Structure and tectonic evolution of the Almanzora Corridor and the western Huércal-Overa basin (Eastern Betic Cordillera)

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"Escribir algo requiere tanto empeño como fabricar una mesa. El escritor trabaja sobre una realidad que es un material duro como la leña."

Gabriel García Márquez

A Braulia y Joaquín

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Resumen

La evolución reciente de la Cordillera Bética está caracterizada por la formación e individualización progresiva de distintas cuencas sedimentarias y el desarrollo del relieve actual. Este proceso está controlado por la actividad de numerosos pliegues y fallas que se desarrollan como consecuencia de la convergencia entre las placas Euroasiática y Africana desde el Serravaliense-Tortoniense inferior. Para establecer con precisión la evolución reciente de la región es necesario caracterizar la deformación que estas estructuras tectónicas producen tanto en el basamento como en los sedimentos.

En este trabajo se determina la estructura superficial y profunda del Corredor del Almanzora y de la cuenca de Huércal-Overa, dos cuencas sedimentarias contiguas situadas en las Zonas Internas de la Cordillera Bética. La formación de estas cuencas tuvo lugar en una posición intermedia entre el sector central de la cordillera, principalmente caracterizado por la formación de grandes pliegues y fallas normales, y el sector oriental, dominado por grades fallas de salto en dirección sinistras. Además, se precisa la sucesión e interacción de las distintas fallas y pliegues así como su relación con la sedimentación durante el Mioceno superior y la posterior continentalización y erosión de las cuencas a partir del Mesiniense. Para alcanzar estos objetivos se combinan datos geológicos de superficie (cartografía geológica, análisis cinemático de las estructuras, nuevas dataciones), prospección geofísica (gravimetría, magnetometría, magnetotelúrico y posición de hipocentros) y un detallado análisis geomorfológico. A partir de la inversión de los datos cinemáticos obtenidos en este sector y del análisis de mecanismos focales de terremotos se establece la evolución de los esfuerzos.

Los resultados obtenidos permiten establecer la estructura de ambas cuencas, principalmente determinada por la geometría de grandes pliegues de dirección E-O a ENE-OSO. El crecimiento de la sinforma del Corredor del Almanzora, modificada por numerosas fallas normales —E-O a NO-SE— y fallas dextras —E-O—, generó el espacio de acomodación necesario para albergar los sedimentos detríticos suministrados por la erosión de las sierras contiguas. Estas sierras —Sierra de Los Filabres, Sierra Almagro y Sierra de Las Estancias— coinciden con la posición de grandes antiformas. A partir de datos magnéticos y magnetotelúricos se ha detectado la existencia de rocas básicas mineralizadas en el núcleo de la antiforma de Sierra de Los Filabres. Estas rocas podrían estar relacionadas con la nucleación del pliegue durante el Serravaliense-Tortoniense inferior. En la parte oriental del sector estudiado, la cuenca de Huércal-Overa constituye la terminación meridional de la falla sinistra de Alhama de Murcía —NE-SO a ENE-OSO—, activa desde el Tortoniense. Pliegues menores y fallas inversas —E-O a ENE-OSO— además de numerosas fallas normales deforman los sedimentos desde el Tortoniense. El desarrollo de estas cuencas tuvo lugar en un contexto de compresión NO-SE y extensión ortogonal asociada desde el Tortoniense, con permutaciones en la posición del eje máximo desde esta posición subhorizontal —con dirección NO-SE— a una posición subvertical. Este marco favorece la formación de estructuras activas, que condicionan la morfología del sector. El cálculo de índices geomorfológicos permite cuantificar cambios en la red de drenaje asociados a algunas de estas estructuras tectónicas. Los datos aportados durante este trabajo permiten discutir el papel de las estructuras activas descritas en marco sismotectónico de la Cordillera Bética oriental. La formación de pliegues relaja parcialmente la deformación producida por la convergencia de placas y atenúa la actividad sísmica, que varía a diferentes niveles corticales. Finalmente, los resultados se enmarcan en la evolución geodinámica reciente de la Cordillera Bético-Rifeña y la terminación del occidental del Mediterráneo y permiten analizar los distintos modelos propuestos.

Abstract

The recent evolution of the Betic Cordillera is characterized by the development and progressive individualization of sedimentary basins during the relief formation. This process is determined by the activity of numerous folds and faults since Serravallian-Early Tortonian. In order to precisely determine the recent evolution of the region it is therefore necessary to describe the deformation produced by these tectonic structures in the sedimentary infill of the basins. The present research is focused on two contiguous basins, the Almanzora Corridor and the Huércal-Overa basin, that are located in the cordillera hinterland. The development of these basins occurred in an intermediate position between the central Betic Cordillera, mainly characterized by large folds and normal faults, and the eastern Betic Cordillera, which is deformed by major sinistral faults.

In this Ph.D. Thesis the shallow and deep structure of the Almanzora Corridor and the Huércal-Overa basin is established. In addition, these data help us to constraint the development and interaction of the different faults and folds as well as their relation with sedimentation during the Late Miocene and with the later basin continentalization and erosion in Messinian times. To do so, detailed structural field work (including geological mapping, kinematic analysis on fault surfaces, and new biostratigraphical constraints), geophysical prospecting (gravity, magnetic, magnetotelluric and hypocenter location), and detailed geomorphological work have been carried out. The stress inversion from the fault data and the analysis of focal mechanisms allow for determination of the stress ellipsoid evolution.

The obtained results lead us to establish the structure of the studied basins, mainly determined by the geometry of E-W to ENE-WSW large folds. The progressive development of the Almanzora synform, modified by numerous E-W to NW-SE normal faults and E-W dextral faults, favoured the deposition of sediments coming from the erosion of the nearby ranges. These position of these ranges —Sierra de Los Filabres, Sierra Almagro and Sierra de Las Estancias— coincides with large antiforms. From magnetic and magnetotelluric data, a basic and mineralized body was detected in the core of Sierra de Los Filabres antiform. These rocks could be related to the fold nucleation during the Serravallian-Early Tortonian. In the eastern sector of the study area lies the Huércal-Overa basin, which constituted the southern termination of the NE-SW to ENE-WSW Alhama de Murcia sinistral Fault, active since Tortonian. E-W to ENE-WSW minor folds and reverse faults deform the Huércal-Overa sediments since Tortonian, coexisting with numerous normal faults. The development of these basins occurred in a framework characterized by NW-SE compression and orthogonal associated extension. The maximum axis alternated from the subhorizontal NW-SE to a vertical position. This setting favored the development of active structures that modify the morphology of the area. Geomorphic indices permit us to quantify the incidence of some active structures in the drainage network. The role of these active structures within the seismotectonic framework of the Eastern cordillera is clarified. Finally, the obtained results serve to explain the tectonic evolution of the Almanzora Corridor and

the Huércal-Overa basin inside the framework of the recent geodynamic evolution of the Betic-Rif Cordillera and the western Mediterranean, with discussion of the different models proposed to explain the recent evolution of the cordillera.

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PART ONE

1. Introduction
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1. Introduction

The Betic and Rif Cordilleras are located along the boundary between the African and Eurasian plates, which is characterized by an unusual tectonic setting that includes the Alborán basin in the central part of the Internal Zones of this compressional orogen. Geological and geophysical studies have focused on the identification of recent and active structures in order to establish the mechanisms responsible for the orogen´s tectonic evolution. Compressional and extensional structures deform the Internal Zones of the Betic Cordillera. The major tectonic structures have a heterogeneous distribution, dominated by fold and normal faults in the central Betics, and by strike-slip faults in the Eastern sector of the cordillera that interact with folds and normal faults. The change in the kinematics of the faults raises several questions as to the style of crustal deformation in that area. Meanwhile, some of the most important features of the crust may be assessed at a regional scale on the basis of geophysical research (seismic tomography, deep seismic reflection profiles, gravity, magnetics and magnetotellurics).

Here I examine the neotectonic structure of two sedimentary basins –the Almanzora Corridor and the Huércal-Overa basin– through the acquisition of new geological field studies and geophysical data. These two basins are located just within the transition between the Central and the Eastern part of the Internal Zones of the Betic Cordillera. This research is focused on the recent and active folds and faults that interact during the basins´ development. The geological and geophysical data presented will provide new insights regarding the recent deformation of this sector of the Cordillera, and will lead to discussion of the evolutionary models for the studied basins and their integration in the different geodynamic scenarios proposed for the Neogene-Quaternary development of the Betic and Rif Cordilleras.

1.1 Geographical setting

The area of study covered in this Ph.D. Thesis is primarily focused on the Almanzora Corridor and the western Huércal-Overa basin, which are located in southeastern Spain, comprising part of the Granada and Almería provinces (Fig. 1.1a). The two sectors are contiguous and represent topographic depressions that extend inside the coordinates 2.65 º W, 1.85 º W of longitude and 37.25 º N and 37.5 º N of latitude.

The Almanzora Corridor is an E-W elongated depression (average 35 km long and 6 km wide), taking its name from the Almanzora River, which crosses the corridor from West to East. The corridor is bordered to the North by the Sierra de Las Estancias range, and the southern border is the Sierra de Los Filabres; to the west lies the Baza basin and to the East the Huércal-Overa basin (Fig. 1.1b). The Huércal-Overa basin is named after a village located in the southeastern sector of the depression. It is flanked by the Sierra de Los Filabres and the Sierra Almagro to the South, and the Sierra de Las Estancias to the North.

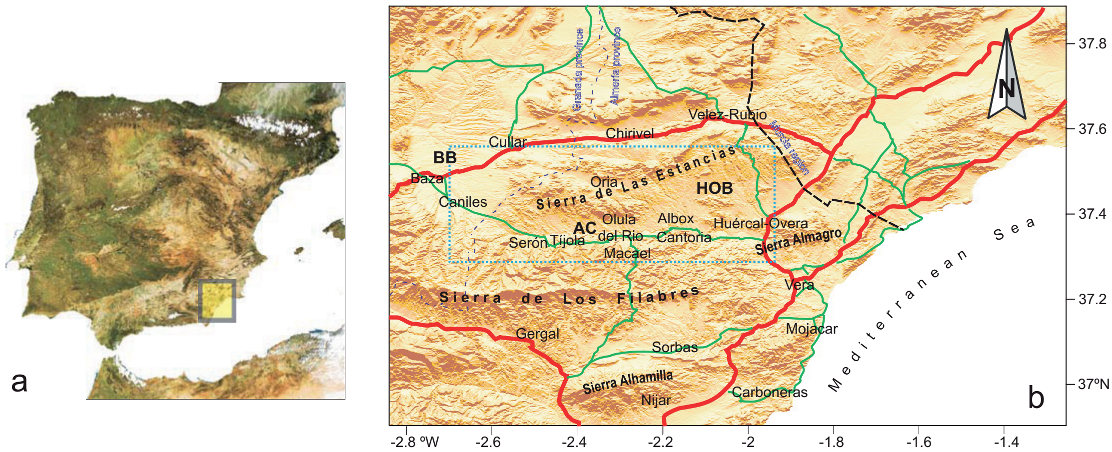

Fig. 1.1. Geographical setting of the study area: a. The study area is located in the Southeastern part of the Iberian Peninsula; b. Detailed geographical location of the Almanzora Corridor and the Huércal-Overa basin, including access roads from major villages. Legend: BB= Baza basin; AC= Almanzora Corridor; HOB= Huércal-Overa basin.

1.2 Geological setting

The Betic Cordillera, located in southern Spain, together with the Rif Cordillera, in northern Morocco, form an arc-shaped orogen situated in the western Mediterranean Sea (Fig. 1.2). The arc developed as consequence of the convergence between the Eurasian and the African plates from the Late Mesozoic to the Cenozoic, and of the progressive opening of the Algero-Balearic basin during the Oligocene and Early Miocene (e.g. Dewey et al., 1989; Rosenbaum et al., 2004).

The studied area is located in the Internal Zones of the Eastern Betic Cordillera (Fig. 1.3). This sector comprises the Almanzora and Huércal-Overa sedimentary basins developed over metamorphic rocks that crop out in the adjacent ranges.

Several tectonic domains were distinguished in the Betic and Rif Cordilleras (Fallot, 1948; Julivert el al., 1974) (Fig. 1.3). The first domain is composed by Mesozoic and Cenozoic sedimentary series with local intercalations of igneous rocks deposited on the south Iberian and northern African paleomargins. These rocks were deformed with a dominant thrust-and-fold structural style, and now form the outer arc of the orogen (External Zones). The second tectonic domain is formed by Cretaceous to Miocene deep-water flysches that were deposited in an ancient basin, probably of oceanic nature

(Durand-Delga et al., 2000), located between the paleomargins and the sector that at present constitutes the inner arc of the orogen. The third tectonic domain is located in this inner arc and is composed of allochthonous tectonic nappes that extensively include Paleozoic rocks and that have partially undergone metamorphism (Internal Zones or Alborán Domain).

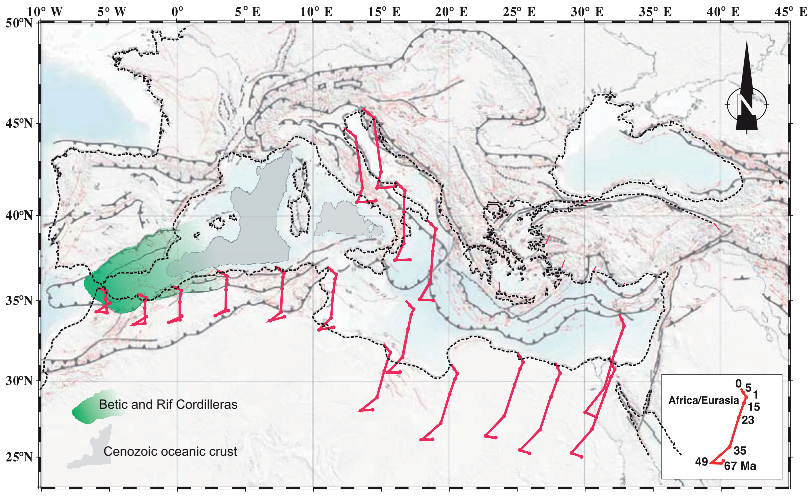

Fig. 1.2. Geological setting of the Betic and Rif Cordilleras in the westernmost end of Mediterranean Alpine Chain. The sectors in grey represent the oceanic crust. Convergence direction between the African and European plates since the Cretaceous, modified from Dewey et al. (1989).

The Internal Zones are subdivided into three main metamorphic complexes: from bottom to top, the Nevado-Filábride (Egeler, 1963), Alpujárride (Van Bemmelen, 1927) (analogous to the Sébtide Complex in the Rif) and Maláguide (Blumenthal, 1927) (equivalent of the Ghomáride Complex in the Rif). These complexes are separated by low-angle normal faults (Aldaya et al., 1984; García-Dueñas et al., 1988; Galindo-Zaldívar et al., 1989; Platt and Vissers, 1989). Both the Nevado-Filábride and the Alpujárride Complexes include several nappes with Paleozoic to Mesozoic lithostratigraphic sequences showing an extensive alpine ductile deformation and metamorphism, in some cases of variscan age, while the Maláguide Complex is formed by Paleozoic to Middle Miocene rocks that were deformed but not metamorphosed (Chalouan and Michard, 1990). In addition, the Dorsal and Predorsal complexes also belong to the Internal Zones, and are formed by Triassic to Early Neogene sedimentary rocks.

The External Zones are formed by Mesozoic and Tertiary rocks that were deposited over the variscan basements of the Iberian Massif and the Moroccan Meseta and Atlas. They have been deformed by folds and thrusts in a thin-skin tectonic style, detached from the variscan basement. Sediments from the Triassic Keuper facies constitute a regional detachment surface. From a paleogeographic standpoint, the External Zones can be interpreted as passive continental margins where several minor domains can be distinguished between the Early Jurassic and the Miocene. In the Betic Cordillera these domains are: the Prebetics, the Intermediate Units and the Subbetics (García-Hernández *et al.*, 1980). In the North-African margin, the External Rif is classically divided into the Prerif, Mesorif and Intrarif (Wildi, 1983). The rocks that compose the External Rif are generally non-metamorphic; however, some units assigned to the Intrarif and Mesorif record low-grade greenschist facies metamorphism (Temsamane units and Ketama units) (Frizon de Lamotte, 1985; Negro, 2005).

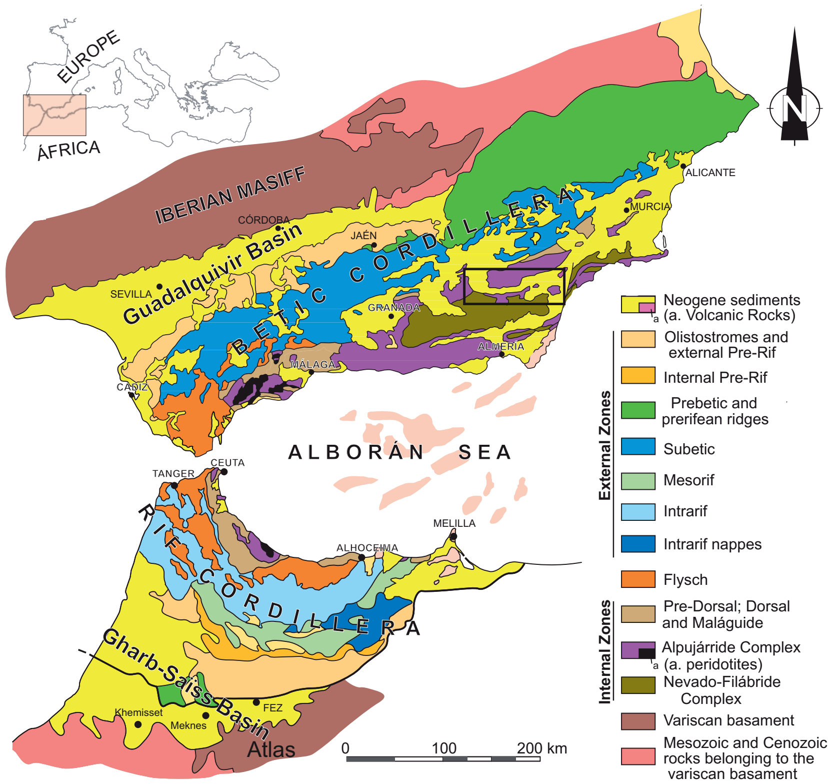

Fig. 1.3. Geological map of the Betic and Rif Cordilleras (Modified from Ruano, 2003).

Between the External Zones and the Iberian massif is lies the Guadalquivir basin, which is considered a foreland basin filled by sediments since the Early Miocene. During the Early and Middle Miocene, the Guadalquivir basin was a large marine basin constituting the northern connection between the Atlantic Ocean and the Mediterranean (the North Betic Strait). To the South, the Gharb-Saïss foreland basin separates the Rif from the Moroccan Meseta. In addition, the most recent evolution of the cordillera includes the development of minor sedimentary basins over the External and the Internal Zones, from the Late Miocene onward. These intramontane basins developed simultaneous to relief uplift, and therefore are highly conditioned by the recent tectonic structures.

The African and Eurasian plates have undergone relative convergence, probably from the Late Cretaceous (Dewey et al., 1989; Rosenbaum et al., 2002). Plate-kinematic reconstructions suggest that this plate boundary experienced continual N-S to NW-SE shortening (Dewey, 1989; Srivastava et al., 1990; Muller and Roest, 1992; Mazzoli and Helman, 1994; Rosenbaum et al., 2002). This collisional setting produced several metamorphic events. The main high-pressure metamorphic event recorded in the Internal Zones is attributed to a nappe-stacking process involving crustal thickening. A range of Ar^{39}-Ar^{40} and K-Ar ages for this high-pressure metamorphism between 48 Ma and 17 Ma has been proposed (Monié et al., 1991; Puga et al., 2004; Augier, 2005a). However, recent geochronological data obtained from Nevado-Filábride samples reveal Lu-Hf garnet ages between 18 and 14 Ma (Platt et al., 2006). In addition, (SHRIMP) U–Pb analysis of zircon in Nevado-Filábride ultramafic rocks gave an age of 15.0 ± 0.6 Myr (López Sanchéz-Vizcaino, 2001), interpreted as the age of high-pressure conditions, and in conflict with the previous proposed data.

The Betic-Rif arc geometry was mainly developed during Latest Oligocene to Middle Miocene, due to the westward drift of the Internal Zones. Focusing on the Betic Cordillera, the migration of the Internal Zones caused the northwestward thrusting and folding of the Mesozoic-Cenozoic rocks of the Subbetic Units (Crespo-Blanc and Campos, 2001) and the Flysch domain (Balanya and García-Dueñas, 1987; Luján et al., 2003; Platt et al., 2003). Simultaneously, the Internal Zones were subjected to an intense process of extension and were accommodated with the progress of low-angle-normal faults. While the Alpujárride/Maláguide contact mainly shows a top-to-the-E sense of motion active during the Earliest Miocene (Aldaya et al., 1991; Lonergan and Platt, 1995), the Alpujárride/Nevado-Filábride contact was subjected to extension with top-to-the-W sense of movement during the Middle Miocene (Galindo-Zaldívar et al., 1989; Platt and Vissers, 1989; Martínez-Martínez and Azañón, 1997). The Alpujárride Complex partially recorded a low pressure-high temperature metamorphism followed by cooling under low pressure conditions that could be related to this extensional process and to the exhumation of deep crustal rocks during the Early Miocene (Zeck et al., 1992; Monié et al., 1994; Balanyá et al., 1997; Azañón et al., 1997; Platt et al., 2005). Thrusting also occurred in this complex (Simancas and Campos, 1993).

During the Late Miocene, the N-S to NW-SE shortening between Europe and Africa continued (Dewey et al., 1989; DeMets et al., 1994). The mountain ranges and the depressed areas respectively coincide with large antiforms and synforms (Weijermars et al., 1985; Braga et al., 2003; Galindo-Zaldívar et al., 2003; Martínez-Martínez et al., 2004). In addition, the large folds are sometimes modified by normal and strike-slip faults (Booth-Rea et al., 2003a). Igneous activity in the Alborán basin and in the Betic-Rif Cordillera is related to these tectonic processes from the Early Miocene to Pleistocene (Duggen et al., 2005).

Two different and clashing views about the structures responsible for the development of the mountains and the basins have been proposed:

(a) Authors who consider the relative shortening between the Eurasian and African plates as the driving mechanism suggest that the development of the main features of the present-day relief of the Cordillera occurred in a context of crustal thickening during the Late Miocene (Galindo-Zaldívar et al., 1993; Galindo-Zaldívar et al., 2003; Sanz de Galdeano and Alfaro, 2004; Martínez-Díaz, 2004). These authors explain the development of normal faulting to a collapse, due to different processes: the presence of over-thickened crust in the Internal Zones, and/or linked to local extension produced by folding, and/or related to a transtensional regime close to the strike-slip faults.

(b) On the other hand, there are authors that propose development of the sedimentary basin to have occurred in an extensional setting, simultaneous to the exhumation and thinning of the metamorphic middle to upper crust during the Late Miocene (Mora, 1993; Vissers et al., 1995; Augier et al., 2005b; Meijninger, 2006). These authors explain the compressive structures as a consequence of tectonic inversion since Late Messinian-Pliocene times.

1.2.1 The main recent tectonic structures

The relief of the Internal Zones of the Betic Cordilleras is related to tectonic structures that have developed since Tortonian times. Antiforms give rise to elongated mountains, whereas synforms correspond to elongated depressions between these mountain ranges. These folds interact with normal faults of variable scale that occasionally have associated asymmetrical sedimentary depocenters. Moreover, the eastern part of the Betic Cordilleras is affected by a fault system characterized by large transcurrent sinistral faults (Alhama de Murcia, Palomares and Carboneras faults) that probably continue along the Alborán Sea and the northern Rif Cordillera. Practically no reverse faults crop out at surface. The following section briefly describes these main

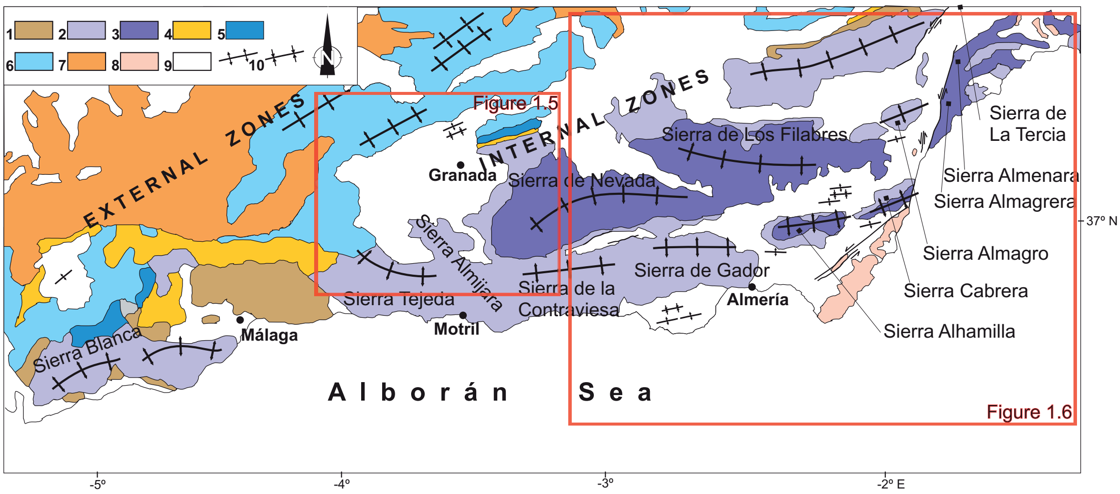

Fig. 1.4. Geological setting of the Betic Cordillera with location of main late Neogene folds. Legend: 1: Maláguide Complex, 2: Alpujárride Complex, 3: Nevado- Filábride Complex, 4: Campo de Gibraltar Flysch units, 5: Dorsal and Predorsal units, 6: External Zones Rocks, 7: Olistostrome units, 8: Volcanic, 9: Neogene and Quaternary basins, 10: Tortonian folds (Modified from Marín-Lechado et al., 2006). Position of figures 1.5 and 1.6 is marked.

recent tectonic structures of the Betic Cordillera.

Late large scale folds

The large scale folds show an E-W to ENE-WSW orientation. The Sierra Nevada and Sierra de Los Filabres, in the central sector, are the highest antiforms. The other parallel sierras coincide in trend with these major antiforms, but at lower altitudes: Sierra de las Estancias located to the northeast; Sierra Alhamilla, Sierra de Almagro, and Sierra Almagrera situated to the southeast; and Sierra Tejeda, Sierra Almijara, Sierra de Gador, and Sierra de la Contraviesa located to the south (Galindo-Zaldívar et al., 2003; Ruano, 2003; Sanz de Galdeano and Alfaro, 2004; Marín-Lechado et al., 2006). All these sierras are separated by synforms that correspond to elongated depressed areas,

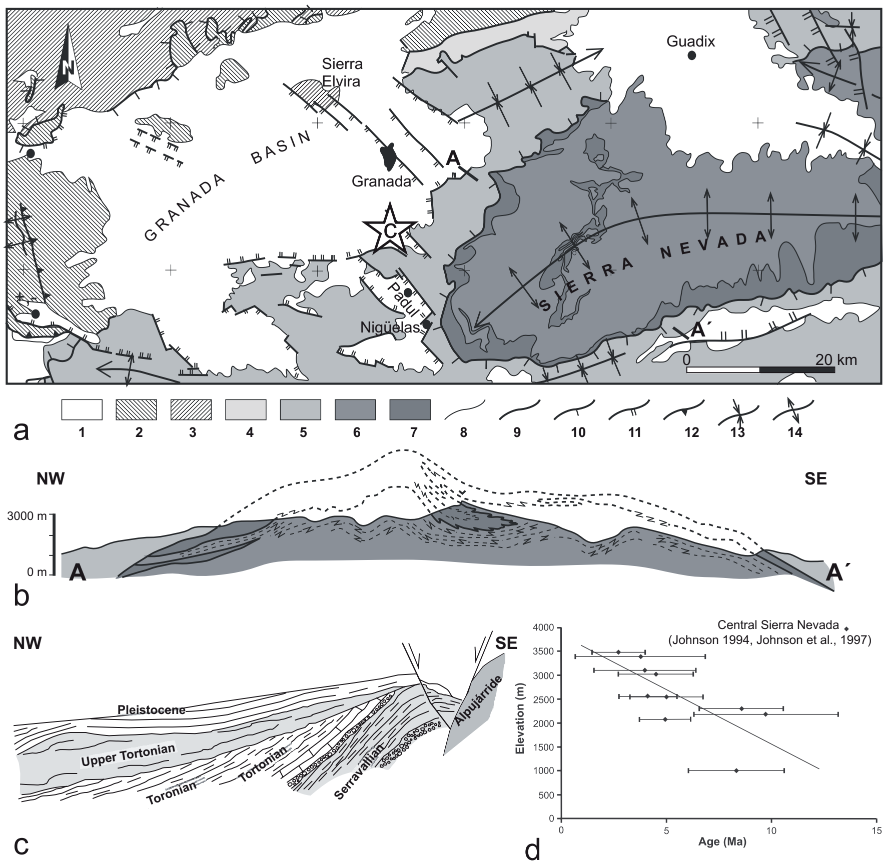

Fig. 1.5. Sierra Nevada and Granada Basin. (a) Tectonic sketch including position of cross-sections 1.5b and 1.5c. Legend: 1, Neogene rocks; 2, Upper Subbetic Units; 3, Intermediate Subbetic Units; 4, Maláguide Complex; 5, Alpujárride Complex; 6, Nevado-Filábride Complex, lower series; 7, Nevado-Filábride Complex, upper series and tectonic intercalations of upper and lower series; 8, unconformity; 9, fault; 10, low-angle normal fault; 11, high-angle normal fault; 12, reverse fault; 13, syncline; 14, anticline, (modified from Galindo-Zaldívar et al., 2003). (b) Cross section of the western Sierra Nevada showing antiform geometry (Galindo-Zaldívar et al., 2003) (c) Progressive unconformities among the Serravallian, the Tortonian, the Late Tortonian and the Pleistocene sediments that are located in the northern limb of the Sierra Nevada antiform (modified from Sanz de Galdeano and López-Garrido, 1999). (d) Apatite fission track pooled ages versus elevation from the central Sierra Nevada (Johnson, 1994, 1997; Johnson et al., 1997).

sometimes modified by faulting (Fig. 1.4).

The detailed fold geometries are difficult to establish due to scarce recent sedimentary cover in antiformal areas. Most of the folded rocks are metamorphic, and were highly deformed during Early and Middle Miocene (Figs. 1.4, 1.5a, and 1.5b). However, the Serravallian to Late Miocene sediments that surround the main reliefs are folded, and allow us to infer the fold geometry and date the deformation. The fold vergence is generally northwards. This vergence is well constrained in Sierra Alhamilla, where the Late Tortonian rocks dip 20º in the southern slopes, yet are vertical or even overturned in the northern slopes (Weijermars et al., 1985b). Most likely the fold growth started in Tortonian times, according to the age of the folded sediments and fission-track analysis conducted in Sierra Nevada and Sierra de Los Filabres (Johnson, 1994, 1997 Johnson et al., 1997), which confirms the time of final uplift stages of the metamorphic rocks (Fig. 1.5).

Strike-slip faults

The tectonic setting in the Eastern Betic Cordillera is characterized by the presence of NNE-SSW to NE-SW large sinistral strike-slip faults. These fault sets have been interpreted as a larger shear zone (Trans-Alborán transcurrent zone) that crosses the Eastern Betic Cordillera and the Alborán Sea up to the Moroccan Rif (De Larouzière et al., 1988). Below I describe the main sinistral strike-slip segments that deform the Eastern Betic Cordillera from North to South (Fig. 1.6).

The **Alhama de Murcia Fault** (AMF) (Bousquet and Montenat, 1974) is a NE–SW (N35ºE to N65ºE), reverse strike–slip segmented fault that extends over 80 km. The AMF runs from Murcia as far as the Huércal-Overa basin to the south, crossing the Guadalentín depression. The earliest AMF activity is poorly constrained; while some authors propose a sinistral behavior since the Tortonian (Montenat et al., 1990a, 1990c; Krijgsman et al., 2000; Vennin et al., 2004) other research comes to support a Latest Miocene-Early Pliocene onset of activity (Meijninger and Vissers, 2006). Fault activity during the Quaternary is better constrained, as deduced from structural data. The AMF deforms the Quaternary sediments as a result of the associated folds and reverse faults (Martínez-Díaz, 2002). In addition, the AMF generates low to moderate seismicity (Silva et al., 1997, Masana et al., 2002; Stich et al., 2003, 2006).

The **Palomares Fault** (PF) deforms the eastern sector of the Vera basin, with a N10ºE to N20ºE orientation. The PF is formed by several segments that show a sinistral slip component (Bousquet, 1979; Weijermars, 1987a). The Miocene sediments of the Vera basin are deformed by the fault, and two depocenters filled by Latest Tortonian to Quaternary sediments are linked to the movement of fault segments (Booth-Rea et al., 2003). This fault zone may also be considered a transcurrent deformation zone active during most of the Neogene and Quaternary (Montenat et al., 1987; Ott d'Estevou et al. 1990; Silva et al., 1993). Using the Late Miocene antiforms of Sierra Cabrera and Sierra

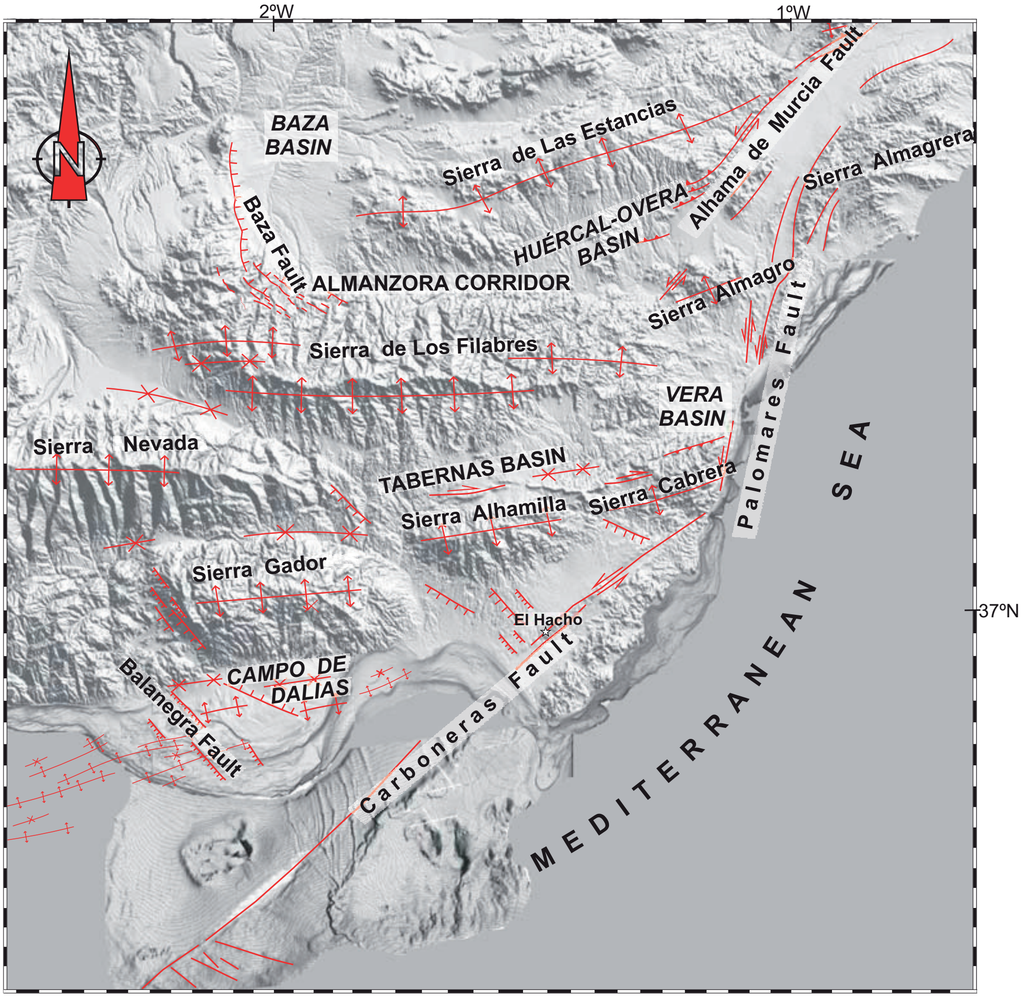

Fig. 1.6. Digital terrain model (USGS) and partial bathymetry (continental platform data from Instituto Español de Oceanografía; offshore data of the Carboneras Fault continuation from Gracia et al., 2005) of the Eastern Betic Cordillera showing the location of the main recent tectonic structures. Note the interaction between large folds, normal faults and strike-slip faults. Compiled information from Booth-Rea et al. (2004), Marín-Lechado et al. (2006), and Pedrera et al. (2006).

Almagrera as markers, the lateral displacement traditionally estimated for the fault is 15 km (Weijermars, 1987; Coppier et al., 1990).

The **Carboneras Fault Zone** (CFZ) crosses the Níjar basin with a N40ºE direction, and divides the area into two main blocks. The CFZ comprises several minor scale structures that record a sinistral slip component (Bousquet and Montenat 1974). The Miocene sediments, together with metamorphic and volcanic basement rocks, crop out along a highly deformed zone (Van de Poel, 1991; Faulkner et al., 2003) where different fault surfaces are linked. Few meters thick fault rocks are also exposed, extending over hundreds of meters in distance (Rutter et al., 1986). Fault surfaces bound an elongated ridge corresponding to La Serrata de Níjar. Authors Montenat and

Ott d'Estevou (1990) consider the activity of the fault to be simultaneous with Late Miocene deep water sedimentation and volcanic rock eruption, whereas Keller et al. (1995) and Scotney et al. (2000) suggest an initial movement during the middle Miocene (11 Ma), as unconformable Tortonian volcanic rocks and even Tortonian sediments lie over fault rocks developed in the metamorphic basement (Ott d'Estevou and Montenat, 1985). The sinistral strike-slip movement from Late Tortonian is estimated at 18 km (Montenat and Ott d'Estevou, 1990; Montenat et al., 1990b). However, other authors estimate a horizontal movement from the middle Messinian of 30-40 km, on the basis of the displacement of volcanic rocks (Rutter et al., 1986; Weijermars et al., 1987). Undisturbed Plio-Quaternary sediments cover the central sector of the fault and point to some recent activity of the CFZ. The recent tectonic activity is only locally observed, for instance in the SW sector, where N30º-45ºE subvertical sinistral strike-slip faults with limited displacement deform Pleistocene sediments (El Hacho zone) (Pedrera et al., 2006). In this locality, paleoseismological studies have been recently carried out. Trenches across the fault exposed colluvial wedges, which have been interpreted as four paleo-earthquakes occurring within the last 50 ka (Moreno et al., 2007). The CFZ continued offshore, with a NE–SW trend extending 100 km in length and featuring two segments –N45ºE and N60ºE oriented (Gràcia et al., 2006)–.

Normal faults

The extensional structures that deform Internal Zones of the Betic Cordillera since the Late Miocene are high dipping normal faults that may be grouped into two principal sets in view of their directions. The first has a NW-SE strike, and the second group is E-W oriented (Galindo-Zaldívar et al., 2003). Their presence is predominant in the Central Betic Cordillera, where the NW-SE normal faults habitually reach the greatest length and frequently condition the denudation/sedimentation areas since Tortonian times. In the next few paragraphs these main recent normal faults are briefly described from West to East.

Several NW-SE oriented normal faults extend from the northern **Granada basin** up to the **Padul-Nigüelas** area, affecting the Sierra Elvira, the city of Granada, and the western end of Sierra Nevada (Fig. 1.5). The geometry of the normal faults can be deduced from field geological observations and seismic reflection profiles (Rodríguez-Fernández and Sanz de Galdeano, 2006). The fault surfaces dip towards the SW, showing variable geometries ranging from listric fans to domino-like systems (Galindo-Zaldívar et al., 1996). They usually have associated asymmetric basins filled by wedge sediments from Tortonian up to Quaternary. Indeed, the Padul-Nigüelas sector constituted an active endorheic depression filled with detritic sediments and peat (Sanz de Galdeano, 1976; Galindo-Zaldívar et al., 1996). In addition, these faults exhibit paleoseismological evidence of recent activity as a seismic source (Alfaro et al., 2001) and have instrumental associated seismicity (Sanz de Galdeano et al., 1995; Galindo-

Zaldívar et al., 1999).

NW-SE oriented normal faults widely deform the western end of **Sierra de Gador** extending to the South as far as the **Campo de Dalías**. These faults are responsible for high slopes and sharp topography in the western part of Sierra de Gádor, and for the straight NW-SE oriented coastline in the Balanegra area (Fig. 1.6). Most of these normal faults deform up to the Quaternary sediments. The Quaternary faults developed in the Sierra de Gádor deform Holocene alluvial sediments generating fault scarps (Marín-Lechado et al., 2005). The average length of these faults is 2 km, but they may attain up to 8 km. The seismic activity in the Campo de Dalías shows NW–SE oriented lineations of epicenters that in some cases coincide with the observed main Quaternary faults (Marín-Lechado et al., 2005).

To the northeast, the main recent normal fault is the **Baza Fault** (Fig. 1.6), which runs more than 30 km along the westernmost Baza basin, showing a N-S to NW-SE variable strike, and dipping to the NE (Alfaro et al. 2007). This fault has associated asymmetric basin infill, by probably since Tortonian, as deduced from seismic profiles and gravimetric model (Alfaro et al. 2007). The fault deforms up to the Quaternary glacis (Botella et al., 1986; Martín-Penela, 1988; Azañón et al., 2006). At present the instrumental seismic activity of the Baza Fault is negligible. However, the Baza Fault was probably at the root of the 1531 Baza earthquake (Alfaro et al., 2007), with a VIII-IX assigned maximum intensity (Martínez-Solares and Mezcua, 2003).

The Internal Zones of the Betic Cordillera are also deformed by E-W trending normal faults, although they are less abundant than the NW-SE oriented faults. The E-W faults sometimes reach great lengths, as is the case of the **Zafarraya Fault** (15 km long), which controls the location of the asymmetric Zafarraya endorheic basin, filled with Tortonian to Present sediments (López-Chicano et al., 2002). The Zafarraya Fault is one of the few structures pertaining to the central part of the Betic Cordilleras that offers historical evidence of tectonic activity. There are reports of ground breaks during the 1884 Andalucía Earthquake; and colluvial wedges near the fault suggest seismic behaviour during the Holocene (Reicherter et al., 2003).

1.3 Previous geophysical data

This section describes the main geophysical data available in the Betic Cordillera, mostly obtained since the 1970´s. This information assembles gravimetric data, magnetic data, seismic refraction profiles, deep seismic reflection profiles, seismic tomography images, and magnetotelluric sounding, all decisive contributions for an understanding of the deep structure of the orogen. A portion of these data will be reinterpreted, taking into account new geological and geophysical data expounded in this Ph.D. Thesis. Unfortunately however, neither detailed reflection seismic profiles nor detailed gravity studies were acquired in the studied area, for which reason the basin geometries are still poorly constrained.

1.3.1 Gravity data

Gravimetric data analysis makes it possible to establish the variation in density of different rocks. The first gravity research carried out in the Betic Cordillera –by the I.G.N. (1975 and 1976)– consists of free air and Bouguer anomaly maps of Spain with a 1:1,000,000 scale (Fig. 1.7). The Bouguer anomaly map holds a clear correlation with the main observed geological features: Bouguer anomaly values approach 0 close to the coast, and are negative within the Iberian Peninsula. In the Betic Cordillera, these geophysical data reveal the presence of a thickened crust located below the Internal Zones, where the values are extremely low (up to –160 mGal). Detailed gravimetric research has improved our knowledge of the sedimentary thickness and depocenter distribution in nearly all the Neogene sedimentary basins of the eastern Betic Cordillera (e.g. Marín-Lechado et al., 2006; Pedrera et al., 2006; Alfaro et al., 2007; Sanz de Galdeano, 2007).

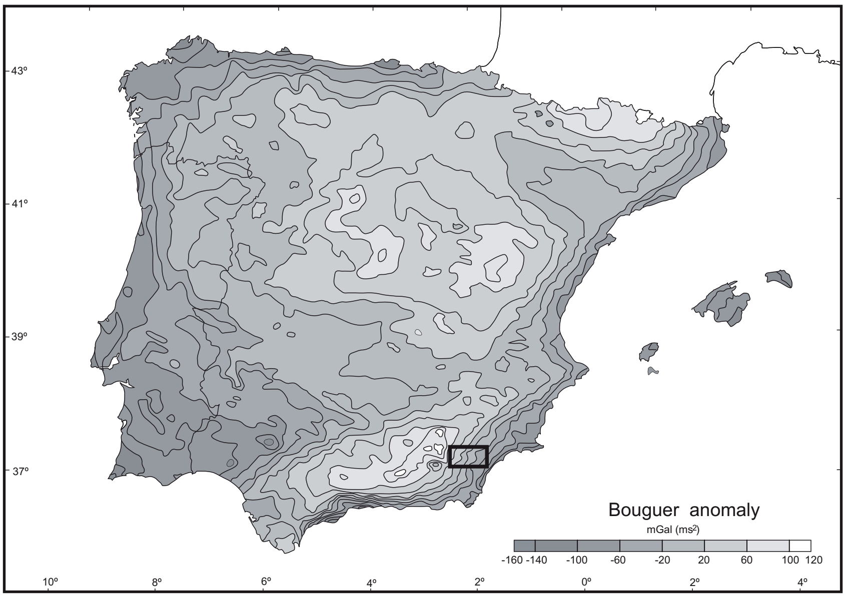

Fig. 1.7. Bouguer anomaly maps of Spain with 1:1,000,000 scale (from IGN, 1976).

