ELSEVIER

Journal of Structural Geology 26 (2004) 2039–2058

JOURNAL OF STRUCTURAL GEOLOGY

www.elsevier.com/locate/jsg

Extensional tectonics in the northeastern Betics (SE Spain): case study of extension in a multilayered upper crust with contrasting rheologies

Guillermo Booth-Rea[a,*], Jose Miguel Azañón[b], Víctor García-Dueñas[b]

[a]*IFM-GEOMAR Leibniz-Institute für Meereswissenschaften, Wischhofstr. 1-3, 24148 Kiel, Germany*
[b]*Departamento de Geodinámica, Universidad de Granada, E-18071 Granada, Spain*

Received 15 August 2003; received in revised form 1 April 2004; accepted 24 April 2004

Abstract

Extension in the northeastern Betics took place along two main directions, corresponding to a minimum of two successive orthogonal extensional systems with N–NW and W–SW sense of shear, respectively. Strain was strongly localised within weaker metapelites and gypsum, leading to the development of several extensional detachments, which accommodated the thinning produced by extensional ramps and listric faults within the stronger carbonate rocks. Extension along several detachments led to the preservation in a single thinned section of layers representative of different crustal depths of a previously thickened upper crust. The N- to NW-directed extensional system was formed by brittle to brittle–ductile detachments, which were active during the Upper Oligocene and Lower Miocene, coeval to vertical ductile thinning of underlying greenschist-facies metamorphic rocks. The W- to SW-directed extensional system, active during the Middle and Upper Miocene, shows multiple slip surfaces, which transferred displacement to a brittle detachment with a ramp-flat geometry that stepped down into the footwall of the previous NW-directed system. The geometry of both extensional systems was determined by the rheological heterogeneity of the studied crustal section. Further Upper Miocene extension was accommodated by radial extension with a dominant set of SW-directed listric faults, which tilted the aforementioned detachments and exhumed them in the core of km-scale elongated extensional domes.

Keywords: Crustal extension; Extensional detachments; Low-angle normal faults; Rheology; Alboran crustal domain; Northeastern Betics

---

1. Introduction

Low-angle normal faults (LANFs) have contributed to the exhumation of previously thickened crustal sections, during both syn- and post-orogenic extension (e.g. Crittenden et al., 1980; Lister et al., 1984; Platt, 1986; Selverstone, 1988; Jolivet et al., 1994; Sedlock, 2002; Martínez-Martínez et al., 2002). This is the case of the Alboran crustal domain, a polymetamorphic allochthonous terrain that forms the basement of the Alboran Sea and of other Neogene basins presently emerged in the Internal Zones of the Gibraltar Arc (Western Mediterranean) (e.g. García-Dueñas et al., 1992; Martínez-Martínez and Azañón, 1997; Platt et al., 1998; Comas et al., 1999; Martínez-Martínez et al., 2002) (Fig. 1).

Several extensional systems that detach within low-angle mylonitic shear zones and exhume greenschist-facies rocks have been identified in the Alboran domain. These detachments form the present boundaries between the metamorphic complexes of this domain (García-Dueñas and Martínez-Martínez, 1988; Galindo-Zaldívar et al., 1989; Aldaya et al., 1991; Tubía et al., 1993; Lonergan and Platt, 1995; Martínez-Martínez et al., 2002). The most recent extensional system, with WSW sense of shear, was formed by a listric fan detaching on two sequential brittle–ductile mylonitic low-angle detachments that exhumed rocks from approximately 20 km depth, resulting in the formation of the Sierra Nevada metamorphic core complex (MCC) (Martínez-Martínez et al., 2002).

The main detachment of the older extensional system locally bounds the two structurally highest complexes of the Alboran domain, the Alpujarride and Malaguide complexes (Fig. 1) (Aldaya et al., 1991; Tubía et al., 1993; Lonergan and Platt, 1995). This earlier extensional system was intensively displaced and cut out by the later WSW-directed extensional system, which produced approximately 100 km

---

* Corresponding author. Tel.: +49-431-600-2330; fax: +49-431-600-2922.

E-mail address: gbooth@ifm-geomar.de (G. Booth-Rea).

0191-8141/$ - see front matter © 2004 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jsg.2004.04.005

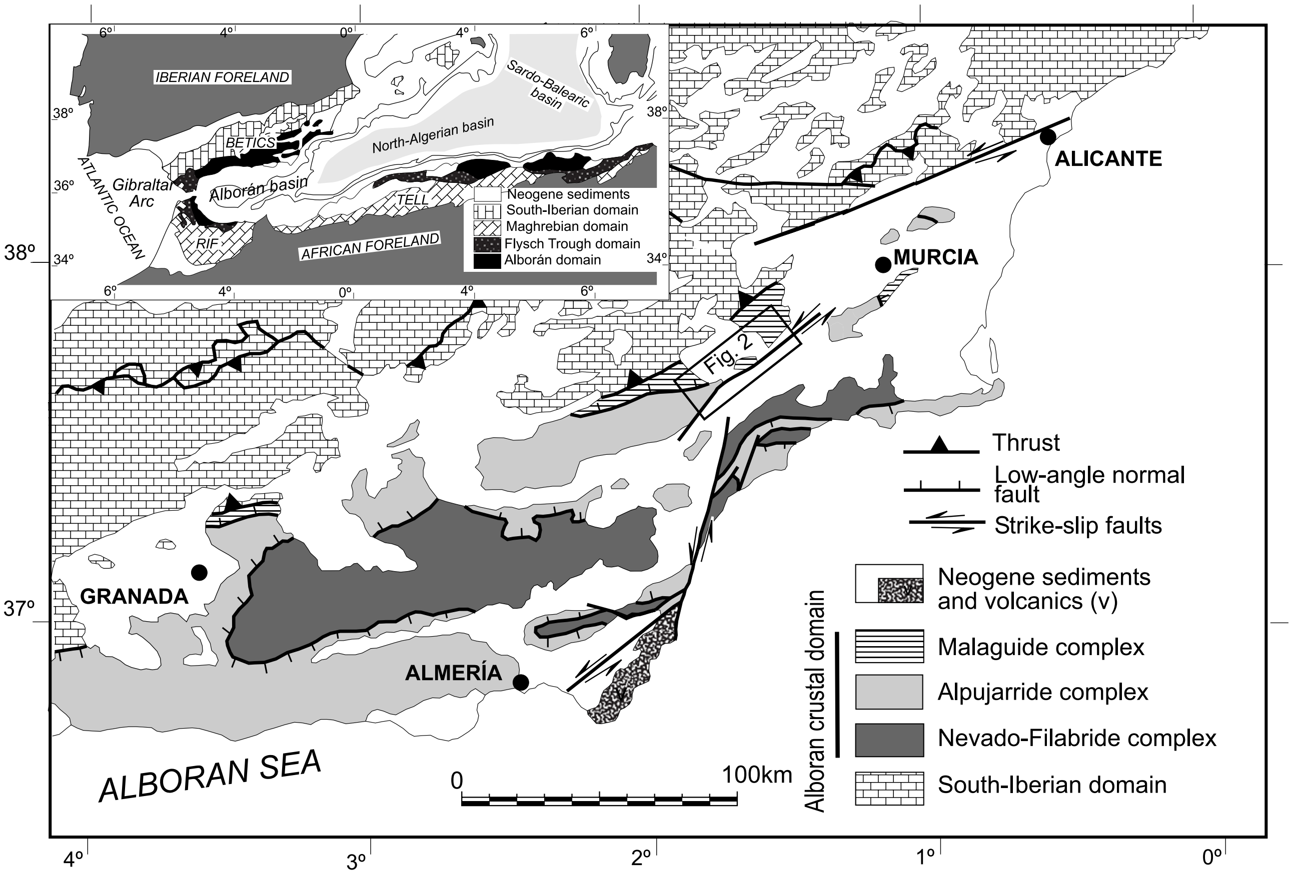


Fig. 1. Regional tectonic setting and structural map of the central and eastern Betics.

of displacement above the Sierra Nevada MCC (Martínez-Martínez et al., 2002). Consequently, the outcrops of the extensional structures that exhumed the two highest complexes of the Alboran domain are fragmentary and distributed over a large area, including most of the Internal Betics. Thus, the geometry and evolution of the extensional system responsible for the thinning of the Malaguide and Alpujarride complexes is not so well understood. Preliminary work has shown the presence of multiple lower-order extensional detachments that thin the Malaguide thrust sheets (Booth-Rea et al., 2002b).

This paper presents new structural data on the geometry and tectonic evolution of sequential systems of LANFs, which thinned the Malaguide–Alpujarride crustal section in the northeastern Betics. The resulting structure differs from typical core complexes, where the related shear zones place the highest-grade rocks of the footwall in direct contact with the sedimentary cover or the lowest-grade rocks of the hanging-wall. In the northeastern Betics the presence of multiple detachments means that the modes of crustal extension are influenced by the contrasting rheological properties of a multilayered upper crust. Furthermore, we analyse the tectonic relationships between the LANFs and a later system of high-angle listric faults that truncated and tilted them during Upper Miocene extension. Finally we consider the implications that the resulting geometry has in the interpretation of rifted margins.

2. Tectonic setting

The Gibraltar Arc was formed by oblique collision of several crustal domains during the Upper Oligocene–Lower Miocene (Bouillin et al., 1986; Balanyá and García-Dueñas, 1987; Crespo-Blanc and Campos, 2001; Platt et al., 2003a). The Alboran crustal domain (ACD), which constitutes the Internal Zones of the Gibraltar Arc, was thrust over the South-Iberian and Magrebian domains, which formed, respectively, the southern and northern Mesozoic paleomargins of the Iberian and African plates (Fig. 1). Towards the west the ACD thrusts the Flyschs Trough units, which were deposited in a deep trough, floored by oceanic or very thin continental crust during the Mesozoic (Durand-Delga et al., 2000). As the Arc migrated westward the ACD was greatly extended in the backarc (García-Dueñas et al., 1992; Comas et al., 1999). Hence, many of the main tectonic units of this domain are extensional units, bounded by brittle and ductile shear zones (García-Dueñas and Martínez-Martínez, 1988; Galindo-Zaldívar et al., 1989; Aldaya et al., 1991; García-Dueñas et al., 1992; Crespo-Blanc et al., 1994;

Crespo-Blanc, 1995; Lonergan and Platt, 1995; Martínez-Martínez and Azañón, 1997; Booth-Rea et al., 2002b, 2003a; Martínez-Martínez et al., 2002).

From bottom to top, the ACD comprises the Nevado-Filabride, Alpujarride and Malaguide poly-metamorphic complexes (Fig. 1). The two structurally highest ones represent a former thrust stack, resulting from the collision of the Alpujarride and Malaguide complexes (Lonergan, 1991, 1993; Lonergan and Platt, 1995) prior to the evolution of the Gibraltar Arc (Balanyá et al., 1997; Azañón and Crespo-Blanc, 2000). During this continental collision the Alpujarride complex was metamorphosed under high-pressure conditions, with some of its units reaching blueschists or eclogite facies (e.g. Goffé et al., 1989; Tubía and Gil-Ibarguchi, 1991; Azañón et al., 1997; Booth-Rea et al., 2002a, 2003b). Simultaneously, the lowest thrust sheets of the Malaguide complex underwent anchizonal metamorphism (Lonergan, 1991; Nieto et al., 1994; Lonergan and Platt, 1995). After this initial stacking event the Alpujarride units followed an isothermal-decompression P–T path, coeval to the formation of their main foliation by vertical ductile thinning during orogenic collapse (e.g. Balanyá et al., 1993, 1997; Azañón et al., 1997; Azañón and Crespo-Blanc, 2000).

The Alpujarride rocks were exhumed during the Burdigalian (Lonergan and Johnson, 1998) by extension related to the formation of the Alboran-basin (e.g. García-Dueñas et al., 1992; Comas et al., 1999). Ductile detachments, in part responsible for this exhumation, are locally preserved in the boundary between the Alpujarride and Malaguide complexes and show NE shear sense in the northeastern Betics (Aldaya et al., 1991; Lonergan and Platt, 1995) and eastward transport in the western Betics (Tubía et al., 1993; Booth-Rea et al., 2003a). After this extension the Alboran domain formed the basement of the Miocene Alboran basin.

NW/SE convergence between Africa and Iberia during the Upper Miocene and the Quaternary (Dewey et al., 1989; Mazzoli and Helman, 1994) uplifted and exposed large areas of the northern Miocene Alboran basin. Remnants of this sedimentary cover are preserved in ENE/WSW to E/W synclinal troughs within the Betics, whereas the metamorphic basement crops out mostly in the core of antiformal ridges (e.g. Weijermars et al., 1985; Martínez-Martínez et al., 2002; Booth-Rea et al., 2004).

3. The Alboran domain in the northeastern Betics

The metamorphic basement in the northeastern Betics is formed by tectonic units of the Malaguide and Alpujarride complexes (Mäkel and Rondeel, 1979), which crop out in the core of ENE-oriented anticlinal ridges of the Sierra de las Estancias, Sierra de la Tercia and Sierra Espuña (Fig. 2). The Malaguide rocks in the eastern Betics show large clockwise vertical-axis paleomagnetic rotations (90–200°), which occurred during the Miocene (Allerton et al., 1993). Consequently, all kinematic indicators with Miocene or pre-Miocene age of the Malaguide and the underlying Alpujarride complex have probably been rotated.

3.1. Alpujarride complex

Two Alpujarride units that represent former thrust sheets outcrop in the studied area; from bottom to top, they are the Pintada and Cortada units (Fig. 3). The Pintada unit (Booth-Rea, 2004) is formed by fine-grained graphite schists of Permo-Triassic or Palaeozoic protolith and by marbles of Triassic protolith (~100 m). The metapelites show a protomylonitic foliation (S_m) developed under greenschist facies metamorphism (Fig. 4a).

