Basin Research (2006) **18**, 547–571, doi: 10.1111/j.1365-2117.2006.00308.x

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

B. M. L. Meijninger and R. L. M. Vissers

Faculty of Geosciences, Utrecht University, Budapestlaan, Utrecht, The Netherlands

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 thrusted 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 evapourites (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

Correspondence: R. L. M. Vissers, Faculty of Geosciences, Utrecht University, Budapestlaan 4, 3584 CD Utrecht, The Netherlands. E-mail: rvissers@geo.uu.nl

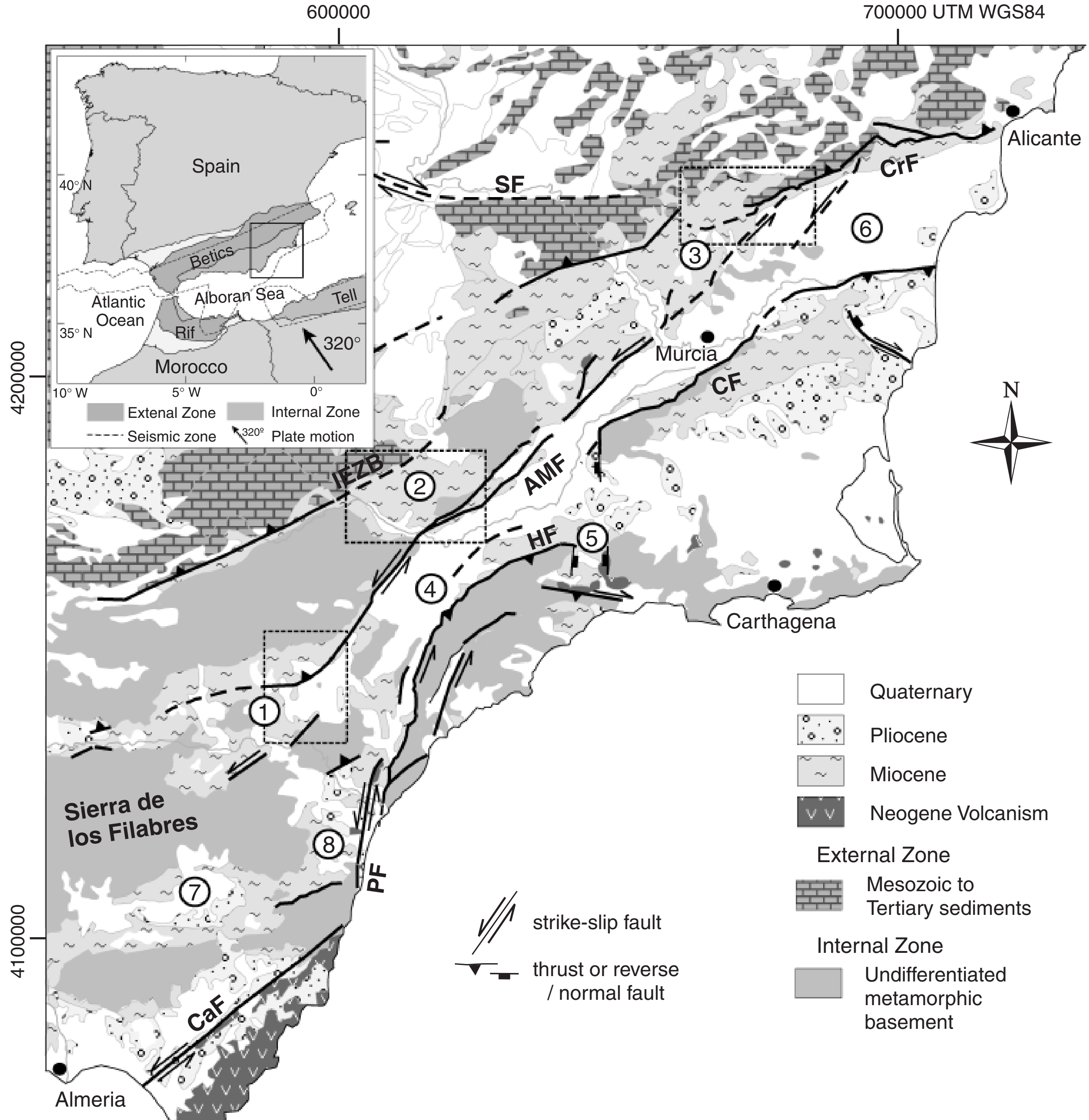

Fig. 1. Geological map of south-eastern Spain. Numbers: (1) Huercal Overa Basin, (2) Lorca Basin, (3) Fortuna Basin, (4) Guadalentin-Hinojar Basin, (5) Mazaron Basin, (6) Alicante-Bajo Segura Basin, (7) Sorbas-Tabernas Basin and (8) Vera Basin. Crf, Crevillente fault; CF, Carrascoy fault; AMF, Alhama de Murcia fault; HF, Hinojar Fault; PF; Palomares fault; CaF, Carboneras fault; SF, Socovos fault; IEZB, Internal–External Zone Boundary (or North Betic Fault). Modified from Mapa Geologico de la Peninsula Iberica (IGME, 1:1.000.000, 1981), de Larouzière *et al.* (1988), Montenat *et al.* (1990) and Gauyau *et al.* (1977). Seismic zone in inset after Buforn *et al.* (1988). African–European plate motion vector after DeMets *et al.* (1994). Frames in Fortuna, Lorca and Huercal Overa Basins mark detailed maps of Figs 5, 6 and 7, respectively.

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; Jabaloy *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

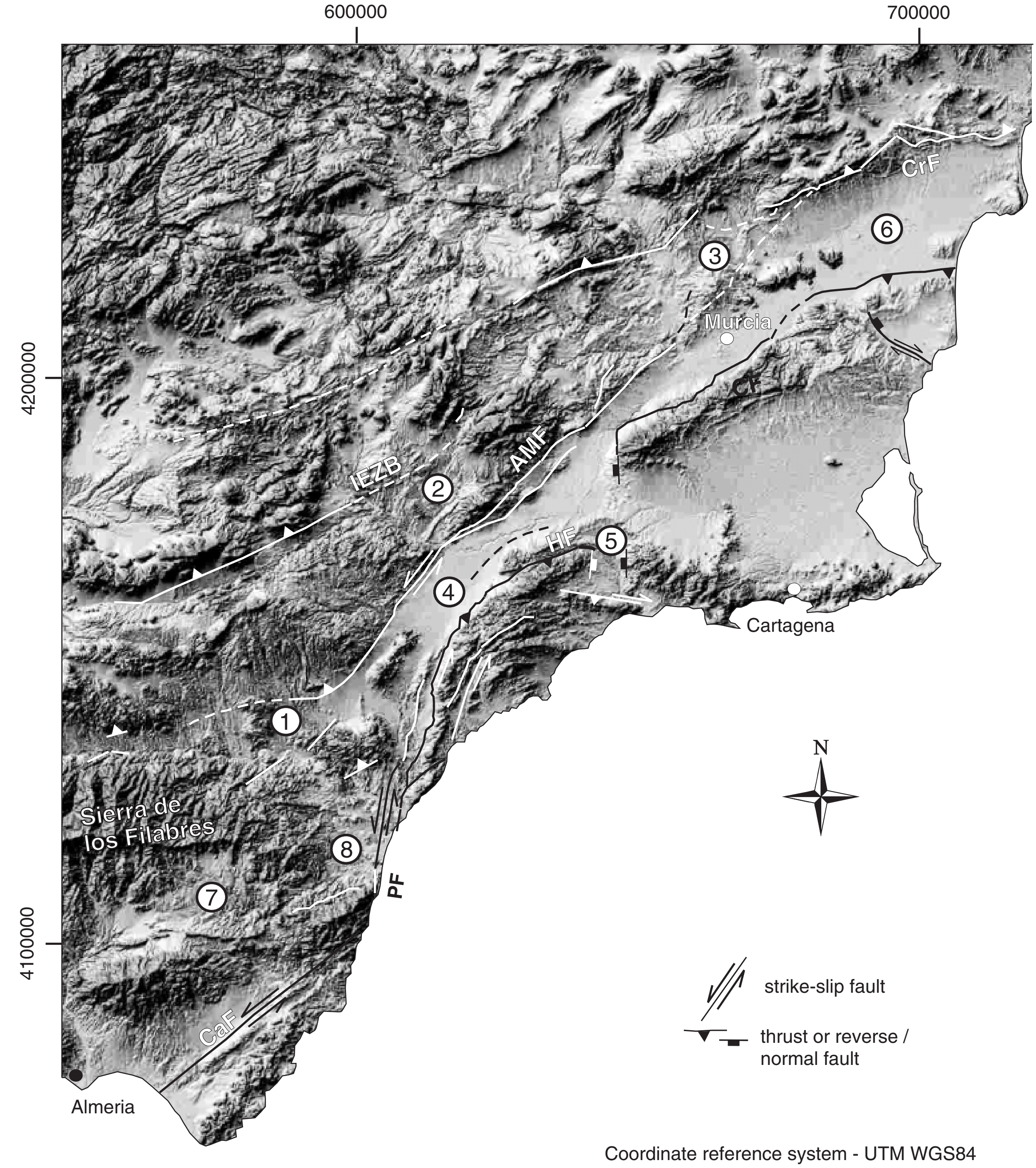

Fig. 2. Shaded relief model of south-eastern Spain. For numbers and abbreviations see Fig. 1.

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 compressional 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 (Bousquet *et al.*, 1975) faults, respectively. Both Bousquet & Montenat (1974), Bousquet *et al.* (1975), Gauyau *et al.* (1977), Bousquet (1979), Silva *et al.* (1997), Martínez-Díaz & Hernández-Enrile (2001), Soler *et al.* (2003) and Masana *et al.* (2004) have shown evidence for the intense deformation of Quaternary sediments close to these faults, which demonstrates recent activity of the Alhama de Murcia, 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. Balanyá & 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 Straaten, 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 Enrile, 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 (Lonergan *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 & Garcés, 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; Schreurs, 1994; Waldron, 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; Keller *et al.*, 1995; Bell *et al.*, 1997; Scotney *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 Enrile (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

