Miocene extensional basin development in the Betic Cordillera, SE Spain revealed through analysis of the Alhama de Murcia and Crevillente Faults

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ABSTRACT

The Alhama de Murcia and Crevillente faults in the Betic Cordillera of southeast Spain form part of a network of prominent faults, bounding several of the late Tertiary and Quaternary intermontane basins. Current tectonic interpretations of these basins vary from late-orogenic extensional structures to a pull-apart origin associated with strike-slip movements along these prominent faults. A strike-slip origin of the basins, however, seems at variance both with recent structural studies of the underlying Betic basement and with the overall basin and fault geometry. We studied the structure and kinematics of the Alhama de Murcia and Crevillente faults as well as the internal structure of the late Miocene basin sediments, to elucidate possible relationships between the prominent faults and the adjacent basins. The structural data lead to the inevitable conclusion that the late Miocene basins developed as genuinely extensional basins, presumably associated with the thinning and exhumation of the underlying basement at that time. During the late Miocene, neither the Crevillente fault nor the Alhama de Murcia fault acted as strike-slip faults controlling basin development. Instead, parts of the Alhama de Murcia fault initiated as extensional normal faults, and reactivated as contraction faults during the latest Miocene-early Pliocene in response to continued African-European plate convergence. Both prominent faults presently act as reverse faults with a movement sense towards the southeast, which is clearly at variance with the commonly inferred dextral or sinistral strike-slip motions on these faults. We argue that the prominent faults form part of a larger scale zone of post-Messinian shortening made up of SSE- and NNW-directed reverse faults and NE to ENE-trending folds including thrust-related fault-bend folds and fault-propagation folds, transected and displaced by, respectively, WNW- and NNE-trending, dextral and sinistral strike-slip (tear or transfer) faults.

INTRODUCTION

The Betic Cordillera of southern Spain, together with the Rif and Tell Mountains in Morocco and Algeria, form the arc-shaped western end of the Alpine orogenic belt (inset of Fig. 1), developed since the early Tertiary due to collision of the African and Eurasian plates. The belt can be divided in a nonmetamorphic External Zone and a dominantly metamorphic and intensely deformed Internal Zone (Fig. 1). The External Zone represents the Mesozoic rifted margin of Iberia (García-Hernández et al., 1980; Peper & Cloetingh, 1992), which became folded and thrust towards the northwest onto the Iberian foreland from possibly the late Oligocene or early Miocene up to the late Miocene (García-Hernández et al., 1980; Banks & Warburton, 1991; Beets & De Ruig, 1992; van der Straaten, 1993; Geel, 1996; Geel & Roep, 1998, 1999; Platt et al., 2003; Guerra et al., 2005). The Internal Zone of the Betic Cordillera has a ‘Basin and Range’-type morphology made up of elongate mountain ranges of mainly metamorphosed Palaeozoic and Mesozoic rocks (e.g. Egeler & Simon, 1969, Platt & Vissers, 1989), which are separated by narrow elongate basins filled with Neogene to recent continental siliciclastics and marine-mixed siliciclastic/carbonate facies, marls and evaporites (e.g. Sanz de Galdeano, 1990; Fig. 1).

A notable feature of the south-eastern part of the Betic Cordillera is a NE-trending network of prominent major faults with a marked morphological expression, i.e. from NE to SW: the Crevillente fault, the Alhama de Murcia fault, the Palomares fault and the Carboneras fault (Figs 1 and 2), which bound several of the late Tertiary (Miocene-Pliocene) and Quaternary basins. Some parts of these faults, i.e. the Alhama de Murcia, Carboneras and Palomares faults, have been studied in detail and their geometry and kinematics have been documented (e.g. Bousquet & Montenat, 1974; Gauyau et al., 1977; Bousquet, 1979; Rutter et al., 1986; Martínez-Díaz & Hernández Enrile, 1992a; Silva et al., 1992; Keller et al., 1995; Jonk & Biermann, 2002; Booth-Rea et al., 2003; Faulkner et al., 2003). Despite these studies, the timing of the initial movements and amounts...
of displacement on these faults, as well as their relationship with the Neogene basin development, are still a matter of debate.

Several recent studies of the metamorphic rocks from the Internal Zones have provided evidence for rapid exhumation and associated extension of a previously thickened crust (Platt & Vissers, 1989; Jabanoy et al., 1992; Vissers et al., 1995), which started in the late Oligocene–early Miocene and continued well into the Miocene (Monie et al., 1994; Johnson et al., 1997; Lonergan & Johnson, 1998; de Jong, 2003; Platt et al., 2005). Seismic studies of the Granada (Morales et al., 1990; Ruano et al., 2004) and Fortuna–Guadalentin Basins (Amores et al., 2001 and 2002), and detailed structural and sedimentological studies, e.g. of the Huercal Overa Basin (Mora Gluckstadt, 1993), demonstrate the existence of late Miocene half graben structures. Seismic surveys in the Alboran Sea have shown similar structures in the Miocene sediments (Comas et al., 1992; Mauffret
et al., 1992; Watts et al., 1993). The simultaneous exhumation and thinning of the metamorphic middle to upper crust and the deposition of upper Miocene sediments in an extensional setting suggest a dynamic link: the extensional intermontane Basins in fact developed on top of a previously thickened, collapsing or stretching continental crust. In essence, two different models have been proposed to explain the late-orogenic extension in the Internal Zone: removal of a thickened subcontinental lithosphere, either by convection (e.g. Platt & Vissers, 1989) or by lithospheric delamination (e.g. García-Dueñas et al., 1992), and subduction roll-back followed by slab-detachment (e.g. Morley, 1993; Lonergan & White, 1997; Spakman & Wortel, 2004). It is emphasized here that the resulting crustal thinning occurred within an overall setting of continuous slow convergence of the African and Eurasian plates.

