Kinematics of a twisted core complex: Oblique axis rotation in an extended terrane (Betic Cordillera, southern Spain)

E. Platzman and J. P. Platt

Department of Earth Sciences, University College London, London, UK

Received 3 June 2003; revised 22 September 2004; accepted 27 October 2004; published 31 December 2004.

[1] The Sierra de las Estancias is a metamorphic core complex that developed during the late Oligocene to early Miocene extensional collapse of the Betic Cordillera. Structural and paleomagnetic analysis shows that the northern half of the complex has been strongly modified by rotation about an inclined axis, requiring reassessment of the kinematics of the extensional phase of deformation. The extensional tectonic event produced two major detachment faults, associated mylonitic foliation and lineation, and pervasive sets of shear bands and brittle normal faults with a top-to-NE shear sense. An older foliation was largely transposed and reoriented during this event. The regional foliation now defines a broad antiform with a steep north dipping limb; and the trend of shear-related lineations swings from NNE to ENE from the southern gently dipping limb into the north dipping limb. The remanent magnetization in a suite of near-vertical early Miocene mafic dikes intruded into the north dipping limb has a declination of 243° and an inclination of −27°. Assuming that the dikes were originally vertical, a rotation of approximately 50° about an inclined SSW plunging axis preserves the near-vertical orientation of the dikes and brings the remanence into agreement with the expected orientation for an early Miocene age. Correction for this rotation brings the foliation and lineation in the surrounding schists into orientations subparallel to those on the present southern limb of the antiform, and the dikes into a vertical E-W orientation. The corrected orientation of the shear-related lineation (NNE), normal faults, and dikes suggests that the original direction of extension during the late orogenic extensional event in the Internal Betic Cordillera may therefore have been around NNE/SSW, rather than E/W as currently accepted. The observed net tectonic rotation can be decomposed into a series of geologically plausible rotations involving domino-style rotation due to slip on the late brittle normal faults, tilting about the regional fold axis related to thrust-ramping onto the Iberian margin during Miocene collision, and a 30° clockwise rotation about a vertical axis related to oblique convergence with the Iberian margin.


1. Introduction

[2] Domal uplifts of metamorphic rocks bounded by regionally gently dipping extensional shear zones or brittle normal faults (referred to as detachments) are common in the hinterland regions of collisional orogenic belts [e.g., Crittenden et al., 1980; Wernicke, 1981; Lister et al., 1984; Davies and Warren, 1988]. The origin of these structures, known as metamorphic core complexes, is still controversial, and the problem is compounded by the fact that they commonly form at a late stage in contractional orogenic settings. Two important structural questions bear on their origin. One is the degree to which the dip of the bounding detachment has been modified by later folding or tilting since its formation [Buck, 1988; Wernicke and Axen, 1988]. The other is whether the sense and direction of motion on the detachment is compatible with relative plate motions in the region, or with gradients in gravitational potential energy that may provide a driving mechanism for extension [Walcott and White, 1998; Jones et al., 1998]. The Sierra de las Estancias in the Betic Cordillera of southern Spain is a metamorphic core complex that developed during the late Oligocene to early Miocene phase of late orogenic extension in the Betic Cordillera of southern Spain. In this study we present an integrated paleomagnetic and structural analysis to unravel the history of rotation, and hence determine the original orientation of the detachments and deformational fabrics within the core complex.

[3] The Betic Cordillera (Figure 1) lies at the western end of the Alpine orogenic system in the Mediterranean. The Internal Zones of the Betics, together with the Internal Rif in Morocco, are part of a more extensive terrane known as the Alboran Domain, which formed by Early Tertiary collisional orogeny involving microcontinental blocks within the Neotethys basin, and now underlies much of...
the Alboran Sea [Comas et al., 1999]. During the late Oligocene to early Miocene the Alboran Domain underwent late orogenic extension, exhuming metamorphic rocks beneath large-scale extensional detachments [Platt and Vissers, 1989]. Extension and westward motion of the Alboran Domain between the converging margins of Africa and Iberia created the External Betic-Rif arc, a tightly curved Miocene thin-skinned thrust belt comprising the deformed Mesozoic and Tertiary sediments of the African and Iberian margins, together with the intervening basins [Platt et al., 2003a].

The Internal Betics are largely made up of Paleozoic and Mesozoic rocks that were penetratively deformed and metamorphosed prior to the middle Miocene. Three major subhorizontal tectonic complexes are generally recognized, known (from bottom to top) as the Nevado-Filabride, Alpujárride, and Malagüide Complexes. These were originally regarded as nappe complexes derived from differing paleogeographical domains [e.g., Egeler and Simon, 1969], but the boundaries between them are now thought to be major low-angle normal sense faults or shear zones that have reactivated or cut earlier thrust contacts [Platt, 1986; García-Dueñas et al., 1992; Lonergan and Platt, 1995]. The detachment between the Nevada-Filabride and Alpujárride Complexes can be traced for 230 km from east to west [Platt et al., 1984], and is folded into a series of major antiforms with amplitudes of up to 8 km [Martínez-Martínez et al., 2002]. The direction and sense of shear inferred from mylonitic rocks below the detachment swing from north through west to SW in a broad arc from east to west along the detachment [Jabaloy et al., 1993; Vissers et al., 1995].

The detachment between the Alpujárride and Malagüide Complexes is less continuously exposed, and may comprise more than one surface. The sense and direction of shear is generally NE to ENE [Argles et al., 1999; Lonergan and Platt, 1995], but northerly senses of shear have also been reported from low-angle normal faults within the Alpujárride Complex [Crespo-Blanc et al., 1994].

