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Influence of strike-slip fault segmentation on drainage evolution and topography. A case study: the Palomares Fault Zone (southeastern Betics, Spain)

Guillermo Booth-Rea[a,*], José-Miguel Azañón[b], Antonio Azor[b], Víctor García-Dueñas[b]

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

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Abstract

The Palomares Fault Zone (PFZ) is one of the main sinistral strike-slip faults in the Betics (SE Spain), with approximately 16 km of north–south displacement. The PFZ initiated during the Tortonian–Messinian as a transfer structure linking areas subject to NW/SE shortening. During the Plio-Quaternary the fault zone lengthened cutting previous fold structures and widened towards the east displacing the active mountain front to the western border of Sierra Almagrera–Sierra Almenara. These Sierras, which show moderate uplift rates of 0.05–0.15 m/ka, formed in response to the oblique-slip regime of the PFZ. The drainage system in the vicinity of the PFZ is asymmetric with respect to a main axial valley that runs parallel to the PFZ on the downthrown fault block. In this block, the drainage density is lower and the streams are longer than in the uplifted block. Furthermore, west of the main axial valley the streams describe eastward directed deflections, indicating the progressive eastward migration of the main axial valley during the Pleistocene. The drainage system on the uplifted ranges shows a consequent pattern, indicating recent uplift and folding under NNW/SSE convergence. Recent activity along segments of the PFZ has increased topographical gradients, favouring dissection of previous streams by headward erosion of streams transverse to the active fault segments.

Keywords: Strike-slip faulting; Fault segmentation; Drainage pattern; Topography; Uplift rates; Southeastern Betics

1. Introduction

Segmentation in strike- and oblique-slip fault systems has been studied extensively in recent years (e.g. Tchalenko, 1970; Tchalenko and Ambraseys, 1970; Wallace, 1973; Aydin and Nur, 1982, 1985; Aydin and Page, 1984; Bilham and Williams, 1985; Sylvester, 1988; Schwartz and Sibson, 1989 and references therein; Keller et al., 1995; Norris and Cooper, 1995; Bayasgalan and Jackson, 1999). In oblique-slip fault systems, displacement generates important topographic gradients with associated uplift and subsidence in antidilational and dilational jogs, respectively (Sibson, 1986a), forming both uplifted ranges and sedimentary depocentres (Wilcox et al., 1973; Sylvester, 1988). Thus, along time variations in the position of active fault segments, together with creation of new segments produces migration of the active sedimentary depocentres and variations in the topography and drainage pattern. This link between geomorphology and geometry of active fault systems has been recently illustrated in several papers (Ollier, 1981; Leeder and Jackson, 1993; Jackson et al., 1996; Bayasgalan et al., 1999; Bayasgalan and Jackson, 1999; Morewood and Roberts, 2000; Walker and Jackson, 2002).

In this paper we present a case study from the southeastern Betic Cordillera (SE Spain; Fig. 1), where displacement through time on the active fault segments of the strike-slip Palomares Fault Zone (PFZ) and creation of new segments have strongly influenced the migration of sedimentary depocentres in the dilatational jogs (Booth-Rea et al., 2003a). Here, we concentrate on how the PFZ segmentation and activity have influenced the evolution of the drainage pattern and topography. To this end, we have

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

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

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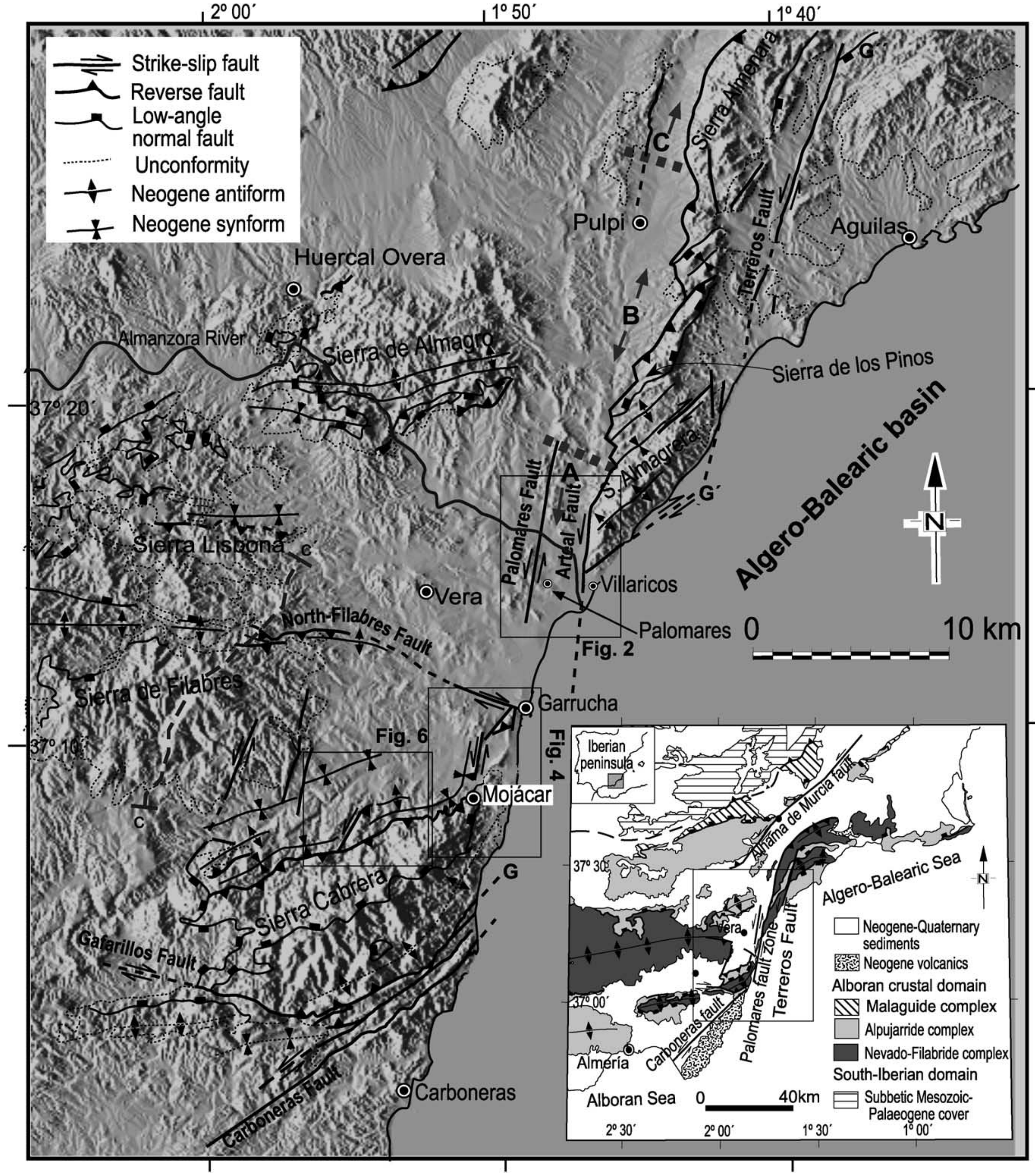


Fig. 1. Tectonic map and DEM model of the south-eastern Betics. Inset in the lower right corner shows a schematic geological map of the eastern Betics.

done a detailed mapping and structural analysis of the PFZ and other associated structures, showing the main fault segments together with their geometry and kinematics. We have determined the Pliocene to present-day displacement along the PFZ from the geomorphic analysis of the drainage pattern and topography, calculating displacement and uplift rates along some of the fault segments. All these data led us to propose a detailed tectonic evolution for the PFZ since its initial formation during the late Tortonian until present-day, as well as to evaluate the influence of strike-slip fault segmentation on the evolution of the drainage pattern and topography.

2. Geological setting

The southeastern Betics (SE Spain) are characterized by the presence of Neogene to Quaternary sedimentary basins that outcrop among E/W- to ENE/WSW-elongated antiformal ridges where metamorphic basement crops out (inset in Fig. 1). This basement is made up of several metamorphic complexes belonging to the Alboran crustal domain, a terrain that collided with the South Iberian and Maghrebian margins during the Early Miocene, forming the Gibraltar Arc and the Betic and Rif cordilleras (Balanyá and García-Dueñas, 1987; Platt et al., 2003). The Alboran crustal domain has been traditionally divided into three metamorphic complexes, which are from top to bottom: the Malaguide complex, the Alpujarride complex, and the Nevado–Filabride complex (inset, Fig. 1). The Alpujarride and Nevado–Filabride complexes underwent HP/LT metamorphism under eclogite or blueschist facies, later overprinted by greenschist or amphibolite facies (e.g. Gómez-Pugnaire and Soler, 1987; Tubía and Gil Ibarguchi, 1991; Booth-Rea et al., 2003b). Meanwhile, the Malaguide complex only underwent anchizone conditions during the Alpine orogeny (Lonergan and Platt, 1995).

The Neogene basins formed during Early and Mid-Miocene extensional tectonics, which markedly attenuated the previous pile of metamorphosed units of the Alboran domain (e.g. Galindo-Zaldívar et al., 1989; Platt and Vissers, 1989; García-Dueñas et al., 1992; Lonergan and Platt, 1995; Martínez-Martínez and Azañón, 1997; Booth-Rea et al., 2002a). The ultimate result of this severe extensional tectonics was the formation of the Alboran Sea between the Betics in Iberia and the Rif in Morocco (Watts et al., 1993; Comas et al., 1999). One of the basins formed in SE Iberia during the Neogene extension was the Vera basin (Völk and Rondeel, 1964; Völk, 1966, 1967), which is located between the Sierra de Filabres to the north and Sierra Cabrera to the south (Fig. 1).

