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Stress field variation related to fault interaction in a reverse oblique-slip fault: the Alhama de Murcia fault, Betic Cordillera, Spain

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Abstract

The interpretation of kinematic data from microstructural observations has led many authors to propose a complex dynamic development for the eastern Betic Cordillera from the Late Miocene to the present in which different—and sometimes contradictory—stress fields explain the generation of the same structures. The main aim of this work is to determine whether the dynamic variability of the study area, observed during the neotectonic period, is coherent with a single regional stress field. The structure of the area was analysed through the detailed mapping of the Alhama de Murcia fault (AMF) and the associated structures. Further, microtectonic data from shear veins in an interaction zone between the main and secondary faults were studied by the stress inversion method of Reches [Tectonics 6 (1987) 849]. A hierarchy is proposed for stress fields and their interpretation with respect to the interaction between structures of different scales. Relative movements of fault-bounded blocks with different sizes produce this hierarchy. These movements depend on boundary conditions of blocks and their position relative to the Alhama fault zone. The study shows that adequate cartography and understanding the context of micro- and mesotectonic data is necessary for determining the dynamic significance of microtectonic data. The use of stress inversion methods without taking the local tectonic context into consideration can give rise to incorrect interpretations, incorrect processing of previous data, and extrapolations inappropriate at other scales.

Keywords: Stress fields; Betic Cordillera; Alhama de Murcia fault; Stress inversion; Neotectonics

1. Introduction

Since the 1970s, numerous micro- and meso-tectonic studies have been undertaken in many geodynamic environments in order to understand the local and the far field stress actives in each area. Some of these studies conclude that the orientation of palaeostresses and current tectonic stresses acting at a given point of the upper crust are largely controlled by local structures (Mattauer and Mercier, 1980; Taha, 1986; Pollard and Segall, 1987; Rebaï, 1988; Mandl, 1988; Hardebeck and Hauksson, 1999). Rebaï et al. (1992)

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mapped the trajectories of current stresses in the geodynamic environment of the Mediterranean. In certain fault zones, with good kinematic features, they studied trajectory changes at different scales and came to the conclusion that "the stress field at a given scale is consistent with geological structures at the same scale and is not necessarily compatible with the kinematics of surrounding, smaller scale faults. This means that the faults and heterogeneities at a given scale are associated with stress deviations of the same scale". Nevertheless, there are still many studies that employ stress inversion methods to obtain the active stress field at regional scale, and use local field data without sufficiently considering their structural context.

As in other parts of the Alpine belt, numerous structural studies have been performed in the southeast of the Betic Cordillera on the deformation occurring from Late Miocene to Present (neotectonic period) (see previous data section below). One of the main purposes has been the identification of the stress fields that generated the high-angle faults active from the Late Miocene. These faults control the main morphotectonic features of the area and produce most of the seismic activity.

The structural data used in previous studies can be classified into four main groups: (a) those from geological and structural maps, (b) data from the use of stress inversion methods applied to microtectonic structures on fault planes, (c) kinematic and dynamic analyses of fragile and ductile deformation structures affecting recent rocks, and (d) tectono-sedimentary features observed in deposits close to the margin of the fault-driven Miocene basins.

The interpretation of these data has led many authors to propose a complex dynamic development

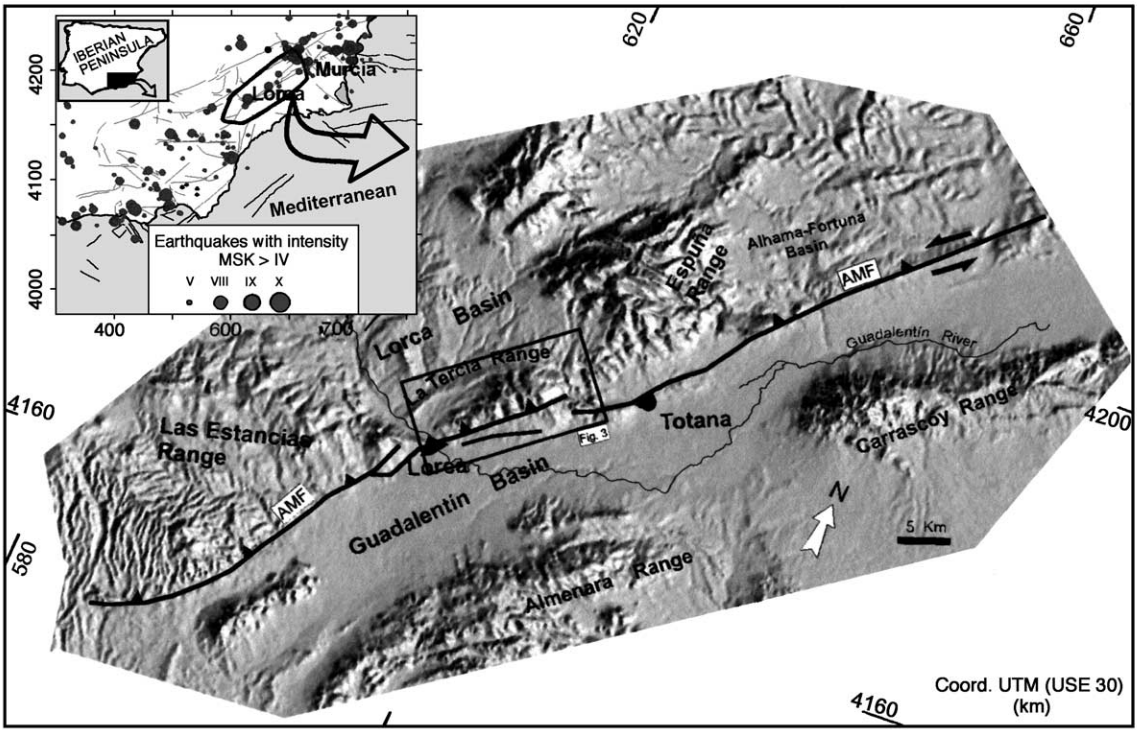


Fig. 1. Morphotectonic of the Alhama de Murcia Fault area. Upper left: location map of the SE Iberian Peninsula with the epicentres of the earthquakes (data from Instituto Geográfico Nacional). The digital elevation model shows the trace of the Alhama de Murcia Fault (AMF) and the morphotectonic units (basins and ranges) related with its recent activity. The area mapped in this study (see Fig. 3) is pointed out by the square.

in which different—and sometimes contradictory—stress fields explain the generation of the same structures (e.g. Larouzière et al., 1987; Montenat and Ott d'Estevou, 1996). This has been reflected in the conclusions of earlier papers on the neotectonics of the study area based on the use of different local structural data. Though the majority of these data are unquestionable, they lead to different dynamic interpretations since they are of different characteristics and scale, and vary in location.