Paleomagnetic work documenting vertical axis rotations in the Betic-Rif arc has mainly focused on the unmetamorphosed and structurally simpler External thrust belt [Osete et al., 1988; Platzman, 1992; Platzman and Lowrie, 1992; Allerton et al., 1993; Platt et al., 1995]. These studies showed that there have been large but variable clockwise rotations over the entire External Betics, resulting primarily from the oblique dextral convergence between the Alboran Domain and the Iberian margin during Miocene thrusting [Platt et al., 2003a]. These results clearly imply

Figure 1. Tectonic map of the eastern half of the Betic Cordilleras. Inset shows regional setting with box identifying location.
the possibility of comparable rotations in the Internal Zones of the orogen, with implications for the interpretation of structural data. The Internal Zones have been less extensively studied, however, because of the widespread ductile deformation, metamorphism, structural complexity, and the scarcity of rocks with magnetic remanences suitable for paleomagnetic analysis. Initial results from the Ronda peridotite massif in the western Betics suggest that these rocks may have undergone about 45° of clockwise rotation [Feinberg et al., 1996], comparable in sense and magnitude to those found in the External Betics. Recently, two studies [Platzman et al., 2000; Calvo et al., 2001] focusing on a suite of earliest Miocene mafic dikes that intrude the Malagnigue and Alpujarride units in the Málaga area, confirmed the clockwise sense but document a much greater magnitude of vertical axis rotation (90°–134°). Work on unmetamorphosed Mesozoic and Tertiary rocks of the Malagnigue Complex much further east, in the Sierra Espuña (Figure 1), suggests progressive clockwise rotation of about 180° during the late Oligocene to early Miocene [Allerton et al., 1993]. Data from middle to late Miocene volcanic rocks in the Cabo de Gata region (Figure 1) show evidence of both clockwise and anticlockwise rotation [Calvo et al., 1994], possibly associated with late Miocene to Recent strike-slip faults in the area.

[6] A suite of mafic dikes in the Sierra de las Estancias, similar to and probably of the same age as the earliest Miocene suite in the Málaga area, offers the possibility of constraining both vertical and horizontal axis rotations in a core complex involving Alpujarride rocks separated from the overlying Malagnigue complex by a fault that has been interpreted as a tilted detachment [Lonergan and Platt, 1995]. The results shed new light on the directions of tectonic transport during the late orogenic extensional event, and the way extensional structures were modified during convergence between the Alboran Domain and the Iberian margin.

2. Geological Setting

[7] The Sierra de las Estancias is an E-W trending mountain range lying along the boundary between the
Internal and External Zones (IEZB) in the eastern Betic Cordillera (Figure 1). The range forms a broad gently SW plunging antiform in rocks of the Alpujárride Complex, with rocks of the Malaguide Complex exposed along its steeply dipping northern margin (Figure 2). The Malaguide Complex comprises largely unmetamorphosed rocks of Paleozoic to Early Miocene age, with a complicated internal pattern of thrust imbrication [Lonergan et al., 1994]. The underlying Alpujárride Complex is made up of graphic phyllites of probable Paleozoic age, predominantly light-colored phyllites and quartzites of probable Permo-Triassic age, and Triassic carbonate rocks, which were all affected by Alpine metamorphism. The two complexes are separated by a steeply north dipping zone of calc-mylonite and fault gouge, 20–30 m thick. It is shown in Figures 2 and 3 as the Malaguide-Alpujárride Detachment (MAD).

Both Malaguide and Alpujárride rocks in the north of the Sierra de las Estancias are cut by a swarm of mafic dikes. The dike rocks were originally fairly coarse-grained (1 mm) olivine-clinopyroxene-hornblende-plagioclase rocks, with a subophitic texture and distinct chilled margins. The mafic minerals have been largely replaced by actinolite, chlorite, and sphene; and the plagioclase shows a lesser degree of alteration to white mica, epidote, and carbonate minerals. The rocks have no deformational fabric, and in the field appear to be largely undeformed. The alteration is therefore likely to be related to their postemplacement cooling history in a low-grade metamorphic environment. The dikes trend NW-SE, and are statistically close to vertical, although individual dikes have dips as low as 60°. They cut all the fabrics in the surrounding rocks, including late stage shear bands related to the Malaguide-Alpujárride Detachment. They are, however, locally affected by brittle faulting.

The age of the dikes in relation to the tectonic evolution of the core complex in the Sierra de las Estancias is crucially important to the interpretation of the paleomagnetic data. The alteration of the dikes precludes successful radiometric dating, but they are petrographically and geochemically similar to the swarm of tholeiitic dikes in the Málaga area. The latter also proved difficult to date precisely, for the same reason, but the best available Ar-Ar age is 23.0 ± 2 Ma (earliest Miocene) [Platzman et al., 2000]. Geochemical data suggest that the melts were produced by shallow decompressional melting of asthenospheric mantle with varying degrees of crustal contamination [Turner et al., 1999], and they probably represent melts produced during the late orogenic extensional event that affected the whole of the Alboran Domain. In both the Málaga region and the Sierra de las Estancias the relationships of the dikes to the country rocks suggests that their emplacement postdates the ductile phase of extensional deformation. We have not found any dikes cutting the Malaguide-Alpujárride Detachment, but they occur in the structurally overlying Malaguide Complex, so their absence in the mylonite zone along the detachment is probably fortuitous. In conclusion, the dikes are likely to have been emplaced in the final stages of extensional deformation and core complex formation, and are therefore ideal for determining the postextensional history of tilting and rotation of the core complex.

