Journal of Structural Geology, Vol. 14, No. 2, pp. 193 to 203, 1992
Printed in Great Britain

0191-8141/92 $05.00+0.00

Tectonic evolution of the Alpujárride Complex (Betic Cordillera, southern Spain)

JOSÉ M. TUBÍA and JULIA CUEVAS

Geodinámica, Facultad de Ciencias, Universidad del País Vasco, 48080 Bilbao, Spain

FRANCISCO NAVARRO-VILÁ and FERNANDO ALVAREZ

Departamento de Geología, Fac. Ciencias, Univ. de Salamanca, 37008 Salamanca, Spain

and

FLORENCIO ALDAYA

Departamento de Geodinámica, Fac. Ciencias, Univ. de Granada, 18071 Granada, Spain

(*Received* 27 *September* 1990; *accepted in revised form* 2 *July* 1991)

Abstract—The Alpujárride Complex, belonging to the Internal Zones of the Betic Cordillera, is an E–W elongated domain of metamorphic nappes, which extends over more than 400 km in southern Spain. The Alpujárride Complex suffered two shearing episodes defined by different kinematic and physical conditions. The first one involved ductile thrusting from the south-west towards the north-east, related to the regional metamorphism of the Alpujárride nappes. This process led to crustal thickening, related to which the hot thrusting of the Ronda peridotites occurred. The second shearing episode, directed northwards, occurred after the metamorphism. It corresponds to a deformation in the brittle–ductile transition that led to the thinning of the crust thickened in the previous episode.

Previous tectonic models of the Betic Cordillera have only considered the northwards shearing, which reflect the N–S convergence of Europe and Africa from the Oligocene onwards. The present work clearly points to the existence of previous episodes of ductile thrusting towards the north-east that reflect an earlier process of continental collision and that in future should be considered in tectonic models of the Betic orogen.

INTRODUCTION

THE Betic Cordillera, in southern Spain, is the northern branch of an Alpine orogenic belt—the Betic Rifian system—arched around the Straits of Gibraltar. Within the Betic Cordillera the following can be differentiated (Fig. 1).

(1) *The External Zones*: these comprise sedimentary rocks corresponding to the Mesozoic and Tertiary cover linked to the South-Iberian paleomargin. Within the External Zones, the following parts have been distinguished (Fallot 1948, Julivert *et al.* 1973): the Prebetic, situated to the north-west and the Subbetic to the south and south-east. These domains are characterized by different depositional sequences and have been affected by thrusting towards the north (García-Dueñas 1969) or north-west (Bourgois 1978), produced by thin-skinned compressive tectonics (García-Hernández *et al.* 1980), that led to the superimposition of the Subbetic over the Prebetic (Fig. 1b).

(2) *The Betic Zone*, also called the Internal Zones, was unrelated to the External Zones until the Tertiary times. Essentially, the zone comprises metamorphosed Paleozoic and Mesozoic rocks, distributed throughout three main complexes (Egeler & Simon 1969). From bottom to top, these are the *Nevado-Filábride Complex*, one of whose units exhibits a high-pressure metamorphism, with eclogites and blueschists (De Roever & Nijhuis 1964, Morten *et al.* 1987) and a dismembered ophiolite suite (Bodinier *et al.* 1987) dated at 146 Ma (Hebeda *et al.* 1980). The *Alpujárride Complex*, situated in an intermediate position, is characterized by an Alpine metamorphism of intermediate pressure type. Above, appears the *Malágide Complex*, formed of Paleozoic rocks affected by low-grade metamorphism of Hercynian age (Chalouan 1986), over which lies the discordant Permo-Triassic and a sequence that reaches the Eocene. There are also other sedimentary units, such as the "allochthonous flysch of the Campo de Gibraltar" (Bourgois 1978) and the "Dorsal Bético-Rifeña" (Bouillin *et al.* 1986), of debatable origins.

The present work discusses the relationships between the minor structures and kinematics of thrusting within the Alpujárride Complex, together with the structural evidence for the existence of the phase of synmetamorphic ductile shearing directed, on average, towards the NE or ENE that occurred before the movement towards the north. It is based on data obtained from the Ph.D. theses of the five authors (Aldaya 1969, Navarro-Vilá 1976, Tubía 1985, Alvarez, 1987b, Cuevas 1988) and observations made in intermediate zones.

The N-directed thrusting that was established some time ago (Brouwer 1926), has been a key part in current geodynamic models of the Betic Cordillera, whose tec-

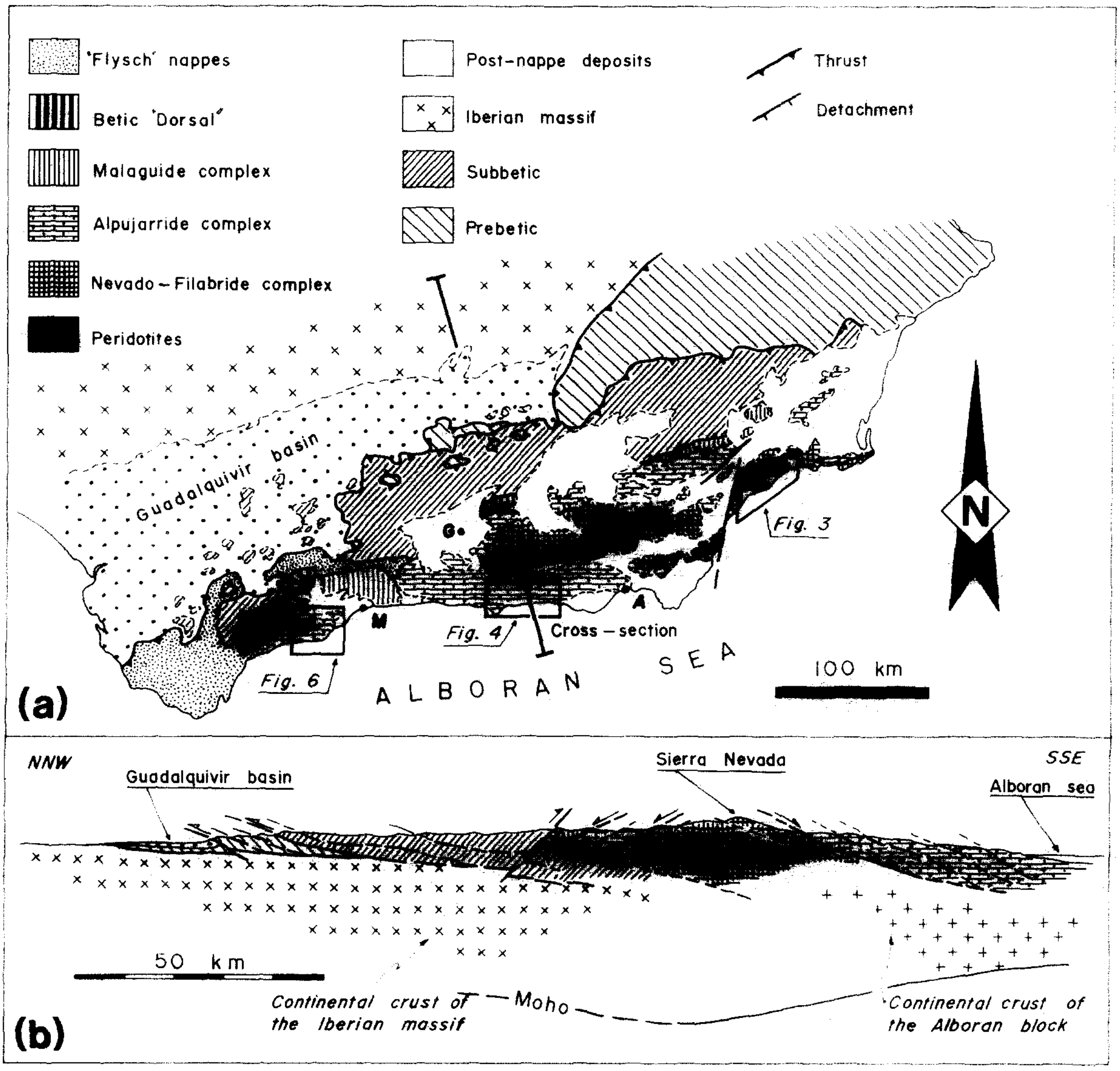

Fig. 1. (a) Sketch map of the Betic Cordilleras, showing the position of the Alpujárride Complex and the location within it of the selected areas. A: Almeria, G: Granada, M: Málaga. (b) General cross-section showing the relationship between the different domains of the Betic Cordilleras. Moho depth according to Banda *et al.* (1983).

tonic history has been explained in different ways. Andrieux *et al.* (1971) proposed the existence of a small microplate—the Alboran block—between the African and European plates. The N–S convergence of these plates and the displacement towards the west of the Alboran block would explain the development of the Gibraltar arc as well as the N-directed nappes of the Betic Cordillera (Andrieux *et al.* 1971). Further models have interpreted the Betic Cordillera as a collisional orogen that has gone through a later episode of extensional collapse (Torres-Roldán 1979, Platt *et al.* 1983, Platt 1986). This extensional collapse has been related, for example, to the delamination of the lithospheric mantle (Platt & Vissers 1989), or to the existence of a mantle diapir under the Alboran Sea (Weijermars 1985). All these models are based on northward movement in the Betic Cordillera and its centrifugal distribution around the Straits of Gibraltar, within the context of the Betic–Rifian orogen. The main problems of such models are to do with the kinematics of the Betic Zone, where displacement directions are generally orientated E–W or NE–SW. This work provides new structural data from the Alpujárride Complex which cannot be explained by such models.