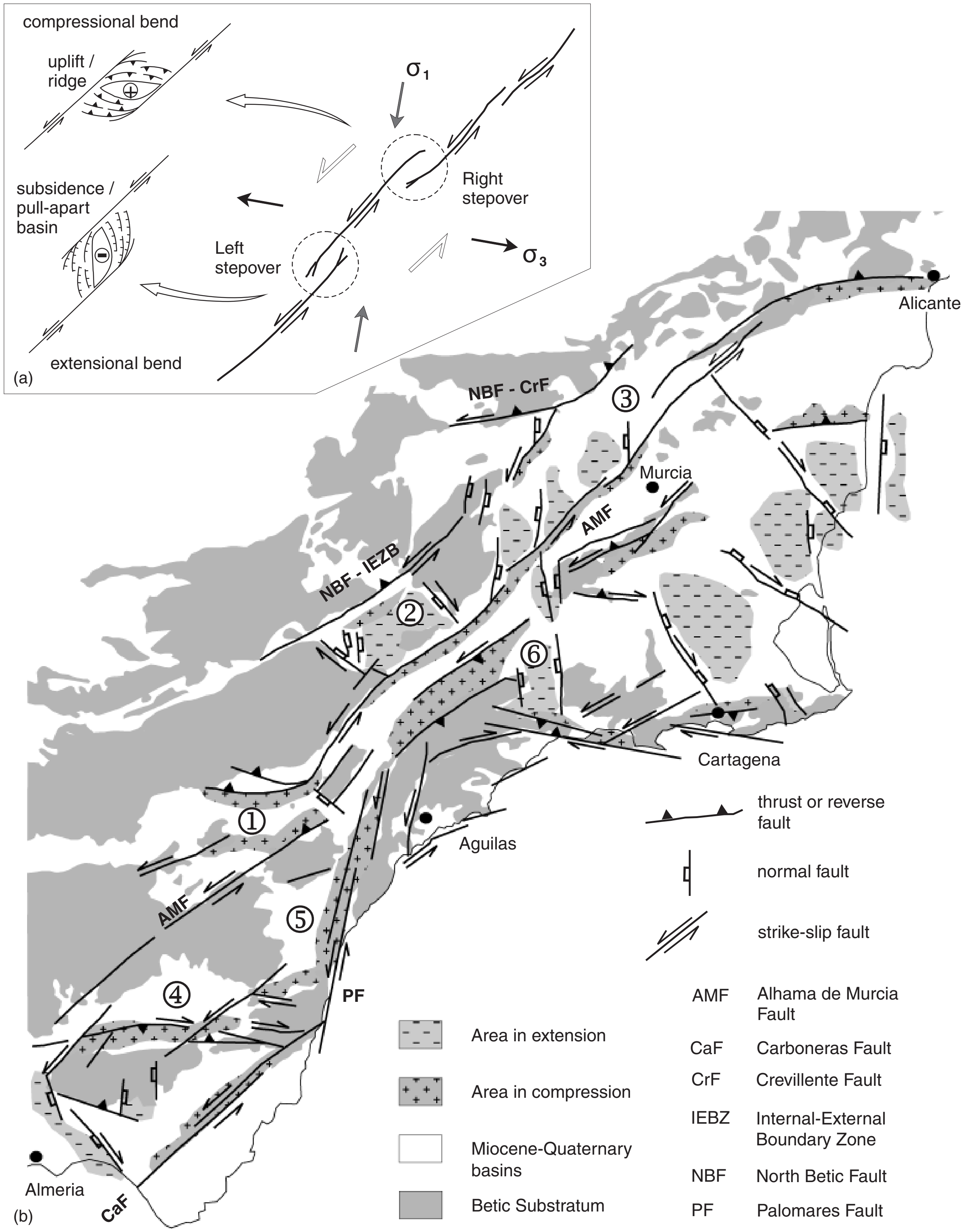

Fig. 3. (a) Sketch map illustrating how regional sinistral shear, shown for an orientation similar to the Alhama de Murcia fault, can be distributed along fault segments that are not coplanar. Slip is relayed from one segment to another at a stepover. At a restraining stepover, compression and thrusting 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.

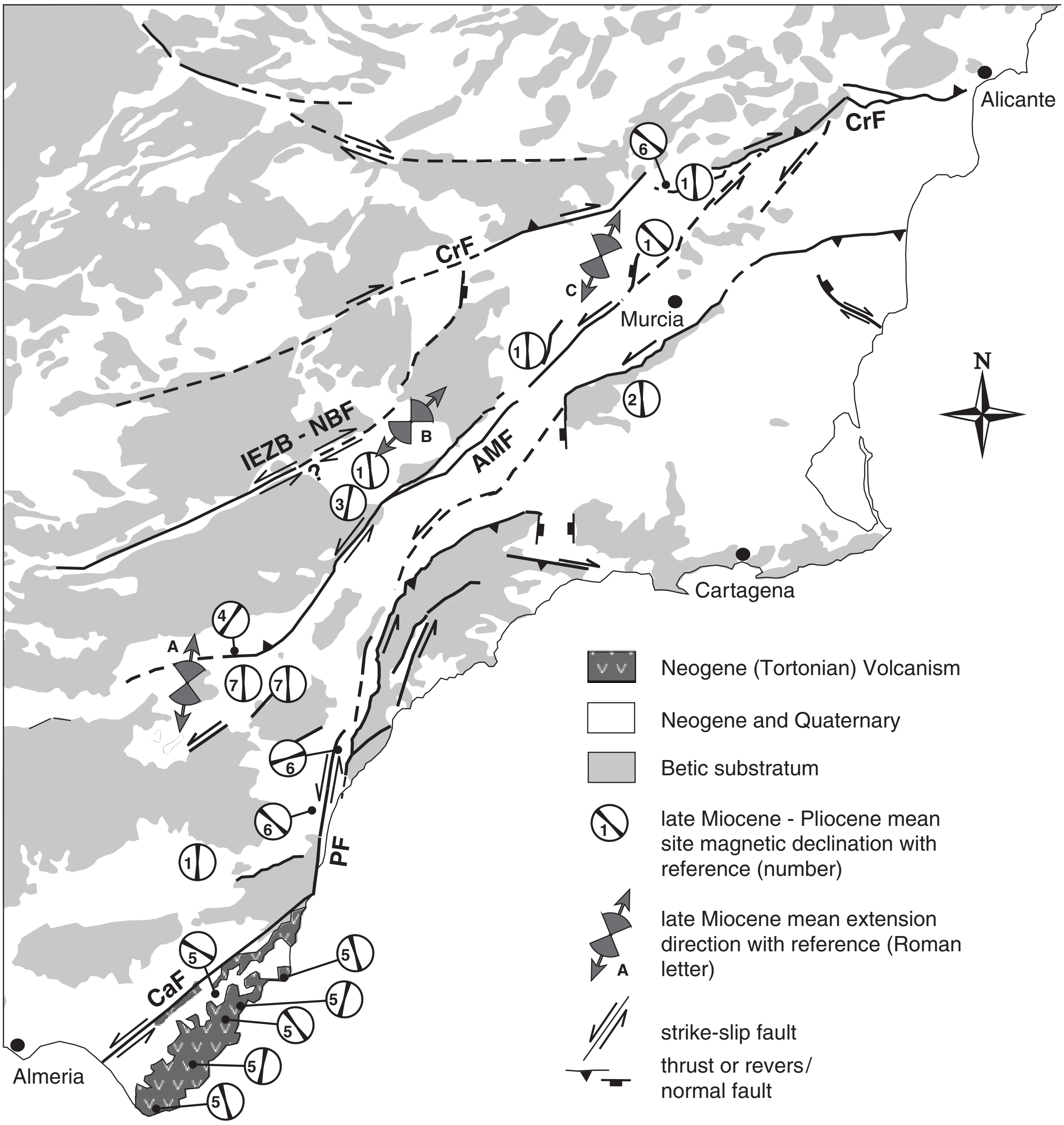

Fig. 4. Tectonic map of south-eastern Spain showing average Miocene extension directions and palaeomagnetic rotations. NBF, North Betic Fault; for other abbreviations see Fig. 1. Miocene extension directions are derived from tectonic structures in Miocene basin sediments (this study) and from literature; (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 & Garćes (2004), (2) Krijgsman *et al.* (2006), (3) Dinarès-Turell *et al.* (1997), (4) Mora Gluckstadt (1993), (5) Calvo *et al.* (1994), (6) Calvo *et al.* (1997) and (7) Meijninger (2006).

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 Serravallian–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.

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, R_2 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 rhomboidal 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; Garcés *et al.*, 2001). 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 palaeorelief (Briend, 1981; Briend *et al.*, 1990; García-Meléndez *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

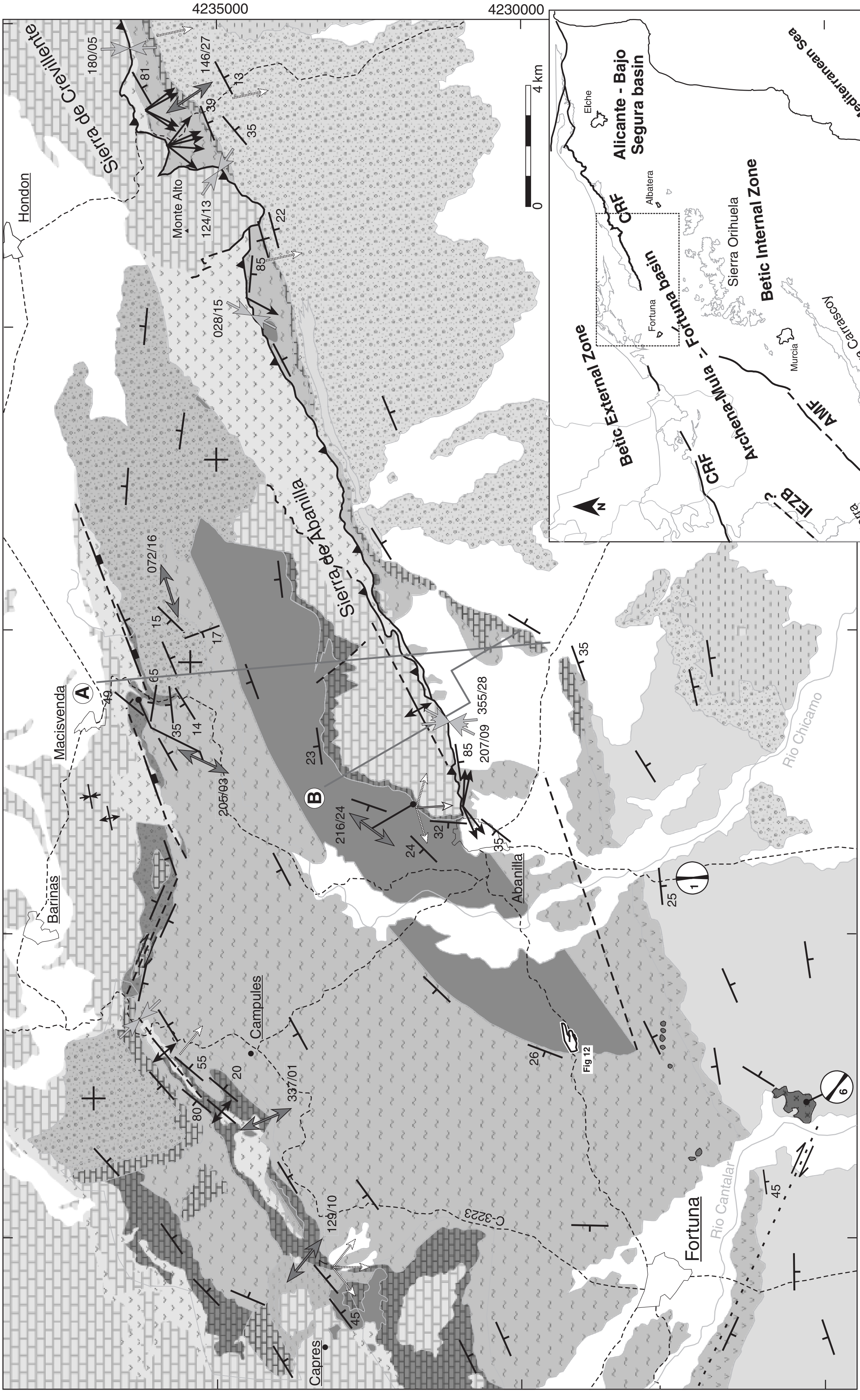

Fig. 5. Fortuna Geological map and cross-section of the northeastern part of the Fortuna Basin. Map after Azema & Montenat (1973) and Lukowski & Poisson (1990), Poisson & Lukowski (1990), Garcés *et al.* (2001) and Meijninger (2006). Age of the Fortuna lamproite after Kuiper *et al.* (2006). Inset: CRF, Crevillente fault; IEZB, Internal–External Zone Boundary; AMF, Alhama de Murcia fault.

