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Faulted hybrid joints: an example from the Campo de Dalias (Betic Cordilleras, Spain)

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Abstract

The development of hybrid and faulted joints has not been studied in detail in natural outcrops. This field study in the Campo de Dalias (Betic Cordilleras) establishes the distinctive features of these structures as compared with those predicted by theoretical studies. Hybrid joints appear as two sets of vertical joints forming variable angles, but generally about 25°, with opening directions orthogonal to joint planes. Their development requires low differential stresses with a tensile minimum stress. The main criteria that indicate the existence of faulted joints are: (1) the presence of subvertical fault planes with oblique slip forming a complex pattern of dextral and sinistral faults developed under a single stress regime; (2) faults with similar geometries as joints in the same outcrop, showing an inconsistent cross-cutting relationship; and (3) the development of small basins with variable polarity of asymmetric wedge filling. A permutation in stress orientation since the Tortonian in the Campo de Dalias was responsible for the development of a faulted hybrid joint system, with a constant ENE–WSW extension trend and a switch of σ_1 between NNW–SSE and vertical.

Keywords: Faulted joints; Hybrid joints; Paleostress; Campo de Dalias; Betic Cordillera

1. Introduction

Oblique slip faults near the Earth's surface cannot be easily explained as neoformed faults because one of the main stresses of the stress ellipsoid should be vertical near the surface (Anderson, 1951). Subvertical fault planes in neoformed faults should mean that faults have strike-slip motion and dipping faults are normal and reverse. Bott (1959) considered that the reactivation of previous discontinuities in a new stress field is the main mechanism that creates oblique slip on faults. 'Faulted joints' (Pollard and Aydin, 1998) are the consequence of sliding on previous developed joints. Wilkins et al. (2001) establish criteria to distinguish faulted joints from neoformed faults. When a fault is reactivated, the slip is independent of the fault length and generally smaller than in neoformed faults. The absence of fault gouge or fault breccias along large faults has also been proposed as indicative of reactivation (Pedley et al., 1976; Wilkins et al., 2001). Reactivated faults do not necessarily show conjugate fault sets and are typically parallel to set of joints (Segall and Pollard, 1983). Peacock (2001) studied the temporal relationships between joints and faults and described several examples of joints that predate faults or faulted joints, joints formed synchronously with faults, and joints that postdate faults.

There are not many examples of faulted joints in the literature (Peacock, 2001). There is an interesting study of a subvertical joint system that was reactivated as strike-slip faults on the Maltese Islands (Pedley et al., 1976) and joints in volcanic rocks reactivated as normal faults in the Koae fault system (Duffield, 1975).

Muehlberger (1961), Hancock (1985), Price and Cosgrove (1990) and Dunne and Hancock (1994), amongst others, describe the architecture of joint systems and indicate that between the two end-member types of extensional fractures and shear fractures, hybrid joints with both extensional and wrench components can exist. Hybrid joints correspond to conjugate joints with dihedral angle $<60°$. These structures are referred to as oblique

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extension fractures (Dennis, 1972), or extensional shear fractures (Etheridge, 1983). However, field descriptions of hybrid joints are scarce, and although well established from a theoretical point of view, their natural features are not well known (Arlegui and Simón, 2001).

The first aim of this contribution is to accurately analyse the features of hybrid joints in several outcrops in the Campo de Dalias (Betic Cordilleras, SE Spain) in order to better understand the development of these structures in nature. The second goal is to determine the mechanisms and kinematics of joint reactivation during faulting, as constrained by new field data. Finally, from a regional point of view, this study contributes to knowledge of the recent evolution of an area of transition between domains dominated by wrench tectonics and extensional tectonics in the eastern Betic Cordilleras.

In order to address these topics, a geometrical study of fractures including several outcrops of the area has been carried out, clearly illustrating the relationship between hybrid joints and faults. The process of reactivation has been integrated in the tectonic evolution of the region. Stress ellipsoids determined from joints and faults allow us to discuss the mechanism involved in the development of faulted joints and explain the large variability in the kinematics of faulting at outcrop and regional scales.

Previous studies of faults carried out in the Campo de Dalias region (Fourniguet, 1976; Baena and Ewert, 1983; Rodríguez-Fernández and Martín-Penela, 1993; Martínez-Díaz, 2000) indicate the presence of several faults with recent activity, although there is no agreement on the kinematics; normal, scissored and strike-slip motions have been proposed. Field studies show that the rocks up to present are cross-cut by several pervasive joint sets (Marín-Lechado et al., 2003). The Balanegra fault (Fig. 1C) is one of the most active structures of the region (Fourniguet, 1976; Galindo-Zaldívar et al., 2003). The earthquake focal mechanisms determined by Stich and Morales (2001) include normal faults with both dextral and sinistral strike-slip components, rare strike-slip faults and some reverse faults suggesting that the active faults develop in a complex tectonic setting.

2. Geological setting

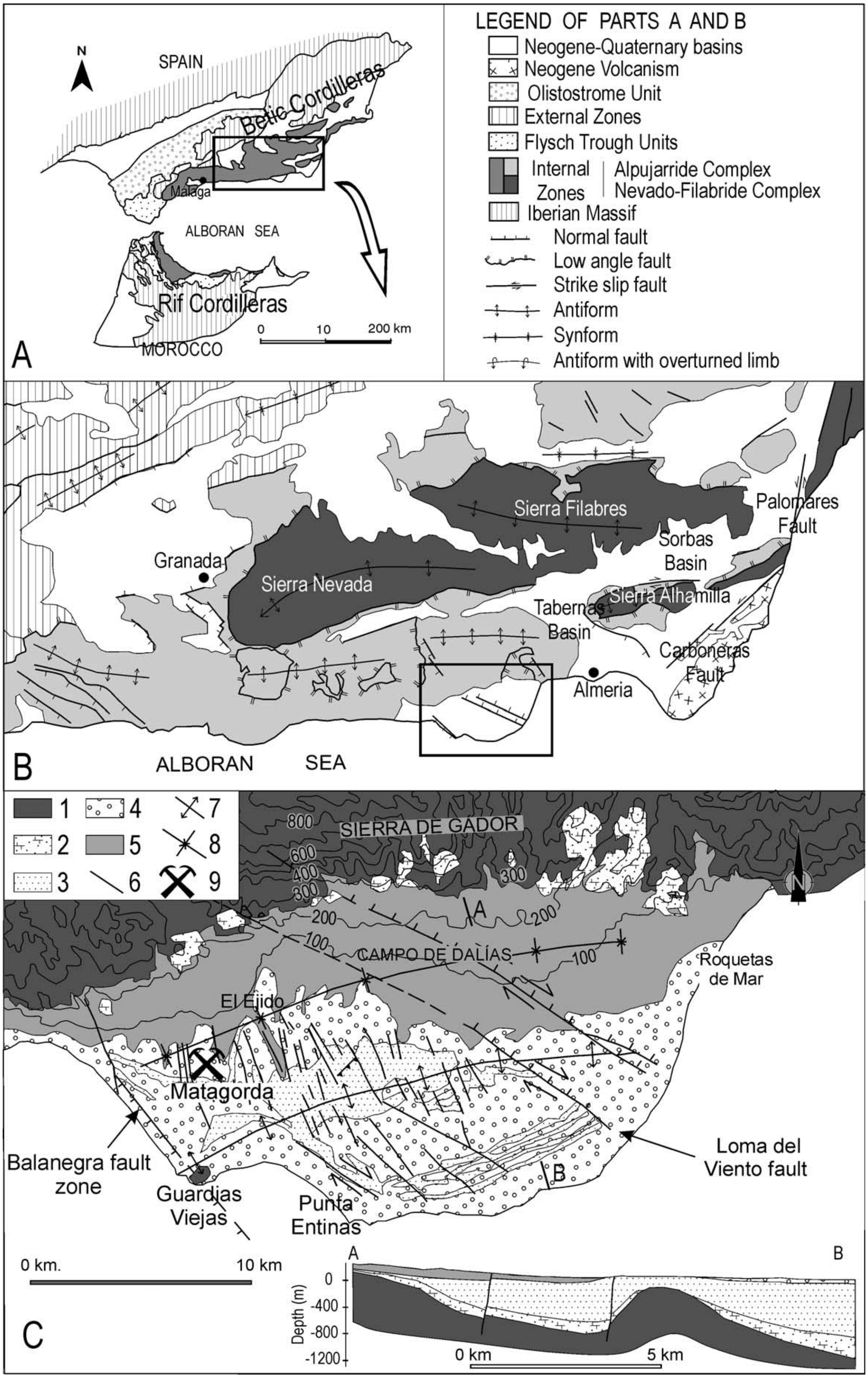
The Betic and Rif Cordilleras are located at the western end of the Mediterranean Sea, between the African and Eurasian plates. These Cordilleras have been traditionally divided into Internal and External Zones, with the so-called Flysch Trough units in between (Fig. 1A). The main Neogene and Quaternary basin is the Alboran Sea, situated between the Rif and Betic Cordilleras. This basin is submerged at present and its basement is formed by rocks of the Internal Zone (Ryan et al., 1973; Comas et al., 1992). Since the Upper Miocene, the 4 mm/yr NW–SE convergence between the European and African Plates (De Mets et al., 1990) has produced a shortening and the development of large open folds with an associated uplift that determines the present-day relief in the central Cordilleras (Weijermars et al., 1985; Johnson, 1997).