THE ALPUJÁRRIDE NAPPES

Within the Betic Zone the Alpujárride Complex crops out almost continuously from east to west. It is composed of a variable number of tectonic units that differ from one traverse to another. From a lithological point of view it is characterized by metapelites in the lower part, presumably of Paleozoic or Permo-Triassic age (Aldaya *et al.* 1979), that are affected by a metamorphism of variable intensity, and a carbonate formation, which in some cases can be dated as the Middle or Upper Triassic (Fallot *et al.* 1960, Kozur & Simon 1972).

In view of the intensity of the metamorphism and the lithological characteristics, the Alpujárride Complex can be grouped (Fig. 2) into three units.

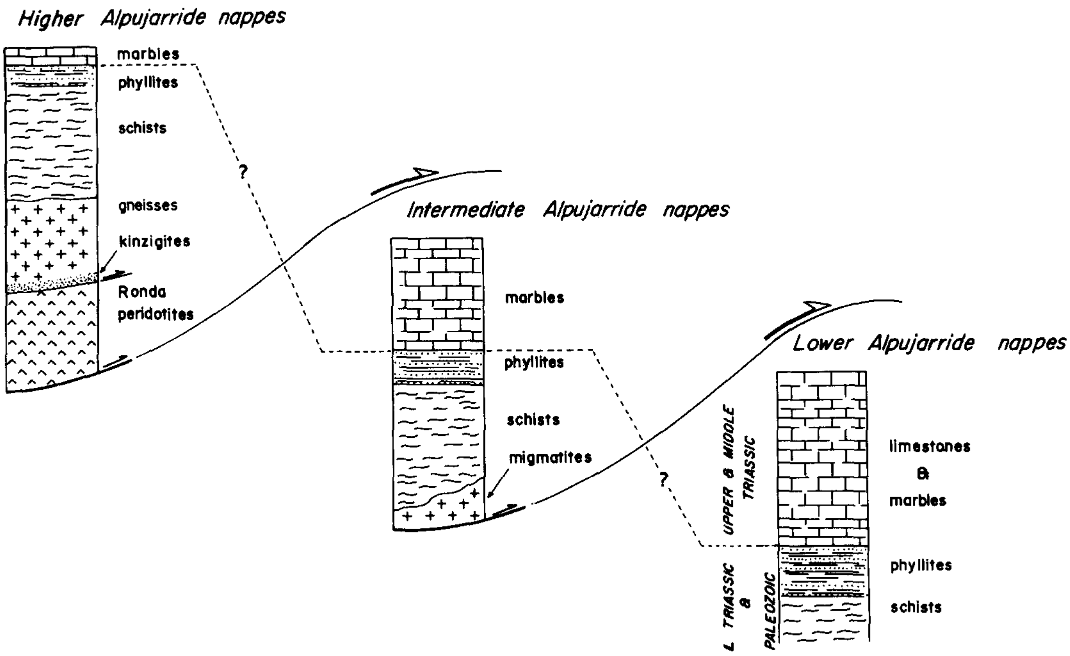

Fig. 2. Composite logs of the three groups of Alpujárride nappes differentiated in the text. Only the carbonate succession of the Lower Alpujárride nappes has been dated paleontologically as belonging to the Middle and Upper Triassic (see text). The Ronda peridotites outcrop exclusively in the Los Reales Nappe, west of Malaga (Fig. 1).

(1) The *Lower Alpujárrides* reached a metamorphism of very low to low grade, as shown by metamorphic associations with chlorite ± biotite or chloritoid. This group exhibits a well-developed carbonate formation paleontologically dated as Middle and Upper Triassic (Kozur *et al.* 1985). Within this group, recent descriptions have reported the presence of carpholite (Goffé *et al.* 1988).

(2) The *Intermediate Alpujárrides*, with a metapelite sequence that reaches medium to high metamorphic grade. The lower portions of the metapelitic sequence in this group of nappes usually show garnet ± staurolite ± sillimanite ± potassic feldspar. Eclogites have been recognized recently in amphibolites interlayered with these metapelites (Tubía & Gil Ibarguchi 1991). They have a well developed and totally metamorphosed carbonate formation in which similar sequences to those dated as Middle and Upper Trias in the Lower Alpujárrides have been recognized (Delgado *et al.* 1981).

(3) The *Higher Alpujárrides*, comprise a group of nappes that always appear in the upper tectonic position and whose metapelite formation reaches the highest metamorphic grade. To the west of Malaga the base of the higher Alpujárrides are formed by the peridotite massifs of Ronda, overlaid by a narrow band of kinzigites and cordierite-bearing migmatites (Navarro-Vilá & Tubía 1983). The Triassic carbonate formation is present sparingly or not at all in this group of nappes.

Some authors have proposed a pre-Alpine age for the metamorphism of the Alpujárride Complex (Simon 1963, Aldaya 1969, Egeler & Simon 1969, Kornprobst 1976, and many others). However, today the Tertiary age (22 Ma) of the metamorphism of this complex is accepted on the basis of radiometric dating of dynamothermal aureoles surrounding the Ronda peridotites (Loomis 1975, Priem *et al.* 1979). Nevertheless, more structural and petrological data are needed in order to understand the geodynamic meaning of this Tertiary age, since post-nappe sediments of Upper Oligocene to Aquitanian age (24–22 Ma) contain metamorphic and peridotite debris (Bourgeois 1978, Martín-Algarra & Estévez 1984).

THE MAIN DEFORMATION PHASES

In all the Alpujárride nappes it is possible to recognize several generations of structures related to a synmetamorphic process of deformation. These structures can be seen even in the Triassic carbonate rocks of the Alpujárride sequences (Navarro-Vilá 1976). Folds, axial plane foliations and lineations can be divided into three groups according to their relationships with the regional foliation. The first group (D_1) is represented by a scarce schistosity that is crenulated by the regional foliation, and that is only preserved in the least metamorphosed rocks of each nappe. The second group (D_2) is characterized by the regional foliation and tight folds. The last group (D_3) comprises folds, that are clearly superimposed on the regional foliation in the higher levels of the nappes and that generate a new schistosity in the zones of greater metamorphism and mylonites close to the contacts of the ductile thrusts associated with this deformation phase.

The present paper discusses the structural evolution of several sectors of the Alpujárride Complex where structural maps exist. The sectors chosen offer good examples of the different structures related with ductile thrusting towards the ENE or NE that have not been described until very recently (Tubía 1985).

