

Lateral interaction between metamorphic core complexes and less-extended, tilt-block domains: the Alpujarras strike-slip transfer fault zone (Betics, SE Spain)

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Received 10 May 2005; received in revised form 13 December 2005; accepted 28 January 2006

Available online 13 March 2006

Abstract

The Alpujarras area in southeastern Spain exhibits one of the scant documented examples of extension related strike-slip faults bordering core complexes in the world. Faults of the Alpujarras fault zone define a regional-scale complex ENE-striking transfer zone that marks the boundary among the Sierra Nevada elongated dome, a highly-extended, constricted core-complex, and a less-extended domain formed by large-scale tilt-blocks. Detailed mapping and structural analysis show that the Alpujarras fault zone is an integral part of the WSW-directed normal fault systems that thinned the Betic hinterland during the middle Miocene to Recent time. Fault patterns and palaeostress analysis both indicate that dextral movement along the strike-slip faults was induced by a local stress field with a sub-horizontal E–W- to ESE–WNW-trending maximum principal stress axis, which is synchronous with the regional stress field driving the normal fault systems. Palaeostress analysis also indicates subsequent variations in the stress field with a sub-horizontal NW–SE- to N–S-trending maximum principal stress axis, thus producing both the tectonic inversion of the northern fault of the Alpujarras system and shortening of the unloaded extensional detachment footwall. A simplified kinematic model for the tectonic evolution of the Alpujarras area from the middle Miocene to Recent emphasizes the kinematic coupling of normal faults and strike-slip transfer zones in the extensional process.

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Keywords: Transfer fault zones; Segmented normal fault systems; Metamorphic core-complexes; Tilt-block domains; Palaeostress analysis; Betics

1. Introduction

The segmentation in normal fault systems is well documented within extensional tectonic provinces (Davis and Burchfiel, 1973; Stewart, 1980; Bally, 1981; Gibbs, 1984; Rosendahl, 1987; Faulds et al., 1990; Wernicke, 1992). All normal faults must terminate both up and down dip and along strike. Segmented fault traces are seen over a large range of scales (e.g. Peacock, 2003). Regions near fault tip lines and between adjacent en échelon segments are often zones of concentrated strain associated with the progressive loss of slip on individual faults and the transfer of displacement between fault segments in order to conserve the regional extensional strain (Morley et al., 1990; Nicol et al., 2002). Accommodation of extension between individual faults gives rise to transverse

or oblique structures that were denominated transfer zones, also known as accommodation zones, relay zones and segment boundaries (Morley et al., 1990; Gawthorpe and Hurst, 1993; Faulds and Varga, 1998).

The term ‘transfer zone’ was previously introduced by Dahlstrom (1970) to give a name to cross structures accommodating differential shortening in thrust terrains. Transfer zones are structures that serve as a linkage between growing isolated faults. Faults that grow while interacting with other developing faults but not physically intersecting with them are said to be ‘soft linked’. Relay ramps are an example of soft linkage, in which the slip transference from one to another fault can essentially be accommodated by ductile strain. Faults with connecting fault surfaces are described as ‘hard linkages’. Transfer faults are an example of hard linkage which requires that there is actual physical linkage of fault surfaces allowing slip to be transferred (Walsh and Watterson, 1991; McClay and Khalil, 1998). At the regional scale, transfer faults generally are complex transfer fault zones where both hard linkages and soft linkages can occur together.

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Transfer faults, originally described in extensional basins (see Gibbs, 1984), are one type of transverse structure within extended terrains that link spatially separated loci of extension. Faults laterally adjoin extended continental blocks showing similar or opposite structural asymmetry and/or contrasting values of upper-crustal extension (Davis and Burchfiel, 1973; Burchfiel et al., 1989; Duebendorfer and Black, 1992; Faults and Varga, 1998). Transfer faults can be described as strike-slip faults if they strike parallel to the direction of extension, or as oblique-slip faults if they strike oblique to the direction of extension.

Strike-slip transfer faults are dynamically different than strike-slip faults in transcurrent tectonic regimes. The most fundamental difference is that transcurrent faults strike obliquely to the principal stress axes, whereas transfer faults commonly parallel the extension direction. In addition, the sense and magnitude of slip on transfer faults can vary significantly along strike due to intimate coupling between systems of normal or reverse faults (Gibbs, 1990; Duebendorfer et al., 1998; Faults and Varga, 1998). Finally, in transcurrent faults the sense of slip is coherent with the offset that increases in time whereas the sense of slip in transfer faults is contrary to the apparent offset of the related normal faults that do not vary in time (Gibbs, 1990).

The Alpujarras fault zone of southeastern Spain strikes WSW–ENE and has been recognized as a major structural element of the Betics for nearly 25 years. It was considered as a transcurrent fault zone developed during middle-to-upper Miocene in a stress field with a sub-horizontal WNW–ESE-trending maximum compressive axis (Bernini et al., 1983; Sanz de Galdeano et al., 1985). Several observations suggest that another interpretation on the origin and nature of this fault zone is possible. (1) The spatial and temporal coexistence of the fault zone with WSW-directed normal fault systems. (2) Despite the large scale of the fault zone (more than 60 km length) the amount of slip cannot be determined with certainty (see Sanz de Galdeano et al., 1985; Sanz de Galdeano, 1996). (3) The Alpujarras fault zone is a major structural boundary between crustal blocks showing different values and modes of extension; the highly-extended Sierra Nevada elongated dome (Martínez-Martínez et al., 2002) and the Sierra de la Contraviesa-Sierra de Gádor tilt-block domain (García-Dueñas et al., 1992) with significantly lower values of extension (Figs. 1 and 2).

In this paper, I present a detailed structural analysis of the Alpujarras fault zone and associated structures focusing on the fault terminations, provide an alternative explanation for their development and discuss the role they played in accommodating regional extension. It is the first time that the Alpujarras fault zone is interpreted as a transfer fault zone linking normal fault systems. A simplified kinematic model for the tectonic evolution of the Alpujarras area from the middle Miocene to Recent, which integrates new and existing structural and stratigraphic data, emphasizes the kinematic coupling of normal faults and strike-slip transfer zones in the extensional process.

2. Tectonic framework

The Betics in southern Spain form the northern branch of the peri-Alborán orogenic system (western Mediterranean) (Martínez-Martínez and Azañón, 1997), which also includes the Rif and Tell mountains in North Africa. The Betics and Rif are linked across the Strait of Gibraltar to form an extremely arcuate orogen commonly known as the Gibraltar arc, which lies between the converging African and Iberian plates (Balanyá and García-Dueñas, 1988; Platt et al., 2003) (inset in Fig. 1). Convergence results in a broad zone of distributed deformation and seismicity in the region, resulting in a diffuse plate boundary. Kinematic reconstructions reveal continuous N–S convergence between Africa and Europe from the late Cretaceous to the upper Miocene (9 Ma), then changing to NW–SE until the Present (Dewey et al., 1989; Srivastava et al., 1990; Mazzoli and Helman, 1994). Nevertheless, convergence in the outermost western Mediterranean was considerably lower than in other more eastward Mediterranean regions (e.g. Dewey et al., 1989).

The arcuate orogen results from the collision between the Alborán domain, which moved some 250–300 km westwards relative to Iberia and Africa during the Miocene, and the Mesozoic–Cenozoic South-Iberian and Maghrebian continental margins partially coeval with the obliteration of the Flysch Trough domain (Balanyá and García-Dueñas, 1988; Platt et al., 2003; Chalouan and Michard, 2004). Collision produced tectonic inversion of both continental margins, causing development of a fold-and-thrust belt (Platt et al., 1995; Crespo-Blanc and Campos, 2001) while the hinterland was simultaneously extended (García-Dueñas and Martínez-Martínez, 1988; Galindo-Zaldívar et al., 1989; Platt and Vissers, 1989; García-Dueñas et al., 1992; Jabaloy et al., 1993; Vissers et al., 1995; González-Lodeiro et al., 1996; Lonergan and White, 1997; Martínez-Martínez and Azañón, 1997).

The Miocene deformation history of the Alborán domain is dominated by extreme crustal extension. Two episodes of nearly orthogonal extension in which normal fault systems developed with directions of extension varying from a NNW–SSE system, orthogonal to the belt axis, in the late Burdigalian–Langhian, to a Serravallian WSW-directed orogen-parallel one have been documented (García-Dueñas et al., 1992; Crespo-Blanc et al., 1994; Martínez-Martínez and Azañón, 1997). The superposition of these two systems resulted in a chocolate tablet boudinage mega-structure (e.g. Crespo-Blanc, 1995).

Inhomogeneous finite extension produces contrasting extended crustal domains, with boundaries that are not well outlined, showing significant differences in the mode and rate of extension. Extension in the Alborán basin involves the whole crust, which has been reduced to 15 km thickness (Torné et al., 2000). In the central and eastern Betics (Fig. 1), the Alborán domain is extended along normal fault systems only affecting the upper crust (Platt et al., 1983; Lonergan and Platt, 1995; González-Lodeiro et al., 1996; Johnson et al., 1997; Martínez-Martínez et al., 2002; Booth-Rea et al., 2004b). Upper crustal extension also is inhomogeneous and