The simultaneous development of NW–SE normal faults superimposed on compressional folds has been described mainly for the southern part of the central Betic Cordilleras (Galindo-Zaldívar et al., 2003; Ruano et al., 2004). However, the eastern Betic Cordilleras are deformed by strike-slip faults that may be grouped in several sets. The NE–SW to NNE–SSW oriented faults (e.g. Carboneras and Palomares faults, Fig. 1B) are sinistral and have been associated with a fault zone denominated Trans-Alboran Shear Zone (De Larouzière et al., 1988). The Carboneras fault has been the target of several recent studies that confirm its Neogene activity that may reach the Quaternary (Bell et al., 1997). In addition, E–W dextral faults have been described, like those located in the northern border of Sierra Alhamilla (Sanz de Galdeano, 1989; Ott d'Estevou and Montenat, 1990). The relationship between fault sets in the strike-slip fault system has been described by several research studies since the seventies (Bousquet and Montenat, 1974; Ott d'Estevou and Montenat, 1985; Montenat et al., 1987).

The Campo de Dalias region constitutes the largest outcrop of Neogene and Quaternary sediments of the northern margin of the Alboran Sea and is located in the southern boundary of the SE Betic Cordilleras, where sedimentary rocks are deposited on metamorphic rocks of the Alpujárride Complex belonging to the Internal Zone. The sedimentary sequence of the Campo de Dalias begins with Tortonian calcarenites and is followed by Pliocene marls and calcarenites. The top of the sequence consists of Pleistocene marine clastic sediments that are located on marine terraces (Goy and Zazo, 1986), continental conglomerates deposited in alluvial fans and red silts, Late Pleistocene–Holocene in age (Baena and Ewert, 1983).

The Neogene sedimentary rocks of the Campo de Dalias and the Alpujárride basement are deformed by open folds with E–W to ENE–WSW trends that have been developing since the Upper Tortonian to Present in age. The Sierra de Gador is the largest anticline in the region and shows the

Fig. 1. Geological setting of study area. (A) The Betic and Rif Cordilleras. (B) Regional Map of eastern part of the Betic Cordillera. (C) Geological Map of the Campo de Dalias and cross-section. Legends: 1. Marbles and dolomites (Alpujárride Complex—Permo–Triassic); 2. Calcarenites (Tortonian); 3. Calcarenites and marls (Pliocene); 4. Marine detritic sediments and Red silts (Quaternary); 5. Alluvial fans (Quaternary); 6. faults; 7. Anticline; 8. Syncline; 9. Quarry.


LEGEND OF PARTS A AND B
Neogene-Quaternary basins
Neogene Volcanism
Olistostrome Unit
External Zones
Flysch Trough Units
Internal Zones
Alpujarride Complex
Nevado-Filabride Complex
Iberian Massif
Normal fault
Low angle fault
Strike slip fault
Antiform
Synform
Antiform with overturned limb
N
SPAIN
Betic Cordilleras
Malaga
ALBORAN SEA
Rif Cordilleras
MOROCCO
0
10
200 km
A
Sierra Filabres
Palomares Fault
Granada
Sierra Nevada
Sorbas Basin
Sierra Alhamilla
Tabernas Basin
Carboneras Fault
Almeria
ALBORAN
SEA
B
1
2
3
4
5
6
7
8
9
800
SIERRA DE GADOR
600
400
300
200
100
A
CAMPO DE DALÍAS
Roquetas de Mar
El Ejido
Matagorda
Balanegra fault zone
Loma del Viento fault
B
Guardias Viejas
Punta Entinas
0 km.
10 km
C
A
B
0
-400
-800
-1200
Depth (m)
0 km
5 km

average E–W trend of the coastline between Almeria and Malaga. This fold is responsible for the uplift of Upper Tortonian marine sediments, which crop out at elevations of 1600 m above sea level. In the Campo de Dalias, the Alpujárride basement and Neogene sediments are also folded and have experienced regional uplift since the Pliocene, as indicated by seismic profiles of the area (Rodríguez-Fernández and Martín-Penela, 1993).

3. Joints and fault system

3.1. Joints

Field data from 12 homogeneously distributed sites in Neogene and Quaternary rocks of the Campo de Dalias indicate the presence of different sets of subvertical joints (Fig. 2A). These joints were studied in cross-section and on horizontal bedding surfaces. The size of the fractures is highly variable, ranging from decimetric to hectometric and recognisable on aerial photographs. Two outcrops of Tortonian calcarenites on the NE side of the Campo de Dalias (sites 5 and 6, Fig. 2A) contain two main sets of subvertical joints that have nearly orthogonal NW–SE and NE–SW trends. However, the NE–SW trend was not identified in younger rocks in the NW part of the Campo de Dalias, where only a single NNW–SSE-trending subvertical set of tensional joints developed (sites 2 and 3, Fig. 2A).