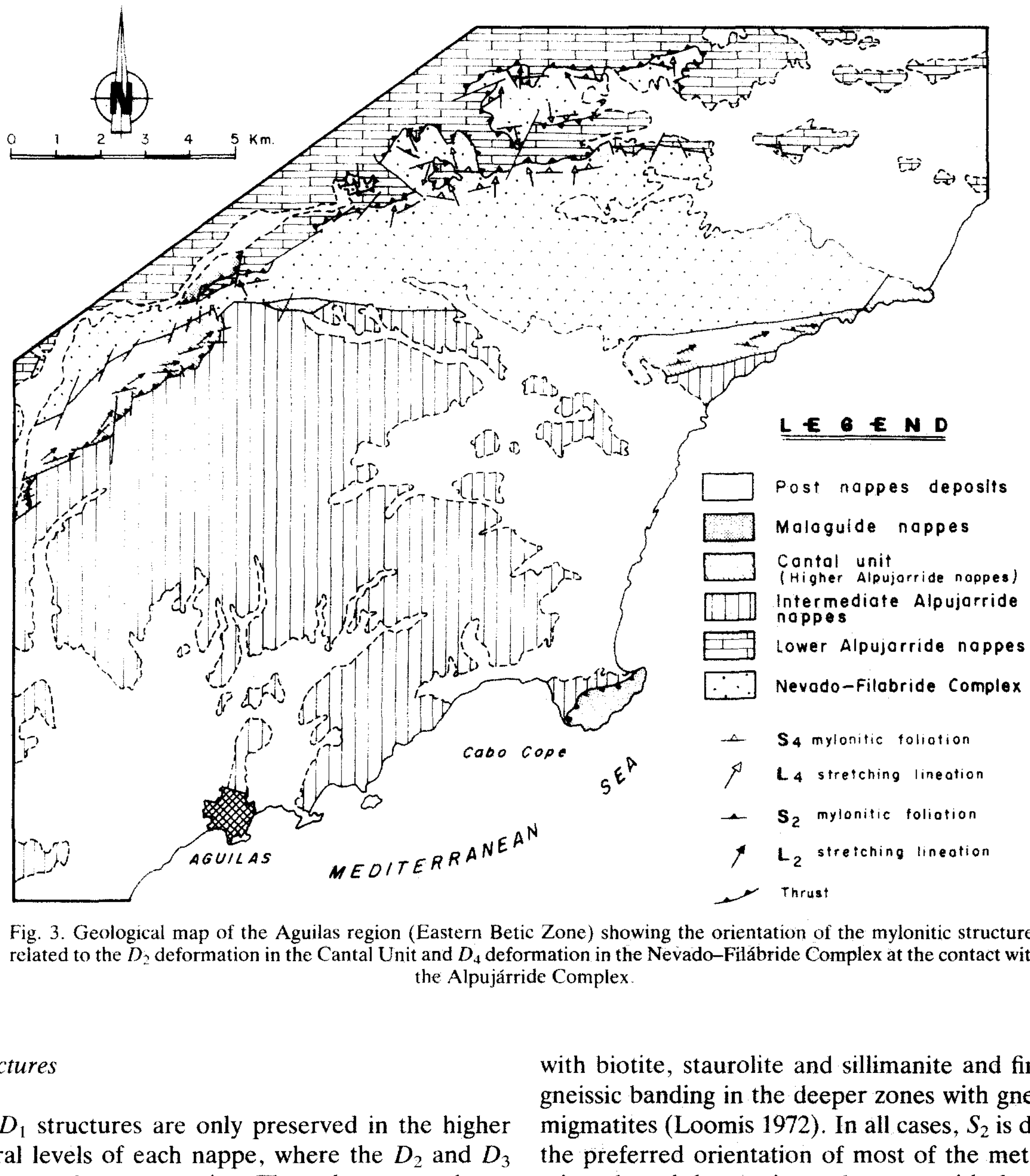

Fig. 3. Geological map of the Aguilas region (Eastern Betic Zone) showing the orientation of the mylonitic structures related to the D_2 deformation in the Cantal Unit and D_4 deformation in the Nevado–Filábride Complex at the contact with the Alpujárride Complex.

D_1 *structures*

The D_1 structures are only preserved in the higher structural levels of each nappe, where the D_2 and D_3 structures are less penetrative. The only structural vestige of D_1 is a S_1 schistosity, defined by the preferred arrangement of chlorite and biotite flakes. S_1 schistosity is strongly crenulated by S_2—the regional schistosity. Neither mesoscopic folds nor shear senses related to S_1 can be recognized, due to the intensity of the succeeding deformations.

D_2 *structures*

The D_2 structures provide the main elements of the fabric of the rocks in most of the Alpujárride nappes. During D_2, isoclinal folds were formed that can even be recognized in the Triassic limestones of the Lower Alpujárrides. These folds always exhibit an axial plane foliation, S_2, which varies in morphology and intensity according to the lithology and structural level at which it is developed. This variation is particularly pronounced in the Higher Alpujárrides, where the S_2 crenulation cleavage of the upper layers of the sequences evolves to a S_2 schistosity in the intermediate levels of the schists with biotite, staurolite and sillimanite and finally a S_2 gneissic banding in the deeper zones with gneisses and migmatites (Loomis 1972). In all cases, S_2 is defined by the preferred orientation of most of the metamorphic minerals and, hence, is synchronous with the prograde metamorphism (Aldaya *et al.* 1979). A D_2 mineral lineation is also developed, which coincides with the stretching lineation defined by the elongation of clasts in conglomerates. This lineation is parallel to the axes of the F_2 folds, which have orientations ranging from N50°E to N70°E.

In the Eastern Alpujárrides, the unit belonging to the Higher Alpujárride group (the Cantal Unit in Fig. 3) exhibits mylonite bands related to the D_2 episode (Alvarez 1987a,b). The stretching lineation, L_2, within D_2 mylonites also trends between N50°E and N70°E (Fig. 3). The micaschists within the D_2 mylonite bands show *S–C* fabrics (Berthé *et al.* 1979), or *S–C* mylonites of type II, according to the classification of Lister & Snoke (1984).

Kinematic criteria, such as *S–C* structures, asymmetric pressure shadows and single girdle patterns of quartz *c*-axes (Alvarez 1987a) in mylonites show that the dominant shear component related to D_2 ductile shearing is top-to-the-NE.

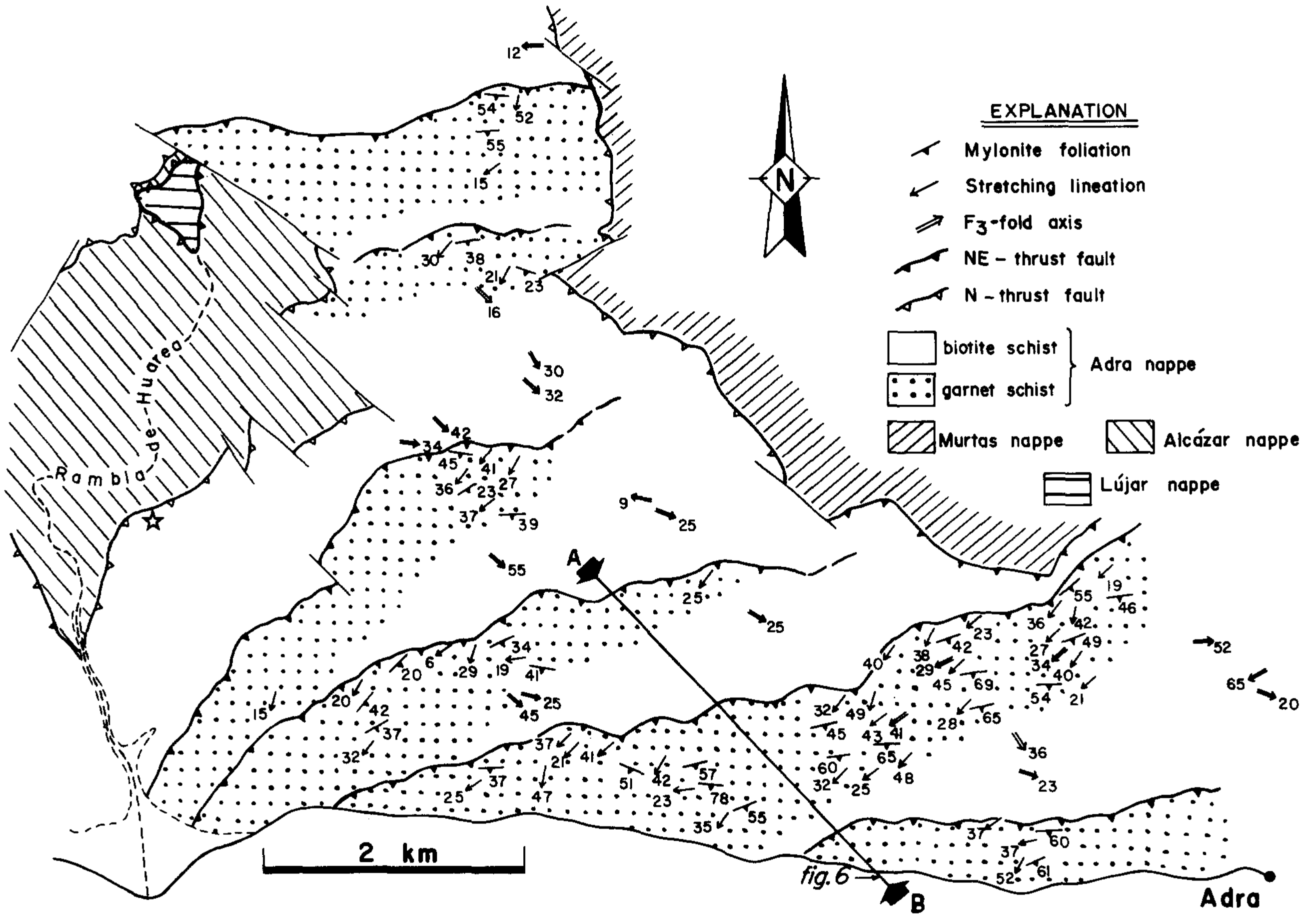

Fig. 4. Structural map of the Adra Nappe (Higher Alpujárrides), showing the coexistence of two shearing episodes that can be recognized in the Alpujárride Complex. The first one, under ductile conditions, is associated with a stretching lineation (L_3) towards the NE. The star indicates the location of Fig. 8. A–B is line of cross-section in Fig. 5.