The Cortada unit is also formed by a Permo-Triassic metapelite and a Triassic carbonate formation, respectively (Mäkel and Rondeel, 1979). The metapelite formation is comprised of, from bottom to top, fine-grained graphite schists alternating with quartzites (~300 m), quartzites alternating with metapelites and carbonate schists (~450 m), and fine-grained light schists with quartzite intercalations (~200 m) (Fig. 3). The Triassic carbonate formation only crops out locally as tectonic lenses.

The oldest foliation in the Cortada-unit metapelites is a relic schistosity (S_s), defined by the preferential orientation of white K mica + chlorite + quartz + graphite ± pyrophyllite ± paragonite, which is preserved in lenticular domains of a later, penetrative crenulation cleavage (S_{cc}). The S_{cc} cleavage is formed by white K mica + chlorite + quartz + graphite ± pyrophyllite ± paragonite (Fig. 4b) and is axial planar to similar folds (F_{cc}). In most pelitic lithologies the folds are unrooted and the quartz hinges form rods with ENE-oriented necks (in Sierra de la Tercia), transverse to an incipient mineral lineation and to the F_{cc} fold axes; suggesting NNW stretching at the end of the S_{cc} foliation development (stereoplot, Fig. 2c). In Sierra de las Estancias the F_{cc} fold hinges show a NE–SW trend (stereoplot, Fig. 2a).

Both schistosity and crenulation cleavage are affected by outcrop-scale asymmetric folds (F_{sc1}), with NE vergence (stereoplot, Fig. 2a) and an associated axial-plane spaced crenulation cleavage (S_{sc1}). These foliations are cut by C′ surfaces on which chlorite + quartz + calcite fibres grow, indicating a predominant N–S extension in Sierra de las Estancias and WNW extension in Sierra de la Tercia (see Fig. 2b and d).

HP/LT mineral associations have been described in Alpujarride rocks of the eastern Betics, including Mg-carpholite bearing assemblages formed at 400 °C and 8–10 kbar (Booth-Rea et al., 2002a, 2003b). However, these associations have not been found in the Cortada and Pintada units. Furthermore, white K mica and chlorite local equilibria were determined using the TWEEQU software of Berman (1991) and the thermodynamic properties of solid solution models for chlorite and white K mica from

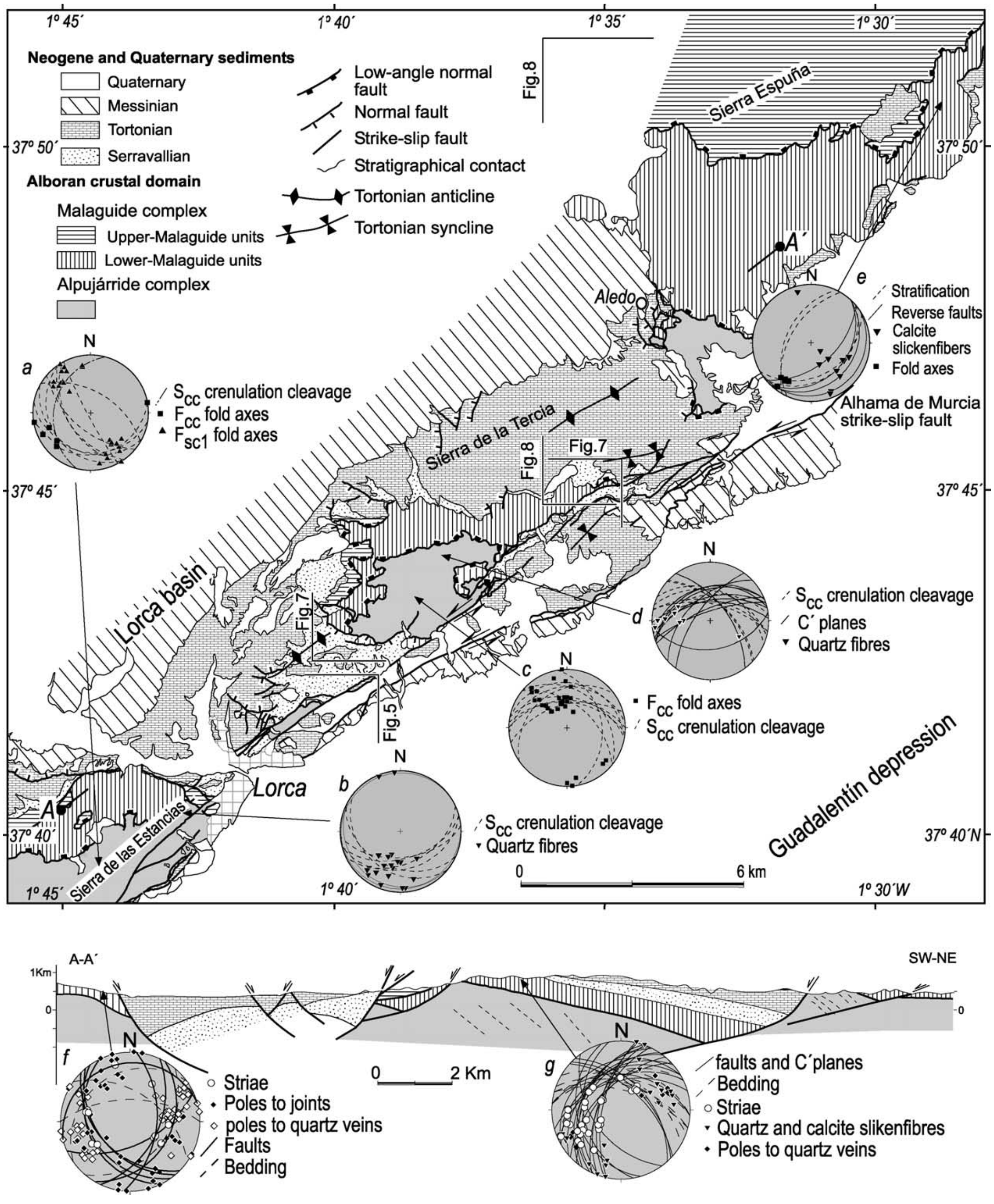


Fig. 2. Tectonic map and cross-section of the studied area. Stereographic projections: (a) main Alpujarride foliation, hinges to F_{cc} folds and to asymmetric northeast-vergent folds (F_{sc1}); (b) main S_{cc} foliation and quartz slicken-lines on extensional shear planes; (c) main foliation and F_{cc} fold hinges; (d) main foliation, extensional shear planes and quartz slicken-fibres; (e) bedding, small-scale reverse faults, axes to north-vergent folds, and calcite slicken-fibres from the highest Lower-Malaguide unit; (f) extensional structures and slaty cleavage in the Lower-Malaguide unit; (g) extensional structures found in the Lower-Malaguide units. Lower-hemisphere equal-angle stereographic projections.

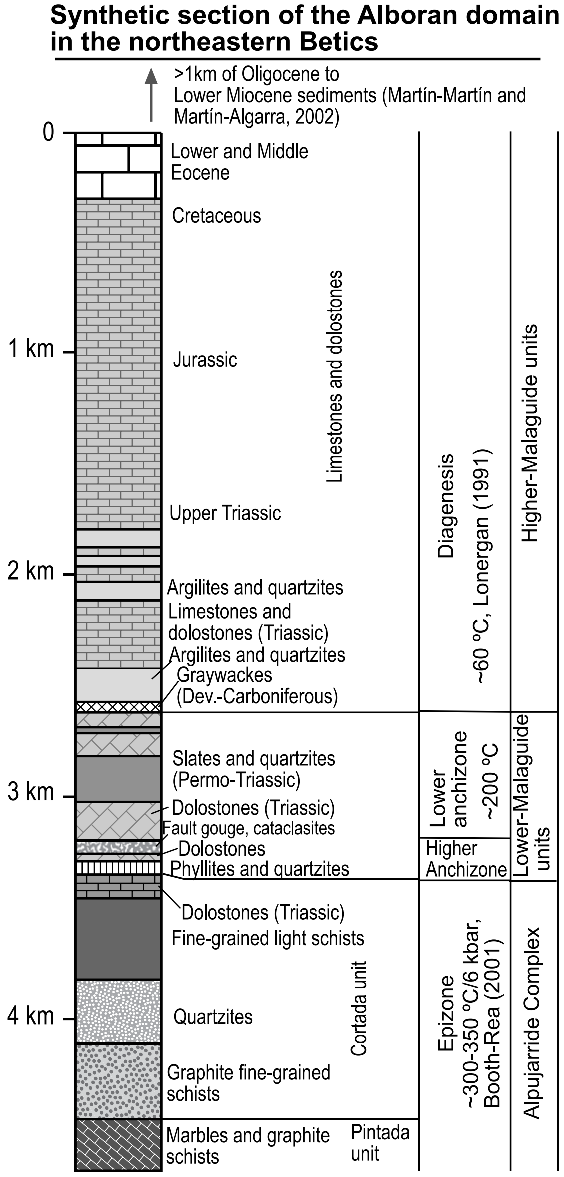


Fig. 3. Synthetic section of the Alboran domain in the northeastern Betics, modified from Lonergan and Platt (1995).

Vidal and Parra (2000), Vidal et al. (2001) and Parra et al. (2001). The P-T results indicate pressures below the stability of Mg-carpholite during the pressure peak of metamorphism, approximately 6 kbar at 300–350 °C (Booth-Rea, 2004). The low metamorphic grade reached by the Cortada and Pintada units together with their structural position below Malaguide units having undergone anchizone metamorphism suggests that these units represent the structurally highest preserved section of the Alpujarride pre-extensional nappe stack within the Betics.

3.2. Malaguide complex

The Malaguide complex in the northeastern Betics comprises at least five tectonic units that represent the remnants of thrust sheets. We have differentiated them in two groups according to the metamorphic grade and structures observed in their Permo-Triassic formations: the Lower-Malaguide units have phyllites or slates and underwent anchizonal metamorphism, and the Upper-Malaguide units have diagenetic shales (Lonergan, 1991; Nieto et al., 1994; Lonergan and Platt, 1995).

The Lower-Malaguide units comprise a quartzite–pelite formation of Permo-Triassic age (Mäkel and Rondeel, 1979) overlain by a carbonate sequence of Triassic age, which includes a gypsum sequence at the base. At least three Lower-Malaguide tectonic units outcrop in the area, metamorphosed between higher- and lower-anchizone conditions (Nieto et al., 1994; Lonergan and Platt, 1995). These units reach their maximum thickness in Sierra Espuña, approximately 700 m (Fig. 3).

The Upper-Malaguide units show a Carboniferous greywacke formation, a Permo-Triassic formation that includes conglomerates, quartzites and shales; a Triassic carbonate formation and a Mesozoic–Tertiary marine sedimentary cover (Paquet, 1969, 1970, 1974; Mäkel and Rondeel, 1979; Mäkel, 1981; Lonergan, 1991, 1993; Martín-Martín et al., 1997). The Upper-Malaguide rocks including the Palaeogene to Lower Miocene sedimentary cover reach a thickness of 3.6 km in Sierra Espuña (Lonergan, 1991; Martín-Martín and Martín-Algarra, 2002) (Fig. 3).

The main foliation in the lowest Malaguide unit is an anastomosed slaty cleavage (S_{sc}) that is defined by concentration of opaque minerals and truncated quartz grains, indicating development by pressure solution mechanisms (Fig. 4c). In most quartzitic lithologies the cleavage has a spacing of 2–3 mm. This slaty cleavage is axial planar to similar folds that show a variable trend, although mostly NE–SW (Lonergan (1991) and stereoplot in Fig. 4c). There is practically no mineral growth related to this cleavage, except in pressure shadows of quartz grains where chlorite + illite + calcite beards grow.

A primary foliation (S_0) can be identified in the microlithons, defined by the preferential orientation of phyllosilicates of detritic and metamorphic origin (white mica, chlorite, sudoite), which is subparallel to the primary compositional zonation (Fig. 4c). These foliations are thinned in the pelites of the lowest Malaguide thrust sheet by spaced C' shears on which predominantly N–S-oriented calcite, quartz and phyllosilicate fibres grow (Fig. 4d and e). When the lithology is formed from alternating pelite and quartzite layers, the latter are extended by open joints and quartz veins. In the pelite-rich layers this extension is accommodated by brecciation, cataclasis and layer-parallel slip (quartz fibres are found on the bedding planes). The pelitic layers show thickness variations at the outcrop scale, related to contractional oversteps (Peacock and Zhang, 1993) formed by the ramp-flat geometry of underlying faults; the pelites are thicker above the ramps that generally affect the quartz-rich layers (Fig. 4f).