This paper presents a structural study of the Alhama de Murcia fault (Fig. 1), an oblique-slip (reverse-strike–slip) fault active during the Neogene and the Quaternary in the eastern Betic Cordillera (Southern Spain), close to the area where the Eurasian and African plates converge (Dewey et al., 1973). The convergence direction is NNW–SSE, with a relative velocity of between 4 and 5 mm/year (Argus et al., 1989; DeMets et al., 1990). The direction of convergence has remained constant for at least the last 9 million years (Late Miocene–present), as inferred from plate kinematics (Dewey et al., 1989), and from the analysis of palaeostresses and the focal mechanisms of earthquakes (Galindo-Zaldívar et al., 1993; Herráiz et al., 2000).

The main aim of this study is to determine whether the dynamic complexity of the study area, observed during the neotectonic period and described in earlier papers, is consistent with a single regional stress field. This evaluation requires precise knowledge of the structure of the area at different scales to avoid erroneous extrapolations.

The kinematic and dynamic data available for the study zone were studied. The structure of the area was then analysed through the detailed mapping of the Alhama de Murcia fault and the structures around it. Further, microtectonic data from shear veins in an interaction zone between the main and secondary faults were studied by the stress inversion method of Reches (1987). A hierarchy is proposed for the stress fields and their interpretation with respect to the interaction between structures of different scale.

Throughout the study, only deformation in late Tortonian or younger rocks were considered, i.e. those generated within the constant NNW–SSE convergence of the Eurasian and African plates.

2. The Alhama de Murcia fault. Tectonic setting and previous dynamic and kinematic interpretations

The study area is located in the Internal Zones of the Betic Cordillera (Fig. 1), commonly referred to as the Alborán Domain (Balanyá and García Dueñas, 1987). This area is composed of Paleozoic, Mesozoic and Paleogene rocks, which developed as a thrust stack during the Alpine Orogen (Egeler and Simon, 1969). The Alboran domain has been interpreted as belonging to the formerly Alpine Orogene that was a continuous structure along the Betics, Northwest Africa, and Western Alps during Cretaceous–Neogene. The thrust contacts between the major tectonic complexes (Nevado-filábride, Alpujárride and Maláguide) were interpreted to be reactivated as low-angle normal faults under regional extensional tectonics (Aldaya et al., 1991; García-Dueñas et al., 1992; Galindo-Zaldívar et al., 1989; Jabaloy et al., 1993). Martínez-Martínez and Azañón (1997) inferred two nearly orthogonal trend extension episodes from the Burdigalian to the Serravalian. After this process the neotectonic period (the last 9 Ma) started and a compressional stress field with a NNW–SSE shortening direction was inferred to be established. Deformation in this stress field formed the high-angle (strike–slip, normal and reverse) faults active from the Late Miocene to the Present. One of these faults is the Alhama de Murcia fault.

The Alhama de Murcia fault (AMF) (Bousquet and Montenat, 1974) is a NE–SW (ranging from N 45° to 65°) oblique-slip (reverse-sinistral) fault up to 100 km long. This fault forms the boundary of the Guadalentín depression to the northwest (Fig. 1). The reverse and left-lateral strike–slip movement of this fault has controlled the development of the Lorca and Alhama–Fortuna Neogene basins from the late Miocene to the Quaternary (Montenat et al., 1987, 1990; Ott d'Estevou and Montenat, 1985). These basins were inferred to have formed during an extensional phase in the Middle–Late Miocene. Since the Tortonian, a compressive tectonic regime resulting in tectonic inversion (Armijo, 1977) that triggered the uplift of the Lorca basin to the NW of the Alhama de Murcia fault, and the formation of the River Guadelentín basin to the southeast has been interpreted.

The many papers on the tectonics and structure of the Alhama de Murcia fault and its surroundings since the 1970s have identified a complex spatial and temporal distribution of the stress fields active from the Middle Miocene to the present. Bousquet and Phillip (1976b) identified post-Pliocene horizontal shortening directions varying from NW–SE to NE–SW. Later, Armijo (1977) performed a stress inversion analysis of the Lorca–Totana sector in post-Middle Miocene materials using slickensides measured on fault planes. He interpreted an evolution of the stress field including extensional up to the Messinian, then compressive with a NE–SW to NNE–SSW Shmax direction during the Late Pliocene (Fig. 2). In this scenario, the Alhama de Murcia fault acts as a sinistral strike–slip boundary. Finally, during the Quaternary, a compressive field was interpreted with NNW–SSE horizontal shortening (Shmax), which induced a progressive blocking of the wrenching movement of the Alhama fault, and an increase in its reverse movement component. Armijo (1977) identified this dual mode in horizontal shortening direction from analysis of macro- and microstructures in the interior of the Lorca–Totana corridor. In the area of the Sierra de Tercia, which lies to the north of the corridor, a single NW–SE shortening direction was identified.

From the 1970s, several French authors performed neotectonic and tectono-sedimentary studies on the Alhama fault and the nearby Neogene basins (Bousquet et al., 1975; Bousquet and Phillip, 1976a,b; Montenat et al., 1987, 1990; Ott d'Estevou and Montenat, 1985). These studies also interpreted a paleostress field evolution, with two rotations in the Shmax direction between NNW–SSE and NNE–SSW. These rotations were inferred to result in changes in the type of movement of major and minor faults. All of these studies were based on the correlation of data at local outcrop scale.

In more recent studies in the Lorca–Totana sector (Martínez Díaz and Hernández Enrile, 1992; Martínez