D_3 *structures*

The D_1 and D_2 structures seen in the Alpujárride sequences are overprinted in successively lower levels by the D_3 structures. In the area of Adra, to the south of the Sierra Nevada (Fig. 4), the development of the D_3 structures is clearly related to ductile thrusting directed towards the NE. The Adra Nappe, which is the highest Alpujárride nappe in this sector (Fig. 4) is formed of a metapelite succession 3 km thick, affected by a progressive metamorphism with normal zoning, that varies from high grade with migmatites, to low grade, represented by schists with chlorite.

Several small thrusts developed by the end of D_3 deformation have been found in the Adra Nappe that give it an imbricated structure (Fig. 4). A transversal section across the Adra Nappe shows increasing intensity of D_3 deformation at successively lower structural levels in all imbricate slabs (Fig. 5). The F_3 folds show considerable geometric variation. In chlorite or biotite schists at high levels, the F_3 folds are generally open and some are chevron-like. They commonly lack axial plane foliation, but sometimes have an axial plane crenulation cleavage in the hinge zones. These F_3 folds have curved hinges and form at high angles to the previous L_2 lineation.

In higher grade metamorphic rocks, located close to the basal thrusts of the imbricates, there is a progressive decrease in the inter-limb angle of F_3 folds, which finally become isoclinal. The modification in the geometry of the F_3 folds is accompanied by considerable variation in their axial orientation. Indeed, at higher levels the F_3 fold axes plunge towards N120°E, whereas in basal zones they plunge towards N235°E. This suggests a reorientation of the F_3 fold axes towards the movement direction related to shearing deformation that can be observed at the base of all the imbricates, where mylonite rocks outcrop. The appearance of a L_3 stretching lineation subparallel to F_3 fold axes and the presence of sheath folds in the mylonite zones supports the above hypothesis. This type of variation is also accompanied by a transition in axial plane foliation from crenulation cleavage in the more open F_3 folds to schistosity in the tighter F_3 folds. Quite commonly, the development of the new S_3 schistosity involves the transposition of previous S_1 and S_2 schistosities.

In the mylonite zones, the schistosity is parallel to the thrust contacts. At first sight, the mylonite foliation produces outcrops with a simple planar geometry, although there are often intrafolial folds that suggest that such apparent simplicity is due to an intense degree of deformation. This kind of situation is particularly

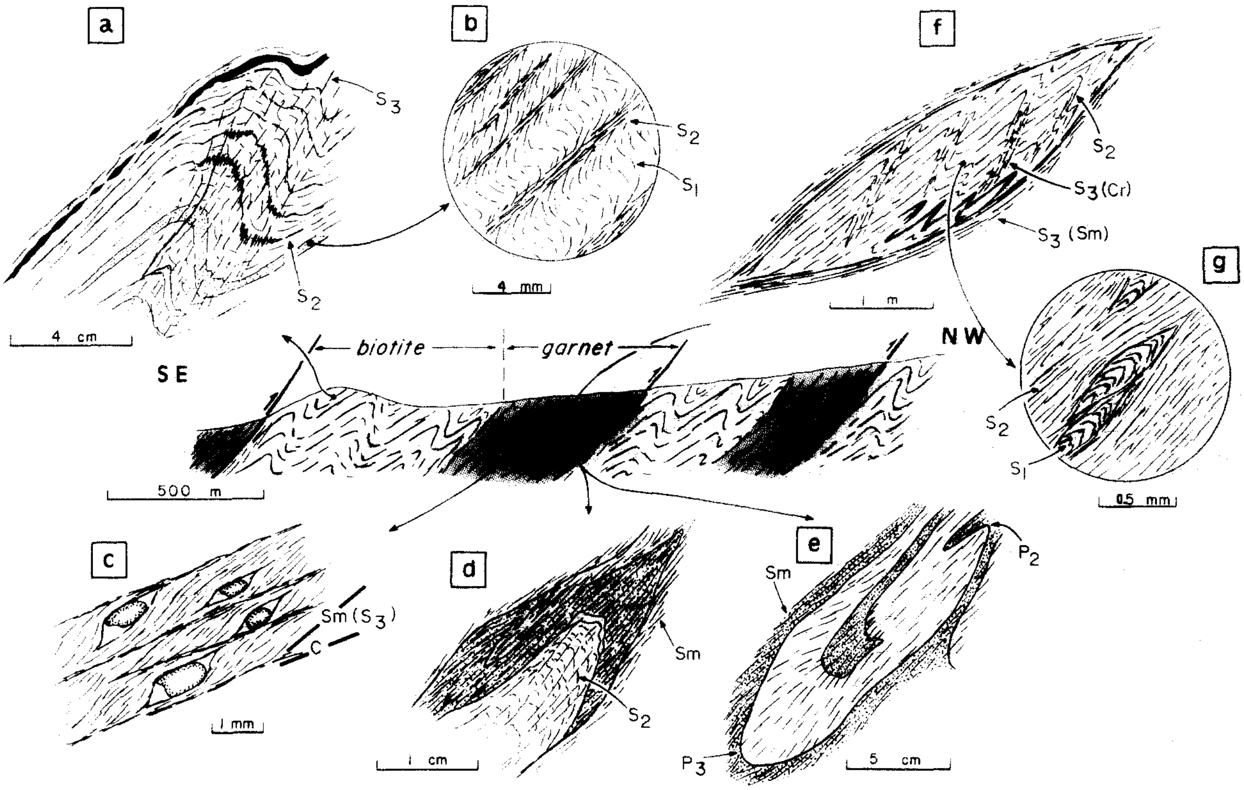

Fig. 5. Structural variation in a thrust sheet of the Adra Nappe. Its upper part, composed of biotite-schists, is characterized by open F_3 folds with a weakly-developed crenulation cleavage (a). In this zone, the S_1 and S_2 schistosities are generally conserved (b). The descent towards the thrust contact involves an increase in the intensity of D_3 deformation which can be recognized by the appearance of a marked *L–S* fabric and of *S–C* structures in the garnet-bearing schists (c). In these rocks, the F_3 folds are tight and develop an axial plane mylonite foliation (Sm) (d & e), although occasionally open F_3 folds are conserved within some quartzite enclaves (f & g). All structural criteria correspond to an *XZ* cross-section.

apparent in lozenge-shaped bodies of boudinaged quartzites in the mylonite zones. Such bodies reveal interference of F_2 and F_3 folds and the coexistence of S_1, S_2 and S_3 foliations (Fig. 5), showing that in the Adra Nappe the mylonitization processes continued during D_3 (Cuevas *et al.* 1986). The thrusts which lead to the imbricate structure of the Adra Nappe developed towards the end of the D_3 episode, after the main D_3 mylonitization. We interpret the thrust faults to originate within the weak D_3 mylonite zones and climb up through the sequence of the Adra Nappe (Fig. 5). Branch lines seem to be located south of the Rambla de Huarea, as suggested by the thinning of imbricate slabs towards the southwest (Fig. 4).

In the Higher Alpujárrides to the west of Malaga, three main deformation phases can be recognized as well as ductile overriding towards the ENE. However, the tectono-thermal evolution of this sector shows certain specific features related to the Ronda peridotites. The ultrabasic rocks of Ronda have been classified as Alpine-type peridotites with an lherzolitic composition (Hernández-Pacheco 1967, Obata 1977, 1980). They form an allochthonous slab (Westerhoff 1977, Thompson-Lundeen 1978) limited by two ductile shear zones and have been thrust from WSW to ENE above two other Alpujárrides nappes (Tubía & Cuevas 1986).

As may be seen in the Sierra Alpujata massif, the Ronda peridotites show the imprint of two successive ductile deformation episodes. The first one is represented by the coarse-grained peridotites with porphyroclastic or protogranular textures of the massif core (Fig. 6). These represent a mantle deformation at high temperature (>1000°C) and low deviatoric stress (10–20 MPa), according to the fabric of the olivine and the size of the neoblasts of olivine, respectively (Tubía 1985). At the edges of the peridotite slab such deformation is replaced by another that would have occurred at lower temperatures (≈800°C) and higher deviatoric stress (100–200 MPa), in agreement with the presence of fine-grained peridotites with mylonite textures.

