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Late extensional shear zones and associated recumbent folds in the Alpujarride subduction complex, Betic Cordillera, southern Spain

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ABSTRACT

The existence in the Alpujarride Complex (Betic Cordillera, southern Spain) of a relatively continuous extensional event (following crustal thickening) is based on detailed structural studies and is consistent with the P-T paths and geochronological data established for the Alpujarride rocks. According to our research, the Alpujarride Complex contains two large-scale shear zones accommodating early Miocene extension. The shear zones contain km-scale recumbent folds, some with sheath fold geometry, and megaboudinage structures, and are closely associated with detachment faults.

Large-scale folds and boudins cause dome-like undulations in the detachments, which are inferred to overlap in time with the deformation in the shear zones. One shear zone in the eastern part of the orogen is top-N; the other, in the western part, is top-E. The change in the shear direction may represent a temporal evolution in the direction of shear, possibly related to a change in the subduction direction in space and time.

KEYWORDS **Extensional shear zones. Recumbent folds. Alpujarride Complex. Betic Cordillera.**

INTRODUCTION

The Alpujarride Complex, which forms part of the Internal Zones of the Betic Cordillera in southern Spain (Fig. 1), is an exhumed subduction complex that formed during Eocene to early Miocene time as a result of the overall convergence between Africa and Eurasia. It forms the major part of the Alboran Domain, which underlies much of the Alboran Sea in the western Mediterranean, and moved westward between the converging plates during the Miocene to form the arcuate Betic-Rif thrust belt (Royden, 1993; Lonergan and White, 1997; Vissers *et al.*, 1995). The early history of the Alpujarride Complex is obscure: it formed by the subduction and accretion of mantle and upper crustal rocks of Paleozoic to Triassic age, probably starting in late Eocene time (Platt *et al.*, 2005), but the polarity and duration of this subduction event are uncertain. Its internal structure is dominated by the effects

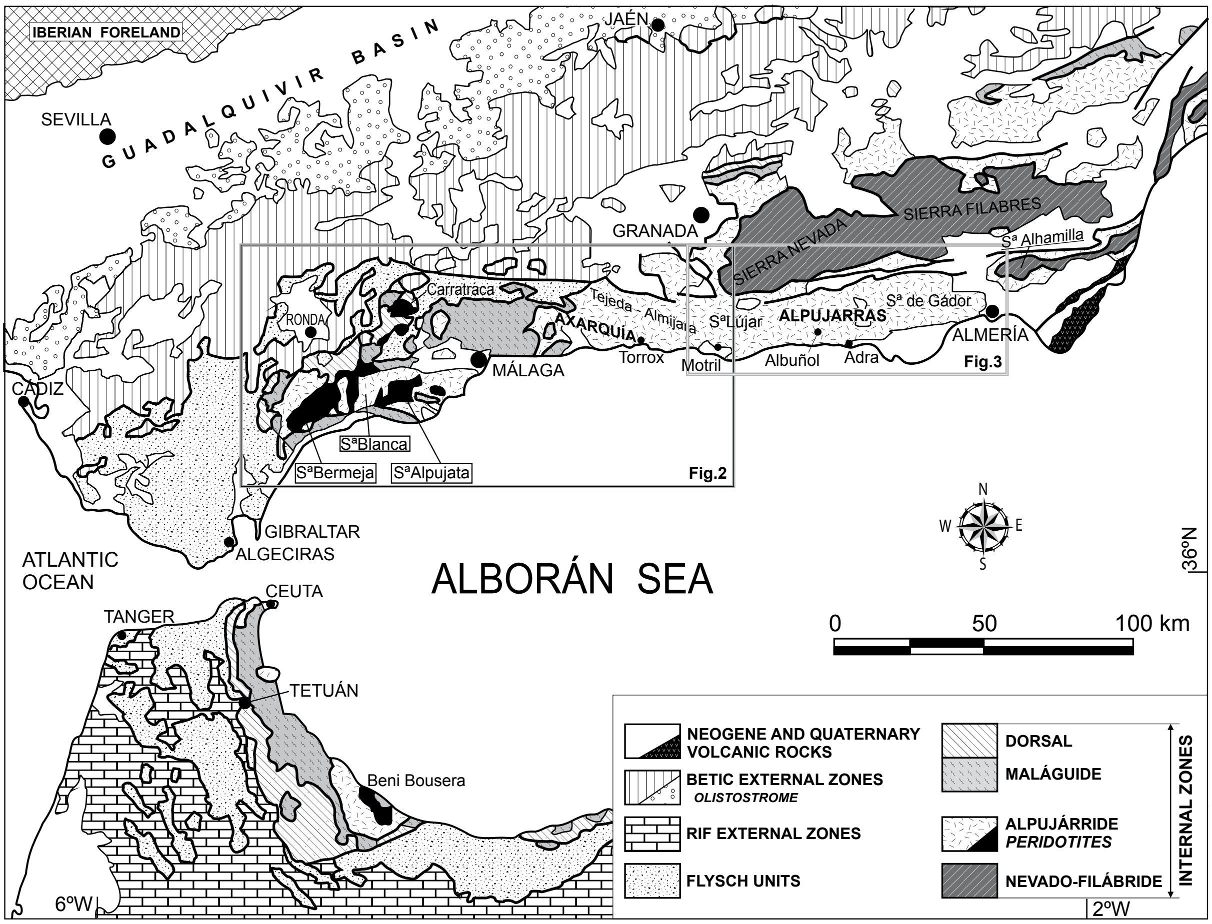

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FIGURE 1. Internal Zones of the Betic-Rifean Alpine orogen in the westernmost part of the Mediterranean Sea. The areas covered by Figures 2 and 3 are framed.

of the late Oligocene to early Miocene extension, and it is now underlain by the exhumed remnants of a younger subduction complex, the Nevado-Filabride Complex, which was subducted beneath it and then exhumed during the early to middle Miocene (López Sánchez-Vizcaino *et al.*, 2001; Platt *et al.*, 2006). The Alpujarride Complex shows a complicated metamorphic evolution, with an early high-pressure low-temperature stage (Goffé *et al.*, 1989; Tubía and Gil-Ibarguchi, 1991), evolving to medium and then low pressure-temperature ratio assemblages (García-Casco and Torres-Roldán, 1996). Metamorphic grade locally reaches granulite facies in the vicinity of the Ronda peridotite massifs (Argles *et al.*, 1999), and localized upper amphibolite facies metamorphism and partial melting occur in several locations through the complex.

The complexity of the structural and metamorphic history have resulted in considerable debate about the overall structure and tectonic evolution of the Alpujárride Complex (*e.g.* Balanya *et al.*, 1997; Platt *et al.*, 2005; Rossetti *et al.*, 2005). The aim of this paper is to show the existence of two very large-scale shear zones, dominated by km-scale recumbent folds, sheath folds, and megaboudinage structures, which formed in association with large-scale detachment faults during early Miocene extension and thinning.

INTERNAL STRUCTURE OF THE ALPUJARRIDE COMPLEX

The Alpujarride Complex now forms a subhorizontal sheet varying in thickness from a few hundred meters to at least 10km. It is regionally overlain by the Maláguide Complex, a largely unmetamorphosed body of rocks with similar provenance to the Alpujarride Complex. Paleozoic rocks of the Maláguide Complex overlie Triassic rocks of the Alpujarride Complex, and both bodies contain numerous repetitions of the stratigraphic sequence, suggesting that they originally formed part of a thrust stack. Additionally, the contrast in metamorphic grade across the contact suggests that as much as 20km of rock are missing (Platt *et al.*, 2003), so the contact is now generally regarded as an extensional detachment (*e.g.* Lonergan and Platt, 1995; Cuevas *et al.*, 2001). Fission-track and Ar-Ar data suggest that exhumation and cooling along this contact occured in the early Miocene, between 22 and 18Ma. (Monié *et al.*, 1994; Platt *et al.*, 2003).

The lower contact of the Alpujarride Complex is also generally regarded as an extensional detachment (*e.g.* Jabaloy *et al.*, 1993). The underlying Nevado-Filabride Complex shows high-pressure low-temperature metamorphism of early Miocene age (18-16Ma) (López Sánchez-Vizcaino *et al.*, 2001; Platt *et al.*, 2006), followed by rapid decompression and exhumation in the middle to late Miocene (Johnson *et al.*, 1997). Late stages of exhumation were accompanied by the formation of the detachment, and by brittle normal faulting that affected parts of the overlying Alpujarride Complex, and which contributed to the formation of late Neogene sedimentary basins.

The internal structure of the Alpujarride Complex is made of a series of repetitions of the original stratigraphic sequence, comprising graphitic mica schist and quartzite of Paleozoic age, light-coloured schists and quartzites of Permian to Early Triassic age, and thick sequences of Middle to Late Triassic carbonate rocks (*e.g.* Aldaya *et al.*, 1979). Many of the tectonic contacts between these repeated sequences are now thought to be low-angle normal faults that formed during later exhumation and thinning of the complex (Crespo-Blanc *et al.*, 1994), however the faults cut or reactivated earlier thrust contacts. Much of the carbonate sequence consists of dolostones, which behaved competently in a highly deformed matrix of calcitic marble and schist, and help define the large-scale structures described in this paper. The schists contain multiple foliations and refolded folds, but in many areas there is a strong foliation (Sp in *e.g.* Orozco *et al.*, 1998; S2 in *e.g.* Azañón *et al.*, 1998, among others), which has the characteristics of a differentiated crenulation cleavage, and was formed about the time of peak temperature in the metamorphic history. In the highest grade rocks this fabric is associated with the growth of sillimanite. It is commonly overprinted by a later crenulation cleavage (Sc in *e.g.* Orozco *et al.*, 1998; S3 in *e.g.* Azañón *et al.*, 1998) associated with mesoscopic and large-scale folds. Sc was formed on the decompression path, and is commonly associated with the growth of andalusite. These two fabrics can be identified over large areas.

MAJOR EXTENSIONAL SHEAR ZONES IN THE ALPUJARRIDE COMPLEX

The structures we described in this paper define two large-scale shear zones that dominate the structure in the southern part of the Alpurride Complex. These extensional shear zones are distinguished and described for the first time in this paper.