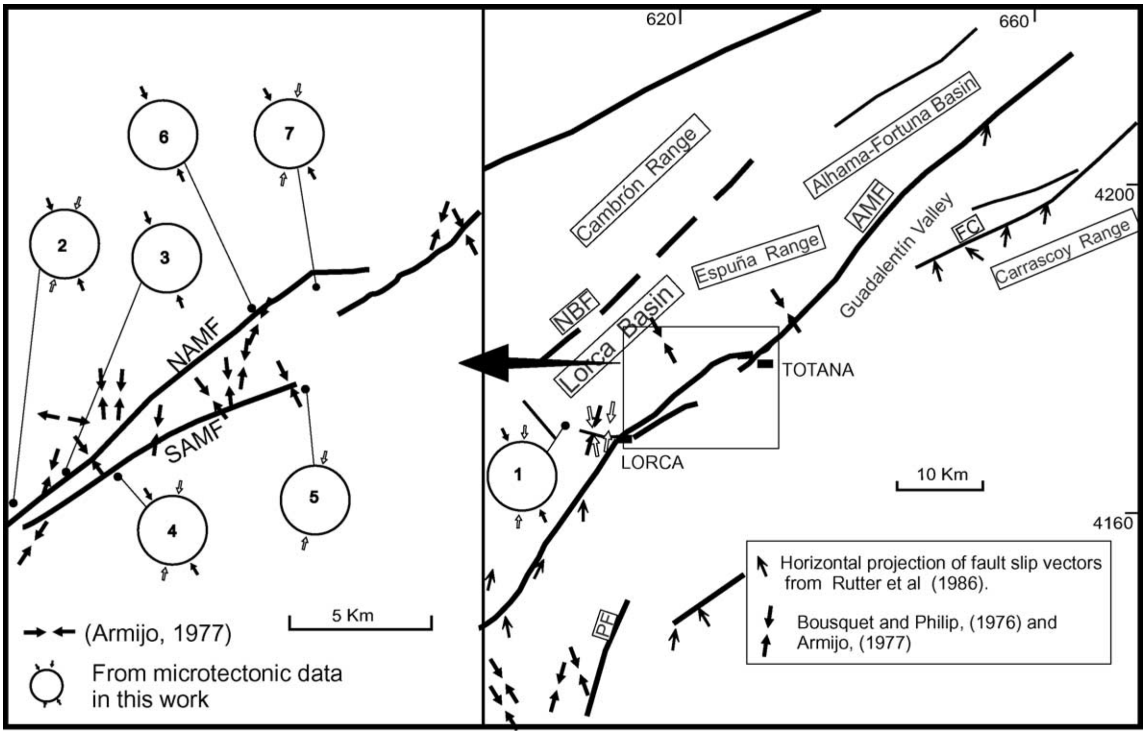


Fig. 2. Horizontal stress orientation and horizontal slip vectors obtained from microtectonic data in Bousquet and Phillip (1976a,b), Armijo (1977) and Rutter et al. (1986) along the Alhama Fault (AMF). Numbers 1 to 7: microtectonic stations shown in Fig. 3. PF: Palomares fault. FC: Carrascoy Fault.

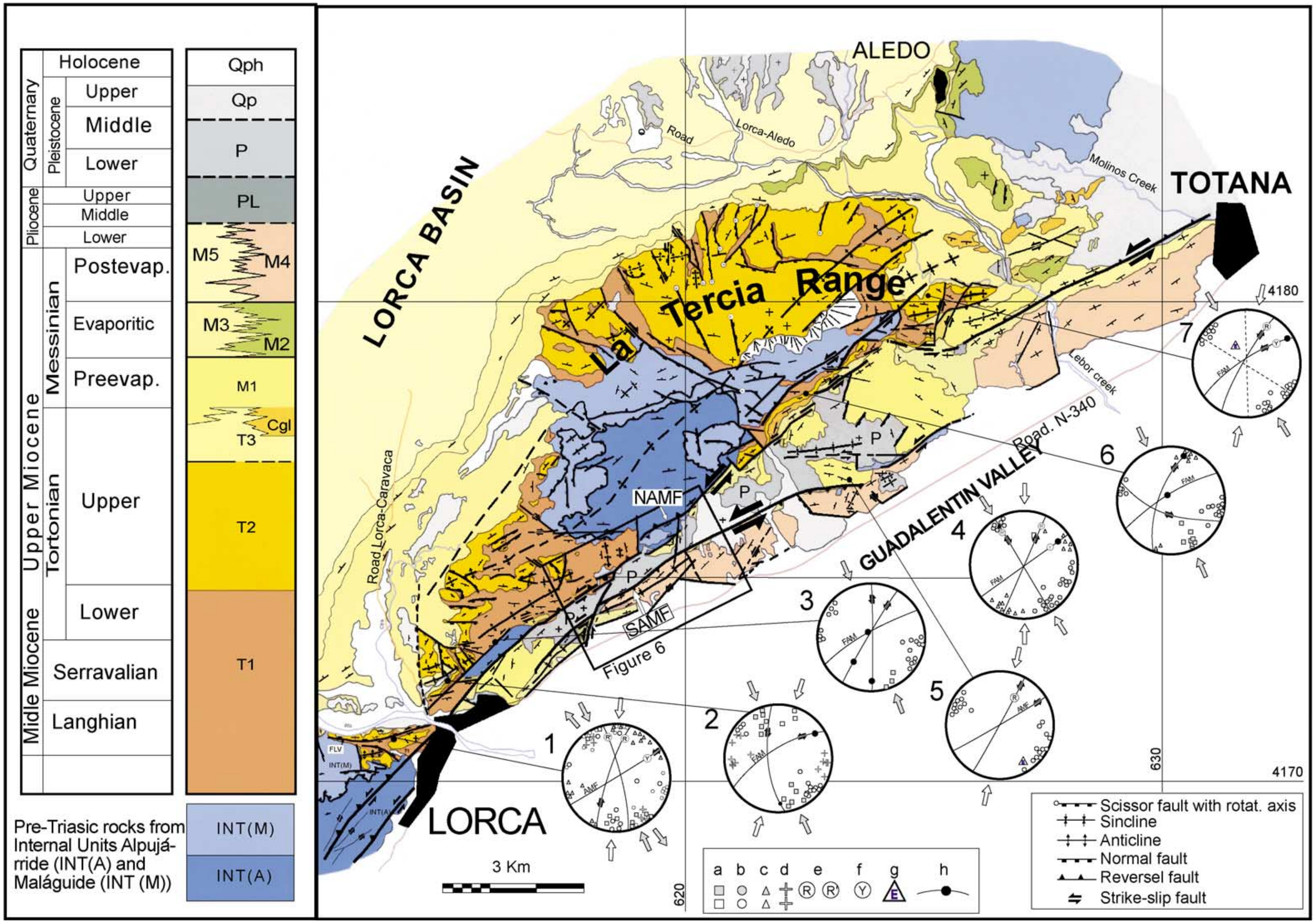


Fig. 3. Geological map of the Alhama de Murcia Fault and the La Tercia range. Numbers 1 to 7: stereographic projection on the lower hemisphere of the microtectonic data measured in Tortonian marls and limestone, (a) reverse fault planes and fold axes, (b) sinistral strike–slip planes, (c) dextral strike–slip fault planes, (d) normal faults, (e) Riedel microplanes, (f) main slip planes (planes Y), (g) bedding, (h) slip vectors on main slip planes. The microstructures with grey and white symbols are compatible with the grey and white shortening directions, respectively. NAMF and SAMF: northern and southern branches of the Alhama fault.

