagnetic polarity time scale for the Late Cretaceous (Cande & Kent 1995). Sources are referred to in the text.

oceanic ridge, with subsequent, Late Cretaceous large-scale thrusting (hundreds of kilometres) to the south of emplaced ophiolites over micro-continental fragments to reach their present positions. These cannot be discounted on a purely palaeomagnetic basis in the absence of reliable data from the eastern Taurides (Morris 2003). Such models are not supported, however, by a number of key geological observations (described in detail elsewhere, e.g. Robertson *et al.* 1996), including the presence of an essentially unbroken Campanian to Lower Tertiary sedimentary sequence overlying the Troodos ophiolite, and also the continuous upper Palaeozoic to Neogene sedimentary sequences exposed in parts of the Tauride Mountains (notably in the Isparta Angle, SW Turkey; e.g. Robertson *et al.* 2003).

Age implications

Available radiometric ages for the Troodos, Hatay and Baër-Bassit ophiolites, and for the Baër-Bassit metamorphic sole, are shown in Figure 10, in relation to the geomagnetic polarity time scale for the Late Cretaceous and the biostratigraphical constraints on the timing of tectonic emplacement of Hatay and Baër-Bassit ophiolites. Pre-deformational characteristic remanences in the Troodos ophiolite are ubiquitously of normal polarity, consistent with the U-Pb age of 90–92 Ma (Mukasa & Ludden 1987) indicating formation during the Cretaceous Long Normal Period (chron C34N; Fig. 10). Reverse polarity overprints are observed in the Troodos Sheeted Dyke Complex (Gee *et al.* 1993), but are not ubiquitous. Where they are present, normal polarity characteristic magnetizations are also isolated. These overprints were demonstrably acquired prior to tilting of the dykes (Gee *et al.* 1993), and are attributed to low-temperature alteration during reversed polarity chron C33R (early Campanian; Gee *et al.* 1993). Polarities of characteristic magnetizations in the Hatay ophiolite are dominantly normal, in contrast to dominantly reversed polarities observed in the Baër-Bassit ophiolite. This suggests acquisition of pre-deformational remanences during at least two polarity chrons and hence significant variations in age within the emplaced ophiolite sheet. Radiometric ages for the Hatay and Baër-Bassit ophiolites are at present too poorly constrained to resolve these age differences, with dykes yielding K–Ar ages in the range 73–99 Ma (Delaloye & Wagner 1984) spanning polarity chrons C33N, C33R and part of C34N (Fig. 10). Whether reversed polarity remanences in Baër-Bassit could be acquired during chron C33R, however, depends critically on the mode of formation of the Baër-Bassit metamorphic sole, which has a K–Ar age of 86–93 Ma (Thuizat *et al.* 1981; Delaloye & Wagner 1984), i.e. within chron C34N (Fig. 10). Assuming that this age is reliable, alternative interpretations are as follows: (1) The metamorphic sole may have formed during initial detachment of the oceanic crust near the Neotethyan spreading axis (Whitechurch 1977; Coleman 1981; Boudier *et al.* 1982), and hence represents the latest age of formation of the ophiolite. The observed reversed polarities would then require a substantial (possibly > 30 Ma) age difference between Baër-Bassit and Troodos, with the magnetization of the former being acquired during the Early Cretaceous or within a poorly documented reverse polarity event within chron C34N (Hailwood 1989). (2) The sole may have formed during the initiation of subduction,

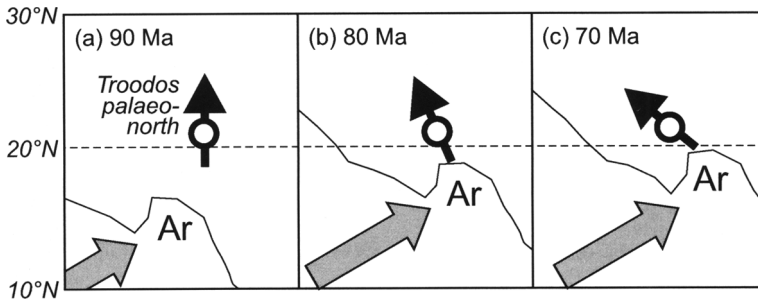


Fig. 11. Schematic illustration of the motion of the Arabian continental margin (Ar) through the Late Cretaceous. Palaeolatitudinal constraints are derived from the African apparent polar wander path of Besse & Courtillot (2002), after correcting for the effects of Red Sea opening (using the Euler pole of Savostin *et al.* (1986)), Large grey arrow indicates the relative motion vector of Africa–Arabia relative to a fixed Eurasia (from Dewey *et al.* 1989). Thick black arrows illustrate the amount of palaeorotation of the Troodos microplate between time frames. The palaeolatitude of the microplate is accurately constrained only in (a), and cannot be determined reliably for subsequent time periods because of the potential effects of sedimentary compaction on palaeomagnetic inclination.

before SSZ spreading of the Baër–Bassit crust (e.g. Casey & Dewey 1984). This would reconcile the available radiometric and magnetic polarity age constraints, and would require SSZ spreading to have continued over a *c.* 10 Ma period between the initiation of subduction in the Turonian and the start of microplate rotation in the Campanian. More reliable, higher resolution radiometric dates for the Hatay and Baër–Bassit ophiolite and metamorphic sole are clearly required to resolve this debate.