Gravimetric models established for the Alborán Sea and Betic Cordilleras help determine the distribution of crustal thickness in the region (e.g. Hatzfeld, 1976; Suriñach and Udías, 1978; Casas and Carbó, 1990; Galindo-Zaldívar et al., 1998; Torné et al., 2000). The crust in the central transect thins from 38 km below the Internal Zones to 18–22 km beneath the Alborán Sea in an area about 30 km wide (Torné et al., 1992). There is a positive anomaly in the central zone of the Alborán Sea, which may be linked to the crustal thinning of this region, where continental crustal thicknesses are less than 15 km (Fig. 1.8).

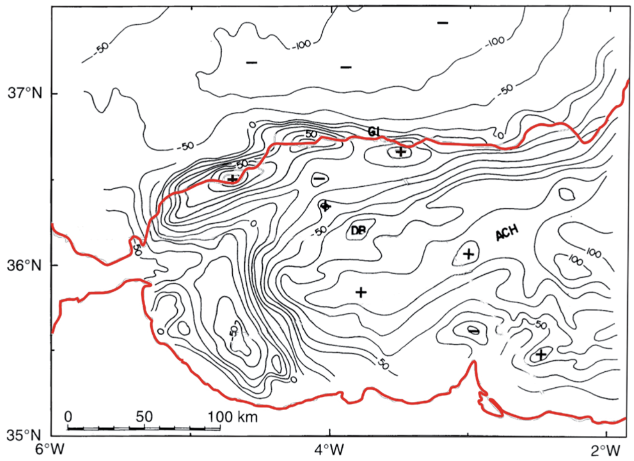

Fig. 1.8. Bouguer Anomaly map of the Alborán Sea (mGal). Based on Casas and Carbo (1990).

The Bouguer anomaly map 1:1,000,000 allows identification of a progressive decrease in the studied area of the anomaly value to the West, from -10 mGal in the Huércal-Overa basin, to -60 mGal in the Baza basin. However, these data have insufficient resolution for determining the geometry of the sedimentary infill of the basins. In order to constrain the thickness and distribution of the sedimentary infill, new gravity data are presented in chapters 5 and 6.

1.3.2 Magnetic data

The regional anomalies are evidenced by the aeromagnetic map of Spain, constructed from 10 km spacing fly lines at an altitude of 3 km and a scale of 1:1,000,000 (Ardizone et al., 1989). Focusing in the South of Spain, important magnetic anomalies are seen to be closely related to the different geological domains (Fig. 1.9). The anomalies related to the rocks belonging to the Iberian massif have a predominantly NW-SE strike. These anomalies extend, at least, beneath the Neogene sediments that fill the Guadalquivir basin. In the Betic Cordillera, excepting some isometric anomalies located in the External Zones (Bohoyo et al., 2000), the magnetic features are generally elongated and characterized by an E-W orientation. One of the largest magnetic anomalies of the Internal Zones is a dipole located in the area of study, over the Sierra de Los Filabres (Fig. 1.9). The dipole is asymmetrical, with a positive anomaly located to the South reaching up to 20 nT and a negative anomaly of – 70 nT.

The magnetometric data collected in the Alborán basin reveal that the main magnetic anomalies are related to the different volcanic seamount identified in the sea floor (Galdeano and Rossignol, 1977; Baniolessi, et al., 1979; Estrada-Llacer, 1994; Galindo-Zaldívar et al., 1998). The largest anomaly has ENE-WSW orientation and coincides with the northwestern border of the Alborán ridge or Alborán Channel, located in a central position (Fig. 1.9).

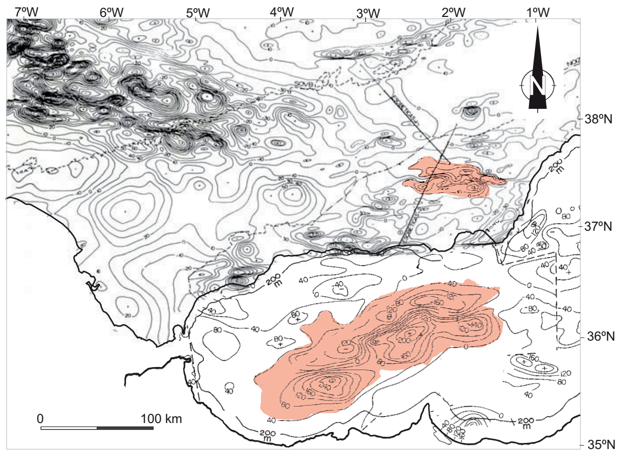

Fig. 1.9. Aeromagnetic map of Spain and magnetic map of Alborán Sea. In red are marked the main magnetic anomalies of the Betic Cordillera located in Sierra de Los Filabres and in the Central Alborán Sea (Modified from Galindo-Zaldívar et al. 1997 and 1998).

1.3.3 Seismic profiles

In order to constrain the deep crustal structure of the Betic Cordillera, seismic refraction profiles and deep seismic reflection profiles have been recorded since the seventies. Although conventional seismic reflection profiles are available for some basins of the Cordillera, the study area was not covered by any of these profiles.

Seismic refraction profiles

Deep seismic refraction profiles have been undertaken in the Betic Cordillera and the Alborán Sea since the seventies (Working Group for Deep Seismic Sounding in the Alborán Sea, 1974-1975, 1978; WGDSSAS-1974-1975, 1978). Interpretations of the profiles located in the Betic Cordillera suggest the presence of crustal detachment levels that may separate the upper crust, corresponding to outcropping rocks, from the lower crust (Banda and Ansorge, 1980; Banda et al., 1993). In addition, these seismic refraction profiles signal a westwardly decreasing crustal thickness in an E-W cross-section, from the uplifted Sierra Nevada (exceeding 30 km in thickness) to the Granada Depression (Banda et al., 1993). The largest profiles (440 km length) cross the study area along the Sierra de Los Filabres with an ENE-WSW strike.

The deep seismic refraction profiles developed in the Alborán Sea show a thinned continental crust (16 km thick) that thickens toward the Betic Cordillera (Hatzfeld, 1976; WGDSSAS-1974-1975, 1978; Suriñach and Vegas, 1993). Furthermore, an area characterized by low P and S spread velocities has been reported in the upper mantle below the Alborán Sea (Hatzfeld, 1976; Suriñach and Vegas, 1993). These seismic data, combined with the high regional heat flow values (Polyak et al., 1996), suggest the existence of an anomalous mantle below the Alborán Sea (Hatzfeld, 1976).

Deep multichannel seismic reflection profiles

The ESCI- BETICAS/ALBORÁN seismic reflection profiles were designed to provide a complete structural transect of the northeastern sector of the Alborán basin and the central Betic Cordillera from the Internal to the External Zones. Two deep seismic profiles were carried out in the central sector of the Betic Cordillera. The profiles show the crustal structure along two segmented profiles, NW-SE (ESCI-BETICAS-1) and NNE-SSW oriented (ESCI-BETICAS-2), with a total length of 196 km. Another two profiles were carried out in the Alborán Sea, one continuing to the South 90 km the NNE-SSW offshore profile (ESCI-ALBORÁN-1), and the second in a central sector of the Alborán Sea, with a WSW-ENE direction and extending 400 km from the eastern Alborán basin to the western Algero-Balearic basin (ESCI-ALBORÁN-2).

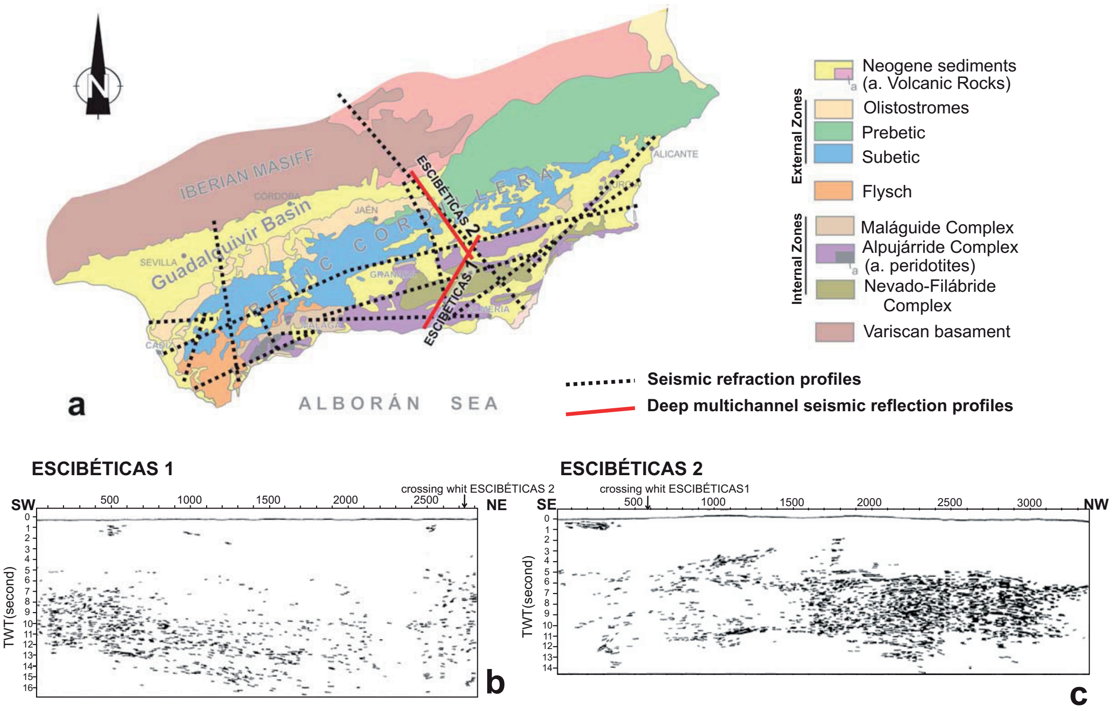

Fig. 1.10. Location of the refraction seismic profiles and the deep multichannel seismic profiles ESCIBÉTICAS 1 and 2. Main reflector observed in the ESCIBÉTICAS 1 and 2 profiles (modified from Galindo-Zaldívar et al., 1997).

Deep reflection seismic profiles ESCI-BETICAS and ESCI-ALBORÁN contributed to an assessment of the deep structure of the Betic Cordillera and its transition to the Alborán crust (García-Dueñas et al., 1994; Galindo-Zaldívar et al., 1997; Martínez-Martínez et al., 1997b; Vegas et al., 1997). Despite the poor quality of these seismic profiles, they reveal noteworthy differences between the crustal structure located below and above 15-20 km (5 s two-way travel-time, TWTT). The upper level is nearly transparent, while the lower sector is reflective and shows some subhorizontal reflectors around 11 s TWTT, which could be interpreted as the Moho.

The ESCIBETICAS-2, crossing both Sierra Nevada and Sierra de Los Filabres, shows sectors with subhorizontal crustal reflectors that could correspond to upper detachment levels under metamorphic ranges (e.g. García-Dueñas et al., 1994; Galindo-Zaldívar et al., 1997; Martínez-Martínez et al., 1997b).

Vegas et al. (1995) described a sharp decrease in thickness between the crust of the Betic Cordillera and the crust of the Alborán basin, with a 23-24 km thick by the coast (Medialdea et al., 1986; Barranco et al., 1990). Comas et al. (1992) describe folds that deform the sediments located in the northern part of the profile ESCI-ALBORÁN-1. In addition, they recognize a SSW-dipping reflector between 5 and 7 s TWTT. More recently, Booth-Rea et al. (2007) reprocessed an ESCI-ALBORÁN-2 profile, determining a crustal thickness diminish from 15 km thick (5 s TWTT) in the east Alborán basin to 6 km thick (2 s TWTT) in the Algero-Balearic basin.

1.3.4 Seismic tomography

Seismic tomography techniques, which use the natural seismic waves with different ray paths to map the differential velocity structure of the earth, have advanced noticeably in recent years, with the widespread development of the seismic station network and assessment of inversion procedures. Such advances have helped recover the resolution of models at a great range of depths.

Hence, the deep structure below the Betic Cordillera and the Alborán Sea has been studied to date from seismic tomography images at crustal depth (Sallarés, 1996; Gurria et al., 1997; Dañobeitia et al., 1998; Serrano et al., 2002) and at mantle depth (Spakman, 1990; Blanco and Spakman, 1993; Plomerová et al., 1993; Gurria and Mezcua, 2000; Spakman and Wortel, 2004). Deep seismic tomography shows high velocity bodies that are interpreted as relatively cold lithosphere within the surrounding hot asthenosphere. These seismic images have therefore been widely used to support the existence of subduction and/or delaminating systems throughout the western Mediterranean. Beneath the Alborán Sea, a North- and East-dipping high velocity body is

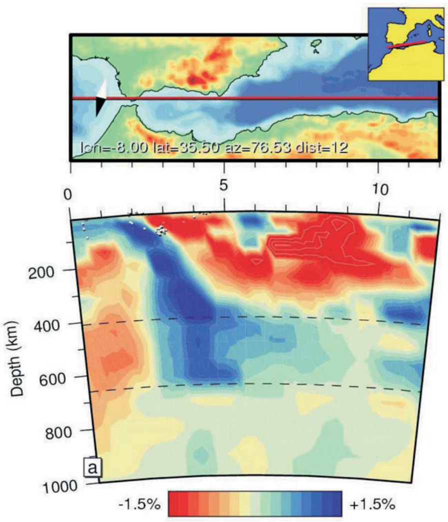

Fig. 1.11. Seismic tomography of the Western Mediterranean from Spakman and Wortel (2004).

located at depths of more than 600 km. Blanco and Spakman (1993), Lonergan and White (1997) and Bijwaard et al. (1998) interpreted this anomaly as a detached slab that belonged to an ancient subduction zone. It has alternatively been interpreted as a delaminated block from the lithospheric mantle (Seber et al. 1996, Calvert et al., 2000). Moreover, P- and S-wave seismic tomography revealed a low-velocity anomaly in the upper mantle beneath the western Betic Cordillera and the Alborán Sea region, beneath the Málaga coast. This structure is interpreted as a result of southward-active continental subduction (Morales et al., 1999).

1.3.5 Magnetotelluric data

Several magnetotelluric (MT) surveys have been carried out in the Betic Cordillera. The first survey crosses the Betic Cordillera from the Guadalquivir foreland basin to the Internal Zones with a NW-SE orientation (Fig. 1.12 a). On the basis of these data, a 2D model was constructed showing a deep conductor body in the lower crust, which was interpreted as partial melting of a thickened continental crust (Carbonell et al., 1998; Pous et al., 1999) (Fig 1.12 b). In the Central-Eastern Betic Internal Zone, the second survey was aimed to obtain a general 3D model (Fig. 1.12 c), which reveals a conductive body under the Sierra de Los Filabres possibly related to basic igneous rocks (Martí, 2006). In addition, Martí et al. (2004) and Martí (2006) completed a detailed dimensionality study from this data set using rotational invariant techniques.

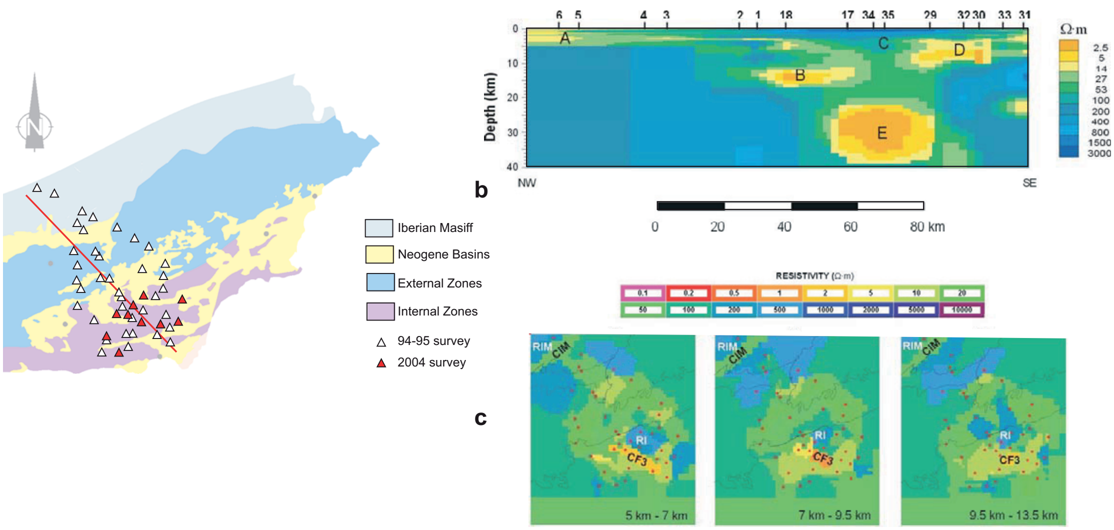

Fig. 1.12. (a) Location of the MT sites realized in the Betic Cordillera. (b) 2D MT resistivity model, where A, B, C and D are the main conductive structures identified (Pous et al., 1999). Representative horizontal cross-sections from the 3D model constructed by Martí (2006) that show the conductive body CF3 between 5 and 13.5 km.

This previous MT research tackled a large area with a regional objective. Yet in order to study specific structures, and to constrain the geometry of the main crustal structures established from surface data, we acquired new MT sounding with less distance between MT sites and with a limited period range.

1.4 Models of the recent tectonic evolution of the Betic and Rif cordilleras

The geodynamic evolution of the Betic and Rif Cordilleras is still a matter of debate. Numerous geodynamic models have been proposed to explain their development during the Neogene, models that have benefited from the progressive inclusion of further geological and geophysical information. A revision of these geodynamic models from a historical perspective is proposed so as to understand how the major geological and geophysical advances have been adopted by the general evolution models of the cordillera.

The Betic and Rif cordilleras withhold several remarkable features: (a) the narrow arc-shaped orogen that is surrounded by their external fold and thrust belt; (b) the existence of compressive structures in the external zones that developed coevally with low-angle normal faults in the internal part of the system during the Early to Middle Miocene; (c) the presence of a thin continental crust in the central part of the hinterland, where the Alborán Sea is located; (d) volcanic episodes since the Middle Miocene; and (e) active tectonics with a complex earthquake pattern.

1.4.1 Historical evolution of the tectonic models

The External Zones, located in the Gibraltar arc, have an arc-shaped and a structural style characterized by a succession of detached folds and thrusts. On the basis of this geological evidence, the Betic and Rif Internal Zones (Alborán Domain) was initially considered as a hinterland that was westwardly emplaced over the external domain, located in the South Iberian and North Africa paleomargins. Accordingly, the first tectonic models considered the Alborán Domain as a rigid microplate (Andrieux et al., 1971; Andrieux and Mattauer, 1973) (Fig. 1.13). Meanwhile, Tapponier (1977) interpreted the movement to the west of the Alborán microplate as an escape-tectonic consequence of the irregularities between the plate's boundaries. The westward displacement of the Alborán microplate was widely proposed as the mechanism responsible for the development of dextral strike-slip faults in the Betic Cordillera and sinistral strike-slip faults in the Rif (Bourgois, 1978; Sanz de Galdeano, 1983; Leblanc and Olivier, 1984; Bouillin et al., 1986, Martín Algarra, 1987; Durand-Delga and Olivier, 1988; Dewey et al., 1989).

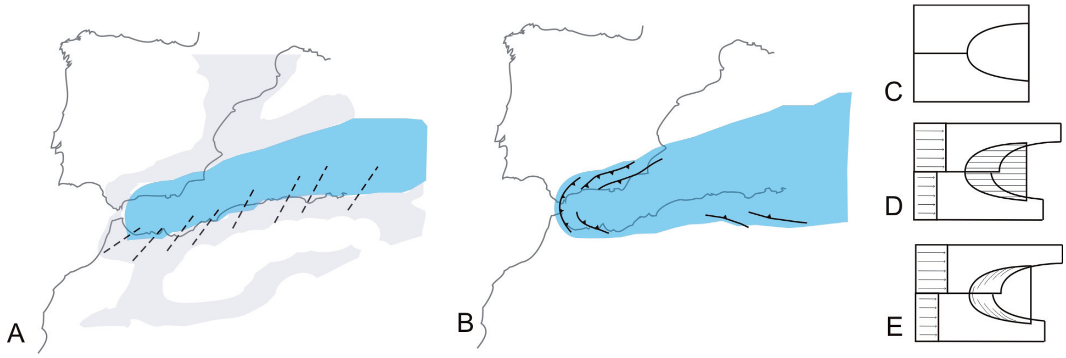

Fig. 1.13. Model proposed by Andrieux et al. (1971). A. Present geometry of the Alborán microplate (in blue); B, Geometry of the Alborán microplate during the Early Miocene. The purple area represents the area folded by the Alpine Orogeny. C-E, Geometrical model that tries to explain the Gibraltar arc development. C, Before plate movement; D, The Alborán microplate cover upon the European and African plates; E, Folding in the boundaries of the microplate.

The mechanism of subsidence involved in the Alborán region, which represents a large sector with thinned lithosphere located just within the Betic-Rif hinterland, was initially attributed to mantle diapir rising and subsequent cooling beneath the Alborán Sea (Cloetingh and Nieuwland, 1985; Weijermars et al., 1985a) (Fig. 1.14). Similar models previously aimed to explain the emplacement of the outcropping Ronda peridotites (Loomis, 1975).

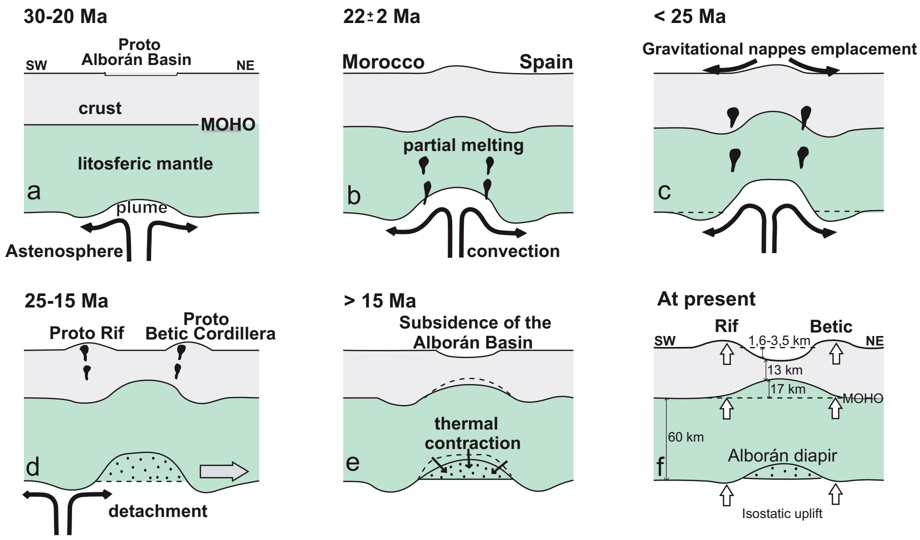

Fig. 1.14. Evolution model based on mantel diapirism proposed by Weijermars (1985a). The existence of an upwelling convection in the mantle produces a thermal instability in the Lithosphere-Asthenosphere boundary 30 Ma ago. (Redrawn from Ruano, 2003)

The contacts between the metamorphic complexes of the Internal Zones were traditionally considered as major thrusts (Egeler and Simon, 1969). During the eighties, these large faults were reinterpreted as low-angle normal faults developed during the

Early and Middle Miocene (Aldaya et al., 1984, Galindo-Zaldívar, 1986; García-Dueñas et al., 1986; Galindo-Zaldívar et al., 1989; Platt and Vissers, 1989). From this new perspective, the Alborán Domain may be considered as a sector subjected to extensional deformation during its emplacement to the west (e.g. Balanyá and García-Dueñas, 1987; Jabaloy et al., 1992).

1.4.2 Latest tectonic models

Several geodynamic models attempt to explain the mechanical causes of the fast extension accompanied by the exhumation of metamorphic rocks during the Miocene. These tectonic models can be grouped into three sets.

(1) Models that involve detachment and/or delamination of subcontinental lithosphere beneath the Alborán Region.

(2) Models that propose the subduction of oceanic lithosphere associated with slab roll-back and/or detachment of the subducted slab.

(3) Models that propose a Miocene subduction of oceanic lithosphere beneath the Alborán Basin generating Late Miocene delamination of subcontinental lithosphere beneath the continental margins of Iberia and Africa.

Detachment and/or delamination of subcontinental lithosphere

The convergence between Africa and Eurasia during the Late Eocene (e.g. Dewey et al., 1989; Monié et al., 1991) was associated with nappe stacking and crustal thickening. This collisional setting developed a thick, cold, and gravitationally unstable lithosphere mantle (Fig. 1.15). The lithospheric root was removed and assimilated in the Late Oligocene-Early Miocene by convection (Houseman et al., 1981; Platt and Vissers, 1989; Houseman, 1996) or by lithospheric delamination (e.g., García Dueñas et al., 1992; Seber et al., 1996; Calvert et al., 2000). The great increase in potential energy led to substantial horizontal extension and exhumation of metamorphic rocks. The radial horizontal stresses decayed in the Late Miocene, when the convergence of Africa and Eurasia again became the main deformational process producing shortening within the External Betic and Rif mountain belts.

The passive delamination model proposed by García-Dueñas et al. (1992) and Seber et al. (1996) differs from the active delamination model proposed by Platt and Vissers (1989) and Houseman (1996) in terms of the removal mechanism of the lithospheric root that could caused by convection. Calvert et al. (2000) detected two high velocity bodies dipping to the SE beneath the Alborán basin –from seismic tomography (between 60 and 400 km, and between 570 and 650 km)– likewise interpreted as delaminated lithosphere.

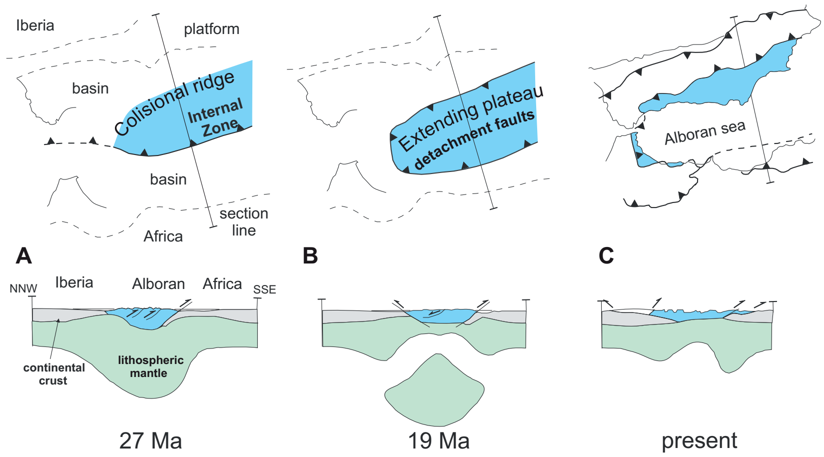

Fig. 1. 15. Delamination of lithospheric mantle by convective removal, from Platt and Vissers (1989). Geodynamic evolution of the Alborán Sea: A, lithospheric thickening due to plate convergence during the Cretaceous-Palaeogene. B, During the Burdigalian, convective delamination of the lithosphere mantle, producing elevation of the cordillera. The potential energy increase in the Internal Zone. C, Extension in the Internal Zones and emplacement over the continental margin. In the Alborán Sea, thermal subsidence prevails in a slow convergence setting.

Subduction of oceanic lithosphere, slab roll-back and/or detachment of the subducted slab

Numerous models propose subduction during the convergence process and the development of the Betic Rif Cordillera. Moreover, existing geochemical data from the derived volcanism and the proposed sense of the dip show significant differences. Some authors have proposed the presence of a subduction zone dipping to the N (Araña and Vegas, 1974; De Jong, 1991 and 1993; Wortel and Spakman, 1992; Zeck et al., 1992). Torres Roldán et al. (1986) suggested the existence of double subduction zone with active oceanic crust up to the Late Miocene. Later, Blanco and Spakman (1993), Zeck (1996) and Hoernle et al. (1999) proposed a model whereby break-off of a NW dipping subducted slab beneath Iberia produced large differences in potential energy and led to the extension and compression evidenced within the region.

With the acquisition of new geological and geophysical data from the region, the number of viable hypotheses has been reduced. Recent seismic tomography studies support the suggested subduction and subsequent slab-rollback and/or retreating-slab model (Blanco and Spakman, 1993; Morley, 1993; Royden, 1993; Lonergan and White, 1997; Hoernle et al., 1999; Gutscher et al., 2002; Gill et al. 2004; Wortel and Spakman, 2004; Thiebot and Gutscher, 2006).

The development of the Alborán Sea occurred during the westward migration of an older subduction zone (Fig. 1.16). This subduction zone migrated to the west due to a fast rollback that was compensated by extension in the continental crust located above. The crust was thinned to ~15 km as result of the extension (between 22-12 Ma, Lonergan and White, 1997). Contemporaneously, fragments of continental crust were emplaced onto the Southern Iberia and Northern Africa margin. This westward migration was accommodated by shortening in the External Zones, probably producing block rotations during the emplacement. Final accretion of the Betic-Rif Cordillera occurred in Early Tortonian (10 Ma), when the subduction zone rolled back as far as Gibraltar. Subduction rollback then ceased, together with the end of back-arc extension in the Alborán Sea (Lonergan and White, 1997).

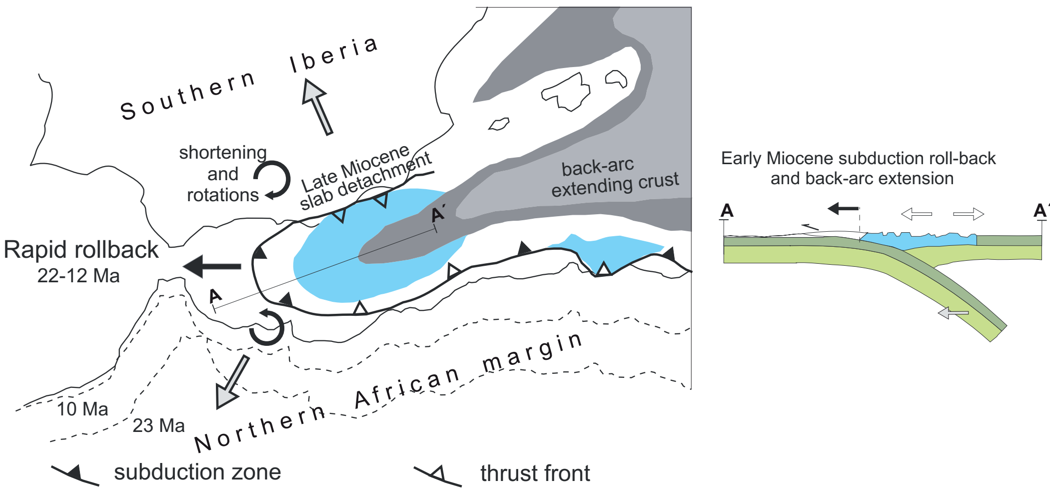

Fig. 1.16. Reconstruction illustrating the Neogene evolution of the Betic-Rif Cordilleras based on subduction (Early Miocene) and roll-back (Late Miocene: clockwise rotations in the Iberian plate and counter-clockwise rotations in the African plates (modified from Lonergan and White, 1997).

Subduction of oceanic lithosphere beneath the Alborán basin and delamination of subcontinental lithosphere

In order to explain the geochemical evolution of magmatism, recent models propose delamination of subcontinental lithosphere beneath the continental margins of Iberia and Africa during the Late Miocene (Duggen et al., 2003, 2004, 2005, 2008) (Fig. 1.17). The roll-back of an E-dipping subducting slab belonging to the old Tethys oceanic lithosphere in the Miocene could have produced the delamination of bands of the subcontinental lithosphere at the southern Iberian and northwestern African continental margins. The upwelling of plume-contaminated sub-lithospheric mantle beneath southern Iberia and northwestern Africa replaced the delaminating subcontinental lithospheric mantle. This model is also proposed to explain the presence of an active transfer fault zone probably linked to a segmented extensional system in the Central Betic Cordillera (Martínez-Martínez et al., 2006); these authors therefore consider that the delamination of subcontinental lithosphere is the mechanism behind extension in the upper crust, and that it would still be operating.

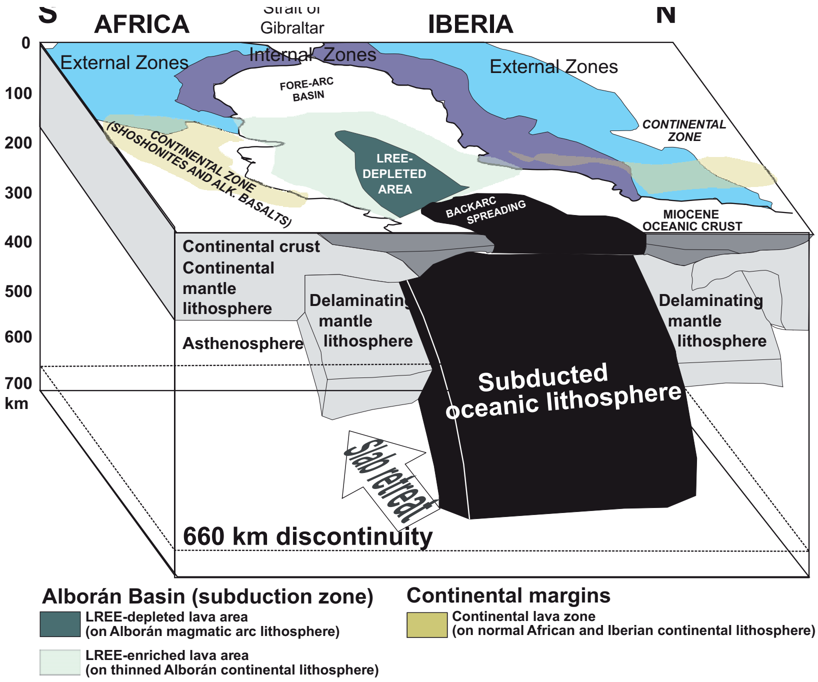

Fig. 1. 17. Three-dimensional geodynamic model of the westernmost Mediterranean based on geochronological and geochemical magmatism (modified from Duggen et al., 2008). The east-dipping subduction oceanic lithosphere beneath the Alborán basin released fluids and melts from the subducting oceanic plate, producing high degrees of partial melting from the overlying mantle wedge (Middle to Late Miocene low-K –tholeiitic- and medium-K -calc-alkaline- series volcanic rocks). In the southern Iberian and northern African plate margins, the westward slab roll-back of the subducted oceanic lithosphere produced (1) delamination of bands of subcontinental lithosphere and (2) upwelling of plume-contaminated sub-lithospheric mantle around the edges of the delaminating lithosphere and beneath the southern Iberian and northwestern African continental margins (Si–K-rich magmatism with a subduction-like geochemical signature; Si-poor intraplate-type magmas).

1.5 Previous geological research in the Almanzora Corridor and in the Huércal-Overa basin

This section offers a concise summary of previous research carried out in the area of study. Numerous authors have investigated the geological characteristics of the Almanzora Corridor and the Huércal-Overa basin from multidisciplinary approaches. Though most contributions are focused on the basin´s stratigraphic features, some authors describe the tectonic and geomorphological features of the sector. These previous studies are carefully revised in the framework of new contributions in the second half of this PhD. Thesis.

1.5.1 Stratigraphic research

The Almanzora Corridor sedimentary record has been a topic of study since the seventies, when Martín-García (1972) first proposed a lithostratigraphic division. Later on, numerous research studies were centered on the western part of the Almanzora Corridor, close to the nearby Baza basin, in view of its major paleogeographic implications. The poor quality of the biostratigraphic data gave rise to equivocal paleogeographic interpretations. For instance, some authors suggested a hypothetical connection between the Mediterranean Sea and the Guadix-Baza basin during the Pliocene through the Almanzora Corridor and the Huércal-Overa basin (Delgado et al., 1980; Peña, 1985; Alberdi et al., 1988, 1989; Bonadonna and Leone, 1989; Goy et al., 1989). However, most researchers supported the view that the Almanzora Corridor was emerged during the Pliocene (Peña, 1979; Sebastián Pardo, 1979; Sebastián Pardo et al., 1980; Cuevas et al., 1984; Vera et al., 1994). Accordingly then, the majority of studies regarding the reefs cropping out in the Almanzora Corridor and in the Huércal-Overa basin assigned them a Tortonian age (e.g. Voermans et al., 1972, 1979; Dabrio, 1974, 1975; Montenat, 1977; Dabrio and Martin, 1978; Esteban, 1979; Simon et al., 1979; Briend, 1981; Braga and Martín, 1987, 1988).

After overcoming these early biostratigraphical problems, detailed stratigraphic and sedimentological descriptions soundly established the essential sedimentary features of the Almanzora and the Huércal-Overa basins (Briend, 1981; Braga and Martín, 1988; Briend et al., 1990; Mora, 1993; Guerra-Merchán, 1992; Guerra-Merchán and Serrano 1993; Poisson et al., 1999; Augier, 2004; Meijninger, 2006; Meijninger and Vissers, 2006) (Fig. 1.18). Some discrepancies still remain, however, between the most recently proposed sequences.

1.5.2 Tectonic research

Our knowledge of the tectonic structure in the Almanzora Corridor and in the Huércal-Overa basin varies from one sector to another. While in the Huércal-Overa basin, and mainly in the southern and eastern sectors, several researchers have described the neotectonic evolution and active structures, for the Almanzora Corridor these studies are scarce, having been undertaken only on a regional scale and focusing on the basement deformation.

Some studies involving the eastern Huércal-Overa basin look into the relation between faults and sedimentation during the Late Miocene, underlining the stratigraphical aspects (Briend, 1981; Briend et al., 1990; Montenat and Ott D'Estevou, 1990). The deformations recorded in the late Miocene sediments of the Huércal-Overa basin have been described more recently (Mora, 1993; Augier, 2004; Meijninger, 2006; Meijninger and Vissers, 2006). Faults deforming the Quaternary sediments in the eastern Huércal-Overa basin were documented in the earliest publication from the Groupe de

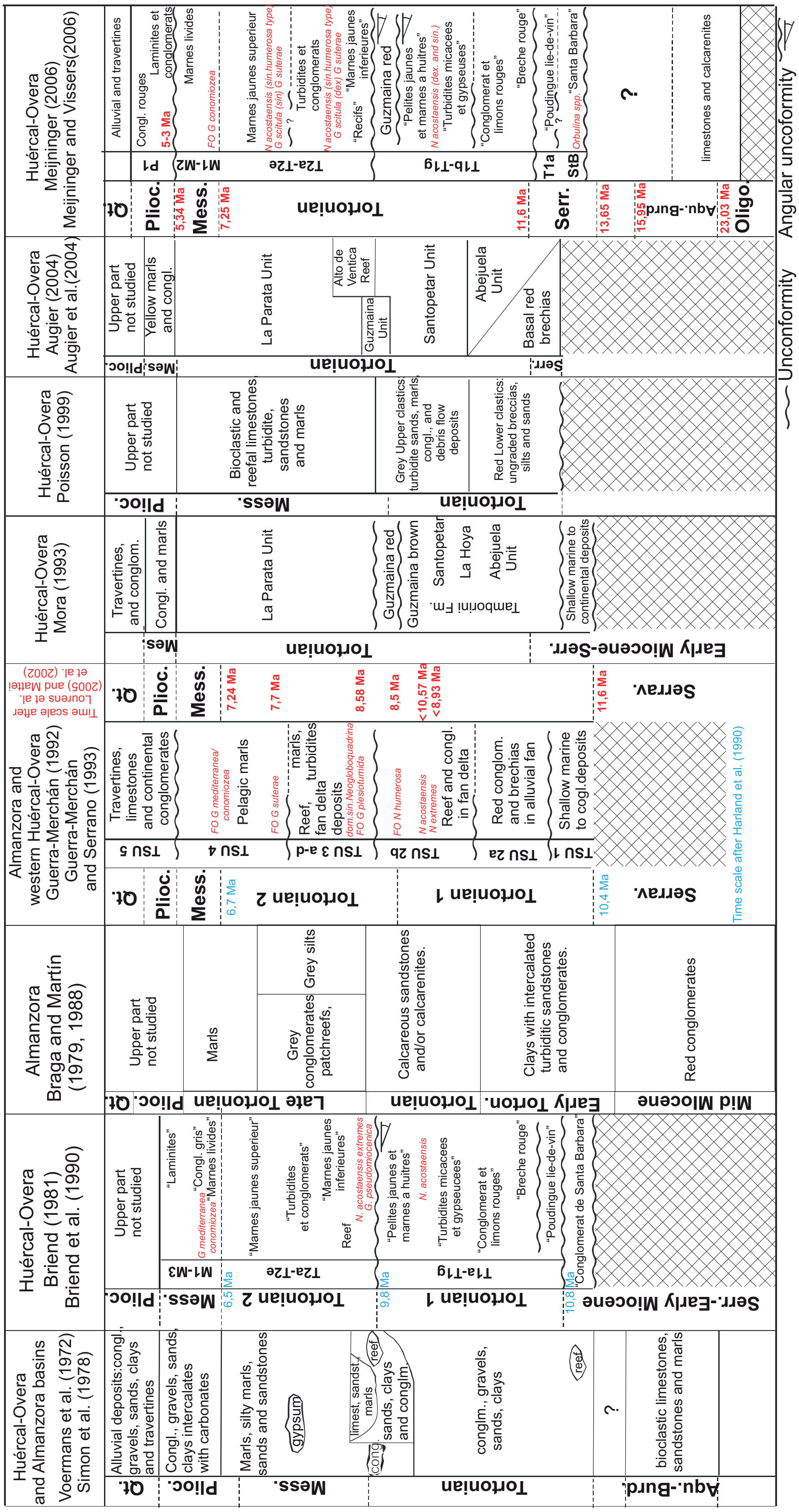

Fig. 1.18. Schematic stratigraphic sequences proposed for the Almanzora and Huércal-Overa Basins (modified from Meijninger 2006, with data from Braga and Martín 1988).

Recherche Néotectonique (1977). The Quaternary deformation of the eastern Huércal-Overa basin has recently been analyzed in detail from geomorphological, structural and paleoseismological points of view (García-Meléndez et al., 2003; Soler et al., 2003; Masana et al., 2005).

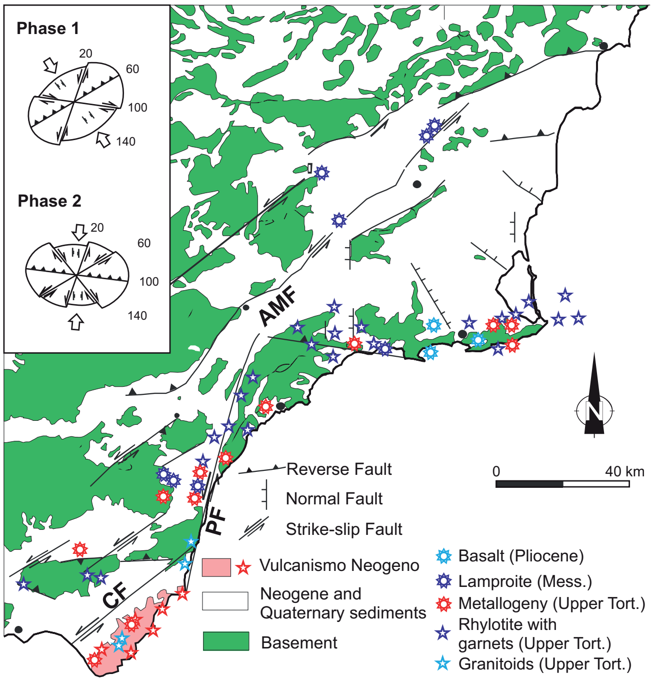

Fig. 1.19. Tectonic sketch of the Eastern Betics with the main Neogene and Quaternary volcanism (modified from Montenat and Ott D'Estevou, 1990). These authors proposed the development of pull-apart basins simultaneous to the strike-slip faulting. They suggest a change in the compressive axis direction during the Neogene, from NW-SE to NNE-SSW. AMF, Alhama de Murcia Fault. CF, Carboneras Fault; PF, Palomares Fault.

Previous authors had put forth extensional models for the basin development based on the growth of large E-W to WNW-ESE normal faults coetaneous to sedimentation (Guerra-Merchán, 1992; Augier et al., 2005b). The latest models are those proposed by Augier (2004), Augier et al (2005b), Meijninger (2006), and Meijninger and Vissers (2006).

Augier (2004) defined the Huércal-Overa as an extensional basin developed under NNE-SSW dominant extensional field stress from Serravallian-Early Tortonian times to the Latest Tortonian (Fig. 1.20). This author holds the extensional framework to be responsible for the basin formation and the coetaneous activity of low-angle normal faults, leading to the exhumation of the Nevado-Filábride rocks. Moreover, it is proposed that the basin ceased to extend and subside at 7.4 Ma, with the onset of basin inversion. In addition, Augier et al. (2005b) extrapolate this extensional model to the development of the nearby Almanzora Corridor. From observation in the basement rocks of the southern border, they interpreted the Almanzora Corridor as a half-graben structure developed in the hanging-wall of the Alpujárride/Nevado-Filábride top-to-the-north low-angle normal fault.