Díaz, 1998), greater complexity in the temporal distribution and the orientation of the neotectonic stress field were interpreted. Two maximum horizontal stress directions were inferred, trending NNE–SSW and NNW–SSE. However, their temporal succession appeared to be more complex. Active extensional tectonics apparently took place during the Late Miocene to the Quaternary, and this is clearly seen in the Tortonian limestones of the Sierra de Tercia (Fig. 3) and in other points around the study area (Bousquet and Phillip, 1976a). This extension appears to have coexisted with the late Miocene to the Quaternary compressive tectonics. Recent palaeoseismic studies, in trenches on the AMF trace indicate reverse and strike–slip motion along this fault during the Quaternary (Silva et al., 1997; Martínez-Díaz et al., 2001). Striations with rakes of 20° NE and 70° NE can bee seen in Pleistocene alluvial deposits.

The dynamic variability deduced from previous studies can be summarised as:

1) Map scale (typical 1:50,000 or lower) data and microtectonic data indicate co-existing compressional and extensional stress fields in the Late Miocene, Pliocene and Quaternary, and

2) The ever-greater number of microstructural studies has increased the number of deformation phases, with different shortening directions proposed from previous studies, to explain the observed structures. These multitudinous phases are hard to comprehend either in time and space.

3. Structure of the Alhama de Murcia fault (Lorca–Totana sector)

The Lorca–Totana sector was selected for the undertaking of a detailed study of the Alhama fault. This particular area was chosen because:

(a) The fault affects sedimentary units of a wide range of ages (Palaeozoic metamorphic rocks, Triassic carbonates, Miocene marine sediments, and Pliocene and Quaternary alluvial deposits), which facilitates dating of the structures;
(b) A clear interaction can be seen between the main shear zones and the secondary faults;
(c) There is a major structure associated with the AMF activity situated to the NW—the Sierra de Tercia—which helps identify the regional effect of the fault's activity under the influence of the regional stress field (Fig. 4).

The 1:30,000 scale mapping of the area (see reduced map in Fig. 3) allows identification of both the structure of the fault zone and deformation in the hanging wall.

3.1. Structure of the fault zone

The main slip zone of the fault shows a N55–65° direction. The shear zone is formed by two main branches; the Northern (NAMF) and Southern (SAMF) Alhama de Murcia faults. The NAMF bounds (on the western side) the basement block and Neogene cover that forms the Sierra de Tercia. The fault trace is irregular with a variable direction of N45°E to N55°E. On the main fault plane, the pitch of slickenside lineations varies from 20° to 70°. At both ends of the segment (close to the towns of Totana and Lorca), the main shear zone of the NAMF splits into two. These subsidiary planes are linked with N90°–100°E sinistral strike–slip faults, forming two strike–slip duplex structures (Fig. 5). In the resulting transpressive zone, between the two structures there has been vertical uplift with respect to the surrounding rocks. In the fault zone, the transpression has generated highly shortened folds parallel to the main shear planes. The SAMF is straighter, with a direction of N65°E, but disappears, both eastward and westward (Fig. 3), and is only seen in the Lorca–Totana sector. The two branches of the AMF have opposing dip directions. The northern fault dips towards the NW, beneath the Sierra de Tercia, while the southern fault dips towards the SE. Between them, a "pop-down" structure is formed that traps the alluvial sediments eroded from the Sierra de Tercia.

The most important secondary faults associated with the two main slip zones are the N90°–100°E trending faults that form strike–slip duplexes and N20°–25°E faults. The latter have different kinematics, one with normal movement and the other with a sinistral strike–slip movement. Both slip directions are observed on fault planes affecting Quaternary and Upper Miocene deposits. The relative chronology between the two striations is complex, suggesting the long-term co-existence of both kinematic types. From a

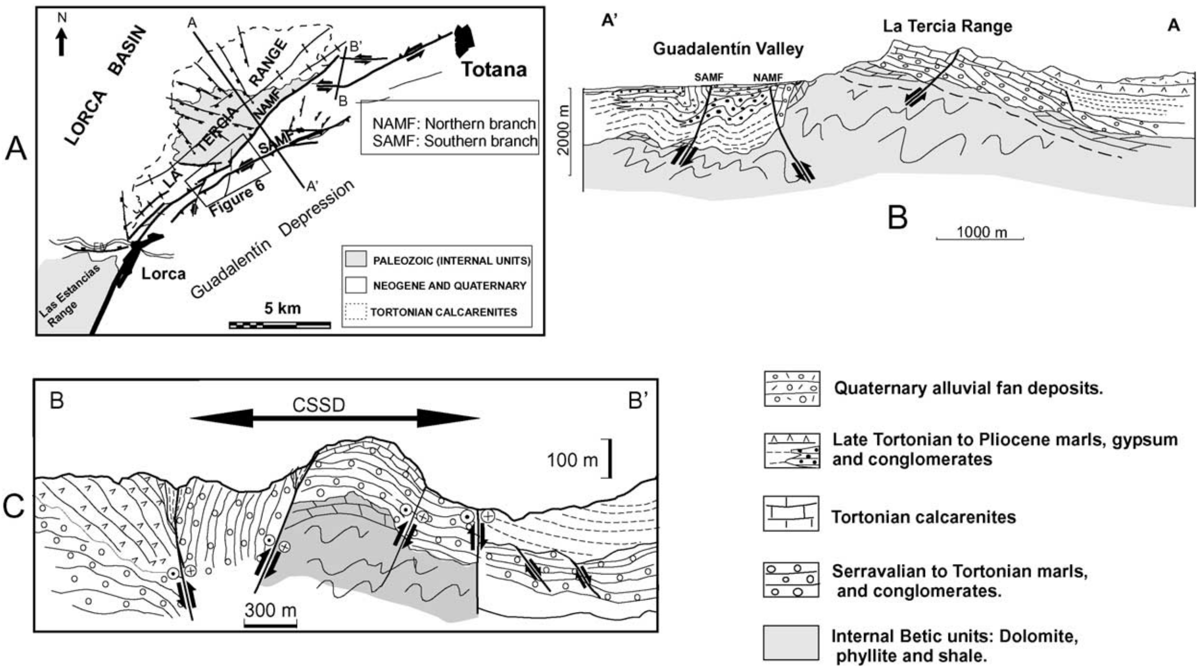


Fig. 4. (A) Schematic map of the faults in the study area, with the situation of the cross sections. (B) Geological cross section transversal to the Tercia Range and Alhama fault. (C) Geological cross section of the Carivete contractional strike–slip duplex that results from the interaction of two NE–SW main slip zones and two N 100° E sinistral planes.

tectono-sedimentary point of view, the normal component of movement controls the thickness of the Quaternary deposits (Fig. 5).