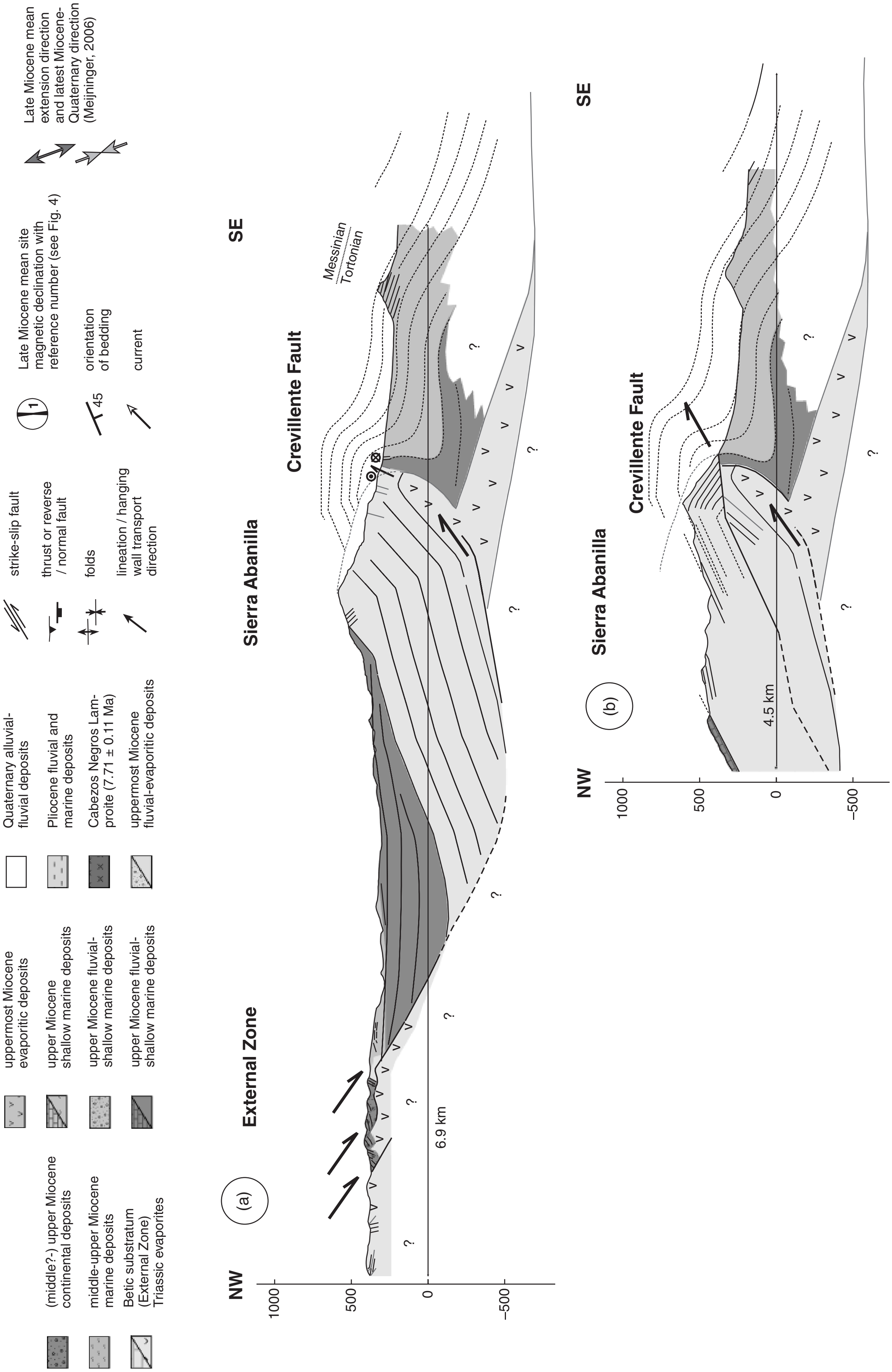

Fig. 5. Continued.

Fig. 6. Geological map and cross-section of the Lorca Basin. Map after Kampschuur *et al.* (1972), Geel (1976), Wrobel (2000) and Meijninger (2006). Brittle–Ductile extension directions in Sierra de la Tercia after Booth-Rea *et al.* (2002).

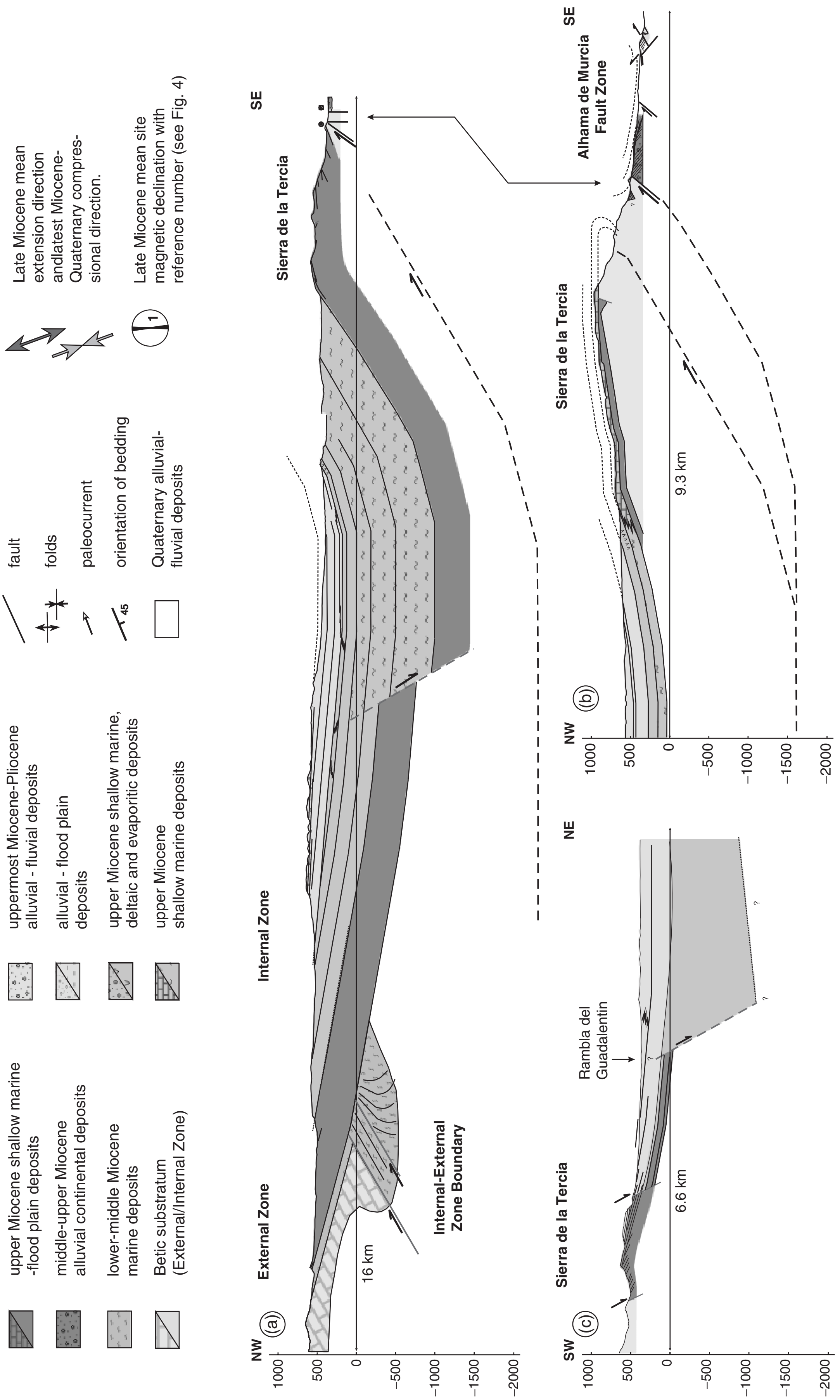

Fig. 6. Continued

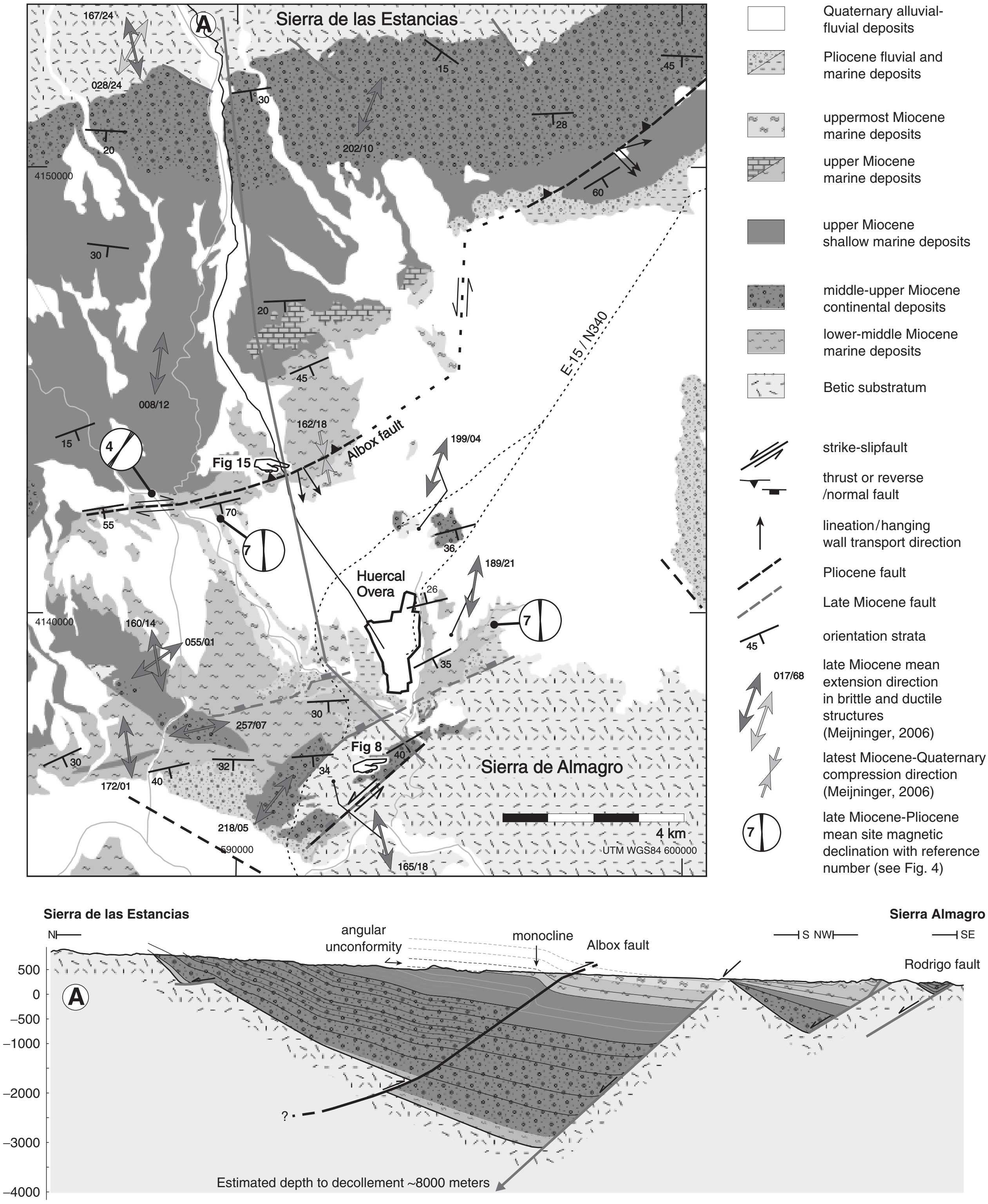

Fig. 7. Geological map and cross-section of the Huercal Overa Basin, partly after Voermans *et al.* (1972), Briend (1981) and Meijninger (2006).