Montenat et al. (1987), Montenat & Ott d’Estevou (1990, 1996, 1999) and De Larouzière et al. (1988), on the other hand, have suggested that the late Miocene intermontane basins, such as the Lorca, Vera, Huercal Overa and Fortuna...
Basins, are in fact, respectively, pull-apart, wrench furrow and compressionally and extensional imbricate fan basins (rhomb–graben, ‘Sillon sur décrochement’ and ‘Queue de cheval’ structures at compressional and extensional ends of strike–slip faults), which developed as a result of sinistral movements along the NE-trending Alhama de Murcia (Bousquet & Montenat, 1974) and the N-trending Palomares and Carboneras faults. According to, e.g. Bousquet (1979) and Masana et al. (2004), such activity may very well be associated with the present-day convergence of the African plate towards Eurasia.

The interpretation, however, of the late Miocene basins as strike–slip-controlled pull-apart or compressional basins raises some problems as follows. First, from a structural point of view, many of the late Miocene depocentres such as for example the Huercal Overa, Sorbas, Vera and Mazaron Basins are not located on the releasing or restraining bends (Sylvester, 1988; Woodcock & Schubert, 1994) on these faults, as is obvious from comparison of the basin and fault geometries shown in Fig. 3.

Second, the NE–SW to N–S–directed extension implied by extensional normal fault structures in the late Miocene basins as described by, e.g. Balanyà & García-Dueñas (1991), García-Dueñas et al. (1992), Mora Gluckstadt (1993), Vissers et al. (1995), Poisson et al. (1999), Augier (2004) and Meijninger (2006), are in direct conflict with the approximately N–S–directed compression that should be associated with a sinistral sense of shear along the Alhama de Murcia and Palomares faults (Figs 3 and 4).

Third, the first-order geometry of the basins at the inferred releasing bends differs from any typical pull-apart basin geometry, and in general the characteristic fault step-over structure (Sylvester, 1988; Dooley & McClay, 1997) seen, e.g. along the San Andreas fault zone, the Dead Sea fault zone or the Abarán Basin in the External Zone of the Betics (van der Staaijen, 1993), is lacking (Fig. 3).

Fourth, the Lorca Basin for example, interpreted as a pull-apart basin by several workers (e.g. Montenat et al., 1990; Guillén Mondéjar et al., 1995; Krijgsman et al., 2000; Vennin et al., 2004), certainly has a rhomboidal shape (Figs 1 and 4). Along its south-eastern margin, however, the basin is bounded by the Alhama de Murcia fault, which is a continuous fault zone that does not terminate at any of the basin corners (Bousquet, 1979; Martínez-Díaz & Hernández-Enríque, 1992a, b; Silva et al., 1992). For the northern margin, De Larouzière et al. (1988), Montenat et al. (1990) and Guillén Mondéjar et al. (1995) have suggested that the basin is bound by the NE-trending North Betic fault (NBF), which they interpret as a sinistral strike–slip fault. On the other hand, according to, e.g. Leblanc & Olivier (1984) and Guillén Mondéjar et al. (1995), the NBF has a dextral sense of shear as opposed to the sinistral movement sense of the Alhama de Murcia fault (Fig. 4). Aside the fact that these inferred movement senses are as yet poorly substantiated by structural studies, the opposing movement senses of the faults at the northern and southern sides of the basin are at variance with the motions expected for a pull-apart fault system. In addition, the inferred NBF is virtually continuous with the south-directed thrusts of the Internal External Zone Boundary (IEZB; Figs 1 and 4), and this structure is unconformably sealed by middle Miocene to Quaternary sediments such that it cannot have played an active role in the development of the Lorca Basin during the late Miocene (Lonegarn et al., 1994; Geel & Roep, 1998, 1999).

Finally, a fifth problem concerns recent palaeomagnetic data from upper Miocene basin sediments and volcanic deposits suggesting that no rotations occurred during the late Miocene (Krijgsman & García, 2004 and Fig. 4) or at least not until after the Tortonian (Calvo et al., 1994, 1997 and Fig. 4), whereas field studies as well as analog and numerical modelling (e.g. Hall, 1981; Ron et al., 1984; Garfunkel & Ron, 1985; Schreurers, 1994; Waldrum, 2004) suggest that such rotations are to be expected in sediments deposited in a strike–slip tectonic setting.