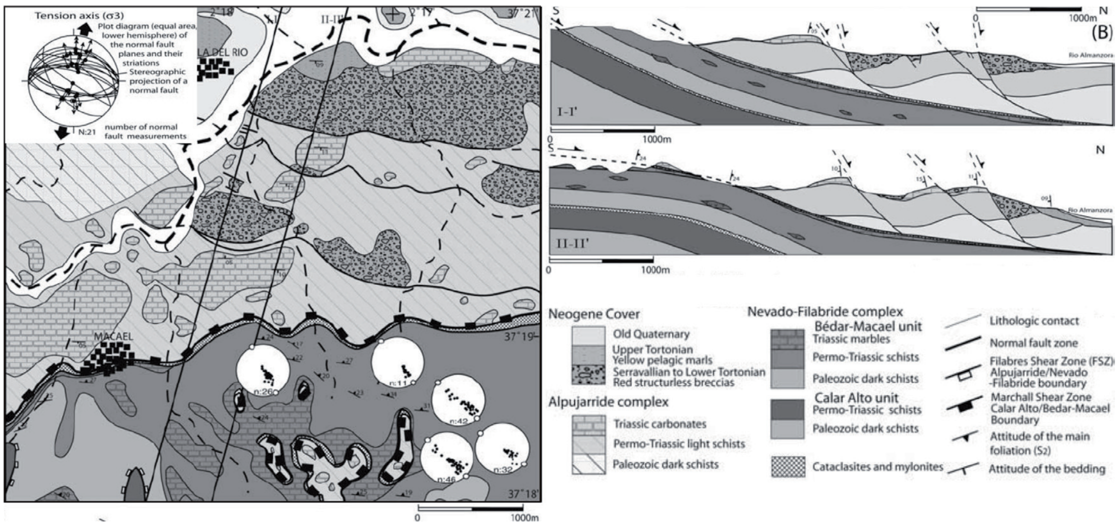

Fig. 1.20. Geological map, cross-section and fault kinematics of the southern boundary of the Central Almanzora Corridor (Augier et al., 2005b).

Meijninger (2006) and Meijninger and Vissers (2006) similarly propose a model for the development of the Huércal-Overa basin in a pure extensional setting characterized by ENE-WSW to NE-SW directed extension and gradual basin subsidence in the early Tortonian (Fig. 1.21). Later, syn-sedimentary faulting would indicate NNE-SSW to NW-SE directed extension during the Tortonian. The extensional tectonic setting changed to roughly NW-SE directed shortening in the Latest Miocene to Pliocene, and the consequent inversion of the basin gave rise to compressive structures.

1.5.3 Geomorphological research

Numerous geomorphological studies have been carried out in the Eastern Betics in an aim to correlate the geomorphological features with active tectonic processes (e.g. Silva et al., 1993, 2003; García-Meléndez et al., 2003; Sanz de Galdeano and Alfaro, 2004; García-Tortosa et al., 2007). Differential uplift, deformation of fluvial current profiles, fast headward erosion and piracy processes have thereby been detected (e.g. Calvache and Viseras, 1997, Calvache et al., 1997; Azañón et al., 2003; Stokes and Mather, 2003; Booth-Rea et al., 2004). Several geomorphological research efforts focus on the southern Baza basin, on the Almanzora Corridor, and on the Huércal-Overa basin.

In the southern Baza basin, Goy et al. (1989) provide a detailed geological and geomorphological map of the westernmost study area, between Baza and Caniles. A number of NW–SE morphological scarps are mapped and interpreted as faults. Heddi et al. (1999) describe linear elements of the landscape in the Guadix-Baza basin gathered from a Landsat TM image (NE-SW, NW-SE, and ENE-WSW oriented), which correspond to assumed major faults in the Guadix-Baza basin. One of them approximately reveals the location of the Baza Fault. The Baza normal Fault is the main active structure in the westernmost part of the Almanzora Corridor and the Baza basin, showing a N-S to NW-SE variable strike, and dipping to the NE (Alfaro et al., 2007). It may be considered as one of the most active faults of the central part of the Betic Cordillera, according to a quantitative analysis of mountain front relief (García-Tortosa et al., 2007).

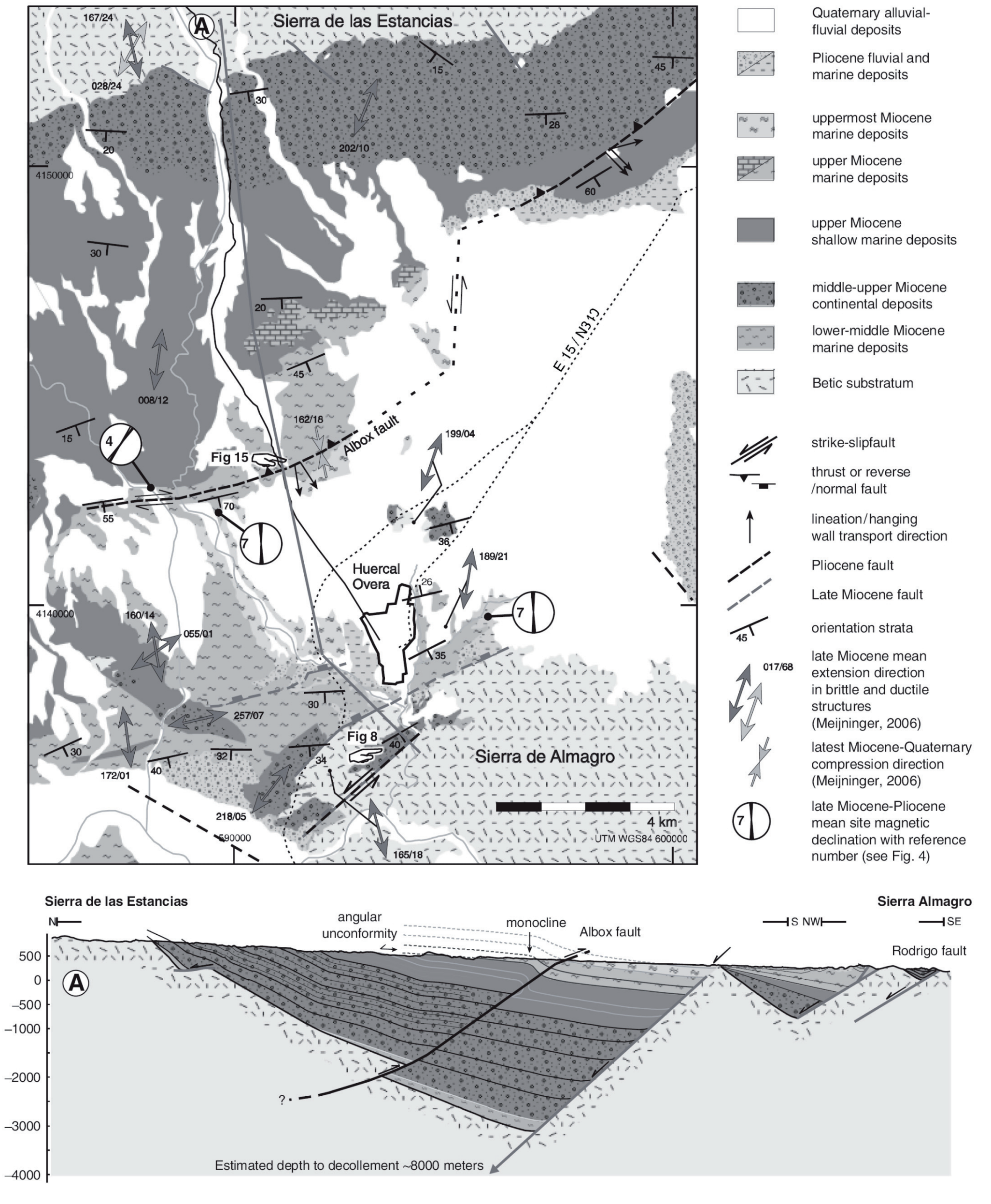

Fig. 1.21. Geological map and cross-section of the Eastern Huércal-Overa Basin (Meijninger and Vissers, 2006).

Ferre Bueno (1979) studied the Almanzora River valley, reporting on three glacis located at different heights. In order to explain river incision and headward erosion observed in the Almanzora River since the Pleistocene, Stokes and Mather (2003) more recently proposed vertical tilting models based on differential uplift and subsidence related to normal faults.

Under a geomorphologic approach, García-Meléndez et al., (2004) defined the Albox Fault as an ENE-WSW to E-W fault zone with reverse-dextral kinematics that extends 30 kilometers from the Eastern Huércal-Overa basin up to the Almanzora Corridor to the West. In addition, García-Meléndez (2000) and García-Meléndez et al. (2003) reconstruct long-term landscape development during the Plio-Quaternary in the eastern Huércal-Overa basin through the integration of geological field observations and geomorphological (GIS and remote sensing) techniques.

1.6 Open questions

Two tectonic processes are clearly active in the westernmost part of the Mediterranean Alpine Chain during the development of the Betic and Rif cordillera: (a) the Internal Zones tectonic displacement to the west with the result of the arc-shaped orogen, the exhumation of metamorphic complexes and development of the Alborán Sea, and (b) the N-S to NW-SE convergence between the Eurasian and African plates.

The previously presented geodynamic models were initially proposed to explain the extensional exhumation of the metamorphic complexes coeval to the development of the Alborán basin and the deformation of the flysh units and External Zones at the front of the cordillera during the Early and Middle Miocene. Recently these extension mechanisms have also been evoked to explain the Late Miocene sedimentary extensional faults and basin development. Given this setting, the Late Miocene sedimentary basins can be considered as purely extensional basins developed over a previously thickened crust subjected to a thinning process. Therefore, some authors have interpreted the development of the relief in the Internal Zones together with the sedimentary basin genesis as a “Basin and Range” model (e.g., Egeler and Simon, 1969; Platt and Vissers, 1989; Augier, 2004; Meijninger, 2006).

The latest studies focussed on the Almanzora Corridor and in the Huércal-Overa basin propose an extensional development of both basins, explaining the compressive structures as a consequence of a posterior tectonic inversion (e.g. Augier, 2004; Meijninger and Vissers, 2006). These neotectonic studies examine the basement deformation and the central and eastern Huércal-Overa sediments. Detailed research on the deformation that affected the Almanzora Corridor sediments and the western Huércal-Overa sector are lacking to date, and there is likewise a total absence of geophysical data that would shed light on the deep structure of these basins and their basement.

Notwithstanding, it is widely accepted that the Neogene development of the Betic and Rif Cordillera took place in a setting of N-S to NW-SE continuous slow convergence between the European and the African plates from the Late Mesozoic to the Cenozoic (e.g., Dewey et al., 1989; Rosenbaum et al., 2002). The relative shortening between the Eurasian and African plates is considered as the driving mechanism since the Tortonian by many authors. Accordingly, the relief growth and the coetaneous sedimentary basin development can be interpreted in a crustal thickening framework (Braga et al., 2003; Galindo-Zaldívar et al., 2003; Sanz de Galdeano and Alfaro, 2004).

There is, in sum, no general consensus with regards to the Neogene basin development mechanisms of the Betic Cordillera. It is therefore essential to acquire new geological and geophysical data so as to advance our understanding of the factors that control the relationship between tectonic evolution and sedimentary basin development.

2. Objectives

This Ph.D. Thesis aims to enhance the corpus of knowledge about the recent evolution and the crustal structure of the Eastern Betic Cordillera, by giving new geological, geomorphological and geophysical data, covering surface and deep crustal levels. In order to better understand this evolution, the Almanzora Corridor and the western Huércal-Overa basin are examined with the following objectives:

(a) To determine the surface and shallow crustal structure. To this end, new geological data (tectonic mapping, meso and microtectonic kinematics data) were acquired and are analyzed.

(b) To determine the deep crustal structure, as was constrained by already available and newly acquired geophysical data (gravity, magnetic, seismological and magnetotelluric data).

(c) To describe the recent and present activity of tectonic structures that deform these basins (folds, faults and joints), determining their kinematics and the paleostress setting responsible for their development.

(d) To characterize the origin and distribution of associated seismicity, and establish the stress field setting in light of the known earthquakes focal mechanism.

(e) To corroborate the suitability of different geomorphic indexes as applied to these moderately active structures.

(f) To establish the tectonic evolution that conditioned the development of the Almanzora Corridor and the Huércal-Overa sedimentary basins. These basins developed in an intermediate position between kilometric sinistral faults (e.g. Alhama de Murcia Fault), large N-vergent folds (Sierra de Las Estancias and Sierra de Los Filabres antiform) and large normal faults (Baza Fault). Therefore, in such complex scenario, it is essential to discern the regional stress evolution behind the great variability of tectonic structures developed from the Serravallian to the Present.

(g) To discuss findings in the overall framework of different geodynamic models proposed to date in attempts to explain the development of the Betic Cordillera in the context of the Eurasian-African plate boundary.

3. Outline

What follows here is a brief description of the underlying organization of this Ph.D. Thesis and the reasons for selecting the articles that make up the main body of the work. Emphasis will be focused on assessing of the tectonic evolution of the Almanzora Corridor and Huércal-Overa basins since the Serravallian, providing new tectonic field observations for shallow geological structures, geophysical data for deep crustal structures, and new field and geomorphological quantification of the active tectonic structures. To do so, five articles are put forth in **Part II**, namely:

Chapter 4, "Fold and fault interactions during the development of an elongated narrow basin: the Almanzora Neogene-Quaternary Corridor (SE Betic Cordillera, Spain)", provides a description of the main tectonic structures that deform the Almanzora Corridor. The development of compressional and extensional deformations is discussed as well as their relation with the sedimentary facies distribution. In addition, a paleocurrent analysis is presented, which entailed reconstruction of the ranges and valley position, especially interesting in Serravallian-Early Tortonian times. The discussion is centered on the genesis of the Almanzora Corridor, and we remark upon some improvements with respect to previous models.

Chapter 5, "Contractional and extensional deformations in the termination of a major sinistral fault: the Alhama de Murcia Fault (Eastern Betic Cordillera)", presents information on the tectonic structures that deform the Huércal-Overa basin, located at the eastern end of the Almanzora Corridor, by the southern termination of the sinistral Alhama de Murcia Fault. Detailed tectonic observations, including small scale to cartographic structures, are combined with the results of gravity prospecting that reveal the depocenter distribution. This contribution attempts to decipher the relationships between the great varieties of compressive and extensional tectonic structures that coexist in this part of the study area. Finally, genetic models for the basin are discussed, along with the relationship between the tectonic structures and the sedimentary thickness distribution.

Chapter 6, "Recent large fold nucleation in the upper crust: insight from gravity, magnetic, magnetotelluric and seismicity data (Sierra de Los Filabres- Sierra de Las Estancias, Internal Zones, Betic Cordillera) presents new geophysical data acquired with an aim to characterize the deep structure of the study area. The geophysical data gathered here clearly reveal the continuity of the large folds identified by field observation. Through magnetotelluric and magnetic data we were able to detect an anomalous body in the upper crust that is probably related with the development of the large Sierra de Los Filabres antiform. The lack of direct relationships between seismicity and the outcropping recent structures is also discussed.

Chapter 7, "The role of small-scale fold and fault development in seismogenic zones: the example of the Western Huércal-Overa basin (Eastern Betic Cordillera, Spain)", describes new small-scale tectonic structures located in the western Huércal-Overa basin that are mainly located over previous faults and evidence progressive activity. We restored and dated the deformation (on the basis of Quaternary mammal fossils) in the most spectacular active fault-propagation fold outcrop, located near Albox. Discussion is focused on the seismotectonic implication of these low-rate minor Quaternary tectonic structures, which mainly release the accumulated elastic energy and decrease the maximum magnitudes of earthquakes taking place during the accommodation of the shortening between the African and Eurasian plates.

Chapter 8, "Testing the sensitivity of geomorphic indices in areas of low-rate active folding (eastern Betic Cordillera, Spain)" presents the application of different geomorphic indices to the Almanzora tributary river that cross Sierra de Las Estancias, in order to check their suitability for determining recent minor folds. To do so, we propose the assessment of some geomorphic indices in the study area that represent unfolded sectors and sectors deformed by low-rate active folds.

Within **Part III**, **Chapter 9** provides a general discussion of the tectonic evolution of the Almanzora Corridor and the Huércal-Overa basin in the context of the general Miocene-Quaternary geodynamic evolution of the Betic Cordillera and the western Mediterranean. Finally, **Chapter 10** highlights the main conclusions.

PART TWO

4. Fold and fault interactions during the development of an elongated narrow basin: the Almanzora Neogene-Quaternary Corridor

5. Contractional and extensional deformations in the termination of a major sinistral fault: the Alhama de Murcia Fault

6. Recent large fold nucleation in the upper crust: insight from gravity, magnetic, magnetotelluric and seismicity data (Sierra de Los Filabres- Sierra de Las Estancias)

7. The role of small-scale fold and fault development in seismogenic zones: the example of the Western Huércal-Overa Basin

8. Testing the sensitivity of geomorphic indices in areas of low-rate active folding

4. Fold and fault interactions during the development of an elongated narrow basin: the Almanzora Neogene-Quaternary Corridor (SE Betic Cordillera, Spain)

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Elongated corridors grow in different tectonic settings, mainly in areas deformed by fold and fault sets parallel to the borders. The Almanzora Corridor, however, is a good example of an E-W elongated asymmetrical narrow basin developed in a changing stress scenario, generated by the interaction of fold and fault sets oriented parallel and oblique to the corridor borders. The initial crustal thickening process was mainly related to the development of the E-W oriented Sierra de Los Filabres large antiform, which constitutes a major heterogeneity. During the Tortonian, a NW-SE convergent tectonic setting —oblique to this already emerged antiform— gives rise to a large dextral simple shear band that determines: the development of a major fold (Las Estancias antiform), the asymmetrical location of minor tectonic structures (faults and minor folds) and the distribution of sedimentation/denudation areas that finally configure the Almanzora Corridor synform. Furthermore, development of NW-SE oriented normal faults points to NE-SW orthogonal extension in a new stress field oblique to the corridor borders. This region illustrates that the elongated character of the corridors may persist, inherited from the orientation of previous crustal rheological heterogeneities. In addition, marine transgression may be produced in compressional settings, favoured by the synform development during initial stages of crustal thickening, finally led to the relief uplift.

Key words
Fold development, paleostress evolution, marine transgression.

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1. Introduction

Long elongated valleys are common in different tectonic frameworks, where faults or folds with dominant trends occur. Fold-and-thrust belts develop orthogonal to the trend of compression and produce a succession of highs and valleys (e.g. Clarke and Carver, 1992; Ferrière, et al., 2004). The depressed areas correspond to the synforms, and are generally filled by sediments. In extensional contexts, the geometry of the elongated depressions is usually controlled by normal fault sets that grow perpendicular to the minimum stress axis, as in the Basin and Range province (e.g. Varga et al., 2004), the African rift zone (e.g. Ebinger, 1989; Chorowicz, 2005) and the Aegean region (e.g. Armijo et al., 1996; Pavlides et al., 2004). In areas deformed by transcurrent faults, elongated valleys are oriented parallel to the fault traces that constitute the basin boundaries, for instance in the California region (e.g. Howell et al., 1980). In areas of overprinted faults and folds with different trends, however, the basins become discontinuous and irregularly shaped (e.g. Matenco and Schmid, 1999; Pedrera et al., 2006). The development of large folds during the initial stages of crustal thickening may point to rheological discontinuities that determine the geometry of the later tectonic deformations. When stresses rotate, faults will occur preferentially subparallel to the previous elongated reliefs due to the inherited anisotropy; yet other structural associations take place as well, determining the development of complex elongated corridors.

The relief of the Betic Cordillera, located in the westernmost part of the Alpine Chain, is produced by the interaction of folds and faults that accommodate the N-S to NW-SE convergence between the Eurasian and African plates (DeMets et al., 1990) (Fig. 4.1). Several domains can be distinguished in the Cordillera on the basis of lithological and tectonometamorphic features: the Internal Zones, mainly formed by three major complexes that include metamorphic rocks, some of them of Paleozoic age: the Nevado-Filábride, Alpujárride and Maláguide complexes (generally not affected by Alpine metamorphism); the Flysch Units, which are Tertiary detritic sedimentary rocks, mainly represented in the western Betics (Egeler, 1963; Egeler and Simon, 1969); and the External Zones, essentially made up of Mesozoic and Cenozoic sedimentary rocks.

During the Middle Miocene, fission-track data indicate the extensional exhumation of the metamorphic Complexes related to the activity of low-angle normal faults (Johnson, 1997; Johnson et al., 1997). On the other hand, the first sedimentary evidence of emerged Internal Zones subjected to important denudation processes is a red conglomerate alluvial and fan-delta unit (eg. Braga et al. 2003). Later, during the Tortonian, E-W and ESE-WNW ranges and basins started to develop, coinciding with large antiforms and synforms (Weijermars et al., 1985; Galindo-Zaldívar et al., 2003; Sanz de Galdeano and Alfaro, 2004; Augier et al., 2005b). During the Late Miocene, faults developed coeval with folds, thus interacting during the basin formation (Estévez et al., 1982; Ott d'Estevou and Montenat, 1985; Stapel et al., 1996; Booth-Rea et al., 2004; Marín-Lechado et al., 2006). The Neogene-Quaternary sedimentary basins generated on the previously structured metamorphic basements are situated in different tectonic frameworks within the Betic Cordillera: they are generally transcurrent in the Eastern Betics (Bousquet and Montenat 1974; Bousquet and Phillip 1976b; Bousquet 1979; Sanz de Galdeano 1983; Montenat et al., 1987; Weijermars, 1987; Huibregtse et al., 1998), while related to normal faults and folds in the central and western Betics (Ruano et al., 2004; Rodríguez-Fernández and Sanz de Galdeano, 2006).

The Almanzora Corridor is an E-W elongated depression (average 35 km long and 6 km wide) situated in the eastern part of the Betic Cordillera. The northern border of the basin is the Sierra de Las Estancias range, consisting of Alpujárride rocks. The southern border is the Sierra de Los Filabres, formed by Alpujárride and Nevado-Filábride rocks (Fig. 4.1). The basin sedimentary infill is characterized by siliciclastic sediments from the Serravallian-Early Tortonian up to Quaternary, including marine and continental deposits that are strongly controlled by different tectonic events and have been the subject of previous research (Braga and Martín, 1998; Martín et al., 1989; Guerra-Merchán and Serrano, 1993).

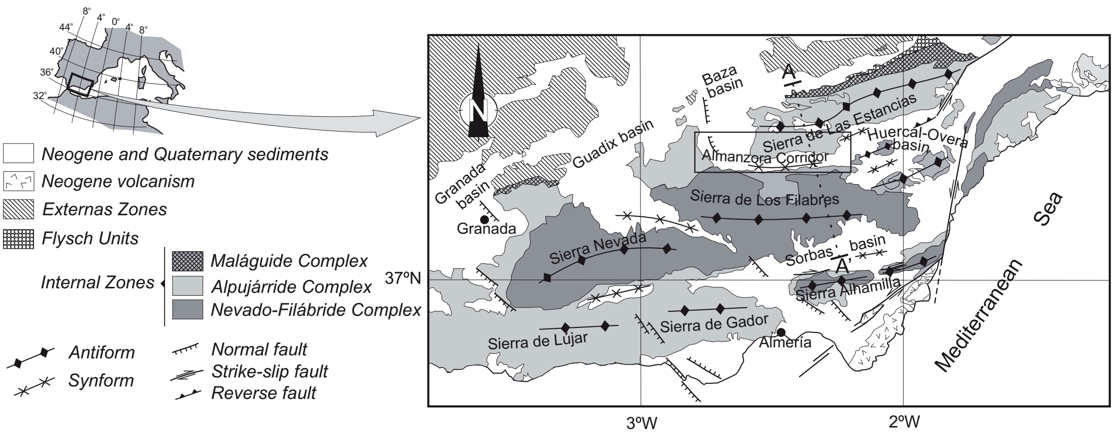


Fig. 4.1. Geological map of the central-eastern Betic Cordillera, showing different domains and the main folds and faults developed since Tortonian times. Note that the synforms coincide with the Neogene-Quaternary basin position. The position of the topographic profile Fig. 7A is marked.

In the Almanzora Corridor, the fold and fault interaction configures the basin geometry and deforms the sediments since Serravallian-Early Tortonian. In the adjacent sedimentary basins, such as Huercal-Overa, some geological studies have focused on active tectonics (García-Meléndez et al., 2003, 2004; Soler et al., 2003; Masana et al., 2005) and neotectonic aspects (Mora, 1993; Augier, 2004). However, neotectonic studies are scarce in the Almanzora Corridor, having been undertaken only on a regional scale and focused on the basement deformation (Augier et al., 2005b).

The aim of this paper is to study the tectonic evolution that finally determines the development of the narrow Almanzora basin. In addition, our contribution clarifies the regional stress evolution that is responsible for the great variability of tectonic structures generated from the Serravallian to the present in the eastern Betic Cordillera. The new insights obtained from this detailed analysis may improve knowledge of the simultaneous development of folds and faults in regimes of oblique convergence that are related to a regional changing stress field.

2. General features of the sedimentary and chronostratigraphic setting

2.1. Lithostratigraphic sequence

The Neogene infilling of the Almanzora Corridor is made up of several units separated by unconformities. The lithostratigraphic sequence considered in this study is based on the proposal of Braga and Martín (1988) and Martín et al. (1989), taking into account chronostratigraphic data from Guerra-Merchán and Serrano (1993); and it agrees with the proposal of Montenat et al. (1987) regarding the Neogene history of the eastern Betic Cordillera (Fig. 4.2).

The first unit is a thick, red, continental conglomerate formation, which lies unconformably on the basement, and is well represented in the southern Corridor border and in the eastern and western terminations. This unit can also be observed in other areas of the Cordillera and consistently contains coarse grained conglomerates from the metamorphic complexes grading into sandstones. The conglomerates are poorly sorted in general, but sometimes show inverted vertical clast distribution, coarsening upward. In the Granada basin, some fossils support a Serravallian age (Martín-Suárez et al., 1993), although other authors suggest an Early Tortonian age, at least for parts of the units (Guerra-Merchán and Serrano, 1993; Doyle et al., 1996). In the Almanzora Corridor, this unit is interpreted as continental alluvial fan deposits generated by the denudation of the mountain front.

The continental Serravallian–Lowermost Tortonian red siliciclastic deposits are overlain by grey marine clays (Braga and Martín, 1988) with intercalated patch reef limestones to the top of the sequence (Guerra-Merchán and Serrano, 1993), dated as being from the Early Tortonian by Briend (1981). This unit corresponds to deltaic deposits mainly located near the northern boundary of the Corridor, related to the distal areas of the previous unit. The relation between the base of the marine deposits and the top of the red conglomerates appears variable: in some outcrops the transition is progressive, whereas in others it is clearly unconformable.

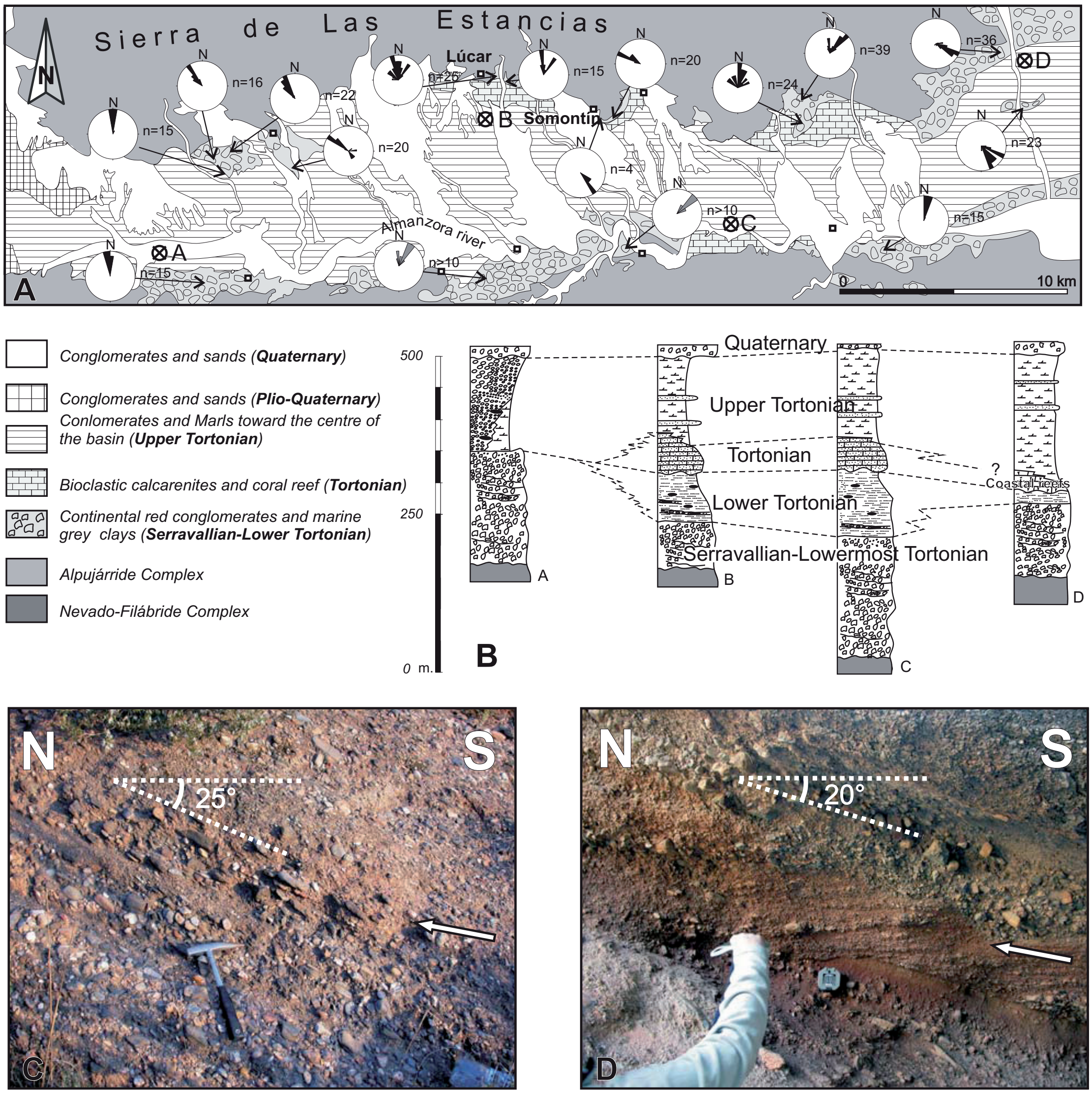


Fig. 4.2. A. Simplified geological map showing the Neogene infilling of the Almanzora Corridor. The rose diagrams show flow directions deduced from the dip of imbricate clasts. In grey diagrams from Guerra-Merchan (1992), only the diagrams with more than 10 measurements are plotted. B. Lithostratigraphic sequences and correlation, modified from Guerra-Merchán and Serrano (1993) and based on the proposal of Braga et al (1988) and Martín et al. (1989), in agreement with Montenat et al. (1987) for the Neogene of the eastern Betic Cordillera. C. D. Field examples of sedimentary structures, imbricate clasts (C) and cross-bedding (D) located in the north basin boundary, which indicate a flow direction to the North. Bedding is tilted by the growth of the Las Estancias antiform.

The relationship between the Lower Tortonian sediments and the uppermost Tortonian sequence constitutes a main unconformity (Fig. 4.2A and B). The grey clays are followed by yellowish bioclastic calcarenites with abundant remains of marine fossils, also from the Tortonian (Braga and Martín 1988; Martín et al., 1989; Guerra-Merchán and Serrano, 1993). These deposits represent shallow platforms adjacent to the two basin borders, in transition to marls toward the centre of the Corridor axis. The cross-bedding in some outcrops indicates that the calcarenites were subjected to strong currents.

The last unit onlaps the margins, comprising at its base greyish conglomerates with patch reef features that change laterally to silts and marls towards the centre of the basin, dated by Guerra-Merchán and Serrano (1993) as the interval corresponding to the early and middle part of the Late Tortonian. Above all these sediments is a thick deposit of yellow marls containing planktonic forams from the Late Tortonian (Briend, 1981). There are no Messinian marine sediments in the Almanzora Corridor, these being limited to the nearby Huércal-Overa basin (Guerra-Merchán and Serrano, 1993).

Plio-Quaternary alluvial sediments pertain to the alluvial fan and to the river deposits, and are discordantly placed over the Miocene rocks. The alluvial fans, now inactive, are generally well developed in the north basin border, determining the topographic asymmetry of the basin.

2.2. Paleocurrent analysis

The coastal facies distribution of the sedimentary units (calcarenites, coral reefs, and proximal deltaic siliciclastic sediments) and the paleocurrent orientation allow us to reconstruct, with confidence, the palaeogeography from the Tortonian-Late Tortonian onward. These deposits signal the presence of a narrow elongated basin since Tortonian times, with an emerged Sierra de Las Estancias and Sierra de Los Filabres (Fig. 4.2A).

Notwithstanding, the existence of an elongated basin during the Early Tortonian, previous to the coastal sediments deposition, is a matter open to question. As a preliminary overview we can remark that the red alluvial fan conglomerates are preferentially at the base of the Sierra de Los Filabres (Figs. 4.2A and 4.2B). In addition, the Lower Tortonian deltaic deposits, related to the distal areas of the red conglomerate units, are mainly placed adjacent to the north Corridor boundary (Fig. 4.2B). In order to determine the clast provenance and the palaeogeography distribution during the Early Tortonian, we carried out a detailed paleocurrent analysis —clast imbrications (Fig. 4.2C) and cross bedding (Fig. 4.2D)— of the red conglomerate beds, with special emphasis on the outcrops located close to the north basin border (Fig. 4.2A). The bedding at the Corridor boundaries is folded, as we will explain in the next section, and so the measurements have been restored to the horizontal.

This study indicates that the Sierra de Los Filabres was the main source area, subjected to growth and to important denudation processes. Only the eastern Corridor sediments show paleocurrents to the South, as does the nearby Huércal-Overa basin (Mora, 1993; Augier, 2004). Consequently, the Almanzora Corridor developed after

Early Tortonian.

3. Main tectonic structures

Brittle deformations and folds deform the Almanzora Corridor (Fig. 4.3 and 4.4) and determine their configuration from the Serravallian-Earliest Tortonian. A grasp of the tectonic event succession requires a detailed structural analysis.

3.1. Faults

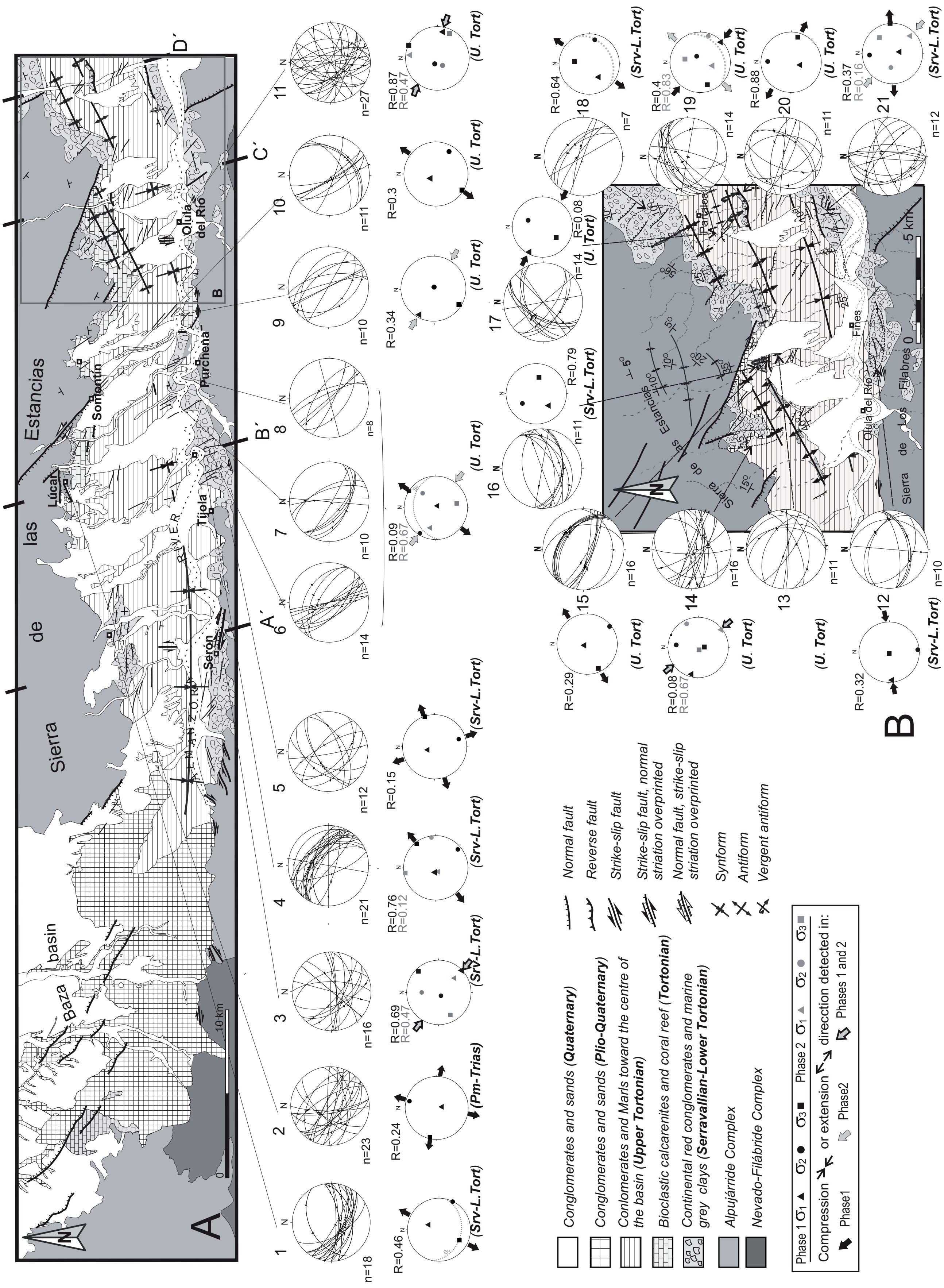
The faults that crop out in the study area have variable orientations and kinematics, as well as overprinted slickensides. Fault description is organized taking into account their kinematics.

3.1.1. Strike-slip faults

Subvertical E-W to ESE-WNW strike-slip right-lateral faults deform the Tortonian sediments that crop out mainly in the south basin border. These faults are well exposed in the basement rocks and only deform the Lower Tortonian conglomerates in the western sector, close to Serón. However, they displaced up to the Tortonian calcarenites in the central sector, close to Purchena (Figs. 4.3 and 4.4).

In addition, a set of N-S left-lateral strike-slip faults deforms only the Tortonian sediments, mainly located in the central and south Corridor (Figs. 4.3, near Olula del Río, 5B and C). These faults are conjugated with respect to the ENE-WSW right-lateral faults, and they likewise often have normal striations overprinted upon the horizontal ones. The above observations evidence that strike-slip faults started to develop during Tortonian and continued growing in post-Tortonian times, mainly toward the central Corridor.

Fig. 4.3. A. Simplified geological map of the Almanzora Corridor, indicating the location of the main faults and folds. The position of cross-sections of Fig. 3 and the map of Fig. 3B are marked. B. Enlarged geological map of the easternmost sector of the Almanzora Corridor. The orientations of microfaults and mesofaults and the paleostress determinations are represented in stereographic projection, lower hemisphere.


A
B
Sierra de las Estancias
Baza basin
Serón
Tíjola
Lúcar
Somontín
Purchena
Olula del Río
Fines
Sierra de Los Filabres
10 km
5 km
Conglomerates and sands (Quaternary)
Conglomerates and sands (Plio-Quaternary)
Conlomerates and Marls toward the centre of the basin (Upper Tortonian)
Bioclastic calcarenites and coral reef (Tortonian)
Continental red conglomerates and marine grey clays (Serravallian-Lower Tortonian)
Alpujárride Complex
Nevado-Filábride Complex
Normal fault
Reverse fault
Strike-slip fault
Strike-slip fault, normal striation overprinted
Normal fault, strike-slip striation overprinted
Synform
Antiform
Vergent antiform
Phase1
Phase2
Phases 1 and 2
(Srv-L.Tort)
(Pm-Trias)
(U. Tort)

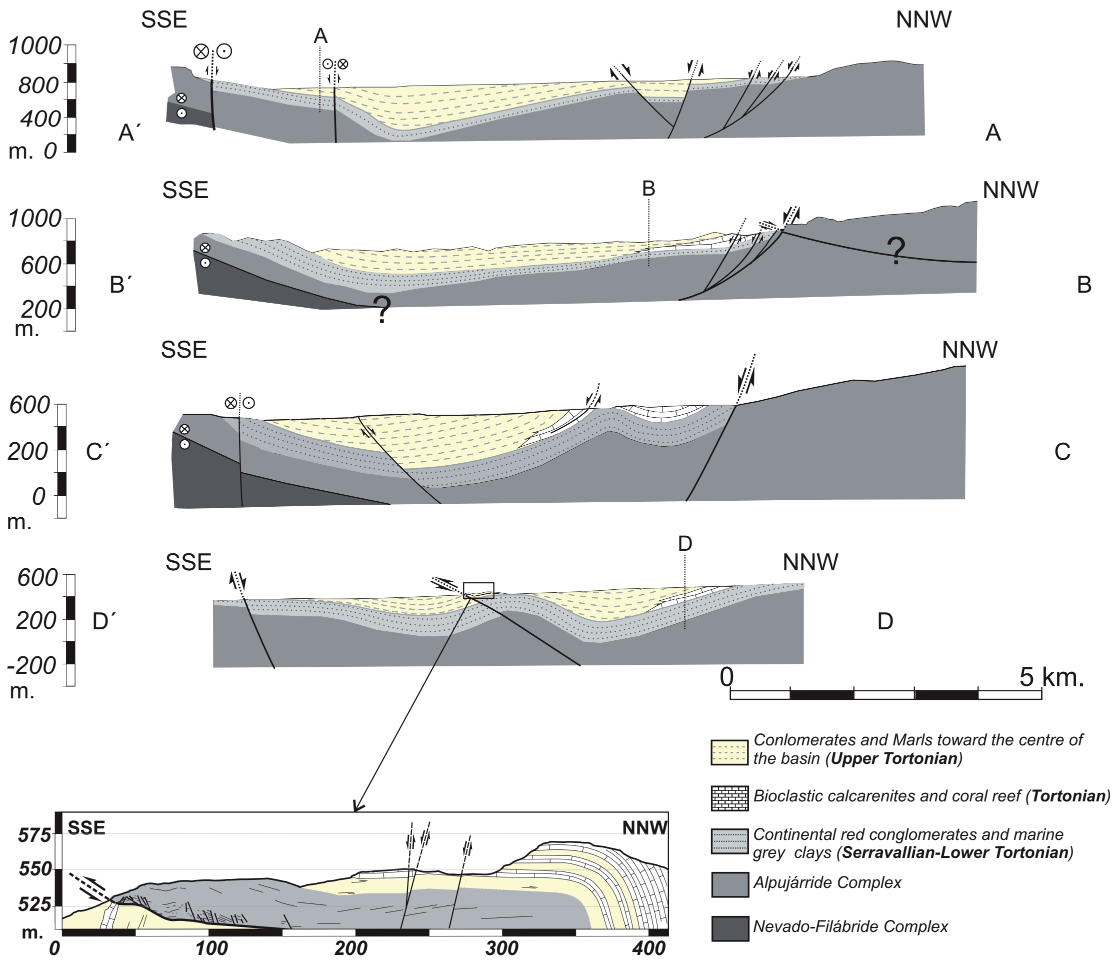


Fig. 4.4. Simplified geological cross-sections showing the Almanzora synform and the fault distribution. Their positions are marked in Fig. 3. Note that the main structure of the basin is the kilometric-scale synform. The position of some lithostratigraphic sequences of Fig. 2 (A, B and D) are marked in the cross-sections. The enlarged blow-up of cross-section D'-D shows the structure of the main reverse fault that crops out in the basin (see also Fig.6 D).

3.1.2. Normal faults

The normal faults can be grouped into two main sets: NW-SE and E-W to ESE-WNW. These faults show evidence of activity in different periods, taking into account their relationships with the sediments.

The NW-SE oriented faults crop out in the entire basin and in the Sierra de Las Estancias range (Figs. 4.3 and 4.4). The longest NW-SE normal faults, however, deform the westernmost Corridor sector and the north Corridor border. Although some faults of this set affect only the Early Tortonian sediments and are covered by Late Tortonian rocks, most deform all the Miocene rocks (Fig. 4.5D), cutting into the previous sets of transcurrent faults (Fig. 4.5C) and affecting even the Quaternary sediments in the westernmost Corridor sector and in the Baza basin (Fig. 4.6). Therefore, these faults started to develop during Tortonian, continued growing in post-Tortonian times, and are still developing in the westernmost part of the study area.

Several NW-SE normal faults that deform the central and eastern Corridor sediments show left-lateral striation overprinted upon the ancient normal striae. In some outcrops, these faults also deform up to the Quaternary sediments (Fig. 4.3, Somontín fault).