The top-to-the-east extensional shear zone

A zone of high ductile strain affects the western part of the Alpujarride Complex, from the Sierra Bermeja peridotite massif in the west, as far as Motril in the east (Figs. 1; 2). This is characterized by predominantly top-to-the–east shear, producing a strong subhorizontal foliation and a regionally east-trending stretching lineation (Fig. 2). In the westernmost region the upper boundary of the shear zone is defined by the floor detachment of the Maláguide complex whereas the lower boundary is not exposed (Fig. 2, map and cross section I-I'). The peridotite massifs of the Sierra Bermeja, Sierra Alpujata and other smaller ones (Fig. 2) are included within this wide heterogeneous shear zone. In the region of La Axarquía, East of Málaga (Fig. 2), where no outcrop of peridotite exists, the upper limit of the shear zone is also the floor detachment of the Maláguide Complex (Fig. 2, cross section II-II'). The original lower boundary of the shear zone is currently masked by recent extensional faults (Alonso-Chaves and Orozco, 2012).

The top-to-the-east shear zone is evidenced by plurikilometric recumbent folds, sheath-folds and boudinaged folds (Fig. 2, map and cross-sections), most obviously developed within the carbonate rocks. The folds commonly show a great variation in the orientation of the hinge line. Nevertheless, although curved in shape, the hinge is contained in a plane whose attitude coincides with the main attitude of the axial-plane foliation, Sc (Orozco and Alonso-Chaves, 2002, 2011). These structures developed under medium- to high-grade metamorphic conditions, during the nearly isothermal decompression segment of the Pression-Temperature (P-T) path (see section below, "Metamorphic P-T-t evolution and phases of deformation"). The petrological data are in good agreement with the results from this structural study. The development of the large recumbent folds of the Sierra Blanca and La Axarquía (Fig. 2) occurred during this decreasing pressure event, because the formation of the associated Sc axial-plane foliation in high-grade rocks took place between only 300 and 400MPa and 600–700ºC (García-Casco and Torres-Roldán, 1996; Soto and Platt, 1999). We therefore associate this shear zone and the related folds with the regional vertical thinning and horizontal extension, which is dated as early Miocene (Zeck *et al.*, 1992; Monié *et al.*, 1994; Sosson *et al.*, 1998).

The top-to-the-north ductile-brittle shear zone

In the region of Las Alpujarras, south of the Sierra Nevada (Fig. 1), another large shear zone developed.

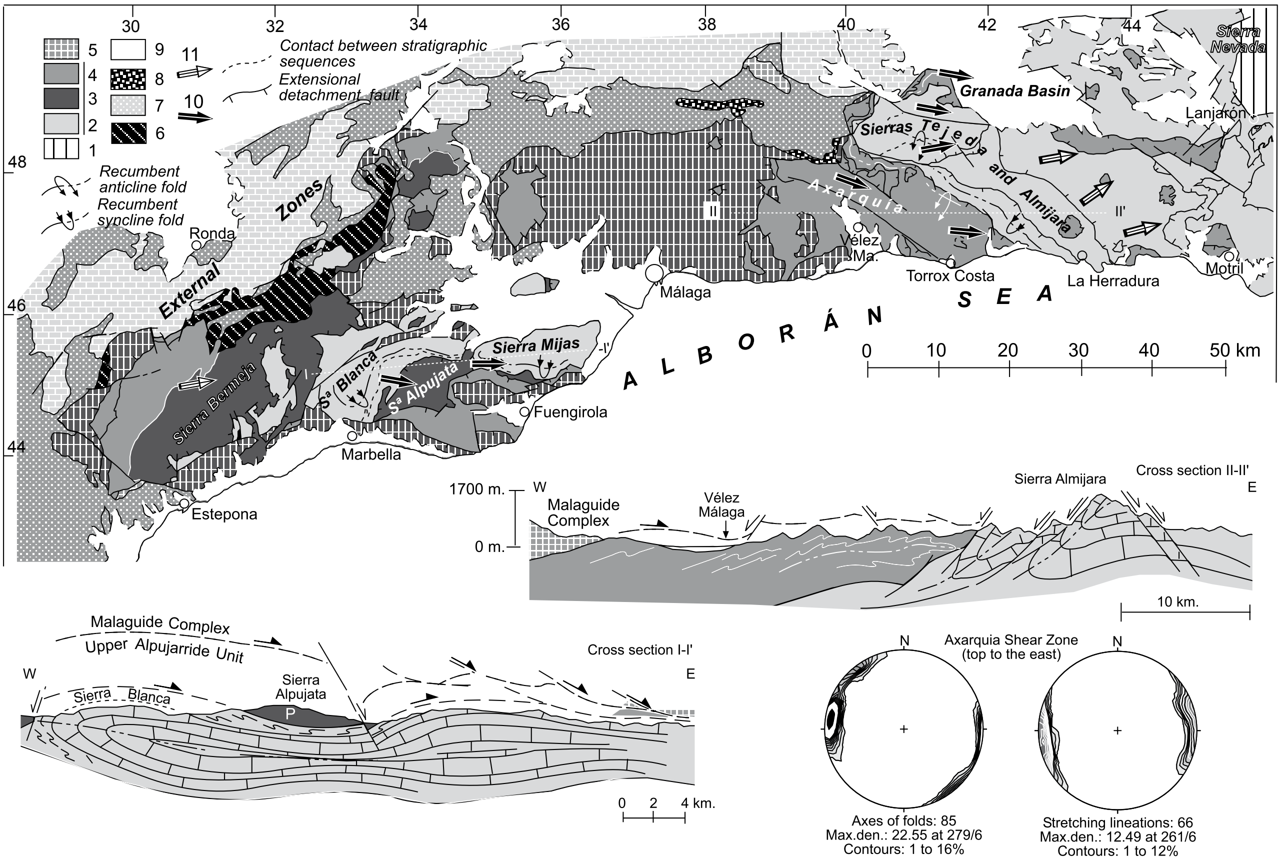


FIGURE 2. Top-to-the-east extensional shear zone in Western and Central Alpujarride Domains. 1) Nevado-Filabride Complex. 2) Lower and Intermediate Alpujarride Extensional units. 3) Peridotites. 4) Upper Alpujarride Extensional Unit. 5) Maláguide Complex. 6) Dorsalian units. 7) Flysch units. 8) Viñuela and related units. 9) Neogene and Plio-Quaternary sediments. 10) Stretching lineation and shear sense. 11) Stretching lineation and shear sense (after Simancas and Campos, 1993; Balanyá *et al.*, 1997; Rossetti *et al.*, 2005). Axial-traces of large recumbent folds and simplified sections across them in the areas of the Sierra Blanca-Sierra de Mijas in the western Betics and the Axarquía region are also represented.

This wide extensional shear zone has a hanging wall displacement toward NNW, and includes both brittle and ductile structures (Fig. 3). The upper boundary is the Contraviesa Normal Fault System (Crespo-Blanc *et al.*, 1994), which overlies plurikilometric recumbent folds and associated deformational structures (Sc axial-plane crenulation cleavage and NNW-trending stretching lineation) (Orozco *et al.*, 1998, 2004). The current lower boundary is the detachment fault separating the Alpujarride Complex from the underlying Nevado-Filabride Complex. Based on structural field data, a common origin for the recumbent folds and the low-angle normal faults was suggested (Orozco *et al.*, 1998) (see below). Ar-Ar and fission track data (Platt *et al.*, 2005) from the Río Grande recumbent fold in the eastern Alpujarras (Orozco *et al.*, 1998) limit the age of the axial-plane crenulation cleavage, and hence the fold, to 19 to 23Ma. The early Miocene age of the structures is confirmed by an early Langhian conglomerate resting unconformably on the low-angle normal faults of the Contraviesa system (Mayoral *et al.*, 1994). Most of the rocks within this shear zone are of low metamorphic grade, locally a condensed metamorphic sequence is developed. In phyllite and upper fine-grained mica schist, at the top of the sequence, Sc is a crenulation cleavage marked by small crystals of phengite, paragonite and chlorite (Orozco *et al.*, 1998). This passes down into fine-grained chloritoid schist, then biotite-bearing schist and metaquartzite, then graphitic garnet-staurolite metapelite, and at the base of the succession sillimanite appears (Azañón *et al.*, 1998). The development of the large folds of Las Alpujarras and of the related Sc crenulation cleavage, occurred during an important decreasing pressure event in a similar way to the folds of the Sierra Blanca and La Axarquía. (Orozco *et al.*, 1998).

STRUCTURE OF THE ALPUJARRAS REGION (TOP-TO-THE-NORTH SHEAR ZONE)

The Sierra de Lújar sheath-fold (western Alpujarras)

Detailed structural analysis of the Sierra de Lújar (Orozco *et al.*, 2004) has revealed the existence of a very