All the kinematic features considered in this study were active after Tortonian sedimentation. However, it is difficult to constrain the exact timing of the calculated stress tensors during the Pliocene and Quaternary. The complicated cross-cutting relations between the structures generated by the inferred different stress fields suggest frequent and repetitive modifications of the stress tensors. These modifications also suggest an apparent coexistence of different stress fields in the area.

3.2. Hanging wall structures

To the north of the NAMF lies the Sierra de Tercia (Fig. 3). This range is essentially an asymmetric anticline made by the drag folding related to reverse movement on the NAMF. The fold exhibits a vertical southern flank bordering the fault, and a northern flank dipping gently towards the NW. This fold formed at the end of the Late Miocene (during the Lower Messinian), and grew throughout the Pliocene and Quaternary. While the fold was growing, the Tortonian calcarenites fractured along NW–SE and N–S normal faults. Most of the faults show scissors movements (Fig. 3) that produce wall-tilting, in turn affecting, in some places, the syntectonic sedimentation of Late Tortonian marls. The rotation axes, deduced from angular unconformities in the marls, are roughly normal to fault direction. Some of these faults show strike–slip reactivations that generated minor folds with axes horizontal and perpendicular to the faults, especially in the northern sector of the anticline. There are also normal faults parallel to the NAMF. The longer NW–SE normal faults are found in the central sector of the Sierra de Tercia, and separate two parts of the fold that reach different topographic heights. To the east of these faults, the Sierra is at its highest (Fig. 3). To the west, fault motion results in relative lowering with respect to the