The second deformation of the peridotites also produced a mylonitization of the underlying migmatites. In both the migmatites and peridotite mylonites there is a marked N70°E stretching lineation (Fig. 6) and the kinematic criteria indicate the same direction of thrusting for the Ronda peridotites, from the WSW to the ENE (Fig. 6). Accordingly, the latter plastic deformation of the peridotites can be integrated into the deformation path that led to the appearance of ductile thrusting towards the ENE in the Alpujárride nappes.

In short, the stretching lineation with a mean SW–NE trend can be observed over more than 350 km along the Alpujárride Complex. From kinematic criteria it can be seen that this lineation is related to top-to-the-NE ductile thrusting, pointing to common kinematics for the three studied areas.

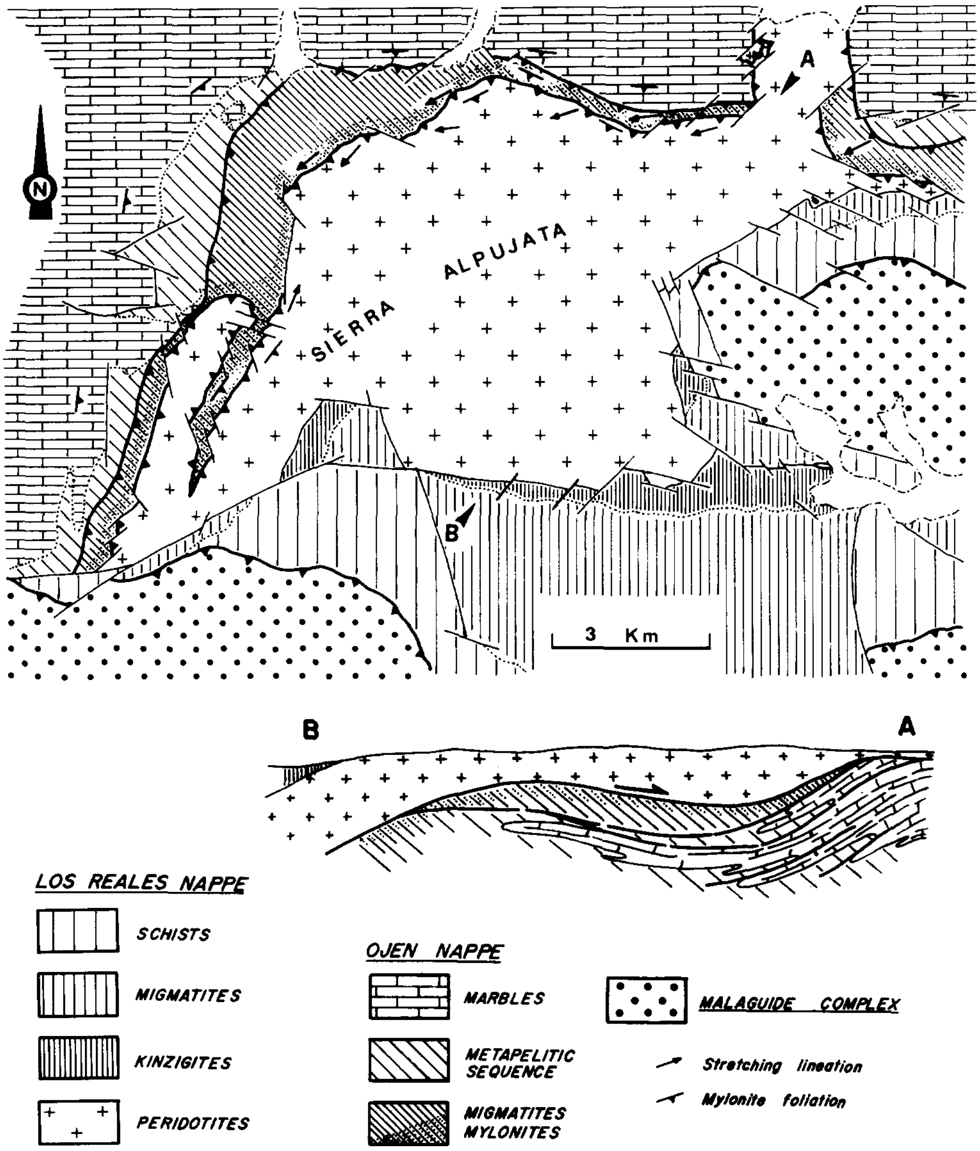

Fig. 6. Schematic map of the Ronda peridotites in the Sierra Alpujata massif (from Tubía & Cuevas 1987, modified). The basal thrusting of the peridotites produces a dynamothermal aureole, with migmatites and mylonites, in the underlying Ojen Nappe. The mylonites exhibit a pronounced stretching lineation with a mean N70°E direction. As may be seen in the cross-section, the peridotites correspond to an allochthonous slab, 1.5 km thick, that has thrusted over the Ojen Nappe (Intermediate Alpujárrides) from the WSW to the ENE. The white indicates the post-nappe deposits.

METAMORPHIC EVOLUTION

A striking characteristic of the Alpujárride metamorphism, regardless of the pressure and temperature conditions reached by the different nappes comprising it, is the existence of a prograde metamorphism that is typical of a low- and medium-grade pressure gradient, followed by a thermal event (Egeler & Simon 1969, Westra 1969, Navarro-Vilá 1976, Aldaya *et al.* 1979).

During D_1, the metamorphism was low grade, with crystallization of quartz, chlorite, white-mica and biotite defining the S_1 slaty cleavage. As may be seen in the Higher Alpujárrides, the peak of prograde metamorphism was reached during the D_2 phase, and the transition from D_2 to D_3 was conditioned by a marked drop in pressure. In the Adra Nappe (Fig. 7) for example, most of the metamorphic blastesis, in particular that of garnet, kyanite and plagioclase, was associated with the S_2 schistosity, as may be inferred from rotated porphyroblasts in which the S_1 trails are continuous with the S_2 schistosity. The degree of crystallization at the time of D_3 was not as important as during D_2. Normally, the new S_3 schistosity is only associated with the formation of biotite, although sillimanite is also related with D_3, indicating that temperature was still fairly high. These facts imply that temperatures of about 660°C and pressures of around 650 MPa were reached during D_2, while during D_3 pressures fell to 450 MPa, with the temperature remaining at 630°C (Cuevas 1988).

In the mylonite schists of the Adra Nappe, the mylonitic foliation, defined by quartz and biotite, contains porphyroclasts of garnet and staurolite. Furthermore, many porphyroclasts of these minerals have undergone stretching and fracturing, leading to the crystallization of biotite and quartz. These observations suggest that the mylonite zones of the Adra Nappe developed later than the metamorphic peak.

This metamorphic pattern is slightly different in the westernmost Alpujárride nappes, where the thrusting of the Ronda peridotites at temperatures of around 800°C led to partial melting in the metapelitic footwall rocks, giving a dynamothermal aureole (Fig. 6) and acidic dykes that intruded into the peridotites (Loomis 1972, Tubía & Cuevas 1987).

D_4 DEFORMATION EPISODE: SHEARING TOWARDS THE NORTH

The synmetamorphic structures reported above are cut by low-angle faults with a movement towards the north. The deformation is confined to the proximity of the faults, where there is a marked inflection of earlier schistosites and mylonite zones. Moreover, the fault rocks developed during this episode are gouges and fault-breccias (Fig. 8). Such evidence suggests that during the motion on the N-directed faults deformation was in the brittle–ductile transition.

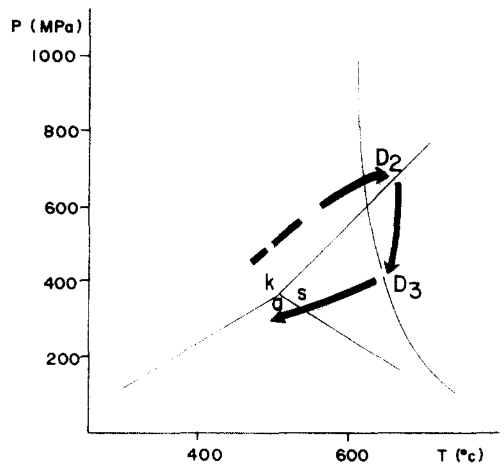

Fig. 7. Metamorphic evolution of the Adra Nappe (Higher Alpujárrides), after Cuevas (1988) modified. The metamorphic peak (650 MPa and 660°C) was reached during D_2. The transition from D_2 to D_3 is characterized by an important pressure fall, under approximately isothermal conditions. The position of the Al_2SiO_5-triple point is after Holdaway (1971).