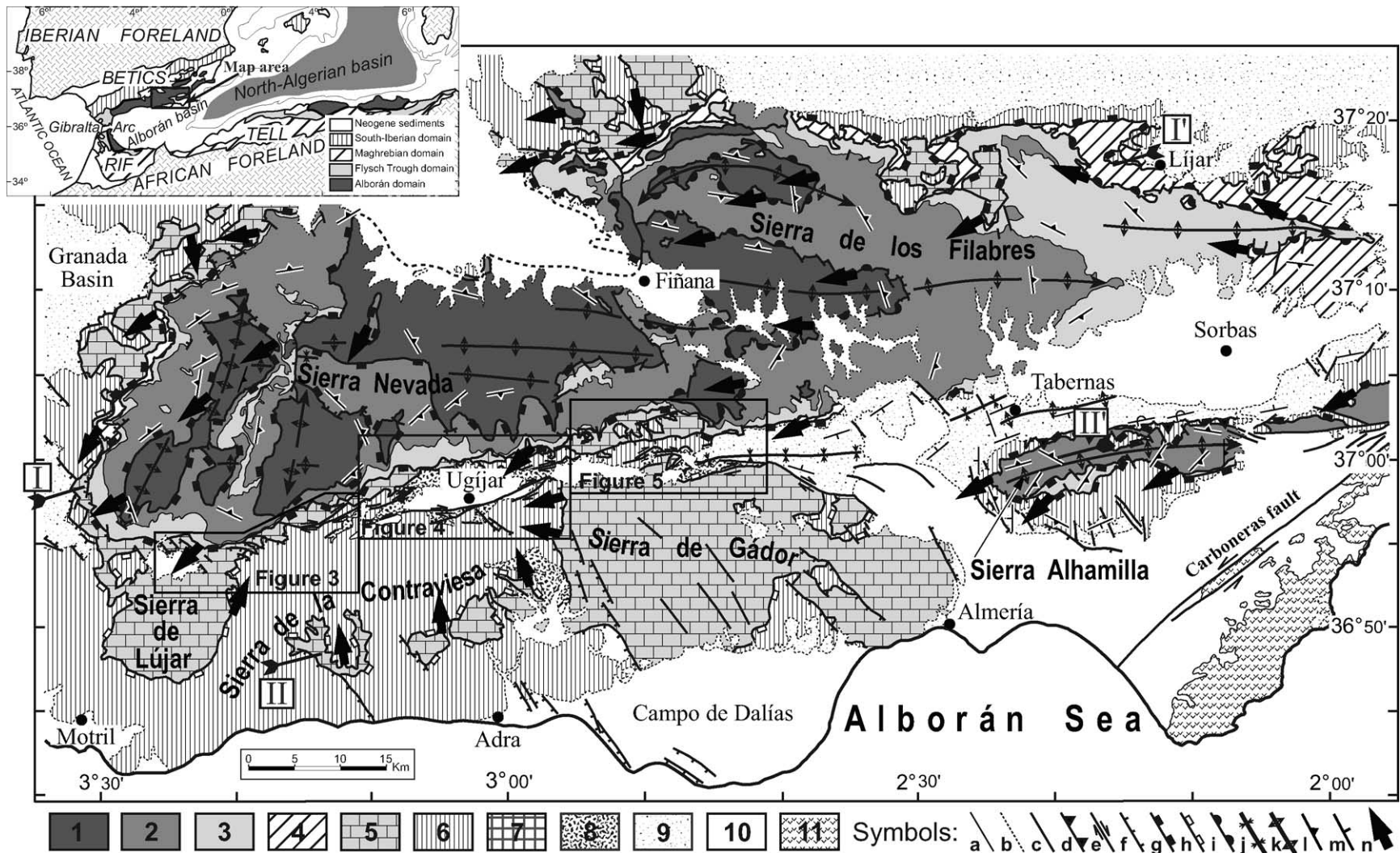


Fig. 1. Tectonic map of the central Alborán domain in the Betics and main tectonic domains around the westernmost Mediterranean (left-upper inset). Legend: *Nevado–Filabride complex*: (1) Ragua unit, (2) and (3) Calar–Alto unit, Palaeozoic and Permo-Triassic rocks, respectively, (4) Bédar–Macaél unit. *Alpujarride complex*: (5) Lújar–Gádor unit, (6) upper Alpujarride units. *Malaguide complex*: (7) undifferentiated. *Neogene sediments*: (8) Langhian–Serravalian, (9) Tortonian, (10) Messinian to Recent. *Neogene volcanic rocks*: (11) undifferentiated. Symbols: (a) lithological contact, (b) unconformity, (c) undifferentiated fault, (d) reverse fault, (e) strike-slip fault, (f) high-angle normal fault, (g) WSW-directed extensional detachment, (h) N-directed low-angle normal fault, (i) W-directed ductile shear zone, (j) syncline, (k) anticline, (l) main foliation dip, (m) bedding dip, (n) sense of hanging wall movement.

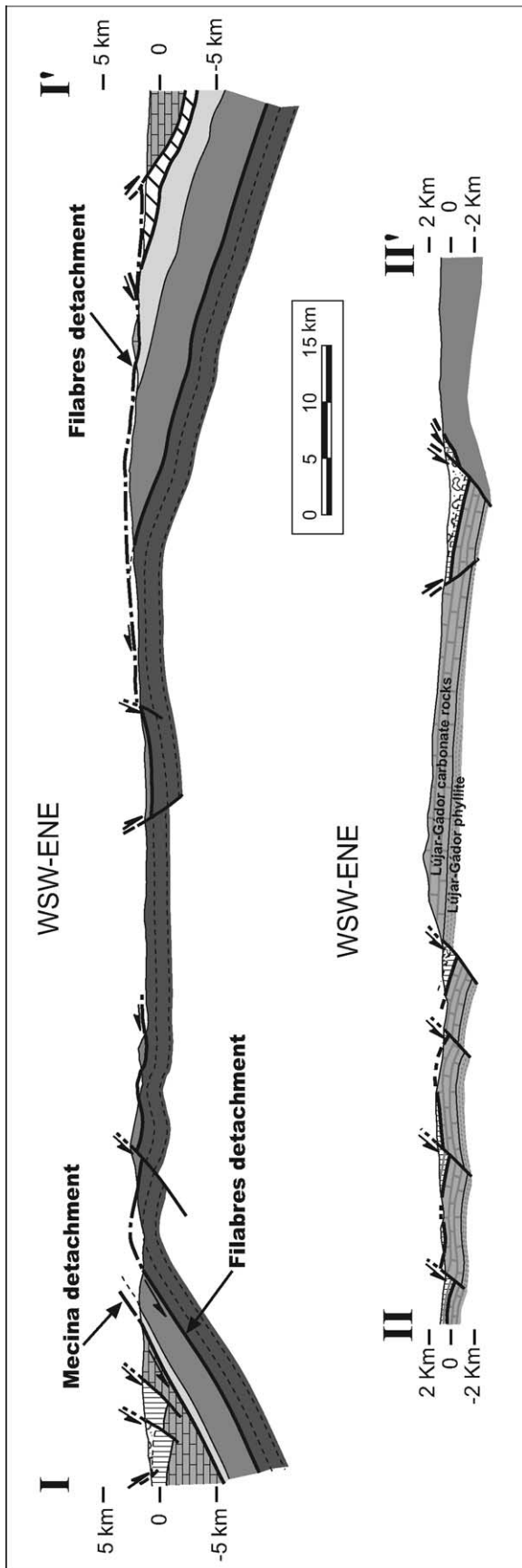


Fig. 2. Structural sections through the Sierra Nevada elongated dome (I–I') and the tilt-block domain (II–II') parallel to the direction of extension (location in Fig. 1).

the extended terrains are partitioned into highly-extended domains characterized by unroofing of extensional detachments around elongated domes (constricted core complexes) (Martínez-Martínez et al., 2002), and broad domains of uniformly WSW-dipping normal faults and accompanying tilt-block domains (García-Dueñas et al., 1992; Martínez-Martínez and Azañón, 1997; Martínez-Díaz and Hernández-Enrile, 2004; Martínez-Martínez et al., 2004). In the highly-extended domains, large-scale folding accompanied tectonic denudation, developing elongated domes with fold hinges both parallel and perpendicular to the direction of extension. A geometric and kinematic model has been recently established (Martínez-Martínez et al., 2002, 2004) to explain the close relationship between extension and shortening, as well as the kinematics and timing of low-angle normal faulting and upright folding. Following these authors, doming was caused by the interference of two orthogonal sets of Miocene–Pliocene, large-scale open folds (trending roughly E–W and N–S) that warp both WSW-directed extensional detachments and the footwall regional foliation. N–S folds were generated by a rolling hinge mechanism while E–W folds formed due to shortening perpendicular to the direction of extension. Driving forces for crustal extension within a tectonic scenario of plate convergence have been attributed to: (1) extensional collapse driven by convective removal of the lithosphere mantle (Platt and Vissers, 1989), (2) delamination of the lithosphere mantle in conjunction with asymmetric thickening of the lithosphere (García-Dueñas et al., 1992; Seber et al., 1996; Calvert et al., 2000), and (3) rapid rollback of a subduction zone (Royden, 1993; Lonergan and White, 1997), among others.

Dextral and sinistral strike-slip faults are other structures that deform the Alborán domain during the late Neogene and Quaternary, particularly in the eastern Betics. The Carboneras fault (Keller et al., 1995; Bell et al., 1997; Faulkner et al., 2003), the Alhama de Murcia fault (Silva et al., 1997; Martínez-Díaz, 2002), the Palomares fault (Weijermars, 1987) and the Terreros fault (Booth-Rea et al., 2004a), all of them with NNE–SSW to NE–SW strike, are examples of sinistral faults. The W–E to NW–SE Gafarillos fault (Stapel et al., 1996) and the Alpujarras fault (Sanz de Galdeano et al., 1985; Martínez-Díaz and Hernández-Enrile, 2004), are examples of dextral faults. Some authors argued that regional extension ceased in the upper Miocene (9 Ma) after which the stress regime changed to a sub-horizontal compressional stress field that induces a N–S to NW–SE shortening developing strike-slip faults and subsidiary normal faults (Stapel et al., 1996; Jonk and Biermann, 2002; Martínez-Díaz and Hernández-Enrile, 2004). The analysis of seismicity, focal mechanisms and active faults in the central and eastern Betics, however, reveals active extension in the upper crust (mostly < 15 km). Active extension predominates in two separated areas in the region, the western Sierra Nevada–Granada basin area (Serrano et al., 1996; Morales et al., 1997; Galindo-Zaldívar et al., 1999; Martínez-Martínez et al., 2002; Muñoz et al., 2002) and the western Sierra de Gádor–Campo de Dalías area (Martínez-Díaz and Hernández-Enrile, 2004; Marín-Lechado et al., 2005) (see Fig. 1).

3. Regional geology

Rocks in the studied area belong to the Alborán domain that consists of a large number of tectonic units grouped into three nappe complexes: the Nevado–Filabrides, the Alpujarrides and the Malaguides, from bottom to top, distinguished according to lithological and metamorphic-grade criteria. The Nevado–Filabride rocks, ranging in age from Palaeozoic to Cretaceous, are for the most part metamorphosed to high-greenschist facies, although they reach amphibolite facies in the uppermost tectonic unit (García-Dueñas et al., 1988; Bakker et al., 1989; Puga et al., 2002). Alpujarride rocks, Palaeozoic to Triassic in age, show variable metamorphic grade, from upper amphibolite to granulite facies at the bottom of certain units to low metamorphic grade at the top (Cuevas, 1990; Tubía et al., 1992; Azañón et al., 1994, 1997). The Malaguide rocks, ranging in age from Silurian to Oligocene, have not undergone significant Alpine metamorphism, although the Silurian series have a very low metamorphic grade (Chalouan and Michard, 1990; Lonergan, 1993).