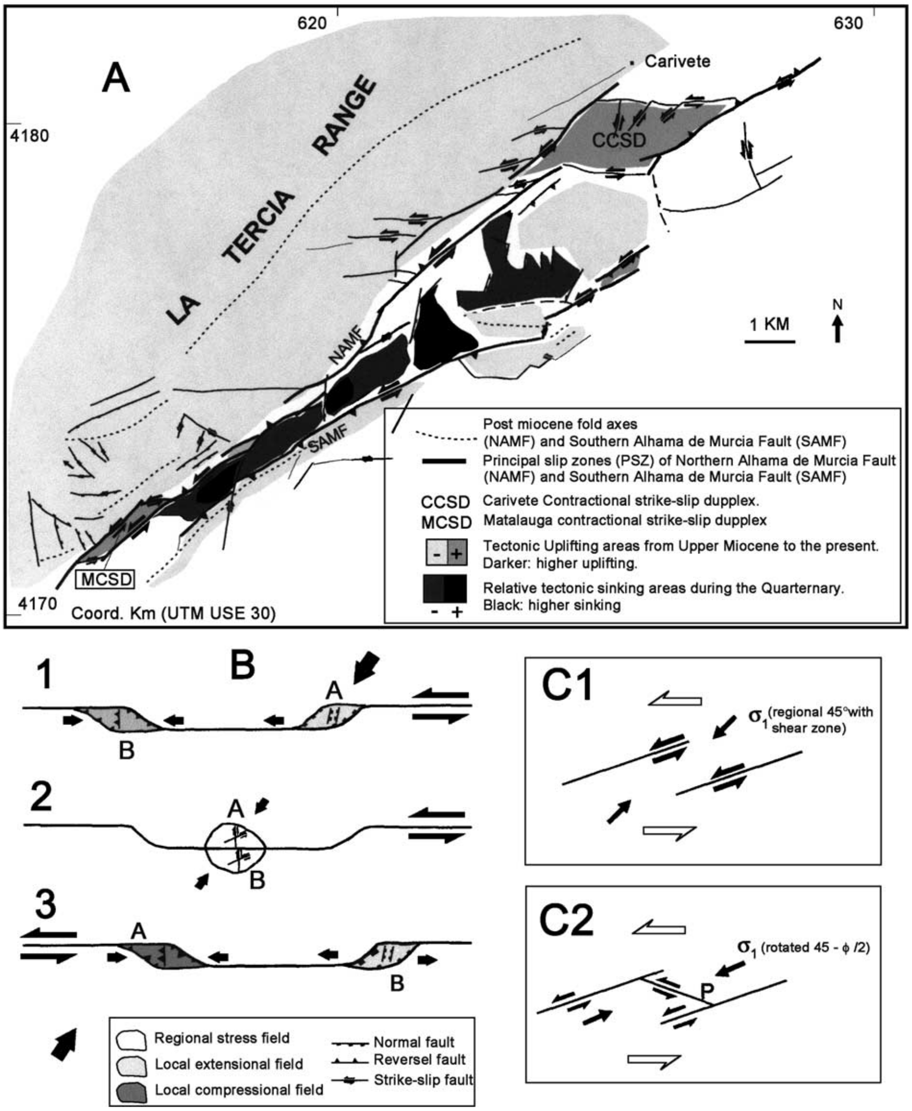


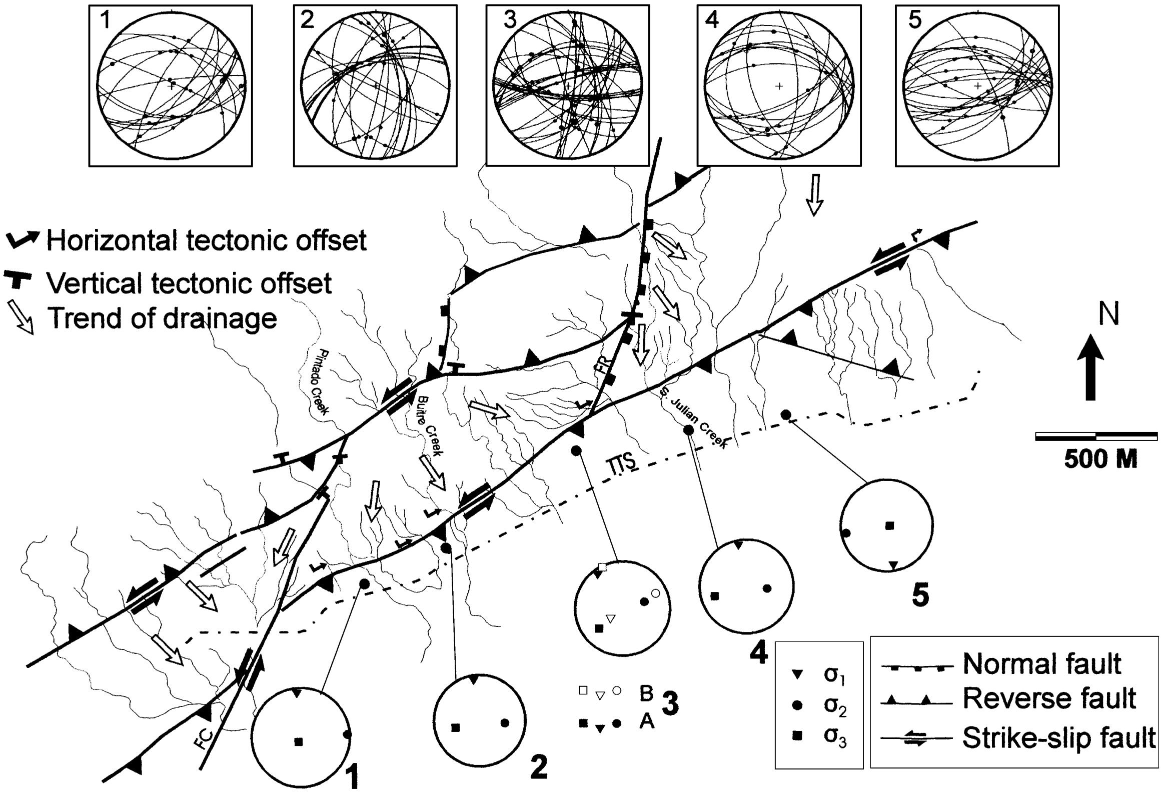
Fig. 5. (A) Map of the main faults studied in the Lorca–Totana sector. The two contractional strike–slip duplexes (following the terminology of Woodcock and Fisher, 1986) created by the interaction of N100°E sinistral P planes and NE–SW faults are indicated at the wedges of the fault zone. Grey areas show the areas that suffered relative tectonic sinking and uplift. (B) Structural sketch showing the different stress fields that can affect a given volume of rock that "travel" along an active fault zone with a constant strike slip movement, (modified from Crowell and Sylvester, 1979). (C) Mechanism of stress rotation in a shear zone to explain the formation of P planes (from Mandl, 1988).

eastern sector. This process also drives the growth of the anticline via the reverse movement on the NAMF.

At map scale (1:15,000 to1:30,000), the structures observed both in the fault zone and in the interior of the Sierra de Tercia show varied kinematics which are apparently incompatible in terms of a single stress field. In fact, geological maps show that the nature of the structures generated since the Late Miocene vary with respect to their position relative to the Alhama fault zone. This supports the idea that the stress field responsible for the formation of each structure depends on its location with respect to the surrounding structures.

4. Local stress field

In order to determine the paleostress field evolution, at least for the Pliocene and Quaternary, and at the same time identify the possible influences of fault interactions upon it, an inversion stress analysis was performed. The selected sector of the Alhama de Murcia fault is characterised by many shear veins filled with fibrous gypsum. Detailed maps of the fracturing in the area (Fig. 6) show that the two main



	NF	Shmax	EJ	Deje	R	Isigma1	SIsigma1	Isigma2	SIsigma2	Isigma3	SIsigma3	SMX/SMN	PMA	SLIP	FRIC	ECM	F. EX.
1	23	175.4	1	10	0.14	8	355	4	86	80	205	1.429915	16.99	9.09	0.2	4.59	13
2	25	171.9	1	5	0.24	9	353	44	92	44	254	2.182228	26.97	13.42	0.4	13.64	19
3	23	145.6	1	13	0.3	11	237	51	72	35	228	1.81848	29.08	20.86	0.3	10.8	20
3a	21	62.6	2	12	0.59	66	233	22	65	4	333	1.98789	26.17	23.62	0.4	9	15
3b	24	172.3	1	16	0.16	1	172	2	262	87	40	1.40737	20.9	15.7	0.2	6.69	14
5	21	173.2	1	25	0.32	10	355	37	93	50	252	1.6232	25.9	16.56	0.3	10.9	11

Fig. 6. Stress inversion performed close to the Alhama de Murcia fault. 1–5: Lower hemisphere projection of the shear veins and slip vectors measured in the seven stations utilised in the stress inversion. The map shows the situation of the faults with Quaternary activity and the stations. The anomalies of tectonic origin that affect the alluvial network are shown. The tensor solutions are represented for each station. The table data are the dynamic parameters obtained from the application of the stress tensor inversion method of Reches (1987), NF: number of faults. Shmax: orientation of the maximum horizontal stress. EJ: maximum vertical stress axis (1: σ_1, 2: σ_2). Dej: maximum misfit of the Shmax orientation. $R=(\sigma_2-\sigma_3)/(\sigma_1-\sigma_3)$. I$\sigma_1$: Plunge of maximum stress. SIσ_1: Dip direction of maximum stress. Iσ_2: Plunge of intermediate stress. SIσ_2: Dip direction of intermediate stress. Iσ_3: Plunge of minimum stress. SIσ_3: Dip direction of minimum stress. SMX/SMN: Relation of the magnitudes of maximum and minimum stress for the tensor solution. PMA: Mean misfit angle for the principal stress axes. SLIP: Mean misfit angle real fibre–theoretical fibre deduced from tensor solution. FRIC: Mean frictional coefficient deduced from tensor solution. ECM: Mean square error for the solution.