The Pliocene calcarenites and Pleistocene conglomerates are affected by generally NW–SE oriented joints, also identified in the Tortonian rocks. These joints can be grouped into two main sets, although intermediate orientations are also present. At several sites, the intermediate orientations are predominant and constitute a joint spectrum as defined by Hancock (1986) (e.g. sites 1, 7, 8, 10 and 12 of Fig. 2A). These orientations are comprised between N120°E and N180°E, with a N170°E predominant trend. The joint patterns observed in these outcrops are mainly of the 'y' type (Hancock, 1985), although 'K', 'Y' and 'X' types were also recognized. The angles between the two main joint sets are variable in different outcrops but generally less than 45° (Fig. 2A).

Pliocene calcarenites exposed in the Matagorda Quarry (Figs. 1 and 3) allowed detailed study of the geometry and distribution of Pliocene joints on a horizontal plane. A plot of the joint trends against their cumulative length shows that more than 80% of all joints trend between N140°E and N170°E, with a maximum at N160°E. The joints of greater length (Fig. 3) belong to a well defined joint spectrum with orientations ranging from N145°E to N165°E. The angle between the two joint sets that define the extremes of the joint spectrum ranges from 20 to 25°. Outcrop-scale joint patterns show indentation of rock wedges bounded by two joint sets, with X and Y geometries and defining variable opening directions of the joints (Fig. 4). In general, the amount of opening is smaller for two pairs of joints meeting at acute angles than for single joints with intermediate orientation.

Upper Pleistocene–Holocene sediments seal the joint spectrum of the Matagorda outcrop (Fig. 5A), as can be observed in other sectors of the central and southern Campo de Dalias. However, in the northern Campo de Dalias these sediments show a single tensional joint set with a N120°E trend (site 4, Fig. 2A).

Many of the joints observed in the region show several opening phases with symmetric calcite fill (Fig. 5B) and maximum values of opening of up to 1 m for the NW–SE set (Fig. 3A). The amount of opening is heterogeneous across the Campo de Dalias, although generally fillings are thicker in more competent rocks such as the marbles of the Alpujárride basement and the Tortonian calcarenites. Generally, outcrops with several joint sets show the greatest values of opening in the NW–SE direction (Fig. 3A).

3.2. Faults

The most conspicuous faults of the Campo de Dalias (Figs. 1C and 2B) affect Plio–Quaternary sediments and have trends comprised between N120°E and N170°E. Most of the faults have straight traces at outcrop and map scales, although some bends at fault terminations were occasionally observed. The distribution of fault trends varies in different outcrops. At some outcrops the fault trend is dispersed (e.g. site 19, Fig. 2B). In other outcrops N140°E-trending normal faults predominate (e.g. sites 15 (near Balanegra Fault) and 16, Fig. 2B) or two distinct sets of faults can be differentiated (e.g. sites 11 and 13, Fig. 2B).

Fault surfaces are generally striated, showing slickensides and grooves that allow determination of fault kinematics. The presence of asymmetric steps on polished surfaces, together with the displacement of subhorizontal bedding and topographic scarps have been used to determine the sense of movement of these faults. Normal faults with dextral strike-slip components and a N140°E–N120°E trend (Loma del Viento Fault) and faults with sinistral strike-slip components trending N140°E–N170°E were observed. We also locally identified a synsedimentary reverse fault with NE–SW trend and SE dip in Pliocene sediments (Fig. 5E). The dips of normal, transtensive dextral and transtensive sinistral faults are variable, but usually between 70 and 90°. In some outcrops, a two fault set dipping northeast and southwest is well represented (e.g. sites 13 and 14, Fig. 2B), while in other outcrops (e.g. sites 15 and 16, Fig. 2B) predominant southwest dips are observed. The average length of faults is 3 km, locally reaching 15 km (Loma del Viento Fault; Figs. 1C and 2).

There is evidence of syn-sedimentary activity of Tortonian faults responsible for thickness variations in the calcarenite layers (Fig. 5D). However, most of the faults are associated with half-graben structures filled by sedimentary wedges that record progressive fault activity during the Late