The antiformal ridges, which show both asymmetric and box-like geometries, were formed during and after the latest extensional episodes in a late Neogene N/S and NNW/SSE shortening regime (Estévez et al., 1982; Ott d'Estevou and Montenat, 1985; Stapel et al., 1996). The upper Neogene sedimentary cover was deposited during this shortening regime in between antiformal ridges and strike-slip faults. Thus, the thickest sedimentary depocentres are located in synclines between the anticlinal ridges or in dilatational jogs within strike-slip fault zones (e.g. Alvado, 1986; Montenat and Ott d'Estevou, 1990; Ott d'Estevou et al., 1990; Booth-Rea et al., 2003a). Strike-slip structures developed under a mostly transpressive regime have accommodated most of the late Neogene and Quaternary N/S to NNW/SSE shortening in the southeastern Betics (Coppier et al., 1990; Griveaud et al., 1990; Montenat and Ott d'Estevou, 1990). The most important strike-slip faults active during the late Neogene and Quaternary are the Carboneras (Keller et al., 1995; Bell et al., 1997; Faulkner et al., 2003), Alhama de Murcia (Bousquet and Montenat, 1974; Silva et al., 1997; Martínez-Díaz, 2002), Palomares (Bousquet, 1979; Weijermars, 1987), and Terreros sinistral fault-zones, all of them with NNE/SSW to NE/SW trend (Fig. 1).

The Vera basin is mostly filled in with marine sediments, which span from Early Miocene to Quaternary in age, and show several unconformities (Völk and Rondeel, 1964; Barragán, 1997; Booth-Rea, 2001), the Upper Miocene ones related to the aforementioned compressive tectonics (Alvado, 1986; Ott d'Estevou et al., 1990). It shows a WSW/ENE-oriented sedimentary depocentre located in a syncline between the Sierra Cabrera and the Sierra de Filabres anticlinal ridges (Fig. 1). This WSW–ENE topographic and geological grain is interrupted east of the basin, where the Sierra Almagrera emerges with a NE–SW orientation, sub-parallel to the PFZ, which bounds the Vera basin to the east (Fig. 1). Two sedimentary depocentres with north–south orientation parallel the PFZ, being bounded by segments of this fault zone (Booth-Rea et al., 2003a). The western Palomares depocentre, bounded to the east by the Palomares fault (Figs. 1 and 2), is mostly filled in with Tortonian to Pliocene sediments. The eastern Palomares depocentre is located between the Palomares and Arteal faults (Figs. 1 and 2) and comprises mostly Pliocene to Quaternary sediments (Booth-Rea et al., 2003a). Sedimentation migrated eastwards from the Tortonian to the Quaternary, following the eastward displacement of the active Palomares fault segments (Booth-Rea et al., 2003a).

3. The Palomares Fault Zone

The Palomares fault was initially mapped by Völk (1967), although it was defined later by Bousquet and Montenat (1974), as a sinistral fault zone formed by several segments with a N10–20°E orientation. According to Bousquet (1979), the fault was active during the Pliocene and Quaternary, cutting the Vera basin between Pulpí to the north and Garrucha to the south (Fig. 1). This fault zone was also referred to as a transcurrent corridor active during most of the Neogene and Quaternary (Alvado, 1986; Montenat et al., 1987; Ott d'Estevou et al., 1990; Silva et al., 1993), producing approximately 15 km of lateral displacement of the upper Neogene Sierra Cabrera antiformal ridge (Weijermars, 1987; Coppier et al., 1990). Some authors have interpreted this fault and other related structures as a major lithospheric boundary, namely the Trans-Alboran shear zone (Hernández et al., 1987; Larouziere et al., 1988), which would have facilitated the pathway for Miocene magmatism in the Alboran Sea and the Southeastern Betics.

In this paper, we shall refer to the PFZ as a NNW/SSE-oriented sinistral strike-slip fault zone formed by several segments that bound the eastern end of the Vera basin. The PFZ is approximately 4 km wide, entering southwards the Mediterranean Sea between the localities of Garrucha and Villaricos (Fig. 1); to the north, it curves towards a NE/SW

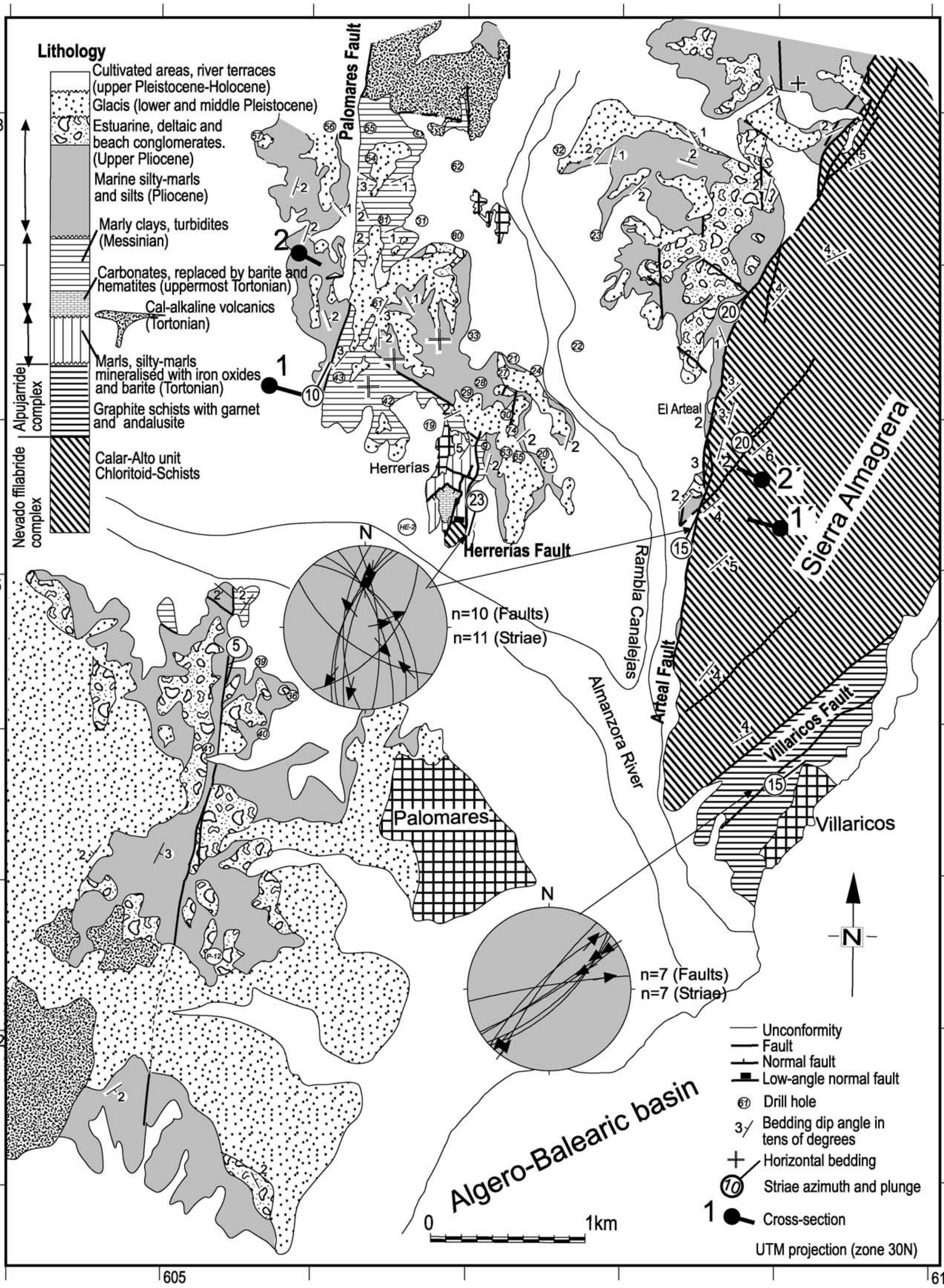


Fig. 2. Geological map of the central segments of the PFZ (see location in Fig. 1). Stereoplots represent structures found in the dextral Villaricos Fault (lower stereoplot) and in the Herrerías and Arteal fault segments. Equal-angle lower-hemisphere projection.

orientation, bounding the northern flank of the Sierra Almenara (Fig. 1).

The southern segments of the PFZ generally dip towards the west, having a slightly oblique regime that favours subsidence on the western blocks (Figs. 2 and 3). In contrast, the northern segments dip towards the ESE, having a sinistral-reverse regime that favours uplift of the mountain ranges located to the east (Sierra Almenara, Sierra de los Pinos; Fig. 1). Thus, the PFZ has an overall helicoidal geometry accommodating extension in the eastern end of the Vera basin and shortening to the north in Sierra Almenara (Fig. 1). This geometry is common in strike-slip fault systems as discussed by Naylor et al. (1986) and Sylvester (1988). South of the Vera basin, the PFZ continues along the sea-bed following the coastline, its termination being undetermined, although it could join the NE/SW-oriented Carboneras sinistral/reverse fault, located further south, which has also been active during the Neogene and Quaternary (Keller et al., 1995; Bell et al., 1997).

3.1. Segmentation and activity of the fault zone

The PFZ shows several segments that cut the sedimentary sequence of the Vera basin (Booth-Rea et al., 2003a). The westernmost fault segments outcrop west of Garrucha and can be followed northwards to Pulpí (Fig. 1); they show a rectilinear geometry and a sinistral regime (striae plunge 5–15°, both to the south and north; Fig. 2). These segments coincide with the Palomares Fault as defined by Bousquet and Montenat (1974); for this reason, we have kept the name ‘Palomares fault segments’ to designate them. Most of the Palomares fault segments cut upper Pliocene shallow marine conglomerates, being sealed by Quaternary river terraces (Barragán, 1997; Fig. 2). Towards the south, some of these segments are sealed by uppermost-Messinian to lowermost-Pliocene sediments (Locality Y; Figs. 4 and 5a), thus indicating fault activity during the Messinian. Even though Pre-Tortonian activity along this fault zone has been suggested by other authors (Alvado, 1986; Weijermars, 1987; Ott d’Estevou et al., 1990), we have not found sediments older than the uppermost Tortonian sealing any of the Palomares fault segments. The oldest evidence we have found of fault activity along the Palomares fault segments is a progressive angular unconformity in temperate carbonates with an age of 7.2 Ma (Braga et al., 2003), which constitute the Azagador Member of the Turre Formation (Völk, 1967). Laterally, this progressive unconformity evolves to an erosive angular unconformity between the Azagador Member and the underlying sediments (Core S-42 in Fig. 2; cross-section 1–1′ in Fig. 3; Figs. 4 and 6). The unconformity is oriented parallel to the Palomares fault segments, although towards the south it curves to an E/W-orientation parallel to Sierra Cabrera (Figs. 4 and 5c), where it dates the uplift and folding of this Sierra (Weijermars et al., 1985; Alvado, 1986; Ott d’Estevou et al., 1990; Booth-Rea, 2001; Booth-Rea et al., 2003a).