Recent structural studies of the major fault systems in SE Spain have so far mainly focussed on the Carboneras (Rutter et al., 1986; Kellert et al., 1995; Bell et al., 1997; Scothney et al., 2000; Reicherter & Reiss, 2001; Faulkner et al., 2003) and Palomares faults (Weijermars, 1987; Jonk & Biermann, 2002; Booth–Rea et al., 2003). Except for few detailed studies of a small segment of the Alhama de Murcia fault by Rutter et al. (1986), Martínez-Díaz & Hernández-Enríque (1992a) and Martínez-Díaz (2002), there are virtually no structural data documented from the Crevillente and Alhama de Murcia faults. Besides the allegedly dextral Crevillente fault (e.g. De Smet, 1984), it has been generally accepted that most of the major faults in the SE Betics represent sinistral strike–slip faults, that they are part of a crustal–scale transcurrent shear zone (Montenat et al., 1987; De Larouzière et al., 1988), and that they essentially controlled the development of the late Miocene basins. Alternatively, Vissers et al. (1995) and Calvo et al. (1997) have suggested that the activity on these faults is essentially late Miocene to Quaternary, i.e. after most of the Miocene basins had ceased to be active depocentres, and that motion on these faults largely reflects the recent stages of ongoing Africa–Europe convergence.

In this paper, we focus on the geometry and kinematics of the prominent faults and on the late Miocene basin fill and basin structure, with the aim to elucidate the relationship between Miocene basin development and the development of the prominent faults. The three basins of interest, the Huercal Overa, Lorca and Fortuna Basins, are situated, respectively, at the end of the Alhama de Murcia fault, alongside the Alhama de Murcia fault and in between the Alhama de Murcia and Crevillente faults. We summarize previous and new data on the basin fill and its
Fig. 3. (a) Sketch map illustrating how regional sinistral shear, shown for an orientation similar to the Alhama de Murcia fault, can be distributed along fault segments that are not coplanar. Slip is relayed from one segment to another at a stepover. At a restraining stepover, compression and thrusting occur, resulting in a ridge. At a releasing stepover, extension and subsidence occur, resulting in a pull-apart basin. Maximum and minimum principal stress axes are shown consistent with Andersonian faulting. (b) Tectonic map of south-eastern Spain, after Montenat et al. (1987). Numbers: (1) Huercal Overa Basin, (2) Lorca Basin, (3) Fortuna Basin, (4) Sorbas Basin, (5) Vera Basin and (6) Hinojar-Mazaron Basin.
structure in each of the three basins, with emphasis on the geometry, kinematics and structural history of the major faults. We conclude that during the Miocene (late Serravalian–late Tortonian), the Huercal Overa, Lorca and Fortuna Basins developed as extensional basins, presumably associated with the thinning and exhumation of the underlying basement. During the Tortonian, neither the Crevillente fault nor the Alhama de Murcia fault acted as strike–slip faults controlling basin development. Instead, parts of the Alhama de Murcia fault came into existence as extensional faults, and these were reactivated as oblique contraction faults in the latest Miocene–early Pliocene, in response to the continued African–European plate convergence. Both prominent faults presently act as reverse faults with a clear movement sense towards the southeast, as opposed to the generally assumed dextral or sinistral strike–slip motion. We argue that these reverse faults form part of a larger scale zone of post-Messinian shortening made up of SSE- and NNW-directed thrusts and NE to ENE-trending folds including thrust-related fault-bend folds and fault-propagation folds, displaced by NNE-trending sinistral and (mostly outcrop-scale) W to WNW-trending dextral strike–slip (tear or transfer) faults, respectively.

Fig. 4. Tectonic map of south-eastern Spain showing average Miocene extension directions and palaeomagnetic rotations. NBF, North Betic Fault; for other abbreviations see Fig. 1. Miocene extension directions are derived from tectonic structures in Miocene basin sediments (this study) and from literature; (a) Mora Gluckstadt (1993), Augier (2004) and Meijninger (2006), (b) Booth-Rea et al. (2002) and Meijninger (2006) and (c) Poisson & Lukowski (1990) and Meijninger (2006). Palaeomagnetic rotations from (1) Krijgsman & Garces (2004), (2) Krijgsman et al. (2006), (3) Dinarés-Turell et al. (1997), (4) Mora Gluckstadt (1993), (5) Calvo et al. (1994), (6) Calvo et al. (1997) and (7) Meijninger (2006).
To determine the sense of shear of faults in the Miocene basins and the kinematics of the prominent Crevillente and Alhama de Murcia faults, we studied both structures on fault planes (such as tensile fractures, Riedel fractures, striations) and shear structures in fault gouges (Riedel, P, Y, R2 and X shears and striations on these shear planes) as described by e.g. Logan et al. (1979), Rutter et al. (1986), Gamond (1987), Hancock & Barka (1987), Means (1987), Petit (1987), Sylvester (1988) and Woodcock & Schubert (1994).

**BASIN STRATIGRAPHY**

The Miocene and Pliocene stratigraphy of the Fortuna, Lorca and Huercal Overa Basins and the geometry of the Lorca and Huercal Overa Basins in particular have been thoroughly studied and documented (Geel, 1976; Briend, 1981; Briend et al., 1990; Lukowski & Poisson, 1990; Montenat et al., 1990; Poisson & Lukowski, 1990; Mora Gluckstadt, 1993; Geel & Roep, 1998, 1999; Rouchy et al., 1998; Wrobel & Michalzik, 1999; Krijgsman et al., 2000; Wrobel, 2000; Augier, 2004; Vennin et al., 2004; Meijninger, 2006). In map view, the Fortuna, Lorca and Huercal Overa Basins have a rhomboïdal shape with an ENE-trending basin axis (overview in Fig. 1, details in Figs 5, 6 and 7). In cross-section, the Fortuna and Lorca Basins have a symmetric geometry of a 10-km scale, very open synform (Montenat et al., 1990; Poisson & Lukowski, 1990; Wrobel & Michalzik, 1999). The Huercal Overa Basin, however, shows a clearly asymmetric (half-graben) geometry with mostly south-dipping strata (Meijninger, 2006). The Fortuna Basin is fault-bounded at its northern and southern sides (Lukowski & Poisson, 1990). The Huercal Overa and Lorca Basins are fault bounded at their southern sides, whereas at their northern margins the Miocene sediments lie unconformably on the basement rocks of, respectively, the Internal and the External Zones (Geel, 1976; Briend 1981; Mora Gluckstadt, 1993).