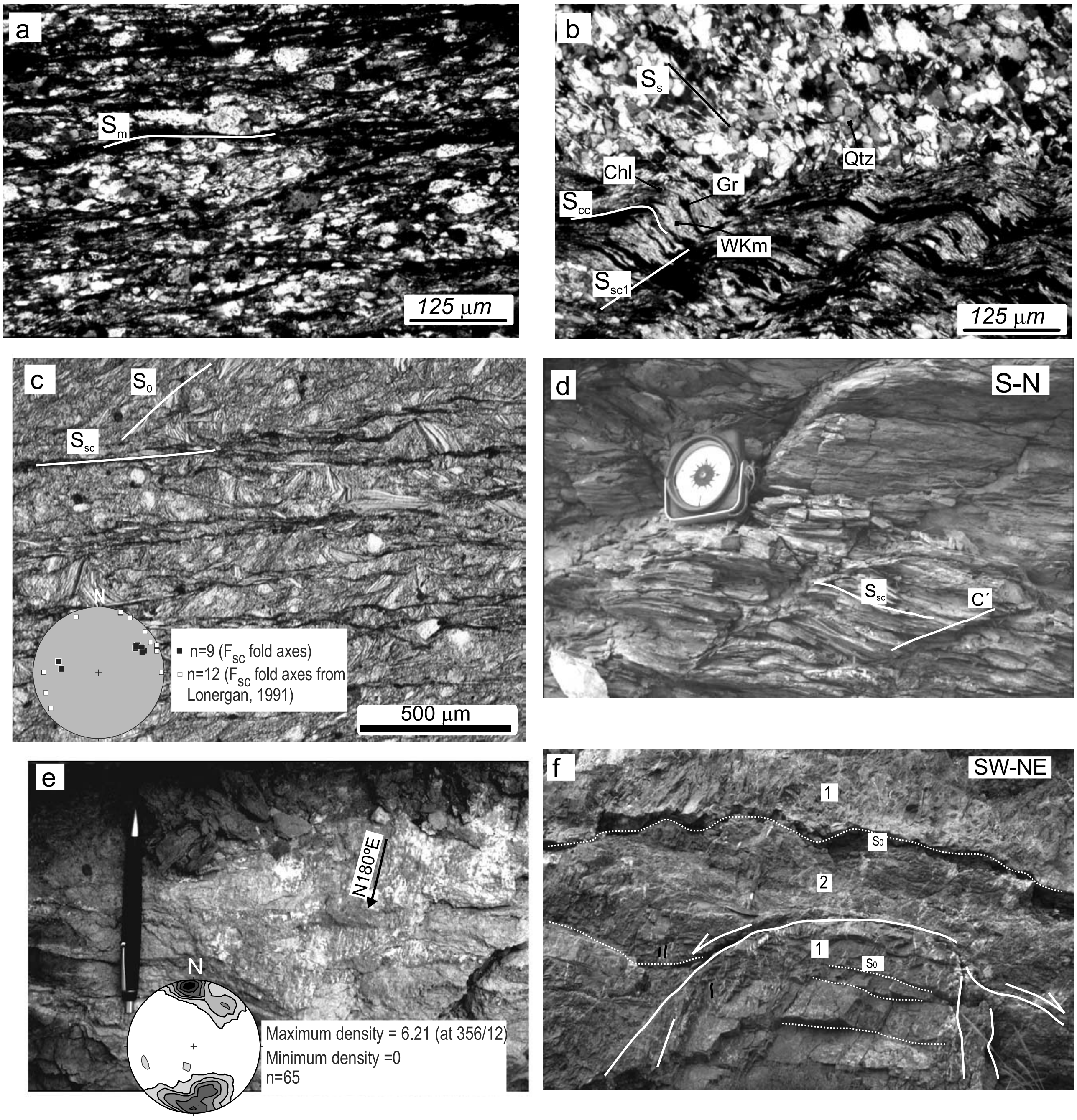


Fig. 4. (a) Fine-grained graphite schists of the Pintada unit showing a protomylonitic foliation (S_m) that overprints the Alpujarride S_{cc} main cleavage. (b) Fine-grained schists from the Cortada unit. Notice the S_s foliation defined by thin phyllosilicate laths preserved in quartz-rich domains of the main S_{cc} crenulation cleavage. Also S_{cc} crenulation folded by late S_{sc1} crenulation. (c) Slaty cleavage (S_{sc}) in phyllite from the lowest-Malaguide thrust sheet. (d) Phyllites from the lowest-Malaguide unit extended by spaced C′ surfaces. (e) Quartz, chlorite and calcite slicken-fibres growing on C′ surfaces in the lowest-Malaguide unit, data represented in stereoplot. (f) Assemblage of extensional structures typically found in the Malaguide units, notice quartz veins and joints transverse to the main extensional direction, lensoid geometry of quartz-rich beds (1) that are cut by metre-scale faults with a ramp-flat geometry and heterogeneous thinning and cataclasis of pelite-rich beds (2).

The S_{sc} slaty cleavage is replaced in the two structurally-highest thrust sheets of the Lower-Malaguide units by a spaced cleavage that is axial planar to asymmetric and recumbent folds, with NW vergence in Sierra Espuña (Lonergan, 1991, 1993; Fig. 2a) and NE vergence in Sierra de las Estancias (stereoplot, Fig. 5). Quartz- and calcite-stepped fibres grow on the axial-plane spaced cleavage related to these folds and on outcrop-scale reverse faults, showing NE and NW shear senses in eastern Sierra de las Estancias (stereoplot, Fig. 5) and Sierra Espuña, respectively (Lonergan, 1991). The Lower-Malaguide thrust sheets have been attenuated by two sets of structures generated by

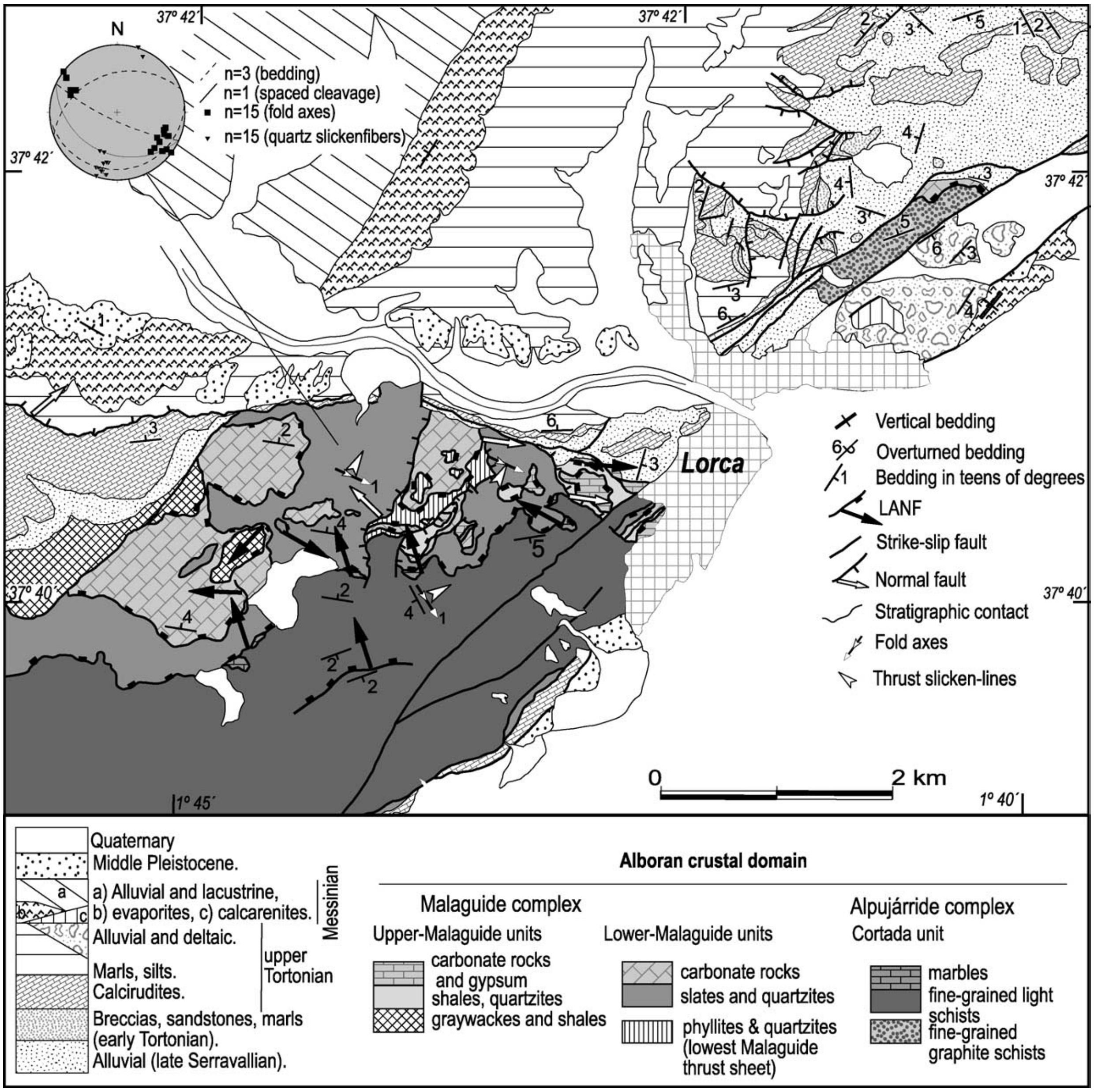


Fig. 5. Structural map of the eastern-end of Sierra de las Estancias. Stereographic projection of slaty cleavage, folded by asymmetric northeast-vergent folds, together with fold axes and quartz slicken-fibres growing on related thrust surfaces in the Lower-Malaguide units are included.

WSW/ENE and NNW/SSE extension and observed at the outcrop-scale: low-angle normal faults and vertical joints and veins (stereoplots f and g, Fig. 2).

The Permo-Triassic formations of the Upper-Malaguide units do not show any penetrative planar fabric and illite crystallinity analyses indicate diagenetic conditions (Nieto et al., 1994; Lonergan and Platt, 1995). The Upper-Malaguide units have been highly attenuated by pervasive cataclasis related to extensional low-angle faults and joints (Fig. 6). The extensional directions measured from these structures are mostly NW/SE and WSW (stereoplot, Fig. 6).

4. Extensional systems in the northeastern Betics

Extensional structures thinning the Alboran domain in the northeastern Betics occur distributed from outcrop to map scales, and show variable directions of extension. The majority of these structures indicate, however, W- to SW- and N- to NW-directed extension (Booth-Rea et al., 2002b; Booth-Rea, 2004; Figs. 5, 7 and 8).

The listric faults and ramps, which cut the stronger carbonate and quartzite formations, detach into low-angle fault zones, within the underlying weak pelites or gypsum layers (Fig. 9). These low-angle fault zones are defined by

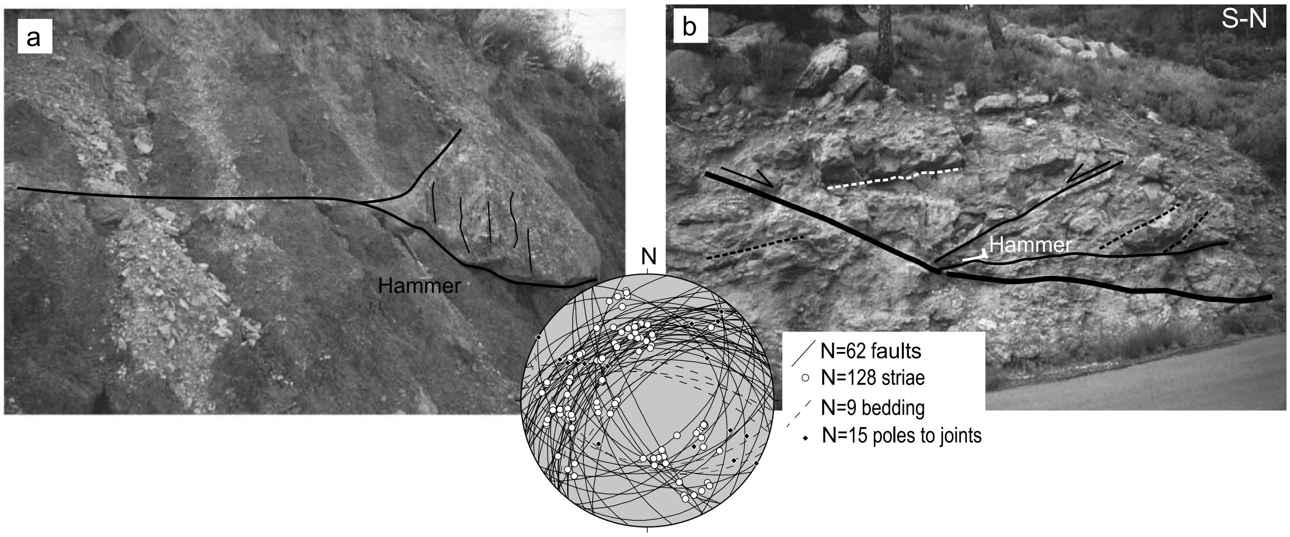


Fig. 6. Outcrops of extensional structures in the Upper-Malaguide units. (a) Fractured conglomerate body within highly comminuted Permo-Triassic red shales. (b) Two outcrop scale low-angle normal faults showing cross-cutting relationships (Triassic carbonates and shales, Sierra Espuña). Stereoplot shows extensional structures measured in the Upper-Malaguide units.

foliated clay gouge in the pelites, by gypsum mylonites when affecting gypsum layers, and also by foliated carbonate and carbonate–gypsum cataclasites and ultracataclasites. The main LANFs separate brecciated-rock volumes with differentiated tectono-metamorphic characteristics (Fig. 3 and cross-section 1–1′, Fig. 7). They commonly detach on the contact between the Triassic carbonates and Permo-Triassic metapelites.

At the outcrop scale, low-angle normal faults greatly extend the lithological sequences, for example at locality Y (Figs. 7 and 10a), two WNW-directed out-of-sequence faults are observed in the Permo-Triassic levels of a Lower-Malaguide unit. The younger faults cut and tilt the older ones defining extensional horses (x in Fig. 10a) bounded by inactive faults at their top and by younger faults at their base. This process has produced a general tilting of the previous reference surfaces (slaty-cleavage), accompanied by layer-parallel extension (e.g. Ferrill et al., 1998) of the tilted bedding.

We have grouped the aforementioned extensional structures into two main systems based on their kinematics and relative age relationships: (1) An Upper Oligocene–Lower Miocene extensional system with mostly N–NW or S shear sense that is especially well preserved in the Malaguide units and (2) a Middle–Upper Miocene system formed mostly by W- to SW-directed detachments and associated listric faults that cut down into the Alpujarride complex.