The Palomares fault segments cut calc–alkaline volcanic domes of Tortonian age (8.2 Ma; Bellon et al., 1983), which outcrop southwest and north of Palomares (Fig. 2). The offset of these domes was used by Bousquet (1979) to estimate the displacement along these fault segments. Continuous cores from drill-holes can be reliably used to better define the volcanic palaeoreliefs, which were onlapped by Messinian marls (Fig. 3). The palaeoreliefs continue 2 km south of their present location at surface, below the Messinian marls in the eastern block of the Palomares fault segments. Thus, the approximate horizontal displacement of the volcanics is 7.2 km.

The eastern strand of the PFZ bounds the western side of Sierra Almagrera, Sierra de los Pinos and Sierra Almenara.

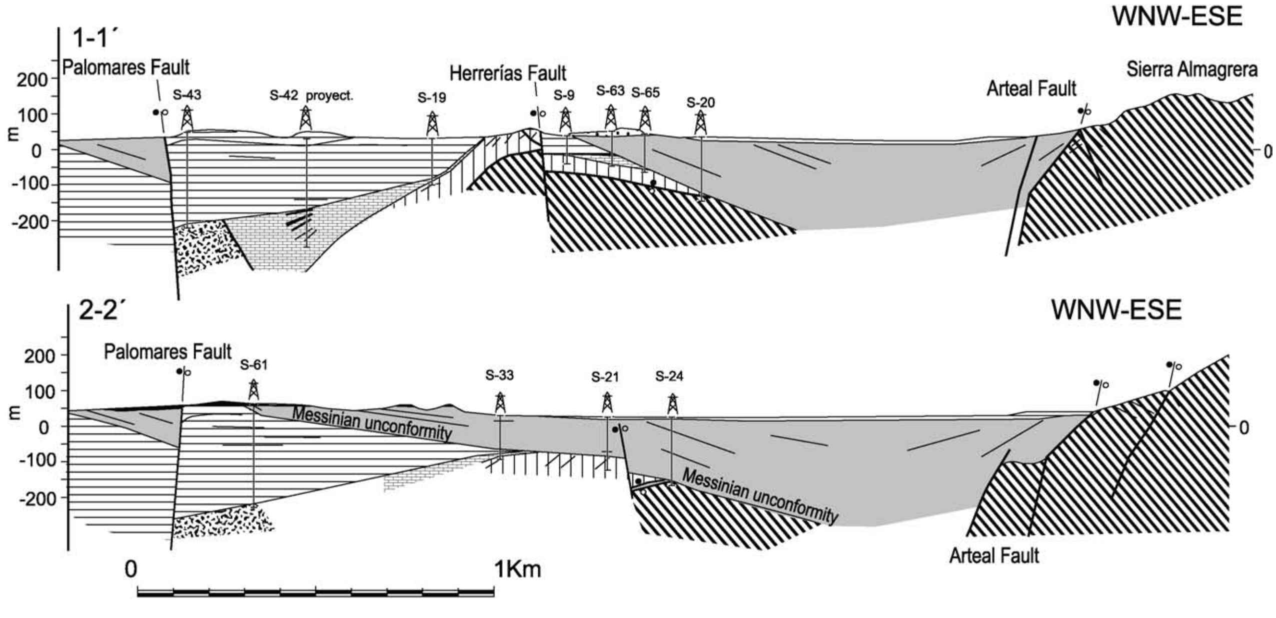


Fig. 3. Cross-sections of the Arteal and Palomares fault segments (see location and lithostratigraphic legend in Fig. 2).

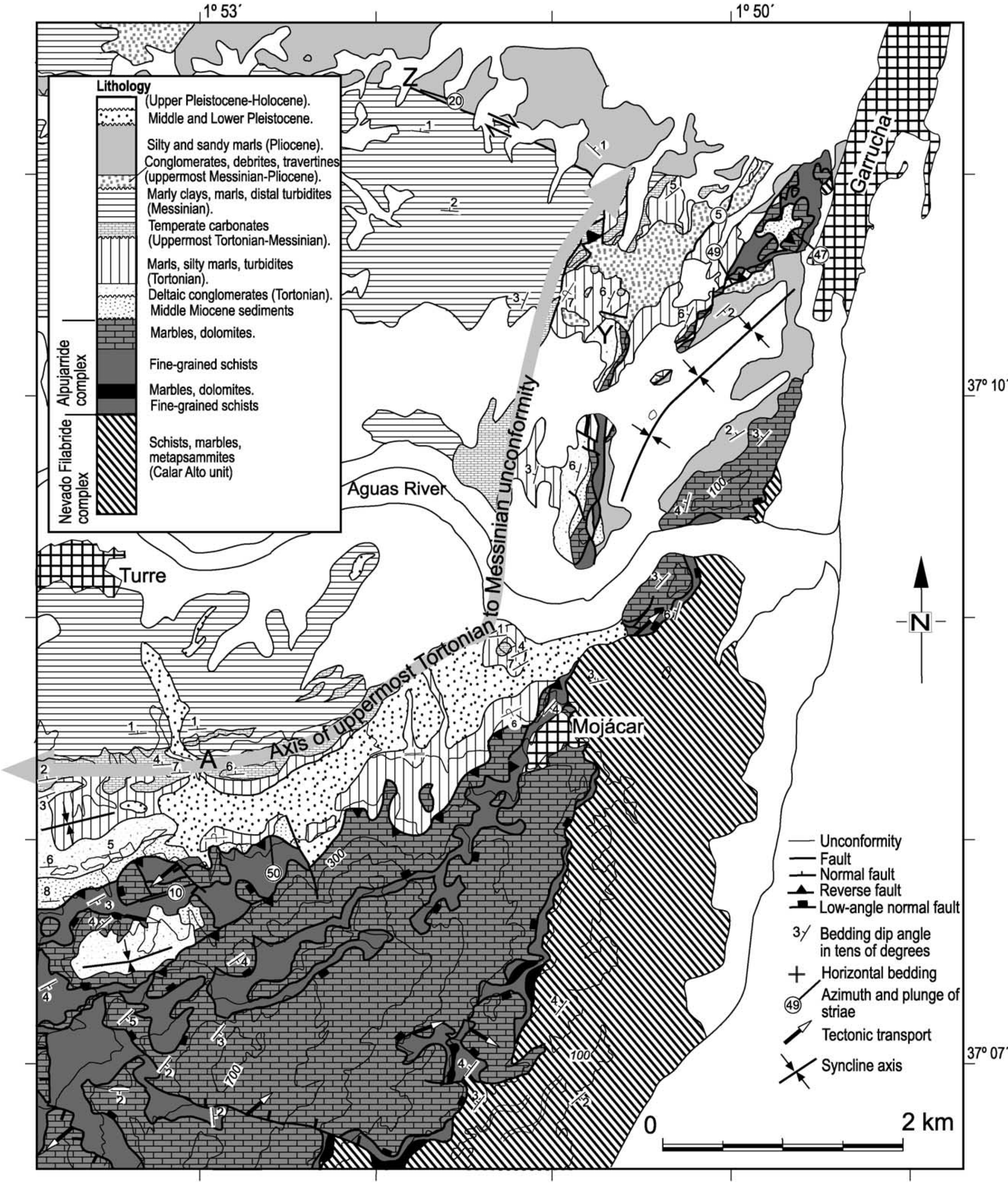
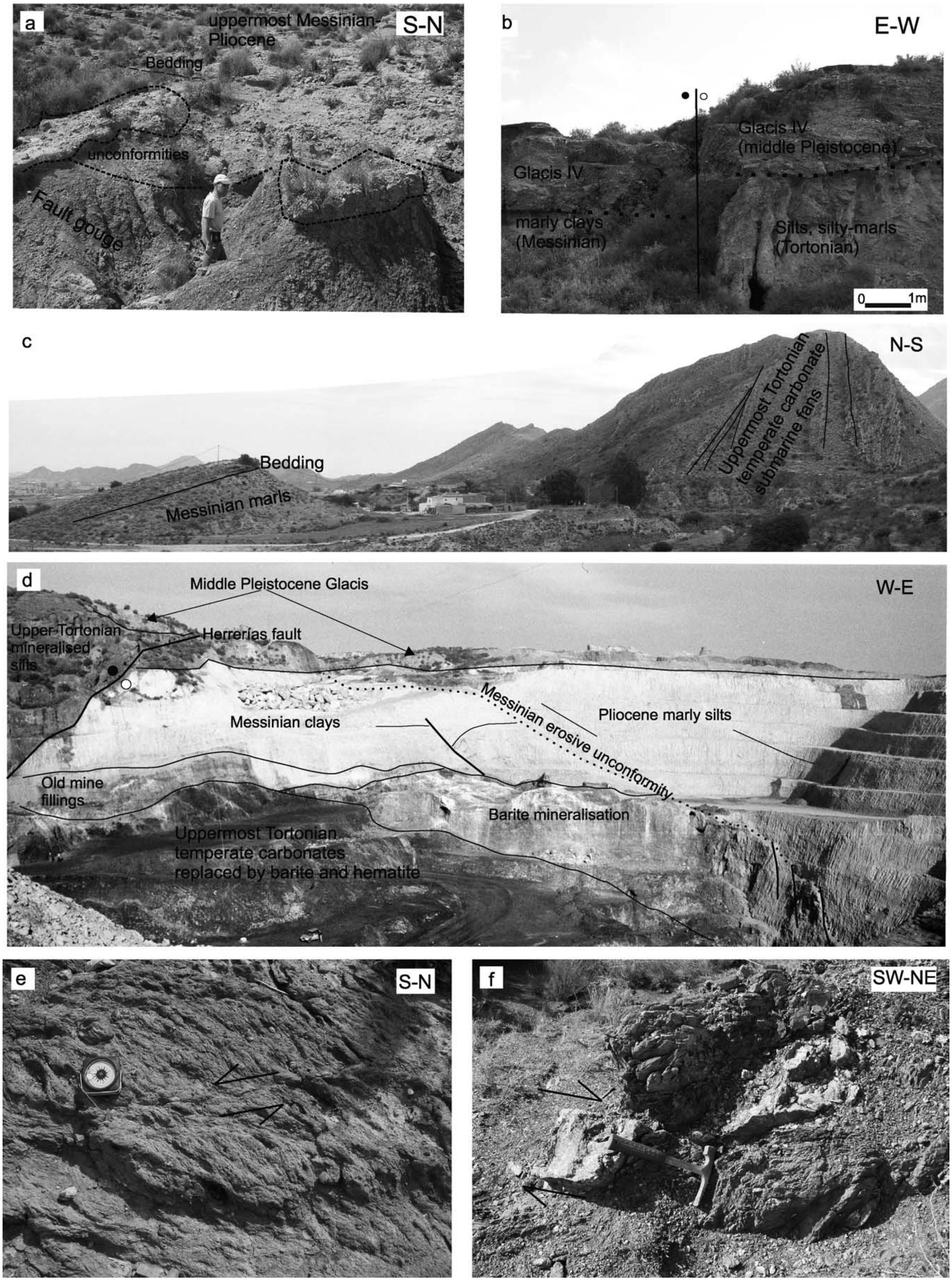