Within the basins studied here, early Miocene sediments are only exposed along the northern margin of the Lorca Basin, which were deposited before the development of the Lorca Basin (Geel & Roep, 1998, 1999). These deposits include Aquitanian and Burdigalian marine sediments that are cut by a low-angle, south-directed thrust of the IEZB and are tectonically overlain by Mesozoic limestones of the External Zone (Lonergan et al., 1994).

The lower Miocene sediments and the basement rocks of the External and the Internal Zone along the northern Lorca Basin margin are unconformably overlapped by middle Miocene (upper Langhian and Serravallian) marine sediments deposited in a prograding delta system (Geel & Roep, 1999). Stratigraphically upwards, these sediments pass into a thick series of continental alluvial fan and playa/sabkha deposits. As compared with the lower Miocene sediments, the detritus of these continental deposits is markedly polymict and includes material derived from both the External and the Internal Zone. The precise age of the continental deposits is unknown, but part of the metamorphic detritus in the Lorca and Huercal Overa Basins clearly originates from the Sierra de los Filabres in the Internal Zone (Fig. 1). According to Johnson et al. (1997), the greenschist facies metamorphic rocks of the Sierra de Los Filabres were cooled to near-surface temperatures during the mid-Serravallian (12 ± 1 Ma), which is consistent with a late Serravallian to early Tortonian age for the continental sediments containing this Filabride detritus.

Both lower-middle Miocene sediments and Internal–External Zone basement rocks are unconformably overlain by Tortonian transgressive marine sediments. Along the margins of the basins, prograding reefs and submarine fans interfinger with marine pelagic marls and turbidites in the central parts of the basins (Geel, 1976; Briend, 1981; Briend et al., 1990; Lukowski & Poisson, 1990; Vennin et al., 2004).

In the Fortuna and Lorca Basins, the upper Tortonian marine sediments change stratigraphically upwards into a regressive sequence of mixed continental alluvial and lacustrine/shallow marine diatomite-evaporitic deposits of late Tortonian to early Pliocene age (Lukowski & Poisson, 1990; Poisson & Lukowski, 1990; Rouchy et al., 1998; Krijgsman et al., 2000; García-Melléndez et al., 2003; Meijninger, 2006). In the Huercal Overa Basin, marine conditions persisted well into the early Messinian, and were followed by a rapid shallowing (Briend, 1981; Briend et al., 1990). Uppermost Miocene–Pliocene continental alluvial and shallow marine deposits partly cover and fill a late Miocene palaeo-relief (Briend, 1981; Briend et al., 1990; García-Melléndez et al., 2003; Meijninger, 2006).

Both Miocene and Pliocene sediments are covered by Quaternary continental alluvial fans and travertine deposits and have been subsequently incised by Quaternary rivers (Briend, 1981; Briend et al., 1990; Stokes & Mather, 2003).

**BASIN STRUCTURE AND GEOMETRY AND KINEMATICS OF THE PROMINENT FAULTS**

Middle and upper Miocene sediments unconformably overlie the lower Miocene deposits and thus seal the lower Miocene compressional structures (Lonergan et al., 1994). The upper Serravallian to upper Tortonian sediments of the Fortuna, Lorca and Huercal Overa Basins contain clear evidence for syn-sedimentary extensional tectonics in the form of a variety of structures at outcrop as well as at larger scales, including large-scale roll-overs and growth-fault structures (Meijninger, 2006). The extensional structures in the upper Serravallian to upper Tortonian basin sediments, as well as the fault-bounded southern side of the Huercal Overa Basin show sets of dip-slip shear indicators (Fig. 8). Moreover, in the eastern part of the Lorca Basin in the Rambla de Lebor, a marked stratigraphic expansion of
Fig. 5. Fortuna Geological map and cross-section of the northeastern part of the Fortuna Basin. Map after Azema & Montenat (1973) and Lukowski & Poisson (1990), Poisson & Lukowski (1990), Garcés et al. (2001) and Meijninger (2006). Age of the Fortuna lamproite after Kuiper et al. (2006). Inset: CRF, Crevillente fault; IEZB, Internal–External Zone Boundary; AMF, Alhama de Murcia fault.
upper Miocene shallow marine deposits

middle-upper Miocene marine deposits

Betic substratum (External Zone)

Triassic evaporites

uppermost Miocene continental deposits

upper Miocene shallow marine deposits

upper Miocene fluvial-shallow marine deposits

upper Miocene fluvial-shallow marine deposits

Quaternary alluvial-fluvial deposits

Pliocene fluvial and marine deposits

Cabezos Negros Lamproite (7.71 ± 0.11 Ma)

uppermost Miocene fluvial-evaporitic deposits

strike-slip fault

thrust or reverse normal fault

folds

orientation of bedding

Late Miocene mean site magnetic declination with reference number (see Fig. 4)

Late Miocene mean extension direction and latest Miocene-Quaternary direction (Meijninger, 2006)

Crevillente Fault

6.9 km

Sierra Abanilla

NW

SE

Fig. 5. Continued.