4.1. The Upper Oligocene–Lower Miocene extensional system

The main structures included in this extensional system are two extensional detachments located in the contact between the Upper- and Lower-Malaguide units and at the top of the lowest Malaguide unit, respectively. These structures show discontinuous outcrops, having been cut and displaced by other younger faults, so it is not possible to analyse the large-scale geometry of this extensional system.

The contact between the Upper- and Lower-Malaguide units places Permo-Triassic red shales and conglomerates on top of Triassic carbonate rocks and slates. Hence, it has been interpreted as a thrust surface with top-to-the-north sense of shear in Sierra Espuña (Lonergan, 1991, 1993). Locally, along this fault zone extensional horses of Palaeozoic greywackes are preserved (for example at locality B, Fig. 8). The shear zone itself is defined by fault gouge and breccia formed mostly by the comminution of the aforementioned lithologies.

In Sierra Espuña lenticular metric-scale bodies of carbonate ultracataclasites are found within the shear zone (Fig. 11). The ultracataclasites show a well-defined cataclastic lineation (Tanaka, 1992), marked by the preferential orientation of dolomite porphyroclasts, which shows N–S orientation (stereoplot, Fig. 11). Both small sheath folds and rotated porphyroclasts in the ultracataclasites indicate southward sense of shear (Fig. 11b and c). In Sierra de la Tercia the sense of shear is mostly towards the north (Booth-Rea et al., 2002b and geological map, Fig. 7).

We have reinterpreted the above shear zone as an extensional detachment, because (1) there is a general omission of the Palaeozoic rocks typically found at the base of other Upper-Malaguide units; (2) there is an abrupt change from diagenetic shales in the hanging wall to anchizone slates in the footwall, indicating a small metamorphic-grade gap (Nieto et al., 1994; Lonergan and Platt, 1995); (3) there is a presence of small-scale

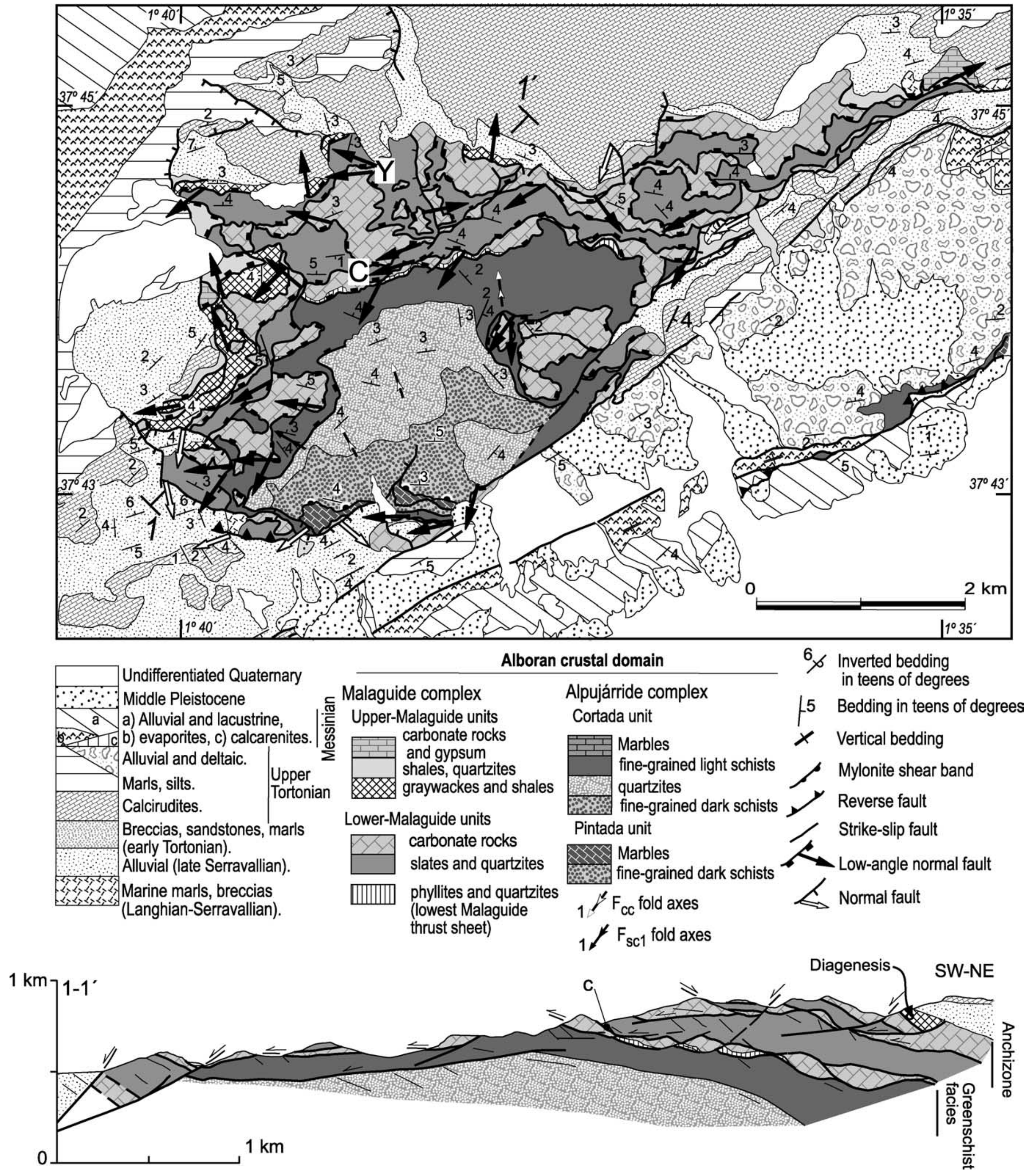
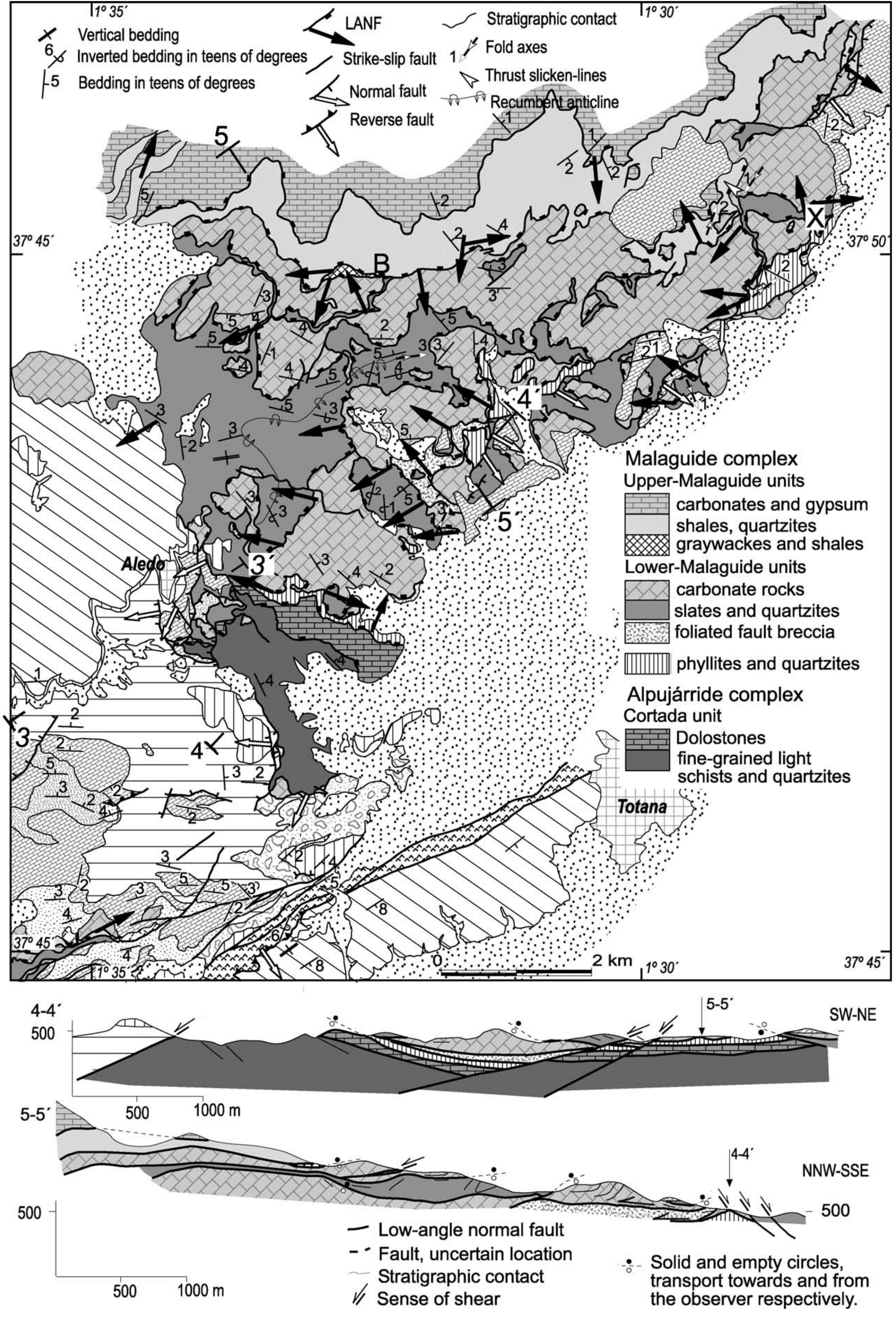


Fig. 7. Structural map and cross-section of Sierra de la Tercia. Modified from Booth-Rea et al. (2002b).

SW-directed normal faults, which cut the Palaeozoic rocks (bounding the extensional horses) and detach at the base of the fault zone; (4) there is a sense of shear along this detachment significantly different from other contractional structures described in Sierra Espuña, such as folds and small-scale reverse faults with NW shear sense (Lonergan, 1991, 1993; Fig. 2e and thrust shear-sense vectors, Fig. 8).

Other structures included in this extensional system are found deeper in the structural pile. In Sierra Espuña the boundary between the two Lower-Malaguide units is


1° 35´
1° 30´
37° 45´
37° 50´
Vertical bedding
Inverted bedding in teens of degrees
Bedding in teens of degrees
LANF
Strike-slip fault
Normal fault
Reverse fault
Stratigraphic contact
Fold axes
Thrust slicken-lines
Recumbent anticline
B
X
5
5´
4
4´
3
3´
Aledo
Totana
Malaguide complex
Upper-Malaguide units
carbonates and gypsum
shales, quartzites
graywackes and shales
Lower-Malaguide units
carbonate rocks
slates and quartzites
foliated fault breccia
phyllites and quartzites
Alpujárride complex
Cortada unit
Dolostones
fine-grained light schists and quartzites
0
2 km
4-4´
500
1000 m
5-5´
SW-NE
NNW-SSE
4-4´
Low-angle normal fault
Fault, uncertain location
Stratigraphic contact
Sense of shear
Solid and empty circles, transport towards and from the observer respectively.

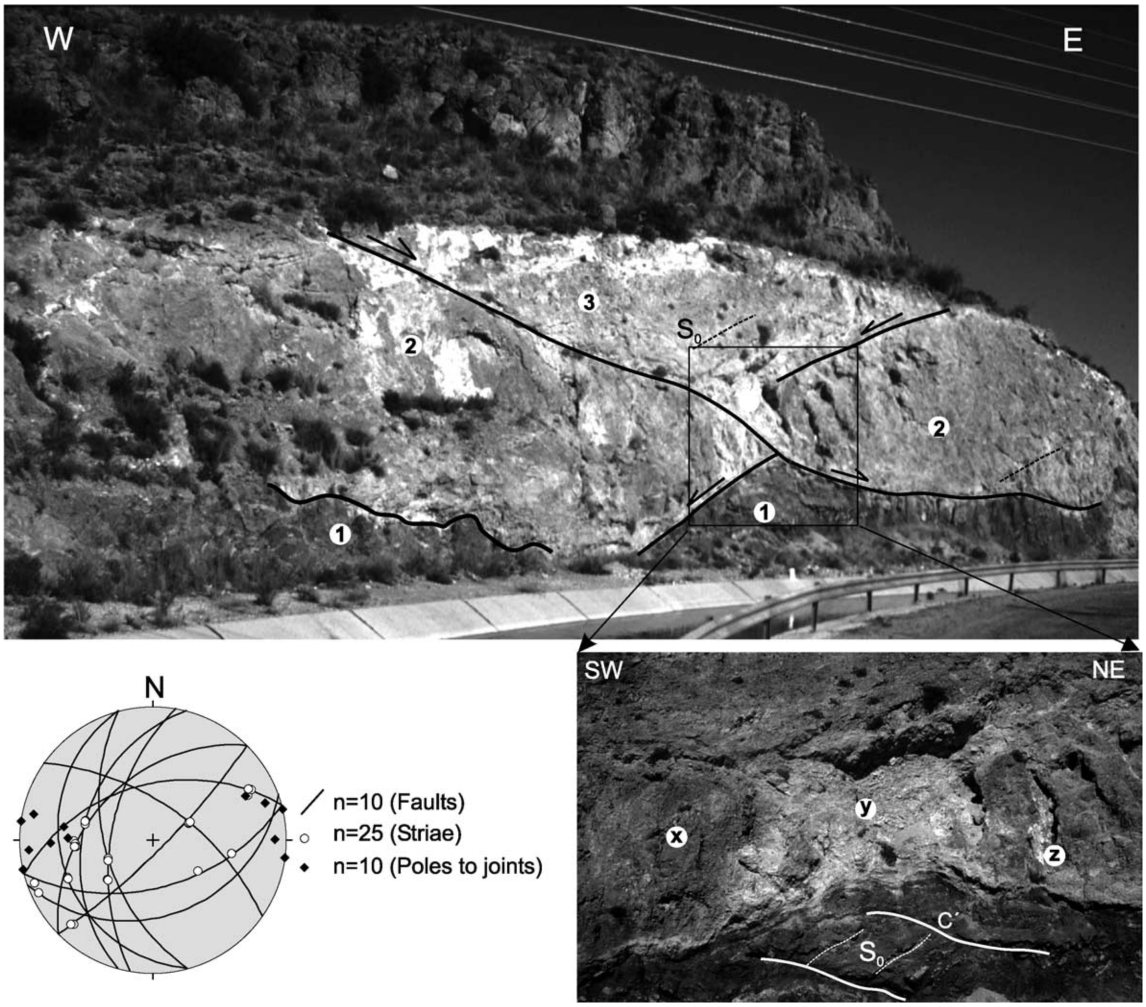


Fig. 9. Listric ramp that transfers displacement to underlying detachment in the contact between dolostones and red slates. (1) Comminuted red slates with quartzite intercalations, (2) massive brecciated dolostone, (3) multilayered dolostone with tilted bedding. Inset rectangle, detail of open fractures in the contact with the underlying slates: brecciated dolostone (x), fault gouge (y) and open joints transverse to the tectonic transport (z). Stereoplot represents structures measured in this section. Notice fault surfaces striking in the direction of extension, interpreted as lateral ramps.