Fig. 4. Geological map of the southern termination of the PFZ (see location in Fig. 1).

Fig. 5. (a) Fault gouge in the Palomares fault segments sealed by uppermost-Messinian to Pliocene beach sediments (locality Y, Fig. 4). (b) Middle Pleistocene Glacis cut by the Herrerias Fault. (c) Uppermost-Tortonian to Messinian progressive unconformity in the northern limb of the Sierra Cabrera antiformal ridge (locality A, Fig. 4). (d) Herrerías open-pit mine. Note Herrerías fault cutting middle Pleistocene Glacis, tilted Messinian erosive unconformity, and Tortonian to Quaternary sedimentary units. (e) Foliated clay-rich cataclasite indicating sinistral displacement in the Terreros Fault. (f) Foliated breccia with quartz porphyroclasts indicating dextral shearing along the Villaricos Fault.


a
uppermost Messinian-Pliocene
S-N
Bedding
unconformities
Fault gouge
b
E-W
Glacis IV
(middle Pleistocene)
Glacis IV
marly clays
(Messinian)
Silts, silty-marls
(Tortonian)
0 1m
c
N-S
Bedding
Messinian marls
Uppermost Tortonian
temperate carbonate
submarine fans
d
Middle Pleistocene Glacis
W-E
Upper Tortonian
mineralised
silts
Herrerías fault
Messinian clays
Messinian erosive unconformity
Pliocene marly silts
Old mine
fillings
Barite mineralisation
Uppermost Tortonian
temperate carbonates
replaced by barite and hematite
e
S-N
f
SW-NE

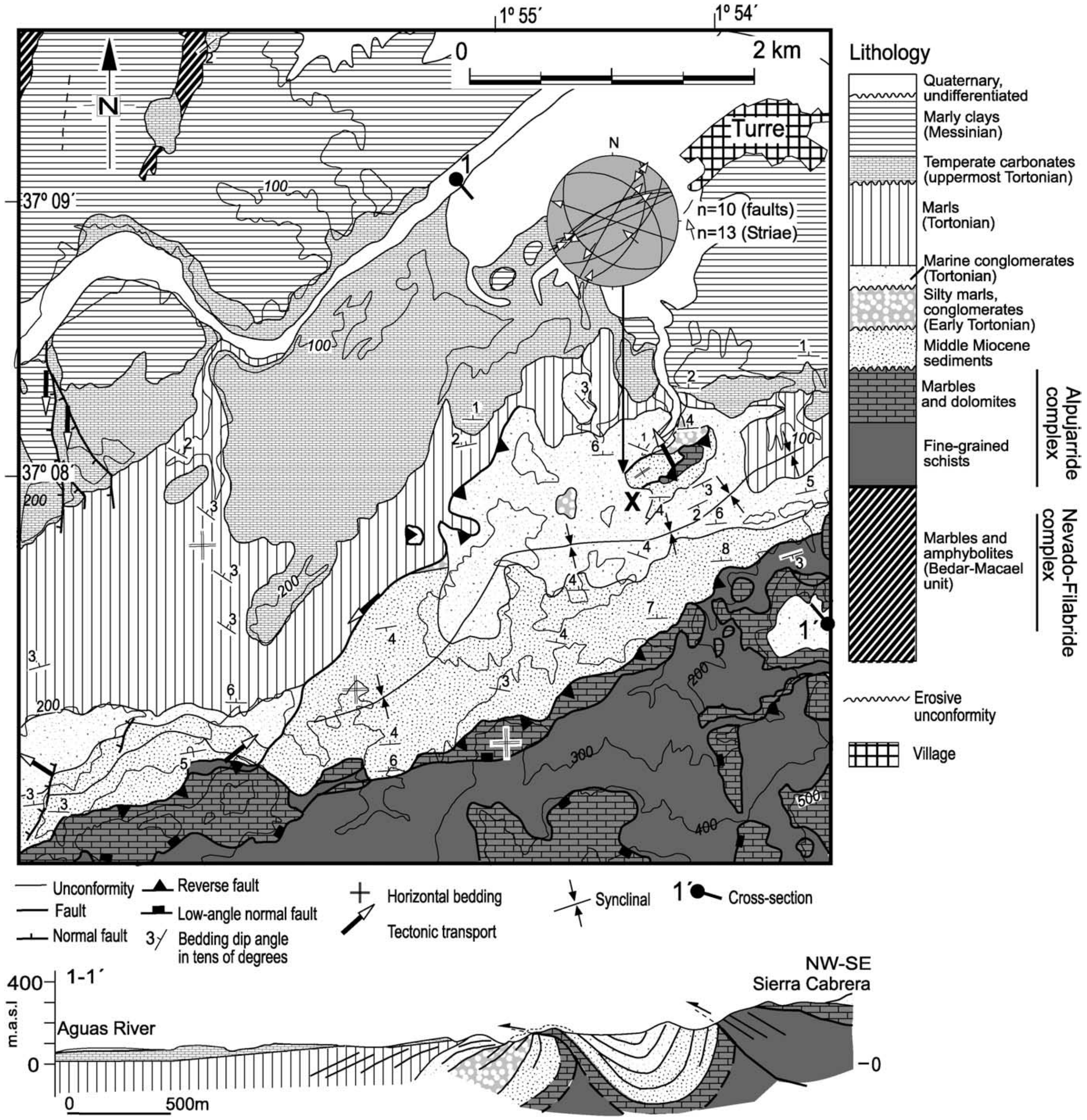


Fig. 6. Geological map and cross-section of the northern limb of the Sierra Cabrera anticline (see location in Fig. 1). Stereoplot represents structures found in locality X on the geological map. Equal-angle lower-hemisphere projection.

This strand shows a complex geometry, being highly segmented in short faults, sometimes only 1 km long. We have divided it into southern, central and northern zones. The southern zone is represented by the Arteal fault (A in Fig. 1). This fault strikes N10°E and dips 45–60° to the west with striae plunging 15–25° to the south, thus having a sinistral-normal regime that has produced tectonic subsidence on the western block (Figs. 2 and 3). Towards the north, the Arteal fault curves to a N30°E orientation. The Arteal fault separates Pliocene marine sediments on its western block from metamorphic schists in the Sierra Almagrera (Figs. 2 and 3). Locally, it is sealed by upper Pleistocene alluvial cones. Quaternary activity along this fault segment seems to have controlled the deposition of a thick sedimentary Quaternary sequence near the mouth of the Almanzora River (Booth-Rea et al., 2003a), as well as the deflection of this river towards the south (Figs. 1 and 2).

The central zone (B in Fig. 1) is strongly segmented with both dilational and antidilational jogs. Normal faults in the dilational jogs have a N140°–160°E strike. The antidilational jogs are formed by en-échelon SE-dipping oblique-reverse faults, linked by sinistral NNW/SSE-oriented faults or by dextral-oblique fault segments with a WNW/ESE strike. These segments cut Pliocene sediments and are mostly sealed by Quaternary alluvial deposits. Locally, some dextral and normal fault segments cut the drainage pattern, thus being probably active.

The northern zone (C in Fig. 1) bounds the Sierra de los Pinos and Sierra Almenara (Fig. 1), being formed by mostly oblique-reverse fault segments (Larouziere and Ott d'Estevou, 1990; Silva et al., 1993). Other smaller fault segments are found between the Palomares fault segment and the Arteal fault, such as the Herrerías fault (Fig. 2), which has a sinistral-inverse regime. The Herrerías fault cuts upper Pleistocene conglomerates (Glacis IV of Wenzens and Wenzens (1995)) and has a total displacement of approximately 150 m (striae plunge 20–26° to the north); its total throw is 60 m, although the Pleistocene glacis is displaced only a few meters (Fig. 5b and d).