Miocene extensional basin development in the Betic Cordillera
Fig. 6. Continued

Late Miocene mean extension direction and latest Miocene-Quaternary compressional direction.

Late Miocene mean site magnetic declination with reference number (see Fig. 4)

Miocene extensional basin development in the Betic Cordillera
Tortonian sediments, in part accommodated by normal faults, occurs towards the Alhama de Murcia fault (Fig. 9). The orientations of the extensional structures in the Miocene basins vary, but lineations and shear senses are in general consistent with a NNE to ENE extension direction (Figs 5, 6 and 7). The faulted upper Miocene sediments are unconformably overlain by the uppermost Miocene and Pliocene sediments, which poses a lower bound to the age of the extensional deformation.

In the surrounding basement rocks of both the Internal and External Zones, earlier (ductile) deformational structures are overprinted by brittle extensional
Fig. 8. (a and b) Fault scarp of basin-bounding Rodrigo fault south of Huercal Overa (for location see Figure 7) viewed normal (a) and oblique (b) to fault strike. *denotes corresponding point on fault plane. The fault separates lower Tortonian continental deposits from Alpujarride limestone of the Sierra Almagro. The fault surface contains two groups of structures: one comprising Riedel fractures, tension cracks and down-plunging to oblique lineations related with dip-slip and dextral-oblique slip motions, overprinted by a second group of Riedel fractures, tension cracks and subhorizontal lineations indicating sinistral strike-slip. (c) Stereographic projections (equal area, lower hemisphere) showing orientations of fault surfaces and lineations of the Rodrigo fault. The fault contains structures pointing to dip to oblique slip and occasionally dextral oblique to strike-slip indicating NNE–SSW to NNW–SSE-directed extension. The second set of Riedel fractures and tension cracks on the fault surface points to sinistral strike-slip motions indicating NNW–SSE-directed compression. P- and T-axes denote principal axes of incremental shortening and extension inferred from fault plane orientation, lineations on the fault plane and slip direction following Marrett & Allmendinger (1990).
structures. Like the extensional structures in the upper Miocene sediments, these latter brittle structures are consistent with an approximately ENE to NE- or NNE to N-directed extension (García-Dueñas et al., 1992; Mora Gluckstadt, 1993; Vissers et al., 1995; Booth-Rea et al., 2002; Augier, 2004; Platzman & Platt, 2004; Meijninger, 2006).

As opposed to these extensional structures, the geometry and kinematics of the morphologically prominent faults bounding the Fortuna, Lorca and Guadalentin-Hi-

**Fig. 9.** (a) Cliff exposure along the Rambla de Lebor, southeastern Lorca Basin, adjacent to the Alhama de Murcia fault (for location see Figure 5.19), showing stratigraphic expansion of Tortonian sediments, in part accommodated by normal faults. Note that some of the faults are sealed by internal unconformities indicating that these faults were active during deposition of the expanding sequence. The structure strongly suggests that during the Tortonian the adjacent Alhama de Murcia fault initiated as a growth fault. (b) Stereographic projection (equal area, lower hemisphere) showing orientations of extensional normal faults, Riedel fractures (dashed lines) and slip-vectors of the outcrop shown in (a). Note two sets of faults, i.e., a dominant set of ENE to NE-trending faults suggesting N–S extension, and a second set of N–S-trending steep faults.
nojar basins indicate that they are in fact thrusts or reverse faults (Fig. 10). Lineations on fault surfaces as well as shear senses in fault gouges associated with these prominent faults systematically indicate hanging-wall transport directions towards the S to SE (Crevillente and Alhama de Murcia faults; Fig. 11a–e) or the N (Hinojar fault; Fig. 11h), which is largely consistent with observations of, e.g. Rutter et al. (1986) also shown in Fig. 10. Segments of the Alhama de Murcia and Crevillente faults, for example, accommodate a southward movement of the hanging-wall basement of respectively the Sierra de la Tercia and the Sierra de Crevillente on the steeply north-dipping reverse faults (Fig. 12). Along the northern sides of these ENE-trending ranges, upper Miocene sediments lie unconformably on the basement rocks but are now tilted to the north. Upper Miocene sediments in the footwall are steeply tilted to the south and are folded along a NE to ENE-trending fold axis associated with an ENE-trending footwall syncline. The (syn-sedimentary) extensional structures in the upper Miocene sediments are tilted and folded or, in the footwall, have been reactivated as reverse faults. Balanced cross-sections of the essentially asymmetric antiformal Sierra de la Tercia (Fig. 6) and Sierra Crevillente (Fig. 5) suggest that their main structure is in fact thrust related: a fault-propagation fold in case of the Sierra de la Tercia and a fault-bend fold in case of the Sier-
Fig. 11. Stereographic projections (equal area, lower hemisphere) showing orientations of faults and lineations in outcrops of the Crevillente, Alhama de Murcia, Albox, Rodrigo, Palomares and Hinojar faults. For locations see Fig. 10. \( P \) - and \( T \)-axes as defined in Fig. 8.
Fig. 12. Structure of the Crevillente Fault near Abanilla. (a) Panoramic view of the Sierra de Abanilla, for location see Fig. 5. (b) View of the southern side of the Sierra de Abanilla showing Mesozoic limestones of the Betic External Zone thrust along a NW-dipping fault onto upper Miocene sediments. (c) Outcrop at Abanilla of the steep faulted contact between Mesozoic rocks of the Sierra de Abanilla and upper Miocene marls. (d) Stereographic projection (equal area, lower hemisphere) showing orientations of fault planes and slip vectors observed on the Crevillente fault at Abanilla. An early set of subhorizontal lineations and Riedel fractures is overprinted by a second set of steeply plunging lineations and Riedel fractures. The first set of structures point to sinistral-reverse motion, the second set suggests reverse motions. $P$- and $T$-axes as defined in Fig. 8.
ra de Crevillente. We estimate that these thrust-related fold structures accommodated at least 1600 m of shortening in the Sierra de la Tercia, and at least 1000 m shortening in the Sierra de Crevillente.