a brittle–ductile NW-directed detachment (Lonergan, 1991; Lonergan and Platt, 1995) defined by foliated carbonate cataclasites and gypsum mylonites (Fig. 12a and b). The lowest Malaguide unit crops out as discontinuous lenticular megabodies (isolated extensional horses) along this shear zone, showing large lateral thickness variations (structural map, Fig. 8). The mylonites are formed by preferentially-oriented gypsum fibres, indicating development by mineral growth, most probably by pressure-solution creep and intracrystalline dislocation mechanisms. A similar shear zone is located at the same structural depth in Sierra de la Tercia. As an example we have selected the outcrop found at locality C (Figs. 7, 10c and 13). It is defined by foliated carbonate breccia, with frequent pelitic porphyroclasts. The contact with the footwall carbonate rocks is formed by carbonate ultracataclasites (Fig. 13b and c) and cataclasites, which include kinematic indicators like S–C structures, sheath folds and rotated porphyroclasts showing southward sense of shear (Fig. 13b). Other common fault rocks that develop in these shear zones, are gypsum mylonites with a penetrative gypsum lineation, parallel to the cataclastic lineation observed in the carbonate lithologies.

Strain was strongly localised within the main detachments, which show a thickness of several metres of clay gouge, foliated carbonate cataclasites and gypsum mylonites. The foliated carbonate cataclasites exhibit layers of brittle dolomite breccia alternating with layers of ultracataclasite with an extreme particle size reduction (Fig. 13b and c). Fabrics observed in the carbonate cataclasites like rotated porphyroclats, sheath folds, S–C structures are typical of ductile deformation, which could have occurred at

---

Fig. 8. Structural map and cross-sections of Sierra Espuña. See Fig. 7 for legend of sedimentary cover.

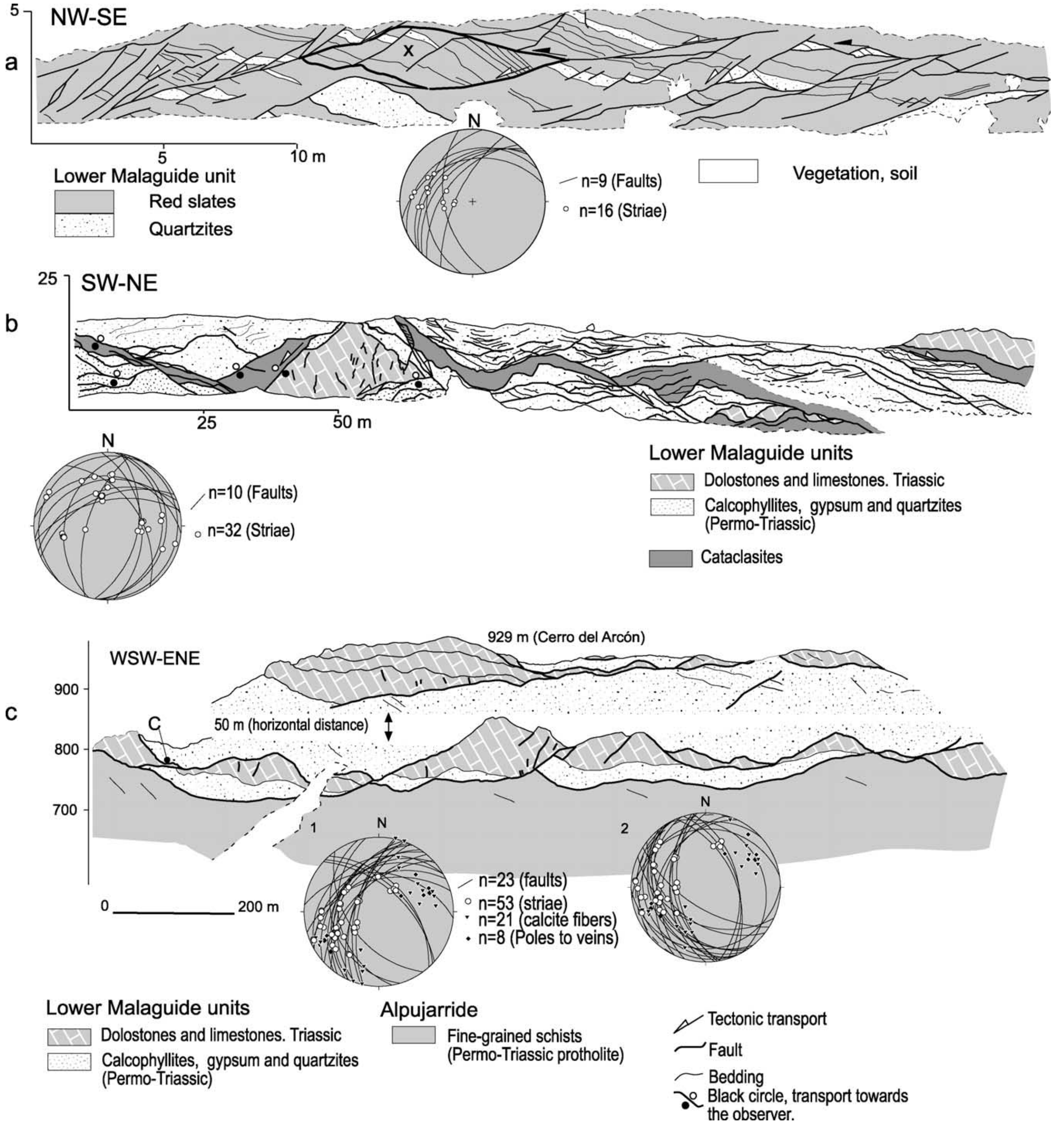


Fig. 10. (a) Outcrop-scale low-angle and high-angle normal faults that extend one of the Lower-Malaguide units. Locality Y, Fig. 7. (b) Hectometre-scale outcrop of two Lower-Malaguide units extended by at least two low-angle extensional systems, discussion in text. Notice extreme thinness of previously kilometre-thick units. Locality X, Fig. 8. (c) Kilometre-scale sketch of units from the Lower-Malaguide and Alpujarride complexes in the core of Sierra de la Tercia. Four tectonic units are represented in this section that is less than 250 m thick. Notice geometry of extensional structures is similar to the one observed at the metre-scale in diagram (a). Most of the extensional low-angle faults found in this section show WSW sense of shear, stereoplot (1). Stereoplot (2) represents the same data as (1) rotated to undo the Upper-Miocene folding of Sierra de la Tercia.

the low temperatures suffered by the Lower-Malaguide units (approximately 150–250 °C; Nieto et al., 1994). Strain localisation in the extensional detachments was probably aided by strain softening, by the generation of clay gouge in pelite layers and by extreme size reduction of carbonate particles in foliated carbonate cataclasites (Fig. 13c). The initial grain-size reduction, probably due to cataclasis, constitutes a strain softening mechanism in calcite rocks (De Bresser et al., 2002) by allowing grain boundary sliding during subsequent cataclastic and plastic flow.

If, as proposed by previous authors, the Alpujarride S_{cc} main foliation formed during vertical ductile thinning,

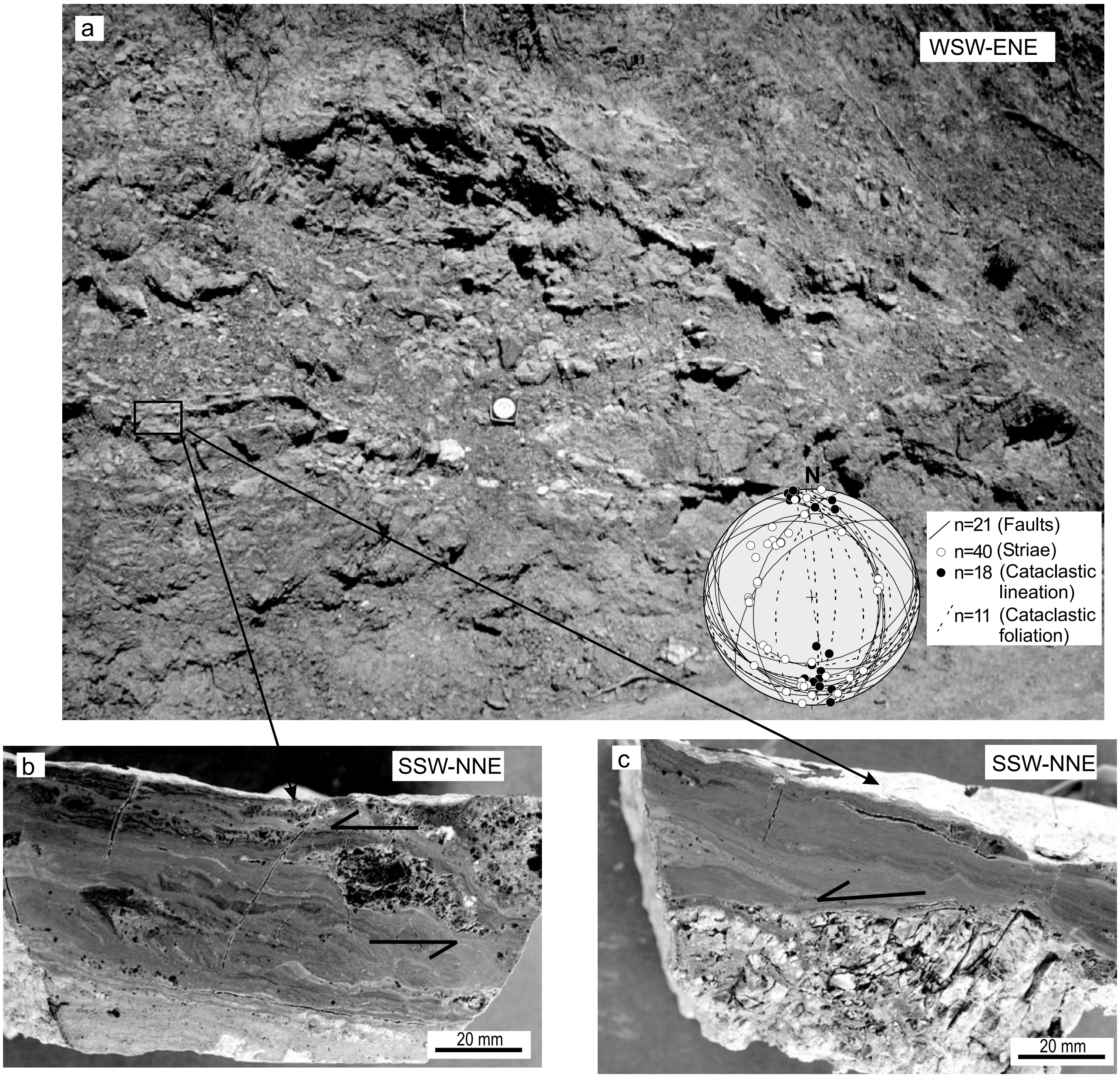


Fig. 11. (a) Detachment at the base of the Higher-Malaguide units in Sierra Espuña formed by fault gouge and breccia. It also includes ultracataclasite lenses that contain a N–S oriented cataclastic lineation (see included stereoplot). Kinematic criteria like rotated porphyroclast with asymmetric tails and sheath folds (b), together with C′ shear cutting reference surface (c) indicate southern shear sense. Locality B, Fig. 8.

coeval to isothermal decompression representing a β thinning factor of approximately three (Balanyá et al., 1993; Azañón et al., 1997; Balanyá et al., 1997; Azañón and Crespo-Blanc, 2000), then the oldest brittle extensional structures found in the overlying Malaguide complex must be coeval to the Alpujarride S_{cc} flattening event, and earlier than the Alpujarride exhumation at 19–20 Ma (Lonergan and Johnson, 1998).

The end of the isothermal decompression P–T path in the Alpujarride complex has been dated as 24–19 Ma (e.g. Monié et al., 1994; Platt and Whitehouse, 1999; Whitehouse and Platt, 2003). However, thermal modelling of the P–T path suggests that this extension started 30 Ma ago (Platt et al., 1998, 2003b; Platt and Whitehouse, 1999). Evidence of this pre-Miocene extension could be indicated by the general Oligocene–Lower-Miocene transgression in the Malaguide sedimentary cover (Lonergan, 1991; Martín-Martín et al., 1997) and by tholeitic dikes of late Oligocene age that intrude the Malaguide complex (Turner et al., 1999). Some of the brittle extensional structures that thin the Upper-Malaguide units probably formed during this initial extension, coeval to ductile thinning of the underlying Alpujarride rocks. Further extension along deeper plastic–brittle detachments exhumed the higher Alpujarride greenschist-facies rocks during the early Miocene (Lonergan and Platt, 1995; Lonergan and Johnson, 1998).