The most complete section of the Nevado–Filabrides can be found in the Sierra de los Filabres, where the three major thrust units crop out extensively (Fig. 1). They are, from bottom to top: the Ragua, the Calar Alto, and the Bédar–Macaël units, with respective structural thicknesses of 4000, 4500 and 600 m (García-Dueñas et al., 1988). The lithostratigraphic sequences of the units consist primarily of black graphitic schist and quartzite of probable pre-Permian age; a sequence of light-coloured metapelites and metapsammities (probably Permo-Triassic); and a calcite and dolomite marble formation, traditionally considered to be Triassic. Permian orthogneiss and late Jurassic metabasites are locally included at different levels of the sequence. The contacts between the units lie within broad ductile shear zones (500–600 m thick) with a flat geometry (García-Dueñas et al., 1988; González-Casado et al., 1995).

In the Alpujarrides outcropping in the study area, up to four types of superimposed units (from top to bottom: the Adra, Salobreña, Escalate and Lújar-Gádor units; Figs. 3–5) have been recognized, showing significant differences in their metamorphic record, from low-grade conditions ($P < 7$ kb/ $T < 400$ °C) in the lowest unit up to high-grade conditions ($P > 10$ kb/ $T > 550$ °C) in the highest unit (Azañón et al., 1994). Their lithostratigraphic sequences have many similarities; the top of the standard section is constituted by a carbonate formation dated as middle to upper Triassic. Below it a formation of fine-grained, light-coloured schist and phyllite, generally attributed to the Permo-Triassic, crops out. The bottom of the sequence is often constituted by a graphite-schist succession (probably Palaeozoic) overlying a gneissic formation that only appears in the higher unit (Tubía et al., 1992).

The Malaguide complex is represented in the region only by a few scattered exposures exhibiting thin slices of at least two tectonic units including Palaeozoic greywacke and Permo-Triassic red conglomerate, sandstone and dolostone overlying the Alpujarride complex.

Middle Miocene to Recent, marine and continental sediments filled a narrow sedimentary basin (Ugíjar basin) that developed in relation to the Alpujarras fault zone activity. Detailed stratigraphic and sedimentological descriptions can be found in Rodríguez-Fernández et al. (1990). On the basis on this stratigraphy a cartographic revision of different sedimentary formations is presented (Figs. 3–5).

The Alpujarras region is a WSW–ENE-trending valley located between two geologically and structurally contrasting domains, namely the Sierra Nevada elongated dome to the north and the Sierra de Gádor-Sierra de la Contraviesa tilt-block domain to the south (Fig. 1). The Sierra Nevada elongated dome is a large-scale structure (more than 150 km in length and around 30 km in width) that coincides with the highest mountains in the Betic hinterland. Core rocks belonging to the Nevado–Filabride complex were exhumed in the footwall of a middle-to-upper Miocene, WSW-directed normal fault system that consists of a multiple set of ductile–brittle detachments and associated imbricate listric normal faults (Martínez-Martínez et al., 2002), including the Mecina detachment (Aldaya et al., 1984; Galindo-Zaldívar et al., 1989) and the Filabres detachment (García-Dueñas and Martínez-Martínez, 1988), the hanging wall mainly consisting of Alpujarride rocks and minor Malaguide rocks (Fig. 2). The extended domain contains a core complex, with distal and proximal antiformal hinges separated by around 60 km and with fold amplitude of about 6 km. Very high values of upper crustal extension have been estimated in this domain. The total amount of extension across the core complex is about 109–116 km ($\beta = 3.5$ –3.9), according to the distance between the axial surfaces of faulting-related folds in the lower plate (distal antiform and proximal synform hinges) and using a geometrical model for sub-vertical simple shear deformation during footwall denudation (more details in Martínez-Martínez et al., 2002). Crustal deformation beneath the dome is partitioned and decoupling between a deep crust (at 20–35 km depth) and an upper crust was documented. Differential upper crustal extension is compensated at depth by mid-crustal flow, thus maintaining the crustal thickness unchanged (Martínez-Martínez et al., 1997, 2004).

After a period of N–S extension in the lower Miocene, in which the upper Alpujarride units (García-Dueñas et al., 1992; Crespo-Blanc et al., 1994) were mainly thinned, middle-to-upper Miocene extension south of the Alpujarras area was accommodated by WSW-directed high-angle normal faults and block tilting (Fig. 2). The amount of extension ($e \sim 14\%$), lower than the one calculated in the Sierra Nevada elongated dome, is clearly insufficient for the exhumation of the underlying Nevado–Filabride complex which was, however, exhumed more towards the east, in the Sierra Alhamilla area (Fig. 1), in the footwall of WSW-directed extensional detachments (Martínez-Martínez and Azañón, 1997).

4. Timing of deformation

Several pieces of evidence constrain the timing of the WSW-directed extensional systems that thinned and exhumed

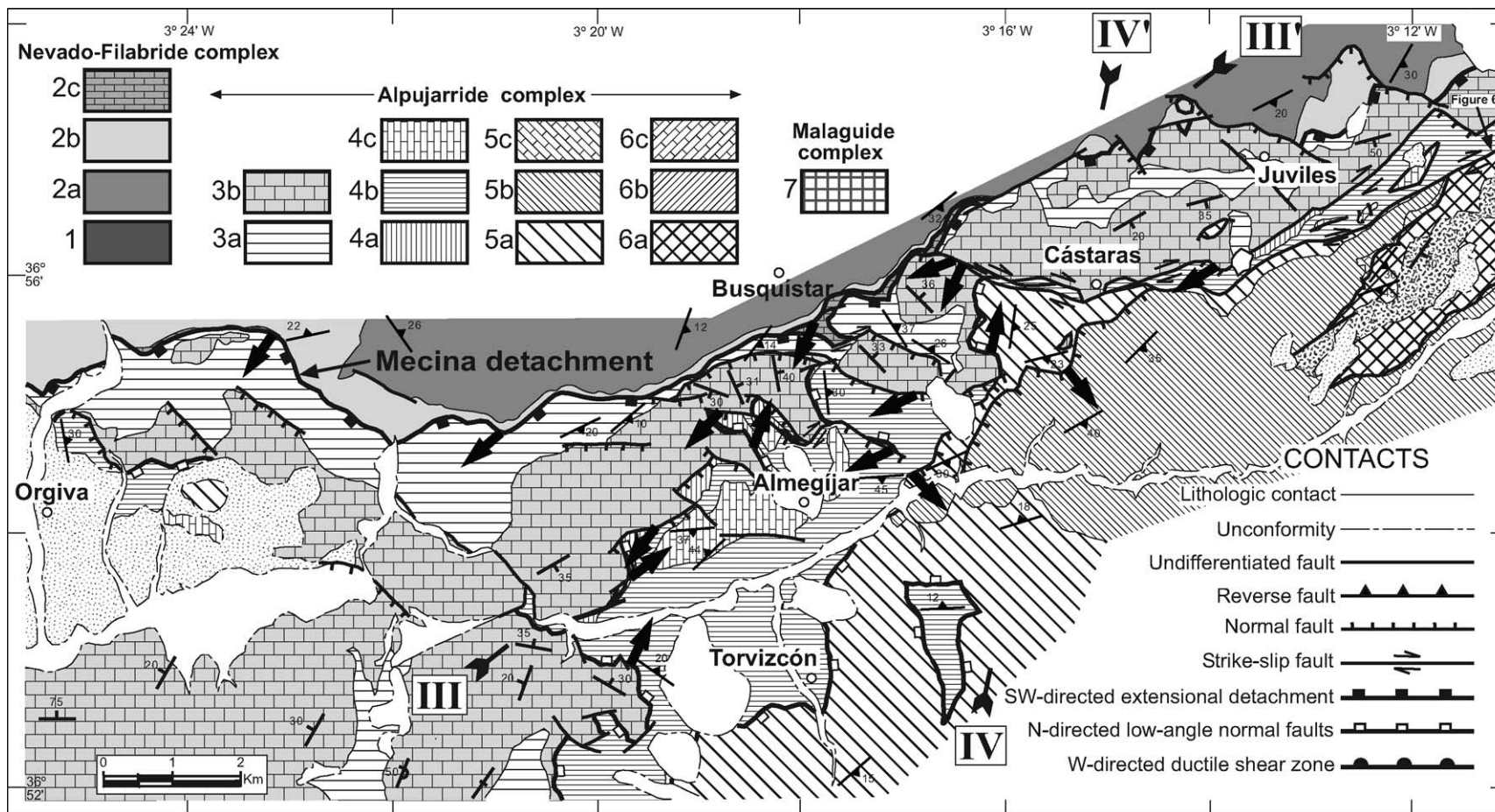


Fig. 3. Structural map of the western Alpujarras sector showing the main strike-slip and normal faults. Black arrows point to sense of normal fault hanging wall movement. Only main foliation and bedding are shown. Lines of sections in Fig. 7 are given by III–III' and IV–IV'. Legend: (1) Ragua unit, (2) Calar Alto unit ((2a) Palaeozoic black schist; (2b) Permo-Triassic light-coloured schist; (2c) carbonate mylonites and cataclasites), (3) Lújar–Gádor unit ((3a) Permo-Triassic phyllite; (3b) Triassic limestone and dolostone), (4) Escalate unit ((4a) Palaeozoic black schist; (4b) Permo-Triassic phyllite; (4c) Triassic limestone and dolostone), (5) Salobreña unit ((5a) Palaeozoic black schist; (5b) Permo-Triassic light-coloured schist and phyllite; (5c) calcite and dolomite marbles), (6) Adra unit ((6a) Palaeozoic black schist; (6b) Permo-Triassic light-coloured schist and phyllite; (6c) calcite and dolomite marbles), (7) undifferentiated Malaguide complex.