The E-W to ESE-WSW normal faults deform the Alpujárride and Nevado-Filábride rocks in the southeastern Corridor border, displacing the Lower Tortonian sediments. In addition, some of the previously described strike-slip faults show overprinted normal striation. The normal faults are more abundant in the northwestern border, where they show variable dips ranging between 50ºS and subvertical. In this sector, faults have short normal slip displacement and usually cut all Tortonian sediments appearing covered by the Plio-Quaternary deposits (Figs. 4.3, 4.4 and 4.5A). Only one fault deforms up to the Plio-Quaternary sediments and generates topographic scarp (Fig. 4.6, Lucar fault). Therefore, the formation of the normal faults that belong to this set mainly occurred between the Latest Tortonian and the Plio-Quaternary. In the nearby Huércal-Overa basin, some authors also identify E-W to ESE-WNW normal faults with activity during the Tortonian (Augier, 2004; Mora, 1993).

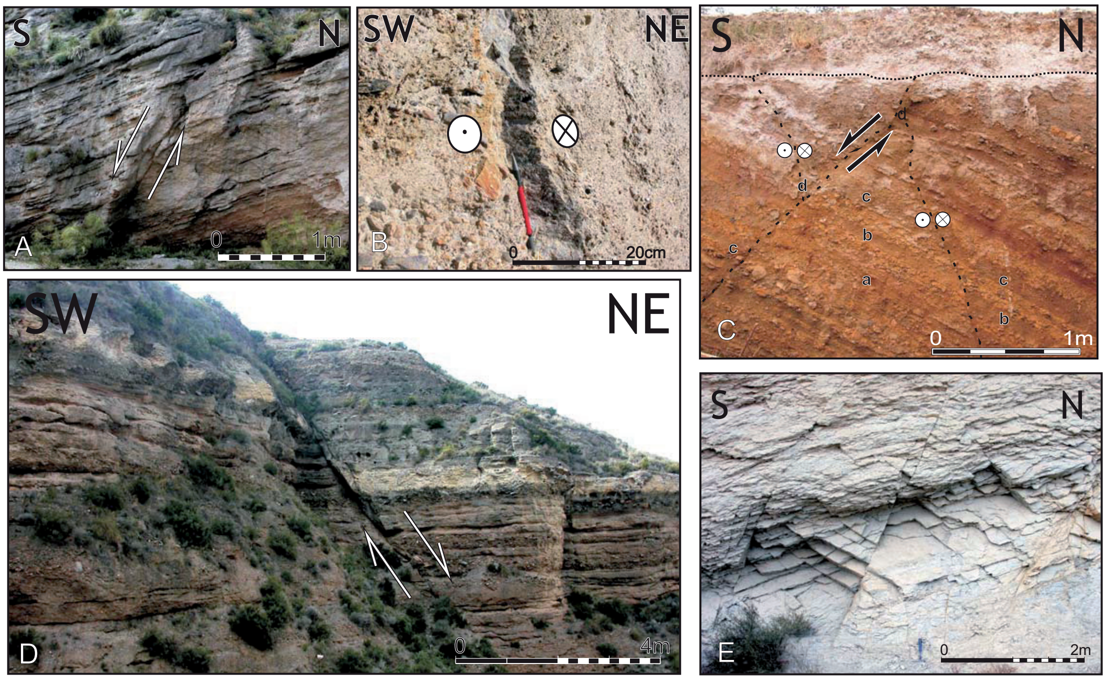


Fig. 4.5. Field examples of faults. A, E-W oriented and 65º south dipping fault that deforms the Tortonian sediments of the north-western Corridor border with a short normal slip displacement. B, N-S left-lateral strike-slip faults deforming the Tortonian sediments in the central Corridor. C, NW-SE oriented normal fault cutting Serravallian- Lower Tortonian sediments and a N-S strike-slip fault. D, Example of NW-SE 50º northeast dipping normal fault that deforms the Tortonian sediments. E, Conjugated normal faults tilted by minor folds in the Eastern Corridor.

3.1.3. Reverse faults

The reverse faults are located in the eastern Corridor (Figs. 4.3, 4.4 and 4.7), near the Huércal-Overa basin (Briend, 1981; Guerra-Merchán, 1992; García-Meléndez et al., 2003; Masana et al., 2005). These faults have orientations from N45ºE to N90ºE, and dips generally towards the NW, but also to the SE; kinematic analysis shows most striations to have directions comprised between N130ºE and N140ºE (Fig. 4.7C). The reverse faults have short slips, in some cases of just a few cm in the central part of the basin (Figs. 4.7A and B), though they may be greater than 40 m in the eastern sector (Fig. 4.7D). These faults produced larger slips in Tortonian sediments than in the Quaternary alluvial sediments that crop out in the eastern Corridor, indicating that they were active before Quaternary times, yet some of them continue to be active at Present (Fig. 4.6).

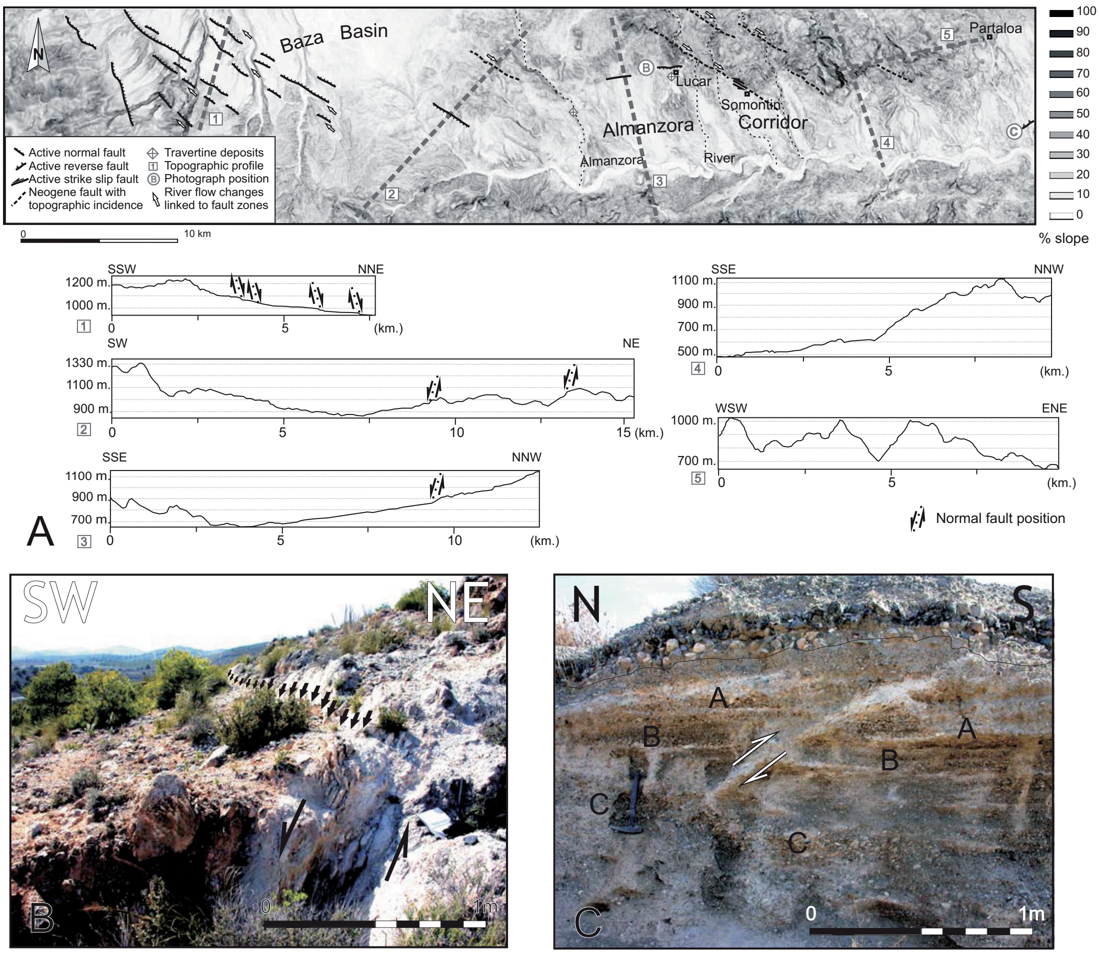


Fig. 4.6. A. Slope map and topographic cross-section constructed from the digital elevation model with a 10 meter spaced cell grid. The slope percentage is indicated, and the areas with high slope are dark grey. Active tectonic structures are located in the map and in the cross-section. The westernmost part of the Corridor is affected by a set of active NW-SE faults and the north basin border shows three main steps that produce changes in the courses of rivers. C. E-W segment of the normal Lúcar fault that deforms Quaternary sediments (UTM: 4140078 m, 550449 m). D. ENE-WSW reverse fault that affects up to Quaternary sediments (UTM: 4137495 m, 569780 m).

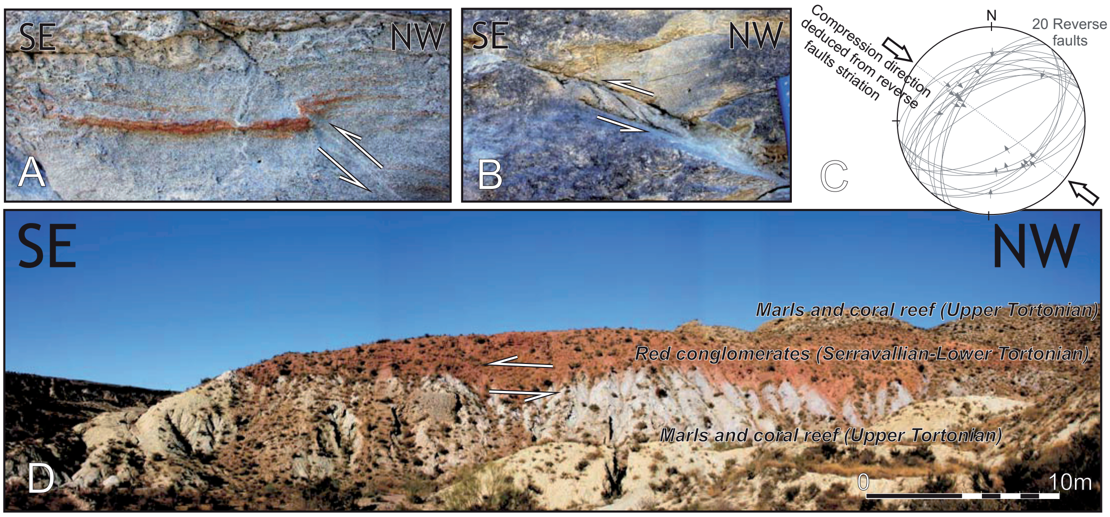


Fig. 4.7. A and B, Examples of ENE-WSW reverse faults showing a few cm slips, in the central part of the basin. C, Orientations and kinematics of 20 reverse faults plotted in a stereographic projection, lower hemisphere. Note that reverse faults have orientations from N45ºE to N90ºE, while the striations have directions comprised between N130ºE and N140ºE. D. The main reverse fault of the study area has a maximum slip greater than 40 m, is located in the eastern sector, and favoured the imbrication of Lower Tortonian conglomerates over upper Tortonian coral reefs.

3.2. Folds

The main ranges and depressions of the central Betic Cordillera are related to kilometric-scale folds. In the study area these are, from south to north (Fig. 4.1 and 4.8A):

- The north-vergent Filabres antiform, with E-W average strike. The Nevado-Filábride rocks crop out in its crest, while in the northern limb rocks from the Alpujárride Complex are also exposed. This antiform is evidenced by the folding of the Alpujárride/Nevado-Filábride contact, the internal foliations of the metamorphic rocks, and the bedding of the Neogene sediments located at their flanks.

- The Almanzora Corridor, which corresponds to a large north-vergent synform, likewise with E-W average strike. Its axial trace is located close to the south Corridor border.

- The Sierra de Las Estancias range also represents a large north-vergent fold that has an orientation changing from ENE-WSW in the eastern sector (outside the study area) to E-W in its western extreme, and constitutes the Almanzora Corridor north boundary. The rock outcrop distribution is asymmetrical, with a southern limb formed by Alpujárride rocks, and a northern limb that also includes rocks from the Maláguide Complex and the Flysch Units.

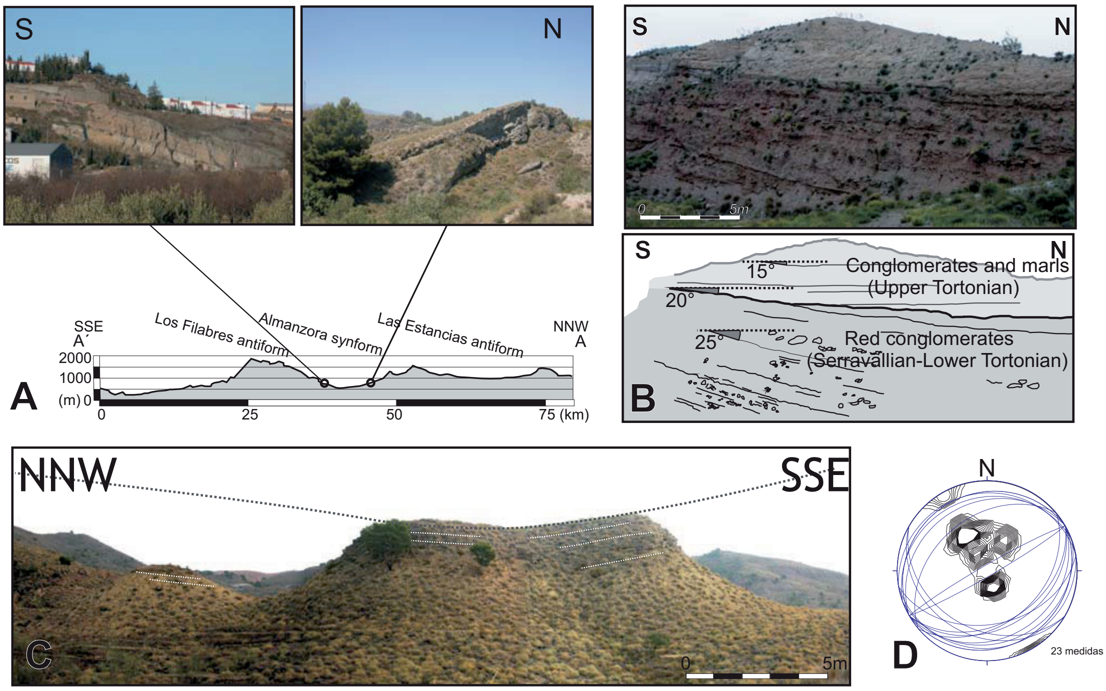


Fig. 4.8. A. Topographic profile where ranges and basin coincide with large antiforms and synforms (position in Fig. 1). Indeed, the sediments adjacent to the south basin border of the Almanzora basin dip to the north and the sediments closest to the north basin boundary dip to the south. B. Folded sediments showing structures synsedimentary to tilting, the older sediments having higher dip that the younger ones. C. An ENE-WSW oriented minor fold that deforms the upper Tortonian sediments in the eastern part of the Corridor. D. Stereographic projection of bedding deformed by the ENE-WSW minor folds in the Eastern Corridor, lower hemisphere projection.

The growth of these kilometric-scale folds was partially coetaneous to sedimentation in the Almanzora Corridor. Indeed, the sediments adjacent to the south basin border dip to the north, whereas the sediment closest to the north basin boundary dips to the south, revealing synsedimentary structures in both margins. The older sediments show higher dip that the recent ones, pointing to the synsedimentary character of folding (Figs. 4.8A and B).

Moreover, en echelon ENE-WSW oriented minor folds deform all the Tortonian sediments in the eastern part of the Corridor (Fig. 4.3B). These folds have variable wavelengths, comprised between 10 meters and several hundreds of meters, and tilt the previous faults (Fig. 4.5E), though they may be affected by the most recent faults. Folds are generally open, yet in some cases produce very high dipping flanks, up to vertical (Figs. 4.8C and 4.8D). The vergence of the folds is generally to the North, as is that of the large kilometre-scale folds. In addition, in the nearby Huércal-Overa basin, some ENE-WSW oriented minor folds deform up to Late Pleistocene sediments (Soler et al., 2003; Masana et al., 2005). Within the hinge zone of the minor folds there develop: (a) coarse axial planar cleavage, (b) closed mesofolds, and (c) striations as a consequence of flexural slip deformation, when a multilayer of silts and calcarenites is folded.

4. Paleostress analysis

The paleostress ellipsoids were determined from microfaults and mesofaults using the method of Galindo-Zaldívar and González-Lodeiro (1988). This method provides data on the main stress axes orientations and the axial ratios ($R = (\sigma_2 - \sigma_3)/(\sigma_1 - \sigma_3)$) of the overprinted deviatoric stress ellipsoids, considering that the striae on microfaults are parallel to the maximum shear stress (Bott, 1959) and that the stress field is homogeneous at the outcrop scale. The fault surface and the striae orientation were determined in the outcropping faults of each measurement station, and the regime was established essentially on the basis of displaced bedding, steps on fault surfaces and tails of microcrushed fault gauges. The overprinted striations on fault surfaces allow for an ordering of the stress superimposition.

Along the Almanzora Corridor sedimentary infill, a total of 21 outcrops —including microfaults and metric size faults— were studied (Fig. 4.3, table 4.1). The geographical proximity, rock homogeneity and low fault number allow for the grouping of stations 6, 7 and 8 for the statistical analysis. Other outcrops were discarded because of an insufficient number of faults (less than 10) or the fact that the faults were clearly deformed by late folds. Although the Quaternary sediment evidences the most recent deformation, it does not provide enough microfaults for determining paleostresses. Most measurement stations are located in the Tortonian sediments, though station number 2 is situated among marbles of the Alpujárride Complex (Fig. 4.3 and Table 4.1).

The paleostress ellipsoids determined in the region evidence at least two main tectonic events. The best represented set (type 1) is characterized by subvertical maximum stress axes, NE-SW extension, and variable axial ratios that are in transition to radial extension (stations: 1, 2, 4, 5; stations: 6, 7, 8 phase 1; station 10; station 15; station 18 and station 19 phase 2). This set is related to the development of normal faults with NW-SE orientations. The axis inclinations suggest that in several measurement stations the folds rotated some of the faults (stations: 6, 7, 8 phase 2, and 15).

A second set (type 2) corresponds to paleostress ellipsoids characterized by a subhorizontal NW-SE maximum stress axis and high to medium axial ratios (station: 3; stations 6, 7 and 8 phase 2; stations 9, 11, 14 and 17; station 19 phase 1; station 21 phase 2) that may be related to the development of compressive structures, such as ENE-WSW reverse faults and folds. In this setting, when the intermediate stress axis becomes vertical, E-W to ESE-WNW dextral and N-S oriented sinistral faults develop. Other local paleostress ellipsoids are also found in the region. Station 20, located on the southern flank of a north vergent fold, evidences WNW-ESE extension related to an oblate stress ellipsoid. Station 12 and the first phase of station 14 indicate a subhorizontal E-W maximum stress axis. Contrariwise, phase 2 of station 21 indicates a local E-W extension with a subvertical maximum stress axis, suggesting additional of the stress field.

Table 4.1. Paleostress analysis results. The main axes orientations are defined by their azimuth and plunge.

Outcrop		Percent Data Used	R	σ_1		σ_2		σ_3	
1	Serv-L.Tort.	68	0.46	N25°E	62°	N116°E	1°	N207°E	28°
2	Pm-Trias	62	0.24	N167°E	77°	N14°E	12°	N283°E	6°
3	Serv-L. Tort.	67	0.69	N137°E	35°	N0°E	46°	N244°E	23°
		40	0.47	N136°E	2°	N237°E	80°	N46°E	10°
4	Serv-L. Tort.	65	0.12	N289°E	78°	N141°E	10°	N50°E	6°
		34	0.76	N233°E	81°	N80°E	8°	N349°E	4°
5	Serv-L. Tort.	69	0.15	N337°E	70°	N163°E	20°	N72°E	2°
6, 7, 8	U. Tort.	48	0.67	N122°E	84°	N302°E	6°	N32°E	0°
		32	0.09	N285°E	35°	N48°E	38°	N168°E	33°
9	U. Tort.	69	0.34	N302°E	3°	N51°E	82°	N211°E	8°
10	U. Tort.	82	0.3	N312°E	72°	N119°E	18°	N210°E	4°
11	U. Tort.	55	0.87	N116°E	16°	N296°E	74°	N26°E	0°
		31	0.47	N6°E	14°	N239°E	67°	N101°E	17°
12	Serv-L. Tort.	85	0.32	N45°E	88°	N175°E	1°	N265°E	2°
14	U. Tort.	59	0.08	N274°E	6°	N6°E	22°	N171°E	67°
		47	0.67	N150°E	2°	N60°E	6°	N258°E	84°
15	U. Tort.	71	0.29	N348°E	84°	N150°E	6°	N240°E	2°
16	Serv-L. Tort.	75	0.79	N215°E	30°	N334°E	40°	N100°E	35°
17	U. Tort.	80	0.08	N306°E	4°	N41°E	48°	N213°E	42°
18	Serv-L. Tort.	85	0.64	N224°E	43°	N122°E	13°	N19°E	44°
19	U. Tort.	60	0.4	N159°E	0°	N68°E	80°	N250°E	10°
		40	0.83	N202°E	48°	N109°E	3°	N16°E	42°
20	U. Tort.	75	0.88	N199°E	69°	N2°E	20°	N94°E	6°
21	Serv-L. Tort.	65	0.37	N176°E	30°	N356°E	60°	N86°E	0°
		35	0.16	N160°E	13°	N278°E	64°	N64°E	22°

[a]The main axes orientations are defined by their azimuth and plunge. In addition, the axial ratio values ($R = (\sigma 2 - \sigma 3)/(\sigma 1 - \sigma 3)$) are given for each station.

5. Active faults and geomorphological features

Several tectonic structures are still active in the Almanzora Corridor, as indicated by structural features, drainage network position and incision. The westernmost part of the Corridor is affected by a set of NW-SE faults that deforms up to the Quaternary glacis and produces the Corridor's western termination (Fig. 4.6A profile 1).

In the central part of the Corridor, the Lúcar fault –formed by a set of E-W oriented and 40º-75º south dipping normal faults– locally deforms the Quaternary sediments, generating high dip in the calcretes and an average of 80 cm topographic scarp. In addition, the deposition of Quaternary travertines close to Lúcar is probably a consequence of the normal active faulting (Figs. 4.6A profile 3 and 4.6B). The north basin border is irregular, but three main steps may be recognized. These steps are due to the presence of normal faults that also determine changes in the direction of the north Almanzora River tributary stream (Fig. 4.6A). Close to Somontín, Quaternary sediments are deformed by a NW-SE oriented high-dipping fault that generates a steep scarp. The fault surface shows horizontal striation with a left-lateral regime overprinted on the normal old striae.

The drainage network of the Almanzora River, along with the development and evolution of the corridor, was highly controlled by tectonics and reflects recent activity of the faults and folds. At present, the position of the ancient alluvial fan channels is taken up by most of the north Almanzora River tributary streams.

Profile 3 shows a longitudinal section of alluvial fan (km 5 to 9) where the slope is very constant. Meanwhile, profile 4 shows a transverse section of an alluvial fan (km 1 to 4) along the folded Neogene sediments. The slope is variable due in part to the folding and the more intense erosion in this sector, associated with uplift. The quaternary uplift is also evidenced by the presence of uplifted alluvial terraces (García-Meléndez et al. 2003; Soler et al., 2003). These alluvial fan quaternary sediments are locally deformed by ENE-WSW oriented reverse faults, dipping 30º to the NE and having centrimetic slip (Fig. 4.6C). Profile 5 shows the tributary stream incision in the Alpujárride rocks, which constitutes the most important one of the entire basin. The development of this stream incision, transverse to WSW-ENE fold axes that deform the sedimentary and metamorphic rocks, suggests a recent uplift of the Sierra de Las Estancias range and the headward erosion of the ancient fan channel. Such geomorphological features evidence recent tectonic activity in the area.

6. Discussion

Although faults and folds may lead to the development of elongated topographies, including linear valleys, the overprinting structures in a changing stress scenario generally disrupt its elongated character. The changing stresses and strain, including rotation of tectonic elements, are very common in geodynamic settings characterized by oblique convergence (Platt et al., 1995; Platzman et al., 2000; Platt et al., 2003). In the Betic Cordillera, to date, corridor development has generally been related to strike-slip faulting (Sanz de Galdeano et al., 1985, Martínez-Martínez, 2006). Sedimentation areas in these tectonic settings are mainly located at pull-apart extensional zones.

The new structural data reported in this paper encourage discussion of the genesis of the Almanzora Corridor, which is related to the progressive activity and interaction of faults and folds in a context of oblique shortening and dextral shear deformation. Its development allows us pinpoint two important implications for our knowledge of the narrow elongated basin growth:

- the formation of narrow elongated basins under non-orthogonal convergence as a result of overprinted oblique tectonic structures.

- the relationships between marine transgressions and fold development.

6.1. The narrow elongated Almanzora Corridor development

Two different successive deformation stages are responsible for the corridor evolution: the initial development of the Los Filabres antiform during the Early Tortonian, which will constitute its southern boundary, and the overprinting of other later structures.

6.1.1. N-S compression during the earliest Tortonian: Sierra de Los Filabres growth

The age of development of the recent reliefs in the Internal Zones of the Cordillera is not precisely determined, although most authors agree that it would have begun at Middle Miocene times (e.g. Braga et al. 2003; Rodríguez-Fernández and Sanz de Galdeano, 2006). The fission track data in the Las Estancias range and Sierra Nevada (Johnson, 1997; Johnson et al., 1997; Platt et al., 2005) indicate Early to Middle Miocene ages for the uprising of Alpujárride and Nevado-Filábride metamorphic rocks. The oldest conglomerates that clearly include Nevado-Filábride rocks are of Serravallian-Lower Tortonian age (e.g. Guerra-Merchán, 1992), suggesting the presence of emerged areas undergoing erosion. In the Almanzora Corridor, paleocurrent directions and facies distribution deduced from the Lower Tortonian sediments indicate the presence of an E-W uplifted Sierra de Los Filabres, which provided coarse sediments to the North, where the paleocoast was located. The uplift of the Sierra de Los Filabres may be related with the onset of an E-W antiform that started to grow during the earliest Tortonian producing unconformities in the sedimentary infill (Fig. 4.8B). At any rate, in the Huércal-Overa basin, east of the study area, there should be other emerged sectors dating from this time period and determining a different pattern of paleocurrents, including southward directions (Mora, 1993; Augier, 2004).

Although the Lower Tortonian conglomerates that crop out in the Almanzora basin are tilted and show well developed brittle deformation, it is difficult to determine the deformation age and the synsedimentary paleostress. Nevertheless, the onset of growth of the E-W oriented Sierra de Los Filabres north-vergent fold suggests that the maximum stress axis was subhorizontal and N-S oriented during this period (Fig. 4.9A). The Sierra de Los Filabres, together with Sierra Nevada, formed a large island at the end of Middle Tortonian (Braga et al., 2003).

6.1.2. NW-SE oriented compression from Tortonian; dextral shear deformation

Our structural analysis indicates a change in the stress field during the Tortonian, with shortening direction changing up to NW-SE (stress ellipsoids type 2), accompanied by local NE-SW extension (stress ellipsoid type 1). The maximum stress axis became oblique to the previous E-W oriented Sierra de Los Filabres fold producing dextral shear deformation along a wide band located to the North. The activity and distribution of different tectonic structures evidenced the dextral simple shear deformation component.

During the Tortonian, the Sierra de Las Estancias ENE-WSW antiform and E-W right-lateral and N-S left-lateral strike-slip faults started to grow, linked to the shortening. The NE-SW associated extension developed NW-SE normal faults that started to open the Baza basin in the westernmost sector of the Corridor (stress ellipsoid type 1). In between the Los Filabres and Las Estancias antiform, the Almanzora synform developed. Its growth favoured Tortonian marine transgression in this area, observed on a regional scale and traditionally linked with extensional events (Fig. 4.9B).

According to the sedimentological studies carried out by Guerra-Merchán (1992) in the Almanzora Corridor and by García-García (2003) in the southern border of the Baza basin, fast uplift linked to a tectonic event took place during the Late Tortonian. Our stress analyses point out that the regional maximum stress axis continues NW-SE during the Latest Tortonian-Early Messinian (stress ellipsoid type 2), oriented obliquely to Sierra de Los Filabres (Fig. 4.9C). Under a regional dextral shear deformation framework, extensional tectonics prevailed in the western Corridor and a compressional setting controlled the eastern end. The related deformations may have produced the progressive clockwise rotation, from ENE-WSW to E-W, of the westernmost sector of

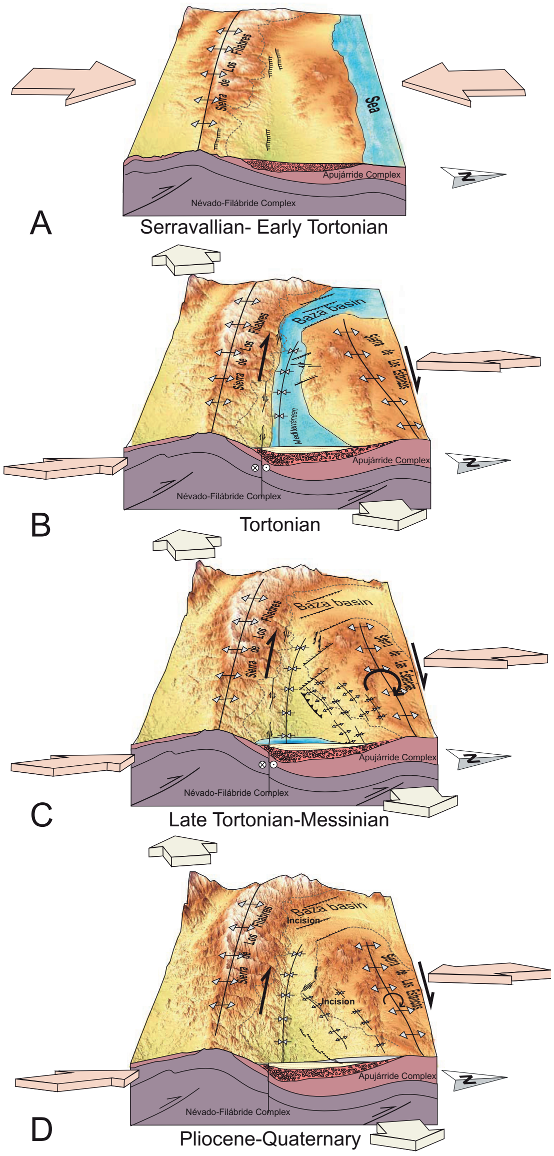


Fig. 4.9. Block diagrams that represent the evolution of the main structures and the regional stress field in the Almanzora Corridor. The tectonic evolution is analyzed in four stages, showing the interaction of the faults and folds during Serravallian-Early Tortonian, Tortonian, Late Tortonian-Messinian and Plio-Quaternary times.

Sierra the Las Estancias antiform. As a result of the eastern Corridor narrowing, the sediments were subjected to a contractional deformation that produced ENE-WSW minor folds and reverse faults. Simultaneously, NW-SE normal faults deformed the Baza basin, the Almanzora Corridor and the Las Estancias range; while E-W dextral faults deformed the south basin border (Fig. 4.9C). Furthermore, the Corridor uplift took place as a consequence of the interaction between the kilometric-scale fold growth and a regional crustal thickening produced by plate convergence. The uplift effects (basin continentalization and river base level changes) are not only observed in the Almanzora Corridor, but also in all the Neogene basins of the Betic Cordillera.

6.1.3. Present-day setting

The kilometric-scale Almanzora synform is responsible for the asymmetrical basin shape characterized by: alluvial fan development only in the northern border, high incision of the north tributary rivers, and the southward position of the Almanzora River. The south basin border is rectilinear and mainly controlled by the strike of inherited Miocene structures (mainly the foliation of the metamorphic rocks), and there are no active faults, as evidenced by undisturbed Quaternary sediments that crop out in this border. The north border geometry is more irregular, mainly because of the interaction between NW-SE normal faults as well as the lower dip of the northern limb of the synform. In this context, the stress field continues to be characterized by NE-SW extension, permitting the activity of the NW-SE normal faults in the Baza basin (stress ellipsoid type 1), and a NW-SE directed compression (stress ellipsoid type 2), detected only in the eastern Corridor, along with the growth of small ENE-WSW reverse faults (Fig. 4.9D).

6.2. Mechanism of basin growth

The Almanzora Corridor and its terminations constitute an example of elongated asymmetric narrow basin development in an oblique convergence framework since the Tortonian. Previous authors propose extensional models for the basin development based on the growth of large E-W normal faults coetaneous to sedimentation (Guerra-Merchán, 1992 and Augier et al., 2005b). The new data presented in this paper may improve understanding of the tectonic evolution, as certain aspects contradict previously proposed models.

Augier et al. (2005b), who describe the deformations of the southern border basement, have recently suggested this basin be interpreted as a half-graben structure in the hanging-wall, related to the Alpujárride/Nevado-Filábride top-to-the north low angle normal fault. This model is contradictory with the W-NW extension direction deduced from the Alpujárride/Nevado-Filábride fault gauges (Jabaloy et al., 1993; Martínez-Martínez et al. 2002). In addition, detailed analysis of the sedimentary infill reveals that the Alpujárride/Nevado-Filábride contact is buried in some sectors by sediments since the Early Tortonian (Fig. 4.10), suggesting that the fault was active mainly prior to basin development.

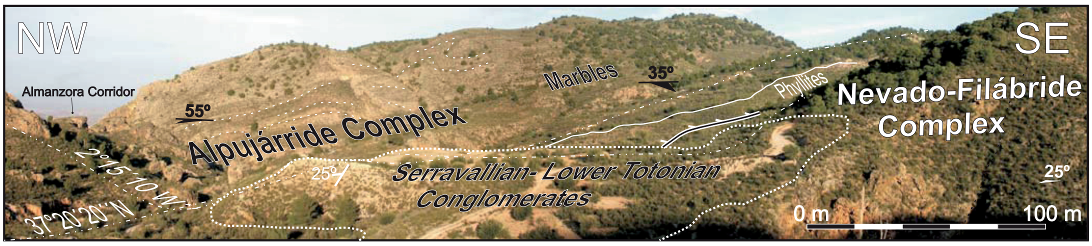


Fig. 4.10. Lower Tortonian sediments covering the Alpujárride/Nevado-Filábride contact close to Fines, suggesting that the fault was active mainly prior to basin development (UTM: 4132647 m, 566103 m).

Our structural data show that in both basin boundaries, the relation between the sediments and basement rocks is generally an unconformity, deformed only by some NW-SE normal faults in the north basin boundary and by dextral strike-slip faults in the south basin border. Indeed, the sediments adjacent to the south basin border dip to the north, whereas the sediments closest to the north basin boundary dip to the south, showing structures synsedimentary with respect to tilting in both margins. Even though abundant faults and folds deform the Almanzora basin, our data clearly indicate the greater significance of the folds than of the normal faulting during the Corridor development. Thus, the corridor development is mainly a consequence of fold growth, modified by a great variability of tectonic structures, including synsedimentary compressional deformations, in a regional stress field determined by NW-SE compression and orthogonal extension.

6.3. Implications for an understanding of narrow elongated basin development under non-orthogonal convergence

In orogens developed in an oblique convergence framework, simple shear components appear as important deformation mechanisms (e.g. Fabbri et al., 2004; Velandia et al., 2005). At a minor scale, the presence of crustal obstacles (e.g. large folds) or anisotropies (e.g. joint and faults) oblique to the compressional direction, favours the appearance of shear deformation bands (Tchalenko, 1970; Jonk and Biermann, 2002) that allow the development of transpressive and transtensive areas (Ramsay, 1980; Sanderson and Marchini, 1984).

The Almanzora Corridor leads us to consider that, under simple shear component deformations, major folds and tectonic element rotations play an important role during a narrow basin development, controlling the local asymmetry of tectonic structures, with the extensional tectonic opening of the western Corridor and the compressional setting controlling the eastern end. In addition, this tectonic setting is responsible for the denudation/sedimentation area distribution, and the final corridor's shape and longitude, which coincide with the extent of the dextral shear zone. The coalescence of extensive and compressive structures is a common feature of the Neogene-Quaternary basins of the Betic Cordillera, although the mechanisms that allow their coexistence are still under debate (eg. Galindo-Zaldívar et al., 1999; Galindo-Zaldívar et al., 2003; Marín-Lechado et al., 2005; Martínez-Martínez et al., 2006; Pedrera et al. 2006). This setting is still actives at the cordillera scale, therefore the distribution of seismicity and the kinematics deduced from the focal mechanism solutions reveal an extensional setting in the upper crust that are in contrast with the NW-SE plate shortening (Morales et al., 1997; Galindo-Zaldívar et al., 1999; Herraiz et al., 2000; Muñoz et al., 2002; Stich and Morales, 2003; Stich et al., 2003; Buforn et al., 2004; Martínez-Martínez et al., 2006), that affected the lower crustal levels. In this sense, our geometric-kinematic model addresses the relationship between extension and shortening in one of these basins since the Tortonian.

In the Almanzora Corridor, the presence of the large Sierra de Los Filabres antiform since the Early Tortonian represents a rigid obstacle conditioning the stress distribution during its more recent evolution. A key question about the formation of the Filabres E-W oriented range is: Did it emerge with the present orientation, or has it rotated since the Early Tortonian?

(a) One possibility is to assume a consistent NW-SE direction of compression throughout Tortonian times. In this setting, the original orientation of the Los Filabres fold would be NE-SW (orthogonal to the shortening), and then subjected to a progressive dextral rotation. Paleomagnetic studies propose dextral rotations for tectonic elements located in the External Zones of the Cordillera during the indentation to the West of the Alboran Domain (Platt et al., 1995; Platzman et al., 2000; Platt et al., 2003; Platt et al., 2005). However, these rotations were previous to Tortonian times, probably being active during the Early to Middle Miocene (Luján et al., 2003).

(b) The other possibility is that the orientation of the range has remained unchanged since its initial stage of formation. Therefore, most authors evoke the origin of E-W trending folds under a N-S contractional event (Platt et al., 1983; Weijermars et al., 1985; Crespo-Blanc et al., 1994; Martínez-Martínez et al., 1997a; Martínez-Martínez et al. 2002; Sanz de Galdeano and Alfaro, 2004). Following this assumption, we consider a counter-clockwise rotation of the directed compression, from N-S (orthogonal to Sierra de Los Filabres antiform) to NW-SE (deduced from our data) during Tortonian. During the initial stages of the orogeny, large folds constitute examples of crustal barriers that favour the development of shear zones parallel to their boundaries where the crust is thinner. These ancient inherited characteristics, later emphasized during the basin evolution, strongly condition the final shape of the corridor.

6.4. Folds development and marine transgression

In convergent margins, contractional tectonic deformation produces crustal thickening and mountain development. Most of the sedimentary basins are a result of uprising sea level or extensional stages with related subsidence (Keller and Pinter, 2001). However, the global sea level change curves (Haq et al., 1987) can not adequately explain the stratigraphical sequence of the Almanzora Corridor, meaning tectonic events conditioned the deposits and the morphology of the basin (Guerra-Merchán, 1992; Guerra-Merchán and Serrano 1993; García-García and Fernández, 2006). On the basis of our structural data, we can discard N-S extension of the Almanzora Corridor as the main mechanism responsible for the basin development. Could fold growth related to crustal thickening explain the Tortonian transgression in the basin?

Folding related to crustal thickening increases the average height of the cordillera (Keller and Pinter, 2001). However, it also augments the difference between minimum and maximum heights, respectively coinciding with synforms and antiforms. In the initial stages, the depressed areas may allow sea water penetration and become marine basins with sediment deposition from the adjacent antiformal mountains (Fig. 4.11B). This mechanism may be responsible for the Almanzora basin Tortonian transgression. The Tortonian sediments lap onto the basal Tortonian red conglomerates and the basement rocks. The sediments located in the Corridor border are deposited in coastal and very shallow marine environments, while a deep sedimentation fills in the Corridor axis.

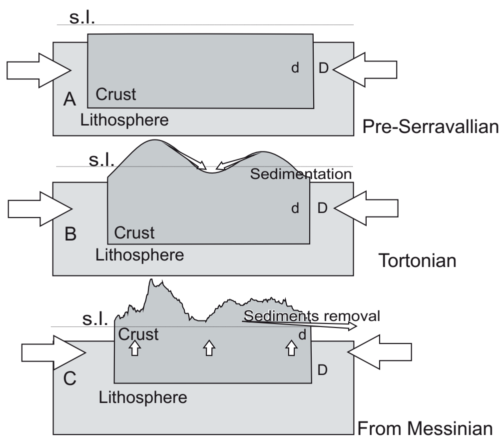


Fig. 4.11. Relationships between folding and marine transgressions, considering as constant the sea level. A. Unfolded crust. B. Fold development. Although the average height of the cordillera increases, so does the difference between minimum and maximum heights, and the depressed areas allow a marine transgression and the onset of sediment deposition. C. Final stage, with the compression continuing to produce crustal thickening while a regional and progressive emersion takes place until the marine basin continentalization.

In a second stage, compression continues producing crustal thickening and a regional and progressive emersion takes place, until marine basin continentalization (Fig. 4.11C). In the Almanzora Corridor, the Uppermost/ Latest Tortonian yellow marls (Briend, 1981) show a shallowing upward sequence that culminates in the basin continentalisation. At this point the erosion rates exceed the uplift and the sediments are removed out by the Almanzora River.

7. Conclusions

Elongated depressions developed in geodynamic settings characterized by oblique convergence are often related to strike-slip faulting. However, the Almanzora Corridor growth is associated with a complex structural interaction developed in a changing stress scenario. (a) During the Early Tortonian, a N-S directed compression allows deformation to advance to the North with a progressive fold growth, starting with the Sierra de Los Filabres antiform and then with the Sierra de Las Estancias antiform. (b) Later, since Tortonian, counter-clockwise rotation in the stress field occurred, and the shortening direction changed to NW-SE (type 2) presenting an orthogonal associated extension (type 1). Therefore, the maximum stress axis became oblique to the previous E-W oriented Sierra de Los Filabres fold, producing dextral shear deformation along a wide band located to the North. The westernmost sector of the Sierra de Las Estancias fold underwent progressive clockwise rotation, from ENE-WSW to E-W, producing the eastern Corridor narrowing. As a result of the rotation, the deformation styles were clearly different in the Baza basin and western Almanzora Corridor (extensional) as compared to the eastern part of the Almanzora Corridor (compressional).

The above regional observations give rise to four major conclusions about the evolution of a narrow and elongated basin. (a) The development of large mountain ranges represents crustal rheological heterogeneities that condition the growth of late structures. (b) A shortening direction oblique to these mountains may produce a deformation framework with an important simple shear component, including extension and compression directions that are oblique to the basin boundaries. Notwithstanding, the elongated character of the corridors may persist. (c) Under these conditions, fold development may play an important role during basin evolution, controlling the location of minor tectonic structures and the sedimentation/denudation areas. (d) In addition to the traditional extensional models, the Almanzora Corridor illustrates that the initial stages of synform growth could be responsible for local marine transgressions.

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5. Contractional and extensional deformations in the termination of a major sinistral fault: the Alhama de Murcia Fault (Eastern Betic Cordillera)

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Submitted for publication

Among the classical minor structural associations on the termination of transcurrent faults are horsetail splay faults formed by reverse, normal or strike-slip faults developing duplexes. Meanwhile, the coexistence of contractional and extensional structures is very rarely documented. The southern termination of the NE-SW Alhama de Murcia transcurrent fault (AMF), in the Eastern Betic Cordillera, has been studied by field mapping, kinematic fault analysis, paleostress determination and gravity prospecting in order to discuss the relationships of fault activity, minor tectonic structures and associated sedimentary depocenters. Here, ENE-WSW and WNW-ESE folds interact with two set of normal faults having the same orientation as well as ENE-WSW reverse faults. Progressive unconformities associated with folds reveal that the beginning of the AMF activity occurred in Tortonian. The folds progressively grew and rotated from ENE-WSW up to WNW-ESE, with an in increase in shear strain close to the transcurrent fault. We propose that the development of the normal faults was a consequence of short-term vertical major stress axis episodes, in turn caused by a potential-energy increase related to crustal thickening and relief uplift. This setting may have become predominant in between the main activity compressive pulses along transcurrent faults.

Keywords
Transcurrent fault, neotectonics, active tectonics, paleostress, gravity prospecting.