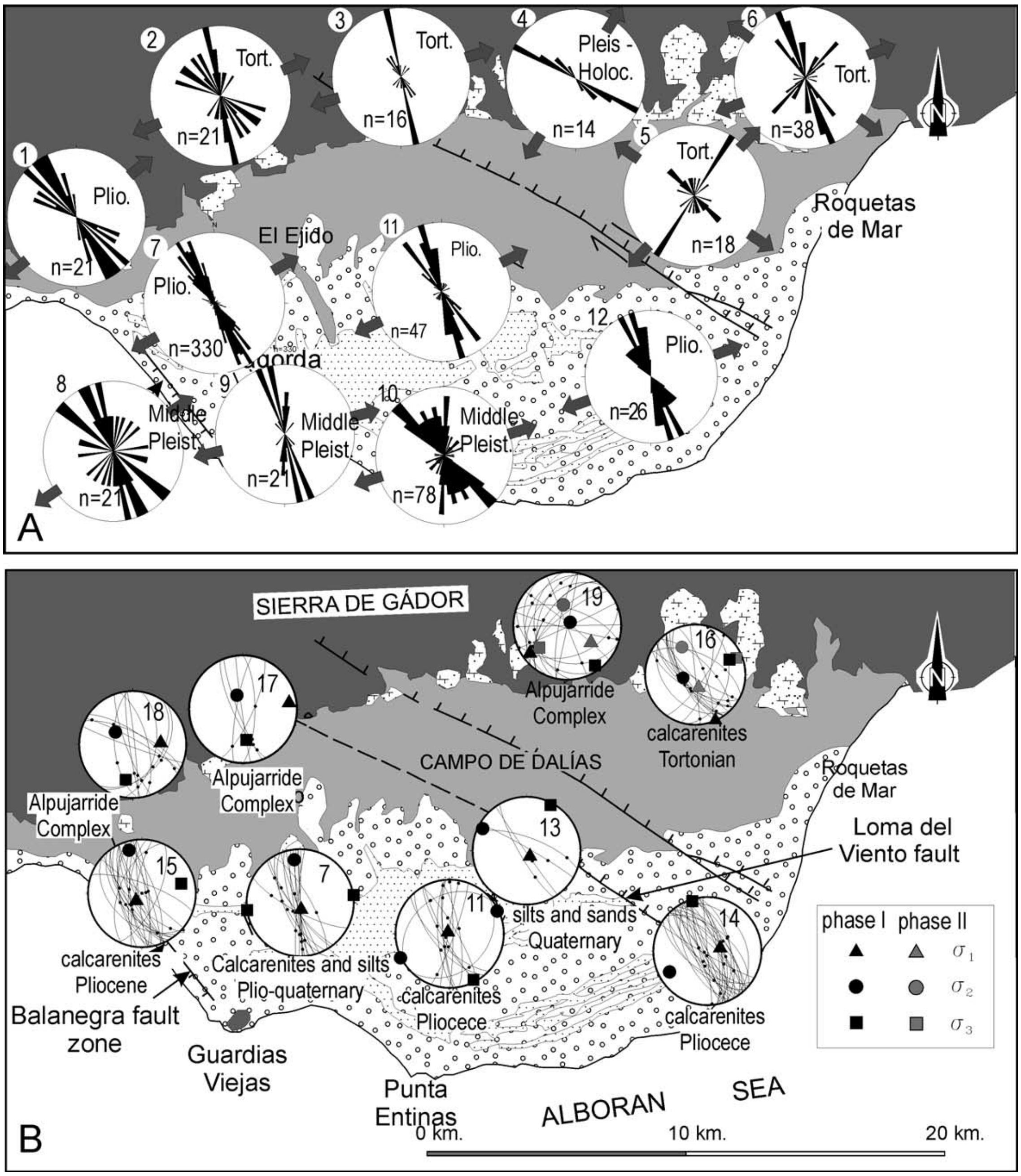


Fig. 2. (A) Rose diagrams of joints from several measurement sites in the Campo de Dalias. The site number is indicated by the upper left number of rose diagrams and the number of data by the lower number (*n*). Age of sediments in each measurement station: Tort., Tortonian; Plio., Pliocene; Pleist., Pleistocene. The grey arrows indicate the trend of maximum extension direction. (B) Stereoplots of fault planes and striae in measured stations. The orientation of principal stress axes obtained from paleostress analysis are indicated in the figure and in Table 1. The right upper number indicates the station. In polyphase stations, the two phases are drawn in different grey scales.

Pleistocene–Holocene (Figs. 5F and 6D). Both polarities of the half-graben were recognised, with sedimentary wedges thickening towards the northeast (e.g. Matagorda Quarry) or southwest (e.g. Loma del Viento Fault). Fault scarps associated with these faults can locally be several tens of metres high (Fig. 5C). Recent activity of these faults is also evidenced by the deformation of the drainage network, of the coastline alignment and of marine terraces dated at 100,000 years (Goy and Zazo, 1986).

4. Paleostresses

To determine paleostress from faults we used the Search Grid method (Galindo-Zaldívar and González-Lodeiro, 1988), which calculates the axial ratio and the orientation of the axes of the stress ellipsoids that acted during superimposed fracturing stages. In some cases we compared the results with those obtained using the method of Etchecopar et al. (1981).

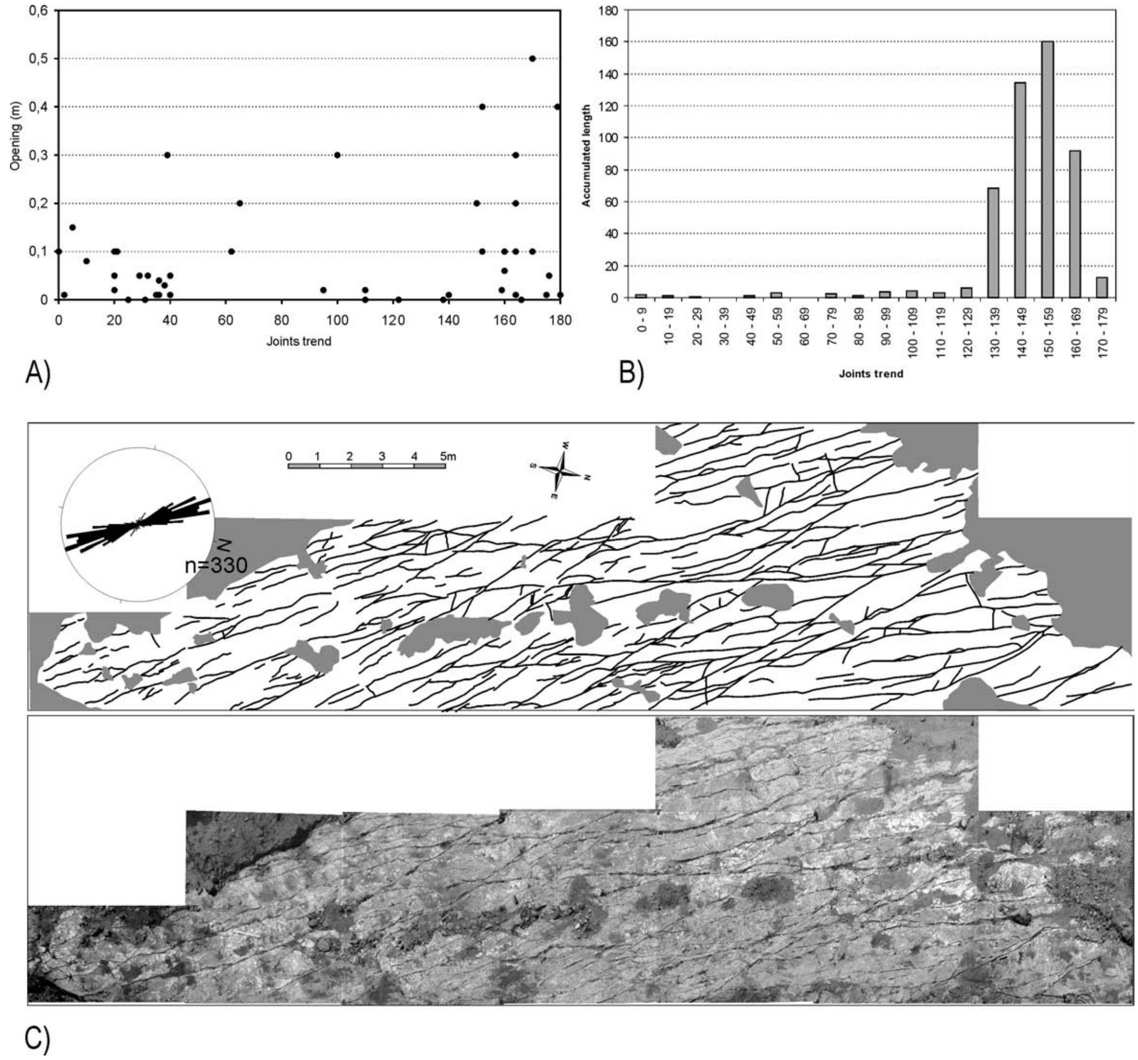


Fig. 3. Example of hybrid and tensional joints constituting a joint spectrum in the Campo de Dalias. Location in Fig. 1. (A) Opening versus joint trend. (B) Accumulated length (m) versus joints trend. (C) Detailed photo mosaic and sketch in plan view, showing the distribution pattern of joints in Matagorda Quarry.

Field observations indicate that jointing generally predates faulting. We will first establish the stress evolution based on joint geometry, and then the subsequent stress field situation based on microfault analysis.

Three different stages characterise the stress since the Tortonian. Joints in Tortonian rocks have a typical architecture of extensional settings with a subvertical maximum stress (σ_1) and a main extension direction (σ_3) oriented NE–SW. There are no large differences between the values of σ_3 and σ_2, which facilitated a permutation of these stress axes, with the result of different trends of extension in different outcrops (sites 2, 3, 5 and 6, Fig. 2A). This architecture of the joint system was not recognized in younger deposits, so that these states of stress were probably active during some period between Tortonian and Pliocene times.

