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The Malaguide–Alpujarride boundary: a major extensional contact in the Internal Zone of the eastern Betic Cordillera, SE Spain

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Abstract—The Internal Zone of the Betic Cordillera in southern Spain was formed by thrusting and horizontal ductile shortening in the Late Cretaceous (?)–Palaeogene, but was subjected to a major phase of vertical thinning during the Neogene. The contact between the Malaguide (the structurally highest thrust complex) and the underlying Alpujarride Complex, is an example of several major tectonic contacts across which the stratigraphy has been repeated by thrusting, but the metamorphic grade increases abruptly downwards. Detailed work in the eastern Betic Cordillera documents the relationships across this contact. In the Sierra Espuña, petrographic and illite crystallinity studies show that the highest imbricate thrusts of Malaguide rocks have only been diagenetically altered, whereas the deeper parts of the thrust stack exhibit anchizone facies metamorphism. In the northern Sierra de las Estancias, apatite fission track studies confirm that there, too, Malaguide rocks have never been above 200°C. In both areas, the underlying Alpujarride rocks exhibit epizone or greenschist facies metamorphism and a major fault zone with both brittle and ductile structures separates the two complexes. The observed rapid increase in metamorphic grade over very small structural thicknesses suggests that part of the original metamorphic zonation has been excised across the contact. Thus, in its present form, we interpret the Malaguide/Alpujarride boundary as an extensional contact. The extensional motion took place in Early–Middle Miocene times, as constrained by fission-track cooling ages. The fault zone at the contact is sub-horizontal in the Sierra Espuña, but in the Sierra de las Estancias it is mainly sub-vertical. Kinematic data from a 5–20 m thick calc-mylonite layer within the fault zone in the Sierra de las Estancias, corrected for later tilting, indicates that the extensional movement was originally directed with the top to the east-northeast.

The interpretation of the Malaguide/Alpujarride boundary as an extensional contact is similar to recent interpretations of the Nevado–Filabride/Alpujarride contact at deeper structural levels in the central and eastern Betics. The identification of another major extension fault system confirms that Miocene extension was widespread at all structural levels. During the early–middle Miocene, the Sierra Espuña and the northern margin of the Sierra de las Estancias lay on the boundary between the region undergoing horizontal extension in the Internal Zones and the Alboran Sea to the south, and the region undergoing horizontal shortening in the External Zones to the north. As a result, the detailed history of the Alpujarride/Malaguide contact is complicated: extensional structures cross-cut structures related to earlier Alpine shortening and were then affected by further shortening as convergence with the External Zones continued.

INTRODUCTION

The Betic Cordillera of southern Spain is the most westerly of the Alpine mountain chains of southern Europe and developed during, and partly in response to, Late Mesozoic–Tertiary convergence between Africa and Iberia. It is commonly divided into External and Internal Zones. The External Zone consists of non-metamorphic Mesozoic and Tertiary sediments deposited on the rifted southern margin of Iberia. These rocks were strongly shortened by thin-skinned thrusting and folding during the Miocene (García-Hernandez *et al.* 1980, Banks & Warburton, 1991, Allerton *et al.* 1993). The Internal or Betic Zone to the south is made up of Palaeozoic and Mesozoic rocks, most of which were affected by penetrative deformation and metamorphism before the Middle Miocene. The bulk of these rocks classically have been grouped into three tectonic complexes (e.g. Torres Roldán 1979). The lowest, Nevado–Filabride Complex, was affected at least in part by glaucophane-schist to eclogite facies metamorphism, evolving during decompression to upper greenschist or amphibolite facies (Bakker *et al.* 1989). The overlying Alpujarride Complex, on the other hand, shows only limited evidence in the eastern and central Betics for an early, very low grade, high pressure–temperature ratio metamorphic event and, for the most part, shows lower greenschist facies metamorphism. The highest complex, the Malaguide, is largely unmetamorphosed. All three include rocks believed to be of Palaeozoic and Triassic age and the Malaguide sequence extends up to the Middle Miocene (Paquet 1969, Lonergan 1993).

These three complexes were originally regarded as large-scale, internally imbricated thrust sheets, and the duplication of stratigraphy from one to the next supports this interpretation. The contact between the Alpujarride and Nevado–Filabride Complexes is now widely regarded as having been reactivated or replaced by a large-scale, low-angle extensional shear zone (Platt 1986, Platt & Vissers 1989, Galindo-Zaldívar *et al.* 1989, Jabaloy *et al.* 1993). This is based mainly on the fact that there is a significant decrease in metamorphic pressure upwards across the contact, indicating that part of the original metamorphic zonation has been excised

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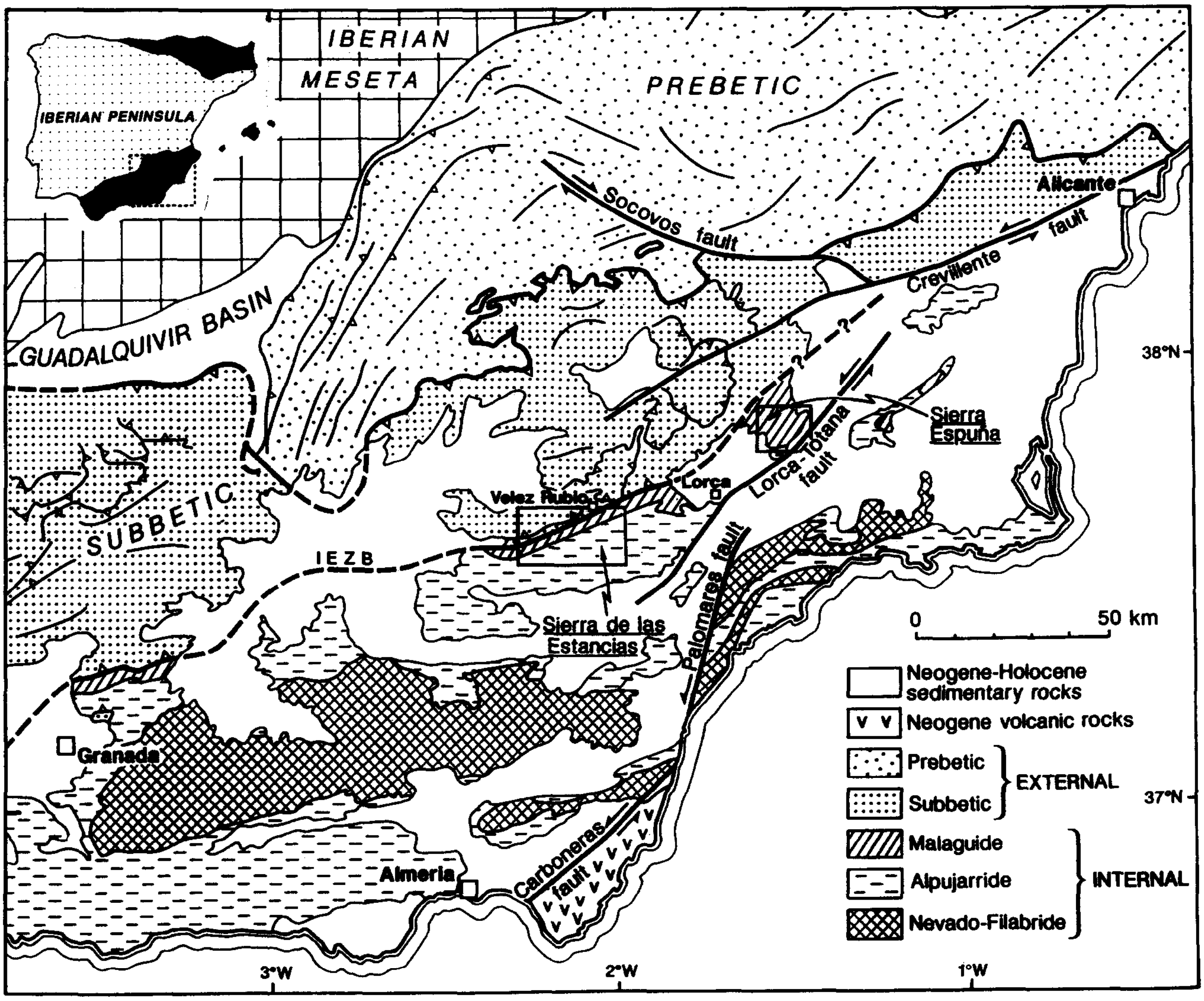

Fig. 1. Regional location map (with inset of Iberian peninsula) showing the distribution of Malaguide and Alpujarride rocks in the Velez Rubio Corridor and the Sierra Espuña. Location of Figs. 2 and 3 (Sierra Espuña) and Fig. 7 (Velez Rubio Corridor) are marked; IEZB is the Internal/External Zone boundary.

(Bakker *et al.* 1989). It is supported by the distribution of fault rocks across the contact, with ductile mylonites in the footwall and cataclastic rocks in the hanging wall; and the evolution in time from ductile to brittle deformation in the footwall suggests that movement on the contact was accompanied by exhumation of the footwall, which is consistent with extensional motion.

The Malaguide/Alpujarride contact has been less intensively studied, but like the Alpujarride/Nevado–Filabride contact, there is commonly an increase in metamorphic grade downwards across it, suggesting that in its present form it may also be extensional (Platt *et al.* 1983, Aldaya *et al.* 1991). The purpose of this paper is to document in more detail the nature of this boundary in the Sierra Espuña and the northern Sierra de las Estancias in the eastern Betic Cordillera, and to present kinematic data on the direction and sense of motion.