Tortonian sediments, in part accomodated 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

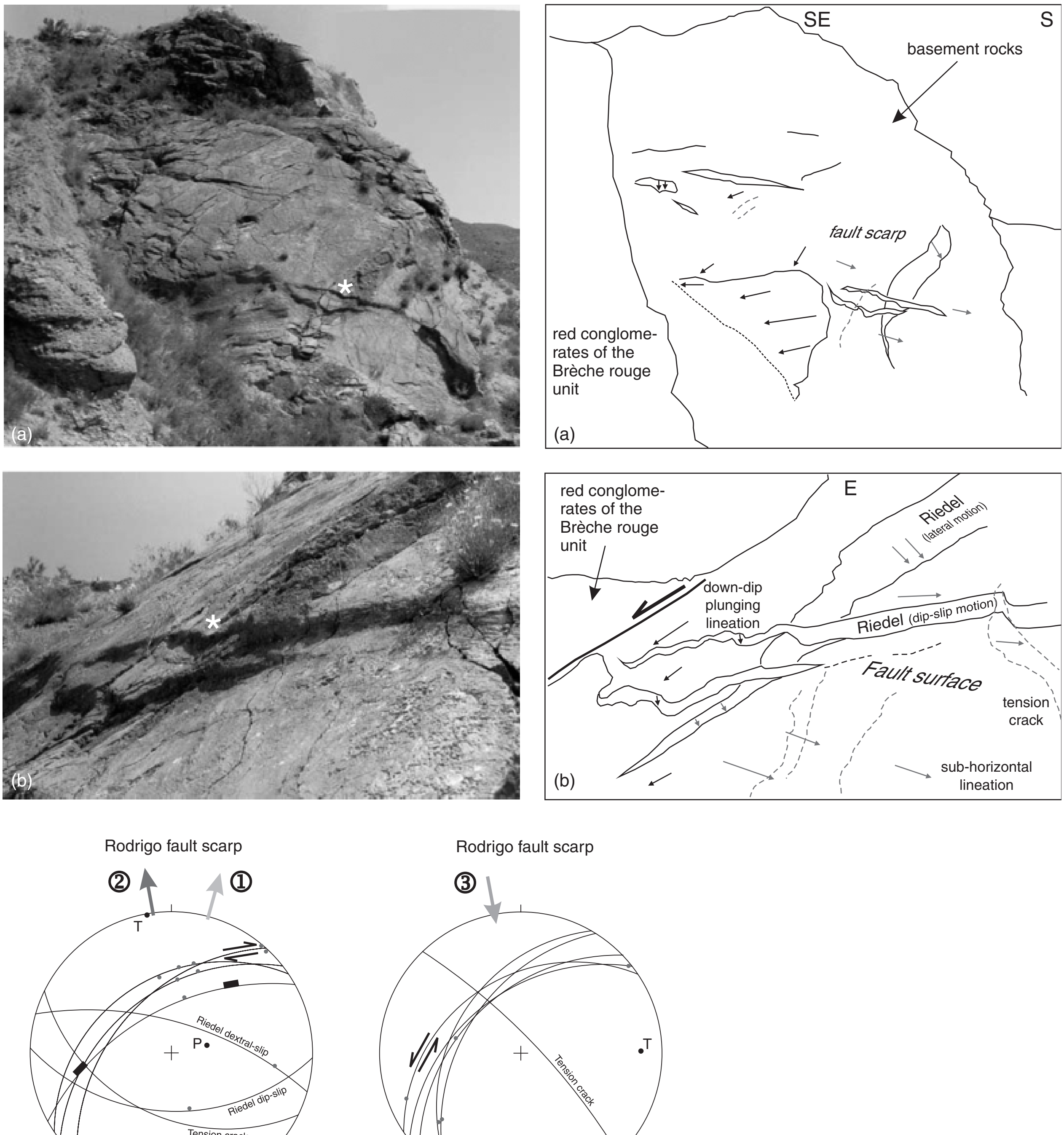

Fig. 8. (a and b) Fault scarp of basin-bounding Rodrigo fault south of Huercal Overa (for location see Figure 7) viewed normal (a) and oblique (b) to fault strike. *denotes corresponding point on fault plane. The fault separates lower Tortonian continental deposits from Alpujarride limestone of the Sierra 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).

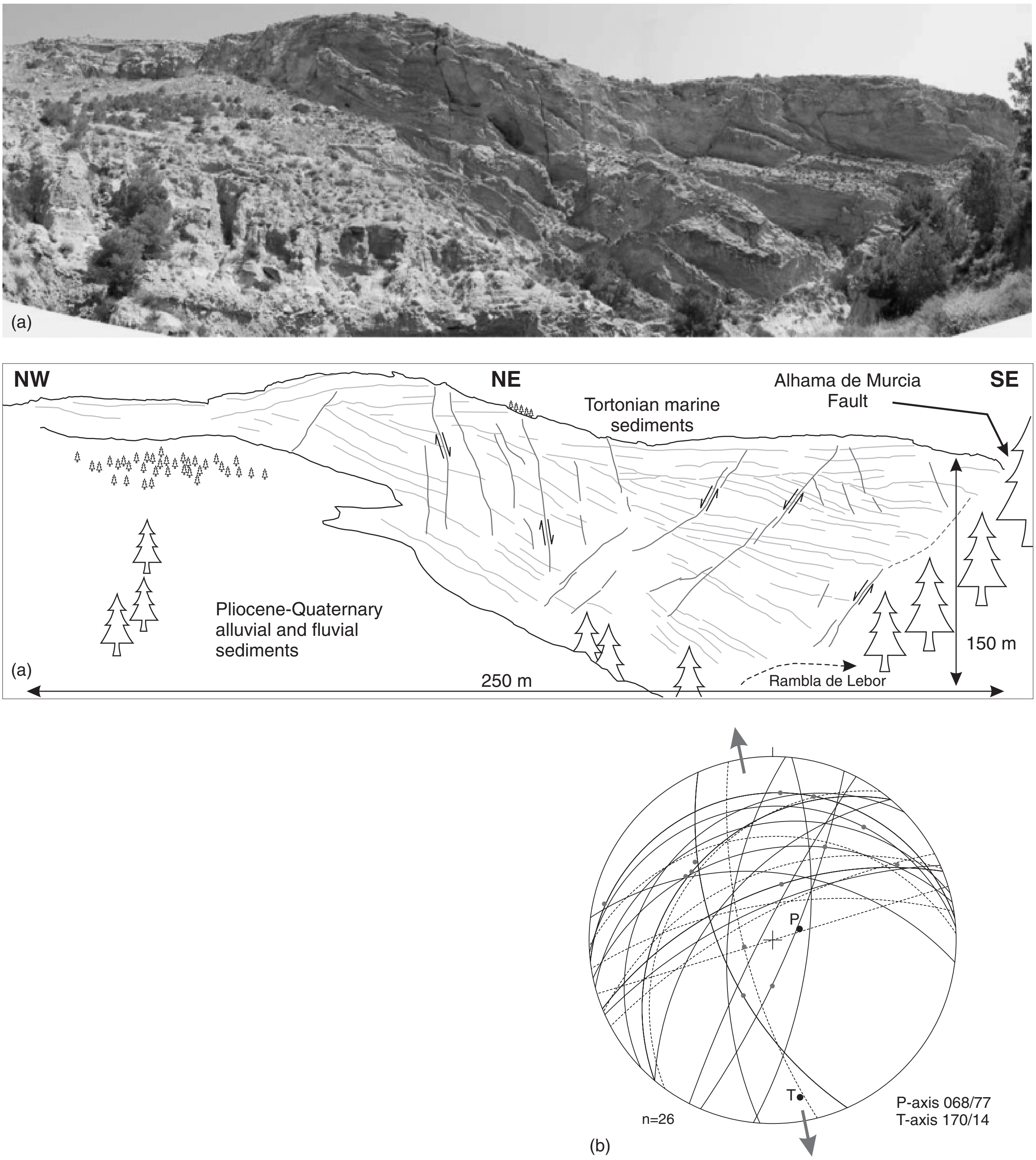

Fig. 9. (a) Cliff exposure along the Rambla de Lebor, southeastern Lorca Basin, adjacent to the Alhama de Murcia fault (for location see Figure 5.19), showing stratigraphic expansion of Tortonian sediments, in part accommodated by normal faults. Note that some of the faults are sealed by internal unconformities 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.

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-

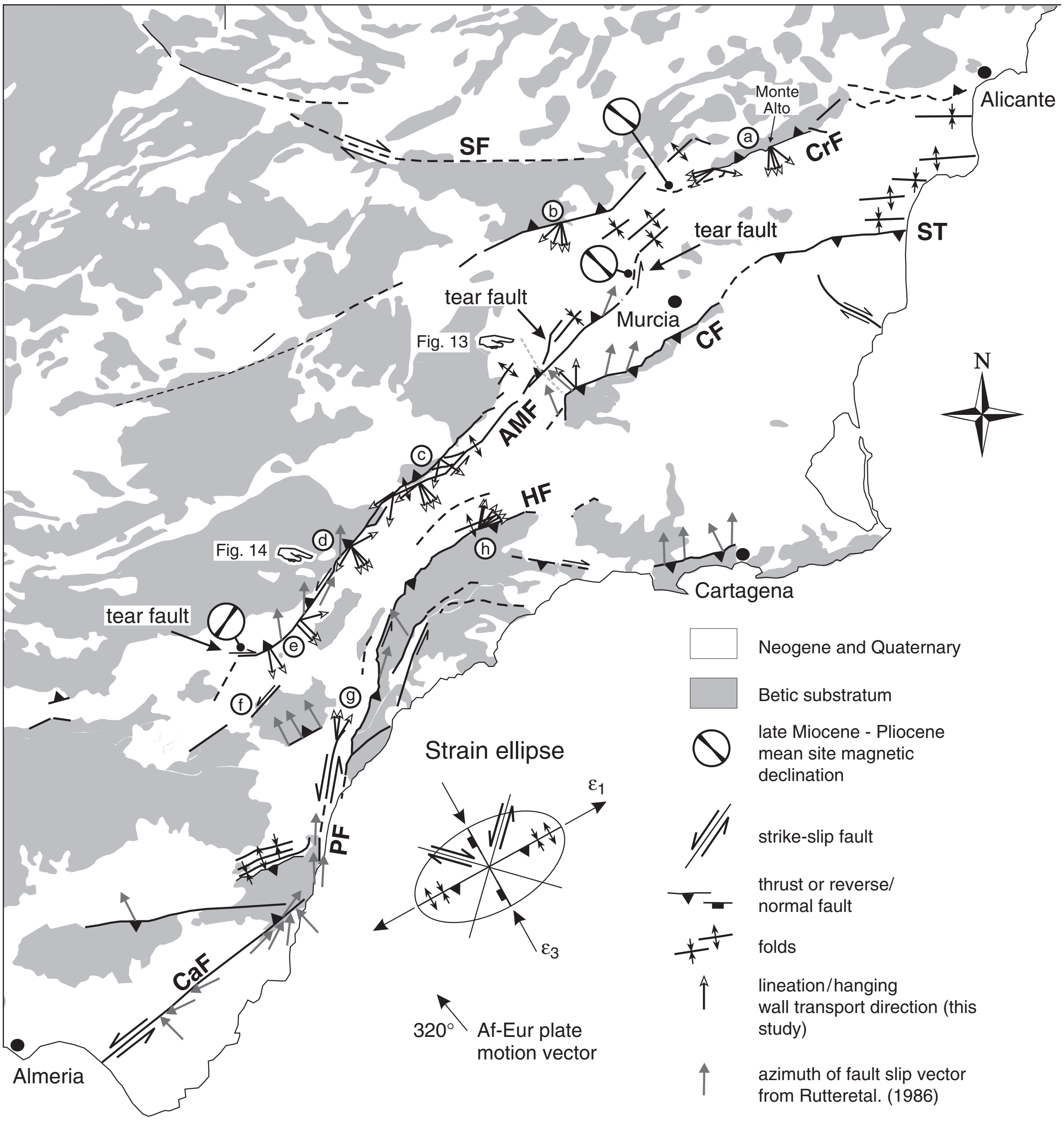

Fig. 10. Tectonic map of south-eastern Spain. For abbreviations see Fig. 1. Slip vectors shown represent either group averages or single measurements, based on striations on fault surfaces and shear planes in fault gouges, or movement directions determined from Riedel shear and P-foliation geometries in fault gouges. Roman letters refer to stereographic projections shown in Fig. 11. (a) Palaeomagnetic rotations from Krijgsman *et al.* (2004) and Mora Gluckstadt (1993). Strain ellipse based on structural data and fault-plane solutions from Jimenez-Munt *et al.* (2001), Stich *et al.* (2003) and Buforn *et al.* (2004). African–European plate motion vector from DeMets *et al.* (1994).