The Arteal fault and other similar ones, like the Terreros fault to the east of Sierra Almagrera (Fig. 1), enter the Mediterranean Sea, clearly cutting the Sierra Cabrera anticline and displacing it towards the north (Fig. 1; Booth-Rea et al., 2002b). The total displacement of the Sierra Cabrera anticline along the PFZ is approximately 16 km. East of Sierra Almagrera, the displacement along the sinistral Terreros fault is approximately 23 km (cut-off lines used for estimating these displacements are the intersections between the faults and the contact between the Alpujarride and Nevado–Filabride complexes, traces G, G′, and G″ in Fig. 1).

Most of the fault-rocks found along the PFZ are highly comminuted clay-rich foliated cataclasites with brittle S–C structures (Fig. 5e and f), indicating that slip along these fault segments has been mostly aseismic. Nevertheless, we have found locally both in the Palomares and Arteal fault segments structures indicative of coseismic activity, such as implosive mineralised breccias (Fig. 7a) and clastic dikes intruding upper Pleistocene beach sediments (Fig. 7f and g). Montenat et al. (1987) described exploded pebbles in Tortonian sediments as evidence of coseismic activity.

4. Structures accommodating the PFZ displacement

The geometry and stratigraphic architecture of the Vera basin is not only determined by the PFZ. In addition, other structures coeval to this fault zone played an important role in the general NNW/SSE-shortening context during the upper Neogene and Quaternary. We describe in this section the most important structures accommodating the sinistral displacement produced along the PFZ, which also influence the topography and the drainage pattern in the southeastern Betics.

4.1. Dextral faults

Several WNW/ESE-oriented dextral faults outcrop along the PFZ. These are interpreted as conjugate structures of the main sinistral PFZ. The most important dextral fault segment is found west of Garrucha (Fig. 1 and locality Z in Fig. 4), forming the southern boundary of a Plio-Quaternary sedimentary depocentre. This fault has a N110°E strike and a dextral-normal regime; it seems to join a dextral-reverse E/W-oriented fault (North-Filabres fault) that cuts the northern limb of the Sierra de Filabres anticline (Fig. 1). The North-Filabres fault produces 70 m of differential uplift between two nearby outcrops of upper-Pliocene conglomerates found west of Vera. Messinian marls are locally inverted and show an internal angular unconformity in the northern limb of the Sierra de Filabres antiform (Barragán, 1997). Thus, the North-Filabres fault has been active at least from the Messinian to the Quaternary.

4.2. Normal faults

Normal faults with N160°–150°E orientation link most of the en-échelon PFZ segments that bound the Sierra Almagrera and Sierra de los Pinos reliefs (Fig. 1). These faults compartmentalize the eastern sedimentary depocentre located between the Arteal and the Palomares faults (Fig. 8). The thickness distribution of upper Pliocene to Quaternary sediments found in this depocentre shows NW/SE-oriented subdepocentres, bounded by these normal and normal-dextral faults (Booth-Rea et al., 2003a). Thus, these faults contributed to the tectonic subsidence registered in the eastern Palomares depocentre during the Plio-Quaternary.

4.3. Reverse faults

The southern segments of the Palomares fault, located west of Garrucha (Fig. 4), do not cut the anticline structure of Sierra Cabrera. They merge with reverse faults found in the northern limb of this anticline, thus accommodating part of their displacement with uplift and folding of Sierra Cabrera (Figs. 4 and 6).

Reverse faults found at the northern mountain front of the Sierra Cabrera mostly show N–S and NW–SE transport, overriding the metamorphic basement onto inverted or strongly dipping Middle Miocene and Tortonian sediments (see cross-section 1–1′ in Fig. 3 and Figs. 4, 6 and 7d). North of the present-day mountain front of Sierra Cabrera, thrusting and folding initiated before the upper Tortonian, since upper Tortonian conglomerates seal structures developed by NW/SE shortening, which affect lower Tortonian sediments (see cross-section 1–1′ in Fig. 3 and locality X in Fig. 6). The structures sealed by upper Tortonian sediments (stereoplot in Fig. 6) include thrusts with NW displacement, dextral strike-slip faults with N70°E and N120° orientations

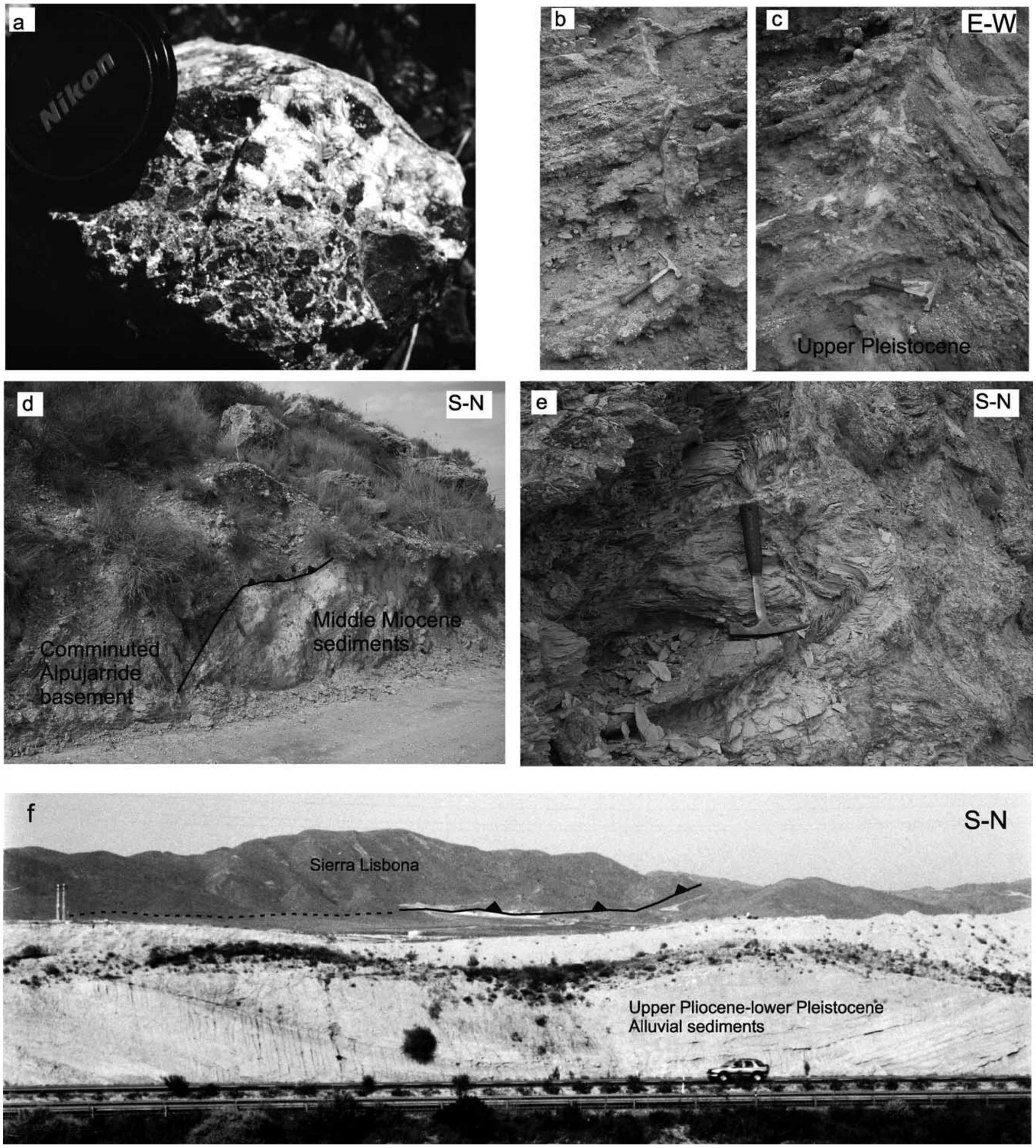


Fig. 7. (a) Implosive breccia found along the Arteal fault segment, formed by schist fragments cemented mostly by barite and hematite. (b) Clastic dike intruding upper Pleistocene beach sediments. (c) Fold formed by fluid escape in upper Pleistocene beach sediments (Garrucha). (d) Comminuted metamorphic basement overriding Middle Miocene sediments in the northern limb of the Sierra Cabrera ridge. (e) Brittle kink folds affecting fine-grained schists in the northern limb of Sierra Cabrera. (f) Gentle fold affecting upper-Pliocene to lower-Pleistocene sediments north of the Sierra Lisbona (see location in Fig. 1).

and helicoidal sinistral N30°E strike-slip to oblique-reverse faults.

North of the area studied, the displacement of the PFZ is accommodated by oblique-reverse faults (Griveaud et al., 1990; Larouziere and Ott d'Estevou, 1990; Silva et al., 1993). Other uplifted areas near the PFZ, like Sierra de Almagro and Sierra Lisbona have reverse faults in their southern and northern mountain fronts (Figs. 1 and 7f).