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1. Introduction

Transcurrent faults and associated structures constitute one of the main topics of earth science research over the past forty years. Evidence of transtension, where the strike-slip faults are associated with normal faults, or transpression, characterized by strike-slip faults linked to folds and reverse faults, is well described within different geodynamic frameworks. Classic research focuses on the San Andreas Fault, which represents a major strike-slip fault that accommodated deformation in a transform plate boundary (Crowell, 1974; Sylvester and Smith, 1976; Sylvester, 1988); and on the Himalaya collision orogen, where large transcurrent faults accommodate the escape tectonics (Tapponnier and Molnar, 1977). These early studies assess our knowledge of the distribution of local contractional and extensional minor structures in strike-slip fault terminations, in fault oversteps (Wilcox et al. 1973; Crowell 1974; Aydin and Nur 1982), and in bent sectors of single faults (McClay and Bonora 2001). Results were checked through analog models establishing the classical minor structural associations on transcurrent fault systems (Tchalenko 1970; Hempton and Neher, 1986; Naylor et al., 1986). These associations consist of a set of horsetail splay faults that overlap the main strike-slip fault (Freund, 1974) and strike-slip duplexes (Woodcock and Fisher, 1986). More recent tectonic research focuses on strike-slip associated structures by taking into account substantial structural variations and more complex settings than former research (Muller and Aidyn 2004; Parson et al. 2005; Bohoyo et al. 2007). In the large database of available field examples, however, there are no detailed case studies of the interaction of parallel compressional and extensional structures, generally considered to develop simultaneously but with oblique trends.

The Neogene evolution of the Betic Cordillera (Fig. 5.1) is characterized by an atypical tectonic setting where contractional and extensional structures simultaneously deform the hinterland of the cordillera at least since Tortonian (Galindo-Zaldívar et al. 2003). This setting has been traditionally explained in terms of different regional stress field superposition (Montenat and Ott d'Estevou 1999). These tectonic structures have a heterogeneous distribution, dominated by folds and normal faults in the central cordillera and by strike-slip faults in the Eastern sector of the cordillera.

The aim of this contribution is to shed light on the relationships between the great varieties of compressive and extensional tectonic structures that coexist in the termination of a large transcurrent fault. This research looks into the interaction of minor structures that deform the Huércal-Overa basin, located by the southern termination of the sinistral strike-slip Alhama de Murcia Fault (Eastern Betic Cordillera). Tectonic observations, including mapping and kinematic analysis, are combined with new gravity data to determine the sedimentary thickness distribution in order to constrain the basin development.

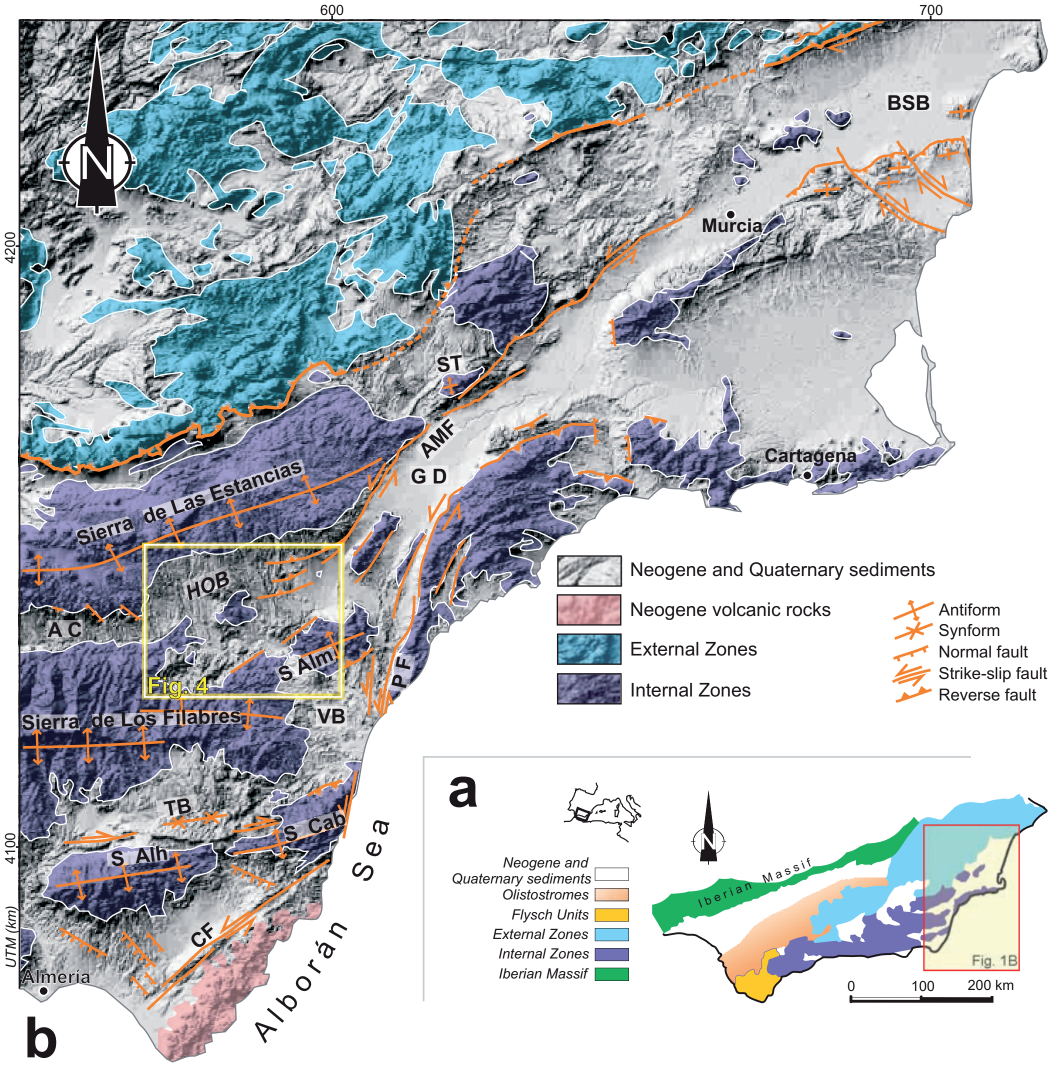


Fig. 5.1. Geological setting. (a) Simplified geological map of the Betic Cordillera and (b) enlarged geological map of the Eastern Betic Cordillera where the location of the main faults and folds is indicated. The position of Figure 4 (chapter 5) is marked. AC: Almanzora Corridor; AMF: Alhama de Murcia Fault; BSB: Bajo Segura Basin; CF: Carboneras Fault; GD: Guadalentín Depression; HOB: Huércal-Overa Basin; PF: Palomares Fault; SC: Sierra Cabrera; SAlh: Sierra Alhamilla; SAlm: Sierra Almagro; TB: Tabernas Basin; VB: Vera Basin.

2. Geological setting

The Betic Cordillera (Fig. 5.1) has been traditionally divided into an external fold-and-thrust belt, deformed by thin-skin tectonics and commonly referred to as the External Zones; and a mostly metamorphic hinterland designated the Internal Zones.

The External Zones are formed by Mesozoic and Tertiary rocks that were deposited over the Variscan basement of the Iberian Massif, paleogeographically interpreted as a passive continental margin. The Internal Zones are mainly formed by three major metamorphic complexes that, from bottom to top, are the Nevado-Filábride (Egeler, 1963), Alpujárride (Van Bemmelen, 1927) and Maláguide (Blumenthal, 1927). These complexes are separated by low-angle normal faults (Aldaya et al., 1984, García-Dueñas et al., 1988; Galindo-Zaldívar et al., 1989; Platt and Vissers 1989). Both the Nevado-Filábride and the Alpujárride Complexes include several thrust sheets with Paleozoic to Mesozoic lithostratigraphic sequences showing alpine ductile deformation and metamorphism, in some cases also of Variscan age. The Maláguide Complex is formed by Paleozoic to Middle Miocene rocks that were deformed but not metamorphosed during the Alpine orogeny. The Dorsal and Predorsal complexes also belong to the Internal Zones, and are formed by Triassic to Early Neogene sedimentary rocks.

The main deformation-driving mechanism since the Serravallian is N-S to NW-SE shortening between Europe and Africa (e.g. Dewey et al., 1989; DeMets et al., 1994; Rosenbaun et al., 2002). This convergence generated the relief of the Betic Cordillera, characterized by mountain ranges and depressed areas featuring sedimentary basins, respectively coinciding with large E-W to ENE-WSW antiforms and synforms. These large folds mainly interact with normal, strike-slip, and reverse faults (e.g. Booth-Rea et al., 2003). The compressive and extensional tectonic structures show features indicating simultaneous development since Tortonian (Galindo-Zaldívar et al., 2003). The Alhama de Murcia Fault and its termination in the Huércal-Overa basin constitute two major structures of this region.

2.1. The Alhama de Murcia sinistral fault (AMF)

The presence of NNE-SSW to NE-SW large sinistral strike-slip faults determines the neotectonic setting in Eastern Betic Cordillera (Fig. 5.1). These set of faults have been interpreted as a large shear zone (Trans-Alborán transcurrent zone, de Larouzière et al., 1988) that represents a crustal discontinuity extending southwestward, crossing the Alborán Sea.

The Alhama de Murcia Fault (AMF) (Bousquet and Montenat, 1974) is the northern segment of these transcurrent faults in the Betic Cordillera (Fig. 5.1). It has a NE–SW orientation showing predominantly reverse strike-slip kinematics (Martínez-Díaz, 2002). The AMF extends over 80 kilometers, from Murcia as far as the Huércal-Overa basin to the south, crossing the northwest boundary of the Guadalentín depression. The most recent fault activity is inferred from Quaternary sediment deformations and their geomorphological expression. The AMF develops mountain fronts related to the sinistral fault segments and associated folds and reverse faults (Martínez-Díaz, 2002), involving vertical axis rotation, as deduced from paleomagnetic results (Mora, 2003;

Krijgsman and Garcés, 2004; Mattei et al., 2006). In addition, the AMF has associated low to moderate seismicity (Silva et al., 1997; Stich et al., 2003, 2007).

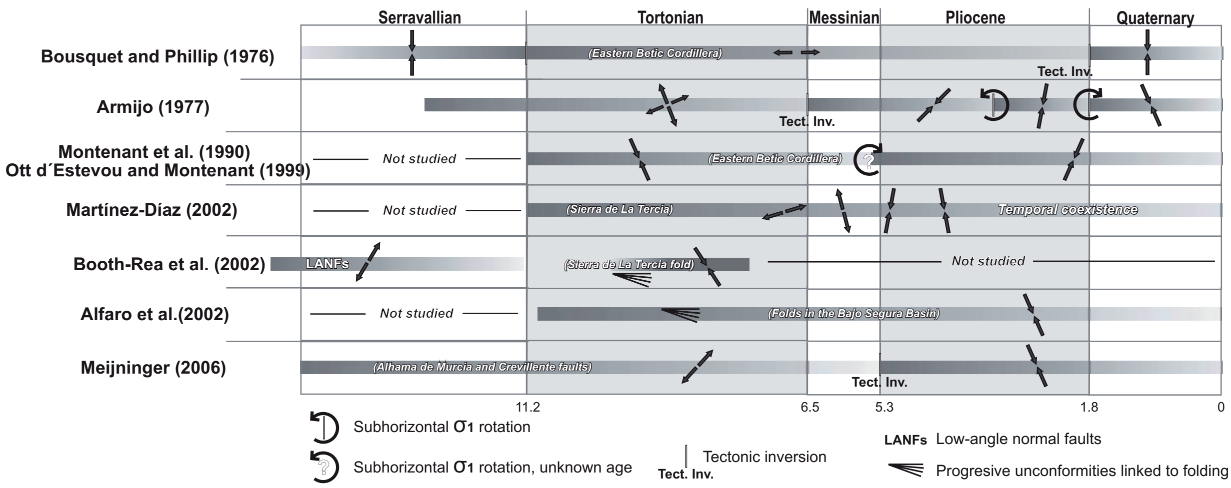


Fig. 5.2. Paleostress evolution proposed in previous research for the AMF and surrounding areas.

Despite the numerous structural data obtained from the AMF and its surrounding sedimentary basins, some questions remain open. The initial activity of AMF is under debate; and while some authors propose sinistral behavior since Tortonian (Ott d'Estevou and Montenat, 1985; Montenat et al., 1987, 1990; Krijgsman et al., 2000; Vennin et al., 2004) other researchers support a Latest Miocene-Early Pliocene onset of activity (Armijo, 1977; Meijninger and Vissers, 2006). Likewise, there is no consensus with regard to the spatial and temporal distribution of stress fields proposed for this sector of the cordillera from the Serravallian (Fig. 5.2). Bousquet and Phillip (1976b) point to E-W extension from the Tortonian up to Pliocene, plus late regional stress fields characterized by horizontal N-S compression. Armijo (1977) studied the Lorca-Totana sector, describing an extension up to the Messinian and a field stress inversion characterized by compression changing from NE–SW to NNE–SSW strike during the Late Pliocene, and NNW–SSE orientation during the Quaternary. Other authors propose a compressive setting since Tortonian, with horizontal compression varying from NNW–SSE to NNE–SSW (Ott d'Estevou and Montenat, 1985; Montenat et al., 1987, 1990; Montenat and Ott d'Estevou, 1999). Recent research evidences the coexistence of NNE–SSW and NNW–SSE horizontal compression and NNW-SSE horizontal extension, active during the Late Miocene to the Quaternary (Martínez-Díaz, 1998, 2002). Booth-Rea et al. (2002) described extensional structures with a top-to-the-W-SW transport affecting Late Serravallian age marine sediments, and sealed by Lower Tortonian conglomerates in the southeastern border of the Sierra de la Tercia fold (Fig. 5.1). These extensional structures are deformed by the Sierra de la Tercia anticline, which shows an intra-Tortonian angular unconformity related with its growth. In the Bajo Segura basin, which constituted the northern termination of the AMF, Alfaro et al. (2002b) describe progressive unconformities related to fold development from the

Late Miocene up to the present, highlighted by seismic reflection profiles. Recently, Meijninger (2006) and Meijninger and Vissers (2006) put forth an inversion tectonic model where the NNE-SSW to NE-SW extension was responsible for the Tortonian basin development, with inversion occurring in post-Messinian times.

2.2. The Huércal-Overa basin

2.2.1. Previous models for basin development

The Huércal-Overa basin started to develop in the Eastern Betic cordillera in the Serravallian-Early Tortonian. The first studies considered it to be a pull-apart basin related to strike-slip activity on NE-SW trending faults (e.g. Bousquet and Montenat, 1974). Poisson et al. (1999) proposed a model where the surrounding ranges are interpreted as westward-verging antiforms developed over deep-seated thrust faults, and the Huércal-Overa basin constitutes a lateral synform oriented parallel to this supposed thrust transport direction. The latest interpretations suggest the development of the Huércal-Overa basin in a purely extensional framework that favours the simultaneous exhumation and thinning of the metamorphic middle to upper crust during the Late Miocene (eg. Mora, 1993 ; Vissers et al., 1995; Augier et al., 2005b; Meijninger, 2006; Meijninger and Vissers, 2006). These authors explain the compressive structures as the consequence of a tectonic inversion since Late Messinian-Pliocene times.

2.2.2. Stratigraphy

The Huércal-Overa basin infill extends from the Middle Miocene up to the Quaternary, and includes several stratigraphic units separated by unconformities (Figs. 5.3 and 4). The oldest sediments that occupy the basin are continental conglomerates, probably deposited during the Middle Miocene, yet poorly represented. A thick continental red conglomerate formation was most likely deposited during the Serravallian and Early Tortonian, overlying an unconformable previous unit and the basement rocks. The paleocurrents, mainly deduced from imbricate pebbles in this continental red conglomerate formation, are predominantly towards the E and N (Montenat et al., 1990c; Meijninger, 2006), which is consistent with the flow data observed in the nearby Almanzora Corridor (Pedrera et al., 2007). These continental deposits lie in gradual transition upwards into a variously colored sequence with alternating beds of conglomerates, sands, grey silts and gypsum, assigned to a fluvial-deltaic environment. An Early Tortonian age is evoked for this unit on the basis of foraminifera sampled in the marine levels (Briend, 1981; Guerra-Merchán and Serrano, 1993; Meijninger, 2006) and micromammals from the continental strata (Guerra-Merchán et al., 2001). At the top there is an angular unconformity where, during the Late Tortonian, bioclastic reefal limestones and fan-delta were deposited (in the southern sector of the basin), gradually in transition to yellow marls toward the center of the basin. Foraminiferal (Guerra-Merchán and Serrano, 1993; Meijninger, 2006) and nannoplankton assemblages (Martín-Pérez, 1997) dated the marls as Late Tortonian. Messinian sediments crop out only in the easternmost part of the study area, close to the village of Huércal-Overa. During the Plio-Quaternary, detrital sediments belonging to the alluvial fan and to the river deposits were unconformably placed over the Miocene rocks.

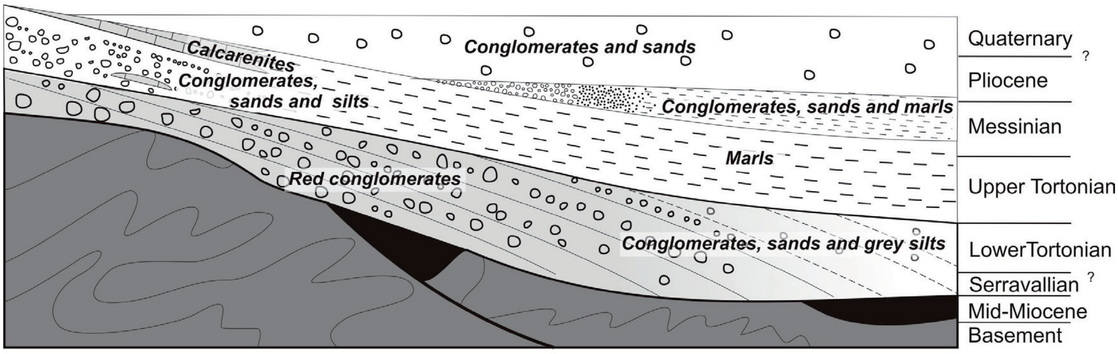


Fig. 5.3. Stratigraphic sketch of the Huércal-Overa Basin.

3. Tectonic structures in the Huércal-Overa basin related to the southern termination of the Alhama de Murcia Fault

The Late Miocene sediments that fill the Huércal-Overa basin are quite deformed by several sets of faults and folds (Fig. 5.4).

3.1 Faults

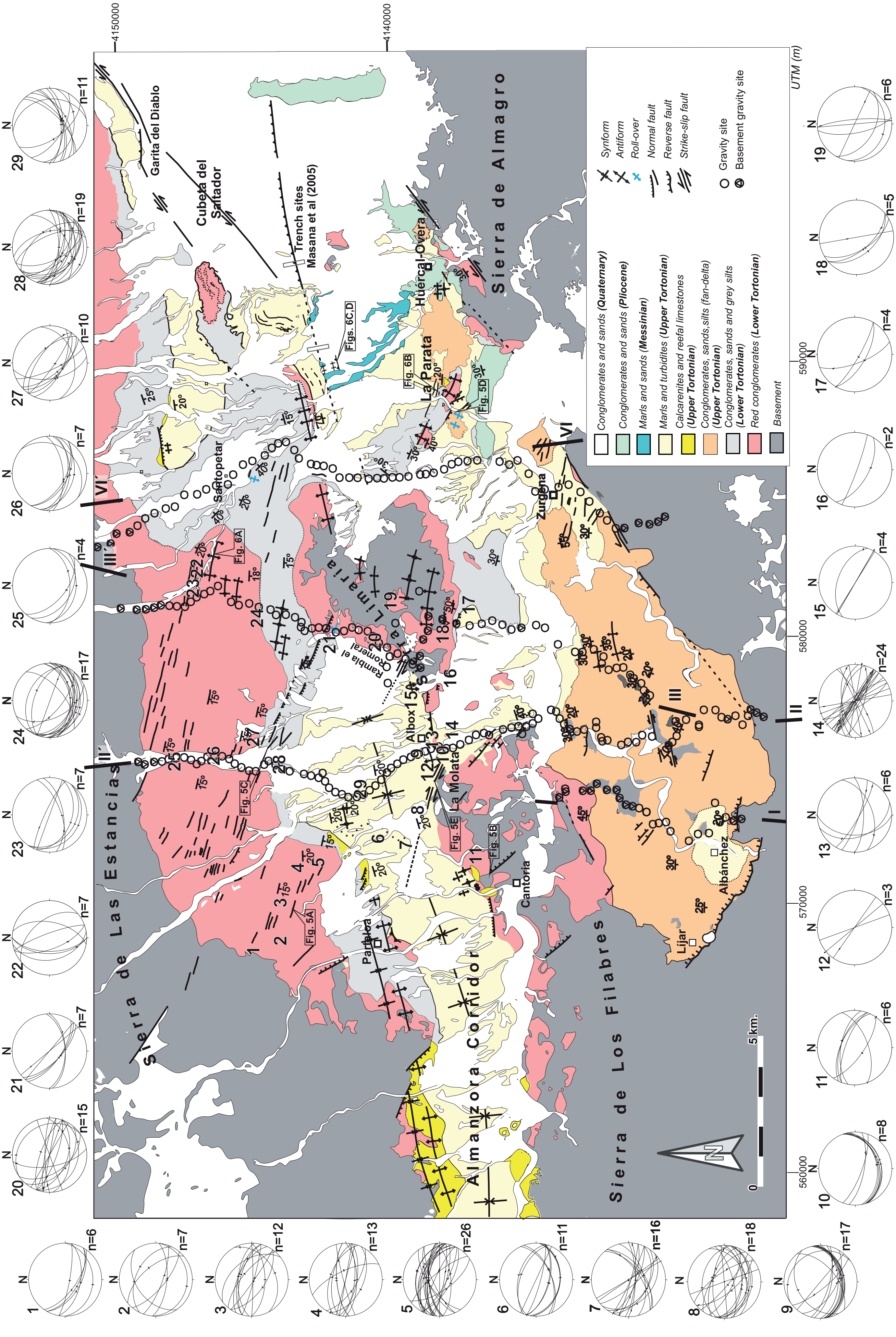
Faults have been previously studied in the Eastern and Southern Huércal-Overa basin: the earliest research (Groupe de Recherche Neotectonique, 1977), was followed by that of Briend (1981), and further efforts (Mora 1993; Poisson et al., 1999; Augier, 2004; Meijninger and Vissers, 2006). However, data on the recentmost faulting to deform the western basin sector are scarce. We present a review of the previous data, along with a careful description of the structures that deform this sector.

The most abundant group corresponds to WNW-ESE to NW-SE normal faults that show a widespread distribution in the basin (Mora, 1993; Augier, 2004; Meijninger, 2006). These faults are usually located inside the basin, presenting a length shorter than 1 km, and short normal slip, between a few centimetres and a few meters (Fig. 5.4). They generally dip to the SW in the northern basin sector and to the NE in the southern region. The presence of conjugated faults with dihedral angles from 50º to 60º is very common (Figs. 5.4 and 5.5). The kinematic analysis from these faults generally shows a pure dip-slip component. However, some fault surfaces show other striae, sometimes overprinted, that suggest a local NW-SE shortening. Only the southwestern basin boundary is limited by normal faults, between Albánchez and Líjar villages. These normal faults commonly present planar surfaces and deform the Early Tortonian continental red conglomerate and the Late Tortonian fan-delta. The scarce synsedimentary features show evidence of activity from the Tortonian, such as the bounding faults located in the Albánchez-Líjar sector, which probably controlled the sedimentation of Late Tortonian marls.

These set of faults change their geometries when deforming the multilayer sequence of conglomerates, sands, grey silts, and gypsum or Early Tortonian age (Fig. 5.5). Examples of flat-and-ramp normal faults affect this sedimentary sequence, where the soft sedimentary layers mostly concentrate the deformation and constitute detachment levels parallel to the bedding. The sediments are folded by fault activity, forming roll-overs, both in the hanging wall and, surprisingly, locally affecting the footwall as well (Figs. 5.4 and 5.5). The most impressive roll-over example is located close to the village of Santopetar (Briend, 1981; Jabaloy et al. 1993; Mora, 1993; Augier, 2004; Meijninger, 2006). This structure is interpreted as the result of Early Tortonian synsedimentary deformation in both the footwall and hanging wall, along a major normal fault system composed of several flat and high dipping ramps.

Our field data show the presence of a second set of scarce ENE-WSW to NE-SW oriented normal faults in the central part of the western Huércal-Overa basin, deforming Late Tortonian marls (Fig. 5.4, stations 6 and 7). The southeastern margin of the Huércal-Overa basin is bounded by sub-vertical to NWward dipping faults of the same orientation and predominantly sinistral strike-slip kinematics, although normal striation has also been observed in some segments (Fig. 5.4). These faults were previously interpreted as transfer fault zones that accommodate the extension produced by the WNW-ESE oriented normal faults (Mora 1993; Poisson et al., 1999), or else considered ancient faults active only during the first stage of the basin evolution and later reactivated as sinistral faults (Augier, 2004). Meijninger (2006) describes a complex history of overprinted slips in one of these faults located close to Huércal-Overa village (Fig. 5.4), where initial dextral strike-slip striations are overprinted by dip-slip, again overprinted by sinistral strike-slip.

Fig. 5.4. Huércal-Overa geological map. The location of the main faults and folds is indicated. The position of the gravity measurement sites, the outcrops shown in Figures 5 and 6 (chapter 5), and the geological cross-sections of Figure 5.10 are marked. The orientations of microfaults and mesofaults are represented in stereographic projection, lower hemisphere.


Conglomerates and sands (Quaternary)
Conglomerates and sands (Pliocene)
Marls and sands (Messinian)
Marls and turbidites (Upper Tortonian)
Calcarenites and reefal limestones (Upper Tortonian)
Conglomerates, sands, silts (fan-delta) (Upper Tortonian)
Conglomerates, sands and grey silts (Lower Tortonian)
Red conglomerates (Lower Tortonian)
Basement
Synform
Antiform
Roll-over
Normal fault
Reverse fault
Strike-slip fault
Gravity site
Basement gravity site
UTM (m)
Sierra de Las Estancias
Sierra de Almagro
Sierra de Los Filabres
Almanzora Corridor
La Limaria
Huércal-Overa
La Parata
Zurgena
Albox
La Molata
Cantoria
Partaloa
Albánchez
Lijar
Santopetar
Garita del Diablo
Cubeta del Saltador
Trench sites Masana et al (2005)
Rambla el Romeral
5 km.

E-W to ESE-WNW oriented subvertical strike-slip dextral faults deform the Tortonian sediments that crop out mainly in the south basin border close to Albox (Fig. 5.4). These faults deform the Late Tortonian sediments and are usually sealed by the Quaternary deposits (Fig. 5.5). However, they affect even the Quaternary deposits in the central sector (Rambla el Romeral, Fig. 5.4). These faults may be conjugated with the NNE-SSW to NE-SW large sinistral-strike-slip faults described above.

The Huércal-Overa basin is deformed by reverse E-W to ENE-WSW oriented faults with related folds (Fig. 5.6) that deform the Tortonian and, locally, the Quaternary sediments (Groupe de Recherche Néotectonique, 1977; Briend, 1981; García Meléndez, 2000; Masana et al., 2005). In the eastern and northeastern sector of the basin, these faults form a splay geometry connected with the AMF (Briend, 1981; Silva, 1994). The Late Pliocene-Early Pleistocene faulting activity was established by the interaction of the Alhama de Murcia fault with these E–W reverse faults, generating a progressive syntectonic unconformity in the Garita del Diablo sector (Fig. 5.4) (García-Meléndez et al., 2003). In the western sector of the basin, the same reverse fault set deforms the Tortonian and locally the Quaternary sediments, sometimes developing synsedimentary features.

3.2 Folds

Most of the mountain ranges located in the Central and Eastern sectors of the Betic Cordillera correspond to kilometric antiforms, and the surrounding basins to synforms (Marín-Lechado et al., 2006 and references therein). The large folds developed coetaneously with the basin infill. Therefore, the folding age could be deduced from the progressive unconformities of the sedimentary units located near the basin boundaries. The large folds located in the study area are: the Sierra de Los Filabres and Sierra de Almagro antiforms, the Almanzora synform, and the Sierra de Las Estancias antiform (Figs. 5.1 and 5.4).

The E-W Sierra de Los Filabres antiform growth probably started in Serravallian to Early Tortonian times, as confirmed by fission-track analysis (~12 Ma, Johnson, 1994; Johnson et al., 1997) and by the age of the folded sediments forming progressive unconformities in the red conglomerate unit, and also with the Late Tortonian sediments (Pedrera et al., 2007). The northward and eastward flow directions deduced in the red conglomerate formation during the Serravallian-Early Tortonian (Montenat et al., 1990c; Meijninger, 2006) points to an enhanced topography in the Sierra de Los Filabres, where there was erosion and an abundant sediment supply. In addition, these data reveal that the Sierra de Las Estancias does not act as a barrier to sediment transport. In fact, uplift of the Sierra de Las Estancias antiform started later, during the Tortonian.

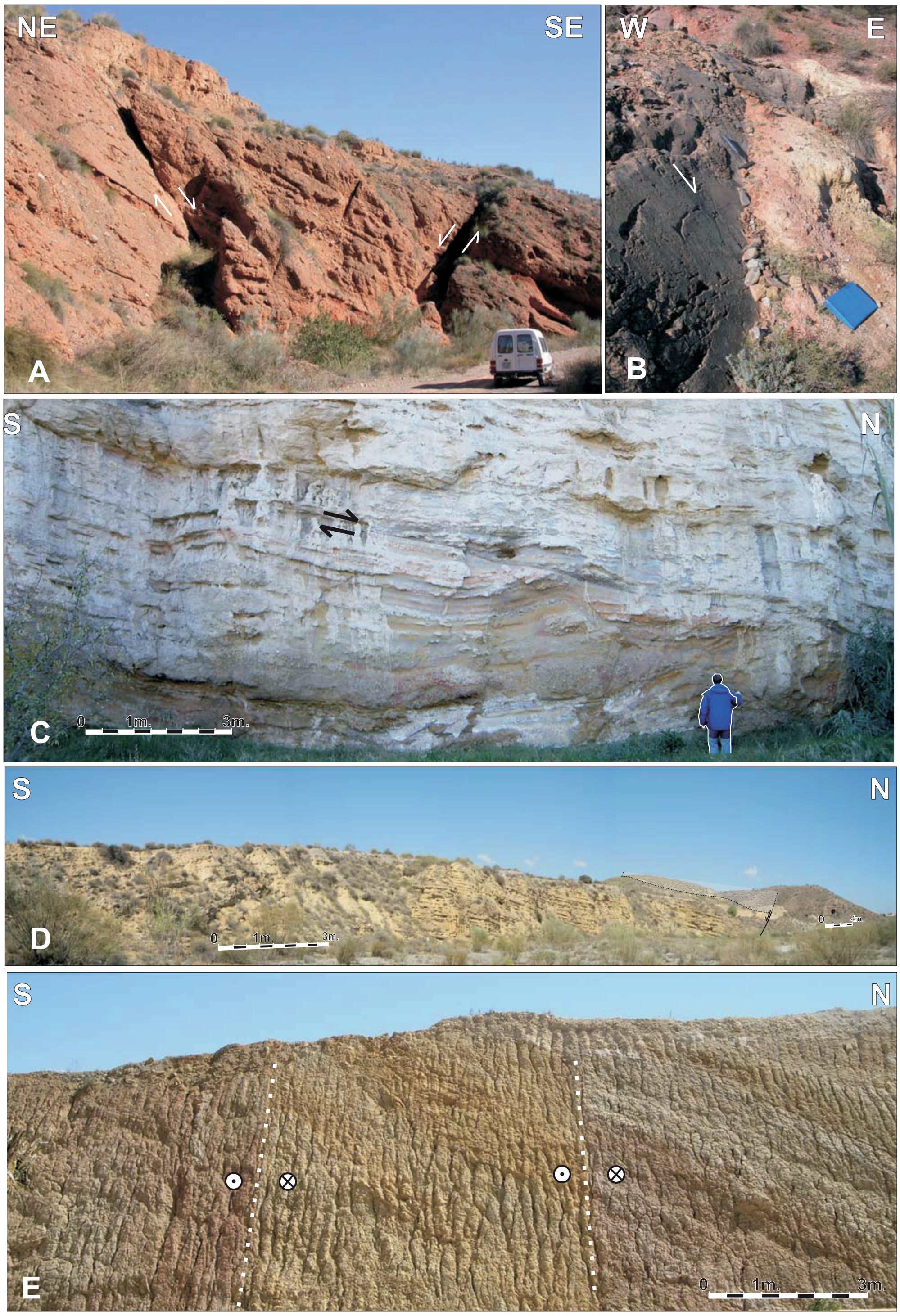


Fig. 5.5. Field examples of faults. (A) Example of WNW-ESE conjugated normal faults with 60º dihedral angle that deform Serravallian-Lower Tortonian conglomerates previously tilted by folding. (B) NW-SE Normal fault located in the southern boundary of the basin. (C) Detachment parallel to the beds with an associated roll-over in the footwall developed in the succession of conglomerates, sands and grey silts layers. (D) Example of a WNW-ESE normal fault with associated roll-over in their hanging-wall affecting a multilayer conglomerates and calcarenites succession. (E) WNW-ESE dextral faults that deform Tortonian sediments. Position in figure 5.4.

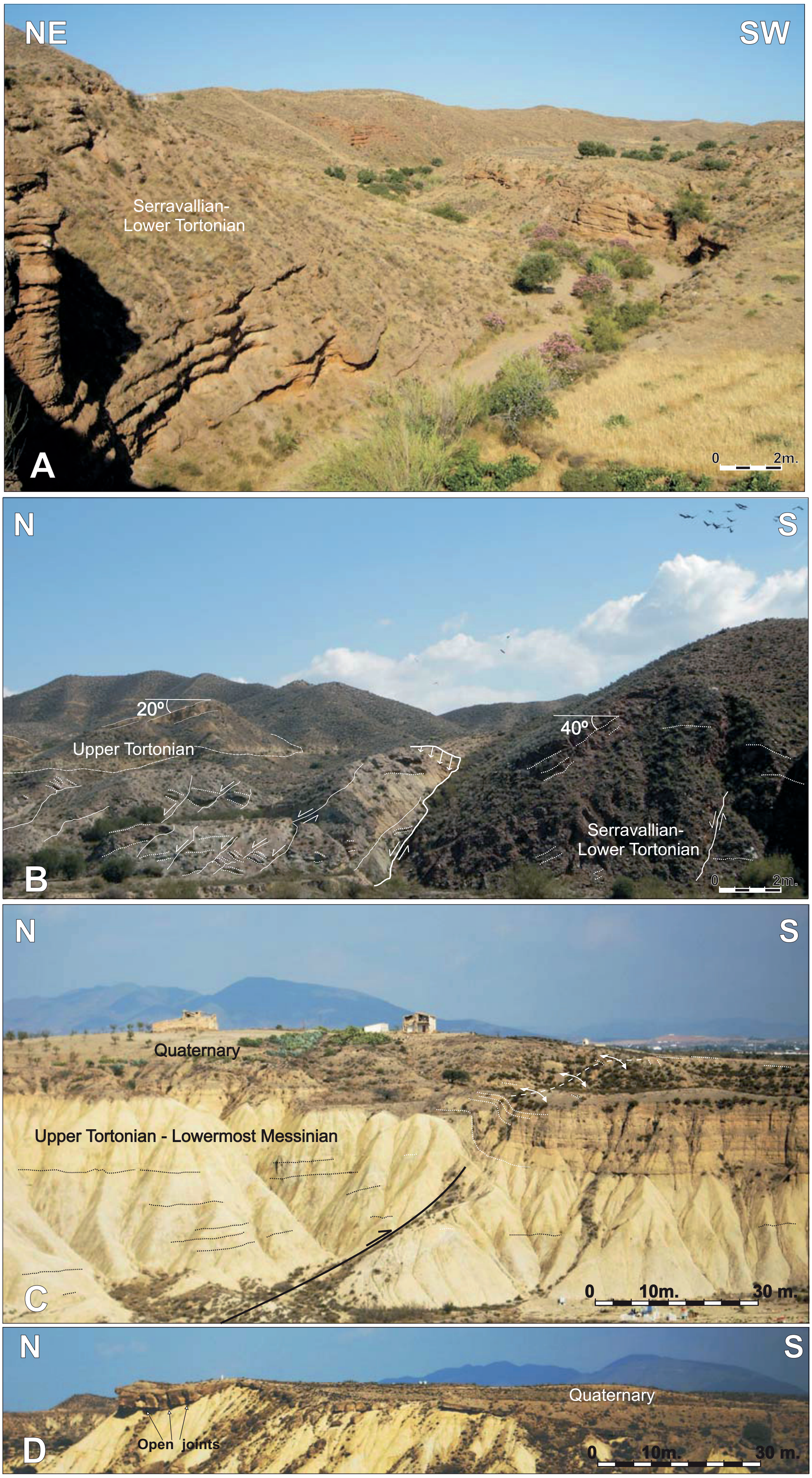
The Almanzora Corridor is determined by an N-vergent large synform with direction changing from E-W to the western corridor to ENE-WSW to the eastern end, near the Huércal-Overa basin. This synform deforms all the Miocene sediments and determines the location of the pelagic sediments along its hinge. The Quaternary continental alluvial fans beds have an initial sedimentary dipping toward the centre of the basin, and they lie unconformably over the folded marine sediments, making it quite difficult to determine if they are folded.

The Sierra Almagro, located in the Eastern prolongation of the Sierra de Los Filabres (Figs. 5.1 and 5.4), is also an ENE-WSW oriented antiform that deforms the Tortonian and Messinian sediments. Its limbs are strongly affected by faults, and ENE-WSW oriented North dipping reverse faults control its southern mountain front (Rutter et al., 1986; Booth-Rea et al., 2004). The northern limb is deformed by the sub-vertical ENE-WSW to NE-SW oriented faults described above, as they constitute the boundary of the Huércal-Overa basin.

In addition to these large folds, the Huércal-Overa basin sediment is deformed by minor folds (Figs. 5.4 and 5.6). They could be grouped, according to the mean strike, as ENE-WSW or WNW-ESE oriented folds. Both set of folds have wavelengths of tens to hundreds meters, being generally open folds, although they occasionally show vertical limbs. Their vergence is variable: for example, in the centre of the basin the antiforms are usually S-vergent with a northern limb characterized by gentle dip to the North and a high dipping to vertical southern limb (e.g. La Parata sector). On the other hand, the folds in the Western sector are usually N-vergent (e.g. La Molata fold, Partaloa area).

In the central sector of the basin, the sediments and the metamorphic rocks of Sierra Limaria (Fig. 5.4) are deformed by a band of WNW-ESE oriented open folds. The fold wavelengths vary between 1 and 4 km, and their strike is parallel to the main normal fault set. There is no a consensus as to their interpretation; and while some authors associate these folds with compression or transpression (Poisson et al., 1999), others interpret them as extensional roll-over anticlines developed above listric normal faults (Meijninger, 2006). Sometimes the normal faults are tilted, and in some outcrops the normal faults deform the tilted strata (Fig. 5.5). In the Huércal-Overa basin, the roll-overs are usually related to listric or flat-and-ramp normal faults that deform the multi-layered sequence of conglomerates, sands, grey silts and gypsum, or the sediments placed immediately atop this unit (Fig. 5.5).

Fig. 5.6. Field examples of folds. (A) Example of WNW-ESE antiform that deform Serravallian-Lower Tortonian conglomerates. (B) Northern limb of the WNW-WSE La Parata antiform highly deformed by normal faulting. Note the variation of the dip between the Serravallian-lower Tortonian and the Upper Tortonian sediments. (C) E-W fault-propagation fold deforming the Quaternary sediments. (D) ENE-WSW to E-W folds succession and related open joints affecting Quaternary sediments. Position of the outcrops marked in figure 5.4.


NE
SW
Serravallian-
Lower Tortonian
A
0 2m.
N
S
20º
Upper Tortonian
40º
Serravallian-
Lower Tortonian
B
0 2m.
N
S
Quaternary
Upper Tortonian - Lowermost Messinian
C
0 10m. 30 m.
N
S
Quaternary
Open joints
D
0 10m. 30 m.

4. Paleostress results

In order to complete the previous paleostress studies in the Huércal-Overa basin (Mora, 1993; Augier, 2004; Meijninger and Vissers, 2006), stress inversion of the measured faults located in the western sector of the basin was performed following the Galindo-Zaldívar and Gozález-Lodeiro (1988) method. The stress ellipsoids (Fig. 5.7 and Table 1) determined at least point three main stress scenarios. (a) The best represented group (type 1) is characterized by a sub-vertical maximum stress axis, NNE-SSW to NE-SW sub-horizontal extension, and variable axial ratios that are in transition to prolate ellipsoids of radial extension. This group is related to normal faults that are WNW-ESE and NW-SE oriented (stations: 1, 2, 3, 4, 5, 8 phase I, 17, 18 and 19, 20, 24, 25, 26, 27 and 28). The maximun axis observed in some stations plunges, suggesting the rotation of the faults by late folds (Table 1, stations 22 and 23). (b) The second set (type 2) has a subvertical maximum stress axis, E-W to NW-SE extension and low axial ratios, also related to prolate ellipsoids of radial extension (stations: 6, 7, 8 phase II and 29). (c) The third group pertains to stress ellipsoids with a sub-horizontal maximum stress axis and low-to-medium axial ratios, likewise suggesting prolate to intermediate ellipsoids related to the development of compressive structures like ENE-WSW reverse faults and folds (9, 10 and 14 phase I).

Station	Data nº	Data used	σ_1	σ_2	σ_3	R
1,2 y 3	25	22	86º / N183ºE	4º / N336ºE	2º/ N66ºE	0
4	14	11	80º / N273ºE	10º / N104ºE	2º/ N14ºE	0.07
5	26	18	82º / N163ºE	6º / N297ºE	6º / N28ºE	0.06
6	11	7	70º / N23ºE	1º / N289ºE	20º / N198ºE	0.21
7	22	14	86 º/ N207ºE	4º / N360ºE	2º / N90ºE	0.21
		8	76º / N205ºE	13º/ N360º E	6º / N91ºE	0.93
8	21	17	86º / N174ºE	4º/ N354ºE	0º / N84ºE	0.07
		6	14º / N84ºE	61º / N327ºE	25º / N181ºE	0.25
9	17	10	18º / N161ºE	2º / N252ºE	72º / N348ºE	0.35
10	8	7	6º / N117ºE	12º / N26ºE	77º / N233ºE	0.56
14	24	17	8º / N313ºE	48º /N52ºE	41º / N216º	0.07
		6	20º / N184ºE	38º / N78ºE	45º / N296ºE	0.57
17, 18 y 19	11	7	82º / N253ºE	6º / N119ºE	6º / N28ºE	0.1
20	14	8	12º / N324ºE	76º / N179ºE	8º / N56ºE	0.33
		6	81º / N94ºE	8º / N301ºE	4º / N210ºE	0.23
22	11	9	56º / N14ºE	8º / N272ºE	33º / N177ºE	0.69
23	19	15	65º / N232ºE	24º / N66ºE	5º / N334ºE	0.08
24	10	9	68º / N42ºE	1º / N136ºE	22º / N227ºE	0.56
25 y 26	11	9	57º / N202ºE	7º / N101ºE	32º / N7ºE	0
27 y 28	13	10	80º / N45ºE	10º / N221ºE	1º / N311ºE	0.03
29	15	12	42º / N200ºE	48º / N20ºE	0º / N110ºE	0.3

Table 5.1. Paleostress determination from microfaults. Measurement sites in Figs. 5.4 and 5.7. The main axes orientations are defined by their azimuth and plunge. In addition, the axial ratio values ($R = (\sigma2- \sigma3)/ (\sigma1- \sigma3)$) are given for each station.

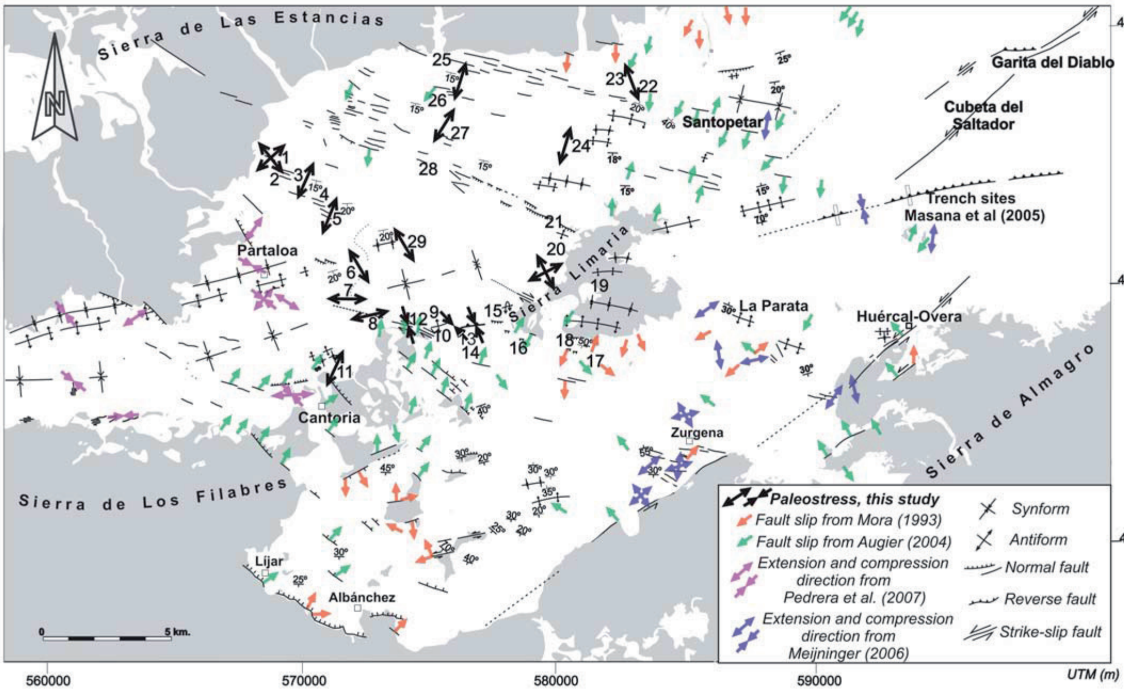


Fig. 5.7. Huércal-Overa tectonic map. Kinematic data compilation and paleostress results from our tectonic data and previous research (Mora, 1993; Augier, 2004; Meijninger, 2006; Pedrera et al., 2007).