3. Structure of the Alpujárride Complex in the Sierra de las Estancias

The Alpujárride Complex is bounded above and to the north by the Malaguide Complex, from which it is separated by the Malaguide-Alpujárride Detachment; evidence from the Sierra de las Filabres to the south suggests that it is underlain by the Nevado-Filabride Complex. The total present structural thickness of the complex in this area is about 12 km [Vissers et al., 1995]. The Malaguide-Alpujárride Detachment in the north is now nearly vertical, and stretching lineations and senses of shear indicators in the calc-mylonites indicate subhorizontal strike-parallel shear with a right-lateral sense. Regional structural evidence suggests the detachment was originally gently dipping, however [Lonergan and Platt, 1995], and after correction for tilting about strike, the sense is top-ENE.
[11] The stratigraphic sequence in the Alpujárride Complex has been largely disrupted by intense folding, thrusting, and later extensional faulting, so that the present sequence of rock types does not have any reliable stratigraphic significance. Younging directions obtained from cross-bedding in Permo-Triassic quartzites in two separate tectonic slices indicate that the sequences are at least locally inverted, and folds are downward facing (Figures 2 and 3). These structures are locally truncated by the Maláguide-Alpujárride Detachment (Figure 3).

[12] In the northern Sierra de las Estancias the rocks of the Alpujárride Complex have a pervasive foliation, with the character of a rough cleavage in the Permo-Triassic quartzites, and a finely penetrative differentiated crenulation cleavage in the phyllites and the graphitic mica schist. This foliation is axial planar to abundant tight medium to large-scale SW plunging folds with a predominantly southerly vergence (Figure 3), which locally refold an earlier differentiated deformational fabric in phyllitic rocks. The main foliation is associated with a metamorphic assemblage that includes muscovite, chlorite, and locally chloritoid, kyanite, or carpholite, characteristic of the early phase of high-pressure metamorphism in the Alpujárride Complex [Azanón and Goffé, 1997]. This assemblage suggests PT conditions close to 400°C at about 7 kbar. The foliation is therefore likely to be related to the main contractional event in the area. Ar-Ar ages around 30 Ma are reported by Platt et al. [2004], who interpret them as the result of slow cooling following a contractional event, of probable early Eocene age.

[13] The main foliation is variably overprinted by a systematically developed set of east to NE directed shear bands, which vary in character from very ductile to discrete planar brittle fractures. These produce a distinctive asymmetric fabric in the schists, defined by asymmetric boudinage in quartz veins and previously folded quartzite layers. The shear bands locally reactivate lithological layering, and are always at a low angle to the foliation; they are commonly associated with an intensification of the foliation and the development of a distinct ENE trending stretching lineation in the foliation plane. In the steep zone adjacent to the Maláguide-Alpujárride Detachment, these shear-bands are themselves steep, and trend E-W; where the foliation is gently dipping they are subhorizontal. East to ESE trending faults with displacements of up to several hundred meters are common, and are likely to be related to the shear bands. The shear bands and associated structures intensify northward toward the Maláguide-Alpujárride Detachment, and appear to be associated with the mylonites along the boundary. Ductile deformation associated with this phase of deformation is everywhere quite strong, however, and the stretching lineation can be recognized in quartzitic layers throughout the area. This suite of structures is likely to be related to the late Oligocene to early Miocene extensional tectonic event (see below).

[14] The main foliation is also locally overprinted by north vergent folds and crenulations with flat-lying axial planes. In places these folds postdate the shear bands; elsewhere they appear to be associated with them, and they may reflect regions where the foliation became locally rotated into the shortening field during the extensional tectonic event.

[15] Along the northern flank of the carbonate ridge in the center of the Sierra de las Estancias (Figure 2) there is an abrupt transition downward from midgreenschist facies chloritoid-bearing phyllites to upper greenschist to amphibolite facies marbles and schists with garnet, staurolite, andalusite, and locally cordierite. The contact dips steeply north, subparallel to the local orientation of the foliation. Calc-schists below the contact show a strong platy foliation, well-developed gently west plunging stretching lineation, and spectacular asymmetric mica-fish and foliation boudinage indicating top-to-ENE sense of shear. Folds in quartzites in the immediate footwall plunge steeply and are downward (southward) facing, away from the contact, reminiscent of the relationships beneath the Maláguide-Alpujárride Detachment further north. The inverted limb of a macroscopic south closing fold in the graphitic mica schists of the hanging wall is truncated against the contact (Figure 3). The stratigraphic sequence is duplicated across this ductile shear zone, suggesting the former presence of a thrust, but in view of the downward increase in metamorphic grade across it, we interpret it in its present state as an another major extensional tectonic boundary (the Estancias Detachment), lying within the Alpujárride Complex, and separating low from medium grade metamorphic sequences.

[16] The tectonic unit beneath the Estancias Detachment is mainly exposed along the crest and southern slopes of the range. The schists in this unit have a strong foliation and symmetamorphic stretching lineation associated with NE directed shear-bands. The foliation is axial planar to abundant mesoscopic isoclinal folds in quartzite layers, and in thin-section has the appearance of a strongly transposed crenulation cleavage. Metamorphic garnet predates the foliation; staurolite grew during its formation. The shear-bands vary from fully ductile to fully brittle structures with the same sense and direction of slip. Ductile shear bands are commonly small-scale low-angle structures: andalusite, which postdates the main foliation, locally grew synchronously with the ductile shear bands. Brittle shear bands are associated with abundant low-angle brittle normal faults with a predominant north to NE sense of slip.

[17] Looking at the Sierra de las Estancias as a whole, the trend of both the ductile stretching lineation and the slip lineations associated with the brittle normal faults swings from NNE along its southern margin to ENE in the northern half of the range, north of the antiformal crest (Figures 2 and 4a, and Table 2). The reason for this change in orientation and the implications for transport directions during formation of the core complex will be discussed together with the paleomagnetic data in the sections that follow.