GEOLOGICAL SETTING

The Malaguide rocks in the eastern Betic Cordillera are largely confined to a belt of intermittent exposure along the Internal/External Zone boundary, extending from the Sierra Espuña to the northern margin of the Sierra de las Estancias (Fig. 1). They consist of Palaeozoic sandstone and slate, Permo-Triassic red beds and dolostones, Jurassic–Cretaceous carbonates, lower Tertiary shallow marine limestones and locally developed Oligo-Miocene slope/deep water deposits. The Palaeozoic rocks were folded and metamorphosed to very low grade (anchizone) during the Variscan orogeny. During the Alpine orogeny, the Permo-Triassic and younger rocks were largely detached from the underlying Palaeozoic and both sequences were strongly shortened and imbricated. In the Sierra Espuña, this imbrication can be precisely dated as latest Eocene and the thrust stack was then refolded into a NW-vergent fold in the earliest Miocene (Lonergan 1993). In the early–middle Miocene, Subbetic rocks of the External Zones were thrust in a SSE–SE direction over the Malaguide Complex (Lonergan *et al.* 1994).

The Alpujarride rocks structurally below the Malaguide/Alpujarride boundary are well exposed in the Sierra de las Estancias, where they consist of predominantly greenschist facies, graphitic mica-schist, interlayered blue-grey and pink phyllite and quartzite, and carbonate rocks. This sequence probably represents an original stratigraphic sequence of Palaeozoic, Permo-Triassic and Triassic rocks broadly comparable to those in the Malaguide Complex (Akkermann *et al.* 1980). The dominant metamorphic mineral assemblages are characteristic of the chlorite zone of the greenschist facies, but rare kyanite (Akkerman *et al.* 1980) and carpholite (Goffé *et al.* 1989) suggest that these rocks experienced relatively high pressure (7 kb) and low temperature conditions at an early stage in their metamorphic history. The rocks are cut by a swarm of dolerite dykes of probably Neogene age that post-date all the ductile deformation.

During the early–middle Miocene, the Sierra Espuña and the northern margin of the Sierra de las Estancias lay on the boundary between the region undergoing horizontal extension in the Internal Zones and the Alboran Sea to the south, and the region undergoing horizontal shortening in the External Zones to the north. The spatial and temporal relationships between extension and shortening in this region are therefore crucial to understanding the nature of late orogenic extension in the Betic Cordillera and its relationship to shortening in the surrounding thrust belts.

FIELD RELATIONS

Sierra Espuña

On the southern side of the Sierra Espuña, virtually unmetamorphosed Permo-Triassic rocks of the Malaguide Complex form an imbricate thrust stack lying above greenschist facies rocks of the Alpujarride Complex (Figs. 1 and 2). The boundary is marked by a thick fault zone containing a variety of brittle and semi-brittle fault rocks, and a substantial sliver of rocks of grade intermediate between the two complexes, referred to as the 'intermediate' unit by Paquet (1969). In outcrop the fault zone is approximately horizontal. The fault is a thrust in a stratigraphic sense, as it emplaces Permo-Triassic sandstone on top of Alpujarride rocks that include dolostone of probable Late Triassic age. In two respects, however, the field relations suggest that the fault is extensional. Firstly, the hangingwall rocks have been deformed primarily in a brittle manner, by thrusting, and they show brecciation close to the contact. The rocks in the footwall, by contrast, exhibit ductile deformational fabrics. Secondly, there is an abrupt increase in metamorphic grade downwards across the fault, documented in more detail below.

Fault zone at the top of the 'intermediate' unit. Over much of its outcrop extent in the Sierra Espuña, only the upper part of the Malaguide/Alpujarride fault zone is exposed, separating the Malaguide rocks from the 'intermediate' unit below. This boundary is shown on the map in Figs. 2 and 3. The fault zone can be traced from Montysol in the south as far as locality Y in Fig. 2 and may continue northeast along the canal to Z. At Z, however, the footwall rocks of the 'intermediate' unit are not exposed and it can only be presumed to be the same fault. Over its entire length, the 2–5 m thick fault zone appears horizontal in outcrop. It is at an elevation of 500 m at Montysol, and 400 m at locality Y, suggesting that it is inclined at about 5° to the north or northeast.

The fault zone contains abundant breccia and gouge, derived from the red Malaguide Permo-Triassic sandstone and shale in the hangingwall, but the most striking fault rock is a yellow dolomitic breccia known as rauhwacke or cargneule. This is a common rock-type in the Betic Cordillera and other Alpine mountain chains, and is commonly associated with Triassic dolomite and evaporite sequences. It is generally thought to be formed by a combination of tectonic (Leine 1968) and solution processes (Warrak 1974). In this fault zone, the rauhwacke is locally laminated and includes strings of relict siliciclastic grains generally less than 1 cm in size. In thin section, these grains have been partly replaced by carbonate and lie in a matrix of recrystallized calcite and dolomite. The laminated texture seen in hand specimens and the occurrence of porphyroclasts with tails compares with structures observed both in mylonites (Simpson & Schmid 1983) and fault gouges (Rutter *et al.* 1986), suggesting that the rauhwacke formed by a combination of brittle and ductile processes.

The fault zone is best exposed in cuttings between 13.25 and 11.5 km on the canal (see Fig. 2) where it can be up to 5 m thick. Figure 4 is a line drawing of part of the fault zone at X in Fig. 2. Black brecciated dolomite in the hangingwall grades downwards into rauhwacke. In the central part of the fault zone, pods or blocks of dolomite, sandstone and rauhwacke form a large-scale augen texture. The pods or lenses of intact dolomite and sandstone resemble metre-scale equivalents of rotated porphyroclasts in mylonites. The underlying sandstone and slate of the 'intermediate' unit is severely disrupted forming fault-bounded lensoid packets. The occurrence of intermingled dolomite and sandstone pods suggests that the fault zone extends below the rauhwacke horizon. Considering the width of the shear zone and the dispersion of rafts of rock from either side of the fault within it, it must have accommodated a large strain and a significant displacement. Nowhere else within the overlying thrust stack is a shear zone of such size exposed.

In sections parallel to the stretching direction in a mylonite, the asymmetry of porporphyroclasts indicates the sense of shear. There is a hint of asymmetry in the lensoid bodies preserved in the central part of the rauhwacke fault zone, but lineation data collected along the fault zone are sparse and quite scattered (Fig. 5). From the Montysol exposures and localities X and Y (Fig. 2), the majority of the lineations cluster in the northwest and southeast quadrants. If these are representative of the stretching direction (X direction of strain), then the sections of the fault zone exposed along the canal are closer to YZ sections and will not yield a shear sense. In the Montysol area, lineation data lying in rauhwacke foliation planes (Fig. 5a) have been separ-

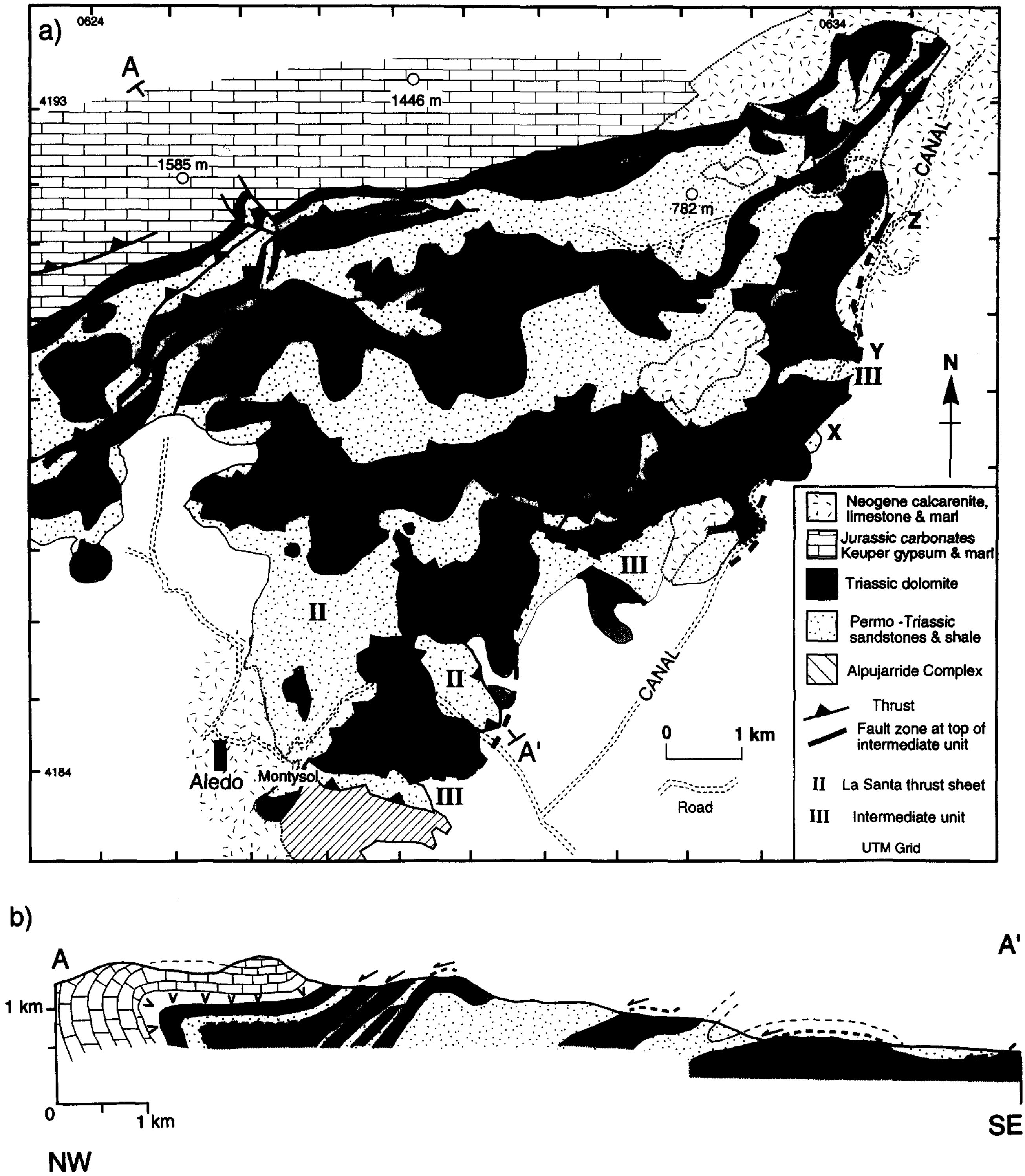

Fig. 2. (a) Geological map of the southern side of the Sierra Espuña, locating the La Santa thrust sheet, the 'intermediate' unit, the fault zone at the base of the Malaguide Complex and localities discussed in the text. (b) Structural cross-section through the imbricate thrust stack of Malaguide rocks. The present dip of the thrusts is the result of early Miocene folding post-dating the thrust imbrication.