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-

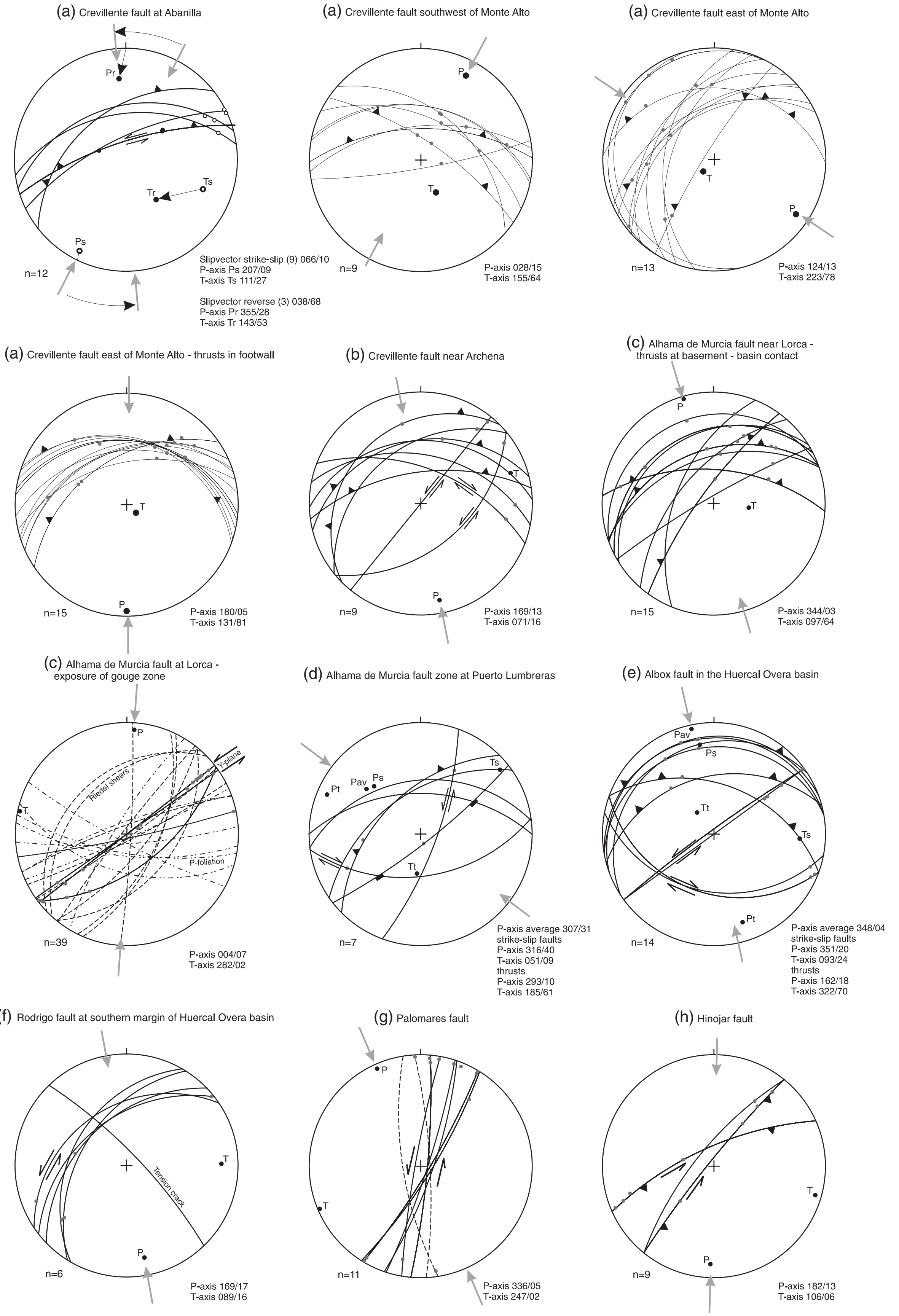

Fig. 11. Stereographic projections (equal area, lower hemisphere) showing orientations of faults and lineations in outcrops of the Crevillente, Alhama de Murcia, Albox, Rodrigo, Palomares and Hinojar faults. For locations see Fig. 10. *P*- and *T*-axes as defined in Fig. 8.

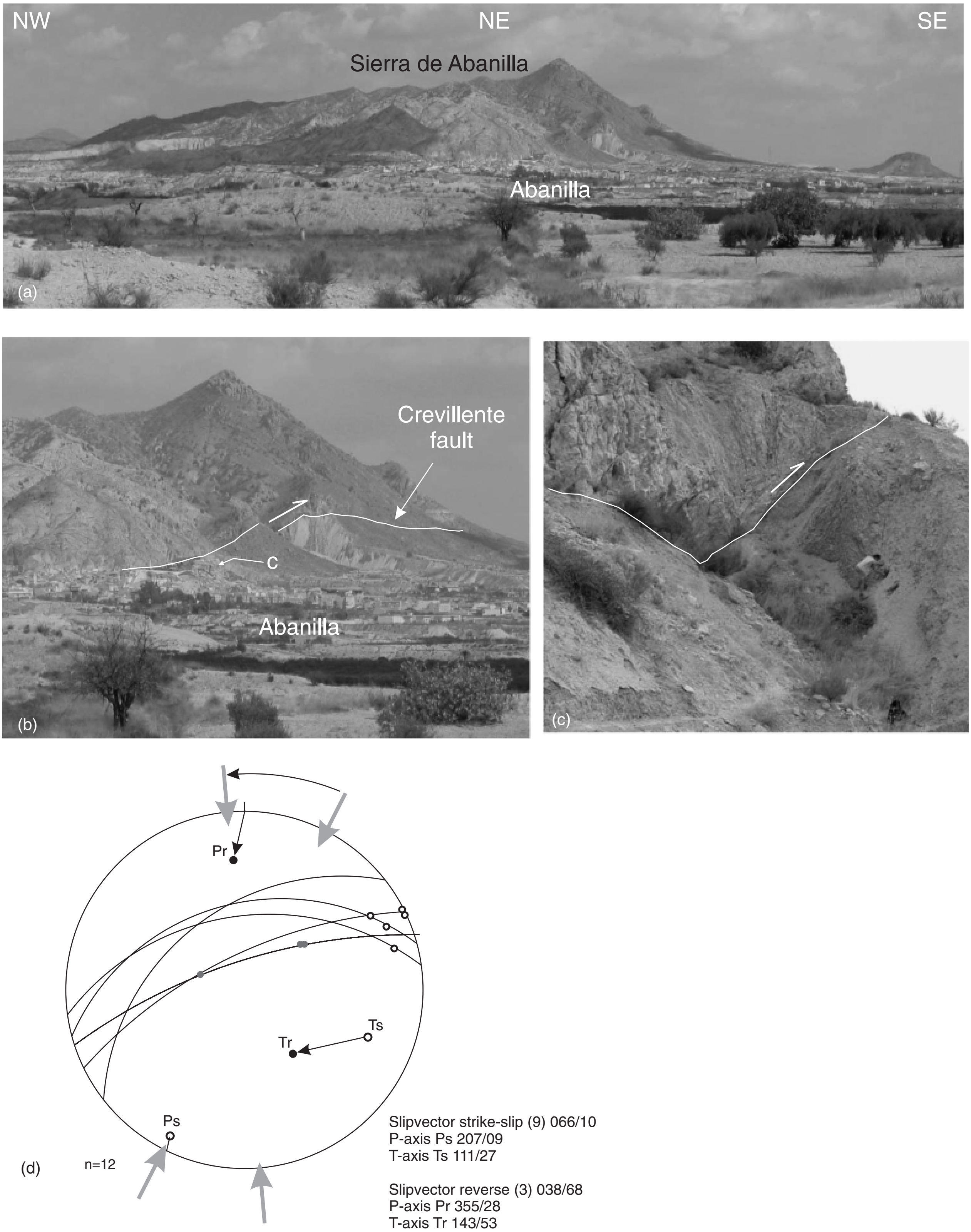

Fig. 12. Structure of the Crevillente Fault near Abanilla. (a) Panoramic view of the Sierra de Abanilla, for location see Fig. 5. (b) View of the southern side of the Sierra de Abanilla showing Mesozoic limestones of the Betic External Zone thrusted along a NW-dipping fault onto upper Miocene sediments. (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.

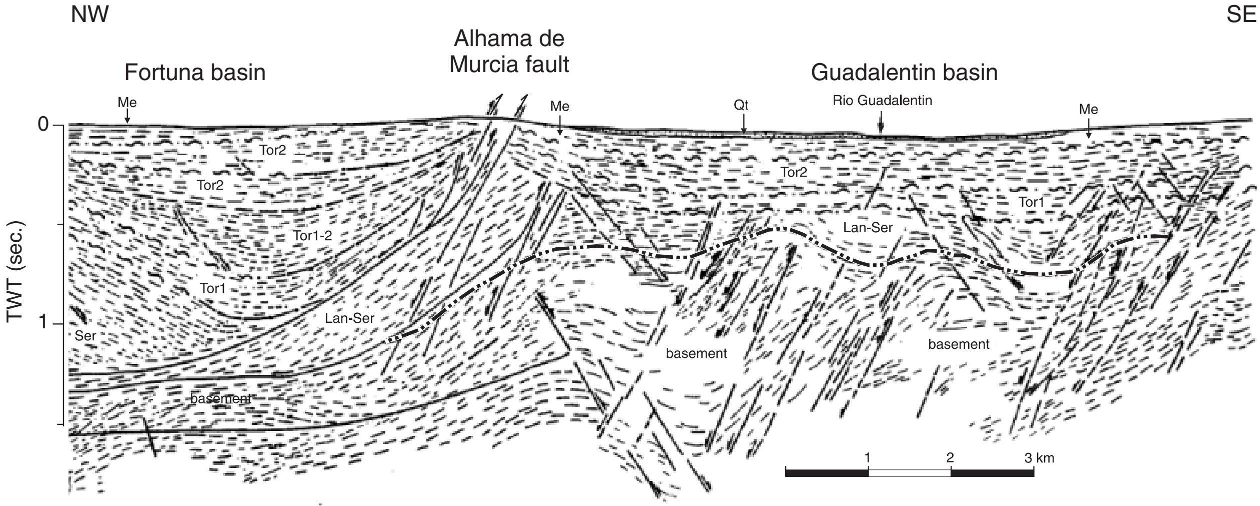

Fig. 13. Seismic profile across the Fortuna Basin, the Alhama de Murcia fault zone and Guadalentin Basin. Modified from Amores *et al.* (2001). For location see Fig. 10. Abbreviations: Lan-Ser–Langhian-Serravallian deposits; Tor1, Tor2, lower and upper Tortonian sediments; Me, Messinian sediments; Qt, Quaternary sediments.