[18] Several lines of evidence suggest that the east to NE directed shear bands and associated ductile deformation throughout the Sierra de las Estancias are related to the late Oligocene to early Miocene extensional tectonic event that affected the whole of the Alborán Domain. (1) The intensity of the deformation increases into both the extensional detach-
ments identified in the area: the Maláguide-Alpujárride Detachment, and the Estancias Detachment further south within the Alpujárride Complex. (2) In the deeper tectonic unit the shear-bands are locally synkinematic with andalusite growth, which is a characteristic low-pressure metamorphic mineral associated with the Miocene decompression and exhumation elsewhere in the Alpujárride Complex [Argles et al., 1999]. (3) The continuous progression from ductile to brittle structures with similar kinematics is characteristic of deformation associated with extensional exhumation and cooling [Argles et al., 1999]. (4) Ar-Ar cooling ages from the deeper unit, and zircon and apatite fission track ages from throughout the Alpujárride of the Sierra de las Estancias, suggest rapid cooling in the period 18–20 Ma [Platt et al., 2005].

[19] In the higher Alpujárride unit of the northern Sierra de las Estancias the main foliation is likely to have been formed during the early Tertiary contractional event. It has been strongly affected by the later extensional deformation, and the low-angle between the foliation and the extensional shear bands suggests that it was either gently dipping at the start of the extensional deformation, or was deformed and rotated into a gentle dip during the extensional deformation. In the lower unit the main foliation has been effectively transposed by the later extensional deformation.

[20] On the scale of the whole of the Sierra de las Estancias the regional foliation defines a broad antiform. In the south the foliation has a very gentle southerly dip; the crest of the antiform lies south of the main watershed, and in the northern half of the range the foliation dips 30°–70° NW, steepening to vertical close to the Maláguide-Alpujárride Detachment. A comparable large-scale asymmetric antiform is present along the entire Internal/External Zone Boundary [e.g., Lonergan, 1993; Platt et al., 2003c; Balanyá et al., 1997], and is likely to be related to the deep-seated NW directed early Miocene thrust along this boundary [Platt et al., 2003a]. This antiform has affected the orientation of folds and lineations in the Alpujárride rocks in the north of the range. Surprisingly, the orientation of the dikes is not obviously affected by the progressive increase in dip of the foliation in the Alpujárride rocks toward the north, which led Lonergan and Platt [1995] to suggest that the dikes postdate the large-scale regional folding. As discussed below, however, the structural and palaeomagnetic data suggest that the dikes have in fact been rotated, but in such a way that their dip was not significantly affected.

4. Paleomagnetic Analysis

4.1. Methods

[21] Samples for magnetic analysis were collected from 10 near vertical dikes in two seasonal river courses (ramblas) along or close to the Alpujárride/Maláguide boundary, Rambla Centenio and Rambla Mata (Figure 2). These two rambles expose a NS transect across the Alpujárride stretching away from the contact. Dikes varied in thickness from 20 cm to 3 m although most were <1 m. Samples were obtained with a portable petrol-powered rock drill. Where
Figure 5
possible samples were drilled both close to the chilled margin and in the center of the dikes to check for magnetic homogeneity. Five to seven cores were drilled from each dike to allow for statistical analysis. The cores were oriented using a Brunton compass and an orienting platform, which includes a sun compass for magnetically strong samples. Standard cylindrical cores of 2.5-cm diameter and 10-cm length were later cut into 2.25-cm length samples.

[22] In the laboratory at University College London the samples were analyzed to isolate the stable characteristic components of remanent magnetization (ChRM). Stepwise thermal and alternating field (AF) demagnetization procedures were used. During the thermal demagnetization procedure each sample was demagnetized with a minimum of 10 steps based on a scheme designed after a detailed pilot demagnetization study. In most cases this involved 100° steps below 300°C, 30° steps over the sulfide blocking temperature interval, 50° steps until 450°C and then 25° steps until the intensity of magnetization fell below the measuring range of the magnetometer (Figure 5). Some samples were demagnetized using a combination of thermal and AF techniques. These samples were initially thermally demagnetized to 330°C, above the Curie temperature of pyrrhotite to thermally define the low and intermediate temperature remanence components. The samples were subsequently AF demagnetized up to a peak value of 100mT to isolate the component of remanence carried by the higher temperature but lower coercivity components of remanent magnetization (usually magnetite). This procedure eliminates complications that often occur because of oxidation and growth of new magnetic phases at high temperatures although it fails to isolate remanence carried by high temperature/high coercivity minerals such as haematite. Natural remanent magnetization (NRM) measurements were made on a JR5A spinner magnetometer. Data obtained from the demagnetization experiments were plotted on Zijderveld vector diagrams. Characteristic components of remanent magnetization were then obtained from these plots using linear regression techniques.

[23] On a set of representative samples, bulk susceptibility and anisotropy of magnetic susceptibility (AMS) was measured. Bulk susceptibility was measured between each thermal demagnetization step to monitor possible changes in magnetic mineralogy that can occur as a result of heating. AMS was measured to establish if the rocks had a magnetic fabric related to deformation or intrusion.

4.2. Natural Remanent Magnetization (NRM)

[24] NRM intensities for the dikes were relatively weak for igneous rocks although consistent with their metamorphic grade and weathering. Values varied from approximately $10^{-1}$–$10^{-4} \text{A/m}$. In all cases the dikes with the weakest intensities cropped out furthest from the Alpujârride/Malâguide boundary along the Rambla Mata. NRM directions were scattered and had both positive and negative inclinations.

[25] Results of thermal and AF demagnetization demonstrate that the remanence in some dikes is unstable. In these dikes either there were no coherent straight line segments on the vector diagrams to perform meaningful regression analysis on or the magnetization of the dike was inhomogeneous with different samples yielding different directions over the same temperature or coercivity intervals. Samples from sites RD7 and RD9 did not carry a stable characteristic remanence.