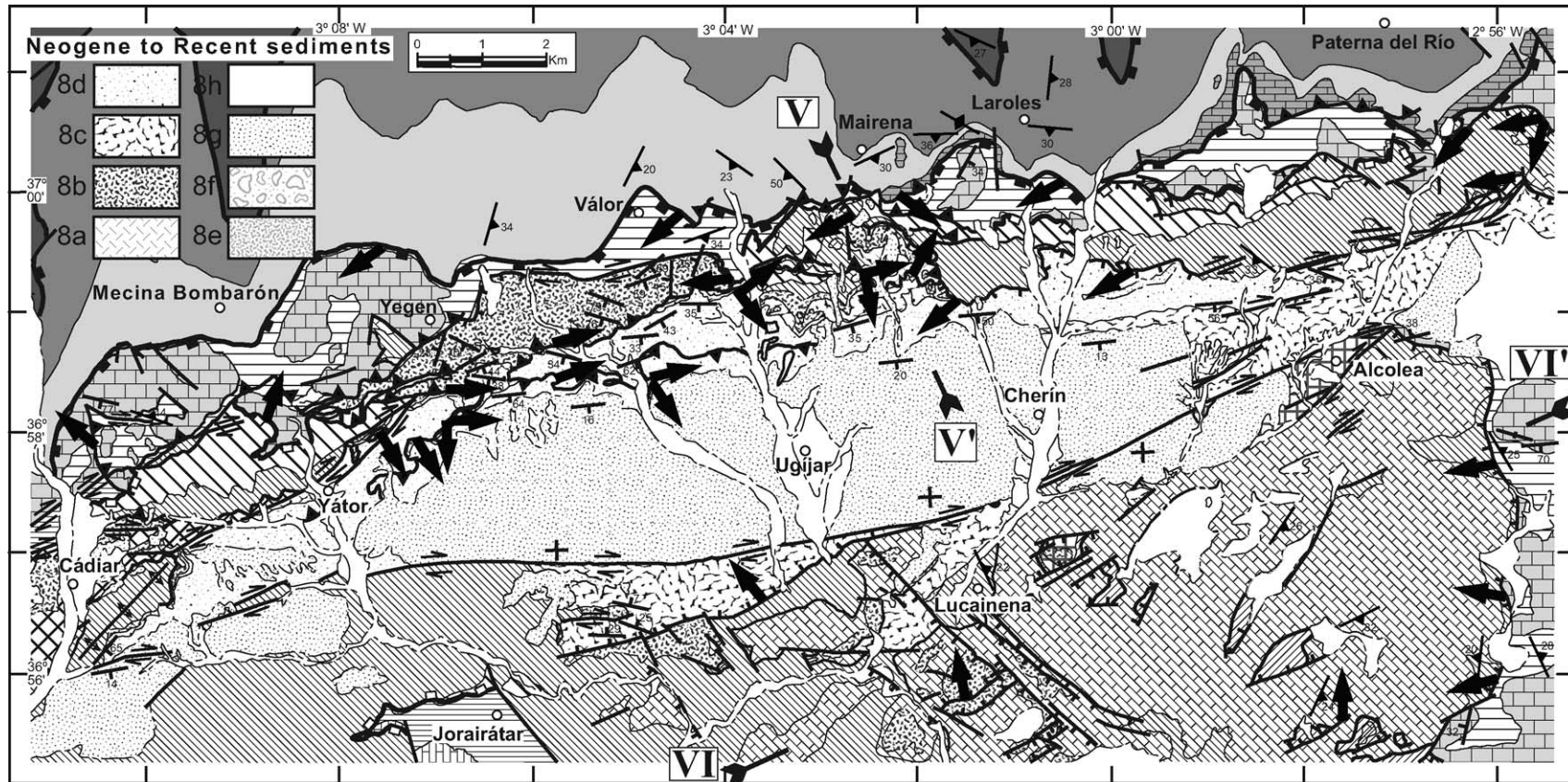


Fig. 4. Structural map of the central Alpujarras sector showing the main strike-slip, reverse and normal faults. Black arrows point to sense of movement of both normal and reverse fault hanging walls. Only main foliation and bedding are shown. Lines of sections in Fig. 7 are given by V–V' and VI–VI'. Legend: (8) Neogene to Recent sediments ((8a) Langhian–lower Serravalian grey marls; (8b) Serravalian red conglomerates; (8c) Serravalian yellow marls and conglomerates; (8d) upper Serravalian dun conglomerates; (8e) upper Serravalian–lower Tortonian red conglomerates; (8f) upper Tortonian grey conglomerates and marls; (8g) Pliocene conglomerates; (8h) Quaternary conglomerates). Both the legend of the other formations and symbols of contacts are the same as in Fig. 3.

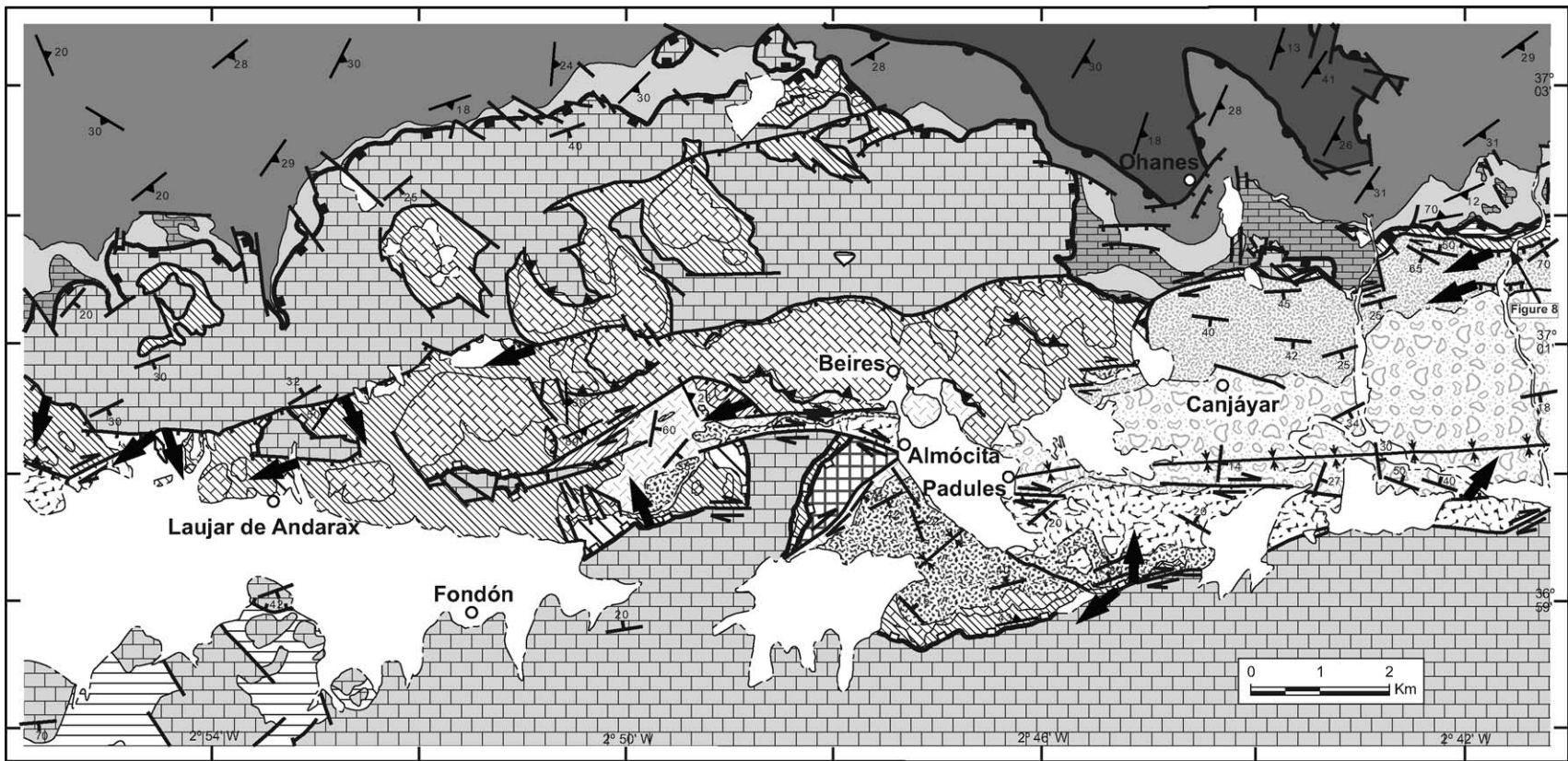


Fig. 5. Structural map of the eastern Alpujarras sector showing the main strike-slip, reverse and normal faults. Black arrows point to sense of movement of normal fault hanging wall. Only main foliation and bedding are shown. Legend and contacts are the same as in Figs. 3 and 4.

the lowest metamorphic complexes in the Betics. Middle Miocene (Serravallian) syn-rift sediments filling half-grabens in the hanging wall of the detachments (Martínez-Martínez and Azañón, 1997) and cooling ages to near-surface temperatures in the footwall that become younger in the direction of hanging wall motion, from 12 Ma in the eastern Sierra de los Filabres to 9 Ma in the western Sierra Nevada (Johnson et al., 1997) point to a middle-to-upper Miocene age for the major detachment faults.

The age of the Alpujarras strike-slip fault zone was constrained on the basis of structural and stratigraphic relationships in the Ugíjar basin (Fig. 1), a narrow Neogene transtensive sedimentary basin whose origin was associated with the movements along the fault zone (Sanz de Galdeano et al., 1985; Rodríguez-Fernández et al., 1990). The initial activity of the Alpujarras fault zone and consequent restriction of the basin is marked by an angular unconformity between uniform Burdigalian–Langhian pelagic marl and Serravallian alluvial fans. The proximal facies of the alluvial fans are distributed along the fault zone that represents the margin of the restricted basin. The alluvial fan sedimentation related to the fault activity continued during the Pliocene after a Tortonian depositional hiatus (Rodríguez-Fernández et al., 1990).

The synchronic development of both extensional detachments and the Alpujarras fault zone together with the basin architecture and fault segmentation relationships suggest a genetic link between both structures.

5. Structure along the Alpujarras fault zone

The Alpujarras fault zone is a band (2–5 km width) of distributed brittle deformation that strikes WSW–ENE along the southern margin of the Sierra Nevada elongated dome (Martínez-Martínez et al., 2004). Striated sub-vertical fault surfaces, brittle fault rocks and other related structures of the system can be observed on the field, both eastward and westward of the Ugíjar village, at least 65 km along strike (Fig. 1). The fault zone was initially mapped and described by Sanz de Galdeano et al. (1985) as a dextral strike-slip fault corridor named the Alpujarran corridor. It was recently referred to as the Alpujarras fault zone by Martínez-Díaz and Hernández-Enrile (2004). The fault zone comprises a complex system of dextral strike-slip, normal and reverse faults whose kinematic linkage is controversial (Galindo-Zaldívar, 1986; Mayoral et al., 1994, 1995; Sanz de Galdeano, 1996). No clear evidence exists on the lateral continuity of the fault zone, but it was argued that strike-slip faults belonging to the system extend both eastward, running through northern Sierra Alhamilla until reaching the Mediterranean coast of south-eastern Spain, and westward connecting with the External/Internal zones boundary near Zafarraya, 50 km NE of Málaga, thus the fault zone would reach near 200 km total length (see Sanz de Galdeano, 1996).