ated from lineations collected from the surfaces of lensoid inclusions and other faults (Fig. 5b) and they dip gently between north-northwest and northeast. Minor fold axes in the immediately underlying rocks of the 'intermediate' unit (Fig. 5c) show a similar trend to the rauhwacke lineations and may indicate that the shear strains were high enough to rotate fold axes into parallelism with the stretching direction. The underlying slate and sandstone is intensely deformed, with dismembered lenses of sandstone floating in slates, with occasional detached fold noses. The hinges of these folds have the same northeast–southwest trend at localities X and Y along the canal, and at Montysol (Figs. 5c & f).

Gypsum fault zone, locality Z. At Z (km 8.25 on canal, Fig. 2), a fault zone is exposed with abundant sense of shear indicators. It crops out at the same topographic and structural level as the rauhwacke fault zone but

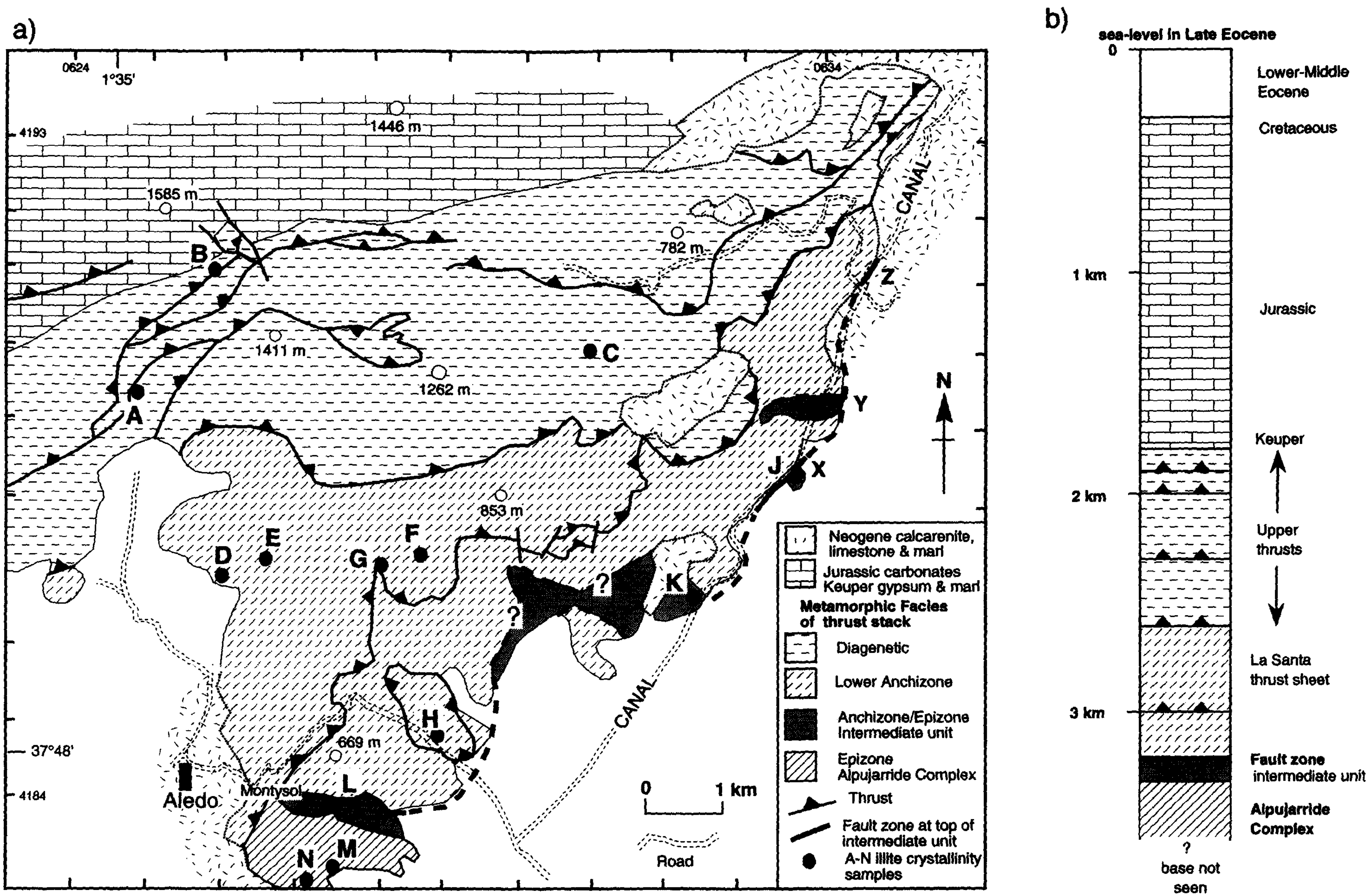

Fig. 3. (a) Map of illite 'crystallinity' sample localities and the measured metamorphic facies of structural units in the Sierra Espuña. (b) Structural thickness of Malaguide Complex after Early Tertiary thrusting, as observed at the present. Thickness of units have been estimated from cross-sections and maps. The thickness of the 'intermediate' unit is not well constrained.

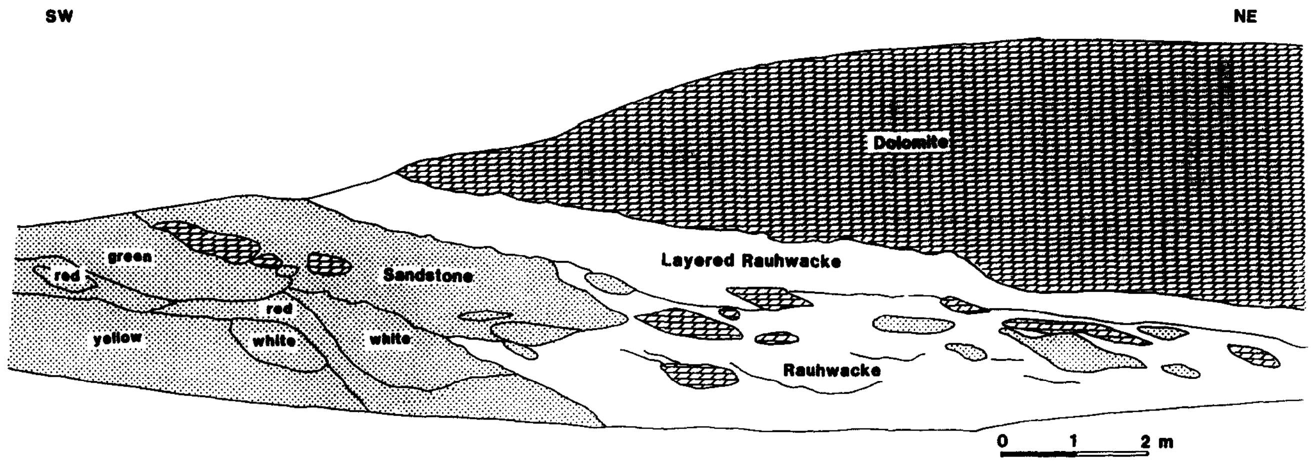

Fig. 4. Line drawing of rauhwacke dominated fault zone, at the top of the 'intermediate' unit, as exposed at km 13.25 (X, Fig. 2) on the canal cutting.