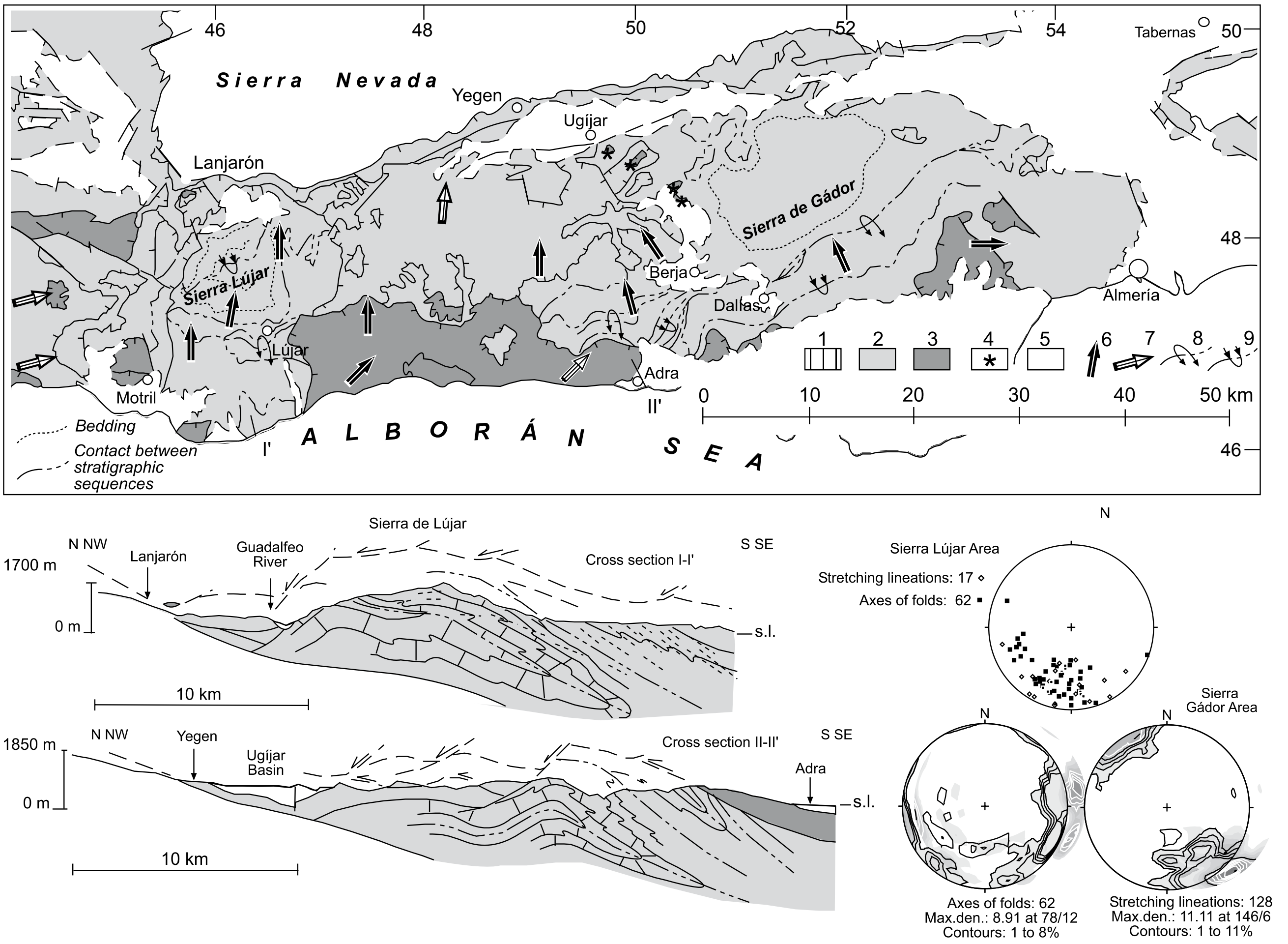


FIGURE 3. Top-to-the-north extensional shear zone in eastern Alpujarride Domain. 1) Nevado-Filabride Complex. 2) Lower and Intermediate Alpujarride Extensional units. 3) Upper Alpujarride Extensional Unit. 4) Maláguide Complex. 5) Neogene and Plio-Quaternary Sediments. 6) Stretching lineation and shear sense. 7) Stretching lineation and shear sense (after Cuevas and Tubía, 1990; Simancas and Campos, 1993; Rossetti *et al.*, 2005). 8) Recumbent anticlinal fold. 9) Recumbent synclinal fold.

large NNW facing recumbent syncline which involves the whole massif and neighbouring areas. Over much of the massif the stratigraphy is overturned (Permo-Triassic phyllites overlie the Late Triassic Lújar limestones along the eastern and southern borders of the Sierra de Lújar). The inverted limb may extend over as much as 10km (Fig. 3, cross section I-I'). The Lújar recumbent syncline shows a great variation in the orientation of the hinge line, but the hinge is contained in a plane whose attitude coincides with the mean attitude of the axial-plane crenulation cleavage, Sc (Orozco *et al.*, 2004). The axes of associated mesoscopic folds show a great variation in trend (Fig. 3), but also lie in a plane close to the mean attitude of Sc surfaces (Orozco *et al.*, 2004). This is particularly true in mesoscopic folds on the overturned limb of the syncline.

Stretching lineations in the Sierra de Lújar range from N150ºE to N200ºE (Fig. 3) although they concentrate mainly between N165ºE and N190ºE. This is in accordance with the mean orientation of the stretching lineation in the western Alpujarras, which is roughly N-S (Fig. 3, see also Simancas and Campos, 1993; Rossetti *et al.*, 2005). The strong variation in orientation of the hinge line of the Lújar recumbent syncline and its isoclinal-to-very tight profile allow it to be classified as a sheath fold (Cobbold and Quinquis, 1980). The existence of a major sheath fold (Fig. 4) and the associated mesoscopic structures (curvilinear folds, sheath folds, shear bands, asymmetric porphyroclasts, and a stretching lineation), indicate that a large-scale deformation zone is located along the overturned limb of the syncline (Orozco *et al.*, 2004).

The upper bounding envelope of the fold structure is the floor detachment of the Contraviesa Normal Fault System (Crespo-Blanc *et al.*, 1994). This is an important extensional system of Langhian age, with a roughly northward transport direction, consistently parallel to the mean orientation of the stretching lineation. The

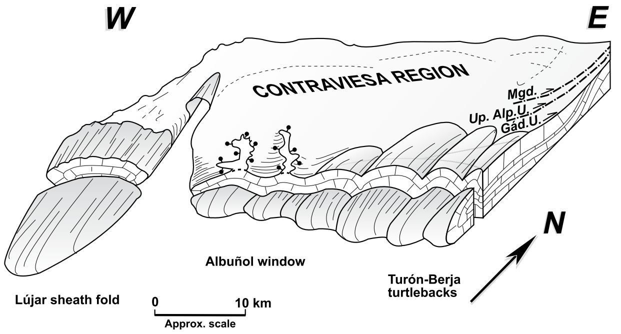


FIGURE 4. Schematic drawing showing the main types of large structures developed in the region of La Contraviesa. The reference surface is the contact between carbonate rocks (upside down) and the overlying phyllites and other rocks: that is, the basal detachment of the Contraviesa Extensional System (see text). From West to East, variation in the types of structures, from sheath fold in the Sierra de Lújar area to recumbent fold with slightly arched hinge, and finally, dome and elongated dome (turtleback) structures in the eastern Contraviesa, is evidenced. These variations in shape could be related, first, with changes in intensity of the shear component of deformation and, in a more advanced stage, with increase in competence contrast between the carbonate sequence as a whole and the well-foliated enveloping phyllites. This late enhancement of the competence contrast, could probably be explained by a decrease in the overlying load and/or an increase in strain rate at an advanced stage of extensional shear.

rapid transition between the overturned carbonate rocks of Lújar, which constitute the footwall of the undulating basal detachment, and the tectonically overlying inverted phyllite and schist which are part of the hanging wall, is consistent with the presence of a ductile shear zone and an extensional detachment as the upper boundary of the ductile shear zone (Fig. 3). In the southeastern part of the Lújar massif, near the village of Lújar (Fig. 3), there is a rapid transition over 200m from very fine-grained white mica phyllite (which overlies the Lújar limestone), through fine-grained (1–2mm) chlorite and chloritoid-bearing schist and metaquartzite to a medium-grained (3–4mm) garnet mica schist. Small-scale structures, both in the schist and the phyllite, are consistent with the overturned attitude of the two lithologic sequences. The high strain shear zone along the limestone-metapelite overturned boundary in the southern part of the Sierra de Lújar and its continuation along the curved axis of the recumbent syncline in the eastern edge of the massif, confirms the existence of a genetic relationship between the Lújar sheath fold and the extensional shear zone (Fig. 4).

The Lújar sheath fold, as shown in a section perpendicular to the mean orientation of the stretching lineation (the approximate shape of the Lújar fold section can be inferred from Figure 4, western part), displays a pronounced elliptic shape (high Y-Z aspect ratio); this is characteristic of general shear deformation, as pointed out by Alsop and Holdsworth (2006).

The Río Grande fold and the associated Turón dome-like structure (eastern Alpujarras)

Detailed structural analysis and mineralogical research carried out in the eastern part of the Alpujarras region (Orozco *et al*., 1998) revealed the existence of very large fold structures, which involve lithological sequences previously considered to belong to different tectonic units.

Thus, according to Crespo-Blanc *et al.* (1994) and Azañón *et al.* (1998), in the area North of Adra, four independent tectonic units, separated by low-angle extensional faults, can be distinguished (see Fig. 5B). Nevertheless, a careful revision of the area including a detailed study of the structures within the different lithological formations, and especially of the contacts between them and a methodical mineralogical study on samples collected along a N-S section following the Adra-Río Grande (see Fig. 5A) revealed the existence of a large north-facing recumbent fold, the Río Grande anticline (Figs. 5A; 3, cross section II-II'). The core of the fold is occupied by Paleozoic chloritoid-bearing graphitic mica schist, and both the overturned and the normal limbs are made up of phyllite, with carbonate sequences stratigraphically above. Small-scale asymmetrical folds and the relationships between the main foliation Sp and the axial-plane crenulation cleavage Sc in the inverted sequence are consistent with a position within the overturned limb of a large north-facing anticline.

The limestones and dolostones of the overturned limb show a dome to elongate dome-like structure (the Turon-Berja "turtlebacks") (Fig. 4). Within the overturned limb of the Río Grande fold a highly strained zone and an undulating extensional detachment mark the contact between the phyllite and the underlying overturned limestones (Figs. 3, cross section II-II'; 5A). Underneath the detachment surface, in the overturned carbonate sequence, boudinage structures and associate well developed stretching lineation are present (Fig. 6). The orientation of the stretching lineation in the high-strain rocks, in the Sierra de Gádor area (Fig. 3) roughly parallels the slip direction of the low-angle normal faults and extensional detachments (Crespo-Blanc *et al*., 1994), and the close association between the large recumbent folds and top-to-the-north low-angle normal faults (Fig. 7) suggest a relationship between the development of the large recumbent folds and early Miocene extensional tectonics (Orozco *et al*., 1998).