4.4. Folds

The main folds found in the area of study are shown in

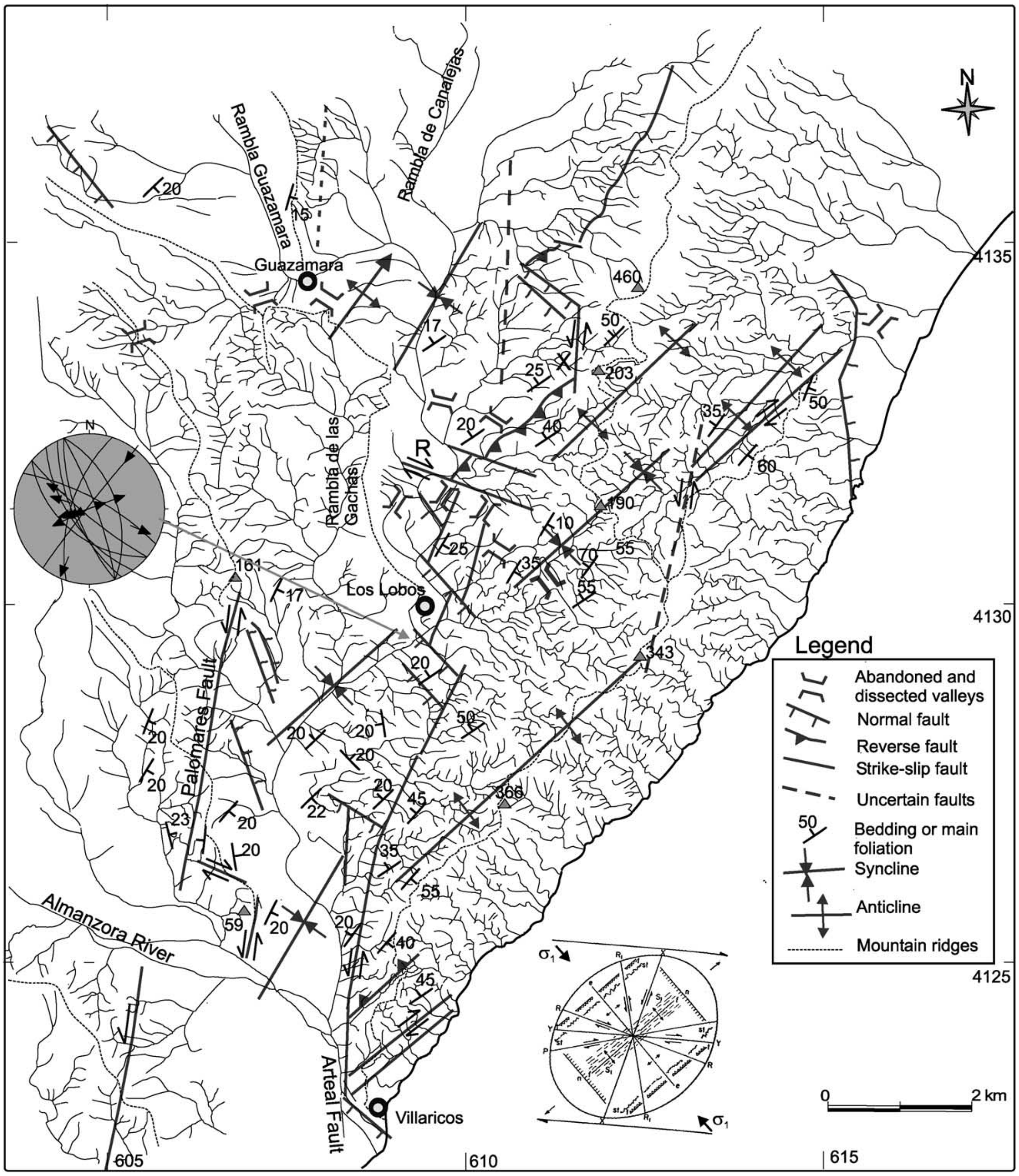


Fig. 8. Detailed drainage pattern of the Sierra Almagrera–Sierra de los Pinos area together with main fault segments and folds associated with the PFZ. Main types of fault segments found near los Lobos are plotted in lower-hemisphere stereographic equal-angle projection. Structures expected under a NNW/SSE-oriented main stress axis are illustrated in the lower right corner.

Fig. 1. The folds defining Sierra Cabrera, Sierra de Filabres and Sierra de Almagro antiformal ridges were mostly formed prior to the PFZ, since they are cut and displaced by the fault zone. However, as discussed above, the upper Tortonian to Messinian uplift of Sierra Cabrera was coeval to the initial activity along the westernmost segments of the PFZ.

En échelon NE/SW-oriented folds affect the upper Pliocene and Pleistocene Glacis within the PFZ (Figs. 4 and 8). Lower Pleistocene Glacis are locally folded by larger E/W-oriented gentle folds, north of Sierra Lisbona (Figs. 1 and 7f). The eastern block of the PFZ (Sierra Almagrera, Sierra de los Pinos and Sierra Almenara) is deformed by slightly asymmetric folds with NE/SW orientation (Figs. 1 and 8), which show a smaller wavelength than the Sierra Cabrera and Sierra de Filabres folds. At the outcrop scale, crenulations associated with these folds are kink-shaped, affecting all of the previous structures, including low-angle brittle extensional shear zones developed during the Middle Miocene extensional tectonics (Fig. 7e). They are oriented E/W in the northern limb of Sierra Cabrera and NE/SW in Sierra Almagrera.

5. Influences of the PFZ on the present drainage pattern

Since the middle Pleistocene, the drainage pattern in the Vera basin has been similar to the present-day one, showing a great asymmetry with respect to the Rambla de Canalejas axial valley, which is located along the PFZ (Fig. 9). East of the main axial valley, streams are short and mainly oriented NW–SE, i.e. transverse to the PFZ west of the Sierra Almagrera divide and perpendicular to the coastline east of the divide. This consequent drainage pattern reflects the recent uplift of the Sierra Almagrera. West of the main axial valley, the drainage pattern is more complex: (1) streams are longer, (2) drainage density is lower, and (3) streams describe eastward directed deflections, many of them at 90° (Fig. 9). All these features suggest that the drainage is older in the western block of the PFZ. Particularly, the eastward deflections seem to indicate the progressive eastward migration of the main axial valley during the PFZ activity. The most important stream in this area is the Almanzora River, which shows a southward directed deflection near its mouth, probably induced by the southern termination of the PFZ (Figs. 8 and 9). The drainage pattern is cut by active fault segments only locally, as in the Rambla de Canalejas, where a dextral deflection related to a N110°E oriented dextral fault is observed (Fault R in Fig. 8).

Lower Pleistocene uplift of the Sierra de Almagro (Fig. 1) and SE-directed tilting of the sedimentary cover in the western block of the PFZ (Wenzens and Wenzens, 1997) favoured headward erosion towards the NW of NW/SE-oriented streams (Rambla de Guazamara, Rambla de García, Rambla de las Norias; Fig. 9). The headward erosion of these streams captured a lower Pleistocene river that had deeply incised the western slope of Sierra de Almagro with an average N–S orientation. This lower Pleistocene river presently forms a deeply incised meandering dry valley (lower-Pleistocene palaeo-valley and Rambla de las Gachas; Fig. 9). Further shortening warped the middle Pleistocene Glacis near the locality of Guazamara (Fig. 8), deflecting the Rambla de Guazamara towards the NE, around the gentle anticlinal nose defined by this Glacis (Fig. 8).

The drainage pattern in the mountain ranges located between the PFZ and the Terreros Fault (Sierra Almagrera, Sierra de los Pinos; Fig. 1) is formed mostly by NW/SE-oriented streams that drain towards NE/SW axial valleys (Rambla del Esparto; Fig. 9). This orientation of the drainage pattern reflects the general NW/SE-shortening

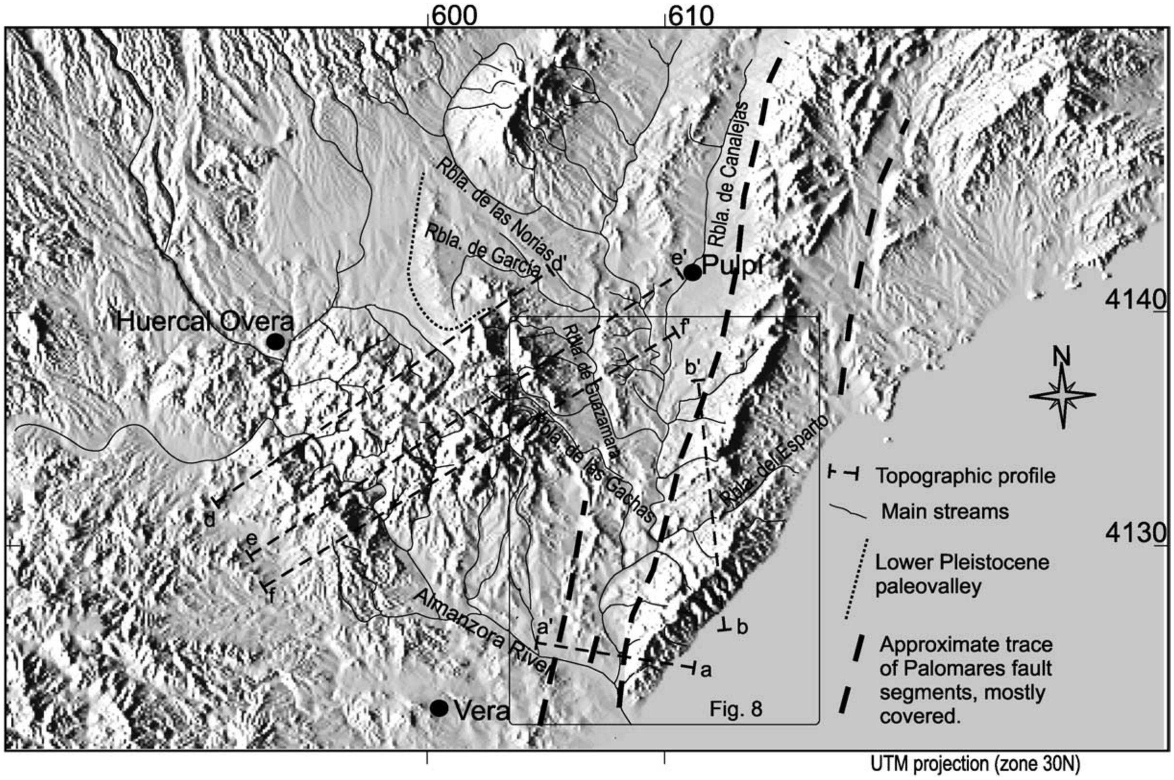


Fig. 9. DEM of the PFZ area with the main streams.

direction in this area. Locally, the NW/SE-oriented streams have been captured by headward erosion of NE/SW-oriented streams (e.g. east of los Lobos; Fig. 8). This NE-directed headward erosion is related to activity along normal and dextral faults that segment the western mountain front of Sierra Almagrera near los Lobos (Fig. 8).