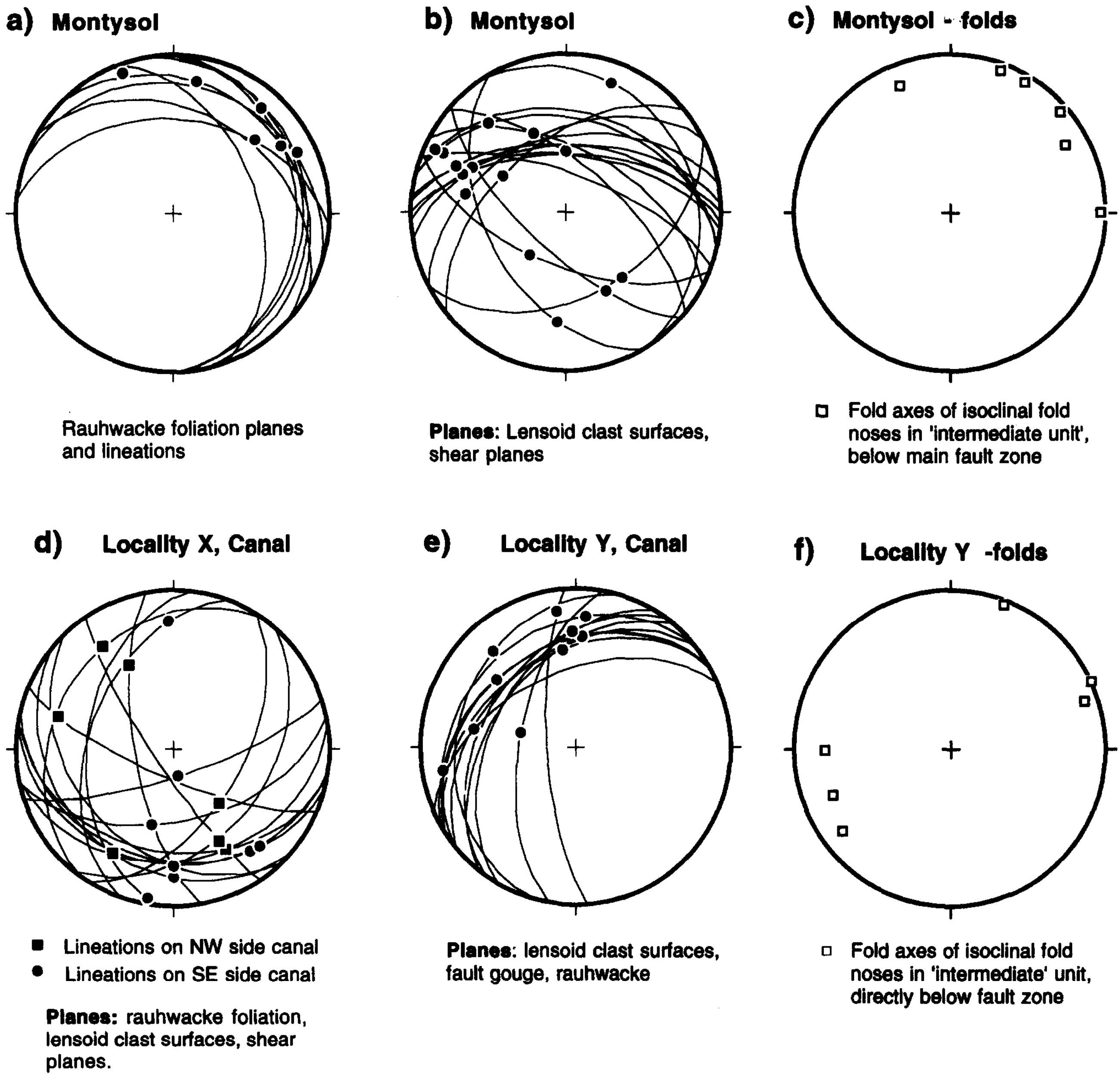

Fig. 5. Lineation data from the fault zone separating the Malaguide and Alpujarride Complexes in the Sierra Espuña. Plots (a) & (b) from the Montysol roadside exposures on the secondary road from Totana to Aledo. Plot (c): minor fold axes of tight isoclinal fold noses in the immediately underlying 'intermediate' unit. Plots (d) & (e) from localities X (km 13.25) and Y (km 11.5) on the canal cutting.

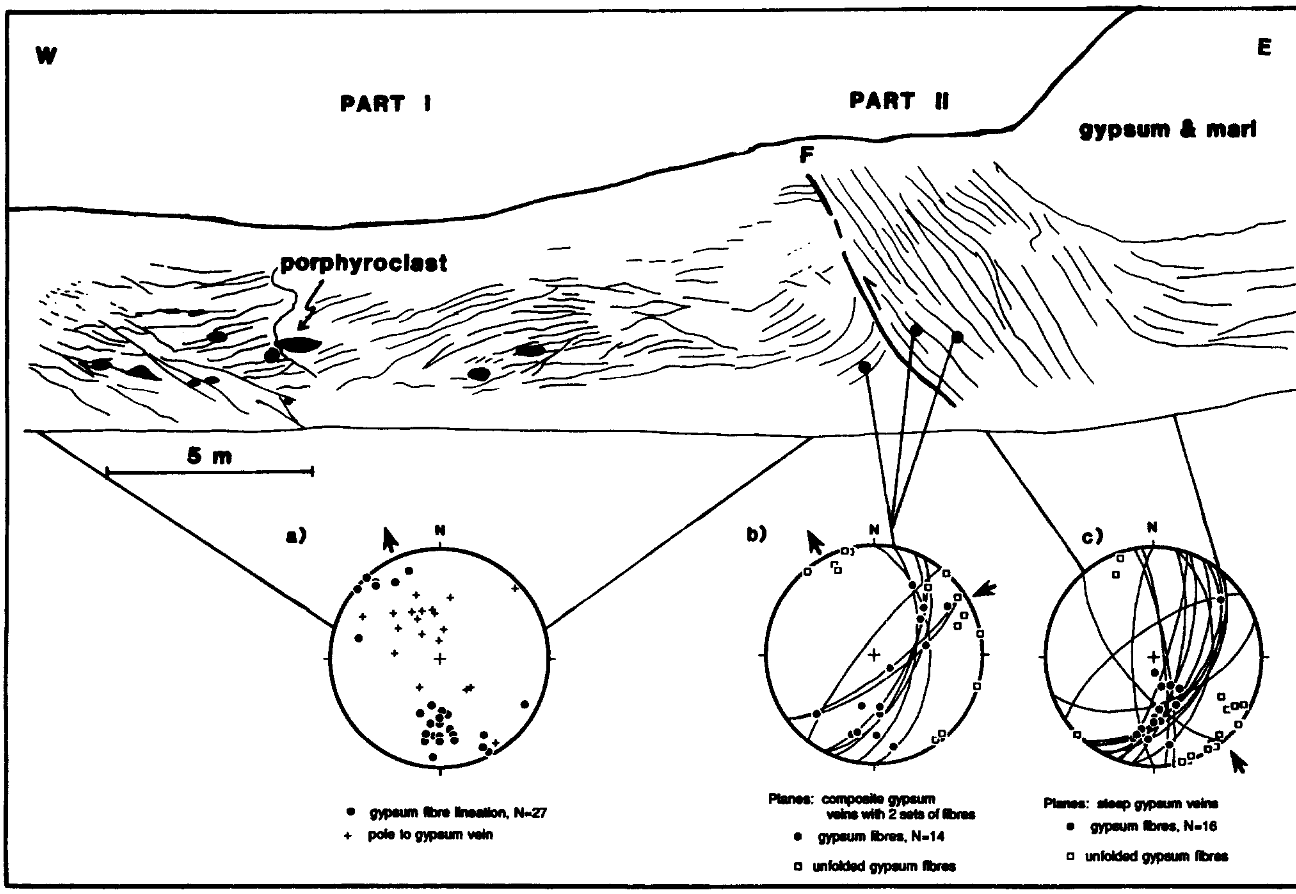

Fig. 6. Gypsum fault zone exposed at 8.25 km along the canal, eastern edge of the Sierra Espuña. Line drawing from photographs of the cutting on the north side of canal illustrating gypsum veins and large porphyroclasts. Plots show gypsum fibre kinematics, with arrow indicating sense of shear; top to NNW or W. The asymmetry of the gypsum fibres and porphyroclasts were used as sense of shear indictors. Composite veins with two sets of fibres occur in the vicinity of the thrust, F, Part II. Composite veins may have formed in one of two ways: (1) flat-lying veins containing N–S oriented fibres as in Part I, were rotated by movement on the fault and new ENE-trending fibres grew as a response to the faulting; or (2) the N–S movement and W movements occurred in pulses but more or less simultaneously and veins grew in either steep or gently dipping orientations with two sets of fibres, depending on the predominant stress state. Assuming that the veins were originally horizontal and that their current steep dip is due to folding, they can be unfolded around the fold axis (14°/027) of the bent veins in the footwall at F. Each vein was corrected for the plunge of the fold and rotated to horizontal about the fold axis and the unfolded fibre lineations are plotted in (b) and (c). Two clusters of lineations can be distinguished: a NNW–SSE and ENE set, the ENE-dipping set indicating thrusting to the WSW on fault F. Both the unfolded and steeply dipping fibres from the steep gypsum veins (plots b and c) show the same NNW-trend of the fibres from Part I.

rocks of the 'intermediate unit' are not exposed in the footwall. The fault rock is made of brecciated layers of grey dolomite in a red weathered clay matrix cut by anastomosing syntectonic gypsum veins composed of oriented crystal fibres. Because the footwall is not exposed and because of the very different appearance of the fault rock, we cannot be certain that it is a continuation of the fault exposed at Montysol and localities X–Y. The section on the north side of the canal cut is illustrated in Fig. 6 and can broadly be divided as follows. Part I, to the west, is dominated by more or less flat-lying gypsum veins and porphyroclasts up to 60 cm in size. Part II is composed of steeply dipping veins, some of which are composite with two sets of fibres. Parts I and II are separated by a thrust fault, F. In the footwall at F, the flat-lying gypsum veins of Part I are rotated and bent due to drag on the fault. Gypsum fibre lineation data collected from the fault zone are plotted in Fig. 6 and indicate that NNW-directed movements dominated in the fault zone but some localized WSW thrusting also occurred, possibly post-dating the NNW-directed movements that generated the flat-lying fabric.