[26] In the remainder of the dikes the NRM is generally composed of two components of remanent magnetization (Figure 5). The lowest temperature component is usually isolated below 200°C (Figures 5a, 5c, and 5e), although it sometimes persists as an overlapping component until approximately 360°C (Figure 5d). In geographic coordinates this component is often in the direction of the present earth’s magnetic field and is interpreted as a viscous overprint acquired post Miocene.

[27] In the majority of the dikes, the characteristic component of remanent magnetization (ChRM) is isolated in the temperature interval between the maximum blocking temperature of the low temperature component and 575°C (Figures 5a, 5b, and 5d). In these dikes, the ChRM is also isolated in AF demagnetization experiments as the high coercivity component demagnetizing between 20–80 mT (Figure 5c). Total intensity decay curves for these dikes, like the one shown in Figure 5b, often show a pronounced inflection at 330°C and complete unblocking by 575°C. In a small number of dikes the maximum unblocking temperature of the ChRM occurs at 360°C (Figures 5e and 5f). These results together with the coercivity spectrum results obtained from the AF demagnetization experiments suggest that the characteristic component of remanent magnetization is likely to be carried by both pyrrhotite and magnetite. Above 575°C the remanence intensity is generally <1% of the initial NRM indicating almost complete lack of higher blocking temperature minerals such as haematite. This observation is corroborated by AF demagnetization performed in samples previously heated to 330°C, which showed virtually complete demagnetization by 80 mT (Figure 5c). As seen in Figure 5d low intensities on the last few temperature steps close to the magnetite blocking temperature sometimes led to higher than usual measurement errors as we approached the noise level of the magnetometer.

[28] From the sampled population, the ChRM of two dikes displays normal polarity (Figures 5e–5f) and five dikes display reverse polarity (Figures 5 and 6; Table 1) in geographic coordinates. The mean directions of these two groups are statistically antipolar but do not constitute a viable reversal test due to the small number of normal polarity dikes. Dike RD3 was eliminated from further analysis both because the remanence showed evidence of

Figure 5. Typical vector diagrams in geographic coordinates of samples undergoing thermal (°C) and AF (mT) demagnetization. Solid dots indicate horizontal projection; open circles indicate vertical projection.
multiple overlapping components that could not be properly isolated and because the anomalously shallow dip (<68°) of the dike could not be properly corrected for the effects of the late brittle faulting observed in the outcrop. The polarity of the majority of the dikes closest to the mylonite zone exhibit reverse polarity ChRM while those furthest away from the contact show normal polarity (Figure 6). In general, the normal polarity ChRM are less well defined with the bulk of the NRM intensity in many cases, removed by around 360°C (Figures 5e–5f). In contrast, the dikes with reverse polarity ChRM show stable demagnetization behavior with a high temperature linear decrease toward the origin. Inverting the normal polarity remanences into the upper hemisphere for statistical analysis, the ChRM has an average declination of 243° and an inclination of −27° (Table 1).

Results of bulk susceptibility measurements during thermal demagnetization show that susceptibility begins to increase when temperatures exceed 450°C. This indicates that a new magnetic phase is being created during the heating process probably reflecting the transformation of pyrrhotite to magnetite, which occurs above 500°C [Bina and Daly, 1994]. In most cases, however, this does not affect the remanence vector, which continues to decrease in intensity, until it reaches the Curie temperature of magnetite.

To constrain the direction and magnitude of any tectonically imposed magnetic fabric in the dikes, anisotropy of magnetic susceptibility (AMS) was measured in 15 positions on a Kly2 susceptibility bridge. Three samples from each dike were measured. Results showed that in almost all cases the percent anisotropy measured in the samples was less then 1%. The exception was RD1 where two samples showed 12% anisotropy.

### 4.3. Interpretation of Paleomagnetic Results

Both the declination and inclination of the mean remanence observed in the dikes differ from the expected field direction for the early Miocene (declination = 04.5°, inclination = 50°), calculated from the combined observational and synthetic polar wander curves of Besse and Courtillot [1991]. The mean declination lies 62° clockwise of the expected direction, consistent with data from other studies in the Internal Zones, which report a range of 60°–150° of clockwise vertical axis rotation over the entire region. The mean inclination (I = −27°), however,

### Table 1. Remanent Magnetization Parameters

<table>
<thead>
<tr>
<th>Site</th>
<th>N</th>
<th>ChRM (Dec/Inc)</th>
<th>n</th>
<th>α95</th>
<th>k</th>
<th>AMS %Anis</th>
<th>Dyke Strike/Dip, deg</th>
</tr>
</thead>
<tbody>
<tr>
<td>RD1</td>
<td>7</td>
<td>060/39</td>
<td>5</td>
<td>9</td>
<td>68</td>
<td>10</td>
<td>106/89N</td>
</tr>
<tr>
<td>RD2</td>
<td>5</td>
<td>230/−15</td>
<td>5</td>
<td>4</td>
<td>307</td>
<td>&lt;1</td>
<td>110/90</td>
</tr>
<tr>
<td>RD3b</td>
<td>5</td>
<td>241/11</td>
<td>5</td>
<td>9</td>
<td>76</td>
<td>1</td>
<td>102/68N</td>
</tr>
<tr>
<td>RD4</td>
<td>5</td>
<td>244/−18</td>
<td>5</td>
<td>9.5</td>
<td>66</td>
<td>&lt;1</td>
<td>097/83N</td>
</tr>
<tr>
<td>RD5</td>
<td>5</td>
<td>247/−26</td>
<td>5</td>
<td>3</td>
<td>685</td>
<td>1.3</td>
<td>117/84N</td>
</tr>
<tr>
<td>RD6</td>
<td>5</td>
<td>243/−26</td>
<td>4</td>
<td>9</td>
<td>99</td>
<td>&lt;1</td>
<td>082/90</td>
</tr>
<tr>
<td>RD7b</td>
<td>5</td>
<td>243/−26</td>
<td>4</td>
<td>9</td>
<td>99</td>
<td>&lt;1</td>
<td>150/90</td>
</tr>
<tr>
<td>RD8</td>
<td>6</td>
<td>065/34</td>
<td>3</td>
<td>20</td>
<td>38</td>
<td>1</td>
<td>110/90</td>
</tr>
<tr>
<td>RD9b</td>
<td>6</td>
<td>257/−32</td>
<td>5</td>
<td>5</td>
<td>223</td>
<td>&lt;1</td>
<td>142/80S</td>
</tr>
<tr>
<td>RD10</td>
<td>6</td>
<td>243/−27</td>
<td>7</td>
<td>9</td>
<td>57</td>
<td></td>
<td>146/80N</td>
</tr>
<tr>
<td>Mean</td>
<td>7</td>
<td>243/−27</td>
<td>7</td>
<td>9</td>
<td>57</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Definitions are as follows: N, number of samples demagnetized; ChRM (Dec/Inc), declination and inclination of the high temperature or high coercivity component of remanent magnetization in geographic coordinates; n, number of samples used to calculate site mean; α95, Fischer 95% confidence angle; k, Fischer precision parameter; AMS %Anis is percent anisotropy of magnetic susceptibility.*