Pliocene rocks and marine terraces of Lower and Middle Pleistocene age are deformed by a joint system (Fig. 2A), including tensional and hybrid joints. The geometry of the joint system indicates a very constant subhorizontal ENE–WSW orientation of σ_3 for the whole area. The two sets of hybrid joints allow us to infer NNW–SSE subhorizontal compression (Fig. 7A).

A low differential stress ($\sigma_1 - \sigma_3$) is necessary to develop hybrid joints. In this setting, the Mohr envelope is cut by the Mohr circle in two symmetrical points corresponding to fractures with low dihedral angle and undergoing both shear and extension (Fig. 7B). For the same rocks, and hence the same Mohr envelope, tensional fractures are formed at even lower differential stresses ($\sigma_1 - \sigma_3$) to produce a single tensional set. Development of joint spectra should indicate variations in the value of the main stress during joint development (Hancock, 1985), by stress release or variation of fluid pressure, which may modify the position of intersection of the Mohr circle and the Mohr envelope, with different angles between the hybrid joint sets.

The presence of tensional and hybrid joints and the absence of pure shear joints indicate low differential stress

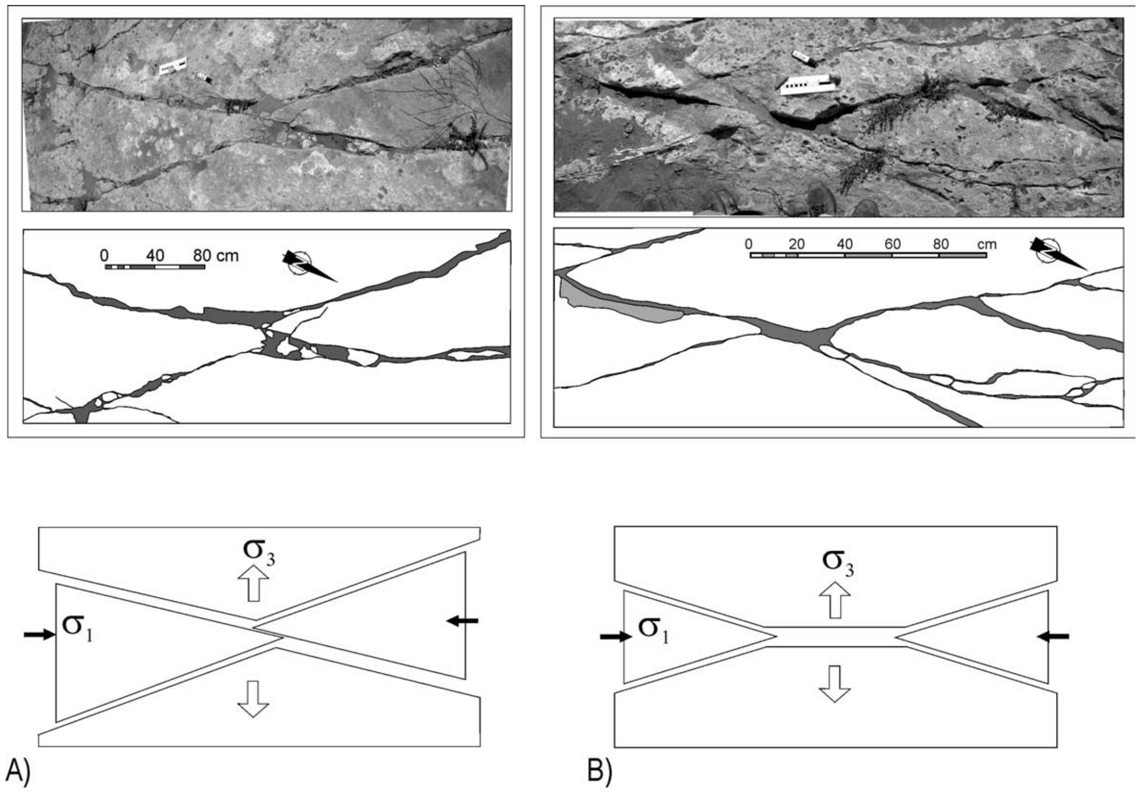


Fig. 4. Detailed photographs showing the opening of hybrid joints in Matagorda Quarry. Location in Fig. 1. Opening in hybrid joints is developed by indentation of opposite rock wedges (A) and/or by extension parallel to the tensional minimum stress axis (B).

during joint development probably at very shallow levels in the crust because the host rocks have not undergone deep burial.

Only a single set of vertical tensional joints showing a NW–SE trend and small openings is found in Late Pleistocene–Holocene deposits (Fig. 2A). These structures indicate that σ_3 is subhorizontal, with NE–SW orientation on the northern Campo de Dalias.

Fault orientations provide the most complete information about the deviatoric stress ellipsoid and also allow determination of the most recent stresses. We tried to select outcrops that fit theoretical requirements in order to have a homogeneous stress state: measurements taken in a small area, uniform lithology, flat fault surfaces with straight striae and small slips that do not produce block rotation.

In order to establish the validity of the Research Grid method (Galindo-Zaldívar and González-Lodeiro, 1988) in the area, paleostresses were also determined for site 7 with Etchecopar's method (Etchecopar et al., 1981) (Fig. 8) where a high number of striae and associated movement senses were determined. Similar results were obtained with the two methods, but the Search Grid method allows the use of striated microfaults whose sense of movement could not be determined.

Nine sites of faulting data have been studied in the area (Fig. 2B). Three of them are situated in the Alpujárride rocks, with a 19–21 Ma metamorphic age (Monié et al., 1991), and the others in the Upper Miocene to Quaternary sediments. The results obtained (Table 1) indicate several types of ellipsoids and homogeneous stresses for each rock type and in each region. The main stress ellipsoid group (ellipsoids in sites 7, 11, 13, 14 and 15) has subvertical σ_1 axes and subhorizontal σ_3 axes with WSW–ENE orientation. The axial ratios of these ellipsoids $((\sigma_2 - \sigma_3)/(\sigma_1 - \sigma_3))$ are low (between 0.04 and 0.29), indicating a prolate shape. In most stress ellipsoids of the first group, σ_3 is oriented WSW–ENE, although in some of them (e.g. sites 11 and 14) this orientation corresponds to σ_2. At site 14, the NW–SE orientation of σ_3 has practically no significance due to the similar values of σ_2 and σ_3 (axial ratio of 0.04). In general, the low axial ratio of these stress ellipsoids would favour local switching between σ_2 and σ_3.

In Tortonian calcarenites of the northern Campo de Dalias triaxial stress ellipsoids indicate NE–SW extension and NW–SE compression (site 16-I). Other ellipsoid groups determined for sites 17, 18 and 19-II in the Alpujárride Complex along the southern slope of Sierra de Gador, show different axial ratios in each sector. In the northwestern sector oblate stress ellipsoids indicate N–S extension with a σ_3 axis plunging towards the south. In addition, a NW–SE compressive stress tensor with a σ_1 axis inclined towards the SE is identified in the northeastern sector.