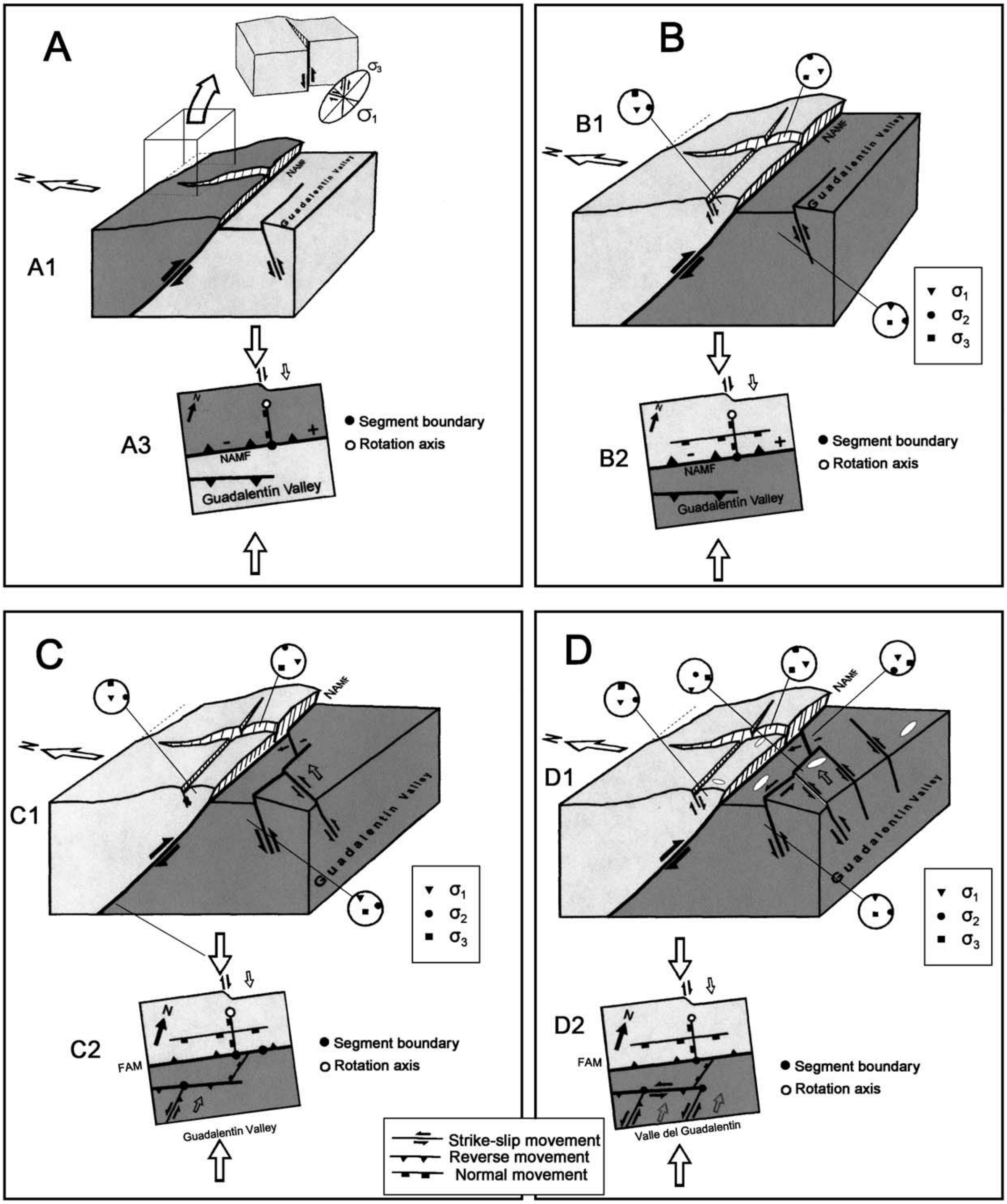
Fig. 7. Frontal view of the gypsum fibres observed on a shear vein situated at the station number 3 (see Fig. 6). The fibres show two different shear movements (reverse movement followed by normal–sinistral movement). This relative chronology of movements is not observed in all veins. Many cases of strike–slip movement followed by reverse kinematic are found.

shear zones of the NAMF and SAMF interact with secondary N25°E faults. The veins appear in the interior of the hanging wall of the SAMF, within Upper Miocene–Pliocene marls (Fig. 6). Gypsum fibres are good kinematic indicators (Fig. 7). They were measured only in the shear veins that showed neither later deformation nor signs of tilting that might have changed their original position.

A total of 120 measurements were taken at five stations along a line more or less parallel to the SAMF. The stations are sufficiently far away from the fault trace to avoid the tilting associated with the drag produced by the reverse movement during the Pliocene and Quaternary. For this reason, the measured veins have only suffered translational movement and conserve their original position.

The stress inversion method of Reches (Reches, 1987; Reches et al., 1992) was applied at each of the five stations (see results in Fig. 6). Among the stress tensors obtained, those of the compressive type with a NNW–SSE shortening direction similar to that of the regional field were the most common. However, the station closest to the intersection between the SAMF and the N25°E Roser fault, which has normal and strike–slip movements showed two tensors, one compressive similar to the regional field but with a Shmax turned to the NW–SE, and another of the extensional type. This result would appear to confirm the influence of the interaction of the faults on the nature of the active tensor at any given point. The change from one type of tensor to another provokes superposition of gypsum fibres with different pitches (Fig. 7).

Fig. 8. Kinematic and dynamic models to explain the existence of several low hierarchy stress fields that are coherent with a regional NNW–SSE compressive stress field in the Lorca–Totana sector of the Alhama fault (AMF). From A to D, the models are more complicated due to the successive inclusion of secondary fault interactions. A1, B1, C1, D1: block-diagram of the models with the stereographic projection on the lower hemisphere of the ideal stress axes for each lower hierarchy field. A2, B2, C2, D2: map view of each model.



A
σ_3
σ_1
NAMF
Guadalentin Valley
A1
A3
N
NAMF
Guadalentín Valley
Segment boundary
Rotation axis
-
+
B
B1
NAMF
Guadalentin Valley
σ_1
σ_2
σ_3
B2
N
NAMF
Guadalentín Valley
Segment boundary
Rotation axis
C
C1
NAMF
Guadalentin Valley
σ_1
σ_2
σ_3
C2
N
FAM
Guadalentin Valley
Segment boundary
Rotation axis
D
D1
NAMF
Guadalentin Valley
σ_1
σ_2
σ_3
D2
N
FAM
Valle del Guadalentin
Segment boundary
Rotation axis
Strike-slip movement
Reverse movement
Normal movement

In addition to the inversion study, seven microstructural stations have been measured along the Lorca–Totana sector, including microfolds, joints, Riedel shear planes, slickensides, opening cracks, reverse microfaults and normal microfaults affecting upper Tortonian and Messinian deposits (Fig. 3). In all the stations, a shortening direction ranging from NNW–SSE to NE–SW is needed to explain all the structures. Therefore, at the local scale, and over the whole of the fault zone, the kinematic variability induced by the interaction of nearby structures is revealed.

5. Stress field hierarchy

Taking into account the previous kinematic data, as well as the structural data described above, it is possible to interpret several local stress fields of different nature and orientation to have acted throughout the Late Miocene and the Plio-Quaternary. The complicated space–time relationships observed between these fields suggest that the structures generated by them do not form in a sequence of two or three different stress fields from the Late Miocene to the Quaternary as previously thought, but through more complex alternations over time and space. They result as successive modifications of the regional stress field due to local perturbations controlled by pre-existing local structures (heterogeneities). Depending on the geometry, spatial position, and kinematics of these structures, the type and orientation of the stress field varies at each point, and this generates lower hierarchy stress fields (LHSF).

Fig. 8 shows a kinematic and dynamic model of the Alhama de Murcia fault in the Lorca–Totana sector. A regional compressive stress field is shown with a N150°E Shmax direction. Several local tectonic processes that lead to lower hierarchy local stress fields on the interior of the hanging wall and around the shear zone are proposed.