*Bsites not used in this study (see text).*  
Unstable magnetization.*
is too shallow for the early Miocene. Explanations for anomalously oriented remanences include (1) a magnetic fabric imposed on the dike rocks as a consequence of penetrative deformation; (2) anomalous behavior of the Earth’s magnetic field during the intrusion interval; (3) overlapping components of remanent magnetization; or (4) tectonic rotation about a horizontal, inclined, or vertical axis.

[32] Petrographic observation under the optical microscope reveals that the dikes have a primary subophitic igneous texture with no apparent deforming fabric. Results from AMS measurements also indicate that for the most part there is a lack of a well-defined magnetic fabric in these rocks. The degree of anisotropy, expressed as ratio of the maximum to the minimum susceptibility, in most of the dikes is around 1.01 indicating approximately 1% anisotropy (Table 1). Lack of a well-defined magnetic fabric rules out the first possible explanation for the anomalous remanence.

[33] The second explanation requires that the magnetization in these dikes was acquired during a period of anomalous behavior of the geomagnetic field. Anomalous field behavior often reflects short-term fluctuations in the direction of the local or regional field, which are relatively short lived. Different dikes in the suite preserve normal and reversed remanences with nearly antipolar orientations, and it is unlikely that anomalous field behavior would persist and retain a fixed deviation from the expected direction over a period of time encompassing a magnetic reversal.

[34] Overlapping components of remanence have been reported in other dikes in southern Spain [Calvo et al., 2001]. In the dikes sampled in the Sierra de las Estancias, however, with the exception of RD3, which has been eliminated from the analysis, there is no evidence of directional overlap after removal of the low temperature viscous component at or around 200°C. Above this temperature the majority of the demagnetization plots show clustering around a stable direction and exhibit straight line (single component) decay to the origin of the Zijderveld vector plot as shown in Figures 5a and 5c. Therefore, in this case, overlapping components of remanent magnetization do not appear to provide an explanation for the anomalous remanences.

[35] Tectonic rotation about a horizontal, inclined, or vertical axis can also change the orientation of the magnetic remanence. In complexly deformed terrains this is best analyzed in terms of the net tectonic rotation, which is the single equivalent rotation that reorients the system from its initial to its present orientation [MacDonald, 1980]. Net tectonic rotations about inclined axes are likely to be common in orogenic zones. A finite rotation on an inclined fault surface about an axis normal to the fault, for example,

**Figure 7.** Equal-area stereographic projection showing (a) observed orientations of dikes with mean pole (box) and α95, (b) determination of original pole to dikes (D₀) with 95% confidence interval shaded, M₀ is expected magnetic remanence vector, D₁ and M₁ are mean dike and magnetic vector after net tectonic rotation, and (c) decomposition of net tectonic rotation of original foliation pole (F₀) into 32° tilt about normal faults trending 095, 52° tilt about regional fold axis trending 215 and vertical axis rotation of 30°. This sequence rotates the pole to foliation from F₀ to F₁, F₂ and F₃ with a resultant net tectonic rotation (F₀ to F₁) of 50°. NTR is axis of net tectonic rotation.
will produce a net tectonic rotation with simultaneous declination and inclination anomalies. A net rotation about an inclined axis may also result from repeated rotations about different axes during successive deformational events.

To determine the orientation and the magnitude of the net tectonic rotation we must assume that (1) the dikes were originally vertical; (2) the expected direction of remanent magnetization can be accurately calculated from the early Miocene geomagnetic pole [Besse and Courtillot, 1991]; and (3) the angle between the remanent magnetization and the pole to the dikes remains constant during rigid body rotation: an assumption that is valid if, as we have shown earlier, there is no internal penetrative deformation of the dike. The observed angle between the mean pole to the dike (209°, 095 = 8.7°; Figure 7a) and remanent magnetization (063°, 095 = 9.0°) averages 47 ± 9.7°. The error was calculated and corrections were made after Demarest [1983]. Given that the angle between the remanent magnetization and the pole to the dikes remains constant the original orientation of the pole to the dikes will lie on a small circle of 47° around the original magnetization. If the dike were originally vertical, the pole would lie at the intersection of this small circle with the primitive, defining two possible solutions. In our case, however, the small circle does not quite intersect the primitive: at its closest approach it lies 3° inside it. This defines 004.5° as a unique solution to the most probable original orientation of the pole to the dike (Figure 7b).