It is not easy to establish the age of faulting and stresses. We found some evidence for synsedimentary faulting in

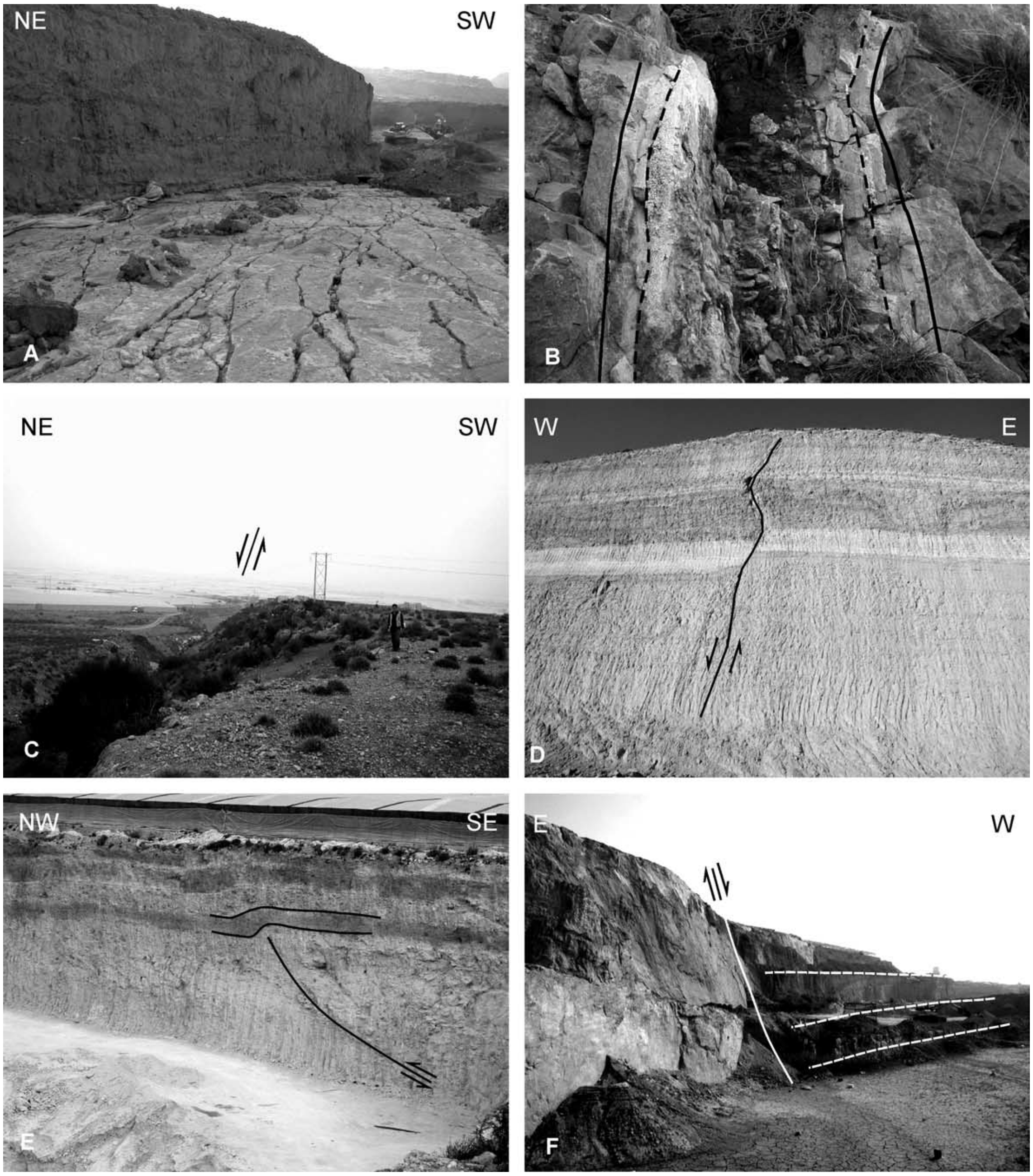


Fig. 5. Example of different fracture types in the Campo de Dalias. (A) Hybrid joints developed in Pliocene calcarenites, sealed by Holocene red silts. (B) Tensional joints with symmetrical calcite and recent soil filling the joint opening. (C) Recent fault scarp displacing a Quaternary alluvial fan, with a NE downthrow block. (D) Synsedimentary fault in Tortonian calcarenites. (E) Synsedimentary reverse fault in Pliocene calcarenites with a N45°E trend. (F) Half graben structure in Quaternary deposits.

some of the outcrops that supports our interpretation of the stress evolution (see discussion). In the NE Campo de Dalias, normal and strike-slip faults show evidence for Tortonian synsedimentary tectonic activity, which probably produced the observed variations in thicknesses between the footwall and hanging wall layers and indicate a NE–SW extension (Fig. 5D). In Pliocene calcarenites, a reverse NE–SW oriented fault has been also identified (Fig. 5E) indicating NW–SE compression. Finally, most of the NW–SE oriented faults affect Quaternary deposits and led to the development of half graben structures, like the Loma del Viento, Matagorda or Balanegra faults, all of them consistent with NE–SW extension (Fig. 5F).

5. Discussion and conclusions

The above established tectonic evolution, including paleostresses, provides insight into the development of hybrid and faulted joints.