In the Fortuna Basin, and between the city of Murcia and the Lorca Basin, the Alhama de Murcia and Crevillente faults are in fact fault zones that consist of a series of en-echelon stepping or parallel-running thrusts and folds (see also Bousquet & Montenat, 1974; Gauyau et al., 1977; Bousquet, 1979; Martínez-Díaz & Hernández Enríquez, 1992a, b; Silva et al., 1992; Amores et al., 2001 and 2002). These compressional structures are discontinuous along strike, and the shortening is transferred via small and large-scale NNE-trending sinistral and mainly small-scale WNW-trending dextral strike-slip faults that act as tear or transfer faults (Sylvester, 1988). These latter faults notably show slip vectors that deviate from the transport direction on the main fault (Fig. 10). Beside these outcrop data, a seismic profile across the Fortuna Basin and the Alhama de Murcia fault zone (Amores et al., 2001; Fig. 13) clearly shows a series of NW-dipping reverse faults that mark the position of the Alhama de Murcia fault zone. This seismic profile shows three other important aspects of the Alhama de Murcia fault zone, i.e.: (1) a listric geometry of the faults of this fault zone, (2) a conspicuous thickening of the middle and late Miocene sediments in the hanging wall towards the fault zone, and (3) intraformational unconformities, all indicating that the Alhama de Murcia fault initially acted as an extensional structure, i.e. as a growth fault.

Along the southern margin of the Lorca Basin and along the Sierra de las Estancias, the Alhama de Murcia fault is a morphologically sharp, NE-trending linear structure (Bousquet & Montenat, 1974; Fig. 2) associated with the contact of basement and Quaternary basin sediments, and defined by a steep NW-dipping fault (Fig. 14). Kinematic indicators consistently indicate a sinistral reverse movement on this fault (Figs 11c–d and 14). Scarcce outcrops of steeply tilted Miocene sediments of the footwall, oriented parallel to the main fault, reveal both layer-parallel reverse and sinistral shear senses and are cut and displaced by NNE-trending sinistral and WNW-trending dextral strike-slip faults.

The Huercal Overa Basin straddles the south-western end of the Alhama de Murcia fault, where the fault passes into a ENE to E-trending morphological structure in the central part of the basin, which is considered part of the Albox fault (Masana et al., 2005; Figs 2 and 7). Here, upper Miocene sediments are folded in a 100-m scale monocline with a NNW-dipping axial plane. To the west, E–W-trending steeply tilted Miocene sediments reveal layer-parallel reverse and dextral shear senses (Fig. 5). Southeast of the monocline fold, thick Pliocene and Quaternary sediments have been deposited in the eastern part of the Huercal Overa Basin. These sediments are occasionally affected by south-directed thrusts (García-Meléndez et al., 2002, 2003; Soler et al., 2003; Masana et al., 2005; Fig. 15). Importantly, dip–slip shear sense markers on exposed fault surfaces of the fault-bounded southern side of the Huercal Overa Basin are clearly overprinted by kinematic indicators pointing to a sinistral strike-slip motion (Fig. 8).

Segments of the Palomares fault on the eastern margin of the Vera Basin are vertical, N to NNE-trending sinistral strike-slip faults, as evidenced by kinematic data illustrated in Figs 10 and 11g (see also Booth-Rea et al., 2003; 2004). The Palomares fault passes into the NE to E-trending Hinojar fault along the southern margin of the Guadalentin–Hinojar Basin (Figs 10 and 11h).

**DISCUSSION**

In this study, we question current interpretations of the Miocene basins in SE Spain as strike-slip-controlled
pull-apart or compressional basins. As outlined above, such interpretations are faced with problems regarding the overall geometry of the basins and adjacent bounding faults, as well as with conflicting structural data.

The largely syn-sedimentary extensional structures in the upper Miocene basin sediments are either unconformably sealed by the uppermost Miocene to Pliocene sediments or have been reactivated since as reverse faults. This interpretation is strongly supported by seismic profiles both onshore (Amores et al., 2001 and 2002; Fig. 13) and offshore (Bourgois et al., 1992; Comas et al., 1992; Woodside & Maldonado, 1992; Watts et al., 1993). Evidence of deformed Quaternary sediments close to the Alhama de Murcia and Palomares faults (Bousquet & Montenat, 1974; Bousquet et al., 1975; Gauyau et al., 1977; Bousquet, 1979; Silva et al., 1997; Martínez-Díaz & Hernández-Enríquez, 2001; Soler et al., 2003; Masana et al., 2004; Fig. 15) demonstrate recent activity of these faults.