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 Enrile, 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 southwest of Murcia (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). Scarce 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 monoclinic 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

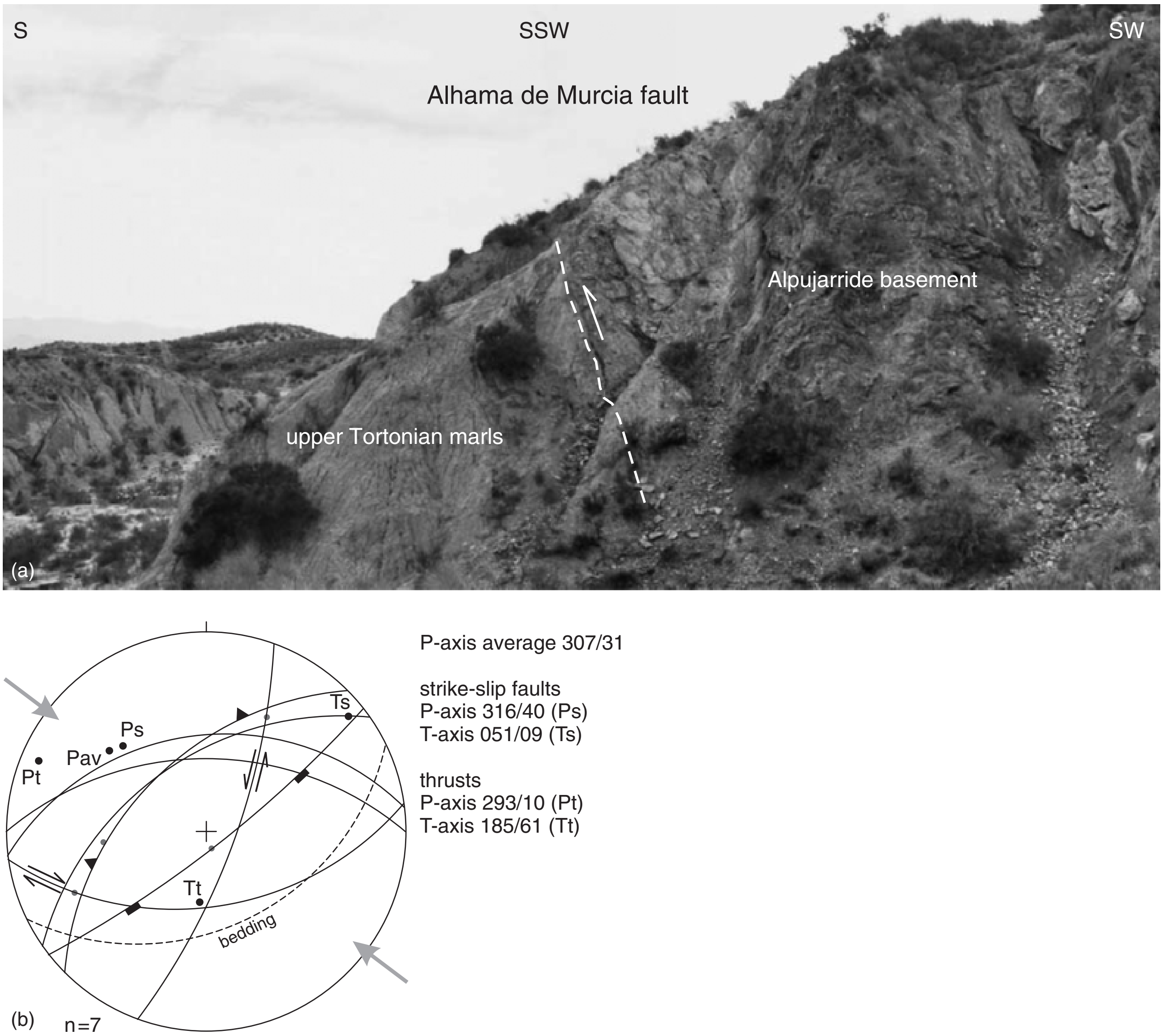

Fig. 14. (a) Exposure of the Alhama de Murcia fault northeast of Puerto Lumbreras, carrying Alpujarride rocks of the Sierra de las Estancias towards the SE onto upper Tortonian marls. For location see Fig. 10. (b) Stereographic projections (equal area, lower hemisphere) showing orientations of reverse 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.

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-Enrile, 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-

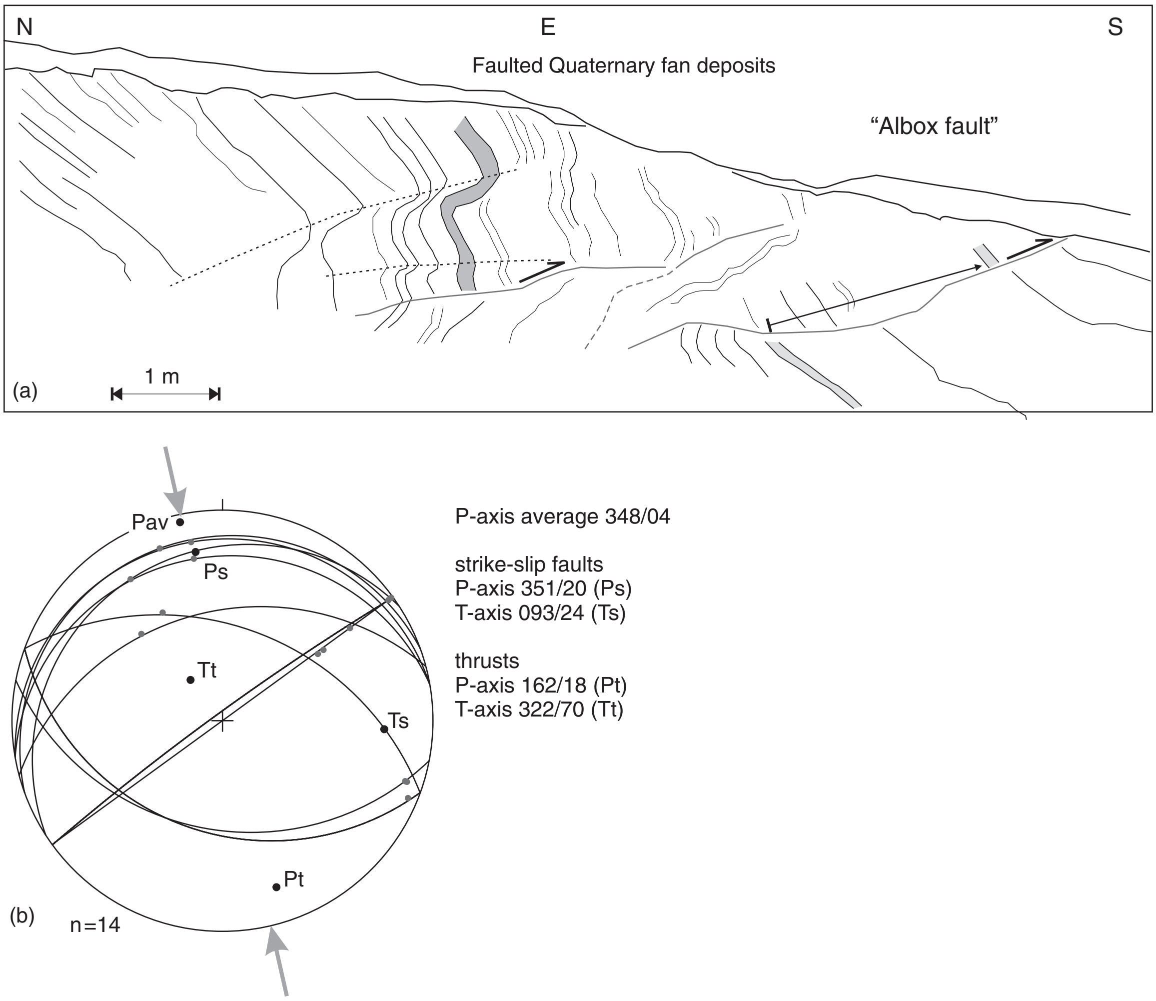

Fig. 15. (a) Trench exposure of Quaternary fan deposits made and investigated by members of the University of Barcelona in the autumn of 2002 (Trench 3 of Masana *et al.*, 2005). For location see Fig. 7. The sediments are tilted, cut and displaced by low-angle south-directed thrusts, which form part 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.

veloped 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 & Garcés, 2004) and Huercal Overa Basins (Mora Gluckstadt, 1993), respectively (Fig. 10).

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 & Garcés, 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–slips 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 NNE-trending sinistral and WNW-trending dextral strike–slip faults are remarkably consistent with a N to NW direction of compression (Giménez *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, tthey 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 extensional 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 southeast, 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.

ACKNOWLEDGEMENTS

We would like to thank Wim Sissingh and Hugo de Boorder for their comments and suggestions on the first drafts of this paper. Special thanks go to Armelle Kloppenburg and her colleagues of Midland Valley Ltd. (Glasgow, UK, website www.mve.com), who kindly provided software for structural analysis. We are indebted to John Platt, Carlos Sanz de Galdeano and Chris Elders for their constructive criticism and suggestions to improve the paper.

REFERENCES

Alfaro, P., Andreu, J.M., Delgado, J., Estévez, A., Soria, J.-M. & Teixido, T. (2002a) Quaternary deformation of the Bajo Segura blind fault (eastern Betic Cordillera, Spain) revealed by high-resolution reflection profiling. *Geol. Mag.*, **139**, 331–341.

Alfaro, P., Delgado, J., Estévez, A., Soria, J.-M. & Yebenes, A. (2002b) Onshore and offshore compressional tectonics in the eastern Betic Cordillera. *Mar. Geol.*, **186**, 337–349.

Amores, R., Hernández-Enrile, J.L. & Martínez-Díaz, J.J. (2001) Sobre los factores relacionados con la evaluación de la peligrosidad sísmica en la región de Murcia. *2o Congreso Iberoamericano de Ingeniería Sísmica*, Madrid, Spain, Asociación Española de Ingeniería Sísmica.

Amores, L.R., Hernández-Enrile, J.L. & Martínez-Díaz, J.J. (2002) Estudio gravimetrico previo aplicado a la identificación de fallas ocultas como fuentes sismogenéticas en la Depresión del Guadalentin (Región de Murcia). *Geogaceta*, **32**, 307–310.

Augier, R. (2004) Evolution Tardi-Orogenique des Cordilleres Betiques (Espagne): Apports d'une etude integree. Unpublished Thesis, Universite Pierre et Marie Curie, Paris, 400pp.

Azema, J. & Montenat, C. (1973) Fortuna (892). *Mapa de Geologico de España* (1:50.000), Instituto Geologico y Minero de España, Madrid.

Balanyá, J.C. & García-Dueñas, V. (1991) Fallas normales de bajo angulo a gran escala en las Beticas occidentales. *Geogaceta*, **9**, 30–32.

Banks, C.J. & Warburton, J. (1991) Mid-crustal detachment in the Betic system of southeast Spain. *Tectonophysics*, **191**, 275–289.

Beets, C.J. & De Ruig, M.J. (1992) $^{87}Sr/^{86}Sr$ dating of coralline algal limestones and its implications for the tectono-stratigraphic evolution of the eastern Prebetic (Spain). *Sediment. Geol.*, **78**, 233–250.

Bell, J.W., Amelung, F. & King, G.C.P. (1997) Preliminary Late Quaternary slip history of the Carboneras fault, southeastern Spain. *J. Geodyn.*, **24**, 51–66.

Booth-Rea, G., Azañón, J.M., Azor, A. & García-Dueñas, V. (2004) Influence of strike–slip fault segmentation on drainage evolution and topography. A case study: the Palomares Fault Zone (southeastern Betics, Spain). *J. Struct. Geol.*, **26**, 1615–1632.

Booth-Rea, G., Azañón, J.M. & García-Dueñas, V. (2003) Uppermost Tortonian to Quaternary depocentre migration related with segmentation of the strike–slip Palomares Fault Zone, Vera Basin (SE Spain). *C. R. Geosci.*, **335**, 751–761.

Booth-Rea, G., García-Dueñas, V. & Miguel Azañón, J. (2002) Extensional attenuation of the Malaguide and Alpujarride thrust sheets in a segment of the Aboran basin folded during the Tortonian (Lorca area, Eastern Betics). *C. R. Geosci.*, **334**, 557–563.

Bourgois, J., Mauffret, A., Ammar, A. & Demnati, A. (1992) Multichannel seismic data imaging of inversion tectonics of the Alboran Ridge (Western Mediterranean Sea). *Geo-Mar. Lett.*, **12**, 117–122.

Bousquet, J.-C. (1979) Quaternary strike–slip faults in southeastern Spain. *Tectonophysics*, **52**, 277–286.

Bousquet, J.-C., Dumas, B. & Montenat, C. (1975) Le Décrochement de Palomares: Décrochement Quaternaire senestre du bassin de Vera. (Cordillères bétiques orientales. Espagne). *Cuad. Geol. Univ. Granada*, **6**, 113–119.

Bousquet, J.-C. & Montenat, C. (1974) Présence de décrochements NE–SW plio-quaternaires, dans les Cordillères bétiques orientales (Espagne). Extension et signification générale. *C. R. Acad. Sci., Ser. D:*, **278**, 2617–2620.

Briend, M. (1981) Evolution morpho-tectonique du basin Neogene de Huercal Overa (cordillères bétiques orientales – espagne). *Doc. et Trav. IGAL*, **4**, 208.

Briend, M., Montenat, C. & Ott d'Estevou, P. (1990) Le Bassin de Huercal Overa. *Doc. et Trav. IGAL*, **12–13**, 239–259.

Buforn, E., Bezzeghoud, M., Udías, A. & Pro, C. (2004) Seismic sources on the Iberia–African plate boundary and their tectonic implication. *Pure Appl. Geophys.*, **161**, 623–646.