Kinematic indicators in the fault rocks, including sub-horizontal striations, brittle S–C structures, asymmetric porphyroclasts in the fault gouge and the attitude of the

cataclastic foliation, clearly point to a dextral sense of shear (Sanz de Galdeano et al., 1985). The amount of slip is not well known because offset is not observed, as the same reference surface does not occur at both sides of the fault zone. Sanz de Galdeano et al. (1985) suggest a displacement of several dozen kilometres based on both the fault length and the width of the fault rock bands, but as the authors admit, without objective proof of that value.

A detailed structural analysis, including mapping and kinematic analysis of the main faults, was carried out in a wide band along the most visible segment of the Alpujarras fault zone (around 65 km) with two main purposes: (1) estimation of the amount of slip, and (2) the nature of the linkages at the tip lines. To facilitate descriptions and map interpretation, the map has been divided into three sectors: western, central and eastern.

5.1. Western sector

This mapped area corresponds to a densely faulted domain where faults highly differ in their kinematics (Fig. 3). The most septentrional fault is the Mecina ductile–brittle extensional detachment (Aldaya et al., 1984; Galindo-Zaldívar et al., 1989). The detachment corresponds to the boundary between the Nevado–Filabride complex and the overlying Alpujarride complex and belongs to the WSW- to SW-directed multiple set of detachments that extended both metamorphic complexes during the middle and upper Miocene (Martínez-Martínez et al., 2002). The hanging wall of the Mecina detachment was previously extended in a rough orthogonal direction during the lower Miocene (Burdigalian–lower Langhian) (García-Dueñas et al., 1992; Mayoral et al., 1994, 1995). N- to NNE-directed low-angle normal faults belonging to the Contraviesa normal fault system (Crespo-Blanc et al., 1994) constitute the current contact between the stacked Alpujarride units. Locally, low-angle normal faults showing top-to-the-SE sense of shear occur (Fig. 3, south of Cástaras village).

Strike-slip faults are located at the NE corner of the map (Fig. 3). Two main WSW–ENE striking, sub-vertical fault traces define the fault zone and merge together near Cástaras showing clear evidence of dextral sense of shear (Fig. 6). Black graphite–schist, phyllite and marble belonging to the Escalate unit are sandwiched between the faults. The fault zone bounds two blocks with contrasting features. The northern one consists of a thinned sequence of phyllite, limestone and dolostone belonging to the lower Alpujarride unit (Lújar–Gádor unit), while the southern block is made up of rocks belonging to the two upper Alpujarride units, the Salobreña unit and the overlying Adra unit. Thus, the amount of offset along the fault zone has not been constrained in this sector.

The fault zone considerably narrows west of Cástaras shifting to a WNW–ESE strike and finally merging with the Mecina extensional detachment. The last fault segment is a releasing bend like two others that are observed more easterly. Extensional deformation is associated with the releasing bends in the respective southwestern blocks (cross-section III–III' on Fig. 7). The cross-section depicts the geometry of this

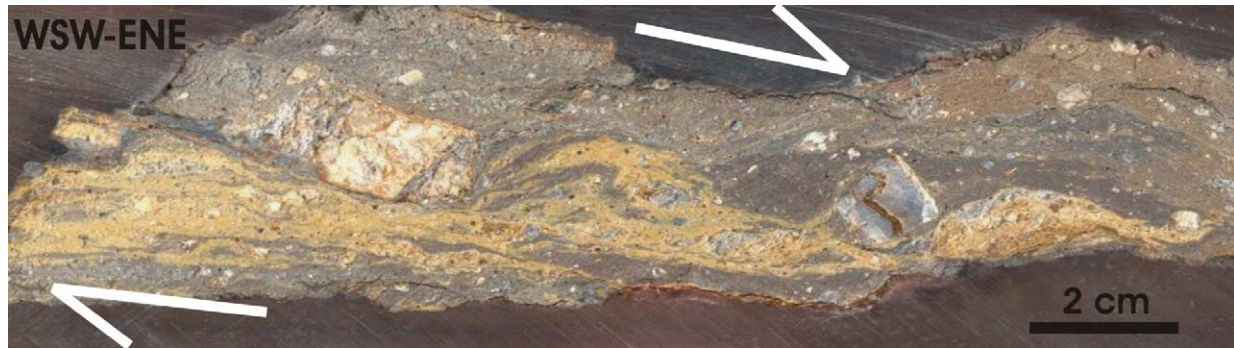


Fig. 6. Brittle S–C structures, asymmetric porphyroclasts and microfolds in the sub-vertical, foliated fault-gouge associated with the northern fault of the Alpujarras fault zone showing dextral sense of shear (see Fig. 3).

extensional sub-domain showing an emergent listric fan coalescing on a detachment fault, the Mecina detachment. The hanging-wall structure consists of a series of emergent imbricate wedges or riders (Gibbs, 1984) where NE tilting of NNE-directed low-angle normal faults occurred. Cross-section IV–IV' shows the contrasting structural domains south and north of the Alpujarras fault zone.

5.2. Central sector

The Alpujarras fault zone widens here reaching 5 km maximum width. Two major strike-slip faults, exhibiting some structural differences, mark the fault zone boundaries. Segments of the northern fault can be followed west to east on the map from immediately north of Cádiz to 3 km south of Paterna del Río (Fig. 4). Some strike-slip segments are linked to WSW-directed normal faults. Other ones are truncated by mainly north-dipping reverse faults that show complex kinematics with at least two sets of striations trending W–E to WSW–ESE and NNW–SSE, respectively. Kinematic indicators point to top-to-the-E sense of shear in the first case, roughly parallel to strike and top-to-the-SSE in the second case, indicating pure reverse fault kinematics. Reverse faults are folded in an open antiform with a sub-horizontal hinge trending WSW–ESE (Galindo-Zaldívar, 1986) and they are sealed by the Pliocene unconformity (cross-section V–V' on Fig. 7).

The hanging wall of the Mecina detachment, consisting of a highly-attenuated Alpujarride nappe-stack with thin remnants of the four main units, constitutes the northern block of the northern strike-slip fault. Neogene sediments of the Ugujjar basin form the southern block. No markers have been observed to constrain the amount of offset in this sector either.

The more continuous southern strike-slip fault warps from the south of Cádiz to the north of Alcolea showing both WSW–ENE and W–E segments. Similarly to the northern fault, the sense of shear is unequivocally dextral along sub-horizontal striations (Sanz de Galdeano et al., 1985), although oblique striations revealing a normal slip component locally occurs (Galindo-Zaldívar, 1986). The structural map on Fig. 4 clearly shows both lithological and structural differences between both fault blocks. Northward, Pliocene sediments

unconformably lie on the middle Miocene sediments. Metapelites of the metamorphic basement crop out SE of Cádiz in a SW–NE-trending anticline core. In the southern block basement rocks together with their sedimentary cover show a sub-orthogonal pattern of extension. High-angle, W-to-SW-directed normal faults postdate both north- and south-dipping high-angle normal faults. Eastwards tilting of bedding and foliation distinctively characterizes this structural domain (cross-section VI–VI' on Fig. 7). The strike-slip fault seems to be a barrier to along-strike propagation of the W-to-SW-directed normal faults because none of them cut across it. The most eastern normal fault geometrically and kinematically links with the strike-slip fault NE of Alcolea (Fig. 4). The offset is contradictory; the basal sedimentary unconformity sinistrally offsets while the Pliocene unconformity dextrally offsets in the western fault segment. In the eastern fault segment, the offset of the Pliocene unconformity is sinistral.

5.3. Eastern sector

The Alpujarras fault zone continues eastward as discontinuous segments of strike-slip faults laterally adjoining the Sierra Nevada elongated dome at the north and the Sierra de Gádor eastwards tilt-block at the south (Figs. 1 and 5). Although evidence for Neogene strike-slip faulting is widespread in this sector, the task of assessing the amount of displacement is difficult here as well because no offset markers are known. Quaternary sediments unconformably lie on the fault zone thus contributing to a poor exposure. In addition, more recent, both reverse and normal faults contribute here to the discontinuous pattern of the Alpujarras fault zone. Such is the case of the high-angle normal fault that strikes WSW–ENE from N of Laujar de Andarax to N of Beires (Fig. 5). This fault shows two sets of striations, the older trending WSW–ENE and the younger trending NNW–SSE and probably represents a fault belonging to the Alpujarras fault zone reworked during the Plio-Quaternary.

The most striking feature of this sector is the fault segment that crops out south of Ohanes village (Fig. 5), where the eastern tip line of the Alpujarras fault zone is located. The fault separates Nevado–Filabride rocks or highly thinned Alpujarride units from upper Serravalian–lower Tortonian red