THE TOP TO THE EAST SHEAR ZONE

Structure of the Sierra Blanca-Sierra de Mijas

The Sierra Blanca and Sierra de Mijas (Figs. 2; 8) are mainly composed of calcite and dolomite marbles with

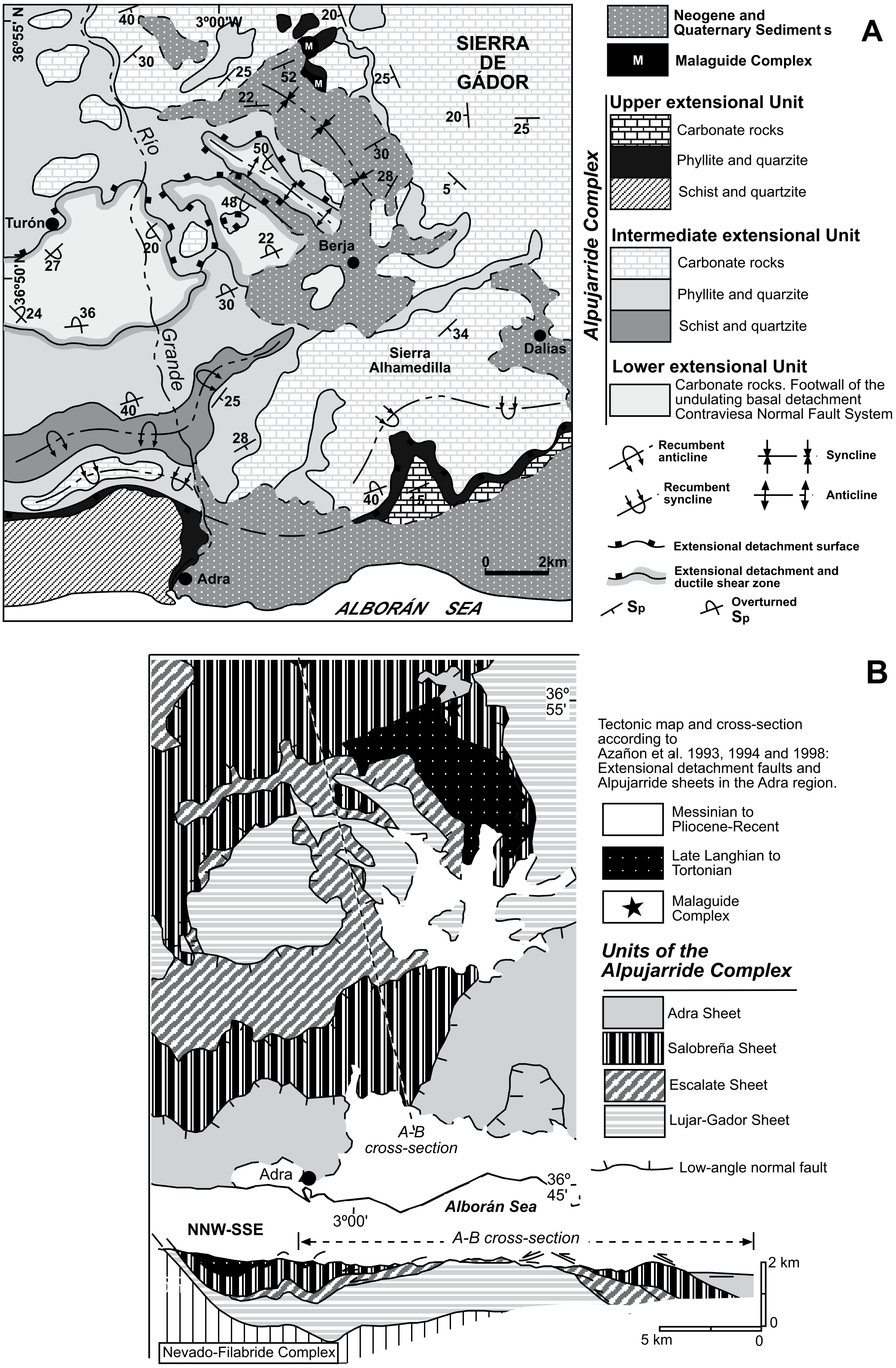


FIGURE 5. Alternative tectonic interpretations of the area North of Adra, eastern Alpujarras. A) On the basis of structural and mineralogical studies, Orozco et al. (1998) interpreted that large overturned recumbent folds involving lithological sequences previously considered to belong to different tectonic units, would be represented in the eastern Alpujarras. According to them a close relationthip between folds and the Early to Middle Miocene extensional even would exist. B) Tectonic interpretation of the Adra region, after Azañón *et al.* (1994; 1998). According to these authors, four independent Alpujarride tectonic units separated by low-angle normal faults would be represented in the area North of Adra.

FIGURE 6. Boudinage structures and associated stretching lineation. Dolostone and calcschists of the overturned limb of the Río Grande fold, a few metres below the undulating detachment surface.

occasional amphibolite and metapelite layers. The age of the carbonate sequence is considered to be Middle-Late Triassic by correlation with other Alpujarride units, where the carbonate rocks are weakly metamorphosed and contain fossils (Delgado *et al.*, 1981; Kozur *et al.*, 1985). The lithological sequence also includes a lower metapelitic formation consisting of biotite-cordierite mylonitic schist and cordierite-sillimanite mylonitic schist. However, due to the regional inversion in the overturned limb of the recumbent folds, the metapelite formation crops out above the marbles, especially along the southern and eastern borders of the Sierra Blanca and the southern border of the Sierra de Mijas (Fig. 8). Overlying the sillimanite schists (in inverted position) there are migmatites, amphibolites, granites and quartz-feldspar mylonites. These are in turn tectonically overlain by the peridotites of the Sierra Alpujata (Tubía *et al.*, 1997).The internal structure of the Sierra Blanca, an elongated massif has been interpreted recently (Orozco and Alonso-Chaves, 2012) as a large recumbent fold with a curved hinge (Fig. 8). Although curved, the hinge line is contained in a plane whose attitude coincides with the axial-plane crenulation foliation (Sc). The plane non-cylindrical character of the large recumbent fold is also manifested in the planar distribution of minor fold axes (Fig. 8A), which parallel the mean attitude of the Sc crenulation foliation. The elliptical cross section of associated minor folds has a high Y-Z aspect ratio (Fig. 9), which is characteristic of sheath folds formed in a general shear deformation (Alsop and Holdsworth, 2006). The sense of shear inferred from the distribution of asymmetric fold axes indicates downward and eastward movement of the upper wall relative to the lower one. This is also consistent with the mean orientation of the stretching lineation (Fig. 8B). The approximate parallelism between the great-circle girdle along which the fold axes are distributed, and the mean attitude of the Sc surfaces, which dip roughly 10º towards the E-SE, supports a close relationship between the arcuate-to sheath folds of the Sierra Blanca with an important, wide heterogeneous ductile shear zone that includes the marble sequence and neighbouring rocks. The large folds of the Sierra Blanca and associated structures developed in the footwall of the peridotite basal contact (Fig. 2) defined as a major extensional detachment by Garcia-Dueñas and Balanyá (1991) and Balanyá *et al.* (1997). The neighbouring carbonate massif of the Sierra de Mijas (Fig. 8) also shows overturned- to recumbent-folds with curved hinge lines (Andreo and Sanz de Galdeano, 1994). The fold axes are preferentially oriented ESE-WNW, except in the western end of the Sierra where they gradually curve (Fig. 8). The stretching lineation is parallel to the fold axes. The shape of the enveloping tectonic surface of the Sierra Blanca-Sierra de Mijas carbonate massifs (Fig. 8), suggests km-scale boudinage structures (Fig. 2, cross section I-I'). The tectonically overlying peridotites of the Sierra Alpujata are currently exposed in the neck between the two massifs. This corridor shows a roughly N-S trend, subperpendicular to the regional stretching lineation (Fig. 8) (see also Tubía, 1988). The folded carbonate rocks show a structure very similar to the "trains" of mesoscopic-scale boudinaged and rootless folds which are commonly found in high-strain zones (Fig. 10) except for the great difference in size. Constraints on the PT path during the development of the shear zone are provided by two types of leucocratic dykes that cut the overlying peridotite of the Sierra Alpujata (Tubía *et al.*, 1997). The older dykes are mylonitic, and were rotated by progressive deformation into parallelism to the shear zone at the base of the peridotite. The dykes show a ENE-trending stretching lineation, and have metamorphic assemblages including

FIGURE 7. Fault-mullion structures developed on the extensional detachment surface which tectonically bounds the overturned carbonate rocks of the Río Grande anticline (footwall) from the overlying phyllite (hanging wall). North of Berja.

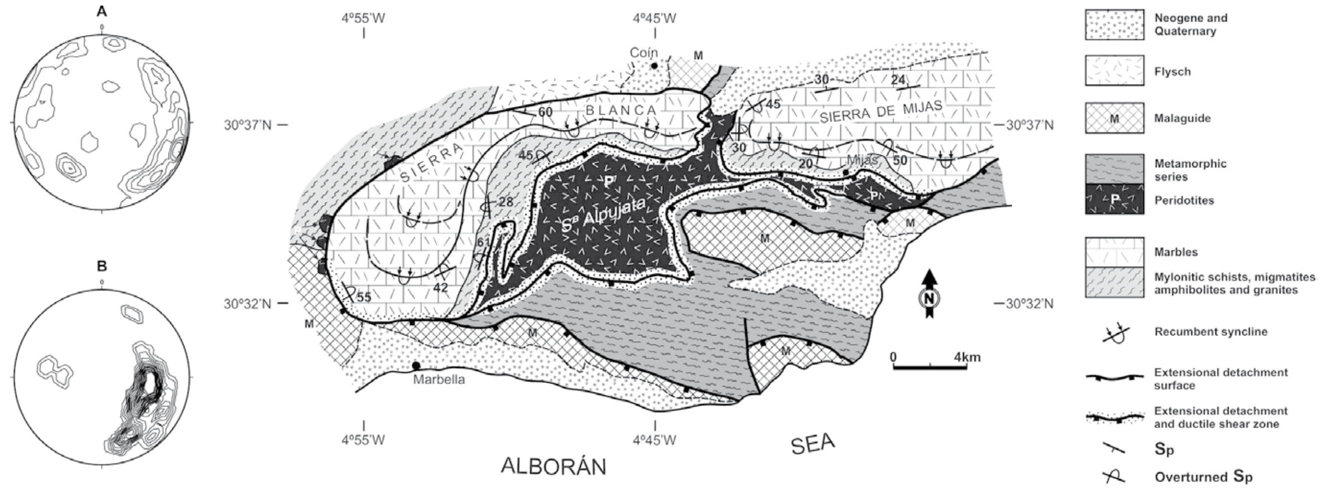


FIGURE 8. Tectonic map of the Sierra Blanca-Sierra de Mijas area, western Betics (see Figure 2 for location), showing the overturned fold structure in both carbonate massifs. The Sª Blanca-Sª de Mijas fold exhibits a great variation in orientation of the hinge line. Associated minor fold axes also present important variations in orientation (Fig. 8A), although they show a nearly planar distribution. Part B, mean orientation of the stretching lineation.

biotite, garnet and sillimanite, indicating conditions of ~650ºC and 500MPa. The younger dykes consist mainly of cordierite and tourmaline-bearing aplites; they are not deformed but are arranged perpendicular to the stretching lineation. According Tubía *et al.* (1997), this second suite of dykes was emplaced at ~300MPa. The data show that there was a significant pressure drop during development of the shear zone, which is consistent with our suggestion that it was related to regional extension and crustal thinning. Ar-Ar ages on hornblende, white mica, and biotite from this area cluster around 19Ma, and reflect cooling during extension and exhumation (Monie *et al.*, 1994, Sossons *et al.*, 1998).