Assuming a reasonable cooling time of less than ten million years (see below), time temperature curves show that while magnetite blocked under these conditions will not retain a remanence for more than 10⁵ years, pyrrhotite will have begun to block in the ChRM above 135°C but below 200°C [Dunlop et al., 2000]. Fission track data from the Alpujarride Complex in the Sierra de las Estancias [Platt et al., 2005] can be used to constrain the time the rocks reached this temperature. Zircon fission track ages varying from 17.6 to 21.5 Ma, with a mean of 19 Ma, constrain the time when temperatures fell below about 300°C. The best apatite fission track age is 16.0 ± 2.3 Ma: this constrains the time when temperatures fell below 120°C. The remanence is therefore likely to have formed in the period 19–16 Ma (early Miocene), and the rotation must have occurred later than 19 Ma.

A similar amount of rotation is recorded in dikes with low temperature normal polarity ChRM and those with high temperature reverse polarity ChRM. This indicates that

Figure 7b, it can be seen that the limits on the possible trend of the dike poles at the 95% confidence level are 335° and 35°.
the remanence in these dikes must have been acquired over a period of time encompassing a reversal of the Earth’s magnetic field, and also that the rotation must have taken place after the magnetic reversal was recorded in these dikes. The simplest explanation for these observations is that the dikes recording the lower temperature normal polarity ChRM blocked in their magnetic remanence later than the dikes recording a reverse polarity high temperature ChRM. As we will discuss later, this is consistent with the fact that the more southerly dikes, which carry the low temperature normal polarity remanence, were originally emplaced about 1.5 km deeper in the crust and were therefore likely to have remained hotter longer than the northerly ones, which have reversed polarity.

5. Discussion

Correction for net tectonic rotation of 50° clockwise about an axis plunging 30° to 185° brings the foliation in the northern Sierra de las Estancias into a subhorizontal orientation (Figures 8b and 9; Table 2). This is consistent with our interpretation that the foliation was modified and transposed during the main phase of extensional deformation and core complex formation. The stretching lineations after this correction trend NNE-SSW (205 ± 15), subparallel to those on the present gently dipping southern limb of the antiform (lineation trend 208, Figure 4b, subareas 6 and 7 in Table 2). The consistency in the corrected orientation of both the foliation and the lineation across the range lends strong support to the inferred net tectonic rotation. The Maláguide-Alpujárride Detachment and its associated mylonites (subarea 1 in Figure 4), and the adjacent steeply dipping belt of Alpujárride phyllite and quartzite (subarea 2), have moderately north dipping foliations after correction, and the stretching lineation plunges NNE (39/037), with a down dip sense of shear. This is consistent with the interpretation of the detachment as a normal sense shear zone with a NNE sense of shear.

Correction for net tectonic rotation therefore reveals the Sierra de las Estancias to have been a multilayer core complex, with three stacked units separated by two gently north dipping extensional detachments with an overall top-to-NNE sense of displacement and shear. The internal structure of these units includes recumbent folds and foliations formed during the earlier contractional tectonic phase, which have been overprinted by extensional deformation that evolved from ductile to brittle during exhumation and cooling. The structural style is closely comparable to that shown by metamorphic complexes elsewhere in the Betic Cordillera (Argles et al., 1999; Galindo-Zaldívar et al., 1989; Jabaloy et al., 1993; Martínez-Martínez et al., 2002; Platt et al., 2003c) and in the Aegean (Avigad, 1998; Ring et al., 2001; Rosenbaum et al., 2002; Wawrzynitz and Krohe, 1998).

What caused the rotation of the northern margin of the Estancias core complex, and when did it happen? A common assumption is that rotations are a result of a combination of a tilt about a horizontal axis (often assumed to be the strike of sedimentary bedding) and a twist about a vertical axis. The net tectonic rotation we have determined can be decomposed into components of rotation about vertical and horizontal axes without reference to the orientation of the structures in the core complex, giving a clockwise vertical-axis rotation of 30° followed by a tilt of 42°W about an axis trending 020°. If the tilt is assumed to have happened first, then the tilt axis trended 350° (this is the same material line, but in its pretwist orientation).

Figure 9. (a) Present-day section across the Sierra de las Estancias, constructed normal to regional strike to constrain structural thicknesses. (b) Restored section after correction for tilting and vertical axis rotation. Dips shown are apparent dips; see Figure 8 for the orientations of fabrics before and after correction.
Neither scenario is particularly attractive, as the inferred northerly tilt to the axis does not correspond to any observed structure. In the south of the Sierra de las Estancias, where the lineation trend is NNE and the amount of vertical axis rotation is likely to be relatively low, the major antiform trends 035° (Figure 2); further north, in the rotated domain, a secondary anticline trends 050°.

[43] An alternative possibility is suggested by the fact that the axis of net tectonic rotation is about normal to the brittle normal faults seen in the northern Sierra de las Estancias (Figure 3), which dip steeply north with an east to ESE trend. Could the observed rotation have been accommodated by rotational slip on these faults? While this idea is appealing, it is not clear why such a large rotation (50°) should have occurred by this mechanism, or how it relates to known tectonic processes in the area.

[44] A third, more complicated possibility is suggested by the fact that most of the dikes were sampled in a panel of rock defined by two of the E-W faults in question, and that the strike of the foliation in this panel is clearly oblique to the regional foliation in the surrounding area, in a manner suggesting back rotation during domino-style faulting (Figure 6). We suggest the following scenario.

[45] 1. As noted above, the foliation in the core complex was likely to have been subhorizontal at the end of the ductile phase of extension (F₀ in Figure 7c).

[46] 2. The dikes were then intruded vertically, with an E-W trend, normal to the main direction of extension.