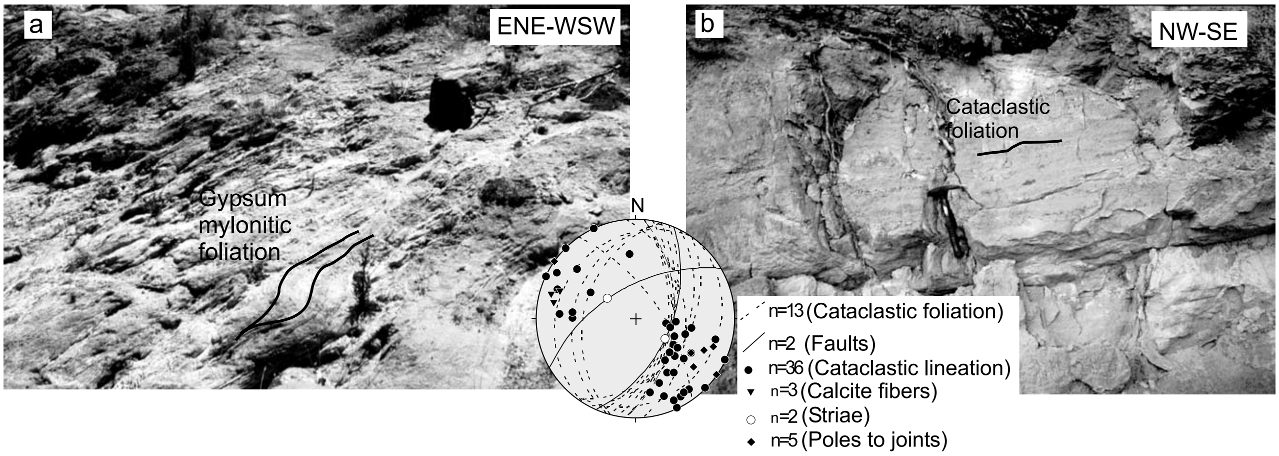


Fig. 12. (a) Gypsum mylonites found above the Lowest-Malaguide thrust sheet in Sierra Espuña that contain a NW–SE-trending lineation. Presently the mylonitic foliation is tilted towards the E by the activity of later W- to SW-directed normal faults (gypsum mylonitic foliation and lineation developed under otherwise cataclastic conditions are represented in the adjoining stereoplot). (b) Foliated carbonate cataclasites and ultracataclasites from the same detachment shown in (a).

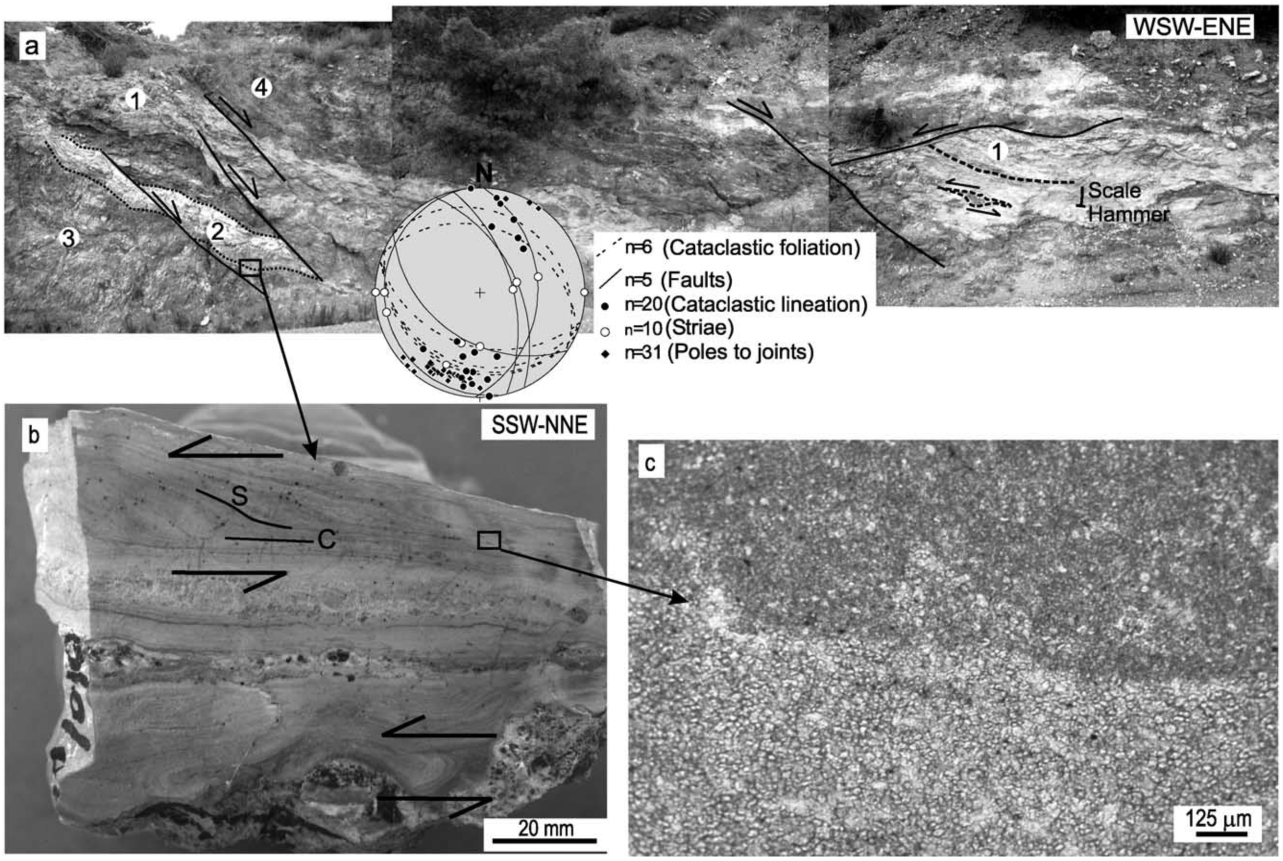


Fig. 13. (a) Detachment fault at the top of the Lowest-Malaguide unit in Sierra de la Tercia. Locality C, Fig. 7. Associated fault rocks include foliated carbonate cataclasites (1) and ultracataclasites (2) in the contact with underlying dolomite breccia (3). This fault zone forms a flat being subparallel to the slaty-cleavage of the Malaguide Permo-Triassic pelites (4). The cataclastic lineation found in the carbonate ultracataclasites is defined by oriented porphyroclasts and calcite fibres. It has a SSW–NNE trend (see adjoining stereoplot). (b) Brittle S–C structures in the ultracataclasites together with sheath folds indicate SSW shear sense. (c) Under the microscope the ultracataclasites show very fine and homogeneous grains with a texture similar to the one observed in carbonate mylonites that have deformed under superplastic flow (Schmid et al., 1977; Gilotti and Hull, 1990).

4.2. The Middle–Upper Miocene extensional system

The S–SSW- and NW-directed detachments are faulted and tilted both in Sierra Espuña and in Sierra de la Tercia by an extensional system that shows mostly W–SW sense of shear. This extensional system consists of several detachments at different structural levels and associated listric faults. For instance, in the Sierra de la Tercia the basal detachment forms the boundary between the Alpujarride and Malaguide complexes before cutting down towards the southwest with flat-ramp geometry into the Alpujarride complex, greatly thinning the Cortada unit (Booth-Rea et al., 2002b; cross-section 1–1′, Fig. 7). This detachment is defined by a clay-rich gouge generated by the comminution of Alpujarride fine-grained schists. Rotated porphyroclasts and brittle S–C cataclasites indicate a SW sense of shear (Booth-Rea et al., 2002b; shear-sense vectors, Fig. 7). The western end of Sierra Espuña also represents a footwall ramp of the SW extensional system, sealed by Serravallian conglomerates and cut by later Upper Miocene high-angle faults (Fig. 14a).

The WSW-directed low-angle normal faults outcropping

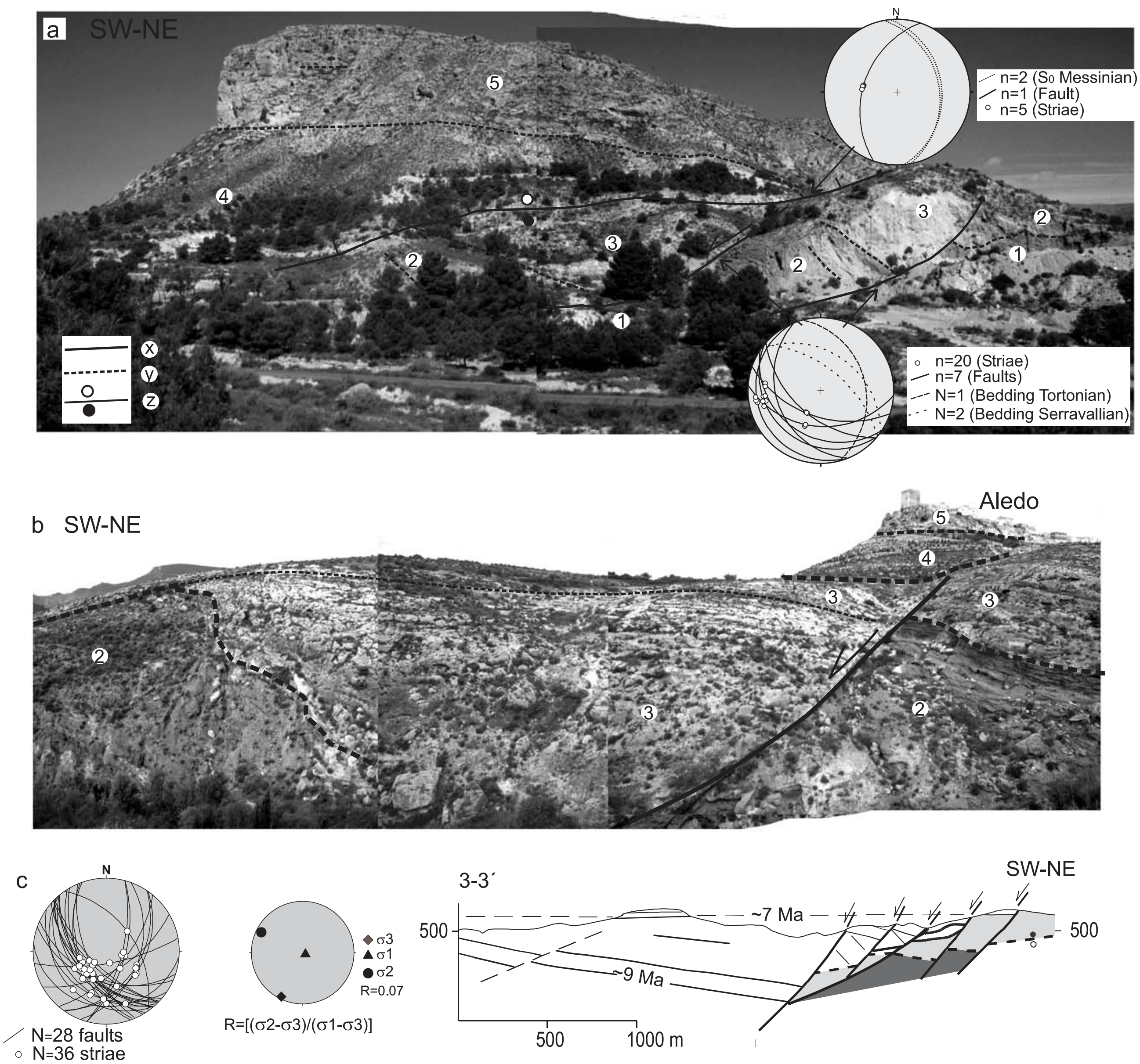


Fig. 14. (a) Listric SSW- and WSW-directed faults that tilt and detach the Lorca-basin Miocene sedimentary sequence from the Alpujarride metamorphic basement in the western end of Sierra Espuña (faults represented in stereographic projection, lower-right corner). These faults a cut by a later W-transport fault that tilts the Messinian calcirudites (5), stereoplot in upper right corner. (2) Upper-Serravallian/Tortonian conglomerates, (3) Tortonian calcirutes, (4) Tortonian marls, (5) Messinian calcirudites. (x) Fault, (y) bedding, (z) black circle indicates transport towards the observer. (b) Listric SW-directed normal growth fault (western border of Sierra Espuña, near Aledo, Fig. 8). See explanation in text. (c) Stereoplot of the Tortonian faults together with paleostress tensor calculated from them (modified from Booth-Rea and Azañón (2003)). Cross-section 3–3′ is located in Fig. 8.

in Sierra de la Tercia truncate the oldest (Burdigalian–Serravallian; Pérez-Lorente et al., 1992) sedimentary unit of the Lorca basin, which is commonly found tectonically detached from its metamorphic basement (Booth-Rea et al., 2002b). These faults are locally sealed by Upper Serravallian to early Tortonian red conglomerates in the core of Sierra de la Tercia (Fig. 7). These conglomerates overlie foliated clay gouge (comminuted Alpujarride fine-grained schists) with a SW shear sense in the southwestern end of Sierra Espuña. However, S- to SW-directed out-of-sequence listric faults truncate and tilt these sediments in the southwestern ends of Sierra de la Tercia (Booth-Rea et al., 2002b) and Sierra Espuña (Booth-Rea and Azañón, 2003). In the southeastern border of Sierra de la Tercia we have identified some high-angle NE/SW-trending fault segments that cut the Tortonian conglomerates and show dextral kinematics that could represent lateral ramps of the SW-directed Tortonian extensional system.