Axarquía region, eastern Málaga province

The region of the Axarquía (Fig. 1) and the neighbouring the Sierra Tejeda and the Sierra Almijara have been the aim of some of our recent structural studies (Orozco and Alonso-Chaves, 2002; Alonso-Chaves and Orozco, 2007, 2012). Boundaries between tectonic units were interpreted as low-angle normal faults that were active at different times during the Neogene, and some of them at younger ages, which reduced the thickness of the Alpujarride units and the overlying Maláguide complex. In addition to the low-angle normal faults, there are large recumbent folds with overturned limbs several kilometres in length, some of which have been dismembered and masked by extensional detachment faults (Alonso-Chaves and Orozco, 2007, 2012). The axial surfaces of these large folds are now folded as a result of a superposition of deformation that occurred during the late Miocene (Alonso-Chaves and Orozco, 2012). The large north-facing recumbent folds, extending at least over the eastern and central parts of the Axarquía region, were reconstructed from geometrical analysis of foliations, minor folds, and other structures (Orozco and Alonso-Chaves, 2002; Alonso-Chaves and Orozco, 2012). Gneiss and migmatitic levels ussually occupy the anticlinal core in the eastern Axarquía region. The folds deform the principal foliation (Sp) and have an axial-plane crenulation foliation (Sc) (Fig. 2, cross section II-II').

The fold axis is nearly parallel, to the direction of the stretching lineation, roughly East-West. Mesoscopic folds are commonly asymmetric, non-cylindrical and their hinge orientations vary widely although they approach a great circle distribution (Orozco and Alonso-Chaves, 2002). The sense of asymmetry of the folds must be consistent with the sense of shear in the zone. Hansen's (1971) method of determining the slip direction is based on this relation of fold asymmetry to shear sense. The slip or shear direction being marked by the bisector of the "separation angle" (across which the shear sense changes) between the two populations of asymmetric folds, the northwestward-plunging clockwise folds and the anticlockwise south-plunging ones. The slip-line trends (shear direction) approximately east-west, and approaches the mean orientation of the stretching lineation maximum (Orozco and Alonso-Chaves, 2002). The sense of shear indicates eastward movement of the upper wall relative to the lower one. This, and the mean attitude of the Sc surfaces, which approach but never match the orientation of the great-circle girdle along which the fold axes are distributed, suggest that the folds formed in a wide shear zone with an approximately eastward transport direction.

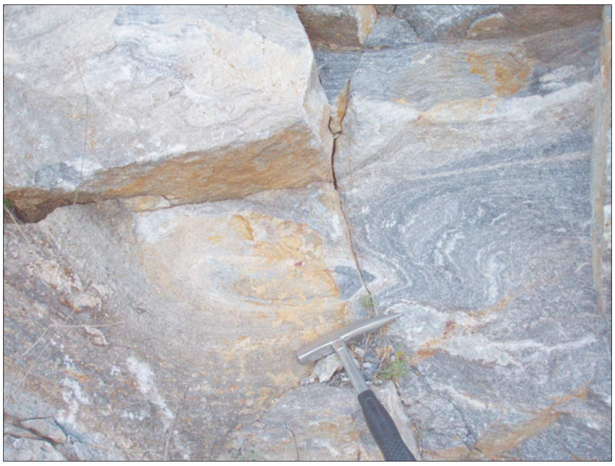


FIGURE 9. Elliptical cross-section of a sheath fold showing a high Y-Z aspect ratio. Marble Formation, Sierra Blanca (Western Betics).

García-Casco and Torres-Roldán (1996) showed that metapelites from the area contain assemblages formed by the combination of St+Bt+Grt+Ky+Sil+And and are characterized by mineralogical disequilibrium induced by fast near-isothermal decompression from 10–12kbar to 2–3kbar, at 550–650ºC. Both the main foliation (Sp) and the crenulation foliation (Sc) developed during this near-isothermal decompression stage. Decompression proceeded at a very fast rate, consistent with a bulk exhumation velocity in the range of 5–10km/Ma, as estimated from available radiometric data for this stage (Monié *et al.*, 1994). Thus the conclusions drawn from these petrological studies are consistent with the proposal for an extensional origin of Sc and therefore of the associated recumbent folds.

DISCUSSION

Relationships between major recumbent folding and the extensional shear zones

An important inference from our work in the Alpujarride shear zones is that large recumbent folds were developed during a phase of intense shear strain associated with decompression, horizontal extension, and vertical shortening.

We suggest that, before the start of the early Miocene extensional event, the rocks of the Alpujarride Domain showed variable orientations of the layering due to the preceding crustal thickening episode associated with HP metamorphism. We infer that deformation during the early Miocene extensional event involved a general strain, with components of sub-horizontal simple shear and vertical shortening, imposed on a previously dipping layering and tectonic fabric. In the Alpujarras region, the shear direction was top NNW, and the original layering is likely to have had a N or NW component of dip. In the western and central Alpujarrides, the shear direction was E or ENE.

In both shear zones, the high shear strain rotated the hinges of the recumbent folds towards the extension direction, producing the sheath-fold geometry. In such a situation, folds may undergo a decrease in the interlimb angle and one or both limbs come to lie within the extension field of the strain ellipsoid (Ramsay and Huber, 1987). As a result, boudinaged limbs, rootless hinges, and intrafolial folds could have been generated.

The proposal that the development of the recumbent folds would be related to the Miocene extensional event, is based on different facts such as: the close relationship existing between these folds and low-angle normal faults and extensional detachments, the gently dipping Sc (=S3) crenulation foliation, parallel to fold axial-plane, and the similarity in orientation of stretching lineation with the slip direction of the low-angle normal faults, as has been recognised in the Adra-Sierra de Gádor area (Orozco *et al.*, 1998), the Sierra de Lújar-western Alpujarras (Orozco *et al.*, 2004), the Axarquía-Sierra Tejeda (Orozco and Alonso-Chaves, 2002; Alonso-Chaves and Orozco, 2007) and the Sierra Blanca area in the western Betics (Orozco and Alonso-Chaves, 2012). Results obtained from structural studies carried out in these different areas along the western, central and eastern parts of the Southern Betics are consistent with extension along subhorizontal to gently dipping shear zones and fault planes. The extension direction derived from stretching lineation and associated shear sense criteria changes from top-E in the western part to top-N in the eastern part of the orogen (Figs. 2; 3; 8).

Metamorphic P-T-t evolution and phases of deformation

P-T paths of metamorphism (Fig. 11) are in good agreement with the results obtained from our structural studies. Actually the rocks from all crustal levels show evidence for decompression along paths that were either isothermal or involved a small degree of heating (Fig.11). In the Sierra Blanca-Sierra Alpujata area, in the western Betics (Fig. 2) the metamorphic sole which underlies the Sierra Alpujata peridotites, evolved from an initial eclogite facies metamorphism (P> 1700Mpa; T= 790ºC) to low-pressure (P< 300Mpa) high-temperature (T= 600ºC) conditions (Tubía *et al.*, 1997) (Fig. 11(4)). Rocks associated to the Carratraca peridotite massif, a few kilometres north of the Sierra Alpujata (Fig. 2), also show substantial decompression, either isothermal or accompanied by some increase in temperature (Fig. 11(1a, 1b, 1c)). In the Torrox area, eastern Axarquía (see Fig. 2), where peridotitic rocks do not crop out, García-

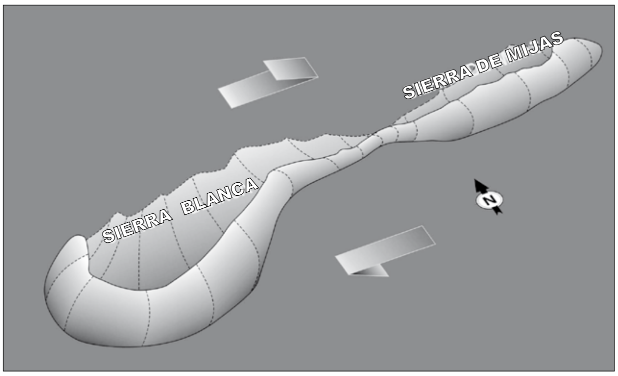


FIGURE 10. Schematic drawing of the Sª Blanca-Sª de Mijas boudinaged sheath-like fold, formed within the shear zone in the footwall of the Alpujata peridotite extensional detachment. Roughly eastward sense of shear is indicated by arrows.