[47] 3. The final phase of extension along the northern margin of the Sierra de las Estancias was achieved by brittle normal faulting on E-W trending normal faults, dipping around 60°N. During this phase, the faults and the panels of rock they separate rotated domino-style about the strike of the faults (095) by about 32° southward, reorienting the pole to the foliation to F₁ in Figure 7c.

[48] 4. This region was tilted 52° NW about the observed regional fold axis trending 215°, bringing the foliation pole to position F₂.

[49] 5. Finally, the region was then subjected to a regional dextral vertical-axis rotation of 30° related to the dextral component of motion on the Internal-External Zone Boundary, reorienting the foliation pole to its final orientation F₃.

[50] The net effect of this series of rotations is exactly equivalent to the inferred net tectonic rotation, but involves processes that are geologically reasonable and are related to observable structures in the rocks. The faults, since they are normal to the axis of net tectonic rotation, end up with the same orientation as they had originally. The dikes, foliation, and lineation from the fault-bounded panel are all correctly reoriented by this procedure.

[51] This scenario also provides an explanation for the orientation of the foliation in the surrounding area of the northern Sierra de las Estancias. Assuming the foliation pole started from the same initial orientation F₀ (Figure 7c), but was not affected by the domino-style rotation induced by the normal faults, the subsequent tilt and twist would bring the foliation pole onto a trajectory that would pass through both its orientation in the northern Sierra de las Estancias in general and in the steep zone near the Malaguaide-Alpujarride detachment, depending on the amount of tilt.

[52] Although the above scenario is speculative, the net tectonic rotation we have inferred is robust, depending only on the assumption that the dikes were originally vertical. The reorientation of the foliation and lineation is also robust, as it can be described simply in terms of the net tectonic rotation.

[53] As discussed earlier, both northwestward tilting and dextral vertical-axis rotation are common along the entire Internal-External Boundary of the Betic Cordillera, and are likely to be related to early to middle Miocene oblique convergence of the Alboran Domain with the south Iberian margin. Tilting and twisting may, in fact, have overlapped in time. Paleomagnetic data from the external thrust belt itself show substantial clockwise rotations associated with early to middle Miocene oblique convergence, and palinspastic restoration of balanced cross sections suggests an average 25° of clockwise rotation of the Internal-External Boundary during this phase of convergence [Platt et al., 2003a].
[54] What are the implications for the originally NNE sense of displacement in the core complex revealed by our analysis? Stretching lineations in the Alpujarride Complex generally trend NE to ENE throughout the Betic Cordillera [Argles et al., 1999; Azahón et al., 1998; Balanyá et al., 1993; Feinberg et al., 1996; Tubía et al., 1992]. For the most part these lineations formed during earliest Miocene ductile extension accompanying exhumation [Platman et al., 2003b]. The available palaeomagnetic data from the Internal Betics suggest that clockwise rotations are widespread [Allerton et al., 1993; Feinberg et al., 1996; Platman et al., 2000; Calvo et al., 2001], however. Palaeomagnetic analysis of the Ronda peridotite, for example, suggests that this body has undergone about 45° of clockwise rotation [Feinberg et al., 1996], and if the lineation trend in the adjacent Alpujarride schists [Argles et al., 1999] is corrected for this rotation it trends around 015°, with a NNE sense of shear. In view of our very similar result from the Sierra de las Estancias, we suggest that the regional trend of the stretching lineation during earliest Miocene exhumation of the Alpujarride Complex was around NNE. Palaeomagnetic data from the Beni Bousera peridotite massif in the Internal Rif suggest 74° of anticlockwise rotation [Saddiqi et al., 1995], and after correction the lineation in the adjacent schists of the Sebtide Unit (the Rifean equivalent of the Alpujarride Complex) also trends close to north [Saddiqi et al., 1995]. A north to NNE direction of extension may therefore have been characteristic of the entire Alboran Domain during the earliest Miocene.

[55] It has been widely assumed that the extension in the Alboran Domain was predominantly E-W in direction, in view of the dominance of E-W to ENE-WSW stretching lineations along both the major detachments, and the overall westward sense of motion implied by the geometry of the external Betic-Rif arc [e.g., Martínez-Martínez and Azahón, 1997]. A northerly sense of motion on brittle normal faults in parts of the Alpujarride Complex has been reported by Crespo-Blanc et al. [1994], however, and the predominant sense of extension in the middle to late Miocene extensional basins in the Betic Cordillera is between north and NE. Our structural and palaeomagnetic analysis suggests that the regional direction of extension in the Alboran Domain during the earliest Miocene was also around NNE.

[56] Palinspastic restoration of the Alboran Domain suggests that it trended NE in the early Miocene [Platman et al., 2003a], forming the western termination of a regionally NE trending Alpine collision orogen linked through the proto-Apennines to the Alps [Facenna et al., 2001]. Our data therefore suggest that the rapid earliest Miocene phase of extension that led to the exhumation of the Alpujarride Complex was roughly parallel to the strike of the orogen, and normal to the WNW direction of convergence between Adria and Eurasia during the Neogene evolution of the Alpine orogen [Platman et al., 1989]. Extension parallel to strike is common during the late stage of orogenic evolution, reflecting the combined constraints imposed by continuing plate convergence and the excess gravitational potential energy of the orogen itself [e.g., England and Houseman, 1989].

Acknowledgments. This work was supported in part by grants GR8/10828 and GR3/13160 from the Natural Environmental Research Council of Great Britain (to J. Platt). The authors would also like to thank two anonymous reviewers and Djordje Gruići for their helpful reviews.

References


______________________________

J. P. Platt and E. Platzman, Department of Earth Sciences, University of Southern California, 3651 Trousdale Avenue, Los Angeles, CA 90089, USA. (platzman@usc.edu)