Timing. Tortonian sedimentary rocks unconformably overlying the fault zone provide an upper limit on its age. Amongst the mainly Permo-Triassic Malaguide porphyroclasts in the gypsum fault zone at Z (Fig. 2), some blocks of a Neogene micaceous calcarenite also occur. This calcarenite occurs locally unconformably above the nearby Permo-Triassic, but beneath the Tortonian sedimentary sequence. To the best of our knowledge, this calcarenite has never before been described in the Sierra Espuña and the limited outcrops did not yield any microfossils to allow an age determination. The detrital heavy mineral assemblage in the calcarenite includes large amounts of blue sodic amphibole of high pressure, metamorphic origin, presumably sourced from the Nevado–Filabride Complex. On the north side of the Sierra Espuña, the amount of metamorphic detritus in the sandstones of a turbidite sequence increases from the Lower Miocene through to the Middle Miocene (Lonergan & Mange 1994) and the first amphiboles of high pressure, metamorphic origin are recorded in a very small quantities in Burdigalian sediments. Though no Nevado–Filabride rocks are currently exposed in the vicinity of the Sierra Espuña, clearly by the Burdigalian some high pressure metamorphic rocks were being exhumed in the hinterland to the Miocene basins. However by the Late Miocene (Tortonian), the high pressure metamorphic rocks must have been entirely eroded or buried, because they no longer provide any detritus to the depositional systems on the margins of the Sierra Espuña (Lonergan & Schreiber 1993). We therefore infer that the micaceous calcerenite located beneath the Tortonian unconformity is of Middle Miocene age. The inclusion of porphyroclasts of this micaceous calcarenite within the shear zone imply that the gypsum fault zone may have been active in the Middle Miocene with NNW-directed motion and minor WSW-directed thrusting.

Sierra de las Estancias

On the northern side of the Sierra de las Estancias, the Malaguide/Alpujarride boundary is a steep, linear ENE-trending zone separating imbricated Malaguide Palaeozoic and Permo-Triassic rocks to the north from Alpujarride phyllite and quartzite to the south (Fig. 7). The boundary is now close to vertical, but for the following reasons we believe that it was previously gently dipping and has been rotated into its present steep orientation in a late regional monocline (Fig. 8). Firstly, the Permo-Triassic and younger rocks of the Malaguide, which dip gently north where they underlie the sub-horizontal backthrust of the Subbetic over the Internal Zones 3 km or more to the north, steepen abruptly southwards towards the Malaguide/Alpujarride boundary. Similarly, the regional foliation in the Alpujarride, which is gently dipping over much of the Sierra de las Estancias, steepens to vertical within a few hundred metres of the boundary (Fig. 8). Secondly, at the eastern end of the Sierra de las Estancias, near Lorca (Fig. 1), the boundary becomes sub-horizontal, with Malaguide above Alpujarride, and the structural elements in both complexes are gently dipping. The axial trace of the monoclinal fold is shown in Fig. 7. The fold is analogous to the large-scale monocline in the Malaguide rocks of the Sierra Espuña (Lonergan *et al.* 1994), and like that structure may be related to NW–SE shortening during backthrusting along the Internal/External Zone boundary.

The fault zone is consistently zoned, with up to 10 m of fault gouge on the north side, derived from Malaguide Palaeozoic sandstone and slate, and 5–20 m of calc-mylonite on the south side, derived from Alpujarride Triassic carbonates. Kinematic data from the gouge zone are reported by Lonergan *et al.* (1994). The fault shows evidence of reactivation, presumably during the formation of the monoclinal fold, the backthrusting event, and later strike-slip faulting; and as a result most of the data are difficult to interpret. Where they are unambiguous, they relate to dextral faults with displacements of a few tens of metres that cut and offset the main boundary zone.

The calc-mylonite, on the other hand, shows a very consistent and simple kinematic pattern. It is very fine-grained (10–15 μm), strongly laminated rock, with an intense platy foliation that wraps around dolomite porphyroclasts varying from a millimetre or less to several hundred metres in extent. The dolostone blocks resemble dolostones of the Alpujarride Complex elsewhere, and interlayers in the calc-mylonite of phyllite identical to immediately adjacent Alpujarride rocks confirm that the whole mylonite zone has been derived by disruption and intense ductile deformation from an Alpujarride carbonate sequence. The dolostone blocks have not been distinguished from the calc-mylonite in Fig. 7. The calc-mylonite wraps around the dolostone blocks and the total thickness of carbonate rocks in the contact zone may locally reach 50 m.

The mylonite has a well-developed, stretching lineation that is regionally sub-horizontal (Fig. 9a). Observations of dolomite porphyroclast systems in outcrop consistently give a dextral sense of shear (Figs. 10a & b) at all the sites shown in Fig. 8. The same sense of shear is confirmed by small-scale shear bands (extensional crenulation cleavage) seen in phyllitic interlayers in thin section. The foliation and the lineation in the mylonite are locally affected by small-scale, asymmetric, intrafolial folds that are associated with the mylonitic microstructure in thin section (Figs. 10b&c). These have variably oriented hinge lines: where the folds are tight, the hinge lines are sub-parallel to the stretching lineation, and the folds may have a sheath geometry (Fig. 10d). Where they are more open, the hinge-lines are at a high angle to the stretching lineation and the sense of asymmetry is consistently dextral.

If the mylonitic foliation and lineation are rotated about the axis of the regional monocline into their originally more gently N-dipping orientation (Fig. 9b), the lineation trends ENE, with a top–ENE sense of shear. This is closely comparable to the sense and direction of shear associated with strong planar–linear fabrics in Alpujarride rocks elsewhere in the Betic Cordillera (Tubía *et al.* 1992), and confirms the observations of Aldaya *et al.* (1991).

The Malaguide/Alpujarride boundary appears to be broadly concordant with the structure in the underlying Alpujarride (Fig. 7), but in detail this is not the case. At UTM (05804 41646), early folds in Alpujarride quartzite immediately south of the boundary are downward facing and plunge steeply southwest. These structures are oblique to and truncated by the mylonite zone. The foliation and lineation in the mylonite zone, however, can be traced structurally downwards as late fabric elements in the Alpujarride quartzites and phyllites. The intensity of strain associated with these fabrics decreases away from the contact and they can be seen to overprint earlier folds and foliations. They are associated with outcrop-scale ductile–brittle shear bands with a dextral or dextral/normal sense of shear. These observations are

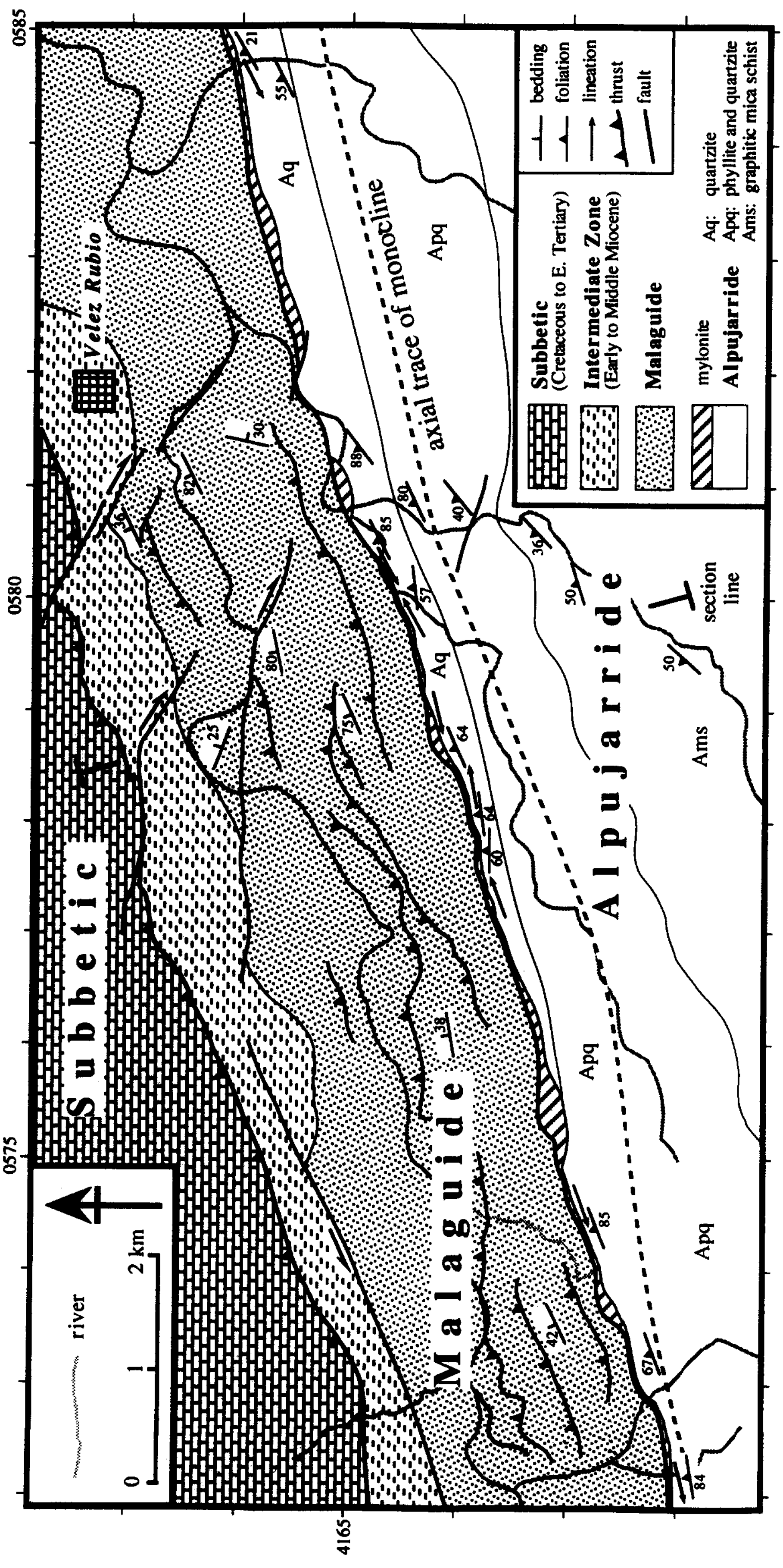

Fig. 7. Structural map of the northern Sierra de las Estancias, modified from Geel (1973) and the IGME geological sheet 974 (IGME, 1978). Foliation and lineation measurements indicated immediately south of the mylonite zone were measured in the mylonite itself. Foliation measurements further south are of the dominant foliation in the Alpujarride quartzites and phyllites.