Buforn, E., de Galdeano, C. Sanz & Udías, A. (1995) Seismotectonics of the Ibero-Maghrebian region. *Tectonophysics*, **248**, 247–261.

Buforn, E., Udias, A. & Colombas, M.A. (1988) Seismicity, source mechanisms and tectonics of the Azores-Gibraltar plate boundary. *Tectonophysics*, **152**, 89–118.

Calvo, M., Osete, M.L. & Vegas, R. (1994) Palaeomagnetic rotations in opposite senses in southeastern Spain. *Geophys. Res. Lett.*, **21**, 761–764.

Calvo, M., Vegas, R. & Osete, M.L. (1997) Palaeomagnetic results from Upper Miocene and Pliocene rocks from the Internal Zone of the eastern Betic Cordilleras (southern Spain). *Tectonophysics*, **277**, 271–283.

Comas, M.C., García-Dueñas, V. & Jurado, M.J. (1992) Neogene tectonic evolution of the Alboran Sea from MCS data. *Geo-Mar. Lett.*, **12**, 157–164.

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

de Larouzière, F.D., Bolze, J., Bordet, P., Hernández, J., Montenat, C. & Ott d'Estevou, P. (1988) The Betic segment of the lithospheric Trans-Alboran shear zone during the Late Miocene. *Tectonophysics*, **152**, 41–52.

DeMets, C., Gordon, R.G., Argus, D.F. & Stein, S. (1994) Effect of recent revisions to the geomagnetic reversal time scale on estimates of current plate motions. *Geophys. Res. Lett.*, **21**, 2191–2194.

De Smet, M.E.M. (1984) Wrenching in the External Zone of the Betic Cordilleras, southern Spain. *Tectonophysics*, **107**, 57–79.

Dewey, J.F., Helman, M.L., Turco, E., Hutton, D.H.W. & Knott, S.D. 1989 Kinematics of the western Mediterranean. In: *Alp. Tecton.* (Ed. by M.P. Coward, D. Dietrich & R.G. Park) *Geol. Soc. Spec. Publ.*, **45**, 265–283.

Dinarès-Turell, J., Sprovieri, R., Caruso, A., Di Stefano, E., Gomis-Coll, E., Pueyo, J.J., Rouchy, J.M. & Taberner, C. (1997) Preliminary integrated magnetostratigraphic and biostratigraphic correlation in the Miocene Lorca basin (Murcia, SE Spain). *Acta Geologica Hispanica*, **32**, 161–170.

Dooley, T. & McClay, K.R. (1997) Analog modelling of pull-apart basins. *Am. Assoc. Petrol. Geol. Bull.*, **81**, 1804–1826.

Egeler, C.G. & Simon, O.J. (1969) Orogenic evolution of the Betic Zone (Betic Cordilleras, Spain), with emphasis on the nappe structures. *Geol. Mijnbouw*, **48**, 296–305.

Faulkner, D.R., Lewis, A.C. & Rutter, E.H. (2003) On the internal structure and mechanics of large strike–slip fault zones: field observations of the Carboneras fault in southeastern Spain. *Tectonophysics*, **367**, 235–251.

Gamond, J.F. (1987) Bridge structures as sense of displacement criteria in brittle fault zones. *J. Struct. Geol.*, **9**, 609–620.

Garcés, M., Krijgsman, W. & Agustí, J. (2001) Chronostratigraphic framework and evolution of the Fortuna basin (Eastern Betics) since the Late Miocene. *Basin Res.*, **13**, 199–216.

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

García-Hernández, M., López-Garrido, A.C., Rivas, P., Sanz de Galdeano, C. & Vera, J.A. (1980) Mesozoic palaeogeographic evolution of the External Zones of the Betic Cordillera. *Geol. Mijnbouw*, **59**, 155–168.

García-Meléndez, E., Ferrer-Julia, M., Goy, J.L. & Zazo, C. (2002) Reconstruccion morfoestructural mediante modelos de elevacion digital en un SIG del fondo de la cuenca sedimentaria de la Cubeta del Saltador (Cordilleras Beticas Orientales). *Geogaceta*, **32**, 203–206.

García-Meléndez, E., Goy, J.L. & Zazo, C. (2003) Neotectonics and PLio-Quaternary landscape development within the eastern Huercal-Overa Basin (Betic Cordilleras, southeast Spain). *Geomorphology*, **50**, 111–133.

Garfunkel, Z. & Ron, H. (1985) Block rotation and deformation by strike–slip faults; 2, the properties of a type of macroscopic discontinuous deformation. *J. Geophys. Res.*, **B 90**, 8589–8602.

Gauyau, F., Bayer, R., Bousquet, J.-C., Lachaud, J.-C., Lesquer, A. & Montenat, C. (1977) Le prolongement de l'accident d'Alhama de Murcia entre Murcia et Alicante (Espagne meridionale). *Bull. Soc. Geol. France*, **7**, 623–629.

Geel, T. 1976 Messinian gypsiferous deposits of the Lorca basin (Province of Murcia, SE Spain). In: *Messinian Evaporites in the Mediterranean* (Ed. by R. Catalano, G. Ruggieri & R. Sprovieri) *Memorie Soc. Geol. Italiana,* **16**, 369–384.

Geel, T. (1996) Paleogene to Early Miocene sedimentary history of the Sierra Espuña (Malaguide complex, Internal Zone of the Betic Cordilleras, SE Spain), Evidence for extra-Malaguide (Sardinian?) Provenance of Oligocene conglomerates: paleogeographic implications. *Estud. Geol.*, **52**, 211–230.

Geel, T. & Roep, T.B. (1998) Oligocene to middle Miocene basin development in the Eastern Betic Cordilleras, SE Spain (Velez Rubio Corridor – Espuña): reflections of West Mediterranean plate-tectonic reorganisations. *Basin Res.*, **10**, 325–343.

Geel, T. & Roep, T.B. (1999) Oligocene to Middle Miocene basin development in the Velez Rubio Corridor – Espuña (Internal–External Zone boundary; Eastern Betic Cordilleras, SE Spain). *Geol. Mijnbouw*, **77**, 39–61.

Giménez, J., Suriñach, E. & Goula, X. (2000) Quantification of vertical movements in the eastern Betics (Spain) by comparing levelling data. *Tectonophysics*, **317**, 237–258.

Guerra, F., Martín-Martín, M., Perrone, V. & Tramontana, M. (2005) Tectono-sedimentary evolution of the southern branch of the western Tethys (Maghrebian Flysch Basin and Lucanian Ocean): consequences for Western Mediterranean geodynamics. *Terra Nova*, **17**, 358–367.

Guillén Mondéjar, F., Rodríguez Estrella, T., Arana, R. & López Aguayo, F. (1995) Historia geológica de la cuenca de Lorca (Murcia): influencia de la tectónica en la sedimentación. *Geogaceta*, **18**, 30–33.

Hall, C.A. (1981) San Luis Obispo Transform Fault and middle Miocene rotation of the Western Transverse Ranges, California. *J. Geophys. Res.*, **86**, 1015–1031.

Hancock, P.L. & Barka, A.A. (1987) Kinematic indicators on active normal faults in western Turkey. *J. Struct. Geol.*, **9**, 573–584.

Jabaloy, A., Galindo-Zaldívar, J. & González-Lodeiro, F. (1992) The Mecina extensional system: its relation with the post-Aquitanian piggy-back basins and the paleostresses evolution (Betic Cordilleras, Spain). *Geo-Mar. Lett.*, **12**, 96–103.

Jimenez-Munt, I., Fernández, M., Torne, M. & Bird, P. (2001) The transition from linear to diffuse boundary in the Azores-Gibraltar region: results from a thin-sheet model. *Earth Planet.Sci. Lett.*, **192**, 175–189.

Johnson, C., Harbury, N. & Hurford, A.J. (1997) The role of extension in the Miocene denudetion of the Nevado-Filabride Complex, Betic Cordillera (SE Spain). *Tectonics*, **16**, 189–204.

Jonk, R. & Biermann, C. (2002) Deformation in Neogene sediments of the Sorbas and Vera basins (SE Spain): constraints on simple-shear deformation and rigid body rotation along major strike–slip faults. *J. Struct. Geol.*, **24**, 963–977.

Kampschuur, W., Langenberg, C.V., Rondeel, H.E., Espejo, J.A., Crespo, A. & Fignatelli, R. (1972) Lorca (953). *Mapa de Geologico de España* (1:50.000), Instituto Geologico y Minero de España, Madrid.

Keller, J.V.A., Hall, S.H., Dart, C.J. & McClay, K.R. (1995) The geometry and evolution of a transpressional strike–slip system: the Carboneras fault, SE Spain. *J. Geol. Soc. London*, **152**, 339–351.

Krijgsman, W. & Garcés, M. (2004) Palaeomagnetic constraints on the geodynamic evolution of the Gibraltar Arc. *Terra Nova*, **16**, 281–287.

Krijgsman, W., Garcés, M., Agustí, J., Raffi, I., Taberner, C. & Zachariasse, W.J. (2000) The 'Tortonian salinity crisis' of the eastern Betics (Spain). *Earth Planet. Sci. Lett.*, **181**, 497–511.

Krijgsman, W., Leewis, M.E., Garcés, M., Kouwenhoven, T.J., Kuiper, K. & Sierro, F.J. (2006) Tectonic control for evaporite formation in the Eastern Betics. *Sediment. Geol.*, **188–189**, 155–170.

Kuiper, K.F., Krijgsman, W., Garcés, M. & Wijbrans, J.R. (2006) Revised isotopic (40Ar/39Ar) age for the lamproite volcano of Cabezos Negros, Fortuna Basin (Eastern Betics, SE Spain). *Palaeogeography, Palaeoclimatology, Palaeoecology*, **258**, 53–63.

Leblanc, D. & Olivier, P. (1984) Role of strike–slip faults in the Betic-Rifian orogeny. *Tectonophysics*, **101**, 345–355.

Logan, J.M., Friedman, M., Higgs, N., Dengo, C. & Shimamoto, T. (1979) Experimental studies of simulated gouge and their application to studies of natural fault zones. In: *Proceedings of Conference VIII; Analysis of Actual Fault Zones in Bedrock. Open Open-File Report* (Ed. by R.C. Speed, R.V. Sharp & J.F. Evernden), pp 305–343. U.S Geological Survey.

Lonergan, L. & Johnson, C. (1998) Reconstructing orogenic exhumation histories using synorogenic detritial zircons and apatites: an example from the Betic Cordillera, SE Spain. *Basin Res.*, **10**, 353–364.

Lonergan, L., Platt, J.P. & Gallagher, L. (1994) The Internal–External Zone Boundary in the eastern Betic Cordillera, SE Spain. *J. Struct. Geol.*, **16**, 175–188.

Lonergan, L. & White, N. (1997) Origin of the Betic-Rif mountain belt. *Tectonics*, **16**, 504–522.

Lukowski, P. & Poisson, A.M. (1990) Le bassin de Fortuna. *Doc. et Trav. IGAL*, **12–13**, 303–311.

López Casado, C., Sanz de Galdeano, C., Molina Palacios, S. & Henares Romero, J. (2001) The structure of the Alboran Sea: an interpretation from seismological and geological data. *Tectonophysics*, **338**, 79–95.

Marrett, R. & Allmendinger, R.W. (1990) Kinematic analysis of fault-slip data. *J. Struct. Geol.*, **12**, 973–986.

Martínez-Díaz, J.J. (2002) Stress field variation related to fault interaction in a reverse oblique-slip fault: the Alhama de Murcia fault, Betic Cordillera, Spain. *Tectonophysics*, **356**, 291–305.

Martínez-Díaz, J.J. & Hernández-Enrile, J.L. (1992a) Tectónica reciente y rasgos sismotectónicos en el sector Lorca-Totana de la falla de Alhama de Murcia. *Estud. Geol.*, **48**, 153–162.

Martínez-Díaz, J.J. & Hernández Enrile, J.L. (1992b) Fracturación y control tectosedimentario neógeno en el borde sureste de la Cuenca de Lorca. *Bolet. Geol. Miner.*, **103**, 3–15.