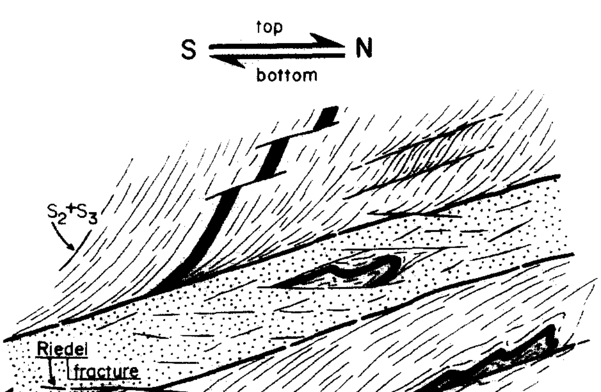

Fig. 8. Kinematic criteria associated with shearing towards the north. The generalized presence of gouge layers and of different types of fractures suggests that deformation occurred during the brittle–ductile transition. Location shown on Fig. 4.

The fault surfaces exhibit slickenside striations with an average orientation of N170°E, which persists very uniformly in the Central and Eastern Alpujárrides. Numerous contacts, specially those showing thick gouges and fault-breccias bounded by competent rocks such as limestones or quartzites, are cut by low-angle normal faults (Fig. 8). These faults, which displace the hanging-wall block towards the north have been interpreted as Riedel fractures associated with the N-directed thrusts (Cuevas *et al.* 1986, Alvarez 1987b).

Apart from the Riedel-type faults, other kinematic criteria that reveal the movement sense towards the north are afforded by the displacement of lithological markers that are cut by minor subhorizontal faults, *S–C* tectonites (in the sense of Lister & Snoke 1984), and asymmetric folds with E–W axes verging towards the north (Fig. 8).

In many cases the N-directed shearing corresponds to an extension (Navarro-Vilá 1976, Cuevas 1988) that causes a dismembering of the earlier former synmetamorphic nappes. This feature, that is well seen to the north of Sierra Nevada, gives rise to numerous thin units of a single nappe dispersed over large areas. Another aspect of these units is that they normally conserve the order of the metamorphic and lithological sequence, i.e. carbonate rocks over a metapelite succession, typical of the Alpujárride Complex.

Related to this shearing phase in the Central Alpujárrides are N-vergent synclines, formed locally in proximity to accumulations of carbonate rocks belonging to the Lower Alpujárrides. They are bounded by the thrusts developed during this episode. These folds deform the S_2 and S_3 regional schistosity and overturn the metamorphic isograds and the lithological succession. A new crenulation cleavage, S_4, is developed in the cores and inverted limbs of these folds, but without formation of new minerals.

DISCUSSION AND CONCLUSIONS

In the overall arrangement of the Alpujárride Complex two main episodes of shearing occurred; these can be distinguished by both their kinematics and relationships with metamorphism. The earlier thrust are synmetamorphic and give rise to stretching lineations ranging from N50°E to N70°E orientations, whereas the later are post-metamorphic and directed towards the NNW.

Geodynamic implications of the NE-thrusting

The structural relationships described in the previous sections suggest that the thrusting towards the NE occurred during the D_3 deformation phase, as evidenced by the widespread development of D_3 mylonites in the Adra and Los Reales nappes. Nevertheless, the first evidence of NE-directed shearing is the presence of D_2 mylonites in the Cantal Unit. This interpretation is consistent with the fact that the metamorphic peak was reached during the D_2 phase, the subsequent metamor-

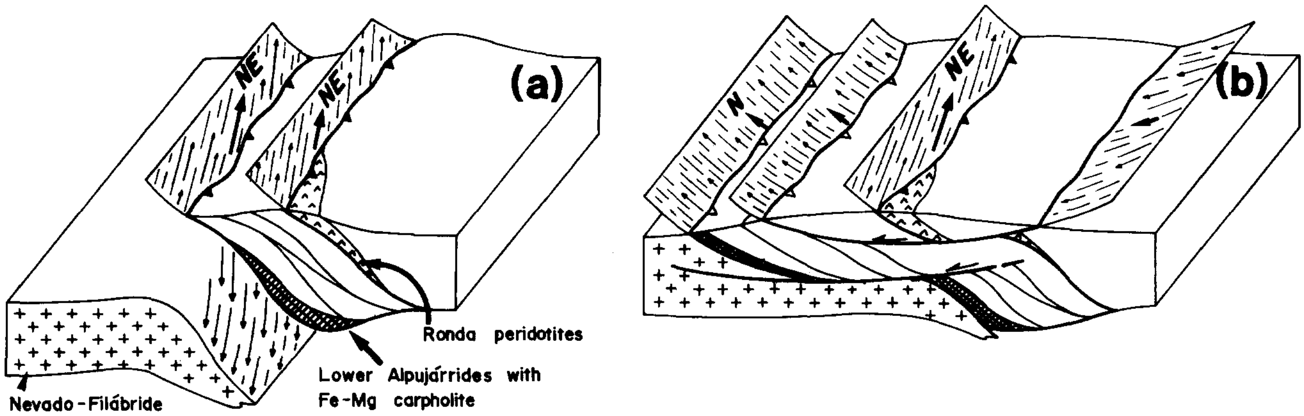

Fig. 9. Proposed geodynamic model for the two shearing episodes recognized in the Alpujárride Complex. (a) Lateral collision along a transform fault, in a continental environment. This process is responsible for the ductile thrusting towards the NE observed in the Alpujárride Complex. (b) Shearing towards the north, that produced the thinning of the crust thickened by the nappes, originated in the previous episode.

phic evolution being characterized by retrogressive conditions (Fig. 7). Furthermore, the NE-directed thrusting explains the appearance of higher grade metamorphism at higher structural position within the nappes of the Alpujárride Complex, and, in general terms, why the metamorphism of the western nappes is more pronounced (Fig. 2). These aspects point to a geodynamic picture typical of continental collision, leading to the tectonic thickening of a previously thinned continental crust. In the westernmost Alpujárrides even the upper subcontinental mantle, represented by the Ronda peridotites, was involved in nappe emplacement towards the north-east (Fig. 6). The isotopic dating of the synkinematic acidic dykes produced during the hot thrusting of the Ronda peridotites (Loomis 1975, Priem *et al.* 1979) points to a minimum age of 22 Ma for this episode of ductile thrusting.

In plagioclase lherzolites of subcontinental type, the flow lines marked by the lineation of the peridotites are generally sub-parallel to the rift axis (see Nicolas 1989 for a review). This implies that in the Ronda peridotites, where both the asthenospheric flow and the stretching lineation of mylonite peridotites show a mean N70°E trend (Tubía & Cuevas 1987), the axis of the rift was roughly parallel to the direction of thrusting, suggesting that the Alpujárride Complex has undergone (Fig. 9) a lateral collision. The lateral collision model is specially attractive for the Betic Cordillera (Vauchez & Nicolas 1991), since it formed in a region between the European and African plates in which movement has been dominated by a strike-slip along the Azores–Gibraltar transform zone. Within such transform zones, extensional and compressive deformations alternate (Bonatti 1978), favouring firstly the ascent of mantle diapirs and then crustal shortening and thickening by lithospheric shearing. The recent finding of Fe–Mg carpholite in some nappes in the Lower Alpujárrides (Goffé *et al.* 1988) is additional evidence consistent with high pressures due to crustal thickening by plate collision.

The existence of such high-pressure metamorphism in the Lower Alpujárrides has been interpreted in the same way as the high-pressure metamorphism, with eclogites and blueschists, of the underlying Nevado–Filábride Complex (Goffé *et al.* 1988). Despite this, for the Nevado–Filábride Complex to be integrated within a tectonic synthesis of the Betic Zone, certain fundamental questions must be clarified, for example: (1) Do the serpentinites, gabbros and other basic Nevado–Filábride rocks dated at 146 Ma by Hebeda *et al.* (1980), belong to an ophiolite suite (Bodinier *et al.* 1987) or to an alkaline vulcanism related to a continental intraplate environment (Muñoz *et al.* 1988)?; (2) Is the shear sense of ductile thrusting in the Nevado–Filábride Complex towards the west (García-Dueñas *et al.* 1987) or to the east (Campos *et al.* 1986, Orozco 1986)?

Modification produced by the N-shearing

The omission of some Alpujárride units together with the thinning often implied by movements towards the north (Navarro-Vilá 1976, Cuevas *et al.* 1986) and the conservation of the structural order obtained during the NE-thrusting suggest that the emplacement of northward nappes is related to an extensional deformation (Fig. 9b). The nearly coeval ages, Upper Oligocene to Lower Miocene, of the two episodes of shearing described here, together with the extensional nature of the latter, point to a tectonic model in which northwards extensional faulting was subordinated to an earlier crustal thickening produced by the lateral transport towards the north-east (Fig. 9).