The most recent stream development occurs in the lower portion of the Rambla de las Gachas (Figs. 8 and 9), which shows a N/S orientation and is presently advancing northwards by headward erosion towards the Rambla de Guazamara. At present, the Rambla de las Gachas is just a few hundred metres away from capturing the Rambla de Guazamara near the locality of Guazamara (Fig. 8). Holocene reactivation of N/S-oriented drainage in the western block of the PFZ is probably related to faulting along the Arteal fault segment and lowering of the local base-level at its southern termination.

In summary, the main streams in this region are dominantly controlled by the general NW/SE shortening and by the NNE–SSW orientation of the PFZ, while some of the minor streams are controlled by segmentation of the PFZ.

6. Topography and relative uplift rates

Topography in this area is controlled by tectonic activity. The ridges coincide with antiforms and uplifted blocks bounded by segments of the PFZ. We have estimated relative uplift rates (U) for the most prominent mountain ranges and compared the altitude above present sea level of reference surfaces (R) with known age (A), such as uppermost Tortonian–lowermost Messinian temperate platform sediments (Azagador Member) and Lower Pliocene shallow platform sediments. U is simply obtained as R/A. In our calculations, we have not taken into account eustatic sea-level changes, which are negligible for the Azagador Member, since the global sea level was only 5 m lower than today (Hardenbol et al., 1998). The error would be larger for Lower Pliocene deposits, which include the highstand of the TB3.4 cycle of Haq et al. (1987) with a highest sea level some 90 m above the present-day level (Hardenbol et al., 1998). However, the uncertainty on the age of these deposits together with the palaeobathymetry error (± 30 m in the case of inner-platform deposits), are of the same order of magnitude as the eustatic sea-level oscillation. The main error in the uplift rates is associated with the absolute age value attributed to the sedimentary reference surfaces. An age of 7.2 ± 0.2 Ma has been used for the Azagador Member, following Braga et al. (2003). Absolute ages for Lower Pliocene platform carbonates are between 5.2 and 3.6 Ma (Aguirre, 1998). Finally, we have used an absolute age of 3.3 Ma for conglomerates deposited during the Early to Late Pliocene transition, representing the end of the marine sedimentation in the Vera basin (Barragán, 1997).

For the Sierra Almagrera, we have used the geometry, kinematics and vertical throw of the Arteal fault to calculate fault displacement rates. The depth of the top of the basement in the eastern Palomares depocentre is known from drill-cores (Booth-Rea et al., 2003a). In this area, the Pliocene sediments directly rest upon the basement, thus dating the beginning of the uplift of Sierra Almagrera as Early Pliocene. The downdip displacement on the Arteal fault was estimated as the present distance between the top of the basement in both blocks of the Arteal fault, measured along the Arteal fault surface and its projection in the air (Fig. 10a). Thus, considering the Arteal fault as active since the Early Pliocene (5.2 Ma), the dip-slip rate would be approximately 0.12 m/ka (Fig. 10a). As for the lateral displacement, a minimum value is 2400 m, which gives lateral slip rates of approximately 0.46 m/ka. The southern sector of the Sierra Almagrera has minimum uplift rates, without considering erosion, of 0.05–0.07 m/ka since the Early Pliocene (Fig. 10a), while the northern sector (north of Rambla del Esparto; Fig. 9) has uplift rates of 0.06 m/ka since 3.3 Ma (Fig. 10a). Further north, in the Sierra de los Pinos, the uplift rate is between 0.06 and 0.08 m/ka since the Early Pliocene. As for the Sierra de Filabres, uplift rates range from 0.07 m/ka for the southern mountain front (since 7.2 Ma) to 0.11 m/ka for the northern one (since 3.3 Ma). Uplift rates for the eastern end of the Sierra de Filabres and Sierra de los Pinos should be considered as minimum values, since the points used for the calculations do not coincide with the locus of maximum uplift, i.e. the anticlinal hinge-zones (Fig. 10b and c).

Uplift rates for the Sierra de Almagro, located NW of the PFZ (Fig. 1), were estimated by means of the differential incision measured between two transverse drainage systems: the present-day Almanzora River and the lower Pleistocene dry-valley found in the western flank of the Sierra de Almagro. Since abandonment of the lower Pleistocene palaeoriver, the Almanzora River has incised approximately 235 m in response to uplift of the Sierra de Almagro. Thus, relative uplift rates are between 0.28 and 0.14 m/ka, depending on the age assumed for the abandonment of the river (1.6–0.84 Ma) (Fig. 10d–f). These uplift rates are similar to the ones calculated for other nearby areas, such as the western Sorbas and eastern Vera basins (0.07–0.1 m/ka; Braga et al., 2003), the Cope basin east of the Terreros fault (0.15 m/ka; Bardají et al., 1990), and the whole southeastern Betics (0.15–0.08 m/ka; Silva et al., 2003).

7. Discussion and conclusions

The PFZ has been active from the Tortonian to the Quaternary, accommodating part of the NNW–SSE convergence between Africa and Iberia. During this period the Betics have acquired their present configuration with basins and ranges separated by both normal and strike-slip faults. During the Pliocene, the PFZ activity migrated

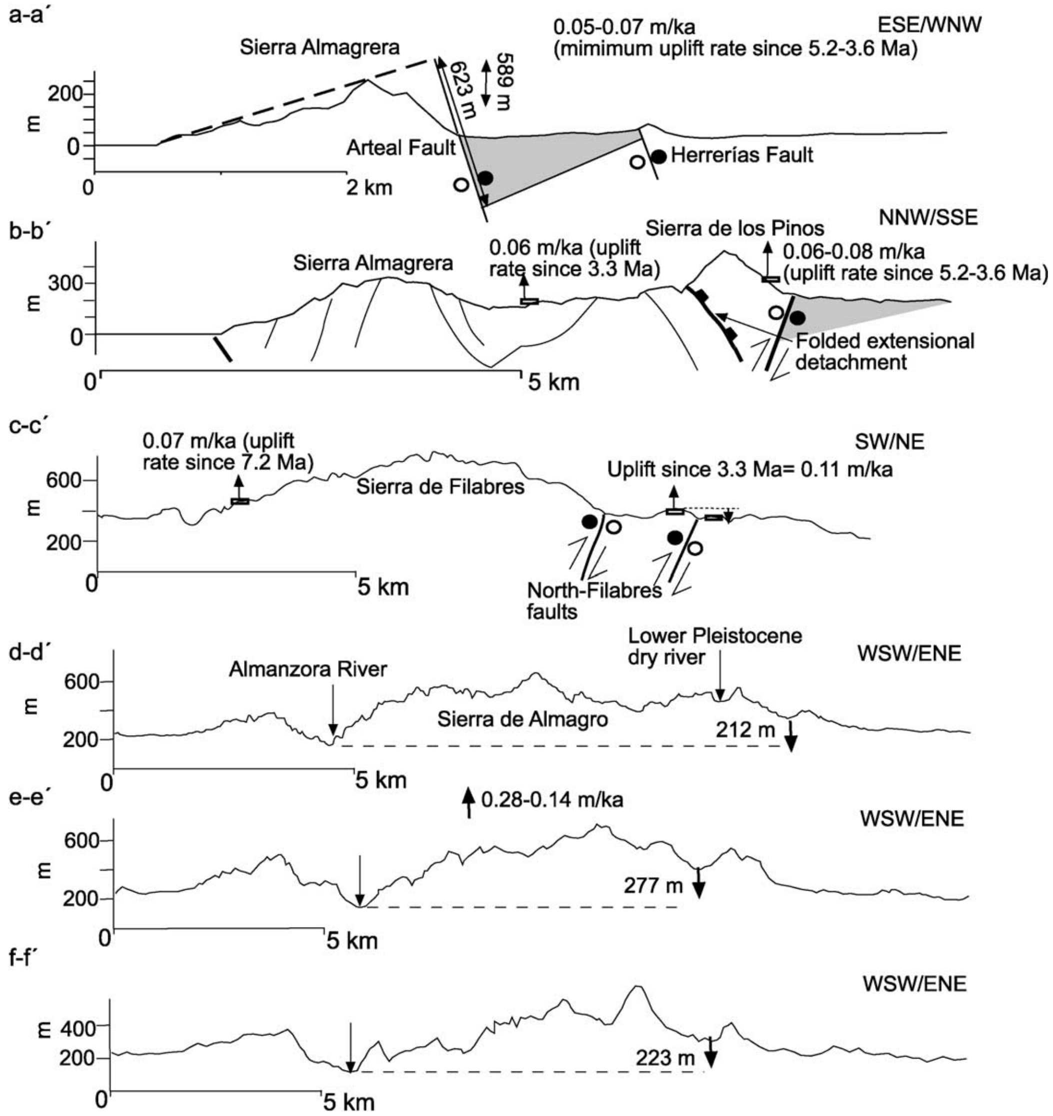


Fig. 10. Topographic profiles and relative uplift rates of ranges associated with the PFZ. Profiles a–a′, b–b′ and d–d′ to f–f′ are located in Fig. 9, and profile c–c′ in Fig. 1. (a) Profile across the Arteal fault in southern Sierra Almagrera. (b) Profile across Sierra Almagrera and Sierra de los Pinos, perpendicular to the main fold axes. (c) Profile across the eastern Sierra de Filabres anticlinal ridge, cutting dextral-inverse fault segments that have accommodated Messinian to Quaternary NNW/SSE shortening. (d)–(f) Profiles parallel to the Sierra de Almagro anticlinal ridge, cutting two transverse drainage systems, the Almanzora River and a palaeoriver dissected and abandoned in the early Pleistocene.

eastward forming the segments bounding the Sierras Almagrera, Los Pinos and Almenara. The most important fault segment in this period is the Arteal fault, which bounds the Sierra Almagrera to the west. During the Quaternary, the activity of the PFZ has continued on the eastern segments. These segments influence the geometry of the drainage pattern and determine the position and geometry of the main Quaternary sedimentary depocentre, found at the mouth of the Almanzora River. The Quaternary faulting was accompanied by increasing relief in the eastern uplifted block of the PFZ (Sierra Almagrera, Sierra de los Pinos and Sierra Almenara).