5. Gravity survey

In contrast to the widespread geological studies developed in the area (Meijninger and Vissers, 2006, and references herein), there are practically no detailed geophysical studies in the sector. Vertical electric sounding data alone allowed García-Meléndez et al. (2003) to approximately reconstruct the three-dimensional shape of the Cubeta del Saltador, located in the northeastern Huércal-Overa basin (Fig. 5.4). For this reason, new gravity data were acquired and interpreted in light of the available geological information in order to determine the deep structure of the Huércal-Overa basin.

5.1. Gravity data acquisition and processing

Gravity data were acquired by means of a Scintrex cg-5 gravity-meter, with a maximum accuracy of 0.001 mGal. The relative positioning of the gravity stations was done with a GPS receiver, and the heights of the stations were determined with a barometric altimeter with an accuracy of 0.5 m. Gravity measurement stations are located along four profiles, N-S oriented (Fig. 5.4), orthogonal to the basin boundaries. These profiles constitute complete sections of the basin, from the Sierra Almagro-Sierra de Los Filabres up to Sierra de Las Estancias, crossing through the Sierra Limaria. The average distance between stations along the profiles was 250 m.

The gravity measures were established with reference to the Baza gravimetric base (Instituto Geográfico Nacional), which allows us to determine the absolute gravity values along all the profiles. After tidal and instrumental drift corrections, the Bouguer anomaly was obtained considering a reference density of 2.67 g/cm^3 and applying the topographic correction to a radius of 22 km, calculated from a digital elevation model with a grid of 90 m, following the Hammer method (Hammer, 1939, 1982). Topography influence outside of this 22 radius tends to smoothly affect the Bouguer anomaly, and was corrected with the regional anomaly subtraction during the residual anomaly determination. The residual gravity anomaly map (Fig. 5.8) was calculated from the Bouguer anomaly by profile interpolation, and subtracting the regional anomaly determined on the basis of 46 measurements over basement rocks in agreement with the regional anomaly maps (IGN, 1975). Finally, residual 2D gravity models along the measured profiles were developed with GRAVMAG v. 1.7 software (Pedley et al. 1993).

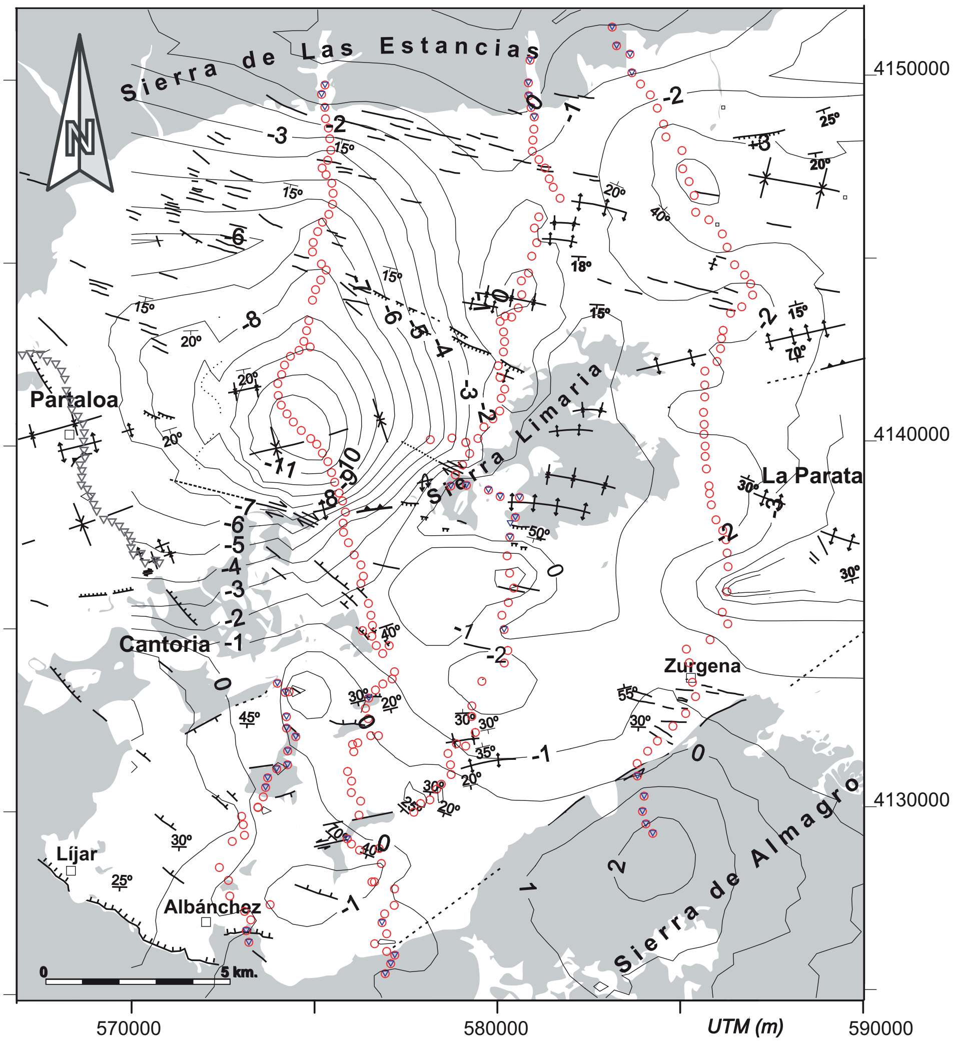


Fig. 5.8. Residual gravity anomalies and tectonic structures. Note the incidence on the anomaly of the different folds.

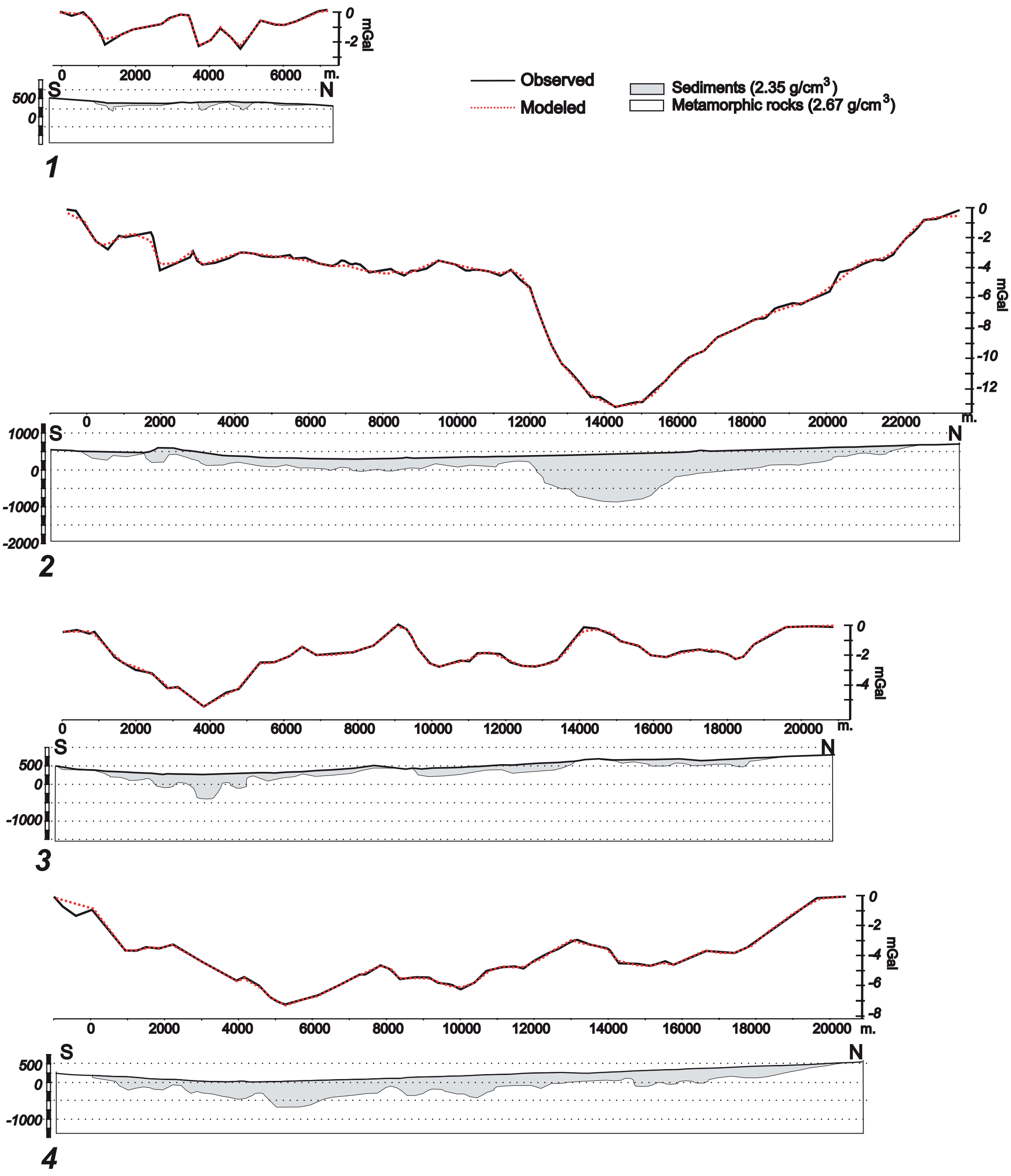


Fig. 5.9. 2D models constructed from the residual gravity anomalies that allow us to establish the sedimentary thickness of the basin. Location in Fig. 5.8.

5.2. Gravity modelling and deep structure

The new gravity data allow us to illustrate the sedimentary infill thickness (Figs. 5.8 and 5.9) with a complex pattern where the minimum values (-12 mGal) are reached in the central part of the western Huércal-Overa basin. Residual gravity anomalies were considered together with surface observations in order to determine the deep structure of the basin by 2D modelling (Fig. 5.9). For gravity modelling, an average density was considered for the whole sedimentary infill (Robinson and Çoruh 1988; Telford et al. 1990), also in agreement with gravity studies previously developed in other sedimentary basins of the Betic Cordillera, with similar lithostratigraphic sequences (Marín-Lechado et al., 2006; Pedrera et al., 2006). The obtained gravity anomalies for each profile are irregular in shape, with minimum values between -12 mGal and -2.5 mGal. The sedimentary infill distribution obtained from the models is also irregular, reaching up to 1000 meters of maximum thickness in profile 2.

The combination between the 2D gravity models and the field geological observations allow us to associate the sediment distribution with the tectonic structures and constrain the geological cross-sections (Fig. 5.10). The residual anomaly map and the 2D model of profile 2 show the maximum sedimentary thickness to coincide with the ENE-WSW Almanzora synform hinge. Other minor discontinuities could be related to normal faults. However, the faults bounding the southern sector of the basin have no associated important thickness of sediments, as might be initially expected.

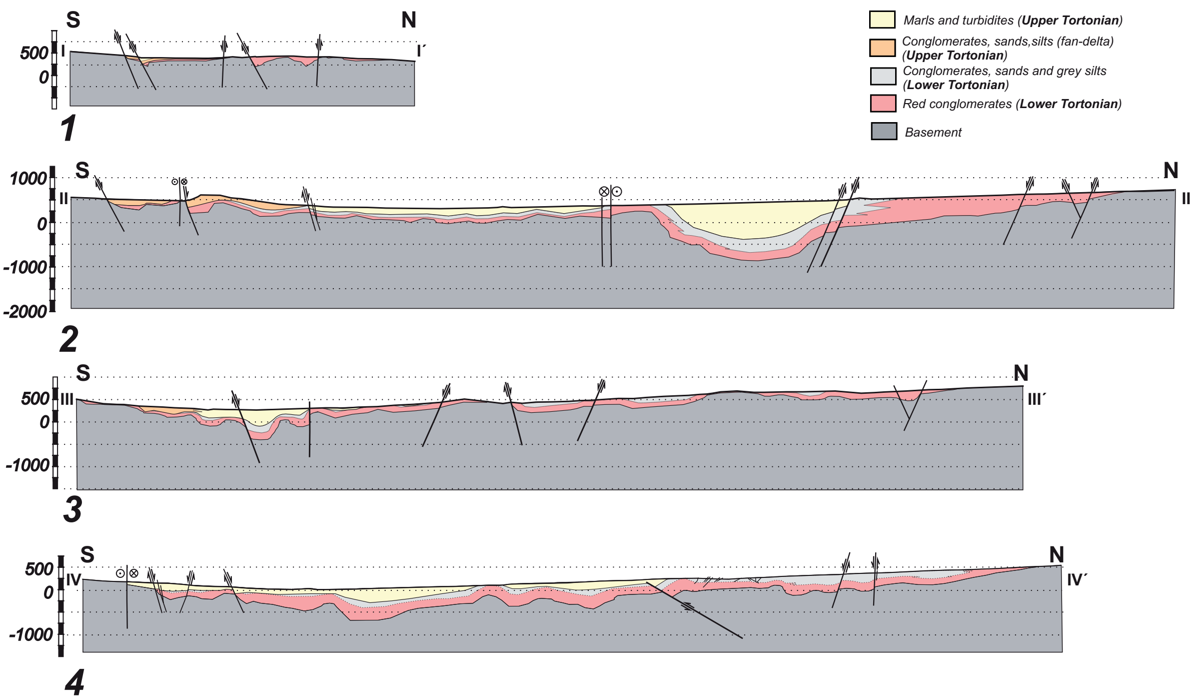


Fig. 5.10. Geological cross-sections from structural and gravity data. The position is marked in Figure 5.4.

6. Discussion

The termination of a major transcurrent fault, like the Alhama de Murcia fault, produces an interaction of compressional and extensional structures that are recorded by the sedimentary infill of the associated basins. In this setting, we first present discussion of the age of basin development and fault activity so as to highlight their relationships. Later, the main geometric features of the sedimentary basin are constrained to constitute new data for discussion of previously proposed regional models. This discussion is focused on the coexistence of extensional and compressional deformations responsible for the recent geological evolution of the region.

6.1. Onset and evolution of the Alhama de Murcia Fault deduced from fold growth

In contrast to reverse and normal faults, which usually have associated wedge deposits that record their progressive development, it would appear quite difficult to date the initial activity of a strike-slip fault. Notwithstanding, we could identify the first occurrence of strike-slip faulting by studying the associated folds, and normal and/or reverse faults.

Local contractional minor structures related to the AMF hold the key to establishing their complete history. The AMF presents a complete set of related folds and reverse faults in its central sector (Sierra de la Tercia fold, Booth-Rea et al., 2002, and Martínez Díaz, 2002), and located at its terminations (to the North in the Bajo Segura basin splay and related folds: Silva, 1994, Alfaro et al., 2002a and 2002b; and to the South in the Huércal-Overa basin: García-Meléndez et al., 2003). By the northern termination of the AMF, seismic profiles point the existence of progressive unconformities related to ENE-WSW folds (Alfaro et al., 2002b). In the central sector, Booth-Rea et al. (2002), from field observations, described Tortonian syn-folding sedimentation related to the Sierra de la Tercia uplift. In the southern termination of the AMF, our structural data point to the presence of a WNW-ESE minor fold band that was active during the Tortonian, as deduced from the progressive unconformities associated with the fold limbs. The activity of the AMF continued during the Plio-Pleistocene, as could be deduced from the syntectonic progressive unconformity located in the Garita del Diablo sector (García-Meléndez et al., 2003), and during the Holocene (Masana et al., 2005). Thus, field evidence supports the Tortonian to present-day activity of the AMF.

6.2. Basin development models

The most recent models proposed for the Huércal-Overa basin by Meijninger (2006) and Meijninger and Vissers (2006) conclude that it is an extensional basin developed on an extending underlying crust and lithosphere. In addition, these authors propose that some parts of the Alhama de Murcia fault zone initiated as normal faults, and were later reactivated as strike-slip-reverse faults. We agree with the development during the Tortonian of normal faults that mainly accommodate ENE-WSW to NE-SW extension. However, geological cross-sections constructed from field data and gravity models indicate that there is no great depocenter linked to the southern border faults (Fig. 5.10). Consequently, we disagree with the most recently proposed cross-sections that interpreted the basin as a half-graben filled by 3000 meters of sediments (Meijninger and Vissers, 2006).

The Huércal-Overa basin has to be explained in the framework of the AMF activity together with the large folds and normal faults since Tortonian. Sedimentary basins commonly developed in sector subjected to horizontal shortening (Cobbold et al., 1993), where folding significantly influences their location, dimension, and geometry (Nicol et al., 1994). In contractional tectonic settings other authors have described the coetaneous formation of compressive and extensional structures, as occurs in the Himalaya (Burchfiel and Royden, 1985; Shanker et al., 2002), and in several sectors of the Mediterranean region along the Alpine mountain range (Oldow et al., 1993; Decker and Peresson, 1996). The geometry of these sedimentary basins became irregular, and the relationship between their sedimentation and tectonic structures could be complex, featuring sectors dominated by compression or by extension, or sectors with overprinted deformation.

Our structural data evidence active compression since Tortonian, developing folds and faults. Progressive unconformities, associated with large and minor folds, evidence continuous deformation. In addition, the maximum sedimentary thickness is related to the Almanzora synform continuation eastward (Fig. 5.10), which represents one of the main compressive structures of the region. The E-W to ENE-WSW synform development favored a transgression during the Late Tortonian (Pedrera et al., 2007). Despite the presence of numerous normal faults, the existence of a succession of antiforms and synforms along fold bands also suggests a compressive origin. In a purely extensional framework, only single and isolated roll-overs occur.

At any rate, WNW-ESE to NW-SE oriented normal faults were active since Tortonian, also indicating the presence of extensional stress ellipsoids —type 1— in the whole basin. Moreover, normal faults that developed in extensional setting with type 2 ellipsoids, are parallel to the ENE-WSW folds, probably corresponding to external arc extensions, and deform the Tortonian marls close to the Almanzora synform hinge.

In addition, minor folds and reverse faults that are ENE-WSW oriented began to grow probably in the Late Tortonian, favouring basin emersion and erosion. In the western sector of the basin, these structures accommodate NW-SE shortening, related to stress fields represented by type 3 ellipsoids.

6.3. Compressive and extensional tectonic structures in a strike-slip fault termination

Associations of compressive and extensional minor structures linked to transcurrence have been widely recognized in the field (Freund, 1974; Woodcock and Fisher, 1986), and their mechanisms of development have been tested through analog models (Tchalenko 1970, Hempton and Neher, 1986; Naylor et al., 1986). The classical minor structural associations on the transcurrent fault termination are sets of splay faults, either normal or reverse. The new structural data reported in this paper promote the discussion of compressive and extensional tectonic structural interaction in a strike-slip fault termination.

In the surroundings of the Alhama the Murcia sinistral strike-slip Fault, the presence of normal faults and compressive tectonic structures has most often been explained by successive stress field changes since the Serravallian (Bousquet and Phillip, 1976a, 1976b; Armijo, 1977; Montenat et al., 1987, 1990; Ott d'Estevou and Montenat, 1985 and 1999; Augier, 2004; Meijninger, 2006; Meijninger and Vissers, 2006). Only recently have proposed models attempted to compile the array of tectonic structures under a regional stable stress field (Martínez-Díaz et al., 2002; Pedrera et al., 2007).

In the framework of the NW-SE Eurasian-African plate convergence (De Mets, 1994), we propose a coeval development since the Tortonian of compressive and extensional structures under the same regional stress field. The folds are related to regional compression (ENE-WSW oriented folds) as well as to the strike-slip fault termination (both WNW-ESE and ENE-WSW oriented folds). While the ENE-WSW folds deform up to the Quaternary sediments, the WNW-ESE folds only deform Tortonian sediments. We propose that AMF activity rotates by shear strain at its ends, the initially ENE-WSW folds thereby becoming WNW-ESE oriented and inactive (Fig. 5.11A and B). These changes in fold strike are also supported by palaeomagnetic data (Mora, 2003; Mattei et al., 2006). Afterwards, the activity of the transcurrent fault was accommodated by new ENE-WSW oriented folds and reverse faults forming a common splay geometry that interacts with all the previous structures (Fig. 5.11 D).

We propose two possible mechanisms to support the development of normal faults with the same orientations as folds (Fig. 5.11 C). (a) The first possibility is a decrease in the horizontal compressive stress produced by relaxation after major transcurrent activity pulses of the AMF. In regions subjected to crustal shortening, transcurrent faults generally show highly variable spatial and temporal slip rates (Benett et al., 2004; Chevalier et al., 2005). When the horizontal stress decreased, normal faults started to grow because the vertical stress axis reached a maximum, induced by gravity. A similar mechanism has been evoked to explain the north-south extension within the convergent Himalayan region (Burchfiel and Royden, 1985). (b) The second hypothesis that may explain the normal fault development is related to the progressive crustal thickening process, which is linked to the plate convergence since Tortonian times. The crustal thickening would have resulted in a potential-energy increase and instability in the upper crust, producing normal faulting. Both mechanisms could explain the presence of the sub-vertical maximum stress axis and sub-horizontal extension, NNE-SSW to NE-SW and E-W to NW-SE, in transition to radial extension.

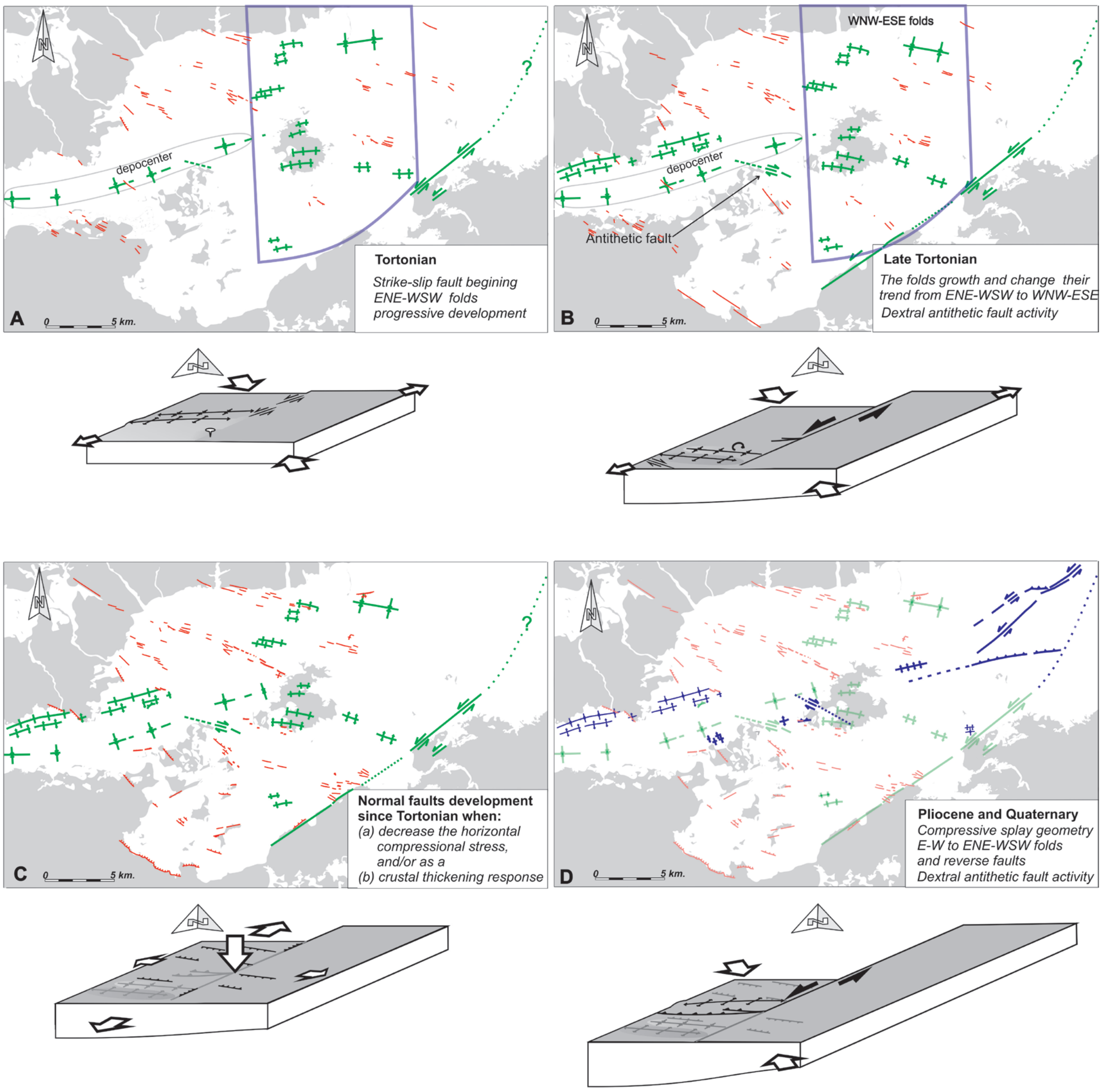


Fig. 5.11. Evolution of the Huércal-Overa Basin and structure interactions in the termination of the Alhama de Murcia Fault.

7. Conclusions

Compressive and extensional structures deformed the Late Miocene-Quaternary Huércal-Overa basin, located in the southern termination of the Alhama de Murcia sinistral fault (AMF). Progressive unconformities associated with the fold limbs reveal a Tortonian onset of its activity. Analysis of fold and fault development, gravity data, and the paleostress inversion from minor structures altogether reveal the coeval interaction of three main stress fields (ellipsoids 1 to 3) in a setting of regional NW-SE plate convergence and crustal thickening since Tortonian.

The compressive structures comprise the major NE-SW to NNE-SSW Alhama de Murcia sinistral fault, kilometric folds and small scale ENE-WSW reverse faults and folds that are developed by a NW-SE oriented sub-horizontal maximum stress axis (ellipsoid 3). In this setting, the eastward extension of the large Almanzora synform constitutes the main structure determining the Huércal-Overa depocenter. Minor folds progressively grew and rotated from ENE-WSW up to WNW-ESE, becoming inactive with the increase of shear strain close to the transcurrent fault termination.

Meanwhile, a sub-vertical maximum stress axis and sub-horizontal extension NNE-SSW to NE-SW (ellipsoids 1) and E-W to NW-SE oriented, in transition to radial extension (ellipsoids 2) is responsible for the widespread normal fault development. This stress setting could be explained as a consequence of potential-energy increase related to crustal thickening, or of the horizontal stress decrease in between activity pulses of the Alhama de Murcia fault. Both mechanisms serve to explain a temporary major vertical stress axis induced by gravity.

The field example tackled in this contribution illustrates the coalescence of compressional and extensional structures interacting in the termination of a large transcurrent fault. The proposed genetic models try to reconcile the great amount of apparently incompatible previous data with new geological and geophysical observations.

Acknowledgements

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6. Recent large fold nucleation in the upper crust: insight from gravity, magnetic, magnetotelluric and seismicity data (Sierra de Los Filabres- Sierra de Las Estancias, Internal Zones, Betic Cordillera)

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Rheological heterogeneities in the upper-crust have a close relationship with the fold position where rigid bodies could constitute initial perturbations that allow the nucleation of folds. Consequently, establish the position and geometry of anomalous rocks located in the upper-crust by geophysical studies help to understand the folded structure observed on surface. New geological observations in the field, along with gravity, magnetic, magnetotelluric and seismicity data, reveal the subsurface structure in the Sierra de Los Filabres- Sierra de Las Estancias folded region part of the Alpine belt in southern Spain. The geometry of the upper crust is determined by geological field data, 2D gravity models, 2D magnetic models and 2D MT resistivity model, while seismicity evidences the location of the deep active structures. These results allow us to propose that a basic rock body at 4 to 9 km depth has determined the nucleation and development of the Sierra de Los Filabres kilometric antiform. N-vergent large late folds are subjected to a variable present-day stress field. Earthquake focal mechanisms suggest the presence in depth of a regional NW-SE compressive stress field. However, most of the seismogenetic structures do not extend up to the surface, where NW-SE and WNW-ESE outcropping active normal faults are observed, thus indicating a NE-SW extension in the upper crust simultaneous to orthogonal NW-SE compression related to reverse faults and minor folds developed in the Eastern Almanzora Corridor and in the nearby Huércal-Overa basin. The recent and active tectonic studies of cordilleras hinterland subjected to late folding greatly benefits from the integration of surface observations together with geophysical data.

Key words
Folding, basic rocks, Neogene basins, neotectonic, Spain.

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1. Introduction

Pre-existing crustal heterogeneities, such as bodies of different rheological properties, represent zones that play an important role during the nucleation and development of folds (Neurath and Smith 1982; Mazzoli and Carnemolla, 1993; Lan and Hudleston, 1996). Analogue models studies have determined the effects of folding of the rheology of different rocks located on detachment levels (Nilforoushan and Koyi, 2007 and references herein). In multilayer successions, the rheology of each layer determines the variability in shear deformation, mainly concentrated around strong undeformed bodies (Poirier, 1980). Creep tests showed that the deformation in gabbros has a slower rate than in granitic rocks (Itô, 1979; Itô and Sasamija 1980). In similar heat flow conditions, comparative studies indicate that crust with predominantly granitic and metapelitic composition, is more deformable than basic igneous rocks (Ranalli and Murphy, 1987; Ranalli, 1997). Therefore, different behavior of rocks constitutes initial perturbation that have a close relationship with the fold location around the rigid bodies (Marques and Cobbod, 1994; Williams and Jiang, 2000). Consequently, establish the position, geometry of anomalous rocks located in the upper-crust by geophysical studies help to understand the folded structure observed on surface. Crustal heterogeneities also contribute to determine the location of other recent and active structures, like low- and high- angle faults related to the seismicity.

The Internal Zones of the Betic Cordillera constitute an example of a hinterland region with large faults that constitute crustal anisotropies. These faults either crop out as low-angle normal faults (Galindo-Zaldívar et al., 1989; Balanyá et al., 1997; Galindo-Zaldívar et al., 1997) or are highlighted by geophysical data (eg. Banda and Ansorge, 1980; García-Dueñas et al., 1994; Morales et al., 1997; Galindo-Zaldívar et al., 1997; Martínez-Martínez et al., 1997b, Jabaloy-Sánchez, 2007). Although most of the outcropping low-angle normal faults are buried by Neogene and Quaternary sediments, some are reactivated as detachments, allowing the growth of the large folds (eg. Galindo-Zaldívar et al., 2003, Marín-Lechado et al., 2006). These late large folds determine the relief of the Cordillera since Serravallian-Early Tortonian (Weijermars et al., 1985; Braga et al., 2003; Galindo-Zaldívar et al., 2003; Martínez-Martínez et al., 2004). Detachments may also evidence low-to-moderate earthquake activity (Galindo-Zaldívar et al., 1993; Serrano et al., 1998) that is a consequence of the present-day NW–SE convergence between Africa and Eurasia at a rate of 5 mm/yr (DeMets et al., 1994; Stich et al., 2006). In addition, local rotations from this regional convergence direction have recently been established (Fernández-Ibáñez, et al. 2007). The seismicity in the eastern Betic Cordillera is clearly concentrated in its Internal Zones (I.G.N., 1991; Buforn et al., 1995; Stich et al., 2003 and 2006), but only a few number of earthquakes can be correlated with specific faults (Buforn et al., 1995; Sanz de Galdeano et al., 1995; Marín-Lechado et al., 2005; Martínez-Martínez et al., 2006). Meanwhile, many faults that clearly deform Quaternary sediments have no associated seismicity (eg. Galindo-Zaldívar et al., 2003).

The aim of this research is to establish the relationship between late large fold growth and upper crustal structure in a cordillera hinterland. In order to propose a integrated tectonic model, we combine new geological and geophysical data (gravity, magnetic, seismological and magnetotelluric data) from a key sector located in the Internal Zones of the Betic Cordillera. In addition, this contribution aims to determine the location and kinematics of active tectonic structures, the origin and distribution of the associated seismicity, and the stress field setting responsible for the deformation.

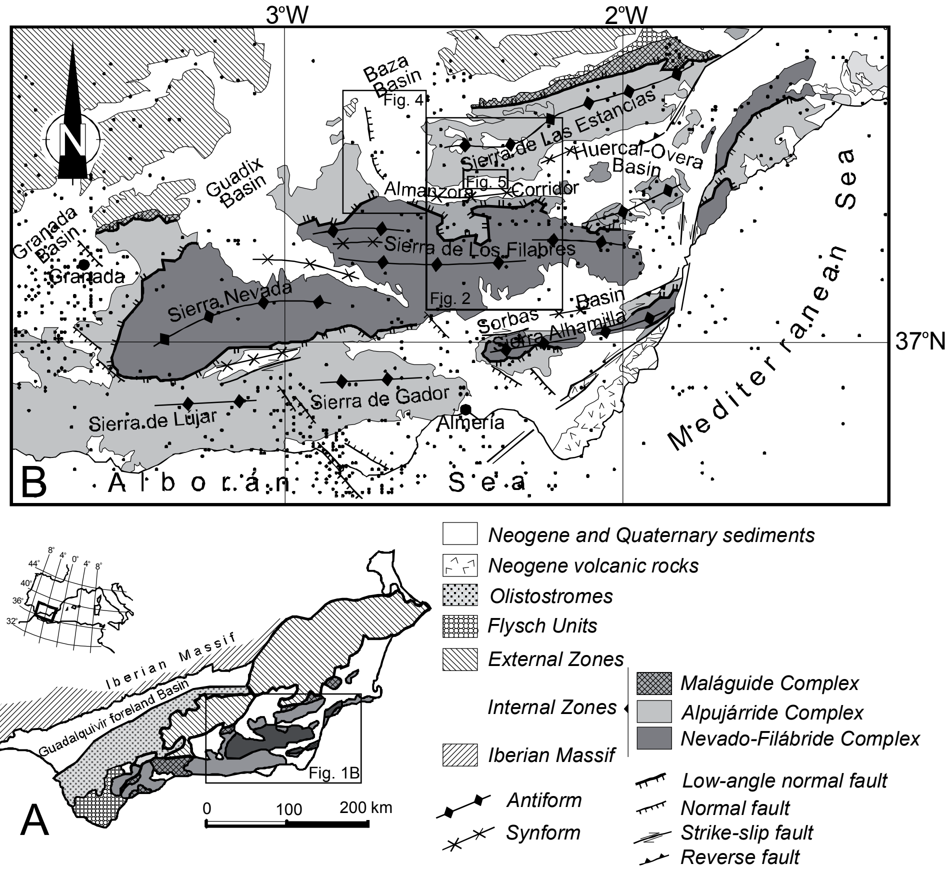

Fig. 6.1. Geological map of the Betic Cordillera (A) and enlarged detail of the central and eastern sector (B) showing the different domains and the main structures, folds and faults, developed since Tortonian times. Seismicity with magnitude over 3 occurred between 1926 and 2007 has been plotted as dots (I.G.N. catalogue). Note that the synforms coincides with the Neogene-Quaternary basin position. The location of Figures 2, 4 and 5 is marked (chapter 6).

2. Tectonic setting

The Betic Cordillera is the westernmost mountain belt of the European Alpine Chain, situated along the western part of the Europe-Africa convergent plate boundary, which has associated active deformation and distributed seismicity. Both plates involve continental crust in this part of the contact. The Alborán Sea represents a sector of thinned continental crust, located in an intermediate position (Comas et al., 1992). The Betic Cordillera has been traditionally divided into three main Domains (Egeler, 1963; Egeler and Simon, 1969): the External Zones, the Flysch Units and the Internal Zones. The External Zones are formed by sediments that were deposited in the southern paleomargin of the Iberian massif since the Mesozoic. The Flysch Units are made up of allochthonous sediments from the Cretaceous–Early Miocene, deposited along an elongated trough between the Internal and External Zones. Three metamorphic complexes, separated by major low-angle normal faults, constitute the Internal Zones of the Betic Cordillera. These metamorphic complexes are, from bottom to top: the Nevado-Filábride, the Alpujárride and the Maláguide (Blumenthal, 1927; Van Bemmelen, 1927; Egeler, 1963) (Fig. 6.1). Both the Nevado-Filábride and the Alpujárride Complexes include several nappes with Paleozoic to Mesozoic lithostratigraphic sequences showing an extensive ductile deformation and metamorphism, while the Maláguide Complex is formed by Paleozoic to Middle Miocene rocks that were deformed but not metamorphosed during the Alpine orogeny.

The relative motion of the Internal Zones with respect to Iberia during Early-Middle Miocene produced the development of a NE-SW to ENE-WSW oriented fold-and-thrust belt that involved the External Zones (Crespo-Blanc and Campos, 2001) and the Flysch Trough domain (Balanya and García-Dueñas, 1987; Luján et al., 2003; Platt et al., 2003). Simultaneously, the Internal Zones were subjected to an intense process of extension and were accommodated with the progress of low-angle-normal faults, like the top-to-the-W Alpujárride/Nevado-Filabride contact (e.g. Galindo-Zaldívar et al., 1989; Platt and Vissers, 1989; Martínez-Martínez and Azañón, 1997). To the North, the Guadalquivir foreland basin was developed during the convergence between the front of the External Zones —where is a large olistostromic unit is located— and the Iberian Massif boundary, which represents the foreland (Fig. 6.1A).

Since the Late Miocene, a N-S to NW-SE shortening between Europe and Africa (Dewey et al., 1989; DeMets et al., 1994) started to develop the main features of the present-day relief of the Cordillera, constituted by mountain ranges and depressed areas that coincide with large E-W to ENE-WSW antiforms and synforms (e.g. Weijermars et al., 1985; Braga et al., 2003; Galindo-Zaldívar et al., 2003; Martínez-Martínez et al., 2004). These large folds are sometimes modified by normal faults in the Central Betics (e.g. Ruano et al., 2004) and by strike-slip faults mainly located in the Eastern Cordillera (e.g. Booth-Rea et al., 2003a). The interaction between folds and faults is responsible for the Neogene sedimentary basin genesis and its later deformation (e.g. Booth-Rea et al., 2004; Marín-Lechado et al., 2003, 2005 and 2006, Pedrera et al. 2006b). In the study area, some research focuses on the development of the basins and the ranges, either through stratigraphic records (e.g. Braga and Martín, 1988; Guerra-Merchán, 1992 and Guerra-Merchán and Serrano, 1993; Haughton, 2001), the Neogene sedimentary rock deformation (eg. Stapel et al., 1996; Jonk and Bierman, 2001; Pedrera et al., 2006a, Meijninger, 2006) or the metamorphic basement deformation (e.g. Augier et al., 2005b).

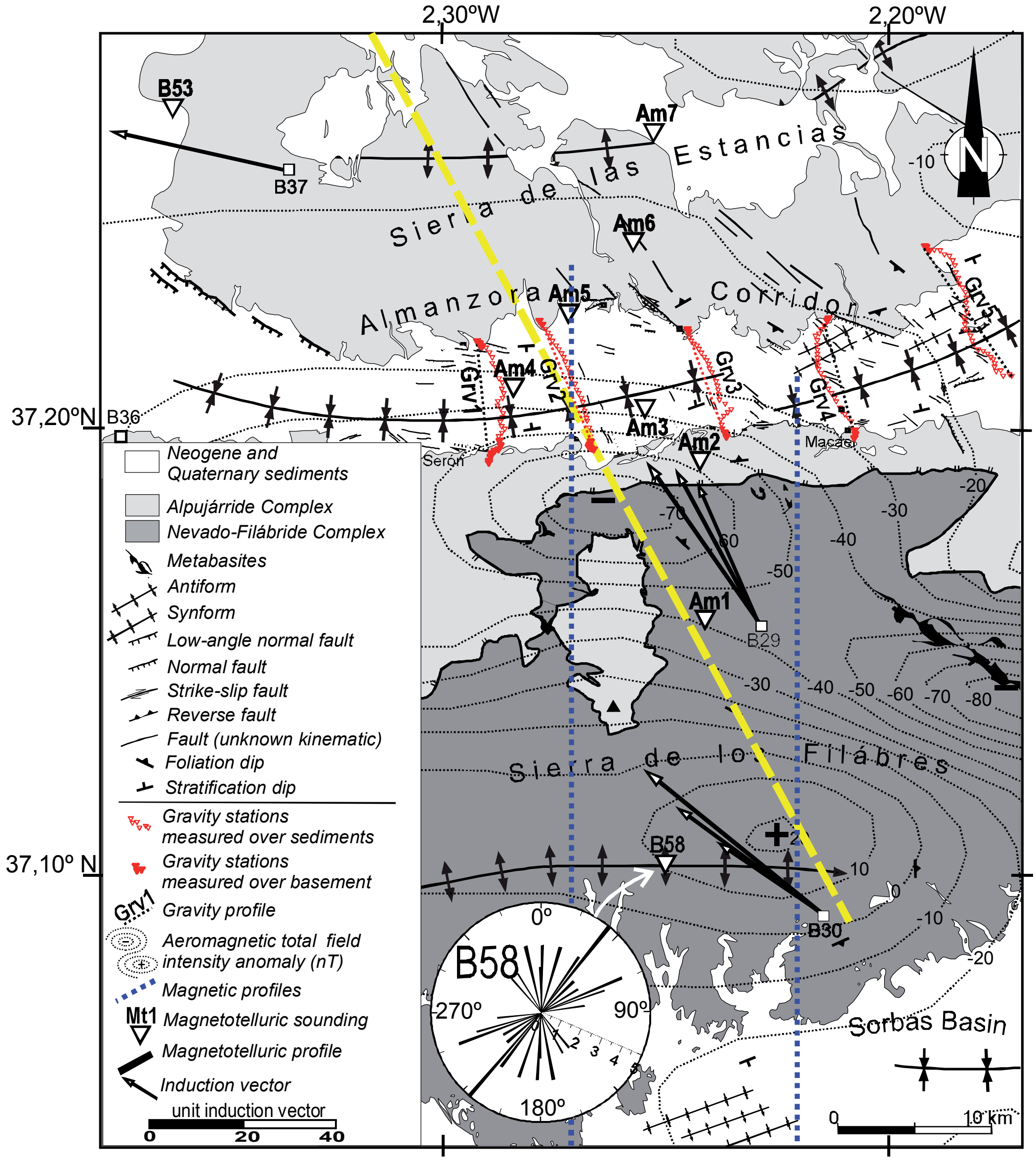

Fig. 6.2. Simplified geological map of the studied area showing overprinted the magnetic total field intensity anomaly and the location of the geophysical stations (gravity and MT). Induction arrows from Pous et al. (1999). Rose diagram showing the strike directions obtained from the Groom and Bailey decomposition in site B58 (Groom and Bailey, 1989).

3. Recent and active structures

3.1. Late large folds

The studied area is located in the Internal Zones of the Eastern Betic Cordillera and comprises a succession of kilometric amplitude folds with an orientation ranging from E-W to ENE-WSW (Figs. 6.1 and 6.2): the Sorbas basin synform, Sierra de Los Filabres antiform, Almanzora Corridor synform and Sierra de Las Estancias antiform.