Implications for intra-oceanic microplate rotation

Palaeomagnetic data from the Troodos ophiolite and its sedimentary cover are near universally interpreted in terms of intra-oceanic rotation of a ‘Troodos microplate’. Data from the sedimentary cover of the Troodos ophiolite indicate that a large component (50–60°; Fig. 7) of intra-oceanic anticlockwise rotation had occurred by the Maastrichtian, i.e. by the time of emplacement of the Hatay and Baër–Bassit ophiolite sheet onto the Arabian margin. This rotation angle is comparable with the mean rotation observed in the Hatay ophiolite (Inwood *et al.* 2003; Inwood 2005; Fig. 8a), after removing the post-emplacment rotation recorded by its post-emplacment sedimentary cover (Inwood *et al.* 2003; Kissel *et al.* 2003; Inwood 2005; Fig. 8c), and also represents a large component of the more extreme rotations observed in Baër–Bassit.

Hence, these data are most readily explained by coherent rotation of a Neotethyan oceanic microplate that was more areally extensive than inferred from the Troodos data alone (Inwood *et al.* 2003; Inwood 2005).

The mechanism of microplate rotation is difficult to identify with certainty, particularly at the level of identifying accommodating (bounding) structures. A common feature of existing models (e.g. Clube *et al.* 1985; Clube & Robertson 1986; Robertson 1990) is that rotation is related to oblique convergence across the southern Neotethyan subduction zone, resulting from NE motion of Arabia relative to Eurasia throughout the Late Cretaceous and Early Tertiary (Dewey *et al.* 1989). After correcting for the effects of opening of the Red Sea, the African apparent polar wander path (Besse & Courtillot 2002) places the northernmost Arabian continental margin at *c.* 16°N during the Turonian, several 100 km to the south of the southern Neotethys spreading axis at 21–24°N (Fig. 11a). Subsequent motion of Arabia to the NE (Fig. 11b and c) may then have generated a sinistral sense of motion across the subduction zone separating the SSZ oceanic crust from Arabia. Within this overall plate-scale framework, impingement of the Arabian continental margin with the subduction trench has been invoked as a potentially major contributor to the initiation and progression of microplate rotation (e.g. Clube & Robertson 1986; Robertson 1990). Although further higher resolution palaeomagnetic and

biostratigraphic data from the Troodos sedimentary cover are required to reduce uncertainties in the progressive history of microplate rotation (Fig. 7b), rotation was clearly under way for at least 10–15 Ma (and possibly up to 20 Ma) prior to ophiolite emplacement in the Maastrichtian. The timing of approach of the Arabian continental margin to the trench cannot be accurately determined, but if this impingement acted as a trigger for initiation of rotation then the palaeomagnetic data suggest that rotation progressed for a substantial period of time before eventual emplacement of part of the rotated unit onto the continental margin. Finally, we note that anticlockwise intra-oceanic rotation of the eastern Mediterranean ophiolites considered here contrasts with the clockwise rotation of the Oman (Semail) ophiolite further to the east (e.g. Weiler 2000). This suggests that rotation in both cases was controlled by plate-scale geometry of the Arabian margin during regional convergence. Palaeomagnetic data are now required from the emplaced ophiolites to the east of Hatay and Baër–Bassit (i.e. the Kermanshah and Neyriz ophiolites of Iran; Fig. 1) to further constrain the pattern and hence the mechanism of Neotethyan intra-oceanic rotations.

Conclusions

- (1) The Late Cretaceous Troodos, Hatay and Baër–Bassit ophiolites of the eastern Mediterranean Tethyan orogenic belt preserve remanent magnetizations of pre-formational age. Palaeomagnetic data from these units, in conjunction with data from the overlying *in situ* (Troodos) and post-emplacement (Hatay and Baër–Bassit) sedimentary cover sequences, therefore provide insights into the styles and timing of rotational deformation that have affected the Neotethyan oceanic crust.
- (2) Within the Troodos ophiolite, localized rotations are demonstrably related to processes operating during construction of oceanic crust at a Neotethyan spreading axis in close proximity to an oceanic transform fault zone. Rotations around (sub)horizontal, dyke-parallel axes are associated with crustal extension during sea-floor spreading. Rotations around (sub)vertical axes dominate in areas adjacent to the South Troodos Transform Fault Zone, reflecting rotation of kilometre-scale fault blocks in response to dextral shearing within weak crust at the ridge–transform intersection.
- (3) The tectonically emplaced Hatay and Baër–Bassit ophiolites record large, and locally extreme, anticlockwise rotations. Within the Baër–Bassit ophiolite, the magnitude of observed rotations increases generally southwards. Analysis of the overlying post-emplacement sedimentary successions suggests that this amplification of rotation reflects the development of a strike-slip fault system related to the initiation of the present-day plate configuration.
- (4) The Hatay ophiolite and the most northerly locality in the Baër–Bassit ophiolite share a similar anticlockwise rotation. After removing the post-emplacement component of rotation documented in the Hatay post-emplacement sedimentary cover, this rotation angle is directly comparable with the pre-Maastrichtian rotation of the ‘Troodos microplate’. At the regional scale, therefore, these data are best explained by intra-oceanic anticlockwise rotation of a more areally extensive oceanic microplate than has been considered previously (Inwood *et al.* 2003; Inwood 2005).

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