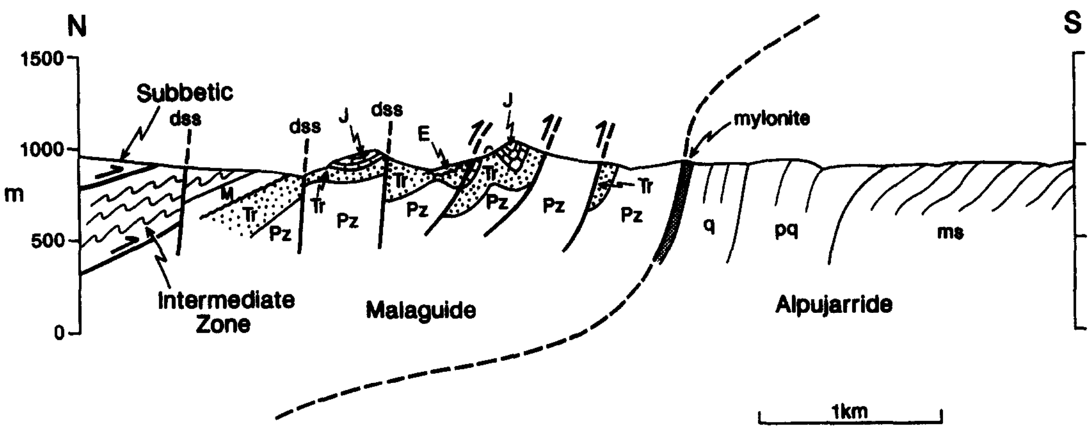

Fig. 8. Section across the Malaguide/Alpujarride boundary in the northern Sierra de las Estancias to illustrate general relationships. Structure in the Malaguide is schematic: neither the detailed thrust geometry nor the direction of thrusting are well constrained. M = Miocene, E = Eocene, J = Jurassic, Tr = Triassic, Pz = Palaeozoic, q = quartzite, pq = phyllite and quartzite, ms = graphitic mica schist.

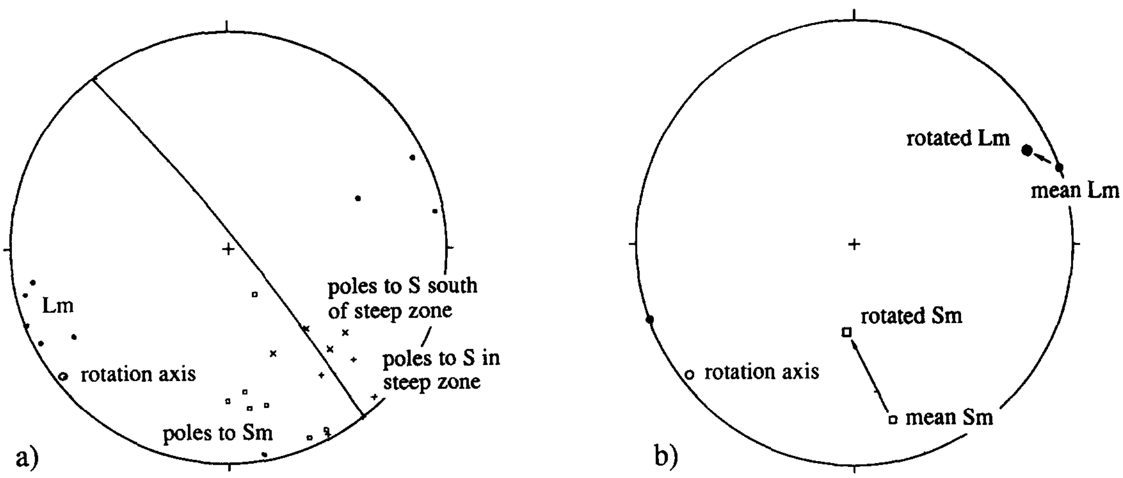

Fig. 9. (a) Structural data from the Malaguide/Alpujarride boundary in the northern Sierra de las Estancias. Sm, Lm: foliation and lineation in the calc-mylonite zone. Each point is the mean of several measurements from a location, as indicated on the map (Fig. 7). Mean poles to the main foliation in the structurally underlying Alpujarride rocks are also shown: these define the regional fold axis of the large-scale monocline shown in Figs. 7 and 8. (b) The mean mylonitic foliation and lineation from all locations, and their orientations after untilting about the axis of the regional monocline.

consistent with the mylonite zone being a late feature, superimposed on the pre-existing folded and thrusted Alpujarride sequence.

It is striking that the Neogene dolerite dykes in the area do not appear to cut the calc-mylonite. They are, however, demonstrably later than the related mylonitic fabrics in the underlying quartzites and phyllites. They also appear to be later than the regional monocline, as they do not change dip across the structure. They occur in both Alpujarride and Malaguide rocks, though they are more common in the Alpujarride. For these reasons, we believe that they post-date the main phase of ductile deformation on the contact, but they may have been deflected by the strong planar anisotropy in the calc-mylonite zone itself.

Timing. There are no stratigraphic constraints on the timing of motion of the Malaguide/Alpujarride boundary in the Sierra de las Estancias. Apatite fission track dating by Johnson (1993), however, provides some important constraints on the thermal and tectonic history. Palaeozoic rocks of the Malaguide structurally above (north) of the boundary yield Palaeozoic zircon fission track ages and early Miocene apatite ages. This indicates that they are unlikely ever to have experienced temperatures above 200°C and that they cooled below 120°C in

Fig. 10. Photographs of the calc-mylonites, northern Sierra de las Estancias. (a) Field photograph. Note asymmetric dolomite porphyroclast systems, and low-angle shear band (bottom), both indicating dextral shear. Horizontal surface, approximately parallel to the stretching lineation. North is at top of photograph. Scale bar (top) is 7.5 cm long. (b) Field photograph. Note train of dextral dolomite porphyroclast systems with dextrally folded recrystallized tails. Horizontal surface, approximately parallel to the stretching lineation. North is at top of photograph. Scale bar is 7.5 cm long. (c) Polished hand specimen, cut parallel to the stretching lineation. Note train of dextral disharmonic syn-mylonite folds. These are offset by late extensional brittle fractures along the axial surfaces of the folds. Scale bar in mm. (d) Polished hand specimen as in (c), cut normal to the stretching lineation. Note sheath-fold geometry. Scale bar in mm.

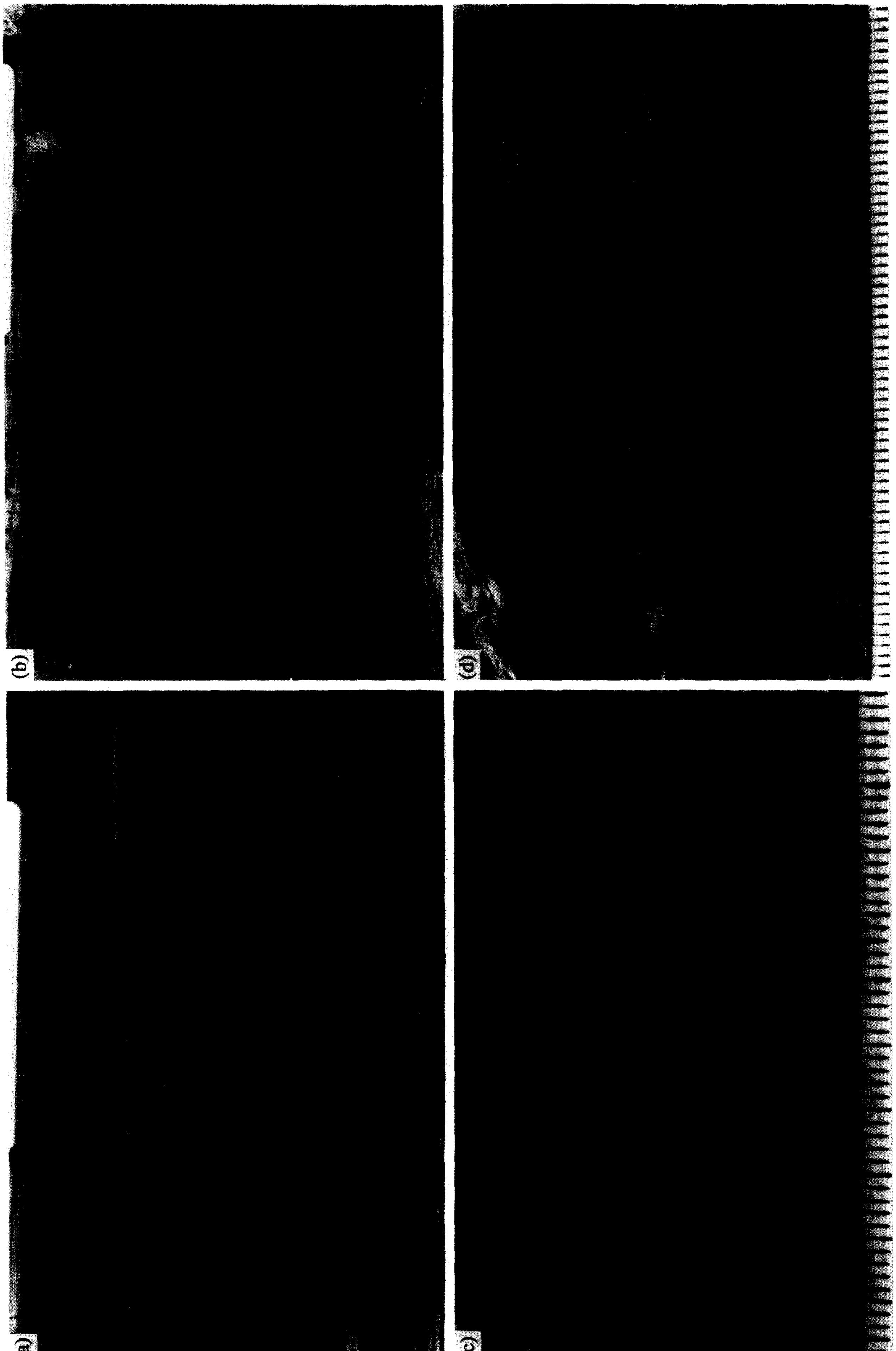

Fig. 10.

early Miocene times. The Alpujarride rocks immediately below the boundary, however, have concordant Early Miocene (18 m.y.) zircon and apatite ages, suggesting that they cooled rapidly below from above 200°C at this time. Johnson (1993) interprets these data as indicating extensional motion on the boundary in the earliest Miocene. This, therefore, raises the possibility that the Middle Miocene motion inferred for the Sierra Espuña may be a result of late reactivation in that area.