The Pliocene eastward widening and lengthening of the PFZ cut and rotated late Tortonian folds, propagating the deformation outwards towards other structures such as the Carboneras fault to the south and the reverse fault that bounds the Sierra Almenara to the north. Moreover, the folds were tightened in the Sierras Almagrera, de los Pinos and Almenara during the Plio-Quaternary activity of the PFZ. As for the rotation of previous folds, Messinian volcanic rocks outcropping near Garrucha have suffered rotations of 48° counter-clockwise, according to palaeomagnetic data (Calvo et al., 1997). Lengthening of the PFZ linked oblique-slip faults that were originally separated, increasing the total length of the strike-slip system.

The structural data presented here suggest that the general Neogene–Quaternary NNW–SSE shortening has been accommodated by reverse and strike-slip faults, as well as folds, this deformation being distributed in a widespread area. In previous works (e.g. Silva et al., 1993) the eastern block of the PFZ has been interpreted as a rigid indentor. In contrast, we suggest that this thin crust segment (22–24 km thick according to Banda and Ansorge (1980)) is largely penetrated by deformation. In our view, the PFZ separates blocks with different structural style, developed coeval to the fault activity. Thus, the PFZ has acted as a transfer fault since the late Tortonian.

The most prominent feature of the Quaternary activity along the PFZ is reflected by the topography and the drainage pattern. The topographic configuration consists of a central elongated depressed area bounded by the eastern and western segments of the PFZ. East of this central depression, several mountain ranges (Sierras Almagrera, de los Pinos and Almenara) define a sharp mountain front coincident with the eastern segments of the PFZ. West of the central depression, the topographic expression of the PFZ activity is not very prominent. The mountain ranges here (Sierra Cabrera, Sierra de Almagro, Sierra Lisbona, eastern end of Sierra de Filabres) are oblique to the PFZ and bounded by reverse faults. The location of a sharp mountain front coincident and parallel to the eastern segments of the PFZ is in accordance with an eastward Plio-Quaternary migration of the fault activity, as also suggested by along-time sedimentary depocentre configuration (Booth-Rea et al., 2003a). The consequent drainage pattern in the uplifted fault block reflects the recent uplift as a consequence of NNW/SSE shortening in the Eastern Betics (Fig. 11). In the subsiding fault block the drainage pattern is more complex suggesting that the streams are older. Particularly, the eastward deflections seem to indicate the progressive eastward migration of the main axial valley coeval to the activity of the eastern segments of the PFZ. Segmentation along the PFZ also controls the drainage pattern, generally by two different processes. First, by lowering local base levels in the downthrown blocks at the proximity of the faults, and second, by directly cutting and displacing channels, resulting in the formation of wind gaps in the uplifted fault blocks (Fig. 11). NE–SW oriented dry valleys were formed by the first process, with streams transverse to active fault segments dissecting by headward erosion the consequent drainage of the uplifted fault blocks (Figs. 8 and 11). WNW–ESE dextral-oblique fault segments have locally cut streams, generating wind gaps in the uplifted fault blocks (Fig. 11).

Despite the main component along the PFZ being subhorizontal, important local reliefs between topographic ridges and subsiding sectors are attributed to the fault activity. Therefore, Pliocene to present-day uplift rates in this area are strongly controlled by recent tectonic activity. Uplift rates in the ranges bounded by the Plio-Quaternary eastern segments of the PFZ are between 0.05 and 0.08 m/ka (Sierra Almagrera). These rates are lower than the 0.17–0.18 m/ka estimated for the Sierras Cabrera and Alhamilla (Braga et al., 2003), located in the western block of the PFZ. These higher uplift rates accord well with the higher altitudes reached by Sierra Cabrera and Sierra Alhamilla (960 and 1387 m, respectively) compared with Sierra Almagrera (367 m) and most probably are the result of both the formation of antiformal ridges and the reverse faulting along the northern mountain fronts of these Sierras. Consequently, the variation in the uplift rates at both sides of the PFZ can be explained by strain partitioning between the eastern block dominated by strike-slip faulting (Sierra Almagrera) and the western block dominated by folding and reverse faulting (Sierra Cabrera). The Sierra de Almagro, also located in the western block of the PFZ, shows uplift rates between 0.28 and 0.14 m/ka, which are significantly higher than the ones in the eastern block. This fact can be related to strain partitioning, as in the case of the Sierra Cabrera, i.e. reverse faulting along the southern mountain front of Sierra de Almagro versus strike-slip faulting in Sierra Almagrera.

The uplift rates obtained here are relatively low for a tectonically active region with seismicity and high local relief. Regional uplift rates in the central Betics (western part of Sierra Nevada), in a context dominated by normal faulting and folding (Martínez-Martínez et al., 2002), are higher (0.2 m/ka since the Tortonian; Braga et al., 2003) than the ones obtained here in the eastern Betics, in a scenario dominated by transcurrent movements. Uplift rates in other classical examples of strike-slip fault zones, such as the Alpine fault in New Zealand (Nicol and Van Dissen, 2002), the Mérida Andes (Audemard, 2003) and SE Iran (Walker and Jackson, 2002), are generally one order of magnitude higher than in the eastern Betics (PFZ). Nevertheless, these relatively low uplift rates are quite reasonable in a context such as the one described here with a slow convergence rate between Africa and stable Eurasia (at most a few mm/yr; Meghraoui et al., 1996; Silver et al., 1998) and dominated by strike-slip faulting.

Present-day uplift rates in the eastern Betics have been recently estimated from levelling data (Giménez et al., 2000), obtaining results sensibly higher than the ones obtained from geological data and periods of several millions of years. According to the geodetic measurements, the PFZ does not show any significant uplift for the period 1934–1976. This fact contrasts with the presence of historical seismicity along the PFZ (Mezcua and Martínez Solares, 1983), which probably means that the activity of the fault is characterized by long periods of quiescence followed by short periods of activity associated with earthquakes.

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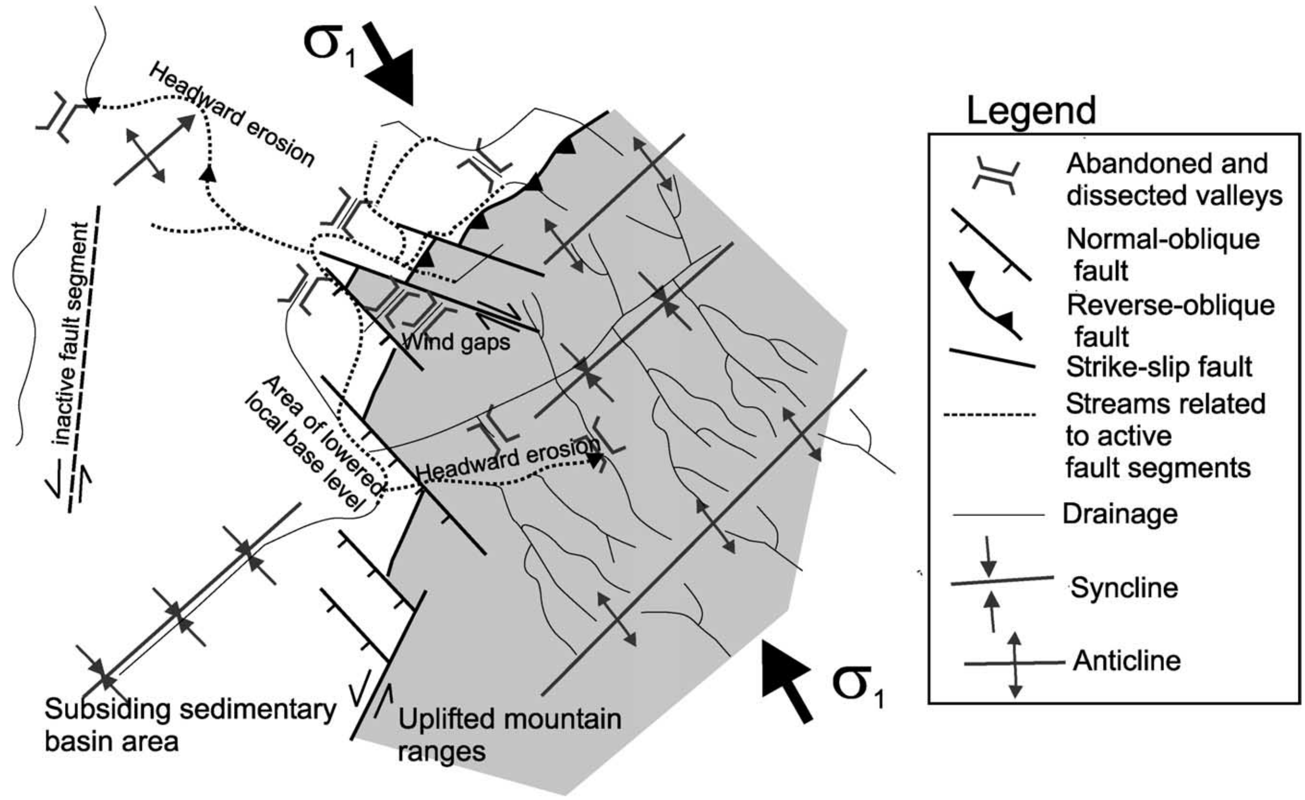

Fig. 11. Sketch showing the evolution of the drainage pattern due to the influence of the activity along the fault segments of the PFZ. See text for further explanations.

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