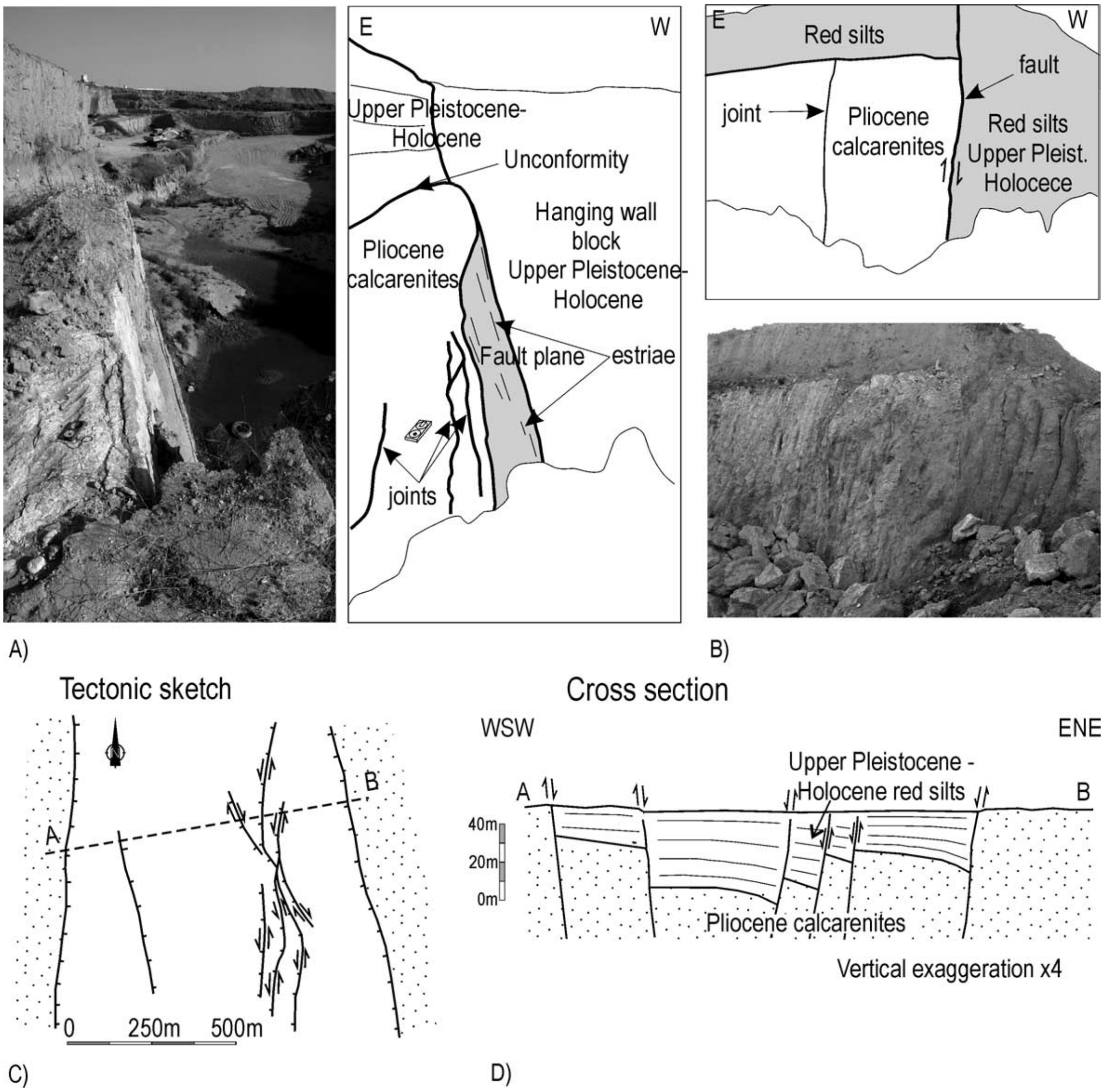


Fig. 6. Faulted joints and related structures in Matagorda Quarry (location in Fig. 1). ((A) and (B)) Joints parallel to faulted joints in Pliocene calcarenites. Note the presence of an unconformity between Pliocene and Upper Pleistocene–Holocene rocks. (C) Tectonic sketch of Matagorda Quarry showing the fault pattern and its similarity with the joint pattern at outcrop scale (Fig. 3). (D) Cross-section of Matagorda Quarry with the development of a half graben structure during Late Pleistocene–Holocene.

Table 1
Paleostress ellipsoids determined by the Search Grid method from microfaults in the study area. Location of measurement stations in Fig. 2

Site		Age/lithology	N	N_{tot}	σ_1	σ_2	σ_3	R[a]
7		Calcarenites and silts/Plio–Quaternary	14	17	172/78	352/12	82/0	0.26
11		Calcarenites/Pliocene	8	9	334/88	64/0	154/2	0.29
13		Silts and sands/Quaternary	5	5	144/81	297/8	28/4	0.10
14		Calcarenites/Pliocene	14	17	073/70	242/20	334/3	0.04
15		Calcarenites/Pliocene	11	13	223/71	334/10	076/16	0.10
16	I	Calcarenites/Tortonian	12	18	156/4	256/70	065/20	0.55
	II		5	6	173/61	334/28	068/8	0.04
17		Com. Alpujárride	5	6	080/8	336/59	175/30	0.95
18		Com. Alpujárride	9	12	85/36	305/47	191/21	0.76
19	I	Com. Alpujárride	12	19	236/11	27/78	144/6	0.06
	II		5	7	124/34	349/46	231/24	0.13

[a] $R = (\sigma_2 - \sigma_3)/(\sigma_1 - \sigma_3)$

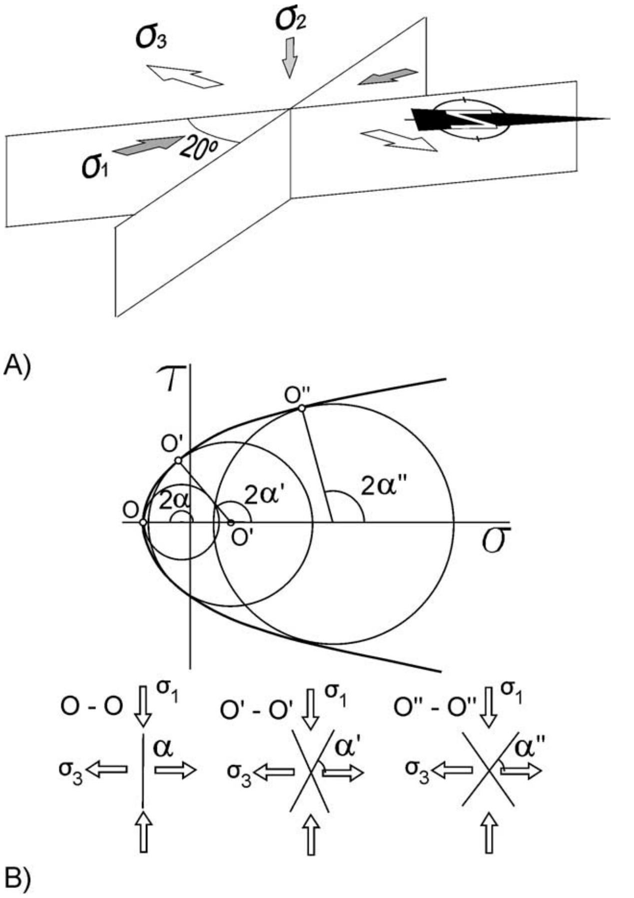


Fig. 7. Development of hybrid joints. (A) Orientation of main stresses during the development of the hybrid joint sets. (B) Mohr circle for Muehlberger model (1961) for conjugate fractures of low angle.

5.1. Hybrid joint development

The development of hybrid joints seems to be simultaneous with the development of gentle ENE–WSW folds. The better examples have been found in Pliocene–Middle Pleistocene rocks, although this setting may have been active since the Tortonian.

These hybrid joints formed with a subvertical σ_2 that corresponds to a wrench regime. Development of tensional and shear hybrid joints requires low differential stress and tensional minimum stress, so that the Mohr circle intersects the Mohr envelope in the tension zone and, in addition, the angle between fractures will be small. The presence of joint spectra (Hancock, 1986) possibly indicates the variation of differential stresses during the development of the joint system modifying the position of the intersections between the Mohr circle and the Mohr envelope and originating different angles between joints.