5.1. Hanging wall

The existence of a gradient in the rate of vertical movement along the NAMF (higher in the eastern sector) is transformed into a shear regime along vertical planes perpendicular to the direction of the NAMF (Fig. 8A). The LHSF generated by this regime induces the formation of the N–S and NW–SE normal-scissor faults. The greater rate of movement in the eastern sector of the NAMF results from the disappearance of the SAMF towards the east. This causes all of the shortening to be transferred to the NAMF. As a consequence of this gradient in the movement rate, the eastern sector of the anticline that forms the Sierra de Tercia reaches a higher altitude than that of the west, because greater long-term reverse slip has been absorbed.

Fig. 8B shows a new LHSF, responsible for the formation of the normal faults parallel to the NAMF in the block uplifted to the NW. There is a flexure mechanism produced in the external arc of the fold in the superficial part of the hanging wall that induces a re-orientation of the regional tensor axes. This mechanism is similar to that described by Philip and Meghraoui (1983) for the normal faults generated in the hanging wall of the El Asnam reverse fault.

5.2. Fault zone

In the regional stress field, both the NAMF and SAMF have reverse-type kinematics with a strike–slip component. The pitch of slickensides on the fault planes showing this horizontal component varies from 20° to 70°. These movements have resulted in the formation of a “pop-down” between the two corridors and, at the same time, uplift of the Sierra de Tercia. The N25°E secondary faults interact with this pop-down and show different kinematics. One fault has sinistral strike–slip motion with a reverse component shown by rakes ranging from 10° to 35°, while the other fault is extensional (Fig. 6). Those faults with strike–slip components are consistent with a N150°E shortening direction. However, the same does not occur on the N25°E normal fault that requires a maximum horizontal stress approximately parallel to their orientation, i.e. NNE–SSW. This shortening would also explain the sinistral strike–slip slickensides with low rake values found at many points along the NAMF and SAMF (Bousquet and Montenat, 1974; Bousquet and Phillip, 1976b). The strain induced by the differential horizontal movement of blocks limited by the N25°E faults explains the local rotation in the direction of the maximum horizontal shortening from NNW–SSE to NNE–SSW. This rotation may explain the different pitches found in the striations on the main shear zone (Fig. 8D). This mechanism would occur in those places where the secondary N25°E faults are in contact with the main faults of the Alhama de Murcia fault, allowing movement of individual blocks.

The secondary N90°–110°E faults that link with the major faults of the NAMF in overstep zones (Fig. 5) show sinistral strike–slip movements that require directions of maximum horizontal stress to be rotated clockwise with respect to the regional stress field. The mechanism proposed by Mandl (1988) explains this rotation associated with the channelling of stresses produced by the main slip zones (Fig. 5). Thus, any microstructures measured in zones of high structural complexity (oversteps, offsets, horsetail splay, en echelon, etc.) have to be interpreted carefully from a dynamic point of view.

There is one other mechanism that could generate structures with different kinematics in a single regional stress field in this area. The Alhama fault exhibits structural complexity all along its length, and it changes in strike at certain points (Figs. 1 and 3). Therefore, a given volume of rock close to the main fault can move through zones dominated by local stress fields of different nature; extensional, compressive and/or strike–slip (Fig. 5B). This mechanism was described as "porpoising effect" by Crowell and Sylvester (1979), and can play even with small displacement along a complex fault zone. The interpretation of microtectonic data in these zones can provide stress tensors that are very different from the tensor driving the overall movement of the fault zone.

6. Conclusions

The study area shows a wide variety of kinematics on local structures, which, in previous papers, has led to interpretations of varying stress fields. In many cases, the conclusions drawn through the use of stress tensor inversion methods using microtectonic data have been extrapolated to the regional scale. This has led to progressively more complicated interpretations of the neotectonic development of the area. In order to explain this spatial and temporal kinematic complexity, the number of deformation phases proposed in previous works from the Upper Miocene to the present has increased. These deformation phases are based on; (a) the change from compressive stress fields to extensional stress fields or vice-versa, or (b) changes in the orientation of the maximum horizontal stress. This has reached a point where it is difficult to reconcile these phases with nearby fault zones. Occasionally, this difficulty has been wrongly attributed to a lack of data or poor quality of data.

The different kinematics of the Lorca–Totana sector of the Alhama de Murcia fault, from the Upper Miocene to the present, can be explained in terms of a single stress field. Similarly, the same can be deduced for the Quaternary development of geologic units near to the Alhama fault (Silva, 1994). The processes of: (1) dynamic interaction between nearby faults; (2) different motion of blocks in the horizontal plane; (3) different uplift rates in the hanging wall; (4) surface flexure that induces local extension; (5) constrained motion of fault bounded blocks; and (6) the "porpoising effect" (c.f. Crowell and Sylvester, 1979) related to local changes in the fault plane direction can explain the occurrence of local stress fields of lower spatial hierarchy, all in terms of a single and constant NNW–SSE maximum horizontal compressive regional stress field since the Late Miocene. This shortening direction is consistent with plate motions deduced from different regional data (Argus et al., 1989; DeMets et al., 1990; Zoback, 1992; Galindo-Zaldívar et al., 1993).

For comparison purposes, a high spatial resolution image of stress orientation in southern California based on the inversion of earthquake focal mechanisms (Hardebeck and Hauksson, 2001) is instructive. They found that the active stress field appears to be highly heterogeneous on a range of length scales. This heterogeneity is attributed to the different geologic provinces, fault complexity, and the occurrence of major earthquakes. An individual earthquake as the 1992 Landers (California) event produced, according to these authors, a 15° rotation in the maximum horizontal stress direction. This rotation is enough to generate a modification in the slip direction of the faults affected by this local stress field. In the long term, tectonic loading should approximately cancel out these stress changes. If these variations in the local stress field develop during a thousand to a few million years, they can produce repeated modifications in the kinematics of fault planes and changes in fold orientation. Similar heterogeneity in kinematics and deformation, perhaps over even longer time scales, in the lower strain rate environment of the Alhama de Murcia fault should be expected. In this zone, most of post-Miocene structures are related to the slip orientation of nearby faults.

This study has demonstrated that appropriate geological mapping and a precise evaluation of the context of micro- and meso-tectonic data is necessary when evaluating the dynamic significance of each microtectonic datum. The use of stress inversion methods without taking the local tectonic context into consideration may give rise to incorrect interpretations, incorrect processing of previous data, and inappropriate extrapolations to other length and temporal scales.

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