The antiforms coincide with the ranges where the metamorphic rocks crop out, while the synforms correspond with the sedimentary basins developed since the Late Miocene. Synsedimentary unconformities located in both boundaries of the Almanzora basin point to a Serravallian-Early Tortonian initial stage of fold development (Pedrera et al.,

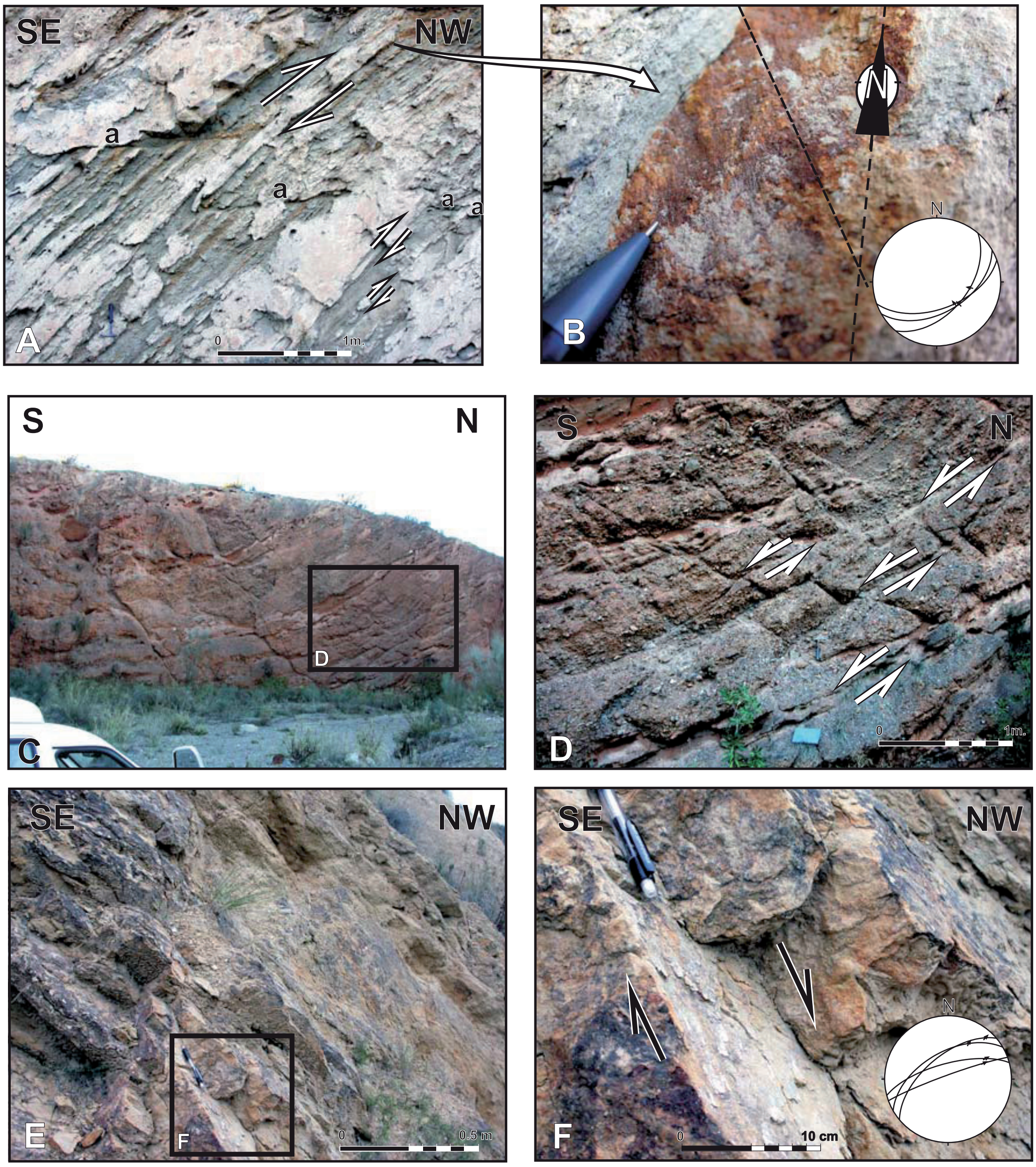

Fig. 6.3. Field examples of flexural slip folding displacing previous normal faults. (A, B) Reverse faults in the inter-bed surfaces of grey silts that displace a sub-horizontal fracture (a) located in the north boundary of the Almanzora Synform. Lower hemisphere stereographic projection of faults. (C, D) The bedding surfaces of red conglomerates are reactivated as normal faults deforming previous tilted conjugated normal faults. (E, F) Calcite fibres on the calcarenitic layers surfaces related to the folding, located in outcrops of the south Almanzora Corridor boundary. Lower hemisphere stereographic projection.

2007). Moreover, these sediments, constituting the infill of the basin, are deformed by ENE-WSW minor folds since Tortonian up to Quaternary (Figs. 6.1 and 6.2).

Bedding parallel faults with associated N130º-160ºE oriented striations are recognized in the Late Miocene silt, sandstones and conglomerates sedimentary succession of the Almanzora synform (Fig. 6.3), indicating that flexural-slip is an important folding mechanism there. In addition, NW-SE to E-W normal, E-W dextral and E-W to ENE-WSW reverse faults deformed the sector simultaneous to folding, though only some of these faults have present-day activity (Pedrera et al., 2007).

3.2. Active faults with surface expression

Previous research of the Huércal-Overa basin, located outside and eastwards of the study area, reported the presence of active ENE-WSW oriented reverse and NE-SW to N-S sinistral faults (Briend, 1981; García-Meléndez et al., 2003; Masana et al., 2005) developed in a tectonic setting of NW-SE compression. However, most of the active faults in the central and western Almanzora Corridor and in the Baza basin are normal. Geological maps were made of selected sites located along the Baza basin and Almanzora Corridor, close to the main normal faults that deform the Quaternary sediments. At each of these sites, the exact locations of surface faulting (geometry and kinematics) were recorded in detail.

The main active structure is the Baza normal Fault (Fig. 6.4) which extends more than 30 km along the westernmost part of the Almanzora Corridor and the Baza basin, showing a N-S to NW-SE variable strike, and dipping to the NE (Alfaro et al. 2007). According to a quantitative analysis mountain front relief, the Baza Fault may be considered as one of the most active faults of the central part of the Betic Cordillera (García-Tortosa et al. 2008).

The fault deforms up to the Quaternary glacis, dated as Late Pleistocene from archaeological-paleontological evidences (~100 ka, Botella et al., 1986; Martín-Penela, 1988), and a calcrete is located over the most recent sediments of the Baza basin (42.6 ± 5.6 ka; Azañón et al., 2006). While a 500 m wide fault zone characterizes the central and northern part of the Baza Fault, the southern segmented zone shows splay geometry deforming a 8000 m wide area close to Caniles (Fig. 6.4). The average topographic displacement in dip direction along the fault surface is 150 m, but the dip angle varies between the central (60ºNE- 90º) and the southern fault branches (45º- 70ºNE) (Fig. 6.4).

It is difficult to relate the instrumental seismicity located in the Baza basin to the Baza Fault segments (Fig. 6.1). However, the Baza Fault probably caused the 1531 Baza earthquake, the strongest historical earthquake recognized in the study area (Alfaro et al., 2007), assigned a VIII-IX maximum intensity (Martínez-Solares and Mezcua, 2003). The main damage was located in the towns of Baza and Benamaurel (Fig. 6.4A).

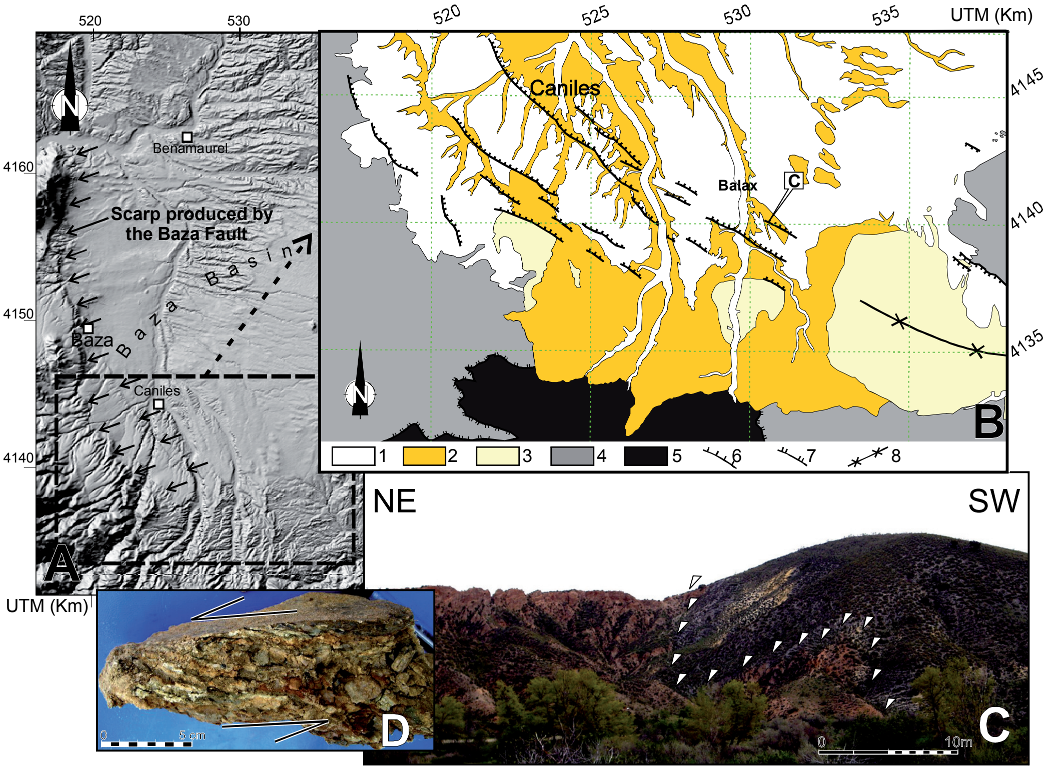

Fig. 6.4. The Baza Fault at the western end of the Almanzora Corridor. (A) Digital elevation model (10 m grid resolution) showing the morphological scarp produced by the activity of the Baza Fault. (B) Geological map of the southern segment of the Baza Fault where it developed a splay geometry (1, Quaternary sediments; 2, Pliocene sediments; 3, Tortonian sediments; 4, Alpujárride rocks; 5, Nevado-filábride rocks; 6, normal fault; 7, low-angle normal fault; 8, synform). (C) View of the fault plane deforming Pleistocene sediments and (D) detail of the fault gauge. The location of the photography is marked in the geological map.

In addition, several faults and joints deform Quaternary sediments in the Almanzora Corridor, well illustrated in the northern boundary. The normal Lúcar Fault (Fig. 6.5B) is composed by a set of N100ºE oriented 40º-75º south-dipping segments deforming all the Upper Tortonian sediments and being covered by Quaternary deposits almost along all the trace. Only one of these segments deforms Quaternary sediments along 300 m and generates an average 0.8 m topographic scarp (Pedrera et al., 2007). Furthermore, the NW-SE Somontín fault, more than 2000 m long, shows Quaternary left lateral reactivation along a 200 m segment (Fig. 6.5C and 6.5D). In addition other studies point out that at the eastern end of the Almanzora Corridor and in the nearby Huércal-Overa basin, small ENE-WSW reverse faults deform the alluvial Quaternary sediments (Briend, 1981; García-Meléndez et al., 2003; Masana et al., 2005). Although the faulting began to be active during the Late Miocene some segments show evidence of Quaternary reactivation. These active brittle structures point to an active NE-SW extension and NW-SE compression (Pedrera et al., 2007).

In order to analyze the interactions between large folds growth and crustal structure, as well as their relationship with faults activity, sediment distribution and seismicity location, we combine different geophysical methods: gravimetric data, magnetic models, a 2D magnetotelluric image, earthquake distribution and focal mechanism analysis.

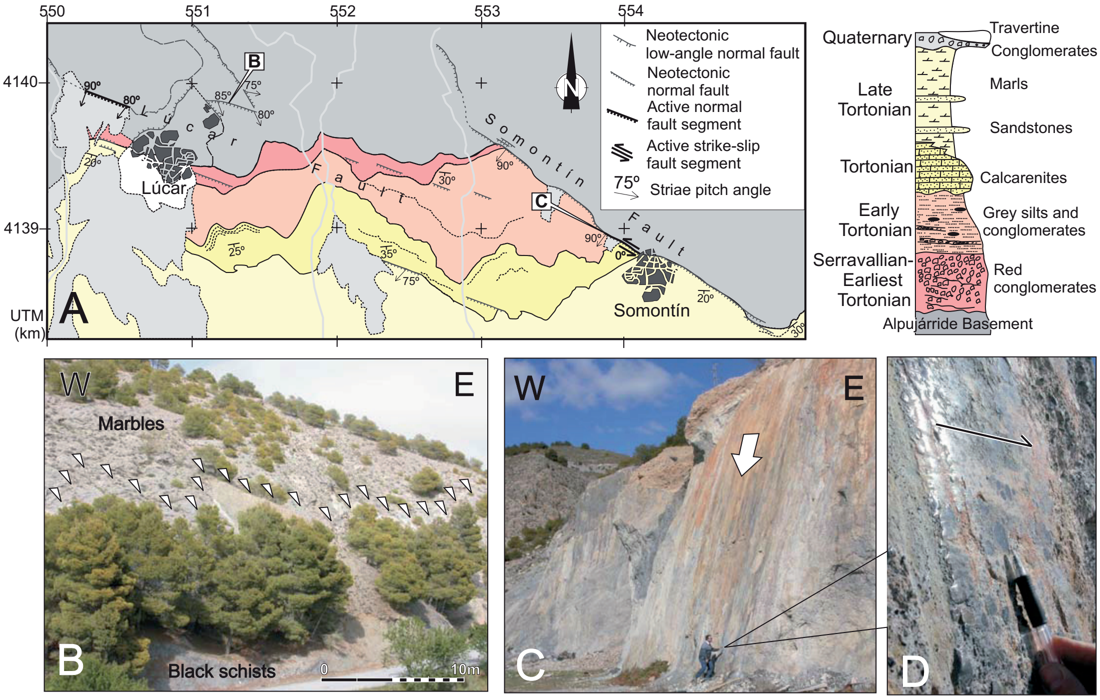

Fig. 6.5. (A) Detailed geological map showing the neotectonic and active faults segments in the Lúcar-Somontín area. (B) View of the Lúcar fault plane deforming Alpujárride rocks. (C) Photograph of the Somontín fault where the normal kinematics is overprinted by modern sinistral movements. (D) Detail of the overprinted sinistral striation. The locations of the photograph are marked in the geological map.

4. Gravity data

For determining the Almanzora sedimentary infill geometry, new gravity data were acquired in the Almanzora Corridor. We used a Worden Master gravimeter with 0.1 mGal of accuracy. The position at each station was given by a GPS Garmin eTrex with 5 m accuracy in the horizontal coordinates, and altitude was obtained from a barometric altimeter with an accuracy of 0.5 m. In order to correct the gravimeter and barometric drifts, the measurement cycles were done in a time period less than 3 hours. The gravity survey consists of 158 gravity stations with a mean separation of 250 m. Relative measurements were calibrated with the Baza reference station from the Instituto Geográfico Nacional. Bouguer Anomaly was calculated in each station, including topographic correction from digital elevation models in a radius of up to 22 km.

These measurements were organized along 5 profiles with a N-S orientation perpendicular to the basin boundaries, extending into the basement rocks in both basin margins. The interpolation between these profiles provides the Bouguer, regional and residual anomalies maps. The Bouguer anomaly clearly decreases westwards along the Almanzora Corridor, regardless of whether there are sediments or basement rocks (Fig. 6.6). To isolate the effect due to the sedimentary infill, we determined in a first stage the regional anomaly smoothing the anomaly data recorded on basement rocks and tacking into account the 1:1.000.000 Bouguer Anomaly Map (IGN, 1976).

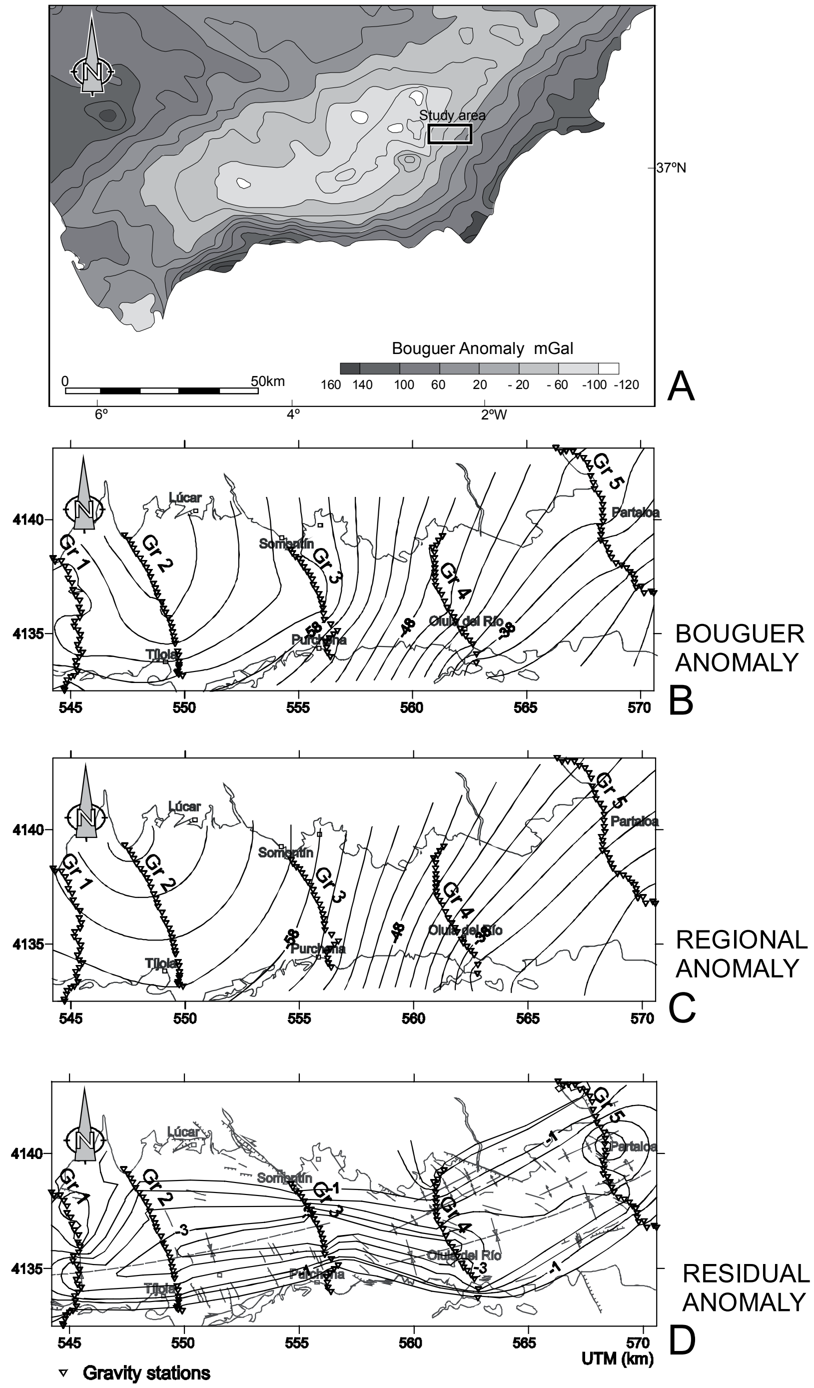

Fig. 6.6. (A) Part of the Bouguer anomaly map of Spain at a scale 1:1000000, the study area is marked (B) Bouguer, (C) regional and (D) residual gravity anomalies. Note that the regional anomaly decreases to the W. The residual anomaly map shows the increasing thickness of the sedimentary infill toward the Almanzora Corridor axis.

From the regional anomaly can be deduced that the continental crust thickness increases westwards, reaching a maximum in the Baza region (Fig. 6.6A). The residual anomaly map shows an increase of the sedimentary infill thickness toward the Almanzora Corridor axis. The minimum of the residual anomaly extends laterally, with an E-W orientation in the western sector and ENE-WSW in the eastern sector of the basin, comprising values between -5.8 mGal and -3 mGal (Fig. 6.6C).

Residual gravity anomalies were modeled using Gravmag V 1.7 software (Pedley et al., 1993) along 2D models to establish the deep structure of the basin (Figs. 6.7 and 6.8). During the modelling we took into account the main tectonic structures that deform the sedimentary rocks of the Almanzora Corridor. The average density assigned was 2.35 g/cm^3 to the sedimentary cover, and 2.67 g/cm^3 to the metamorphic basement rocks, taking into account the mean density rocks (Robinson and Çoruh, 1988; Telford et al., 1990) as in other basins of the Internal Zone of the Cordillera with similar sedimentary infill and basement rocks (Ruiz-Constán et al., 2005; Marín-Lechado et al., 2006; Pedrera et al., 2006). Previous geological analysis indicates that the main structure is the Almanzora kilometric-scale synform (Fig. 6.2). Therefore, in both basin boundaries, the relation between the sediments and basement rocks is an unconformity, locally deformed by NW-SE and E-W normal faults in the north basin boundary, and by dextral strike-slip faults in the south basin border (Pedrera et al., 2007). The gravity data illustrate the sedimentary infill thickness of the basin that has a clear correlation with the outcropping tectonic structures. The minimum of the residual anomaly, in map and profiles, coincides with the synform hinge position; lateral variation can be interpreted as interactions between the folds and the outcropping NW-SE normal faults. Other residual anomalies may correspond to highs and valleys related with a paleorelief, or faults covered by the younger sediments (Fig. 6.7). Profiles 1 and 2 show the maximum sedimentary thickness (reaching up to 600 m), displaced toward the south basin boundary, suggesting in this sector a northward vergence for the synform. The shape of the fold is disrupted by faults in the profiles 3, 4 and 5. Profile 3 shows a graben geometry, bounded by conjugated NW-SE normal faults that determine a central depocenter. Profiles 4 and 5 are located in the eastern sector of the Almanzora basin, where the sediments are deformed by compressive structures. Therefore, in the central and north sides of these two profiles, deformation of the basement may be related to the outcropping set of ENE-WSW minor folds and a reverse fault (Fig. 6.8).

The gravimetric models are in agreement with the previous geological data. The structure of the Almanzora Corridor sedimentary infill is determined by a north-vergent synform that shows an E-W direction in the western sector, shifting to ENE-WSW in the eastern area. In addition, there are several faults with variable orientation and slip that deform this kilometric-scale fold (Fig. 6.8). Although gravity data provide new details on the basin sedimentary infill thickness, however, other geophysical methods improve the knowledge on the basement structure.

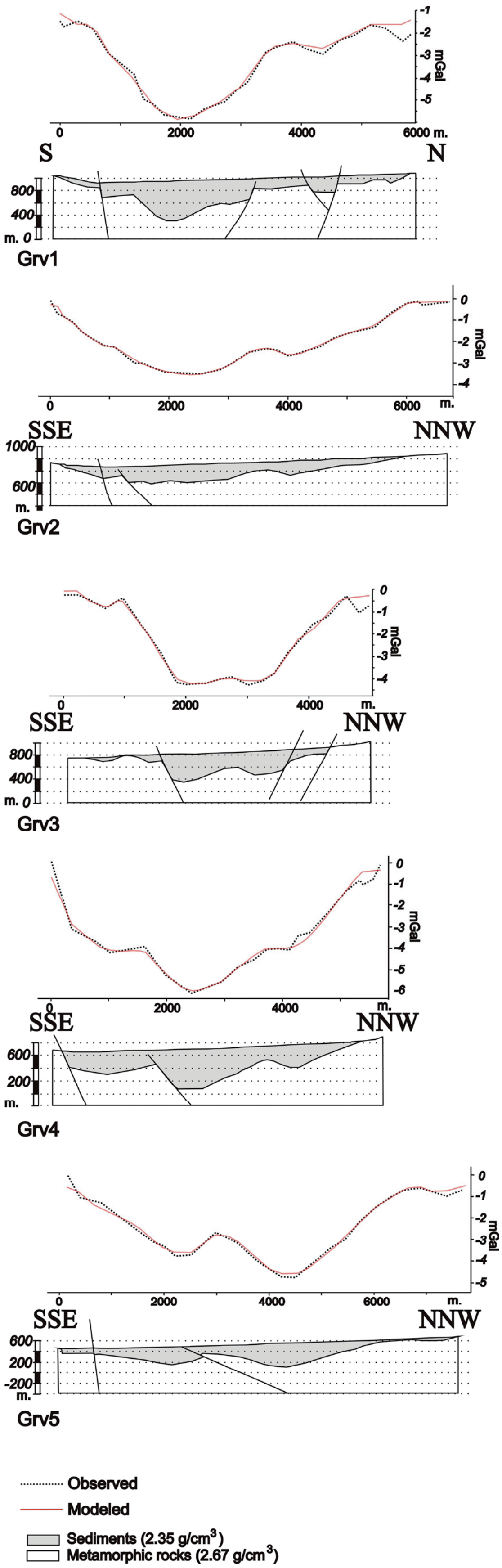

Fig. 6.7. 2D models constructed from the residual gravity anomalies that allow establishing the deep structure of the basin, taking into account the main tectonic structures that crop out in the area. Location in figs. 2 and 6 (Chapter 6).

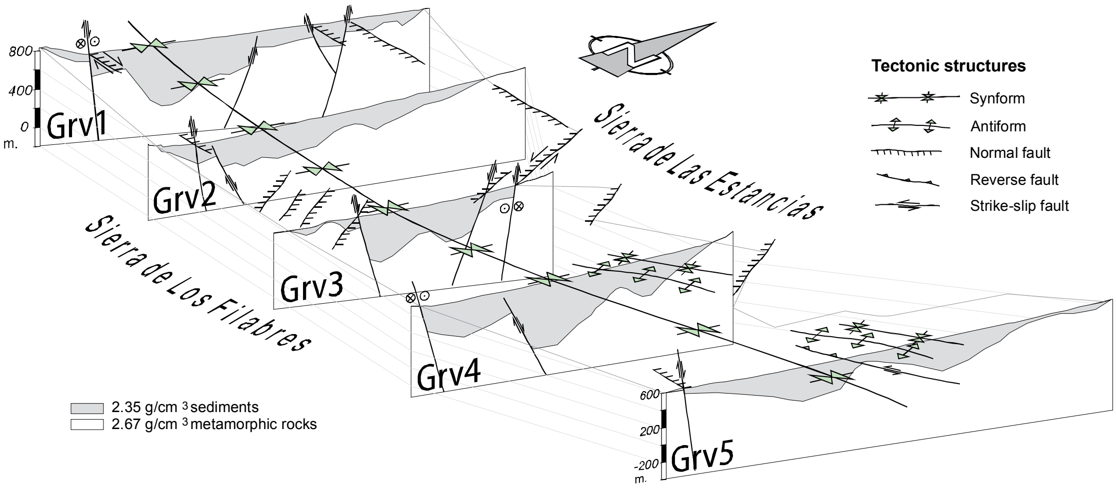

Fig. 6.8. Interpretative 3D perspective of the basement top geometry, sedimentary infill from gravity models and its relationship with the main tectonic structures (field data from Pedrera et al., 2007).

5. Magnetic study

The aeromagnetic map of Spain at a scale 1:1000000 (Ardizone et al., 1989), constructed from 10 km spacing fly lines at altitude of 3 km, show an important dipole over Sierra de Los Filabres (Fig. 6.2). This anomaly is the most important of the Eastern Betic Cordillera and has an E-W elongate shape that extends in an area more than 80 km long and 35 km wide. The dipole show a positive anomaly located to the South reaching up to 20 nT and a negative anomaly of – 70 nT.

In order to establish the shape and the magnetic properties of the anomalous body we have constructed three 2D models using the software of Pedley et al. (1993). The constructed models cross the Sierra de Los Filabres with N-S direction, which is orthogonal to the magnetic dipole. The dipole geometry with a maximum to the South may be produced (a) only by a contrast in susceptibility values, or (b) as a result of a remanent magnetization parallel to the induced one. The anomalous body does not outcrop, and then we have considered for modelling a value of magnetic susceptibility that may also take into account the unknown remanent magnetization. The best fit of measured and theoretical magnetic anomalies was obtained whit susceptibility of 0.07 SI (Fig. 6.9). In the three magnetic models the body is located at a depth between 4 and 7 kilometers with a geometry that varies from convex (Fig. 6.9 b and d) to flat Fig. 6.9 c). Considering the geological setting of the region, the rocks responsible of the anomaly may be interpreted as a large basic rock body (eg. Telford et al., 1990).

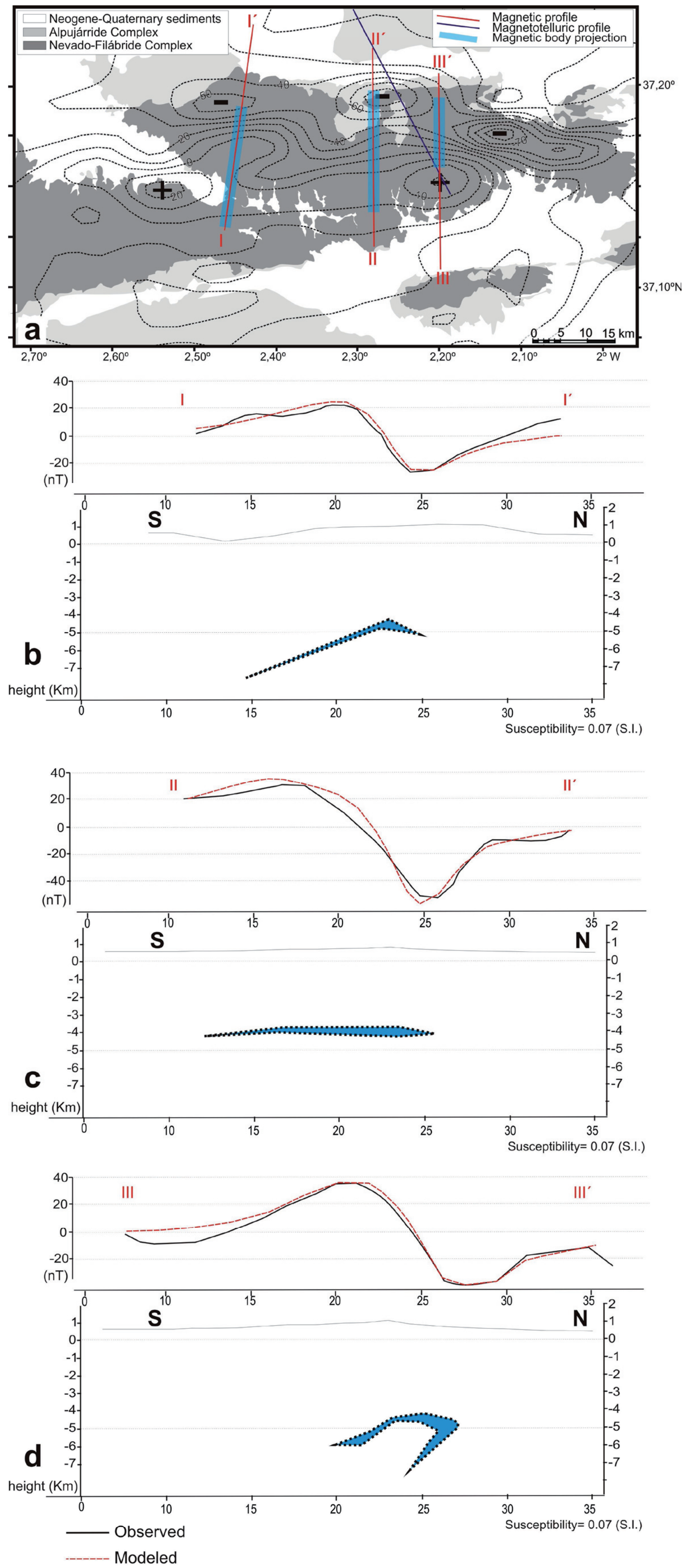

Fig. 6.9. 2D magnetic model constructed from the data of the aeromagnetic map of Spain at a scale 1:1000000 (Ardizone et al., 1989). The position is marked in the figure 2 (chapter 6).

6. Magnetotelluric survey

Since the 1990´s three magnetotelluric surveys have been carried out in the Eastern Betic Cordillera. A NW-SE 2D model was constructed from the data of the first survey, which were acquired using Metronix-03E systems. The 2D model crosses the Betic Cordillera from the Guadalquivir foreland basin to the Internal Zones, showing a deep conductor in the lower crust, interpreted as partial melting (Carbonell et al., 1998; Pous et al., 1999). In the Central-Eastern Betic Internal Zone the second survey was carried out using Metronix ADU06 equipment. These data allow us to construct a 3D model of the crustal region that reveals the conductive body under Sierra de Los Filabres to be shallow and possibly correspond to basic igneous rocks (Martí, 2006).

Pous et al. (1999) determined a N45ºE consistent magnetotelluric strike of the Central Betic Cordillera. In addition, they obtained real induction arrows pointing to the NW for periods of 100 s, 350 s and 1000 s (Fig. 6.2). Recently, Martí et al. (2004) and Martí (2006) realized a detailed dimensionality study using rotational invariants techniques. The results revealed a high complexity at shortest period (10^{-3} s), a 2D dimensionality between 0.01 and 1 s with a predominantly strike comprises between E-W and NE-SW, and a generally 3D behaviour at longer periods.

Groom and Bailey decomposition results from the site B58 show a good strike correlation with the previous dimensionality analysis (Martí, 2006). The results obtained from different period band show a strike predominantly NE-SW (Fig. 6.2). Accordingly, a NW–SE profile including 8 sites (Fig. 6.2) was interpreted taking into account that the 3D behavior of the data particularly affects the longest periods; and that the strike direction, determined from the 0.01s to 1s is approximately NE–SW.

The newly acquired data and some data from previous sites were processed using a robust processing code. The 2D inversion (Figs. 6.10 and 6.11) was constructed from 8 sites using the code RLM2DI (Mackie et al., 1997), inverting TM and TE resistivities and phases. Static-shift problems were detected as displacements between TE and TM mode at the shortest periods of the curves B58, Am1 and Am 7. All the corrections were smaller than one decade. During the 2D inversion we have tested several possibilities including the curves with and without the static-shift corrections. In addition, the correlation between the MT resulting 2D models and the magnetic anomaly model give us confidence in these static shift corrections in the southern part of the model.

Periods from 0.001s to 100s were inverted, and the models reached a confidence depth of approximately 9 km. During the inversion we used a mesh made up of cells increasing in size at greater depth, and these were extended laterally in order to stabilize the inversion responses. The smoothing factor (τ) used during the inversion was 3; the floor standard deviation errors considered for TM and TE, resistivity and phases, were 5.0 %. After 30 iterations, the inversion error (R.M.S.) obtained was 3.85.

The model shows the position and geometry of the Almanzora synform filled by sediments below the MT sounding Am 4 (Figs. 6.10 and 6.12). The low resistivity values that coincide with the basin could be related with the presence of silts and gypsum in the sedimentary infill (Meijninger, 2006). Under the Corridor (below MT soundings Am 3 and Am 4) appears a highly resistive body (~5000 Ω·m) located a depth of 2 km. Yet the resolution in depth of soundings Am 3 and Am 4 are limited by the conductive Almanzora sedimentary cover and the deeper part of this resistive body remain unconstrained. The profile crosses the contact between the Nevado-Filábride and Alpujárride complexes (dipping to the north about 30º) that constitutes the major low-angle normal fault cropping out in the central part of the Betic Cordillera. The MT sounding Am 3 is located close to the south Almanzora basin boundary where the sediments are over the Alpujárride rocks, whereas sounding Am 1 is situated 7 km to the South, over Nevado-Filábride rocks (Fig. 6.10). In the MT model, the northern deep extension of the contact is recognized, from the outcropping position up to 4 km depth under sounding Am 5, then ending in the seismicity band that extends along the northern part of the cross-section at 3 km depth (Figs. 6.10 and 6.12). The conductive body (~0.5 Ω ·m), located between 4 and 9 km in the core of the Sierra de Los Filabres antiform under soundings B 58 and Am1, is related to a large total intensity dipole anomaly of the magnetic field (Fig. 6.2), suggesting correspondence to basic igneous rocks below Curie temperature. Under Sierra de Los Filabres, the model reveals a zone with heterogeneous resistivity surrounding the conductive body fitting the shape of the N-vergent Los Filabres antiform (Figs. 6.10 and 6.12).

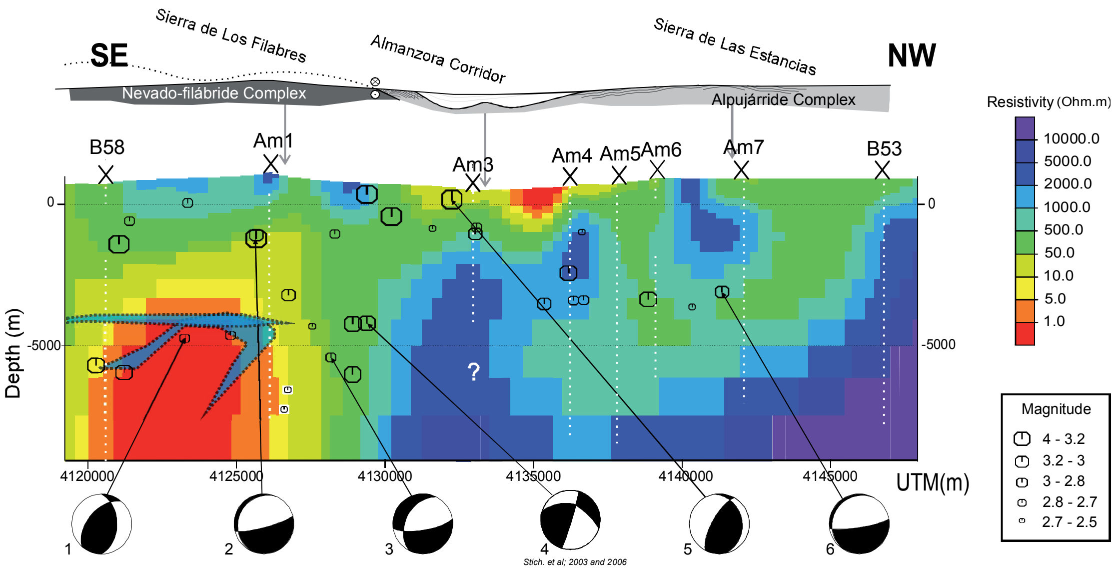

Fig. 6.10. 2D Magnetotelluric (MT) image and plotted seismicity distribution from the period 1992-2005 as recorded by the Red Sísmica de Andalucía (RSA) in a band of 60 km wide corresponding to the Almanzora Corridor. The TM and TE modes resistivities and phases were fitted during the 2D MT inversion using the code RLM2DI (Mackie et al., 1997). The white dots indicate the estimated skin-depth for each site, and the question marks indicate uncertainity in the model related to skin-depth limitations. The focal mechanism solutions, calculated from P-wave first motion polarities and projected in the lower hemisphere, were determined for 6 earthquakes that were digitally recorded by at least 10 seismic stations of the RSA. The white sectors are compressional ones. Stippled line above the Sierra de los Filabres represents the folded top-to-the W Alpujarride/Nevado-Filabride contact that was active during Early-Middle Miocene.

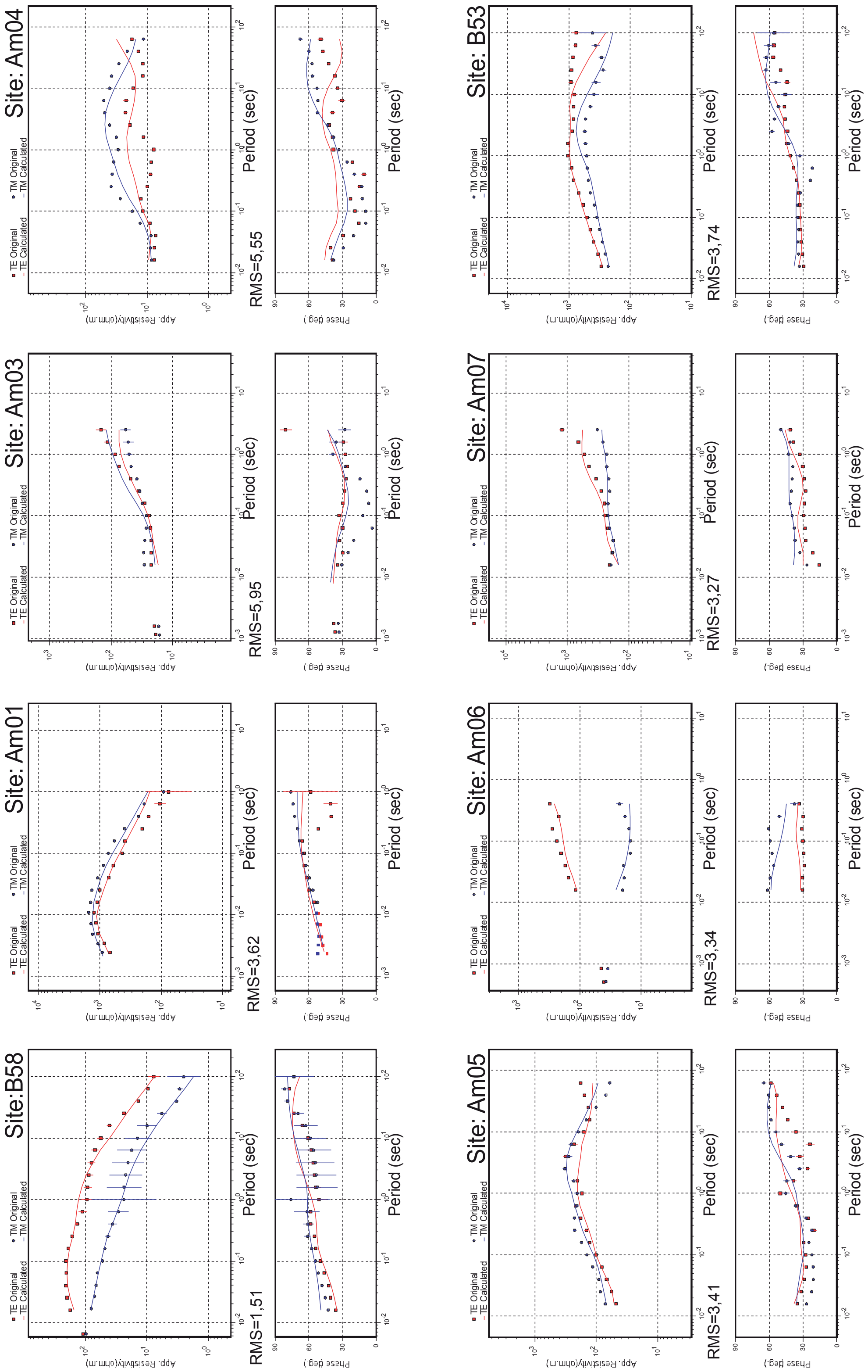

Fig. 6.11. MT rotated curves for each site, apparent resistivities and phase. The model responses and the R.M.S. are indicating for each curve.

7. Seismicity distribution

Seismicity distribution makes it possible to delimit the location of deep active structures that do not crop out in surface. Seismicity data came from the Instituto Andaluz de Geofísica y Prevención de Desastres Sísmicos (IAGPDS) database. We considered the events recorded digitally between 1992 and 2005, with magnitude greater than 2.5 and included in the rectangle limited by the UTM coordinates (km): x=540 – y=4120; x=610 – y=4155 that extends along the E-W oriented Almanzora Corridor and have been plotted on the NNW-SSE studied profile. The location of the earthquakes was acquired using the software HYP of SEISAN (Havskov and Ottemöller, 2001). Only the earthquakes providing good quality of the hypocenter location, with magnitude greater than 2.5 were plotted. Shallow events related with quarry explosions were eliminated. Most of the studied earthquakes (85 %) have been detected at least in 4 seismic stations. Therefore, the quality of the hypocenters locations of the selected earthquakes is excellent or good. The studied earthquakes present a mean least squares error in the coordinates between 0.1 and 0.8. Standard errors in latitude and longitude are between 1 and 7 km, and in focal depth are generally below 4 km.

The folded studied area is characterized by a low-to-moderate earthquake activity. Although most earthquakes are very shallow (0-10 km), it is impossible to associate seismicity with the outcropping faults that deform the Quaternary sediments. The main structures in this sector of the Betic Cordillera have an E-W to ENE-WSW average strike: sediment bedding, metamorphic rock foliation, low angle normal faults, dextral strike-slip faults, reverse faults and some high dipping normal faults. Only one set of NW-SE normal faults, which deform the upper part of crust, diverge from the E-W striking structures (Fig. 6.1 and 6.2). Therefore, the best section for plotting and analyzing the seismicity distribution is a NNW-SSE oriented section, perpendicular to the regional structures. On the basis of the earthquake distribution (Fig. 6.10), the limited amount of recorded earthquakes make difficult to correlate with confidence their distribution with the MT models. Although, the seismic distribution is stochastic south of 413500 meters latitude, a 10º south dipping surface aligned at 3-8 km in depth could be distinguished that cross-cuts the base of all MT structures.

8. Earthquake focal solutions

Fault plane solutions using P-wave first motion polarities were determined for six earthquakes digitally recorded by at least 10 seismic stations of the Red Sísmica de Andalucía (RSA). In addition, we used data from the Seismological Network of the Instituto Geográfico Nacional of Spain in order to improve the earthquake focal solutions. Focal mechanisms were calculated using the program Focmec (Snoke et al., 1984) included in SEISAN (Havskov and Ottemöller, 2001). The software performs a systematic search of the focal sphere, reporting acceptable solutions based on selection criteria for the given number of polarity in amplitude ratio errors. The search of the focal sphere is uniform in angle, with selectable step size and bounds. The selection criteria, both for polarities and angles, allows for correction or weightings for near-nodal solutions.

The earthquake focal solutions show a variety of faulting regimes. Reverse (Fig. 6.10, mechanisms 1 and 5) and strike-slip focal mechanisms (Fig. 6.10, mechanism 4) point to NW-SE directed compression. The presence of earthquake focal mechanisms with subhorizontal and subvertical nodal planes (Fig. 6.10, mechanisms 2 and 6) suggest inclined stress axes in depth that may be related to subvertical faults with vertical slips, or to the activity of detachment faults with a top-to-the N sense of motion. Finally, mechanism 3 (Fig. 6.10) shows normal faulting generated by a subvertical compressive axis and NW-SE extension. This focal mechanism solution is in transition with the last two focal mechanisms and represents a permutation of stresses with respect to the NW-SE compressional mechanisms.

9. Discussion

New data acquired along a transect deformed by large tectonic structures in the Central-Eastern part of the Betic Cordilleras provide insight to the relationships between large fold development and anomalous rocks located in the upper-crust, which may be transferred to the study of other internal orogenic zones. Although the previous seismic profile ESCIBETICAS-2, crossing Sierra Nevada and Sierra de Los Filabres antiforms, allowed identification in small sectors of the detachment levels under metamorphic ranges (eg. García-Dueñas et al., 1994; Galindo-Zaldívar et al., 1997; Martínez-Martínez et al. 1997), the poor quality of the images does not suffice to characterize folded structures in the upper crust. The geophysical data gathered here contribute to asses the late kilometric folded crustal structure in the Internal Zone of the Betic Cordillera that gives rise to crustal thickening, folds and relief growth. In addition, we present the first detailed gravity data along 5 cross sections of the Almanzora basin. These 5 modeled sections confirm the presence of an asymmetric N-vergent synform, shifting from E-W in the western sector to ENE-WSW in the eastern area, and having a maximum sedimentary thickness of 600 m located within the hinge zone.