Our structural data indicate that the basins discussed here developed their rhomboidal geometry from the late Serravallian to the late Tortonian in response to the approximately N to NE-directed extension. This stage of Miocene basin development thus represents a precursor stage to the present-day ‘Basin and Range’ type morphology of the region. We emphasize that the average N to NE-oriented extension direction, inferred from extensional faults in the basins and in the underlying basement, is entirely inconsistent with sinistral motion on main faults such as the Alhama de Murcia fault. Consequently, and in view of the various other problems surrounding pull-apart or imbricate fan interpretations of the late Miocene basins as outlined above, we suggest that these basins de-

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**Fig. 14.** (a) Exposure of the Alhama de Murcia fault northeast of Puerto Lumbreras, carrying Alpujarride rocks of the Sierra de las Estancias towards the SE onto upper Tortonian marls. For location see Fig. 10. (b) Stereographic projections (equal area, lower hemisphere) showing orientations of reverse and strike-slip faults in Miocene–Quaternary sediments and basement rocks in the Alhama de Murcia fault zone near Puerto Lumbreras. P- and T-axes as defined in Fig. 8.
Developed as genuinely extensional basins (half-grabens) until the latest Miocene, a process presumably associated with the thinning and exhumation of the underlying basement before inversion of both basins and faults.

This raises the question in how far prominent faults such as the Alhama de Murcia and Crevillente faults, or their precursors, played a role in late Miocene basin development. As outlined above, the Alhama de Murcia and Crevillente faults in fact define a fault zone (deformation zone) running from Alicante towards the Huercal Overa Basin (Fig. 10). This deformation zone embraces a number of discontinuous, ENE to NE-trending morphologically prominent reverse faults and thrusts, which bound the northern and/or southern margins of the Miocene–Quaternary basins, as well as folds (mainly in the Fortuna and Alicante Basins) and thrust-related folds (Huercal Overa Basin, Sierra de la Tercia and Sierra de Crevillente). Similar structures have been observed on seismic profiles onshore and offshore of Alicante (Alfaro et al., 2002a, b: the Bajo Segura fault) and the Alboran Sea (Comas et al., 1992). Segments of the Alhama de Murcia and Crevillente faults unequivocally reveal a reverse sense of movement on ENE-trending, steeply NNW-dipping faults, accommodating hanging-wall movements to the S to SE (Fig. 11). These compressional structures are clearly discontinuous along strike, and the associated shortening is transferred via small and large-scale NNE-trending sinistral and mostly small-scale WNW-trending dextral strike-slip faults (tear or transfer faults). The NNE-trending sinistral Palomares fault is the clearest and the largest-scale example of such a transfer fault, as already suggested by Booth-Rea et al. (2003). The Palomares fault connects the compressive structures along the southern margin of the Vera Basin and/or the Carboneras fault zone with the Hinojar fault at the southern margin of the Guadalentin–Hinojar Basin. The existence of such transfer faults is also supported by counter clockwise and clockwise palaeomagnetic rotations in the Fortuna (Krijgsman & Garces, 2004) and Huercal Overa Basins (Mora Gluckstadt, 1993), respectively (Fig. 10).

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Fig. 15. (a) Trench exposure of Quaternary fan deposits made and investigated by members of the University of Barcelona in the autumn of 2002 (Trench 3 of Masana et al., 2005). For location see Fig. 7. The sediments are tilted, cut and displaced by low-angle south-directed thrusts, which form part of the Albox fault. (b) Stereographic projections (equal area, lower hemisphere) showing orientations of thrust and strike-slip faults in Miocene–Quaternary sediments of the Huercal Overa Basin along the Albox fault. P- and T-axes as defined in Fig. 8.
An important notion to be emphasized here concerns the age of the structure. The Huercal Overa, Guadalentin-Hinojar, Fortuna and Alicante Basins form a large ENE to NE-trending synclinal depocentre of the Plio-Quaternary age, bound by compressive structures along its northern and southern margins (Fig. 10). This depocentre was syn-tectonically and progressively filled with Pliocene and Quaternary sediments as demonstrated by Briend (1981), Briend et al. (1990), Alfaro et al. (2002a, b) and García-Meléndez et al. (2002, 2003). The activity of the strike-slip tear/transfer faults started not earlier than the latest Miocene–early Pliocene as substantiated with palaeomagnetic data (Calvo et al., 1994, 1997; Krijgsman & Garces, 2004), although Booth-Rea et al. (2003) suggest a latest Tortonian age for the initial activity of the Palomares fault. In other words, the Alhama de Murcia, Crevillente and Palomares faults clearly form part of a compression zone that was initiated at the end of the Miocene or onset of the early Pliocene.

It follows that there are in essence, two problems arising from the structural data. First, the late Miocene motions on the extensional faults in and adjacent to the late Miocene sediments are inconsistent with sinistral strike-slip on the main faults. Second, the geometry and kinematics of most of these main faults are consistent with NNW-SSE-directed shortening rather than genuine strike-slip, albeit that the Alhama de Murcia Fault certainly has a component of sinistral strike-slip motion. But more importantly, these main faults became active (or reactivated) in the latest Miocene or early Pliocene, hence motions on these faults postdate late Miocene basin development.