Martínez-Díaz, J.J. & Hernández-Enrile, J.L. (2001) Using travertine deformations to characterize paleoseismic activity along an active oblique-slip fault: the Alhama de Murcia fault (Betic Cordillera, Spain). *Acta Geol. Hispan.*, **36**, 297–313.

Masana, E., Martínez-Díaz, J.J., Hernández Enrile, J.L. & Santanach, P. (2004) The Alhama de Murcia fault (SE Spain), a seismogenic fault in a diffuse plate boundary: Seismotectonic implications for the Ibero-Magrebian region. *J. Geophys. Res.*, **109**, B01301.

Masana, E., Pallas, R., Perea, H., Ortuno, M., Martínez-Díaz, J.J., García-Meléndez, E. & Santanach, P. (2005) Large Holocene morphogenic earthquakes along the Albox fault, Betic Cordilleras, Spain. *J. Geodyn.*, **40**, 119–133.

Mauffret, A., Maldonado, A. & Campillo, A.C. (1992) Tectonic framework of the eastern Alboran and the western Algerian basins, western Mediterranean. *Geo-Mar. Lett.*, **12**, 104–110.

Mazzoli, S. & Helman, M.L. (1994) Neogene patterns of relative plate motion for Africa–Europe: some implications for recent central Mediterranean tectonics. *Geol. Rundsch.*, **83**, 464–468.

Means, W.D. (1987) A newly recognized type of slickenside striation. *J. Struct. Geol.*, **9**, 585–590.

Meijninger, B.M.L. (2006) Late-orogenic extension and strike–slip deformation in the Neogene of southeastern Spain. PhD Thesis, Universiteit Utrecht. *Geologica Ultraiectina*, **269**, 179 pp.

Monie, P., Torres Roldán, R.L. & García Casco, A. (1994) Cooling and exhumation of the western Betic Cordilleras, (super 40) Ar/(super 39) Ar thermochronological constraints on a collapsed terrane. *Tectonophysics*, **238**, 353–379.

Montenat, C. & Ott d'Estevou, P. (1990) Eastern Betic Neogene basins – A review. *Documents et Travaux de l'Institut Geologique Albert de Lapparent (IGAL)*, **12–13**, 9–15.

Montenat, C. & Ott d'Estevou, P. (1996) Late Neogene basins evolving in the Eastern Betic transcurrent fault zone: an illustrated review. Cambridge Univ. Press. *World and Region. Geol.*, **6**, 372–386.

Montenat, C. & Ott d'Estevou, P. (1999) The diversity of Late Neogene sedimentary basins generated by wrench faulting in the Eastern Betic Cordillera, SE Spain. *J. Petrol. Geol.*, **22**, 61–80.

Montenat, C., Ott d'Estevou, P. & Delort, T. (1990) Le Bassin de Lorca. *Doc. et Trav. IGAL*, **12–13**, 261–280.

Montenat, C., Ott d'Estevou, P. & Masse, P. (1987) Tectonic-sedimentary characters of the Betic Neogene basins evolving in a crustal transcurrent shear zone (SE Spain). *Bull. Centr. Rech. Expl. Prod. Elf Aquitaine*, **11**, 1–22.

Mora Gluckstadt, M. (1993) Tectonic and sedimentary analysis of the Huercal Overa region, South East Spain, Betic Cordillera. Unpublished Thesis, University of Oxford, 300pp.

Morales, J., Vidal, F., de Miguel, F., Alguacil, G., Posadas, A.M., Ibáñez, J.M., Guzmán, A. & Guirao, J.M. (1990) Basement structure of the Granada basin, Betic Cordilleras, Southern Spain. *Tectonophysics*, **177**, 337–348.

Morley, C.K. (1993) Discussion of origins of hinterland basins to the Rif-Betic Cordillera and Carpathians. *Tectonophysics*, **226**, 359–376.

Peper, T. & Cloetingh, S. (1992) Lithosphere dynamics and tectono-stratigraphic evolution of the Mesozoic Betic rifted margin (southeastern Spain). *Tectonophysics*, **203**, 345–361.

Petit, J.P. (1987) Criteria for the sense of movement on fault surfaces in brittle rocks. *J. Struct. Geol.*, **9**, 597–608.

Platt, J.P., Allerton, S., Kirker, A., Mandeville, C., Mayfield, A., Platzman, E.S. & Rimi, A. (2003) The ultimate arc: differential displacement, oroclinal bending, and vertical axis rotation in the External Betic-Rif arc. *Tectonics*, **22**, 29.

Platt, J.P., Kelley, S.P., Carter, A. & Orozco, M. (2005) Timing of tectonic events in the Alpujarride Complex, Betic Cordillera, southern Spain. *J. Geol. Soc. London*, **162**, 1–12.

Platt, J.P. & Vissers, R.L.M. (1989) Extensional collapse of thickened continental lithosphere: a working hypothesis for the Alboran Sea and Gibraltar arc. *Geology*, **17**, 540–543.

Platzman, E.S. & Platt, J.P. (2004) Kinematics of a twisted core complex: a paleomagnetic and structural investigation of the Sierra de las Estancias (Betic Cordillera, southern Spain). *Tectonics*, **23**.

Poisson, A.M. & Lukowski, P. (1990) The fortuna basin: a piggyback basin in the Eastern Betic Cordilleras (SE Spain). *Ann. Tecton.*, **4**, 52–67.

Poisson, A.M., Morel, J.L., Andrieux, J., Coulon, M., Wernli, R. & Guernet, C. (1999) The origin and development of Neogene basins in the SE Betic Cordillera (SE Spain):

a case study of the Tabernas–Sorbas and Huercal Overa Basins. *J. Petrol. Geol.*, **22**, 97–114.

Reicherter, K.R. & Reiss, S. (2001) The Carboneras Fault Zone (southeastern Spain) revisited with Ground Penetrating Radar – Quarternary structural styles from high-resolution images. *Neth. J. Geosci./Geol. Mijnbouw*, **80**, 129–138.

Ron, H., Freund, R., Garfunkel, Z. & Nur, A. (1984) Block rotation by strike–slip faulting; structural and paleomagnetic evidence. *J. Geophys. Res.*, **B 89**, 6256–6270.

Rouchy, J.M., Taberner, C., Blanc-Valleron, M.-M., Sprovieri, R., Russell, M., Pierre, C., Stefano, E.D., Pueyo, J.J., Caruso, A., Dinarès-Turell, J., Gomis-Coll, E., Wolff, G.A., Cespuflio, G., Ditchfield, P., Pestrea, S., Combourieu-Nebout, N., Santisteban, C. & Grimalt, J.O. (1998) Sedimentary and diagenetic markers of the restriction in a marine basin: the Lorca basin (SE Spain) during the Messinian. *Sediment. Geol.*, **121**, 23–55.

Ruano, P., Galindo Zaldívar, J. & Jabaloy, A. (2004) Recent tectonic structures in a transect of the Central Betic Cordillera. *Pure Appl. Geophys.*, **161**, 541–563.

Rutter, E.H., Maddock, R.H., Hall, S.H. & White, S.H. (1986) Comparative microstructures of natural and experimentally produced clay-bearing fault gouges. In: *International Structure of Fault Zones* (Ed. by Y. Wang-Chi), *Pure Appl. Geophys.*, **124**, 3–30.

Sanz de Galdeano, C. (1990) Geologic evolution of the Betic Cordilleras in Western Mediterranean, Miocene to the present. *Tectonophysics*, **172**, 107–119.

Sanz de Galdeano, C., López Casado, C., Delgado, J. & Peinado, M.A. (1995) Shallow seismicity and active faults in the Betic Cordillera. A preliminary approach to seismic sources associated with specific faults. *Tectonophysics*, **248**, 293–302.

Schreurs, G. (1994) Experiments on strike–slip faulting and block rotation. *Geology*, **22**, 567–570.

Scotney, P., Burgess, R. & Rutter, E.H. (2000) ^{40}Ar/^{39}Ar age of the Cabo the Gata volcanic series and displacements on the Carboneras fault zone, SE Spain. *J. Geol. Soc. London*, **157**, 1003–1008.

Silva, P.G., Goy, D.L. & Zazo, C. (1992) Características estructurales y geométricas de la falla de desgarre de Lorca-Alhama. *Geogaceta*, **12**, 7–10.

Silva, P.G., Goy, J.L., Zazo, C., Lario, J. & Bardají, T. (1997) Paleoseismic indications along ‘aseismic’ fault segments in the Guadalentin depression (SE Spain). *J. Geodyn.*, **24**, 105–115.

Soler, R., Masana, E. & Santanach, P. (2003) Evidencias geomorfológicos y estructurales del levantamiento tectónico reciente debido al movimiento inverso de la terminacion sudoccidental de la falla de Alhama de Murcia (Cordillera Betica Oriental). *Rev. Soc. Geol. España*, **16**, 123–134.

Spakman, W. & Wortel, M.J.R. (2004) A tomographic view on Western Mediterranean Geodynamics. In: *The TRANSMED Atlas: The Mediterranean Region from Crust to Mantle* (Ed. by W. Cavazza, F. Roure, W. Spakman, G.M. Stamplfli & P.A. Ziegler), pp. 31–52. Springer Verlag, Berlin.

Stich, D., Ammon, C.J. & Morales, J. (2003) Moment tensor solutions for small and moderate earthquakes in the Ibero-Maghreb region. *J. Geophys. Res.*, **108**, B3, 2148, doi:10.1029/2002JB002057.

Stokes, M. & Mather, A.E. (2003) Tectonic origin and evolution of a transverse drainage: the Rio Almanzora, Betic Cordillera, Southeast Spain. *Geomorphology*, **50**, 59–81.

Sylvester, A.G. (1988) Strike–slip faults. *Geol. Soc. Am. Bull.*, **100**, 1666–1703.

Van der Straaten, H.C. (1993) Neogene strike–slip faulting in southeastern Spain; the deformation of the pull-apart basin of Abaran. *Geol. Mijnbouw*, **71**, 205–225.

Vennin, E., Rouchy, J.M., Chaix, C., Blanc-Valleron, M.-M., Caruso, A. & Rommevau, V. (2004) Paleoecology constraints on reef-coral morphologies in the Tortonian–early Messinian of the Lorca basin, SE Spain. *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, **213**, 163–185.

Vissers, R.L.M., Platt, J.P. & Wal, D.v.d. (1995) Late Orogenic extension of the Betic Cordillera and the Alboran Domain: a lithospehric view. *Tectonics*, **14**, 786–803.

Voermans, F.M., Simon, O.J., Martín García, L. & Gómez Prieto, J.A. (1972) Huercal Overa (996). *Mapa de Geologico de España* (1:50.000), Instituto Geologico y Minero de España, Madrid.

Waldron, J.W.F. (2004) Anatomy and evolution of a pull-apart basin, Stellarton, Nova Scotia. *Geol. Soc. Am. Bull.*, **116**, 109–127.

Watts, A.B., Platt, J.P. & Buhl, P. (1993) Tectonic evolution of the Alboran Sea Basin. *Basin Res.*, **5**, 153–177.

Weijermars, R. (1987) The Palomares brittle–ductile Shear Zone of southern Spain. *J. Struct. Geol.*, **9**, 139–157.

Woodcock, N.H. & Schubert, C. (1994) Continental strike–slip tectonics. In: *Continental Deformation* (Ed. by P.L. Hancock), pp. 251–263. Pergamon Press, New York.

Woodside, J.M. & Maldonado, A. (1992) Styles of compressional neotectonics in the eastern Alboran Sea. *Geo-Mar. Lett.*, **12**, 111–116.

Wrobel, F. (2000) Das Lorca-Becken (Obermiozan, SE Spanien) – Faziesinterpretation, Sequenz-stratigraphie, Beckenanalyse. Unpublished Thesis, Universitat Hannover, 143pp.

Wrobel, F. & Michalzik, D. (1999) Facies successions in the pre-evaporitic Late Miocene of the Lorca Basin, SE Spain. *Sediment. Geol.*, **127**, 171–191.