4.3. Interference pattern between extensional systems

The activity of two orthogonal extensional systems has produced extensional horses and riders along the two main directions of extension. At the hectometre scale, e.g. at locality X (Figs. 8 and 10b) N- and WSW-directed cataclasite and breccia shear zones are frequently folded by accommodation to ramp-flat or listric geometry of later W- to WNW-directed faults. A syncline affecting a cataclasite zone with westward transport is evident in Fig. 10b, formed by a hanging-wall flat, within weak pelites, lying upon a footwall ramp, which cuts the underlying carbonate rocks. Accommodation folds to the ramp-flat geometry of low-angle normal faults are frequent in the study area. The most common folds are anticline and syncline couples, formed by displacement of a hanging-wall ramp-flat geometry upon a footwall flat-ramp (locality C, cross-section 1–1′ and structural map, Fig. 7). Ramps normally cut the most competent layers (quartzites and carbonate rocks), whereas the flats are found in the incompetent layers (metapelites and gypsum). Layer-parallel extension and development of normal faults that form a low-angle with the bedding or with inactive older fault zones are common features thinning the tilted roll-over limbs (locality C, Fig. 10c and Fig. 13a). These faults compensate part of the tilting related to the listric geometry of underlying ramps or are related to rotation of hanging-wall ramps above footwall flats. Larger-scale NE- or E-directed faults thin the back-rotated eastern ends of Sierra de las Estancias (Fig. 5) and Sierra de la Tercia (Fig. 7).

Variable amounts of extension in two perpendicular directions generally produce a ‘chocolate-tablet structure’. This is observed in the study area where unusually the ‘pieces’ are bounded by low-angle normal faults. This geometry has been described in other areas of the Betics, such as in northern Sierra Nevada (Crespo-Blanc, 1995) and the eastern Betics (Martínez-Martínez and Azañón, 1997). This mega-structure is not as evident in Sierra de la Tercia because the Alboran domain outcrops show a NE–SW distribution, having a limited N–S width. Although, the NE–SW high-extension horses are evident, and the kinematic data indicate that they fault previous N–S transport low-angle normal faults (Booth-Rea et al., 2002b; cross-section 1–1′ and shear-sense vectors in Fig. 7). However, in Sierra Espuña, where the N–S width of the Alboran domain outcrops is greater, the ‘chocolate-tablet’ structure resulting from the interference between extensional faults is clear. This structure is shown in the two perpendicular cross-sections 4–4′ and 5–5′ in Fig. 8, where kilometre-scale brittle lenticular bodies of Malaguide Triassic carbonates are found in both NW–SE and NE–SW directions.

The interference between extensional systems in the northeastern Betics is responsible for the controversy concerning the nature and kinematics of the boundary between the Alpujarride and Malaguide complexes. Although presently there is a general agreement about the extensional nature of this boundary (Aldaya et al., 1991; Lonergan, 1991; Tubía et al., 1993; Lonergan and Platt, 1995), the shear sense of this contact is variable. The Alpujarride–Malaguide boundary is defined by mylonites and brittle fault rocks with mostly NE shear sense in Sierra de las Estancias (Lonergan and Platt, 1995). This NE-directed mylonite shear zone does not crop out in the eastern end of Sierra de las Estancias, probably having been cut out by an out-of-sequence N-directed low-angle brittle fault (shear-sense vectors, Fig. 5). In Sierra Espuña it coincides with a NW-directed detachment, whilst in Sierra de la Tercia the boundary coincides with a SW-directed detachment of Middle Miocene age.

4.4. Upper Miocene extension and its effects on the pre-existent fault systems

Upper Miocene high-angle normal faults cut the aforementioned extensional detachments, commonly cutting out whole units of the Alboran domain. For example, in the southeastern border of Sierra Espuña, a high-angle S- to SE-directed fault omits the lowest Malaguide unit (cross-section 5–5′, Fig. 8). These faults generally show a listric geometry that contributed to the tilting of the isostatically readjusted segments of the previous detachments and the overlying sediments. Tortonian calcirudites are tilted 45–50° and constitute high-extension riders, truncated by listric faults, which detach on a LANF that cuts down into the Alpujarride complex (Fig. 14a and geological map of Sierra Espuña, Fig. 8). Moreover, the listric faults also tilted the Upper-Tortonian fold that affects Sierra de la Tercia. This fold has a N70°E-trending hinge (geological map, Fig. 7) and shows a perianticlinal closure in its northeasten end with a 20° axial plunge. The tilting of the antiform’s hinge is related to the activity of SW-directed listric normal faults that bound the western end of Sierra Espuña, near the locality of Aledo (geological map, Fig. 8 and cross-section 3–3′, Fig. 14). Tortonian marls (4 in Fig. 14b) dated by Montenat et al. (1990), seal some faults, although basinwards they are also faulted (cross-section 3–3′, Fig. 14). The entire listric fan developed in the western border of Sierra Espuña is sealed by Messinian calcirudites (cross-section 3–3′, Fig. 14) with an age of approximately 7 Ma (Rouchy et al., 1998).

Upper Miocene faults form the present boundaries of the Lorca basin. The two largest sedimentary depocentres found in the Lorca basin, to the north of Lorca and to the south of Aledo (cross-section A–A′, Fig. 2 and cross-section 3–3′, Fig. 14), are bounded by NE- and SW-directed faults, which were active during the deposition of Tortonian marls. Most of the Tortonian high-angle faults show SW shear sense, especially in the western terminations of Sierra de la Tercia and Sierra Espuña; however, other faults active during this period were S- or SE-directed (Lonergan and Schreiber, 1993; Booth-Rea and Azañón, 2003). Taken together these faults produced radial extension during the Upper-Tortonian (Booth-Rea and Azañón, 2003; Fig. 14c).

5. Discussion and conclusions

The Malaguide complex together with the highest Alpujarride unit underwent protracted extension from the Oligocene to the Upper Miocene, with only a few structures indicating probable shortening. These structures are asymmetric folds and associated crenulation cleavage, which affect the Alpujarride main foliation, and late Miocene–Quaternary folds and strike-slip faults. As discussed by Lonergan and Platt (1995) the Malaguide–Alpujarride section in this area shows no evidence of thrusting after the development of the Alpujarride main foliation, in contrast with other areas in the Betics where late-to-post-metamorphic northwards thrusting has inverted the metamorphic grade order (e.g. Azañón et al., 1997; Balanyá et al., 1997; Azañón and Crespo-Blanc, 2000; Booth-Rea et al., 2003b). The Malaguide–Alpujarride section preserved in the northeastern Betics contains no metamorphic recurrences, suggesting that thrusting in this crustal section was pre-metamorphic. This has permitted previous authors to use the metamorphic gap found across the detachment between the Malaguide and Alpujarride complexes as an indicator of its extensional character (Lonergan, 1991; Lonergan and Platt, 1995).

Locally the Alpujarride–Malaguide crustal section outcropping in the northeastern Betics is approximately 1 km thick and it includes at least six former thrust sheets metamorphosed between lower-greenschist facies (300–350 °C; Booth-Rea, 2004) and diagenesis (approximately 60 °C; Lonergan, 1991) (Fig. 3 and cross-section 1–1′, Fig. 7). This proximity between the epizone and diagenetic rocks demonstrates the strong extensional attenuation undergone by the Alpujarride rocks outcropping in the study area.

During HP/LT metamorphism (6 kbar/300–350 °C) the brittle–plastic boundary was at approximately 20 km depth (Booth-Rea, 2004). During the formation of the flat-lying S_{cc} crenulation cleavage in the Alpujarride rocks and isothermal decompression, the plastic–brittle boundary was at approximately 2–3 kbar and 325 °C (Booth-Rea, 2004). Post-S_{cc} ductile shearing in the Alpujarride complex shows N–NW sense of shear, for example in the carbonate mylonites found between the Cortada and Pintada units. This shear sense coincides with the one observed in the structurally highest extensional detachments that thin the Malaguide complex. Consequently, ductile thinning of the middle- and lower-upper crust (Alpujarride complex) was probably coeval to the activity of multiple detachments in the brittle upper crust (Malaguide complex). Combined brittle and ductile thinning favoured progressive tectonic denudation of the Alpujarride complex, raising the plastic–brittle boundary from approximately 20 to 8 km depth at the end of the S_{cc} development. Brittle extension during the Lower and Middle Miocenes exhumed the Cortada unit from approximately 8 km depth (equivalent to the lowest pressures, 2.5 kbar, attained after ductile vertical thinning of the Cortada unit (Booth-Rea, 2004) to its present depth, below 1 km of anchizonal and diagenetic rocks of the Malaguide complex and constituting the basement of the Lorca basin.

The Alpujarride–Malaguide crustal section was extended by at least two sets of pervasive brittle structures, including low-angle normal faults, extensional shear fractures, veins and joints at all structural levels with predominantly N–S to NW–SE and E–W to SW–NE directions of extension. In both extensional systems outcrop-scale faults are observed to detach on larger faults, finally accommodating extension along the principal detachments that bound the main tectonic units (cross-section 1–1′, Fig. 7). Strain localisation and the development of extensional detachments were controlled by the rheological boundaries between rocks, occurring in the weaker rocks (metapelites and gypsum). Strain localisation within weak layers at different levels within the Alpujarride–Malaguide upper crust permitted large amounts of extension of the crustal sections to be transferred to the detachments. This mode of extension resulted in structures different to those generally associated with metamorphic-core complexes, where asymmetric shearing of the entire upper crust places the highest-grade rocks of the footwall in direct contact with the sedimentary cover or the lowest-grade rocks of the hanging-wall. The formation of different extensional detachments, controlled by the contrasting rheology of the upper crust led to the preservation in a single vertical of several layers representative of different depths of the previous unthinned crust.

The sequential activity of extensional detachments affecting a crust without rheological contrasts could probably result in a similar structure to the one observed in the northeastern Betics. However, the low angle observed between the internal reference surfaces of the Malaguide and Alpujarride units and the extensional detachments, together with the evident rheological contrasts between different rock types, suggest that the latter play an important role in the geometry of the studied extensional systems.

A dominant set of SW-directed listric normal faults and other W-, S- and SE-directed faults, truncated the low-angle normal faults during the Tortonian, cutting out units of the Malaguide–Alpujarride crustal section. The listric faults break out in NW/SE and WSW/ENE oriented borders of the topographically uplifted ENE/WSW-oriented antiformal ridges, producing elongated domes that emerge within the Neogene sedimentary depocentres developed in the hanging-walls of the listric faults. These small domes (10–16 km long) formed by the combined effect of extension and orthogonal shortening (Booth-Rea et al., 2002b; Booth-Rea and Azañón, 2003). This process has been described at a larger scale (150 km) in the Sierra-Nevada Core Complex, where there is evidence of pressure-driven differential lateral flow of crustal material into the area beneath the dome (Martínez-Martínez et al., 1997, 2002). However, in the smaller domes there is no evidence that ductile flow of crustal material has influenced their present topographical features (Booth-Rea et al., 2003a).

The amount of extension produced by the Upper Miocene extensional system is smaller than the one accumulated previously and preserved within its extensional riders. However, if the resulting structure were observed in reflection seismics of a rifted margin the only visible extension would be related to the late listric faults (e.g. Reston et al., 1996), as the previous low-angle detachments would look like tilted pre-kinematic layers. Hence, calculations of the amount of extension restoring balanced sections would result in an undervaluation of the total extensional thinning.

Acknowledgements

The CICYT Spanish projects REN2001-3868-CO3-01/MAR, REN2001-3378 and FEDER funds of the UE supported the field and laboratory research. José Miguel Martínez and an anonymous reviewer are thanked for their thorough and constructive reviews of the manuscript. Tim Reston suggested some improvements to the manuscript.

References

Aldaya, F., Álvarez, F., Galindo-Zaldívar, J., González-Lodeiro, F., Jabaloy, A., Navarro-Vilá, F., 1991. The Malaguide–Alpujarride contact (Betic Cordilleras, Spain): a brittle extensional detachment. Comptes Rendus de l'Academie des Sciences du Paris (Série II) 313, 1447–1453.

Allerton, S., Lonergan, L., Platt, J.P., Platzman, E.S., McClelland, E., 1993. Paleomagnetic rotations in the eastern Betic Cordillera, Southern Spain. Earth and Planetary Science Letters 119, 225–241.

Azañón, J.M., Crespo-Blanc, A., 2000. Exhumation during a continental collision inferred from the tectonometamorphic evolution of the Alpujarride Complex in the central Betics (Alboran Domain, SE Spain). Tectonics 19, 549–565.

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

Balanyá, J.C., García-Dueñas, V., 1987. Les directions structurales dans le Domaine d'Alborán de part et d'autre du Détroit de Gibraltar. Comptes Rendus de l'Academie des Sciences du Paris (Série II) 304, 929–932.

Balanyá, J.C., Azañón, J.M., Sánchez-Gómez, M., García-Dueñas, V., 1993. Pervasive ductile extension, isothermal decompression and thinning of the Jubrique unit in the Paleogene (Alpujárride Complex, western Betics Spain). Comptes Rendus de l'Academie des Sciences du Paris 316, 1595–1601.

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, 226–238.

Berman, R.G., 1991. Thermobarometry using multi-equilibrium calculations—a new technique, with petrological applications. Canadian Mineralogist 29, 833–855.

Booth-Rea, G., 2004. Tectónica cenozoica en el Dominio Cortical de Alborán. Ph.D. Thesis, University of Granada, Granada, Spain, 253pp, ISBN: 84-338-3090-2.

Booth-Rea, G., Azañón, J.M., 2003. Extensión versus compresión durante el Mioceno Superior en la Cuenca de Lorca (Béticas orientales). Geogaceta 34, 83–86.