ILLITE CRYSTALLINITY STUDIES IN THE SIERRA ESPUÑA

Petrographic observations

In the highest imbricates of the Malaguide thrust stack in both the Sierra Espuña and Sierra de las Estancias, the Permo-Triassic red beds mainly consist of reddish-purple shales, red and white sandstones and rare conglomerates. The quartz-rich rocks are dominantly sandstones composed of quartz, minor amounts of feldspar and volcanic grains, some flakes of detrital mica and traces of heavy minerals. The quartz grains include both monocrystalline and polycrystalline sutured grains of metamorphic origin. There is no cleavage in the shales and the only effects of deformation of the sandstones are strongly sutured contacts between grains.

In the Sierra Espuña, the 'intermediate' unit of slate and quartzite within the Malaguide/Alpujarride fault zone is significantly more deformed than the red beds of the overlying La Santa thrust sheet (Fig. 2) and, in outcrop, appears to be transitional between a sediment and a metamorphic rock. Paquet (1969) assigned the dolostones beneath the La Santa thrust sheet to this unit, but these lie above the fault zone described above, so we restrict the term to the body of slate and quartzite within the fault zone. The most notable feature of these rocks is the presence of small m-scale recumbent fold closures that have become detached from their limbs. A slaty cleavage is associated with these folds. In samples from the canal section, the cleavage is sinuous and defined by clay minerals and some large detrital micas. It produces an augen texture around rounded detrital quartz grains. Fibrous, fine-grained mica and quartz overgrowths occur in the tails of quartz grains but the quartz itself is not significantly deformed.

In comparison, grey phyllites, semipelites and quartzites from the underlying Alpujarride Complex have a strong penetrative cleavage. This is typically defined by bands of 50–100 μm recrystallized mica that anastomose around relict detrital quartz and feldspar. Relict detrital mica is largely recrystallized and not always distinguishable. Detrital quartz grains exhibit undulatory extinction, sub-grain formation and dynamic recrystallization, forming small grains around the margins of larger grains. Pressure shadows around detrital quartz are filled with finely recrystallized quartz and oriented mica, and may be sufficiently extensive to give the rock a differentiated layering parallel to the cleavage. Phyllites commonly show crenulation cleavages, in addition to the primary deformational fabric.

The thrust stack as a whole, therefore, shows a gradient in ductile strain from undeformed sandstones in the higher thrusts to the strongly deformed quartzites of the Alpujarride Complex. Accompanying the strain gradient, there is a change in metamorphic grade from the unmetamorphosed rocks in the structurally highest parts of the sequence to greenschist facies in the Alpujarride Complex.

Illite crystallinity

To investigate any jumps in grade across fault contacts and to obtain a more quantitative estimate of the change in metamorphic grade between the thrust sheets of the Malaguide and Alpujarride Complexes that has been described above, 17 shales and slates were collected through the Malaguide and Alpujarride thrust stack (Fig. 3) for illite 'crystallinity' studies.

Illite 'crystallinity' is a parameter that quantifies the 'sharpness' of the (001) X-ray diffraction (XRD) peak. From upper diagenesis to lower greenschist conditions, the 10 Å illite peak decreases in width. The illite structure becomes more ordered and finally recrystallizes as muscovite which has a narrow, well-defined peak. This empirical method of relating the shape of the 10 Å diffraction peak of illite minerals to metamorphic grade was developed by Weaver (1960) and subsequently by Kubler (1967) who introduced the concept of an illite 'crystallinity' index. This index has been used to define very low-grade, metamorphic facies; the diagenetic zone, anchizone and epizone respectively. The Kubler index, used in this study, measures the width of the illite peak at half-peak height, allowing for background changes in intensity.

Experimental method and results. Sample preparation and determination of illite 'crystallinity' values were carried as recommended by the IGCP 294 working group (Kisch 1991). The <2 μm clay mineral fraction was separated from shales, slates and phyllites and two powder XRD slides per sample were prepared. For some of the slates and phyllites, polished slabs were also prepared. The slide mounts were irradiated using a Philips X-ray diffractometer 1320/00, goniometer 1050. Illite peaks of 10 Å were determined using Cu–Ka radiation at a tube rating of 45 kV and 32 mA. A pyrolitic graphite monochromator, scan speeds of 0.5°2Ø min^{-1} and two slit settings were used as follows: divergent and receiving slits 1/4°, anti-scatter slit 0.3 mm; and divergent and receiving slits 1/2°, anti-scatter slit 0.3 mm. The chart speed was set at 2 cm min^{-1} such that 40 mm represents 1°2Ø. Samples were scanned over the 7–10°2Ø range.

The XRD machine in Oxford was calibrated with interlaboratory standards of Kisch at the two different slit settings. Using calibration graphs, all results have been converted to a Kisch equivalent so that the anchizone boundaries are defined as 0.21–0.38° Δ2Ø (Kisch

Table 1. Illite crystallinity results in °Δ2Ø. For a full listing of the measurements on Oxford settings from which the means have been calculated; see Lonergan (1991)

Sample	I <2µm Powder mean	I SD	II <90µm	III Polished Slab mean	III SD	
Highest imbricates						
A X7	0.39	0.04	-	-		**Diagenetic Zone**
B 1244	0.54	0.06	-	-		
C 1503	0.46	0.07	-	-		
La Santa thrust sheet						
D X6A	0.291	0.009	-	-		**Lwr. Anchizone**
D X6B	0.25	0.01	-	-		
E 1512red	0.32	0.01	-	0.22	0.01	
E 1512gr.	0.277	0.009	-	0.21	0.02	
F 1510	0.336	0.009	-	-		
G 540	0.26	0.01	-	-		
H X1	0.38	0.02	-	0.27	0.02	
Intermediate thrust						
Canal						
J C13red	0.225	0.009	-	-		**Upr. Anchizone**
J C13green	0.227	0.009	0.211	-		
K C5	0.38	0.01	-	-		
Montysol						
L 569	0.21	0.01	0.179	0.22	0.01	**Anchizone/ Epizone**
Alpujarride phyllites						
M X3A	0.37	0.01	0.215	0.169	0.007	**Epizone**
M X3B	0.19	0.009	-	0.16	0.05	
N X5	0.17	0.01	-	-		

EPIZONE | ANCHIZONE | DIAGENETIC

0.21° 0.38° ° 2Ø

(Kisch 1990)

1990). Full details of the calibration runs and the individual measurements on each sample can be found in Lonergan (1991).

For each sample, the 10 Å illite peak was measured on the two slides three or four times. Thus the illite 'crystallinity' value (Kubler index) obtained for each sample is the mean of six or seven measurements. The results are shown in Table 1, column I. In the diagenetic zone, broad peaks may result from the presence of smectites or mixed layer structures. Samples with 'crystallinity' values in the diagenetic zone were treated with glycol and none showed any significant broadening in the peak half-width.

From these initial powder specimen results, sample X3A, a phyllite from the Alpujarride Complex, shows an anomalously broad peak yet, from thin section work, these phyllites are known to contain recrystallized mica and should yield epizone values. It was feared that the use of the $\leq 2\,\mu m$ clay fraction meant that the presence of weathered, diagenetically altered clays and other minerals were being measured which were broadening the illite peak. Therefore, for some samples that on petrographic grounds were expected to have small crystallinity values, slides with a coarser grain size were measured ($\leq 90\,\mu m$) and the samples show an increased crystallinity (column II, Table 1). However, this introduces the problem of detrital micas, known to occur throughout the thrust stack, influencing the results. Hence, for selected samples, polished slabs were made in an attempt to average the crystallinity from all grain sizes and the results are shown in column III, Table 1. All the samples show increased crystallinity (smaller values) except sample 569. For sample X3A, the XRD analysis of the polished slab resolved a second peak at 9.15°2Ø, which is a reflection of chlorite and was the cause of the anomalously broad peak measured on the powder sample. The presence of chlorite was confirmed by the occurrence of another chlorite peak at 6.2°2Ø. Though all the peaks are sharpened when a polished slab is used, in general the samples remain within the facies zones defined from the $\leq 2\,\mu m$ powder specimens.