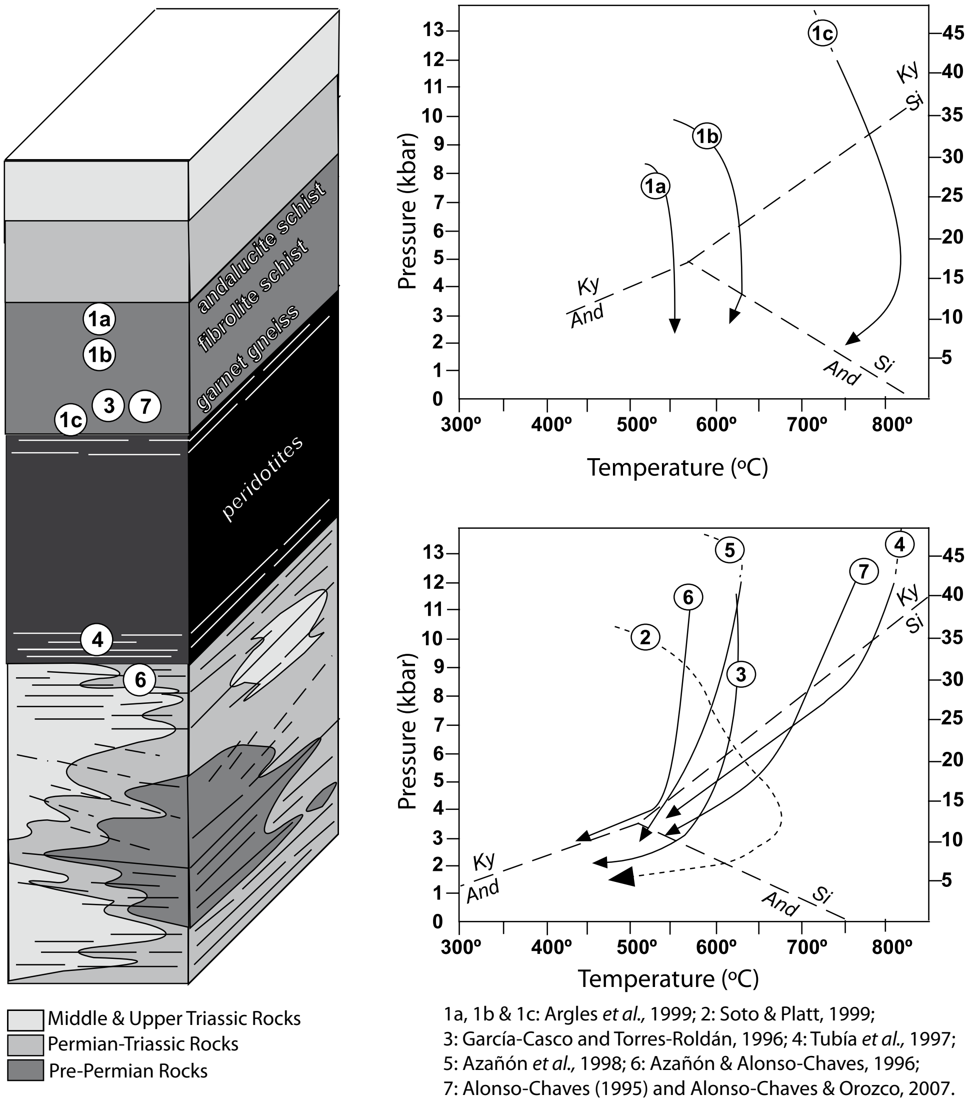
Casco and Torres-Roldán (1996) distinguished four steps in the P-T path for the Torrox schists (which presumably overly the peridotite). The first two steps (which are not represented in Figure 11(3)) would be characterized by heating at moderately decreasing pressure in the kyanite stability field (step 1) and a compressional pulse (step 2), followed by near-isothermal decompression from the kyanite to the andalusite stability field with cooling starting at intermediate to low pressure (step 3) and finally near-isobaric cooling at low P (step 4) (Fig. 11(3)). The development of both the Sp (=S2) and Sc (=S3) foliation surfaces seems directly related to the step 3 of García-Casco and Torres-Roldán, 1996). The development of Sc surfaces in high-grade metamorphic rocks occurred at 3 to 4kbar and 600-700ºC (García-Casco and Torres-Roldán, 1996; Soto and Platt, 1999). P-T paths inferred for the Permo-Triassic schists in the region of the Sierra Tejeda (see Figs. 2; 11(6)), also indicate the existence of an initial high-pressure metamorphic event (10–12kbar, 525–650ºC), followed by decompression under nearly isothermal conditions (Azañón and Alonso-Chaves, 1996), with Sp and Sc metamorphic foliations developed during the decompression. A temperature of 500–550ºC at low pressure (3–4kbar) can be estimated for the end of Sp development. Metamorphic zircons from the highest grade rocks give U-Pb ages of 21-23Ma, and Ar-Ar and fission track data suggest rapid cooling in the interval 20-18Ma (Monié *et al.*, 1994; Sosson *et al.*, 1998; Platt *et al.*, 2003). High rates of cooling and uplift during the final step of the P-T paths are also deduced from the fact that the early Miocene Viñuela Formation (González-Donoso *et al.*, 1982), which transgressively rests on the tectonic unit contacts, has a palaeontological age that largely overlaps with cooling ages.

In the region of Las Alpujarras, (Figs. 1; 3), P-T paths modelling in different levels of an Alpujarride unit (Azañón *et al.*, 1998) also reveal the existence of an early contractional stage of deformation accompanied by high-pressure metamorphism leading to carpholite-kyanite and chloritoid-staurolite-kyanite assemblages in Permo-Triassic metapelites and garnet-kyanite-plagioclase assemblages in the lower part of the Palaeozoic metapelite sequence. Average conditions of 13kbar/625ºC were reached at the bottom of the Palaeozoic sequence during the high-pressure metamorphic stage (Azañón *et al.*, 1998) (Fig. 11(5)). Peak pressures are thought to have resulted from a subduction event involving the continental rocks of the Alborán Domain.

Ar-Ar dating of low-grade white mica from Alpujarride phyllites suggests that cleavage formation associated with early contractional deformation may have occurred at about 50Ma (Platt *et al.*, 2005). The high-pressure metamorphic event was followed by decompression associated with important mineral growth and the development of a flat-lying regional foliation (Sp). The decompression path or at least part of it, is likely to be associated with the important extensional event which affected the Alborán Domain in early Miocene times and produced crustal thinning, ductile shear zones as well as low-angle normal faults (Azañón *et al.*, 1998; Orozco *et al.*, 1998; Platt *et al.*, 1998). Staurolite growth from kyanite and garnet was mainly syn-kinematic with respect to the S2 foliation. According to Azañón *et al.* (1998) the D2 deformation phase should have continued at least to below 5,5kbar (at 580ºC) for the kyanite-sillimanite transformation (Fig. 11(5)).

The P-T conditions during the development of Sc (=S3) crenulation foliation in the sillimanite schists are well-constrained (Azañón *et al.*, 1998). Fibrolite aggregates indicate that during D3 deformation phase T was still >500º C. Andalusite growth generally postdates the D3 deformation phase; however, locally, andalusite crystals are affected by folds from this phase, which consequently must have developed close to the univariant andalusite-sillimanite reaction. As pointed out by Azañón *et al.* (1998) P-T conditions for the D3 deformation phase at these structural levels are 3–4kbars and 500–590ºC (Azañón *et al.*, 1998) (Fig. 11(5)).

In short, P-T paths established for different areas of the Alpujarride region, reveal a continuous drop in pressure of up to 10kbar following the HP-LT metamorphic event (*e.g.* Alonso-Chaves, 1995; Azañón and Alonso-Chaves, 1996; García-Casco and Torres-Roldán, 1996; Soto and Platt, 1999; Tubía *et al.*, 1997; Arglés *et al.*, 1999; Azañón *et al.*, 1998). The inferred, more or less continuous extensional shearing event (following crustal thickening) during which both Sp (=S2) and Sc (=S3) foliation surfaces were generated is consistent with the documented P-T paths. Moreover, the development of large recumbent folds and



1a, 1b & 1c: Argles *et al.,* 1999; 2: Soto & Platt, 1999;
3: García-Casco and Torres-Roldán, 1996; 4: Tubía *et al.,* 1997;
5: Azañón *et al.,* 1998; 6: Azañón & Alonso-Chaves, 1996;
7: Alonso-Chaves (1995) and Alonso-Chaves & Orozco, 2007.

FIGURE 11. P-T paths for different units of the Alpujarride Complex. Western Alpujarride: 1a, 1b,1c (Argles *et al.*, 1999), 4 (Tubía *et al.*, 1997); 2 ODP Site 976 in the Alboran Sea (Soto and Platt, 1999); Central Alpujarride, Axarquía-Tejeda area: 3 (García-Casco and Torres-Roldán, 1996), 6 (Azañón and Alonso-Chaves, 1996), 7 (Alonso-Chaves, 1995 and Alonso-Chaves & Orozco, 2007); eastern area, Alpujarras region: 5 (Azañón *et al.*, 1998).

the associated Sc crenulation cleavage occurred during this stage of decreasing pressure (Orozco *et al.*, 1998).

Ar-Ar and fission track data from large recumbent folds in the eastern Alpujarras (see Figs. 3, cross-section II-II´; 5A) confine the age of the axial-plane crenulation cleavage (Sc= S3) and hence of the folds, to 19-23Ma (Platt *et al.*, 2005). That is precisely the age range of the main phase of late-orogenic extension and exhumation in the Alborán Domain as a whole (Platt *et al.*, 2003). These data are in good agreement with the palaeontological lower Langhian age of a transgressive conglomerate sequence that overlies the Alpujarride and Maláguide complexes sealing the low-angle normal faults that limit both tectonic complexes in the neighbouring Berja region (Mayoral *et al.*, 1994).

The tectonic evolution proposed in this paper differs from other, alternative interpretations like those of Azañón *et al.* (1997) and Rossetti *et al.* (2005). In both studies the deformation phases D1 to D3 and the metamorphism associated with them are attributed to pre-Miocene tectono-metamorphic events. Azañón *et al.* (1997) have suggested that the superposition of structures and the metamorphic evolution in the Alpujarride Complex would result from a sequence of alternating contractional and extensional events. According to them, extensional fault systems resulting in the opening of the Alborán Sea developed during the late Oligocene-early Miocene which would suggest that the alternating contractional and extensional events were pre-Miocene. The sequence of tectono-metamorphic events inferred in our study also presents clear differences with that of Rossetti *et al.* (2005) for the Alpujarrides of the Central part of the Cordillera. According to these authors, "much of the exhumation of the Alpujarride Complex was achieved during the build-up of the Betic Internal Zone, pre-dating the Early Miocene post-orogenic extensional process associated with the Alborán rifting". According to them, the D1 to D3 deformation phases would all be of contractional character.