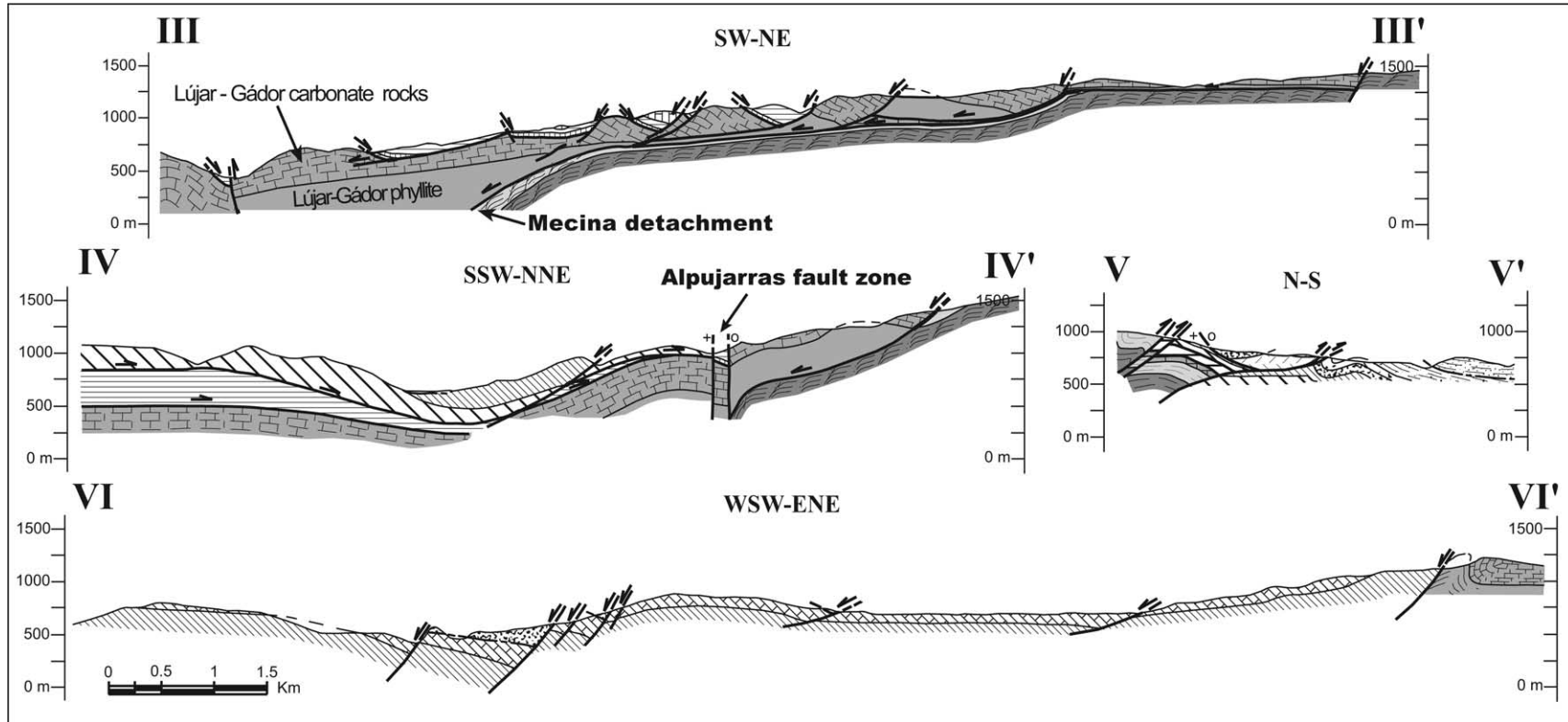


Fig. 7. Several structural sections through the Alpujarras region are shown. Section III–III' (location in Fig. 3) depicts the mode of extensional tectonics at the western termination of the Alpujarras transfer fault zone. Section IV–IV' (location in Fig. 3) shows the contrasting structural domains at both side of the fault zone. Section V–V' (location in Fig. 4) illustrates the tectonic inversion of the transfer fault zone and the shortening of the Neogene sedimentary basin. And section VI–VI' (location in Fig. 4) emphasizes the geometry of the tilted block domain.

conglomerate. The nature of this contact changes eastwards along strike from a sub-vertical dextral strike-slip fault to a WSW-directed low-angle normal fault, thus suggesting a kinematic link between strike-slip and normal faults. Fig. 8 shows the features of the fault rocks associated with the normal fault, the red conglomerate being transformed in breccia and gouge developing cataclastic foliation and shear surfaces that indicate top-to-SW sense of shear. This fault belongs to a normal fault system that can continue further east, south of the Sierra de los Filabres and in Sierra Alhamilla (see Fig. 1).

6. Palaeostress analysis

Both dextral and sinistral striated strike-slip faults together with diversely orientated reverse and normal faults occur at the outcrop scale along the Alpujarras fault zone. Kinematic indicators, including tails of microcrushed material behind striating clasts, slickenfibres and the attitude of the cataclastic foliation, are not uncommon in the area and have been used to deduce the sense of displacement on fault planes. Localities where the orientations and senses of displacement on sufficient fault planes with different orientations can be known are the best suitable sites for palaeostress analysis. Notwithstanding the limitations and assumptions of the stress inversion methods, the reduced stress tensor, consisting of four components, can be extracted from fault-slip data. These are the directions of the three principal stresses ($\sigma_1 \geq \sigma_2 \geq \sigma_3$) and the relative magnitudes for the principal stress axes, expressed by the axial ratio $R = (\sigma_2 - \sigma_3) / (\sigma_1 - \sigma_3)$, with $0 < R < 1$ (e.g. Angelier, 1994; Wallbrecher et al., 1996).

The Alpujarras fault zone operated from the middle Miocene to Recent (Rodríguez-Fernández et al., 1990). Geometric and kinematic analysis of the fault zone suggests that some of the strike-slip faults were inverted from the upper Miocene onwards, whereas others continued with the same regime until recently. I used palaeostress analysis to approach the stress field that induced the movement along the strike-slip faults, the possible change in the stress field, thus producing tectonic inversion and the lateral variations in the stress field. The search grid method (Galindo-Zaldívar and González-Lo-deiro, 1988) was the chosen routine for these purposes as it allows for differentiating of overprinted stages of faulting.

Five sites in the studied area were carefully selected (Table 1, Fig. 9). Sites 1 and 5 are located near the western and eastern terminations of the northern fault, respectively. Site 2 is close to the southern fault, which clearly worked during the Pliocene as a strike-slip fault. Sites 3 and 4 are at locations where deformation is dominated by both strike-slip and reverse faults. The results show that the measured fault-slip data in sites 1–4 congruently fit a single stress tensor while the data collected in site 5 must be separated in two populations fitting two different stress tensors. Stress tensors with a sub-horizontal E–W-trending σ_1 and a sub-horizontal σ_3 were calculated in sites 1 and 2. Jonk and Biermann (2002) detected similar stress tensors in the eastern Betics and suggest they represent a stress-regime that existed in pre-Tortonian time. In the Alpujarras area, however, this stress-regime seems to remain until Recent.

Other significantly different stress tensors characterize sites 3 and 4. Site 3 shows a tensor with a sub-horizontal NW–SE-trending σ_1 and a sub-horizontal NE–SW-trending σ_3 . In site 4 the maximum compressive axis of stress σ_1 roughly trends N–S. Stress tensors similar to these two have been broadly detected in the eastern Betics (Stapel et al., 1996; Huibregtse et al., 1998; Jonk and Biermann, 2002). These authors agree that the state of stress changed from NW–SE compression to N–S compression in the earliest Messinian time. Finally, two stress tensors with a sub-horizontal E–W-trending σ_1 and a sub-horizontal N–S-trending σ_3 , respectively, have been discriminated in the most eastern site suggesting overprinting of two very different stress fields with permutations between the maximum and minimum principal stress axes (Fig. 9).

Palaeostress analysis suggests that σ_3 is typically oblique to the Alpujarras fault zone, a result that could appear to be inconsistent with the transfer fault model, which requires that extension is parallel to fault strike. Nevertheless, being the Alpujarras fault zone parallel to the regional extension direction, the transcurrent movement along the fault zone necessarily induces a local rotation in the attitude of σ_3 , such as in oceanic transform faults (Angelier et al., 2004).

7. Discussion and conclusions

The Alpujarras area contains one of the scant documented examples of extension related strike-slip faults bordering core complexes in the world. Faults of the Alpujarras fault zone define a regional-scale complex transfer zone that marks the boundary among the Sierra Nevada elongated dome, a highly-extended, constricted core-complex and a less-extended domain formed by large-scale tilt-blocks, yet their role in accommodating regional extension has been unnoticed. Sanz de Galdeano et al. (1985) and Sanz de Galdeano (1996) argued that faults of the Alpujarras fault zone are transcurrent faults essentially formed in a stress field with a sub-horizontal WNW–ESE-trending maximum compressive axis. The fault zone would favour the westwards motion of compartmentalized cortical blocks of the Alborán domain in a tectonic escape model similar to that proposed by Leblanc and Olivier (1984). The presence of subsidiary structures such as pull-apart basins was argued by Sanz de Galdeano et al. (1985) to suggest that strike-slip faults are the principal structures governing deformation and basin development in the Alborán domain during the middle and upper Miocene. Galindo-Zaldívar (1986) hypothesizes that both dextral strike-slip faults and reverse faults of the Alpujarras fault zone would develop in the hanging wall of a supposedly convex segment of the Mecina detachment, due to transtensional deformation along the detachment. Martínez-Díaz and Hernández-Enrile (2004) interpreted the Alpujarras (right-handed) and the Carboneras (left-handed) fault zones (see Fig. 1) as conjugated strike-slip faults and they proposed a block tectonic model in which the wedge between the faults southwestwards escapes and extends to absorb the traction produced in the wedge by the strike-slip movement along the faults. In the Martínez-Díaz and Hernández-Enrile model, extensional structures would be