Our inference, that the main faults in fact represent a zone of shortening rather than a strike-slip corridor, is consistent with independent observations. First, earthquakes are clearly abundant and distributed over the south-eastern part of the Betic Cordillera (Buforn et al., 1995; Sanz de Galdeano et al., 1995; López Casado et al., 2001; Stich et al., 2003; Buforn et al., 2004; Masana et al., 2004), but the characteristic marked localization of earthquake epicentres along strike-slip faults, such as seen, e.g. along the North Anatolian fault in northern Turkey or the Dead Sea fault in the Middle East, is lacking, albeit that this localization along these main faults clearly concerns the large-magnitude earthquakes. Moreover, the absence of earthquakes in the eastern offshore as well as the lack of any strike-slip-related submarine morphological structures suggests the absence of any continuation of the Crevillente fault as a strike-slip structure offshore Alicante. Second, the orientations and kinematics of the ENE-trending thrusts, reverse faults, folds and thrust-related faults, and the NNW-trending dextral strike-slip faults are remarkably consistent with a N to NW direction of compression (Jiménez et al., 2000; Figs 10 and 11), which is supported by fault-plane solutions of recent earthquakes (Buforn et al., 1995, 2004; López Casado et al., 2001; Stich et al., 2003; Masana et al., 2004) showing a NW to NNW-trending compression axis and allied orthogonal extension. This suggests that the present day, as well as Pliocene to Quaternary, crustal deformations in the Betic Cordillera are mainly driven by the NW-directed convergence of Africa–Eurasian plates (Dewey et al., 1989; DeMets et al., 1994; Mazzoli & Helman, 1994; Jimenez-Munt et al., 2001; Stich et al., 2003).

All available data indicate that the prominent faults such as the Alhama de Murcia fault did not act as sinistral strike-slip faults during the late Miocene, and that their latest Miocene to Quaternary motion was reverse, in places with a sinistral component of motion. An important remaining question, however, concerns the possible role of these faults during the late Miocene. In this context, we emphasize the marked stratigraphic expansion of the late Miocene strata seen in the Lebor section near the NE termination of the Sierra de la Tercia as well as in the seismic profile across the Fortuna Basin (Figs 9 and 13), clearly suggesting that during sedimentation the Alhama de Murcia Fault acted as a growth fault, hence a normal fault. Likewise, the moderately dipping main bounding fault of the Huercal Overa Basin, separating the basin sediments from the Sierra Almagro to the south (Fig. 8), clearly shows a multiple-slip history, with early dip-slip, normal fault displacements overprinted by younger kinematic indicators pointing to sinistral strike-slip motion.

On the basis of these data, we conclude that the prominent faults may have been active during late Miocene basin development; however, they did not act as strike-slip faults but principally as normal faults accommodating the N to NE-directed extension. The basins were thus not generated as strike-slip-controlled pull-apart or compressional basins but as truly extensional structures. Many of the prominent faults commonly referred to as strike-slip faults may indeed have a strike-slip component but are dominated by a reverse component related to latest Miocene to Quaternary shortening. The Palomares fault, however, acted as a transfer fault and is probably one of the very few indisputable strike-slip faults.

CONCLUSIONS

We conclude that the late Miocene basins are truly extensional basins developed on an extending underlying crust and lithosphere. This notion is clearly at variance with prevailing interpretations of these basins in the south-eastern Betic Cordillera as pull-apart or compressional basins related to alleged strike-slip motions on the Alhama de Murcia and Crevillente faults. The syn-sedimentary extensional fault structures seen in the late Serravallian to late Tortonian sediments as well as in the underlying basement of the Internal Zone point to the approximately NE-directed extension, which is in conflict with the N–S-directed compression necessarily associated with a sinistral sense of shear on the Alhama de Murcia fault. In fact, during the late Serravallian to the late Tortonian, neither the Crevillente fault nor the Alhama de Murcia fault acted as strike-slip faults controlling basin development. Instead, parts of the Alhama de Murcia fault zone initiated as ex-
tensional faults, and these were reactivated as oblique contraction faults in the early Pliocene, presumably in response to continued African–European plate convergence. Our structural data indicate that both prominent faults are at present reverse faults, with a clear movement sense of their hanging walls towards the south-east, i.e. they show movement senses that clearly differ from the commonly quoted dextral (Crevillente fault) or sinistral (Alhama de Murcia fault) strike–slip motion. These reverse faults form part of a larger scale zone of post-Messinian shortening, made up of SSE- and NNW-directed thrusts and NE to ENE-trending folds including thrust-related fault–bend folds and fault–propagation folds, displaced by WNW and NNE-trending dextral and sinistral strike–slip (tear or transfer) faults, respectively.

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REFERENCES


de Jong, K. (2003) Very fast exhumation of high-pressure metamorphic rocks with excess ⁴⁰Ar and inherited ⁸⁷Sr, Betic Cor dilleras, southern Spain. Lithos, 70, 91–110.


Miocene extensional basin development in the Betic Cordillera


Miocene extensional basin development in the Betic Cordillera


Soler, R., Masana, E. & Santanché, P. (2003) Evidencias geomorfológicas y estructurales del levantamiento tectónico reciente debido al movimiento inverso de la terminación su-


Van der Straaten, H.C. (1993) Neogene strike-slip faulting in southeastern Spain; the deformation of the pull-apart basin of Aba