In summary, our structural studies carried out in different areas of the Alpujárride Complex, from the westernmost part of the Betic Cordillera to the region of Almería in the East, show the existence of two wide heterogeneous extensional shear zones developed during the D3 deformation phase. Recumbent folds and associated flat-lying S3 axial plane foliation developed in relation to the extensional shear zones. These data are in agreement with the existing P-T paths (see Fig. 11) and the radiometric data as outlined above. As reported previously, the age of the axial-plane crenulation cleavage (Sc= S3) and hence the F3 folds in the Alpujarras region, is limited to 19-23Ma (Platt *et al.*, 2005), *i.e.* the age range of the main phase of late-orogenic extension and exhumation of the Alborán Domain (Platt *et al.*, 2003).

The development of carbonate domes in Las Alpujarras and their relation to other structures

The internal structure of the eastern Alpujarras carbonate domes is that of a large north-facing boudinaged syncline in which a main detachment surface is located along the upper surface of the inverted limb, with carbonate rocks in the footwall, and phyllites in the hanging-wall (Figs. 4; 7). There are several notable features of the elongate domes of the Turón-Berja area that support a close association of these structures with the extensional detachment that lies above them.

i) They are developed within the highly strained overturned limb of the Río Grande plurikilometric fold (Fig.4).

ii) They have a mullion geometry with rounded antiforms alternating with pinched synforms at decametric to the kilometric scales (Fig. 7). The orientation of mullions is NNW–SSE, approximately parallel to the stretching lineation.

iii) The orientation of the associated stretching lineation is N150º-170ºE, roughly perpendicular to the mean orientation of the boudin necks (N240º-260ºE) (Fig. 6).

iv) The slip direction of the associated low-angle-normal faults trends N330º-350ºE (Crespo-Blanc *et al.*, 1994).

Plurikilometric mullions in the carbonate rocks of the inverted limb have created a number of elongate domes, roughly parallel to the regional stretching lineation, which warp the detachment surface. The presence of domiform detachment faults in regions of extended continental crust has been highlighted in other parts of the world (*e.g.* Lister *et al.*, 1984; Davis *et al.*, 2002; Whitney *et al.*, 2004). Wright *et al.* (1974) coined the term "turtleback surfaces" to denominate three peculiar domical fault surfaces several kilometres in length which crop out in the eastern part of the Death Valley. According to these authors, the "turtleback surfaces of Death Valley may be colossal fault mullions resulting from severe crustal extension, which were localized along undulating and northwest-plunging zones of weakness". Extension-parallel fault corrugations in Arizona core complexes have recently been interpreted as the result of shortening (Singleton, 2013). According to this author, the most important mechanism for driving extension-perpendicular shortening was probably the reduction of vertical stresses through crustal thinning and tectonic denudation.

We interpret the Turon-Berja domes as structures analogous to the Death Valley turtlebacks, and to other corrugations and elongate domes formed parallel to the slip direction in detachment faults. The eastern Alpujarras elongate domes developed during a relatively late stage of the early Miocene extensional event, probably related to vertical crustal thinning.

The relationships between the two shear zones

The deformation in both the top-to-the-east and the top-to-the-north shear zones seems to have been partly contemporary, as inferred from muscovite Ar-Ar radiometric data (Zeck *et al.*, 1992; Monie *et al.*, 1994; Sosson *et al.*, 1998, Platt *et al.*, 2003, 2005), but may have continued to slightly later times in the top-to-the-north shear zone. Apatite fission track data (Sossons *et al.*, 1998, Platt *et al.*, 2003) and paleontological sealing data (González-Donoso *et al.*, 1982; Aguado *et al.*, 1990) from western and central areas give congruent (Burdigalian) ages. On the other hand, in the top-to-the-north shear zone of Las Alpujarras, the age of the exhumation established by zircon and apatite fission track (Platt *et al.*, 2005) and the paleontological dating of the conglomerate sequence that unconformably overlies the Alpujarride sequence in the area of Berja (Fig. 1), is slightly younger (Early Langhian, according to Mayoral *et al.*, 1994).

The region between the villages of Torrox and Almuñecar, just west of Motril, with mean shear directions SW-NE, could be interpreted as a lateral transition zone between the east-directed shear zone in the western part of the Alpujarride Complex and the top-to-the-north shear zone found in the region of Las Alpujarras, east of Motril (Fig. 1). Nevertheless, the nature of this transition is not clear at present, as the tectonic units cannot easily be correlated across this boundary. In the upper parts of the Adra unit, which lies tectonically above the top-to-the-north shear zone in Las Alpujarras, the average orientation of the stretching lineation is roughly SW-NE, whereas in areas close to the basal detachment of the unit and to the underlying shear zone, the stretching lineation is more variable in orientation, also with orientations closer to N-S (Fig. 3). This could indicate that there is also a transition in the vertical direction.

CONCLUDING REMARKS

Two large extensional shear zones were developed within the Alpujarride Complex of the Betic Cordillera, one with an eastward sense of movement, which mainly affected the tectonic units of the western half of the orogen, and the other with top-to-the-north sense of movement developed in the units which occupy the central-eastern region of Las Alpujarras. Geochronological and stratigraphic data suggest that these two shear zones overlapped in time during the early Miocene, but the top-to-the-north shear zone may have ceased activity a little later, during the middle Miocene.

Previous structural work in the Alpujarride Complex identified several phases of deformation, involving both ductile deformation (*e.g*. Rossetti *et al*., 2005) and brittle slip on low-angle normal faults (*e.g*. Crespo-Blanc, 1995). In this study we have integrated the deformation history, relating the ductile to the brittle deformation, and placed it in the context of the metamorphic evolution and available geochronological constraints. We have shown that there are two large scale shear zones with different kinematics developed along the length of the Alpujarride Complex, both of which involve large-scale folding, boudinage, and the formation of a regional foliation, and both of which formed during decompression and an evolution to low-pressure metamorphism.

The changing kinematics of these extensional shear zones may be consistent with a geodynamic model involving east-directed subduction in the frontal (western) areas of the Gibraltar arc (Lonergan and White, 1997; Gutscher *et al*., 2002, 2012), and subsequent north-directed subduction along the southern margin of the orogen. This change in subduction direction would have taken place below a lithospheric domain (Alborán Domain) that progressively acquired an arcuate shape during its gradual shift to the W relative to the Iberian and African plates. Inside the Alborán Domain, lithospheric thinning and crustal extension were associated with westwards to southwards roll-back of an E- to roughly N-directed subduction zone.

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REFERENCES

Aguado, R., Feinberg, H., Durand-Delga, M., Martín-Algarra, A., Esteras, M., Didon, J., 1990. Nuevos datos sobre la edad de formaciones miocenas transgresivas sobre las Zonas Internas béticas: la formación de San Pedro Alcántara (Prov. de Málaga). Revista de la Sociedad Geológica de España, 3, 79-85.

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 Geológica Hispánica, 14, 154-166.

Alonso-Chaves, F.M., 1995. Evolución tectónica de Sierra Tejeda y su relación con procesos de engrosamiento y adelgazamiento corticales en las Cordilleras Béticas. PhD Thesis. Universidad de Granada, 265pp.

Alonso-Chaves, F.M., Orozco, M., 2007. Evolución tectónica de las Sierras de Tejeda y Almijara: colapso extensional y exhumación de áreas metamórficas en el Dominio de Alborán (Cordilleras Béticas). Revista de la Sociedad Geológica de España, 20, 211-228.

Alonso-Chaves, F.M., Orozco, M., 2012. El Complejo Alpujárride de la Axarquía: zonas de cizalla dúctiles a escala cortical y pliegues recumbentes asociados. Geogaceta, 52, 5-8.

Alsop, G.I., Holdsworth, R.E., 2006. Sheath folds as discriminators of bulk strain type. Journal of Structural Geology, 28, 1588-1606.

Andreo, B., Sanz de Galdeano, C., 1994. Structure of the Sierra Mijas (Alpujarride complex, Betic Cordillera). Annales Tectonicae, 8, 23-35.

Argles, T.W., Platt, J.P., Walters, T.J., 1999. Attenuation and excision of a crustal section during extensional exhumation: The Carratraca massif, Betic Cordillera, southern Spain. Journal of the Geological Society, 156, 149-162.

Azañón, J.M., Alonso-Chaves, F.M., 1996. Alpine tectono-metamorphic evolution of the Tejeda Unit, an extensionally dismembered Alpujarride Nappe (Western Betics). Comtes Rendus de l'Académie des Sciences, 322, série IIa, 47-54.

Azañón, J.M., García-Dueñas, V., Martínez-Martínez, J.M., Crespo-Blanc, A., 1994. Alpujarride tectonic sheets in the central Betics and similar Eastern alloctonous units (S.E. Spain). Comtes Rendus de l'Académie des Sciences, 318, série II, 667-674.

Azañón, J.M., Crespo-Blanc, A., García-Dueñas, V., 1997. Continental collision, crustal thinning and nappe-forming during the pre-Miocene evolution of the Alpujarride Complex (Alboran Domain, Betics). Journal of Structural Geology, 19, 1055-1071.

Azañón, J.M., García-Dueñas, V., Goffé, B., 1998. Exhumation of high pressure metapelites and coeval crustal extensión in the Alpujarride Complex (Betic Cordillera). Tectonophysics, 285, 231-252.

Balanyá, J.C., García-Dueñas, V., Azañón, J.M., Sánchez-Gómez, M., 1997. Alternating contractional and extensional events in the Alpujarride nappes of the Alboran Domain (Betics, Gibraltar Arc). Tectonics, 16(2), 226-238.

Crespo-Blanc, A., 1995. Interference of extensional fault systems: a case study of the Miocene riftng of the Alboran basement (North of Sierra Nevada, Betic Chain). Journal of Structural Geology, 17, 1559-1569.

Crespo-Blanc, A., Orozco, M., García-Dueñas, V., 1994. Extension versus compression during the Miocene tectonic evolution of the Betic Chain. Late folding of normal fault systems. Tectonics, 13, 78-88.

Cobbold, P.R., Quinquis, H., 1980. Development of sheath folds in shear regimes. Journal of Structural Geology, 2, 119-126.