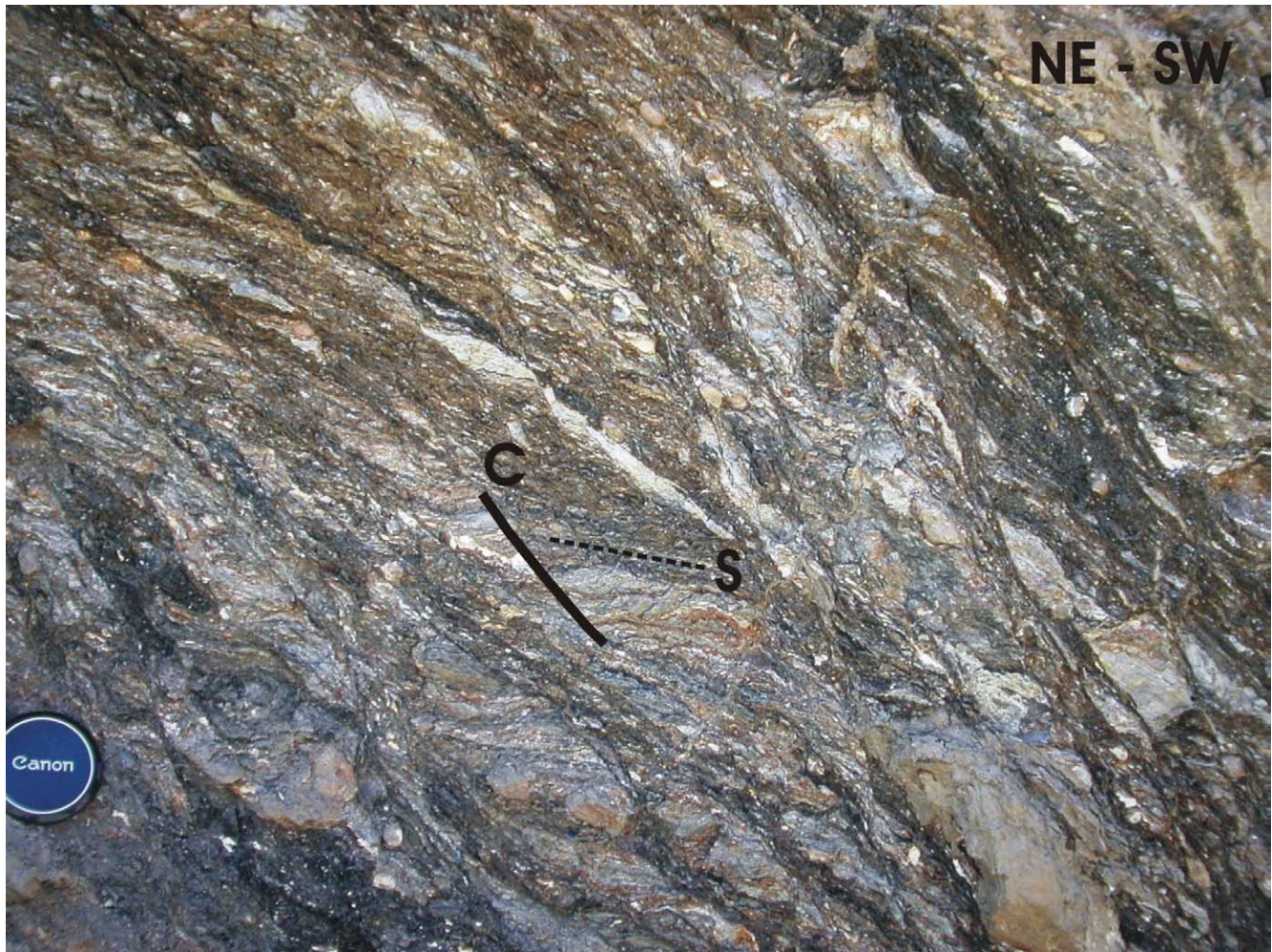


Fig. 8. Fault gouge overprinting lower Tortonian conglomerates from the WSW-directed low-angle normal fault separating the metamorphic basement from the sedimentary cover E of Ohanes village (see Fig. 5). Cataclastic foliation (S) and spaced shear planes (C) show normal sense of shear.

restricted to the wedge and would be related to local extension linked with the NNW–SSE compressive tectonics.

Strike-slip faults of the Alpujarras fault zone can be described, however, as extension-related transfer faults because they have most of the characteristics of transfer faults as defined by Gibbs (1984). Such faults must not be confused with strike-slip faults in the Andersonian sense because they are an integral part of the normal fault systems in inhomogeneous extended terrains. Thus, while transcurrent faults strike obliquely to the regional extension trend, strike-slip transfer faults strike parallel to the regional direction of

extension. Several other considerations suggest that the strike-slip faults of the Alpujarras system can be defined as transfer faults. (1) WSW–ENE striking, dextral, strike-slip faults and WSW-directed extensional detachments are coeval, thus suggesting a kinematic linking between normal and strike-slip faults. (2) The Alpujarras fault zone is a major structural boundary between crustal blocks with radically different middle-to-upper Miocene structural evolution. The fault zone laterally juxtaposes two differentially extended domains, a northern highly-extended domain, including a constricted core complex, and a southern tilt-block domain with significantly

Table 1
Calculated palaeostress tensors in several sites along the Alpujarras fault zone

No.	Lithology	N	N_{tot}	σ_1	σ_2	σ_3	R
1.	Triassic dolostone (Alpujarride)	9	10	082/12	262/78	352/0	0.340
2.	Serravalian marl and Malaguide sandstone	20	24	110/12	281/78	020/2	0.420
3.	Permo-Triassic sandstone and dolostone (Malaguide)	12	14	138/12	318/78	048/0	0.750
4.	Triassic dolostone (Alpujarride)	11	14	162/18	273/49	058/36	0.600
5a.	Serravalian–Tortonian conglomerate	16	22	254/12	131/68	348/18	0.790
5b.	Serravalian–Tortonian conglomerate	14	22	167/28	342/62	076/2	0.880

N , number of slip data fitting the calculated stress tensor; N_{tot} , total number of slip data; σ_1 , σ_2 , σ_3 , trend and plunge of the main axes of stress ellipsoid; R , axial ratio: $(\sigma_2 - \sigma_3)/(\sigma_1 - \sigma_3)$.

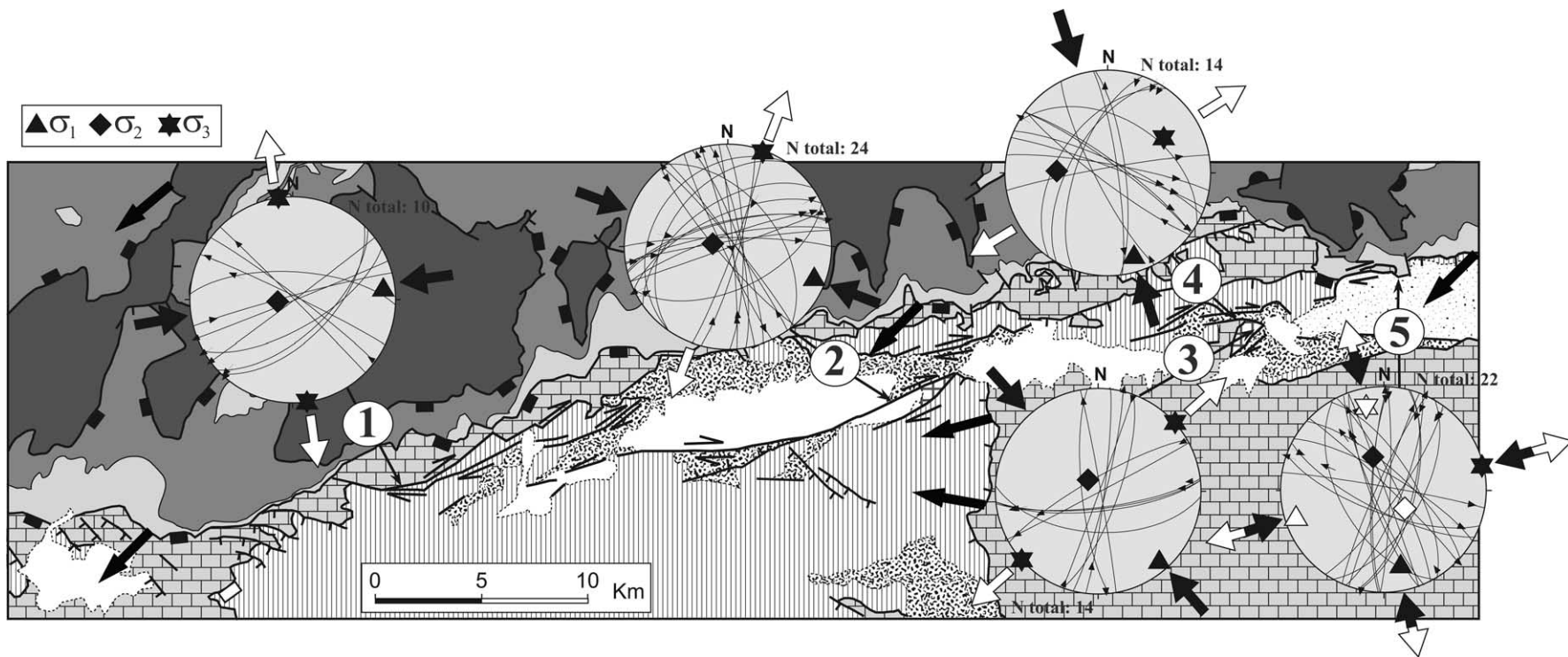


Fig. 9. Localization of the palaeostress sites along the Alpujarras fault zone. Equal-area stereoplots including the measured fault planes and striations together with the determined sense of hanging wall movement are shown. The orientation of the calculated principal stress axes is also included in the stereoplots.

lower values of extension. (3) Notwithstanding the large length of the fault zone (around 65 km), there is an apparent lack of strike-slip offset along the fault. Due to the great values of extension that the northern domain underwent (more than 100 km), the lower plate of the extensional detachment (mainly the Alpujarride complex) in its relative eastwards motion exceeded the eastern termination of the fault zone, thus no comparable pre-extensional reference indicators remain on both sides of the fault zone (Fig. 10). (4) High-angle, W-to-

SW-directed normal faults do not cut through the strike-slip fault zone, which is a barrier to along-strike propagation of the normal faults. The western Sierra de Gádor normal fault merges with a strike-slip fault NE of Alcolea (Figs. 1 and 4). (5) The Alpujarras fault zone merges westwards with the WSW-directed extensional detachment of western Sierra Nevada and eastwards with the WSW-directed extensional detachment cropping out at southern Sierra de los Filabres (Fig. 1). The last detachment is folded around the Tabernas