The largest joint openings have been observed in tensional sets because they are oriented orthogonal to σ_3, but also by the transfer of motion between neighbouring fractures with oblique displacements. In the outcrop of the Matagorda Quarry (Fig. 4), rock wedges are indented by compression parallel to σ_1, producing a forced additional

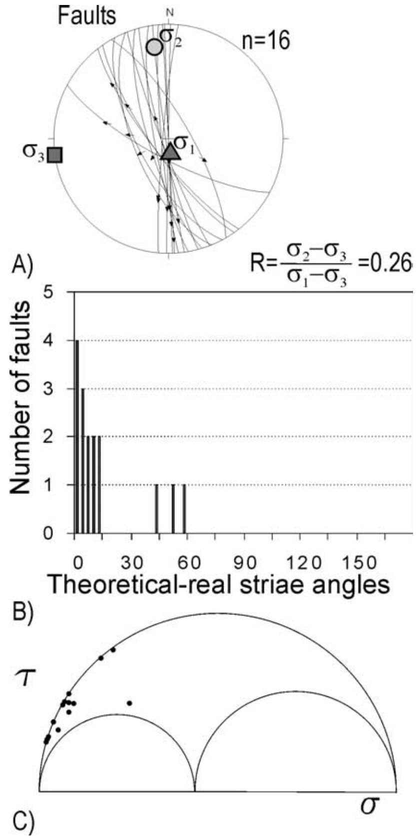


Fig. 8. Paleostress determination in Matagorda Quarry (site 2) by Etchecopar's method (Etchecopar et al., 1981). (A) Stereographic diagram of fault plane and striae, lower hemisphere. The main stresses calculated are indicated. (B) Frequency diagram of the angles between the real striae and the calculated theoretical striae. (C) Representation of the position of each fault in the Mohr diagram.

opening of the tensional joint that may have led to an increase in rock volume. This outcrop also shows that there is shortening parallel to the deduced σ_1 axis and extension parallel to the tensional σ_3 axis.

5.2. Faulted joints

In this region faults developed mainly from the Late Pleistocene to Present. The recent activity of the faults can be deduced from geomorphological features. The coastline is aligned with major faults like the Balanegra and Punta Entinas Faults (Fig. 1C). In addition, the development of fault scarps in the region (in some cases about 10 m high) and deformation of active alluvial fans constitute other field criteria for recognising recent tectonic activity. Meanwhile, tectonic activity is highlighted by the presence of distributed seismicity with small-magnitude earthquakes (mb < 5.0) (Stich and Morales, 2001). The focal mechanisms of these earthquakes were determined by the local seismic network of the Instituto Andaluz de Geofísica and suggest that the active faults developed in a complex setting, with associated normal faults (often with dextral components) and some reverse faults.

The faults of the study area have, at the surface, nearly vertical fault planes that feature Upper Pleistocene–Holocene activity, evidenced by the development of sedimentary wedges of variable polarities (Figs. 5F and 6D). There is not enough additional data to determine if half graben structures develop in a domino-like model or are related to listric normal faults that may decrease their dip downwards in the Pliocene silts and marls.

These faults have apparently different orientations and regimes with oblique slips, sometimes dextral and sometimes sinistral, and generally with subvertical fault planes. This apparent kinematic complexity may point to the existence of several deformation phases or a heterogeneous stress field in a very short time period responsible for the different motions. However, the paleostress calculations for the measured stations (Fig. 2B) yield a consistent stress ellipsoid compatible with the variety of measured orientations of striae and faults. The stress ellipsoids are generally prolate with subvertical σ_1 and the most predominant orientation of subhorizontal σ_3 axes is WSW–ENE.

Site 7 (Figs. 2 and 6) clearly shows a parallelism between the original Pliocene joints, which acted as planes of weakness along which faults developed. In this sense, they represent faulted joints (Wilkins et al., 2001). The fault slip is generally oblique, as a function of initial joint orientation.

This relationship between joint orientation and faulting indicative of faulted joints is very clear at outcrop scale. There are several criteria that show how the faults use preexisting joints as easy-slip planes. Subvertical joints and faults (Fig. 6A and B) show similar patterns at outcrop scale and in aerial photographs. The fault distribution with angles in-between of 30° in map view is quite similar to the attitude of joints at outcrop scale (Fig. 3) defining joint spectra. The presence of variable polarities of sedimentary wedges and opposite rotations of hanging wall blocks may be a consequence of the vertical attitude of fault planes. The relative chronology of different faults from cross-cut relationships in the case of faulted joints is more difficult to establish because the fault system has an inherited geometry from preexisting joints.

5.3. Tectonic evolution and paleostresses

Synsedimentary normal faults in the Tortonian calcarenites of the NE Campo de Dalias indicate NE–SW extension. This is compatible with the presence of two sets of joints that indicate possible local stress permutations in this area, with a dominant NE–SW trend of extension.

ENE–WSW oriented folds developed in the region since the Tortonian and produced uplift of the Sierra de Gador. Both compressional and extensional stresses may be associated with fold development. In Tortonian calcarenites and in the Alpujárride marbles of the NE Campo de Dalias, NW–SE compressional stresses have been determined (sites 16 and 19-II, Fig. 2B). The N–S extension associated with oblate stress ellipsoids found in the Alpujárride marbles of northwestern Campo de Dalias (sites 17 and 18, Fig. 2B) may be a consequence of deformation in the external arch of a regional-scale fold. In addition, the stress axes that have been determined in the marbles of southern Sierra de Gador were probably tilted southwards during fold development.

Tensional and hybrid joint sets in Pliocene calcarenites together with the development of ENE–WSW oriented synsedimentary reverse faults indicate paleostresses with NNW–SSE compression and ENE–WSW extension, in a setting of low differential stresses active up to the Middle Pleistocene and compatible with fold development. The die-out upwards of the joints at the top of the Pliocene calcarenites may be a consequence of the different mechanical stratigraphy. However, the presence of Pliocene marine shells and pebbles in the open joints, the absence of overlying continental red silts and the incompatibility of the Upper Pleistocene–Holocene wedge filling with hybrid joint development indicate that joints formed at the Pliocene–Upper Pleistocene time period.

Faults and joint sets affecting Late Pleistocene–Quaternary sediments signal a change in paleostresses during continuous ENE–WSW extension. The new paleostresses are dominated by subvertical maximum compression, with prolate stress ellipsoids that contribute to a local permutation of stress axes. In addition, in the northern Campo de Dalias, tensional joints of site 4 (Fig. 2A) show local deviations of the regional trend of extension due to the proximity to the Loma del Viento Fault. These extensional stresses are similar to those found in the Central Betic Cordillera.

5.4. Regional implications

The determination of paleostress ellipsoids has allowed us to define several stress states since the Tortonian. The common feature of these stress states determined in the upper crust is an ENE–WSW trend of extension axes that has also been determined in the Eastern Betic Cordillera, dominated by wrench faults, and in the central Betic Cordillera, dominated by normal faults (Galindo-Zaldívar et al., 2003). These extensional stress states may be a secondary order response to the regional NNW–SSE compression also determined by the joint system and that is in agreement with the convergence between Africa and Europe. In fact, stress tensors determined for the Neogene sedimentary basins of the Eastern Betic Cordilleras indicate NNW–SSE compression associated with a strike-slip regime from the Early Messinian to Early Pliocene (Stapel et al., 1996; Huibregtse et al., 1998; Jonk and Biermann, 2002). In addition, faults in these basins yield extensional paleostresses related to the development of normal faults during the Late Pliocene and Quaternary, although the trend of extension axes is poorly constrained. The paleostress evolution of the region studied in this paper is similar to that of other basins recognised in the Central–Eastern Betic Cordilleras, yet the transcurrent deformations only develop joints sensu stricto and not strike-slip faults in a regime of low differential stresses, probably related as well to the low intensity of the deformation near the Alboran Sea. In addition, the proximity to the central Betic Cordillera induces a well-defined trend of ENE–WSW extension for the most recent deformations. This area represents the transition between two areas subjected to different stress states and undergoing different deformations.

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