Cuevas, J., Tubía, J.M., 1990. Quartz fabric evolution within the Adra Nappe (Betic Cordilleras, Spain). Journal of Structural Geology, 12, 823-833.

Cuevas, J., Navarro-Vilá, F., Tubía, J.M., 2001. Evolución estructural poliorogénica del Complejo Maláguide (Cordilleras Béticas). Boletín Geológico y Minero de España, 112, 47-48.

Davis, G.A., Derby, B.J., Yadong, Z., Spell, T.L., 2002. Geometric and temporal evolution of and extensional detachment fault, Hohhot metamorphic core complex, Inner Mongolia, China. Geology, 30(11), 1003-1006.

Delgado, F., Estévez, A., Martín, J.M., Martín-Algarra, A., 1981. Observaciones sobre la estratigrafía de la formación carbonatada de los mantos alpujárrides (Cordilleras Béticas). Estudios Geológicos, 37, 45-57.

García-Casco, A., Torres-Roldán, R.L., 1996. Disequilibrium Induced by Fast Decompression in St-Bt-Grt-Ky-Sil-And Metapelites from the Betic Belt (Southern Spain). Journal of Petrology, 37, 1207-1239.

García-Dueñas, V., Balanyá, J.C., 1991. Fallas normales de bajo ángulo a gran escala en las Béticas occidentales. Geogaceta, 9, 33-37.

Goffé, B., Michard, A., García-Dueñas, V., González-Lodeiro, F., Monié, P., Campos, J., Galindo-Zaldívar, J., Jabaloy, A., Martínez-Martínez, J.M., Simancas, F., 1989. First evidence of high-pressure, low-temperature metamorphism in the Alpujárride nappes, Betic Cordillera (SE Spain). European Journal of Mineralogy, 1, 139-142.

González-Donoso, J.M., Linares, D., Molina, E., Serrano, F., Vera, J.A., 1982. Sobre la edad de la formación de la Viñuela (Cordilleras Béticas, Provincia de Málaga). Real Sociedad Española de Historia Natural, Boletín 80, 255-275.

Gutscher, M.A., Malod, J., Rehault, J.P., Contrucci, I., Klingelhoefer, F., Mendes-Victor, L., Spakman, W., 2002. Evidence for active subduction beneath Gibraltar. Geology, 30, 1071-1074.

Gutscher, M.A., Dominguez, S., Westbrook, G.K., Le Roy, P., Rosas, F., Duarte, J.C., Terrinha, P., Miranda, J.M., Graindorge, D., Gailler, A., Sallares, V., Bartolome, R., 2012. The Gibraltar subduction: A decade of new geophysical data. Tectonophysics, 574-575, 72-91.

Hansen, E., 1971. Strain Facies. Springer, Berlin, 207pp.

Jabaloy, A., Galindo-Zaldívar, J., González-Lodeiro, F., 1993. The Alpujárride-Nevado-Filábride extensional shear zone, Betic Cordillera, SE Spain. Journal of Structural Geology, 15, 555-569.

Johnson, B.J., Harbury, N., Hurford, A.J., 1997. The role of extension in the Miocene denudation of the Nevado-Filábride Complex, Betic Cordillera (SE Spain). Tectonics, 16, 189-204. DOI: 10.1029/96TC03289

Kozur, H., Mulder-Blaken, C.W.H., Simon, O.J., 1985. On the Triassic of the Betic Cordilleras (Southern Spain) with special emphasis on holothurian sclerites. Mededeling/Geologisch Instituut, Universiteit van Amsterdam, Stratigraphy. Paleontology, 88, 83-110.

Lister, G.S., Banga, G., Feenstra, A., 1984. Metamorphic core complexes of Cordilleran type in the Cyclades, Aegean Sea, Greece. Geology, 12, 221-225.

Lonergan, L., Platt, J.P., 1995. The Maláguide-Alpujarride boundary: a major extensional contact in the Internal Zone of the eastern Betic Cordillera, SE Spain. Journal of Structural Geology, 17, 1665-1671.

Lonergan, L., White, N., 1997. Origin of the Betic-Rif mountain belt. Tectonics, 16, 504-522.

López Sánchez-Vizcaino, V., Rubatto, D., Gómez-Pugnaire, M.T., Trommsdorff, V., Müntener, O., 2001. Middle Miocene high-pressure metamorphism and fast exhumation of the Nevado-Filábride Complex, SE Spain. Terra Nova, 13, 327-332.

Mayoral, E., Crespo-Blanc, A., Díaz, M.G., Benot, C., Orozco, M., 1994. Rifting miocène du Domaine d'Alboran: datations de sédiments discordants sur les unités alpujarrides en extension (Sud de la Sierra Nevada, Chaîne Bétique). Comtes Rendus de l'Académie des Sciences, 319, 581-588.

Monié, P., Torres-Roldán, R.L., García-Casco, A., 1994. Cooling and exhumation of the Western Betic Cordilleras, ^{40}Ar/^{39}Ar thermochronological constraints on a collapsed terrane. Tectonophysics, 238, 353-379.

Orozco, M., Alonso-Chaves, F.M., Nieto F., 1998. Development of large north-facing folds and their relation to crustal extension in the Alborán domain (Alpujarras region, Betic Cordilleras, Spain). Tectonophysics, 298, 271-295.

Orozco, M., Alonso-Chaves, F.M., 2002. Estructuras de colapso extensional en el Dominio de Alborán. Región de La Axarquía-Sierra Tejeda (provincias de Málaga y Granada). Granada, Comisión de Tectónica de la Sociedad Geológica de España, 127pp. ISBN: 84-607-5712-9

Orozco, M., Álvarez-Valero, A.M., Alonso-Chaves, F.M., Platt, J.P., 2004. Internal structure of a collapsed terrain. The Lújar syncline and its significance for the fold- and sheet-structure of the Alborán Domain (Betic Cordilleras, Spain). Tectonophysics, 385, 85-104.

Orozco, M., Alonso-Chaves, F.M., 2012. Kilometre-scale sheath folds in the western Betics (south of Spain). International Journal of Earth Sciences (Geologische Rundschau), 101, 505-519.

Platt, J.P., Soto, J.I., Whitehouse, M.J., Hurtford, A.J., Kelley, S.P., 1998. Thermal evolution, rate of exhumation and tectonic significance of metamorphic rocks from the floor of the Alboran extensional basin, western Mediterranean. Tectonics, 17, 671-689.

Platt, J.P., Argles, T.W., Carter, A., Kelley, S.P., Whitehouse, M.J., Lonergan, L., 2003. Exhumation of the Ronda peridotite and its crustal envelope: constraints from thermal modelling of a P-T-time array. Journal of the Geological Society, 160, 655-676.

Platt, J.P., Kelley, S.P., Carter, A., Orozco, M., 2005. Timing of tectonic events in the Alpujárride Complex, Betic Cordillera, southern Spain. Journal of the Geological Society, 162, 451-462.

Platt, J.P., Anczkiewicz, R., Soto, J.I., Kelley, S.P., Thirlwall, M., 2006. Early Miocene continental subduction and rapid exhumation in the western Mediteranean. Geology, 34, 981-984.

Ramsay, J.G., Huber, M.I., 1987. The techniques of modern Structural Geology, Volume 2: Folds and Fractures. London, Academic Press Inc., 391pp.

Rossetti, F., Faccenna, C., Crespo-Blanc, A., 2005. Structural and kinematic constraints to the exhumation of the Alpujarride Complex (Central Betic Cordillera, Spain). Journal of Structural Geology, 27, 199-216.

Royden, L.H., 1993. The tectonic expression of slab pull at continental convergent boundaries. Tectonics, 12, 303-325.

Simancas, J.F., Campos, J., 1993. Compresión NNW-SSE tardi a postmetamórfica y extensión subordinada en el Complejo Alpujárride (Dominio de Alborán, Orógeno Bético). Revista de la Sociedad Geológica de España, 6, 23-35.

Singleton, J.S., 2013. Development of extension-parallel corrugations in the Buckskin-Rawhide metamorphic core complex, west-central Arizona. Geological Society of America (GSA) Bulletin, 125, 453-472.

Sosson, M., Morillon, A.C., Bourgois, J., Feraud, G., Poupeau, G., Saintmarc, P., 1998. Late exhumation stages of the Alpujárride complex (western Betic Cordilleras, Spain): new thermochronological and structural data on Los-Reales and Ojén nappes. Tectonophysics, 285, 253-273.

Soto, J.I., Platt, J.P., 1999. Petrological and structural evolution of high-grade metamorphic rocks from the floor of the Alboran Sea basin, Western Mediterranean. Journal of Petrology, 40, 21-60.

Tubía, J.M., 1988. Estructura de los Alpujárrides occidentales: cinemática y condiciones de emplazamiento de las peridotitas de Ronda. Publicaciones Especiales del Boletín Geológico y Minero de España. Madrid, 124pp.

Tubía, J.M., Gil-Ibarguchi, J.I., 1991. Eclogites of the Ojén nappe: a record of subduction in the Alpujarride complex (Betic Cordilleras, southern Spain). Journal of the Geological Society, 148, 801-804.

Tubía, J.M., Cuevas, J., Gil-Ibarguchi, J.I., 1997. Sequential development of the metamorphic aureole beneath the Ronda peridotites and its bearing on the tectonic evolution of the Betic Cordillera. Tectonophysics, 279, 227-252.

Vissers, R.L.M., Platt, J.P., Van Der Wal, D., 1995. Late orogenic extension of the Betic Cordillera and the Alboran domain: A lithospheric view. Tectonics, 14, 786-803.

Whitney, D.L., Teyssier, Ch., Siddoway, Ch.S., (eds.), 2004. Gneiss Domes in Orogeny. Geological Society of America Special Paper, 380, 393pp.

Wright, L.A., Otton, J.K., Troxel, B.W., 1974. Turtleback surfaces of Death Valley viewed as phenomena of extensional tectonics. Geology, 2, 53-54.

Zeck, H.P., Monié, P., Villa, I.M., Hansen, B.T., 1992. Very high rates of cooling and uplift in the Alpine belt of the Betic Cordilleras, southern Spain. Geology, 20, 79-82.

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