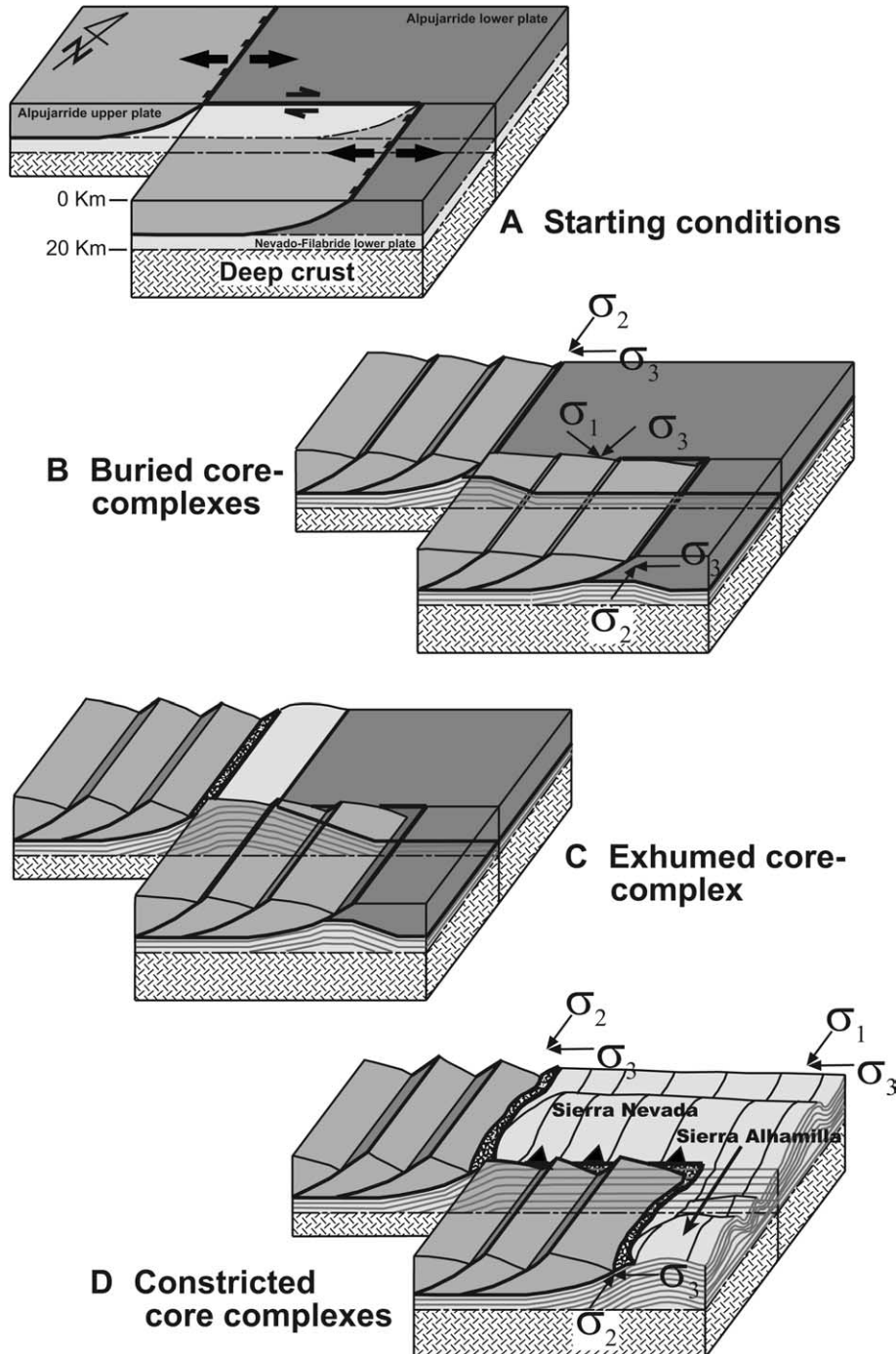


Fig. 10. Simplified kinematic model on the evolution of the Alpujarras transfer fault zone and linked normal fault systems from the middle Miocene to Recent. Explanation in text.

syncline and is exposed in both limbs of the Sierra Alhamilla anticline. These observations suggest that the Alpujarras fault zone is a transfer zone that links spatially separate loci of extension, which are situated in the west of Sierra Nevada and in the west of Sierra Alhamilla, respectively (see location in Fig. 1).

Because the Alpujarras fault zone is an extension-related transfer zone, its tectonic evolution was closely associated with the tectonic evolution of the normal fault systems and to the relative amount of motion between the upper and lower plates. Fig. 10 depicts a simplified kinematic model to explain the evolution of the system from the middle Miocene to Recent in four significant sketches. In sketch A (Langhian) WSW–ENE extension of the Alpujarride and Nevado–Filabride complexes started after a period of roughly N–S extension that thinned the Malaguide and the Alpujarride complexes. The starting conditions are based on the rolling-hinge model proposed by Martínez-Martínez et al. (2002) to explain the mode of lower-plate tectonic unroofing and the final sub-horizontal attitude of the detachment over a hundred square kilometres in the Sierra Nevada elongated dome. The detachments flatten at 15 km depth overlying a mid-crustal flow channel located above a crustal decoupling discontinuity at 20 km depth (see also Martínez-Martínez et al., 2004). Being related to delamination (García-Dueñas et al., 1992), convective removal (Platt and

Visser, 1989), or rollback of a subduction zone (Royden, 1993), forces driving extension dominated over forces related to plate convergence. Inhomogeneous extension results in two separated loci of extension that, in subsequent stages, will be linked by a dextral strike-slip transfer fault zone. Fig. 10B represents a moment in the lower Serravallian. The amount of extension was still low and footwall deep rocks (Nevado–Filabride complex) were not still exhumed, but it was uplifted in two core complexes (orthogonal to the direction of extension) compensating upper crustal extension. For simplification, the Alpujarride in the lower plate is considered rigid. Even though the regional stress field was essentially characterized by a sub-vertical maximum principal stress axis, the transfer fault zone induced inhomogeneities in the stress field. Near to the main strike-slip fault, palaeostress analysis (Fig. 9) points to a local stress field with roughly E–W sub-horizontal compression and N–S sub-horizontal tension. Fig. 11 shows an example on the outcrop scale on how the strike of normal faults changes when they approach a transfer fault. This structure is similar to ‘J’ structures described in the rift-to-rift transform faults, where changes in the strike of topography, faults and dikes near the transform fault are common (Moores and Twiss, 1995).

Continued extension leads to core complex amplification and subsequent exhumation of the Nevado–Filabride, the

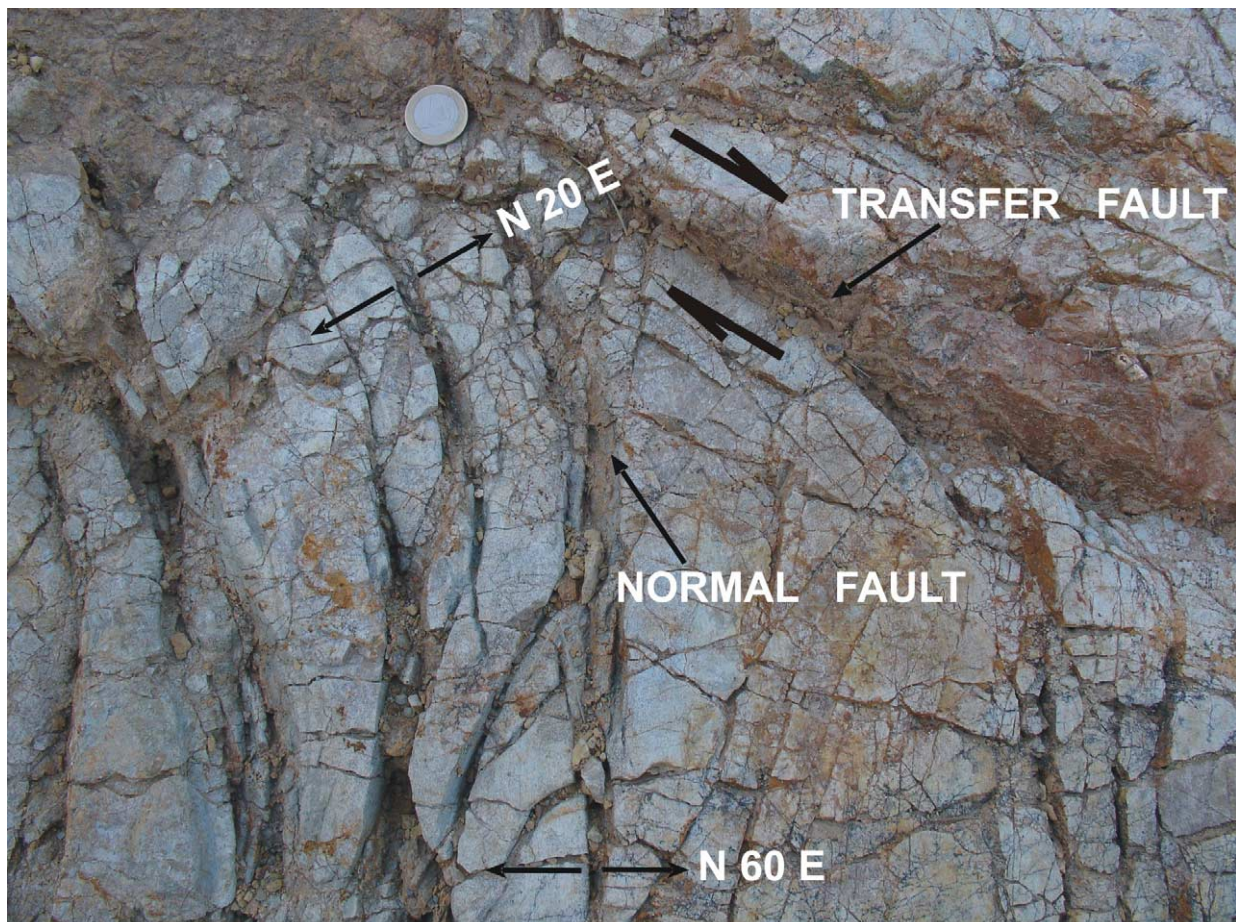


Fig. 11. Photograph showing variations in the strike of normal faults when they approach a linked transfer fault.

deepest metamorphic complex in the lower plate. Fig. 10C illustrates the moment, during the Serravalian, in which the exhumation of this complex in an antiform perpendicular to the direction of extension began (Johnson et al., 1997). Successively, because of the great values of upper crustal extension undergone by the core complexes, the lower plate of the detachment could be broadly unloaded. Folds parallel to the direction of extension formed due to perpendicular shortening (Martínez-Martínez et al., 2002). Shortening was particularly effective after a certain amount of unloading, when the thickness of the elastic–brittle upper crust was so thin that shortening perpendicular to the extension direction could cause buckling (Yin, 1991). Fig. 10D shows a moment in the Messinian to Recent time interval. Regions unloaded, including the extensional detachments, are distinctively characterized by E–W, large-scale, open folds, that are not formed in the upper plates. As a consequence of N–S to NW–SE shortening, transfer fault inversion took place developing SE-directed reverse faults. Reverse faults overprint the northern fault of the Alpujarras zone while the southern fault worked as a transfer fault until Recent.

Competitive forces driving both extension and shortening must be taking into account for a better understanding of the middle Miocene to Recent tectonic evolution of the Betic–Rif orogen. Forces driving extension, probably due to lithosphere delamination, are internal forces that produced crustal extension in the orogenic system until reaching a critical value of extension. N–S shortening was driven by plate convergence that was effective behind the westward-migrating front of extensional deformation after the mentioned critical value of extension.

Acknowledgements

I thank Drs J.C. Balanyá and G. Booth-Rea for critical reading of the manuscript. Constructive revisions by Drs J.E. Faulds and A. Nicol improved the manuscript. The research was supported by Comision Interministerial de Ciencia y Tecnología, Spain (CICYT) grants REN2001-3868-C03MAR and CGL2004-03333.

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