The general trend of increasing metamorphic grade downwards in the structural pile confirms the observations made in outcrop and from thin section. The highest thrust imbricates lie within the diagenetic zone. The values for the La Santa thrust sheet fall within the lower anchizone, confirming the thin section observations that no recrystallization of muscovite has occurred. Rocks from the 'intermediate' unit have values clustering around the anchizone/epizone boundary and the Alpujarride rocks, containing abundant recrystallized muscovite, lie well into the epizone, confirming their greenschist facies grade. Illite 'crystallinity' measurements reported in a recent study by Nieto *et al.* (1994) on the metamorphism in the lower parts of the thrust stack in the Sierra Espuña are in broad agreement with the results presented here. The results in Table 1 are displayed as a map of illite crystallinity facies in Fig. 3, which highlights the rapid change in grade from lower anchizone facies of the La Santa thrust sheet to greenschist facies of Alpujarride rocks over a very short distance.

DISCUSSION

Nature of the contact between Alpujarride and Malaguide rocks

Petrographic and illite crystallinity studies show that the highest thrust slices of the Malaguide rocks in the Sierra Espuña have only been diagenetically altered whereas the deeper parts of the thrust stack (the La Santa thrust sheet) fall within the lower part of the anchizone. Petrographic and fission track studies in the Sierra de las Estancias confirm that the Malaguide rocks there have never been above 200°C (Johnson 1993). The 'intermediate' unit in the Sierra Espuña lies at the upper anchizone/epizone boundary and is separated from the overlying rocks by a major fault zone. The underlying rocks of the Alpujarride Complex exhibit epizone or greenschist facies metamorphism. It is difficult to constrain the P–T conditions for very low grade metamorphism because of the lack of chemically well-defined mineral reactions, but from the correlation of data on clay mineralogy and reactions, illite 'crystallinity', fluid inclusions, index mineral assemblages in volcanogenic rocks, coal rank and vitrinite reflectance, there is general consensus that the anchizone represents temperatures of 200–300°C (e.g. Dunoyer de Segonzac 1970, Frey 1986, 1987, Hoffman & Hower 1979, Robinson & Bevins 1986, Stalder 1979, Winkler 1979).

These simple observations pose significant problems. In the Sierra Espuña, the present structural thickness, from Eocene rocks in the highest thrust sheet to the base of the Permo-Triassic imbricates, is about 3 km (Fig. 3b). This thickness is an estimate of the total overburden after the thrust stacking in the Late Eocene (Lonergan 1993). Burial of 3 km is not enough to generate temperatures on the order of 200–300°C required for the 'intermediate' unit metamorphism nor the 300°C required for the greenschist facies metamorphism of the underlying Alpujarride rocks for any normal geothermal gradient.

The most interesting and puzzling feature of these results is the rapid increase in metamorphic grade that occurs over small structural thicknesses at the Malaguide/Alpujarride boundary both in the Sierra Espuña and the Sierra de las Estancias. There are a number of mechanisms that might explain the rapid increase in metamorphic grade: (1) the metamorphism occurred prior to the present thrust stacking, as postulated by Egeler (1974); (2) the present structural thickness is a reduced section and parts of the sequence have been excised, as suggested by Platt (1986) and Aldaya *et al.* (1991); (3) the original geothermal gradient generating the metamorphism was abnormally high. However, while an abnormally high geothermal gradient would explain the lack of sufficient structural thickness, it does not explain the juxtaposition of metamorphic grades at the faulted contact between the Malaguide and Alpujarride Complexes and hence can be discounted as a mechanism.

The large fault zone between the Alpujarride and Malaguide Complexes in both the Sierra Espuña and the Sierra de las Estancias juxtaposes units with differing metamorphic grade. There are no stratigraphic markers that indicate the nature of the offset on this fault zone but it does represent the excision of a significant structural thickness in that rocks deformed at a maximum of 200°C are in contact with rocks deformed at a minimum of 300°C. In other words, the shear zone brings lower grade rocks on top of higher grade rocks. Platt (1986) and Platt & Vissers (1989) interpret this sort of relationship as an extensional contact. Similarly, Thompson & Ridley (1987) postulate that if crustal thickening is followed by extension of the thickened pile, there will be local areas of condensed isograds. From the available data, the most reasonable interpretation of the Malaguide/Alpujarride contact is that it is an extensional fault that post-dates the Alpine thrusting and compressional deformation that originally thickened both complexes, emplaced one above the other, and caused the synkinematic metamorphism.

Pervasive Miocene brittle normal faults that post-date the thrusting dissect the whole of the Permo-Triassic imbricate thrust stack in the Sierra Espuña (Lonergan 1991). Most of the observed faults are metre-sized, with no stratigraphic cutoffs, so that it is impossible to estimate the amount of extension that they may have accommodated. Assuming a geothermal gradient of 20–30°C km^{-1}, a minimum burial of 7–10 km was required to generate anchizone metamorphism at the base of the Malaguide thrust stack. Distributed extension on the brittle faults may have contributed to the overall thinning of the structural pile, but is unlikely to account for the minimum estimate of 230% extension required to thin the thrust stack from 10 to 3 km. The majority of the extension was accommodated along the fault at the Malaguide/Alpujarride contact, with the brittle faults in the hangingwall testifying to the pervasive nature of the extension throughout the thrust stack.

Timing of movement on the Malaguide/Alpujarride contact

The constraints provided by the fission track results in the Sierra de las Estancias (Johnson 1993) suggest that the extensional motion on the Malaguide/Alpujarride boundary occurred in the earliest Miocene. This clearly post-dated the original stacking of the Malaguide above the Alpujarride Complex. The compressional motion on the boundary probably pre-dates the early high P/T ratio metamorphic event in the Alpujarrides, as this is likely to have been a consequence of the crustal thickening. A minimum age of 25 Ma was determined for this event by Monié *et al* (1991). Compressional motion may well have roughly coincided with thrusting in the Malaguides, which started in the Late Eocene (Lonergan 1993).

In the Sierra Espuña, the evidence from the gypsum fault zone indicates that there has been movement on the fault as late as Middle Miocene times, but we cannot be certain that the gypsum fault is linked to the main rauhwacke fault zone in the Sierra Espuña. Nor can we be certain that the Middle Miocene stratigraphic age represents the extensional motion on this contact, because the latest motion on this segment of the fault involves WSW-directed thrusting. Given these uncertainties, we feel that the Middle Miocene stratigraphic age probably represents a compressional reactivation of the gypsum fault zone. During the Early–Middle Miocene, just to the north of the Malaguide/Alpujarride boundary, convergence continued between the Internal and External zones along the Internal/External zone boundary (IEZB on Fig. 1) (Lonergan *et al.* 1994). The calc-mylonite in the Sierra de las Estancias was folded after its extensional history due to this convergence, so Middle Miocene compressional reactivation in the Sierra Espuña is not surprising. At the boundary between the extending Internal Zones and the region of shortening in the External Zones, extension and shortening are likely to have alternated during Early–Middle Miocene times.

Monié *et al.* (1991) dated micas in a mylonitic quartzite from the predominantly W-directed extensional shear zone between the Alpujarride Complex and the underlying Nevado–Filabride Complex and obtained ages between 16 and 17 Ma. If these ages are regionally representative, it appears that extensional motion on the Malaguide/Alpujarride contact occurred earlier than on the deeper Alpujarride/Nevado–Filabride contact.

Kinematics of the Malaguide/Alpujarride contact in the eastern Betics

In the Sierra de las Estancias, the sense of motion on the contact when it is unfolded is clearly ENE-directed. In the Sierra Espuña, the most consistent kinematic indicators are from the gypsum fault zone and give a sense of shear of top–NNW; it is likely that the extensional fault has been reactivated at this locality, however, and hence the sense and direction of shear from the gypsum fibres may not represent the original kinematics on the extensional fault. From the rauhwacke shear zone the sense of shear ranges from top-NW to top-NE, but again the possibility of reactivation precludes us from interpreting this data as representative of the original extensional sense of shear.

Significant vertical-axis rotations have been documented from the External Zones of the Betic Cordillera (Allerton *et al.* 1993, Platzman & Lowrie 1992), and these largely occurred during Early–Middle Miocene thrusting (Allerton 1994, Platt *et al.* 1995). These are predominantly clockwise and of the order of 60–90°, though they are locally larger. Allerton *et al.* (1993) have also shown that the Sierra Espuña thrust stack rotated about 200° clockwise about a vertical axis between the Late Oligocene and the Late Miocene. These authors proposed that the Internal/External Zone boundary on the north side of the Sierra Espuña and the Malaguide/Alpujarride boundary fault zone on the southern side of the thrust stack accommodated this rotation. In view of these large rotations, the kinematic data documented in this paper may have been differently oriented (with respect to geographic coordinates) at the time they formed.

CONCLUSIONS

The simplest explanation of anchizone metamorphism at the base of the thin Malaguide thrust stack and the rapid increase of metamorphic grade observed across the Malaguide/Alpujarride contact is that Miocene extension has significantly thinned a previously thickened orogenic thrust stack. In the Sierra de las Estancias, kinematic data collected along the extensional contact suggest that movement was ENE-directed and that extension took place in the Early Miocene. In the Sierra Espuña, at least part of the original extensional contact may have been reactivated later and hence the sense of shear is not so clearly defined. The detailed history of the contact is complicated, with extension cross-cutting structures relating to earlier Alpine shortening and then the extensional contact itself undergoing further shortening as convergence with the nearby External Zones continued.

The interpretation of the Malaguide/Alpujarride contact documented here is similar to the interpretation of Alpujarride/Nevado–Filabride at deeper structural levels (Platt 1986, Platt & Vissers 1989, Galindo-Zaldívar *et al.* 1989, Jabaloy *et al.* 1993) and confirms that Miocene extension was widespread at all structural levels in the Internal Zones. Extensional motion on the Malaguide/Alpujarride contact may have finished somewhat earlier than that on the Alpujarride/Nevado–Filabride contact. The opposing sense of shear on the two contacts contributes to a picture of large-scale, roughly co-axial horizontal extension during the Early–Middle Miocene.

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