The wide development of gouges and fault-breccias suggest that the emplacement of nappes towards the north occurred at pressures lower that 100 MPa as pointed out by Sibson's (1977) model for major shear zones. The brittle–ductile behaviour that characterizes nappe emplacement, may pass into more ductile conditions at deeper levels of the Betic Zone. The existence of broad mylonite layers with N–S stretching lineations (Fig. 3) at the contact zone between the Alpujárride and Nevado–Filábride complexes (Platt *et al.* 1984, Alvarez 1987a,b) and within the Nevado–Filábride complex

(Martínez-Martínez 1984) could be explained in this way, since they also indicate a top-to-the-N shear sense. This is an important observation since in many areas the NE-thrusting, the main structural feature of the Alpujárride Complex, has been almost obliterated by later N-directed movement.

In recent years many contacts between units have been reinterpreted as extensional faults (Aldaya *et al.* 1984, García Dueñas *et al.* 1986, Alvarez 1987b, Galindo-Zaldívar & González-Lodeiro 1989, Platt & Vissers 1989, Alvarez *et al.* in press). These late faults, which have not been described here, can explain the lack of the *Lower* and *Intermediate Alpujárride Nappes* in many areas, where the *Higher Alpujárride Nappes* directly overlay the Nevado–Filábride Complex. Even a Metamorphic Core Complex model has been proposed for the Alpujárride/Nevado–Filábride superimposition (Galindo-Zaldívar & González-Lodeiro 1989) on the basis of the structures existing in the contact and the radial translations observed along the contact on the western edge of Sierra Nevada. This hypothesis is tempting but it would be necessary to elucidate whether there is some causal relationship between these movements and those that occurred during the phase of shearing towards the north.

Acknowledgements—This study was carried out during a research project PB87-0737-C03-01/02/03 entitled "Zonas de cizalla en dominios dúctil, dúctil-frágil y frágil en la Meseta Ibérica y en las Cordilleras Béticas. Análisis mecánico y relación con procesos metamórficos" auspiced by the D.G.I.C.Y.T. The authors would like to thank an anonymous reviewer and particularly John Platt for many useful comments in their reviews. We thank Nick Skinner for invaluable help in the English version of the manuscript.

REFERENCES

Aldaya, F. 1969. Los Mantos Alpujárrides al Sur de Sierra Nevada. Unpublished Doctoral thesis, University of Granada.

Aldaya, F., Campos, J., García-Dueñas, V., González-Lodeiro, F. & Orozco, M. 1984. El contacto Alpujárrides/Nevado-Filábrides en la vertiente meridional de Sierra Nevada. Implicaciones tectónicas. *El borde Mediterráneo español: evolución del orógeno bético y geodinámica de las depresiones neógenas*, Granada, 18–20.

Aldaya, F., García-Dueñas, V. & Navarro-Vilá, F. 1979. Los Mantos Alpujárrides del tercio central de las Cordilleras Béticas. Ensayo de correlación tectónica de los alpujárrides. *Acta geol. Hisp.* **14**, 154–166.

Alvarez, F. 1987a. Subhorizontal shear zones and their relation to nappe movements in the Cantal and Miñarros units. Eastern Betic Zone (Spain). *Geologie Mijnb.* **66**, 101–110.

Alvarez, F. 1987b. La tectónica de la Zona Bética en la región de Aguilas. Unpublished Doctoral thesis, University of Salamanca.

Alvarez, F., Aldaya, F. & Navarro-Vilá, F. In press. Miocene extensional deformations in the region of Aguilas-Mazarron (Eastern Betic Cordilleras). *Estudios geol.*

Andrieux, J., Fontboté, J. M. & Mattauer, M. 1971. Sur un modele explicatif de l'arc de Gibraltar. *Earth Planet. Sci. Lett.* **12**, 191–198.

Banda, E., Udías, A., Mueller, St., Mezcua, J., Boloix, M., Gallart, J. & Aparicio, A. 1983. Crustal structure beneath Spain from deep seismic sounding experiments. *Phys. Earth & Planet. Interiors* **31**, 277–280.

Berthé, D., Choukroune, P. & Jégouzo, P. 1979. Orthogneiss, mylonite and non-coaxial deformation of granites: the example of the South Armorican shear zone. *J. Struct. Geol.* **1**, 31–42.

Bodinier, J.-L., Morten, L., Puga, E. & Díaz de Federico, A. 1987. Geochemistry of metabasites from the Nevado–Filábride Complex, Betic Cordilleras, Spain: Relics of a dismembered ophiolitic sequence. *Lithos* **20**, 235–245.

Bonatti, E. 1978. Vertical tectonism in oceanic fracture zones. *Earth Planet. Sci. Lett.* **37**, 369–379.

Bouillin, J. P., Durand-Delga, M. & Olivier, Ph. 1986. Betic-Rifian and Tyrrhenian Arcs: distinctive features, genesis and development stages. In: *The Origin of Arcs.* Wezel, Amsterdam, 281–304.

Bourgois, J. 1978. La transversale de Ronda (Cordilleres Bétiques, Espagne). Données géologiques pour un modele d'évolution de l'arc de Gibraltar. Unpublished Doctoral thesis, University of Besancon.

Brouwer, H. A. 1926. Zur Tektonik der betischen Kordilleren. *Geol. Rdsch.* **17**, 332–336.

Campos, J., García-Dueñas, V., González-Lodeiro, F. & Orozco, M. 1986. La zona de cizalla del contacto entre el grupo de mantos de Mulhacén y la unidad del Veleta (Sierra Nevada y Sierra de los Filabres, Andalucía). *Geogaceta* **1**, 15–17.

Chalouan, A. 1986. Les nappes Ghomarides (Rif septentrional, Maroc), un terrain varisque dans la Chaine Alpine. Unpublished thesis, University of Strasbourg.

Cuevas, J. 1988. Microtentónica y metamorfismo de los Mantos Alpujárrides del Tercio Central de las Cordilleras Béticas (entre Motril y Adra). Unpublished Doctoral thesis, University of País Vasco.

Cuevas, J., Aldaya, F., Navarro-Vilá, F. & Tubía, J. M. 1986. Caractérisation de deux étapes de charriage principales dans les nappes Alpujárrides centrales (Cordilleres Bétiques, Espagne). *C. r. Acad. Sci., Paris* **302**, 1177–1180.

Delgado, F., Estévez, A., Martín, J. M. & Martín-Algarra, A. 1981. Observaciones sobre la estratigrafía de la formación carbonatada de los Mantos Alpujárrides (Cordillera Bética). *Estudios geol.* **37**, 45–57.

De Roever, W. P. & Nijhuis, H. S. 1964. Plurifacial alpine metamorphism in the eastern Betic Cordilleras (SE Spain), with special references to the genesis of the glaucophane. *Geol. Rdsch.* **53**, 324–336.

Dewey, J. F., Helman, M. L., Turco, E., Hutton, D. W. H. & Knott, S. D. 1989. Kinematics of the western Mediterranean. In: *Alpine Tectonics* (edited by Coward, M. P., Dietrich, D. & Park, R. G.). *Spec. Publs geol. Soc. Lond.* **45**, 265–283.

Egeler, C. G. & Simon, O. J. 1969. Sur la tectonique de la zone Bétique. *Verh. K. Ned. Akad. Wetens. Natuur* **25**.

Fallot, P. 1948. Les Cordilleres Bétiques. *Estudios geol.* **8**, 83–172.

Fallot, P., Faure-Muret, A., Fontboté, J. M. & Solé-Sabarís, L. 1960. Estudios sobre las series de Sierra Nevada y de la llamada Mischungszone. *Boln Inst. geol. min. Esp.* **71**, 347–557.

Galindo-Zaldívar, J. & González-Lodeiro, F. 1989. Progressive extensional shear structures in a detachment contact in the western Sierra Nevada (Betic Cordilleras, Spain). *Geod. Acta* **3**, 73–85.

García-Dueñas, V. 1969. Les unités allochtones de la zone Subbétique, dans la transversale de Grenade (Cordilleres Bétiques, Espagne). *Rev. Geogr. phys. Geol. dyn.* **2**, 211–222.

García-Dueñas, V., Martínez-Martínez, J. M. & Navarro-Vilá, F. 1986. La zona de Falla de Torres Cartas, conjunto de fallas normales de bajo ángulo entre Nevado-Filábrides y Alpujárrides (Sierra Alhamilla, Béticas Orientales). *Geogaceta* **1**, 17–19.