Booth-Rea, G., Azañón, J.M., Goffe, B., Vidal, O., Martínez-Martínez, J.M., 2002a. High-pressure, low-temperature metamorphism in the Alpujarride units outcropping in southeastern Betics (Spain). Comptes Rendus Geosciences 334, 1–9.

Booth-Rea, G., García-Dueñas, V., Azañón, J.M., 2002b. Extensional attenuation of the Malaguide and Alpujarride thrust sheets in a segment of the Alboran basin folded during the Tortonian (Lorca area, Eastern Betics). Comptes Rendus Geosciences 334, 557–563.

Booth-Rea, G., Azañón, J.M., García-Dueñas, V., Sánchez-Gómez, M., 2003a. A "core-complex-type structure" formed by superposed ductile and brittle extension followed by folding and high-angle normal faulting. The Santi Petri dome (western Betics, Spain). Comptes Rendus Geosciences 335, 265–274.

Booth-Rea, G., Azañón, J.M., Martínez-Martínez, J.M., Vidal, O., García-Dueñas, V., 2003b. Análisis estructural y evolución tectonometamórfica del basamento de las cuencas neógenas de Vera y Huercal-Overa, Béticas orientales. Revista de la Sociedad Geológica de España 16(3-4), 193–211.

Booth-Rea, G., Azañón, J.M., Azor, A., García-Dueñas, V., 2004. Influence of strike-slip fault segmentation on drainage evolution and topography. A case study: the Palomares fault zone (southeastern Betics, Spain). Journal of Structural Geology, in press.

Bouillin, J.P., Durand-Delga, M., Olivier, P., 1986. Betic–Rifian and Tyrhenian Arcs: distinctive features, genesis, and development stages. In: Wezel, F.C., (Ed.), The Origin of Arcs, Elsevier Science Publications, 21., pp. 281–304.

Comas, M.C., Platt, J.P., Soto, J.I., Watts, A.B., 1999. The origin and tectonic history of the Alborán Basin: insights from Leg 161 Results. In: Zahn, R., Comas, M.C., Klaus (Eds.), Proceedings of the ODP Scientific Results 161, pp. 555–579.

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

Crespo-Blanc, A., Campos, J., 2001. Structure and kinematics of the South Iberian paleomargin and its relationship with the Flysch Trough units: extensional tectonics within the Gibraltar Arc fold-and-thrust belt (western Betics). Journal of Structural Geology 23, 1615–1630.

Crittenden, M., Coney, P., Davis, G., 1980. Tectonic significance of metamorphic core complexes of the North American Cordillera. Memoirs of the Geological Society of America 153.

De Bresser, J.H.P., Evans, B., Renner, J., 2002. On estimating the strength of calcite rocks under natural conditions. In: De Meer, S., Drury, M.R., Bresser, J.H.P., Pennock, G.M. (Eds.), Deformation Mechanisms, Rheology and Tectonics: Current Status and Future Perspectives, Geological Society, London, Special Publications, 200., pp. 309–329.

Dewey, J.F., Helman, M.L., Turco, E., Hutton, D.H.W., Knott, S.D., 1989. Kinematics of the western Mediterranean. In: Coward, M.P., Dietrich, D., Park, R.G. (Eds.), Alpine Tectonics, Special Publication of the Geological Society of London, 45., pp. 265–283.

Durand-Delga, M., Rossi, P., Olivier, P., Puglisi, D., 2000. Situation structurale et nature ophiolitique de roches basiques jurassiques associées aux flyschs maghrébins du Rif (Maroc) et de Sicile (Italie). Comptes Rendus de l'Academie des Sciences du Paris 331, 29–38.

Ferrill, D.A., Morris, A.P., Jones, S.M., Stamatakos, J.A., 1998. Extensional layer-parallel shear and normal faulting. Journal of Structural Geology 20, 355–362.

Galindo-Zaldívar, J., González-Lodeiro, F., Jabaloy, A., 1989. Progressive extensional shear structures in a detachment contact in the Western Sierra Nevada (Betic Cordilleras, Spain). Geodinamica Acta 3, 73–85.

García-Dueñas, V., Martínez-Martínez, J.M., 1988. Sobre el adelgazamiento mioceno del Dominio Cortical de Alborán, el Despegue Extensional de Filabres (Béticas orientales). Geogaceta 5, 53–55.

García-Dueñas, V., Balanyá, J.C., Martínez-Martínez, J.M., 1992. Miocene extensional detachments in the outcropping basement of the Northern Alboran basin (Betics) and their tectonic implications. Geo Marine Letters 12, 88–95.

Gilotti, J.A., Hull, J.M., 1990. Phenomenological superplasticity in rocks. In: Knipe, R.J.R., Rutter, E.H. (Eds.), Deformation Mechanisms, Rheology and Tectonics, Geological Society, London, Special Publication, 54., pp. 229–240.

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 Alpujarride nappes, Betic Cordillera (SE Spain). European Journal of Mineralogy 1, 139–142.

Jolivet, L., Daniel, J., Truffert, C., Goffé, B., 1994. Exhumation of deep crustal metamorphic rocks and crustal extension in arc and back-arc regions. Lithos 33, 3–30.

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., 1991. Structural evolution of the Sierra Espuña, Betic Cordillera, SE Spain. Ph.D. Thesis, University of Oxford.

Lonergan, L., 1993. Timing and kinematics of deformation in the Malaguide Complex, Internal Zone of the Betic Cordillera, Southeast Spain. Tectonics 12, 460–476.

Lonergan, L., Johnson, C., 1998. Reconstructing orogenic exhumation histories using syn-orogenic detrital zircons and apatites: an example from the Betic Cordillera, SE Spain. Basin Research 10, 353–364.

Lonergan, L., Platt, J.P., 1995. The Malaguide–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., Schreiber, B.C., 1993. Proximal deposits at a fault-controlled basin margin, Upper Miocene, SE Spain. Journal of the Geological Society of London 150, 719–727.

Mäkel, G.H., 1981. Differences in tectonic evolution of superimposed Malaguide and Alpujarride tectonic units in the Espuña area (Betic Cordilleras, Spain). Geologische in Mijnbouw 60, 203–208.

Mäkel, G.H., Rondeel, H.E., 1979. Differences in the stratigraphy and metamorphism between superposed Maláguide and Alpujárride units in the Espuña area (Betic Cordilleras, SE Spain). Estudios Geológicos 35, 109–117.

Martín-Martín, M., Martín-Algarra, A., 2002. Thrust sequence and syntectonic sedimentation in a piggy-back basin: the Oligo–Aquitanian Mula–Pliego Basin (Internal Betic Zone, SE Spain). Comptes Rendus Geoscience 334, 363–370.

Martín-Martín, M., Martín-Algarra, A., Serra-Kiel, J., 1997. El terciario del Dominio Maláguide en Sierra Espuña (Prov. de Murcia, SE de España). Revista de la Sociedad Geológica de España 10, 265–280.

Martínez-Martínez, J.M., Azañón, J.M., 1997. Mode of extensional tectonics in the south-eastern Betics (SE Spain). Implications for the tectonic evolution of the peri-Alborán orogenic system. Tectonics 16, 205–225.

Martínez-Martínez, J.M., Soto, J.I., Balanyá, J.C., 1997. Crustal decoupling and intracrustal flow beneath domal exhumed core complexes, Betic (SE Spain). Terra Nova 9, 223–227.

Martínez-Martínez, J.M., Soto, J.I., Balanyá, J.C., 2002. Orthogonal folding of extensional detachments: structure and origin of the Sierra Nevada elongated dome (Betics, SE Spain). Tectonics 21, 1012DOI: 10.1029/2001TC001283.

Mazzoli, S., Helman, M., 1994. Neogene patterns of relative plate motion for Africa–Europe: some implications for recent central Mediterranean tectonics. Geologische Rundschau 83, 464–468.

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.

Montenat, C., Ott d'Estevou, P., Delort, T., 1990. Le Bassin de Lorca. In: Montenat, C., (Ed.), Les bassins Neogenes du Domaine Betique Oriental (Espagne), Documents et Travaux, 12-13. IGAL, Paris, pp. 261–280.

Nieto, F., Velilla, N., Peacor, D.R., Ortega-Huertas, M., 1994. Regional retrograde alteration of sub-greenschist facies chlorite to smectite. Contributions to Mineralogy and Petrology 115, 243–252.

Paquet, J., 1969. Etude Géologique de l'Ouest de la province de Murcie (Espagne). Mémoires Société, Géologique du France 111, 1–270.

Paquet, J., 1970. Transgressivite de l'Eocene superieur dans les malaguides de la Sierra de Espuña (Cordilleres Bétiques, Sud Est de l'Espagne) Mise au point. Geologische in Mijnbouw 49, 61–64.

Paquet, J., 1974. Tectonique éocène dans les Cordilléres Bétiques: Vers une nouvelle conception de la paleogéographie en Mediterraneé occidentale. Bulletin de la Société Géologique du France 16, 58–71.

Parra, T., Vidal, O., Agard, P., 2001. A thermodynamic model for Fe–Mg dioctahedral K-white micas using data from phase equilibrium experiments and natural pelitic assemblages. Contributions to Mineralogy and Petrology 143, 706–732.

Peacock, D.C.P., Zhang, X., 1993. Field examples and numerical modelling of oversteps and bends along normal faults in cross-section. Tectonophysics 234, 147–167.

Pérez-Lorente, F., Rodríguez-Estrella, T., Serrano, F., Mancheño, M.A., Guillén-Mondéjar, F., 1992. Contribución a la bioestratigrafía neógena de la Cuenca de Lorca (Murcia). III Congreso Geológico de España y VIII Congreso Latinoamericano de Geología, pp. 185–190.

Platt, J.P., 1986. Dynamics of orogenic wedges and the uplift of high-presure metamorphic rocks. Geological Society of America Bulletin 97, 1037–1053.

Platt, J.P., Whitehouse, M.J., 1999. Early Miocene high-temperature metamorphism and rapid exhumation in the Betic-Cordillera (Spain)—Evidence from U–Pb zircon ages. Earth and Planetary Science Letters 171, 591–605.

Platt, J.P., Soto, J.I., Whitehouse, M.J., Hurford, 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., Allerton, S., Kirker, A., Mandeville, C., Mayfield, A., Platzman, E.S., Rimi, A., 2003a. The ultimate arc: differential displacement, oroclinal bending, and vertical axis rotation in the External Betic-Rif arc. Tectonics 22(3), 1017DOI: 10.1029/2001TC001283.

Platt, J.P., Whitehouse, M.J., Kelley, S.P., Carter, A., Hollick, L., 2003b. Simultaneous extensional exhumation across the Alboran Basin:

implications for the causes of late orogenic extension. Geology 31, 251–254.

Reston, T.J., Krawczyk, C.M., Klaeschen, D., 1996. The S reflector west of Galicia (Spain): evidence for detachment faulting during continental breakup from prestack depth migration. Journal of Geophysical Research 101, 8075–8091.

Rouchy, J.M., Taberner, C., Blancvalleron, M.M., Sprovieri, R., Russell, M., Pierre, C., Distefano, E., Pueyo, J.J., Caruso, A., Dinaresturell, J., Gomiscoll, E., Wolff, G.A., Cespuglio, G., Ditchfield, P., Pestrea, S., Combourieunebout, N., Santisteban, C., Grimalt, J.O., 1998. Sedimentary and diagenetic markers of the restriction in a marine basin—the Lorca Basin (Se Spain) during the Messinian. Sedimentary Geology 121, 23–55.

Schmid, S.M., Boland, J.N., Paterson, M.S., 1977. Superplastic flow in fine grained limestone. Tectonophysics 43, 257–291.

Sedlock, R.L., 2002. Evaluation of exhumation mechanisms for coherent blueschists in western Baja California, Mexico. In: Ring, U., Brandon, M.T., Lister, G.S., Willett, S.D. (Eds.), Exhumation Processes: Normal faulting, Ductile Flow and Erosion, Geological Society, London, Special Publications, 154., pp. 29–54.

Selverstone, J., 1988. Evidence of east–west crustal extension in the eastern Alps: implications for the unroofing history of the Tauern window. Tectonics 7, 87–105.

Tanaka, H., 1992. Cataclastic lineations. Journal of Structural Geology 14, 1239–1252.

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

Tubía, J., Navarro-Vila, F., Cuevas, J., 1993. The Maláguide–Los Reales Nappe: an example of crustal thinning related to the emplacement of the Ronda peridotites (Betic Cordillera). Physics of the Earth and Planetary Interiors 78, 343–354.

Turner, S.P., Platt, J.P., George, R.M.M., Kelley, S.P., Pearson, D.G., Nowell, G.M., 1999. Magmatism associated with orogenic collapse of the Betic–Alboran Domain, SE Spain. Journal of Petrology 40, 1011–1036.

Vidal, O., Parra, T., 2000. Exhumation paths of high pressure metapelites obtained from local equilibria for chlorite–phengite assemblages. Geology Journal 35, 139–161.

Vidal, O., Parra, T., Trotet, F., 2001. A thermodynamic model for Fe–Mg aluminous chlorite using data from phase equilibrium experiments and natural pelitic assemblages in the 100–600 °C, 1–25 kbar P–T range. American Journal of Science 301, 557–592.

Weijermars, R., Roep, T.B., Van den Eeckhout, B., Postma, G., Kleverlaan, K., 1985. Uplift history of a Betic fold nappe inferred from Neogene–Quaternary sedimentation and tectonics (in the Sierra Alhamilla and Almería, Sorbas and Tabernas Basins of the Betic Cordilleras, SE Spain). Geologische en Mijnbouw 64, 397–411.

Whitehouse, M.J., Platt, J.P., 2003. Dating high-grade metamorphism-constraints from rare-earth elements in zircon and garnet. Contributions to Mineralogy and Petrology 145, 61–74.