García-Dueñas, V., Martínez-Martínez, J. M., Orozco, M. & Martín Ramos, D. 1987. El sentido de desplazamiento de los Mantos Nevado-Filábrides. *Geogaceta* **3**, 11–13.

García-Hernández, M., López-Garrido, A. C., Rivas, P., Sanz de Galdeano, C. & Vera, J. A. 1980. Mesozoic paleogeographic evolution of the External Zones of the Betic Cordillera. *Geol. Mijnb.* **59**, 155–168.

Goffé, B., Michard, A., García-Dueñas, V. & Gonzalez-Lodeiro, F. 1988. Métamorphisme haute pression-basse temperature dans les Nappes Alpujárrides (Espagne); conséquences tectoniques. In: *Proc. Symposium Pyrenees and Betics*, Barcelona.

Hebeda, E. H., Boelrijk, N. A. I. M., Priem, H. N. A., Verdurmen, E. A. Th. & Verschure, R. H. 1980. Excess radiogenic Ar and undisturbed Rb-Sr systems in basic intrusives subjected to alpine metamorphism in southeastern Spain. *Earth Planet. Sci. Lett.* **47**, 81–90.

Hernández-Pacheco, A. 1967. Estudio petrográfico y geoquímico del macizo ultramáfico de Ojén (Málaga). *Estudios geol.* **23**, 85–143.

Holdaway, M. J. 1971. Stability of andalusite and the aluminum-silicate diagram. *Am. J. Sci.* **271**, 97–131.

Julivert, M., Fontboté, J. M., Ribeiro, A. & Conde, L. 1973. Mapa tectónico de la península Ibérica y Baleares. *Boln Inst. geol. min. Esp.*

Kornprobst, J. 1976. A propos des péridotites du massif des Beni-Bouchera (Rif Septentrional, Maroc). *Bull. Soc. géol. Fr.* **18**, 607–618.

Kozur, H. & Simon, O. J. 1972. Contribution to the Triassic microfauna and stratigraphy of the Betic Zone (Southern Spain). *Revta Esp. Micropal.* **4**, 143–158.

Kozur, H., Mulder-Blanken, C. W. H. & Simon, O. J. 1985. On the Triassic of the Betic Cordilleras (southern Spain), with special emphasis on holothurian sclerites. *Stratigr. & Palaeont.* **B88**, 83–110.

Lister, G. S. & Snoke, A. W. 1984. S–C mylonites. *J. Struct. Geol.* **6**, 617–638.

Loomis, T. P. 1972. Contact metamorphism of pelitic rock by the Ronda ultramafic intrusion, Southern Spain. *Bull. geol. Soc. Am.* **83**, 2449–2474.

Loomis, T. P. 1975. Tertiary mantle diapirism, orogeny and plate tectonics east of the Straits of Gibraltar. *Am. J. Sci.* **275**, 1–30.

Martín-Algarra, A. & Estévez, A. 1984. La Breche de la Nava: depot continental synchrone de la structuration pendant le Miocene inférieur des zones internes de l'Ouest des Cordilleres Bétiques. *C. r. Acad. Sci., Paris* **299**, 463–466.

Martínez-Martínez, J. M. 1984. Evolución tectonometamórfica del Complejo Nevado-Filábride en el sector de unión de Sierra Nevada y Sierra de Los Filabres (Cordilleras Béticas). Unpublished Doctoral thesis, University of Granada.

Morten, L., Bargossi, G. M., Martínez-Martínez, J. M., Puga, E. & Díaz de Federico, A. 1987. Metagabbro and associated eclogites in the Lubrín area, Nevado-Filábride Complex, Spain. *J. metamorph. Geol.* **5**, 155–174.

Muñoz, M., Gómez Pugnaire, M. T. & Fernández Soler, J. M. 1988. Los clinopiroxenos de las metabasitas hipoabisales del Complejo Nevado-Filábride (Cordilleras Béticas) como indicadores de la afinidad magmática y del ambiente paleotectónico. *II Congres. Geol. Esp.*, Granada, 425–433.

Navarro-Vilá, F. 1976. Los Mantos Alpujárrides y Maláguides al N de Sierra Nevada. Unpublished Doctoral thesis, University of País Vasco.

Navarro-Vilá, F. & Tubía, J. M. 1983. Essai d'une nouvelle différenciation des Nappes Alpujárrides dans le secteur occidental des Cordilleres Bétiques (Andalousie, Espagne). *C. r. Acad. Sci., Paris* **296**, 111–114.

Nicolas, A. 1989. *Structures of Ophiolites and Dynamics of Ocean Lithosphere*. Kluwer, Utrecht.

Obata, M. 1977. Petrology and petrogenesis of the Ronda high-temperature peridotite intrusion, Southern Spain. Unpublished Ph.D. thesis, Massachusetts Institute of Technology.

Obata, M. 1980. The Ronda peridotite: Garnet-, Spinel-, and Plagioclasa-Lherzolite facies and the *P–T* trajectories of a high-temperature mantle intrusion. *J. Petrol.* **21**, 533–572.

Orozco, M. 1986. Fábrica de cuarzo y cabalgamientos hacia el ENE en Sierra Nevada y Sierra de los Filabres (Cordilleras Béticas). *Geogaceta* **1**, 40–41.

Platt, J. P. 1986. Dynamics of orogenic wedges and the uplift of high-pressure metamorphic rocks. *Bull. geol. Soc. Am.* **97**, 1037–1053.

Platt, J. P. & Vissers, R. L. M. 1989. Extensional collapse of thickened continental lithosphere: A working hypothesis for the Alboran Sea and Gibraltar arc. *Geology* **17**, 540–543.

Platt, J., Van den Eeckhout, B., Janzen, E., Konert, G., Simon, O. J. & Weijermars, R. 1983. The structure and tectonic evolution of the Aguilón fold-nappe, Sierra Alhamilla, Betic Cordilleras, SE Spain. *J. Struct. Geol.* **5**, 519–538.

Priem, H. N. A., Boelrijk, N. A. I. M., Hebeda, E. H., Oen, I. S., Verdurmen, E. A. Th. & Verschure, R. H. 1979. Isotopic dating of the emplacement of the ultramafic masses in the Serrania de Ronda, Southern Spain. *Contr. Miner. Petrol.* **70**, 103–109.

Sibson, R. H. 1977. Fault rocks and fault mechanisms. *J. geol. Soc. Lond.* **133**, 237–248.

Simon, O. J. 1963. Geological investigations in the Sierra de Almagro, South Eastern Spain. Unpublished Doctoral thesis, University of Amsterdam.

Thompson-Lundeen, M. 1978. Emplacement of the Ronda peridotite, Sierra Bermeja, Spain. *Bull. geol. Soc. Am.* **89**, 172–180.

Torres-Roldán, R. L. 1979. The tectonic subdivision of the Betic Zone (Betic Cordilleras, Southern Spain): its significance and one possible geotectonic scenario for the western Alpine belt. *Am. J. Sci.* **279**, 19–51.

Tubía, J. M. 1985. Sucesiónes metamórficas asociadas a rocas ultramáficas en los Alpujárrides Occidentales (Cordilleras Béticas, Málaga). Unpublished Doctoral thesis, University of País Vasco.

Tubía, J. M. & Cuevas, J. 1986. High-temperature emplacement of the Los Reales peridotite nappe (Betic Cordillera, Spain). *J. Struct. Geol.* **8**, 473–482.

Tubía, J. M. & Cuevas, J. 1987. Structures et cinématiques liées à la mise en place des péridotites de Ronda (Cordilleres Bétiques, Espagne). *Geodin. Acta.* **1**, 59–69.

Tubía, J. M. & Gil Ibarguchi, J. I. 1991. Eclogites of the Ojen nappe: a record of subduction in the Alpujárride complex (Betic Cordilleras, southern Spain). *J. geol. Soc. Lond.* **148**, 801–804.

Vauchez, A. & Nicolas, A. 1991. Mountain building: strike-slip-parallel motion and mantle anisotropy. *Tectonophysics* **185**, 183–201.

Weijermars, R. 1985. Uplift and subsidence history of the Alboran Basin and a profile of the Alboran Diapir (W-Mediterranean). *Geol. Mijnb.* **64**, 349–356.

Westerhoff, A. B. 1977. On the contact relations of high-temperature peridotites in the Serranía de Ronda, southern Spain. *Tectonophysics* **39**, 579–591.

Westra, G. 1969. Petrogenesis of a composite metamorphic facies series in an intrincate fault-zone in the South-Eastern Sierra Cabrera, SE Spain. Unpublished Doctoral thesis, University of Amsterdam.