Our contribution helps pinpoint (a) the role of rheological anomalous bodies during fold nucleation, and (b) a possible relation between late large fold growth, and the variability of the seismogenic fault features formed in a heterogeneous stress setting.

9.1. The role of rheological anomalous bodies during fold nucleation

One of the main features that points the MT profile orthogonal to the fold trend is the presence of a large conductive body (~0.5 Ω ·m) located at shallow crustal levels (probably at least 4 to 9 km) in the antiform under the Sierra de Los Filabres, associated with a large total intensity anomaly dipole in the magnetic field. The deeper part of the body is not well constrained due to its high conductivity and thickness.

The resistivity value of the rocks depends on several factors: mineral composition, porosity, fracturation, concentration on fluids, fluids composition… Therefore, each rocks show a wide resistivity margin depending on these factors and low resistivity bodies allow several interpretations. The most common are: presence of graphite impregnations, presence of metallic minerals, an important amount of free conductive fluids, partial melting, or a combination of these mechanisms. The integration of electrical and magnetic parameters suggests that the most realistic mechanism to explain the observed data is the presence of metabasites in the core of Sierra de Los Filabres. The very low resistivity value can be explained by a combination of factors, the metabasite composition probably have important impregnations of metallic minerals. In other hand, the position of the conductive body located just in the core of an antiform could condition a tectonic fracturation that would let the metallic enrich fluid circulation. The related magnetic anomalies indicate that the conductive body has a temperature below the Curie point. The magnetic anomaly associated to the conductive body allow us to discard the graphite enrich schists and the partial melting hypothesis. Previous research developed with a larger spaced MT sounding network (Martí, 2006) suggests this body is roughly elongated, runs parallel to the Sierra de Los Filabres, and has a maximum length of about 80 km.

Sierra de Los Filabres is mainly formed by Nevado-Filábride schists and marbles, with scarce outcrops of metabasites, surrounded by the Alpujarride phyllites and marbles. These metamorphic rocks have an important contrast in their rheological behavior as compared with the large body of basic rocks located at their core. This contrast controls the deformation, which is mainly concentrated in the weak rocks located around strong basic undeformed bodies (Mackwell et al., 1998). Based on the new geophysical images we propose the pre-existing strong lithological bodies to constitute basic rock bodies that may condition the nucleation and development of this late north vergent kilometric antiform.

Rheological studies (Itô, 1979; Itô and Sasamija 1980; Ranally and Murphy, 1987) show that basic igneous rocks are more resistant to the deformation than granitic crust. In addition, the presence of this large basic igneous rock body may be the reason behind the relatively lower seismic activity in the core areas of the Sierra de Los Filabres as opposed to the northern Almanzora Corridor or the Sorbas Basin-Sierra Alhamilla, located to the south (Fig. 6.1B).

9.2. Late large fold in a heterogeneous stress setting

The combination of MT images with seismicity position provides an important tool for the identification of active faults in depth (e.g. Fisher et al. 2004; Tank et al. 2005). Combining field geology and magnetotelluric data with the position of low-to-moderate hypocenters advance to recognize the origin and position of deep faults linked to folding in the Eastern-Central Betics.

The shallow seismicity is better recognized in Sierra de Los Filabres than in Sierra de Las Estancias. The seismicity decrease to the North, only few earthquakes are located at 3 kilometers in the central part of the MT crustal image below the Almanzora Corridor. The hypocenters distribution bellows the Sierra de Los Filabres are disorganized mainly located at the border of the highly resistive anomalous body. Although, available data are not conclusive, a possible origin for the seismicity below the Sierra de Los Filabres could be related to the large antiform activity, which may locally reactivate lithological contacts in a flexural slip model. This folding mechanism has been active in the Almanzora Corridor, where striation parallel to sedimentary bedding is recognized, producing both compressive and extensive faults.

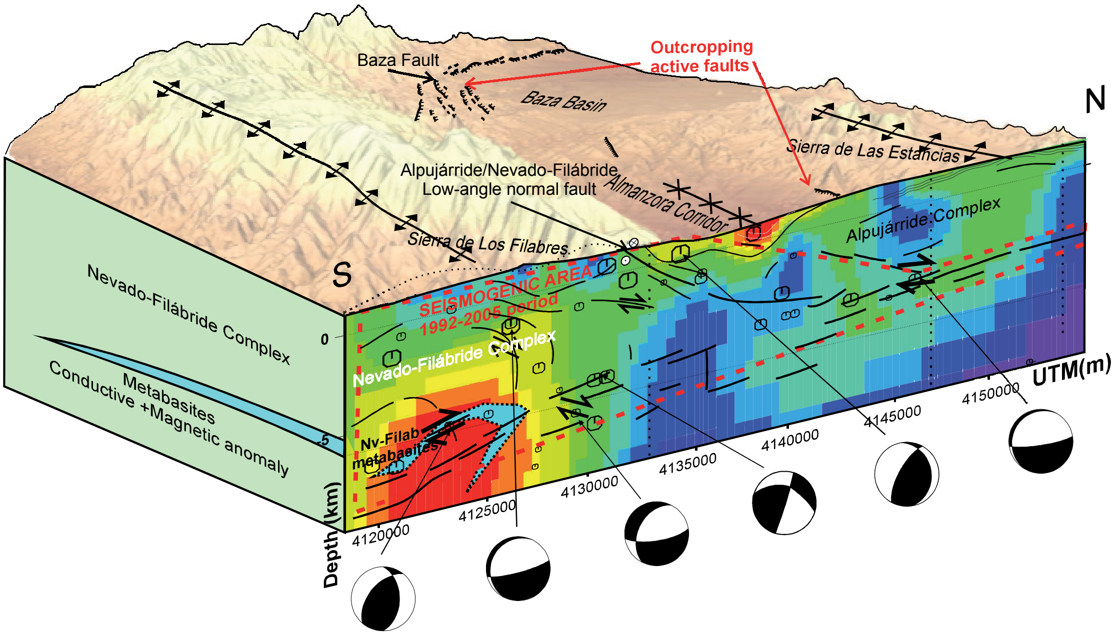

Fig. 6.12. Three-dimensional sketch showing the main active outcropping structures and the upper crust of the Sierra de Los Filabres-Sierra de Las Estancias folded region, from surface geology and geophysical data (seismicity, magnetic and MT). The MT model has been plotted to the N-S direction. The position of the magnetic and conductive body interpreted as basic rocks within the core of the Sierra de Los Filabres antiform is marked in the upper crust.

The earthquake focal mechanisms determined in the study area (Figs. 6.10 and 6.12) support a variable present-day stress field in this small region. As mentioned above, at present the tectonic framework of the Betic Cordillera is dominated by the NW-SE shortening at a rate of 5 mm/yr (DeMets et al. 1994) and by a shallow low-to-moderate seismicity linked to the shortening setting. Nonetheless, the focal mechanism solutions in the Central Betics reveal both active compression and extension (Morales et al., 1997; Galindo-Zaldívar et al., 1999; Stich et al., 2003; Buforn et al., 2004). In addition, since Tortonian the largest tectonic structures in Betics are the E-W to ENE-WSW oriented folds, while the active faults are normal and NW-SE to E-W oriented. In this sector of the Betic Cordillera numerous faults interact with the folds since the Late Miocene, though they mainly deform the Alpujárride Complex and the Almanzora sedimentary basin, as confirmed by the gravity models of the Almanzora Corridor. These faults are generally located over the Nevado-Filábride/Alpujárride low-angle normal fault (Fig. 6.2), which may constitute a major shallow crustal discontinuity. Field observations indicate that some of these faults are still active in the Almanzora Corridor and in the South of the Baza basin, conditioning the present-day NE-SW dominant extension and vertical compression in the upper crust. In the eastern Almanzora and in the Huércal-Overa basin, reverse faults indicate that orthogonal NW-SE compression dominates. This stress field is more complex in depth, where the compressional structures responsible for relief uplift continue to be active, as revealed by the deep seismicity and the presence of reverse and strike-slip focal mechanisms.

In order to explain the seismicity in this variable stress scenario, we must assume a setting that links the surface and deep observations. Indeed, the main recent and active deformations related to crustal thickening are the large folds that are probably related to detachments in depth (Banda and Ansorge, 1980; García-Dueñas et al., 1994; Galindo-Zaldívar et al., 1997; Martínez-Martínez et al., 1997b). At surface, the active normal faulting dominates, as deduced from the outcropping normal faults without instrumental associated seismicity. A possible explanation may involve stress partitioning characterized by NW-SE horizontal compression mainly affecting deep levels, and responsible for the relief uplift that led to gravity instabilities in the shallowest crust. These gravity instabilities are resolved by a horizontal extensional stress field producing the E-W to NW-SE normal faults.

10. Conclusions

New geological observations in the field, combined with gravity, magnetic, magnetotelluric and seismicity data, reveal the subsurface structure in a sector of the Betic Cordillera hinterland. These results allow us to propose that the Sierra de Los Filabres antiform core corresponds to a large basic rock body located at a depth between 4 and 9 km depth, signaled by a low resistivity body (~0.5 Ω·m) that produces a large total intensity dipole of magnetic field anomaly. This basic rock body would have determined the nucleation and development of the kilometric antiform.

In this sector of the Betic Cordillera, the large N-vergent folds that started to develop since the Serravallian-Early Tortonian are now subjected to a complex stress scenario. The present-day dominant stress field is characterized by subhorizontal NE-SW extension in the shallowest crust and NW-SE subhorizontal compression in depth (Fig. 6.12). However, there are frequent stress perturbations, and even permutations, related to crustal heterogeneities. Our contribution reveals the position and kinematics of the principal outcropping active faults —mainly NW-SE to E-W normal and locally with ENE-WSW reversal— without associated seismicity. The instrumental seismicity is probably concentrated along the deep detachments and minor faults related to fold growth. This field example may contribute to understand the relationships between large fold nucleation, active fold development and seismicity in the internal zones of the cordilleras.

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7. The role of small-scale fold and fault development in seismogenic zones: the example of the Western Huércal-Overa basin (Eastern Betic Cordillera, Spain)

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The NW-SE shortening between the African and the Eurasian plates is accommodated in the eastern Betic Cordillera along a broad area that includes large N-vergent folds and kilometric NE-SW sinistral faults with related seismicity. We have selected the best exposed small-scale tectonic structures located in the western Huércal-Overa basin (Betic Cordillera) to discuss the seismotectonic implications of the small-scale tectonic structures that usually developed in seismogenic zones. Subvertical ESE-WNW pure dextral faults and E-W to ENE-ESW reverse-dextral faults and folds deform the Quaternary sediments. The La Molata structure is the most impressive example, including dextral ESE-WNW Neogene faults, active southward-dipping reverse faults and associated ENE-WSW folds. A molar M1 assigned to *Mimomys savini* allows for precise dating of the folded sediments (0.95-0.83 Ma). Strain rates calculated across this structure give ~0.006 mm/yr horizontal shortening from the mid-Pleistocene up to now. The widespread active deformations on small-scale structures contribute to elastic energy dissipation around the large seismogenic zones of eastern Betics, decreasing the seismic hazard of major fault zones.

Key words
Active tectonics, fault-related folding, creep/seismogenic fault, mammal fossils, Pleistocene.

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1. Introduction

Elastic energy is released in seismogenic faults during earthquakes (Scholz, 1990; Cow1e and Scholz, 1992). As displacement rates increase in an active region, the development of small-scale faults could become predominant (England and Jackson, 1989; Vendeville, 1987). The presence of a fractured crust releases the accumulation of elastic energy and could influence the expected earthquake maximum magnitude. Therefore, it is important to characterize the minor fault network and related folds to estimate the regional background strain in seismogenic areas (Segard and Pollard, 1980; Davison, 1994; Dee et al., 2007). Especially interesting are the field observations on small-scale Quaternary fold related-faults, which are bounded by syn-tectonic sediments and provide very important information about the successive deformation stages. The geometrical features of these growth strata are related to the folding mechanism (e.g. Suppe et al., 1992; Hardy and Poblet, 1994, 1995) and to the ratio between deformation velocity and sedimentation rate (Rafini and Mercier, 2002). Therefore, the analysis of growth strata in Quaternary folds constitutes an important tool for understanding the continuity of the deformation of deeper faults during the Quaternary as well as the present tectonic setting, which is closely related to seismicity (e.g. Fu et al., 2003).

The aim of this contribution is to evaluate the role of faults and folds that accommodate displacement during Quaternary times, occasionally interacting with previous fault zones. Detailed structural field work has been carried out to describe the Quaternary tectonic structures that deform the western Huércal-Overa basin and accommodate part of the shortening between the African and Eurasian plates, focusing on the La Molata fold-related faults. The study of small-scale active tectonic structures allows us to discuss the seismotectonic setting in a diffuse plate boundary.

The La Molata structure includes reactivated Neogene faults, active reverse faults and associated folding. For the selected example, we have restored and dated the deformation from Quaternary mammal fossils. The stress inversion from the Quaternary faults and the analysis of focal mechanisms allow the present stress ellipsoid to be determined.

2. Geological setting

The Betics comprise an alpine mountain range located in the western Mediterranean Sea that is formed by the relative motion between Eurasia and Africa (Fig. 7.1A). Although deformation —including metamorphic events— started in Cretaceous times, the main metamorphic phase is related to maximum crustal thickening in Early Miocene (Monié et al., 1991). The Betic Cordillera is divided into the External Zones, mainly formed by Triassic to Miocene sediments deposited on the continental boundary of the southern Iberian massif, and the Internal Zones, which include Paleozoic and Mesozoic metamorphic rocks. In turn, the Internal Zones are formed by three main metamorphic complexes, that from bottom to top are the Nevado-Filábride, Alpujárride and Maláguide, separated by low-angle normal faults active during the Lower and Middle Miocene (e.g. Aldaya et al., 1984; Galindo-Zaldívar et al., 1989; Platt and Vissers, 1989; Jabaloy et al., 1992). The present-day relief of the Betic Cordillera started to develop in Tortonian related to N-S/NW-SE shortening. It is characterized by mountain uplift related to large antiforms, and basins associated with synform growth and normal fault interaction (e.g. Galindo-Zaldívar et al., 2003). However, the eastern cordillera is mainly deformed by kilometric sinistral transcurrent faults that are NNE-SSW to NE-SW oriented (the Alhama de Murcia, Palomares and Carboneras faults) (Fig. 7.1B). These faults have been interpreted as a left-lateral crustal-scale shear zone (e.g., Leblanc and Olivier, 1984; Montenat et al., 1987; De Larouziere et al., 1988). During the Quaternary, the shortening continued at a rate of 4-5 mm/year (e.g. DeMets, 1994; Fernández-Ibáñez et al., 2007) determining the continuity in time of the large folds growth (eg. Marín-Lechado et al, 2006), the activity of some segments belonging to the kilometric sinistral faults (e.g. Booth-Rea et al., 2004; Pedrera et al., 2006) and the Cordillera uplift. In addition, other minor compressive structures are still active in the eastern cordillera.

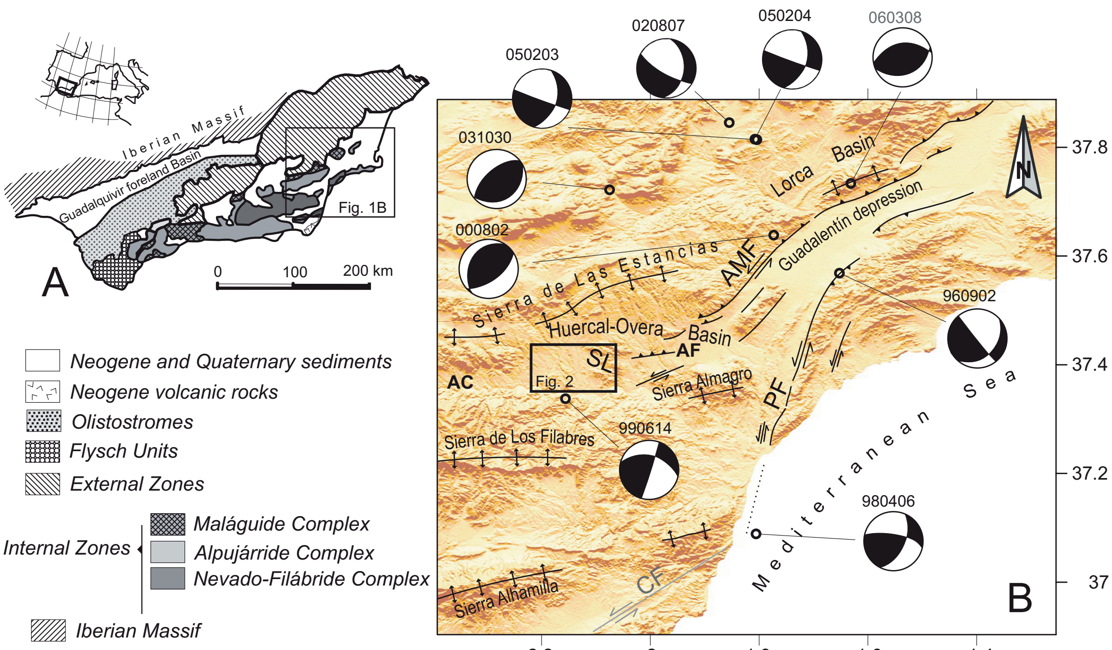

Fig. 7.1. Geological map of the Betic Cordillera showing the different domains (A) and enlarged detail of the eastern sector where are indicated the main active folds and faults (B). Focal mechanisms obtained from the seismicity occurred in the area between 1995 and 2006 have been plotted (Stich et al., 2003, 2006, I.G.N. catalogue). SL: Sierra Limaria; AC: Almanzora Corridor; AF: Albox Fault; AMF: Alhama de Murcia Fault; PF: Palomares Fault; CF: Carboneras Faults (in grey because this segment do not disturb the Quaternary rocks). The location of Figure 2 (chapter 7) is marked.

The Huércal-Overa basin is an ENE-WSW-oriented basin located in the eastern Betic Cordillera, close to the southern end of the Alhama de Murcia Fault, flanked by kilometric wave-length antiforms to the South —Sierra de Los Filabres and Sierra Almagro— and to the North —Sierra the Las Estancias (Fig. 7.1B). The basin is filled by Late Miocene sediments (e.g. Voermans et al., 1972; Briend, 1981; Guerra-Merchán and Serrano, 1993; Mora, 1993; Poisson et al., 1999, Augier, 2004 and Meijninger, 2006) that are fully covered by Pliocene and Quaternary rocks in the eastern sector (García-Meléndez et al., 2003). The Late Miocene sediments that fill the Huércal-Overa basin are quite deformed by several sets of faults. The most prolific group consists of WNW-ESE to NW-SE normal faults are widespread distributed in the basin (Mora, 1993; Augier, 2004; Meijninger, 2006) and throughout the Betic Cordillera (e.g. Sanz de Galdeano, 1983). Our study concentrates on the western part of the basin, also designated as the Albox basin (e.g. Mora, 1993). The Quaternary rocks are exposed discontinuously in the western part, allowing recognition of the recent activity of deformation that affects the Neogene sediments.

3. Quaternary tectonic structures in the Huércal-Overa basin

The Quaternary activity in the Huércal-Overa basin is quite complex, owing to its intermediate position between the kilometric Alhama de Murcia Fault (AMF) and the large N-vergent folds developed over a deep crustal detachment. The AMF (Bousquet and Montenat, 1974) is a NE–SW (N35ºE to N65ºE), reverse-strike-slip segmented fault that extends over 90 km. Although many authors have obtained structural and geophysical data, the starting time of fault activity and its relation with the Neogene basin genesis is still under debate. On the other hand, its Quaternary and present activity related to the shortening between Eurasia and Africa is generally accepted (e.g. Silva et al., 1993; Meijninger and Vissers, 2006). Thus, the AMF has developed mountain fronts related to the sinistral faults segments (~N35ºE) and to the associated folds and reverse faults (~N65ºE) (e.g. Silva et al., 2003). In addition, the AMF generates a low to moderate seismicity (e.g. Sanz de Galdeano et al., 1995; Martínez-Díaz et al., 2003) that allows us to determine earthquake focal mechanisms (numerical solutions for moment tensors from 1996 to 2006, Stich et al., 2003, 2007; IGN, http://www.ign.es/). Such solutions reveal the present activity of strike-slip and reverse faults capable of generating instrumental earthquakes with a magnitude of at least 4.4 (Fig. 7.1), although paleoseismological studies suggest higher magnitudes, up to 6.1-7.0 (Masana et al., 2004).

The AMF represents the northwest boundary of the Guadalentín depression, ending to the south in the Huércal-Overa basin. The southern end of the AMF is accommodated by several ENE-WSW reverse faults that have splay geometry (Fig. 7.1B). These faults deform the Quaternary sediments located in the eastern Huércal-

Overa basin and were described for the first time 40 years ago (e.g. Groupe de Recherche Néotectonique, 1977; Briend, 1981); more recently they have been studied in detail from geomorphological, structural and paleoseismological points of view (Garcia-Meléndez et al. 2003; Soler et al., 2003; Masana et al. 2005; Meijninger and Vissers, 2006). Briend (1981) described a three-kilometer-wide area of Quaternary deformation located northeast of Sierra Limaria (Fig. 7.1). The deformation is characterized by N50ºE sinistral, N75ºE sinistral-reverse and N110ºE dextral-reverse faults. Using a geomorphological approach, García-Meléndez et al. (2003) defined the Albox Fault as an ENE-WSW to E-W fault zone with reverse-dextral kinematics that extends 30 kilometers from the Eastern Huércal-Overa basin as far as the Almanzora Corridor to the West (Fig. 7.1). Masana et al. (2005) allocate two Holocene morphogenic earthquakes associated with the eastern Albox fault, the larger one with a maximum Mw of 6.5±0.1 (considering one meter of vertical offset).

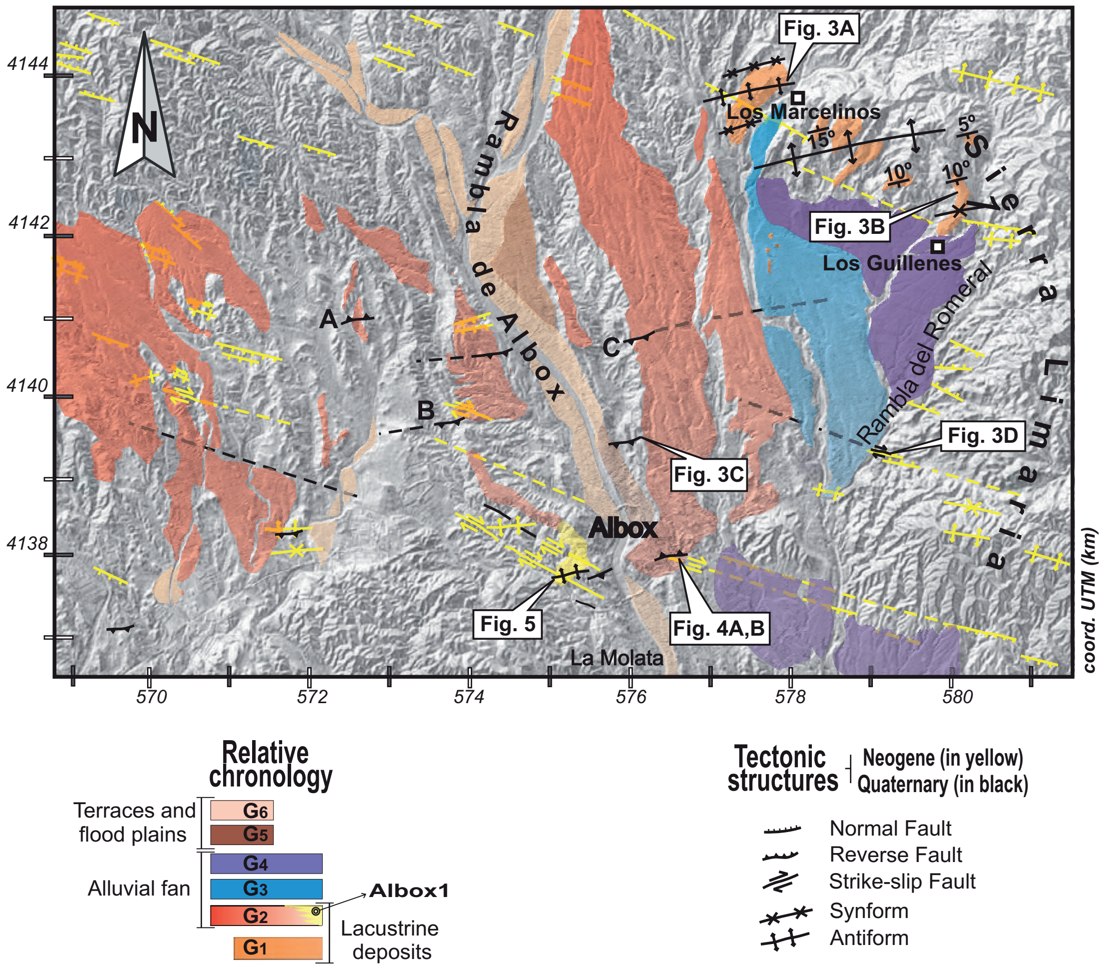

Fig. 7.2. Digital elevation model (10 m resolution) of the north-western Huércal-Overa Basin where is indicated the Quaternary sediments distribution and the location of the main faults and folds. The position of the outcrops in the figures 3, 4 and 6 (chapter 7) are marked. The reverse faults A, B and C were described by Guerra-Merchán (1992).

Fig. 7.3. Field examples of Quaternary structures. (A) NE-SW oriented open antiform located close to Los Marcelinos. (B) Example of NW-SE open joints. (C) Reverse fault N80ºE oriented with flat and ramp geometry deforming a Quaternary alluvial fan. (D) Dextral strike-slip fault affecting a homogeneous layer of Quaternary conglomerates in the Rambla El Romeral. Position of the outcrops is marked in figure 2 (chapter 7).

The Quaternary deformation of the western Huércal-Overa basin is still poorly known. The tectonic structures (folds, reverse and strike-slip faults) crop out discontinuously in a band 8 km wide. Guerra-Merchán and Serrano (1993) described small E-W reverse faults with displacements of a few meters affecting the Quaternary sediments, two kilometers northeast of the town of Albox.

New field observations point out, a NE-SW-trending open antiform with a 1.5 kilometer wavelength, which includes minor folds of 100 m wavelength, deforms lacustrine limestone beds, probably of Early Pleistocene age, close to Los Marcelinos (Fig. 7.2). Their geometry is open, with flanks dipping around 15-20º and without vergence (Fig. 7.3A). In addition, there are NW-SE open joints filled by red clay, which also affect lacustrine sediments and probably are related to these folds as could be deduced from their orientation (Fig. 7.3B).

Small segments of ESE-WNW dextral faults locally deform the Quaternary sediments, as in the outcrop “Rambla El Romeral” (Figs. 7.2 and 7.3D). These isolated segments are difficult to follow in the field and may correspond to discontinuous faults that were locally activated. The “Rambla El Romeral” strike-slip fault is placed over a subvertical Tortonian fault zone where it is possible to identify dextral striae overprinted upon normal ones.

Fig. 7.4. Field example of Quaternary structure (A) Reverse N70ºE oriented fault that deforms the most recent Quaternary alluvial fan of the area. (B) Enlarged picture that show the reoriented pebbles in the fault plane indicating the reverse slip. Position of the outcrops is marked in figure 2 (chapter 7).

Close to the town of Albox, several outcrops show small reverse faults and associated compressive structures deforming Quaternary fluvial sediments (Figs. 7.2, 7.3C, and 7.4). The trends of these faults are between N70ºE and N90ºE, dipping indistinctly northwards and southwards between 20º and 40º, and sometimes up to 60º. The kinematics deduced from the striations located on the fault planes indicate pure reverse faulting when they are N70ºE oriented, and reverse-dextral faulting when the orientation is close to E-W. These results are in agreement with the observations of Briend (1981) in the eastern part of the basin. When the sediments deformed by the fault zone are conglomerates, the pebbles are reoriented during the reverse slip but never appear fractured (Fig. 7.4B). The most impressive reverse faults with associated folds are located in La Molata (Fig. 7.5).

4. La Molata structure

Along the new road from Albox to La Molata there is a very well exposed complex compressive structure that includes reactivated Neogene faults, active reverse faults and associated active folds (Fig. 7.5). At its base, the outcrop shows a multilayer sequence, formed by centimeter-thick beds with alternating continental red conglomerates, sands and silts. These sediments can be assigned to the Late Tortonian alluvial rocks described in the basin (e.g. Guerra-Merchán and Serrano, 1993). These continental deposits grade into a various-colored sequence of conglomerates, sands, grey silts, and caliches that probably developed in a shallow-marine environment. These levels possibly belong laterally to the nearby stratigraphical section studied by Guerra-Merchán et al. (2001) and dated as Tortonian due to the presence of a micromammal site located in fluvial levels. At the top of this unit there is an angular unconformity (U_1) and a thin deposit formed by conglomerates and a yellow sandy matrix. The age of these sediments is not well constrained, but could correspond laterally with Early Messinian marls defined by Briend (1981) and recently dated by Meijninger (2006). Just at the top appears a new angular unconformity (U_2) overlain by a lacustrine formation, harboring a new micromammal site "Albox1" assigned to a mid-Pleistocene age, which is described in detail in the next section.

At a large scale the structure consists of a N-vergent disharmonic antiform that interacts with dextral-reverse and pure reverse faults. In the internal part the antiform is closed and bounded by two high-angle transcurrent faults. The kinematics deduced from the gouges developed in these faults exhibit main dextral-reverse behavior, although sinistral movements were also found. The orientation of the axis of this fold coincides with the dextral fault trends that vary between N145ºE and N100ºE. Transcurrent faults developed in multi-colored fault rocks where the relatively resistant blocks are surrounded by finely deformed gouges. Only two dextral-reverse faults are associated with the antiform that deforms the Pleistocene sediments and cuts the U_1 (Fig. 7.5B).

This antiform is N-vergent, has a N70ºE orientation and is clearly syn-sedimentary with respect to the mid-Pleistocene lacustrine deposits that have an internal unconformity (U_3). The antiform is active at present, as we deduce from the topographic high. In addition, the lacustrine deposits are deformed by secondary south-dipping reverse faults that are N70ºE oriented.

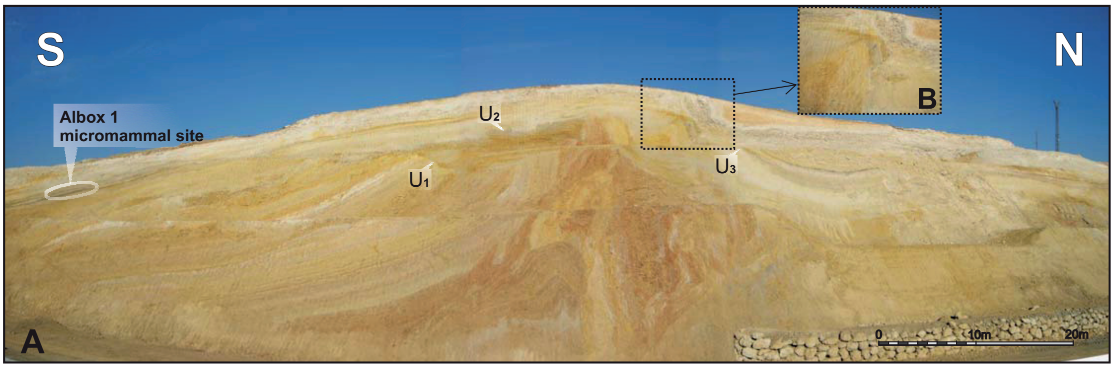

Fig. 7.5. La Molata structure. (A) The unconformities and the Albox 1 micromammal site are plotted. Position of the outcrop is marked in figure 2 (chapter 7). (B) Enlarged picture showing the two dextral-reverse faults that deform the unconformity 1 (U_1) and are associated to the Quaternary antiform.

4.1. New Quaternary biostratigraphical data

The Plio-Pleistocene continental record of the Huércal-Overa basin displays several generations of alluvial and lacustrine formations that crop out discontinuously (Fig. 7.2). Some of these deposits are deformed by faults and folds, sometimes showing syn-sedimentary development as we described for the La Molata structure. In order to date the deformation of this structure, we collected sediment samples from a folded lacustrine dark layer for biostratigraphical studies (Albox1 site, position in Figs. 7.2 and 7.4).

In this section we found a molar M_1 assigned to *Mimomys (Villanyia) savini* (Hinton, 1910) (Fig. 7.6). Using Enamel Units methodology (Ruiz Bustos, 1999 and 2002a), which describes and quantifies the enamel line on the crown of the tooth, we analyzed M_1 morphologically, identifying the Reference Sequence R.S.-M_1 (*Mimomys savini*)-1. The index results are shown in Table 8.1 and in Figure 8.5.

Linear regression (correlation coefficient r^2) was used to compare the molar M_1 with the micromammal population recognized in the Betic Cordillera (Ruiz Bustos 1987, 2002b and 2007). The morphological features correspond with the average values of the R.S-M_1 (*Mimomys savini*)-1, Biozone SI18-6 (99.9% correlation). This correlation value decreases progressively in contiguous Biozones (SI20-1: 92.2 %; SI20-3: 90.2%). Further palaeontological sampling in the Albox site has displayed three fragments of molar microtinae without root, impossible to identify taxonomically. In addition, we encountered a piece of thin enamel, very undulated and a few centimeters long, assigned to *Mammuthus indet*. All the faunal data indicate the SI18-6 stratigraphical Biozone and allow for a precise dating of the folded sediment as mid-Pleistocene (0.95-0.83 Ma). This biozone is very well constrained in the nearby Baza basin by the correlation between mammal's assemblage (Mazo et al., 1985; Ruiz Bustos, 2007) and magnetostratigraphy (Gibert, 2007).

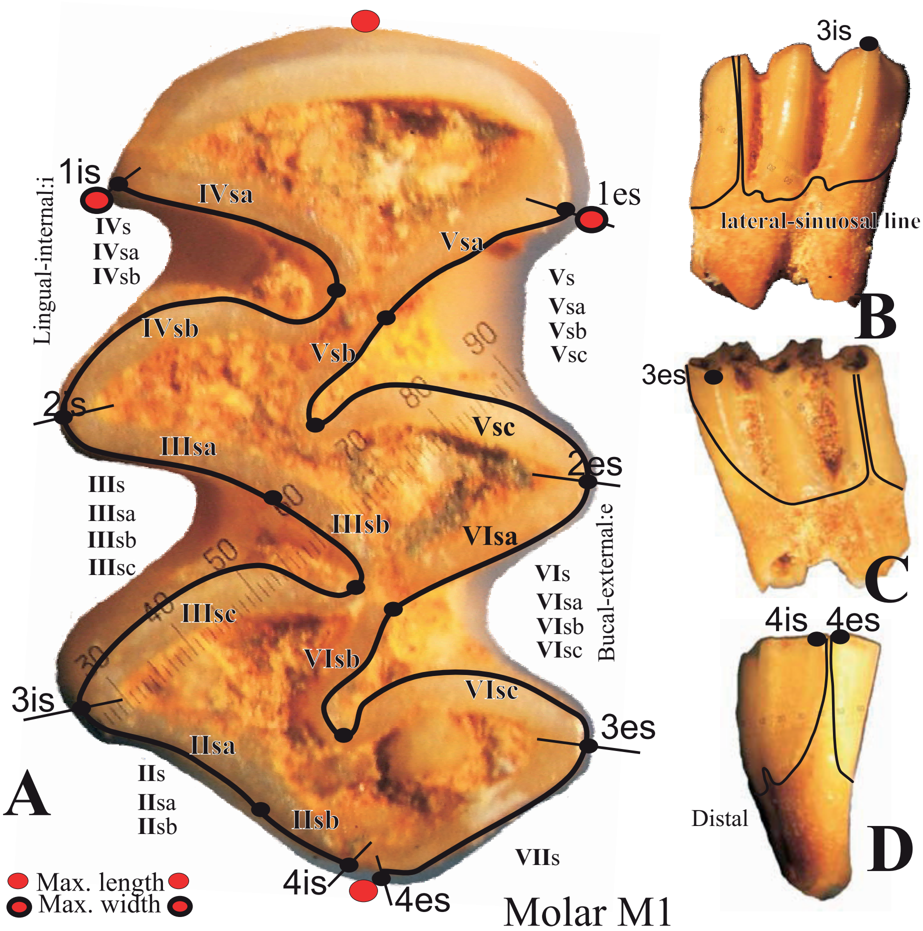

*Fig. 7.6. Left molar M_1 belong to Mimomys (Villanyia) savini (Hinton, 1910). Parameter that constitute the Reference Sequence R.S. -M_1 (Mimomys savini)-1: 1-VIIs, 2-VIs, 3-VIsa, 4-VIsb, 5-VIsc, 6-Vs, 7-Vsa, 8-Vsb, 9-Vsc, 10-IVs, 11-IVsa, 12-IVsb, 13-IIIs, 14-IIIsa, 15-IIIsb, 16-IIIsc, 17-IIs, 18-IIsa, 19-IIsb, 20-Maximum length., 21-Maximun width (values in table 7.1). The values obtained for the parameters 1 to 19 have been calculated using the equation: (R. S. parameter * 100/ 2* enamel length (bucal + lingual). Position of the outcrop is marked in figure 4 (chapter 7).*

Table 7.1. Values of the parameter (in mm) that constitute the Reference Sequence R.S.-M_1 (Mimomys savini)-1.

1-VIIs	2-VIs	3-VIsa	4-VIsb	5-VIsc	6-Vs	7-Vsa	8-Vsb	9-Vsc	10-IVs	
4.10	11.36	3.38	2.55	4.99	10.92	3.57	2.10	5.25	9.52	
11-IVsa	**12-IVsb**	**13-IIIs**	**14-IIIsa**	**15-IIIsb**	**16-IIIsc**	**17-IIs**	**18-IIsa**	**19-IIsb**	**20-Max.length**	**21-Max.width**
4.03	5.49	11.14	3.64	2.15	5.35	5.01	3.12	1.88	2.39	1.34

4.2. Tectonic evolution

We restored the deformation produced by the folds and faults in the La Molata structure cross-section. Unfortunately, the presence of faults with a strike-slip component, mainly affecting the Tortonian sediments, makes it impossible to balance and quantify the deformation before the Quaternary. We can, however, establish the deformation rate from the mid-Pleistocene up to now using the new biostratigraphical data and restoring the unconformities up to the horizontal.

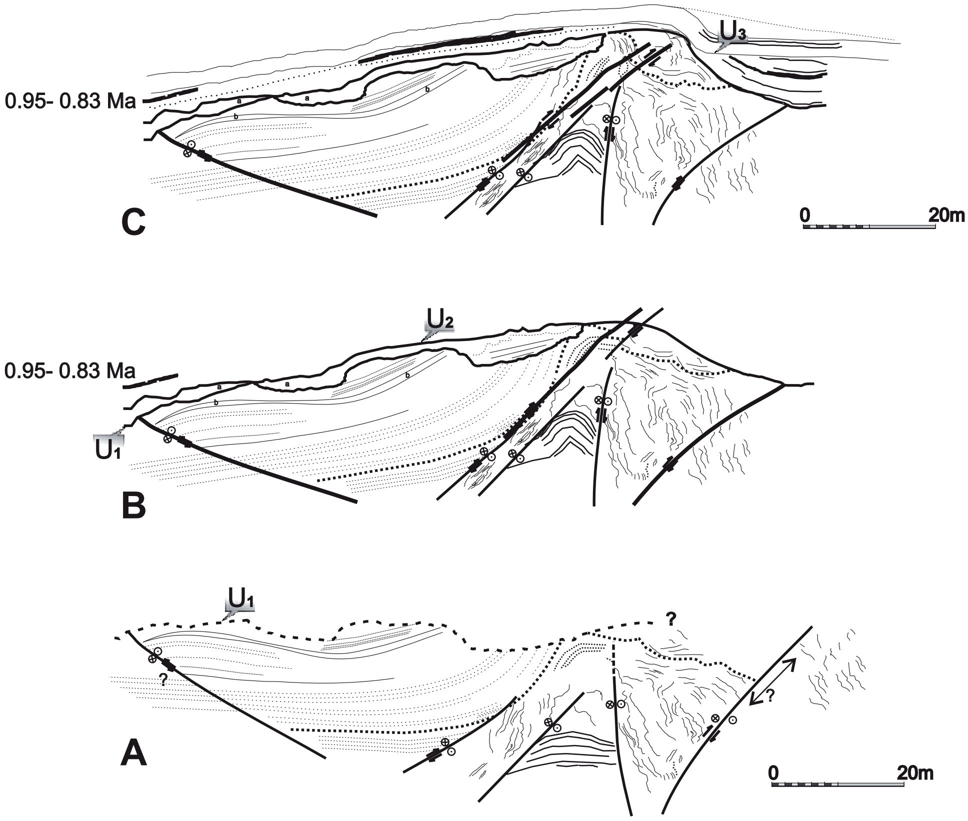

Fig. 7.7. Tectonic evolution of the La Molata structure. (A) Strike-slip faulting with development of thick fault gouge, uplift, erosion and formation of the unconformity 1 (U_1). (B) The old dipping faults zones are reactivated as reverse faults with associated folds that are coetaneous to the lacustrine Quaternary sediments deposition. (C) The Quaternary syn-tectonic sedimentation continues.

The model of Figure 7.7 shows a general tectonic restoration. In a first stage (A), WNW-ESE dextral-reverse faults with associated wide fault gouge were active, prior to the U_1 erosive unconformity. These precursory faults gouges constitute heterogeneities that favor the progression of deformation parallel to these weak sectors during the Quaternary. Stages B and C illustrate the development of reverse faults and the associated antiforms. The vergence to the north of the upper folds highly conditioned the accommodation space in both flanks, and causes the lacustrine sediments to become thicker in the northern flank.

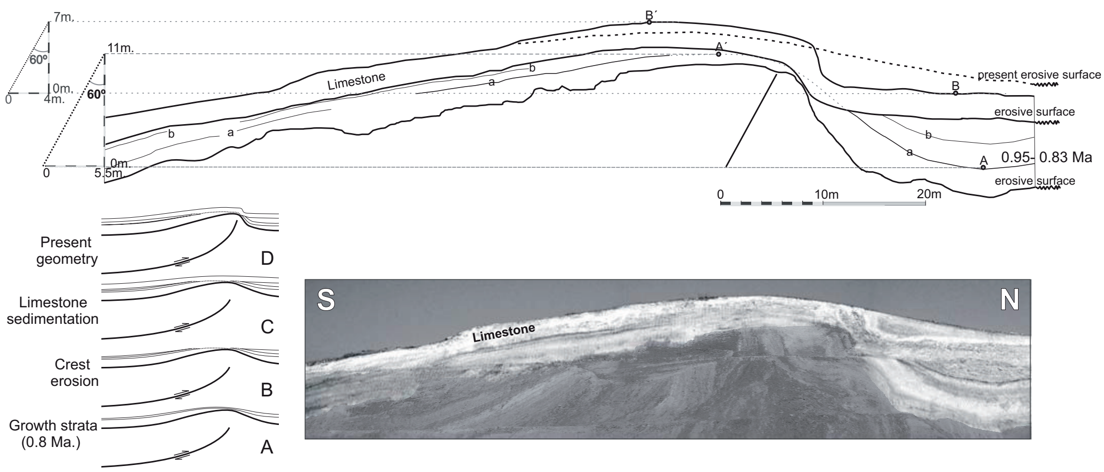

Fig. 7.8. Restoration of the Quaternary fault-propagation fold in the La Molata structure (A-D). We have restored up to the horizontal the 11 m of vertical displacement (point A-A´) in the layer "a" (0.95-0.83 Ma) obtaining 5.5 m of horizontal shortening. The same procedure for the limestone layer footwall ("b"): 7 m of vertical uplift and 4 m of horizontal shortening. In both cases the obtained fault dip is 60º to the South.

4.3. Deformation rates

The Quaternary sedimentation was affected by the fold growth, giving rise to growth strata (Fig. 7.8). The folding is related to a northward-propagating N70ºE oriented reverse fault dipping 55º S. We sequentially reconstructed the folding inferred from the syn-tectonic geometry of the growth strata, deducing a limb rotation of synclinal hinge during the development of the fold (Fig. 7.8). The thin layer "a", dated as mid-Pleistocene, and the footwall of the limestone layer "b" were considered to determine the deformation rates and to establish the active fault dipping. In these reference surfaces, the lowest (A, B) and highest (A', B') points were determined in order to establish the vertical offset of each layer. Horizontal shortening was determined by restoring the cross section. We deduce that the deformation propagates over a 60º S dipping reverse fault, fitting quite well with the younger measured fault in the outcrop (55º S dip). Using layer "a", containing fossils from 0.95-0.83 Ma, and taking into account that it was deposited during the first stage of the fold development, we obtain ~0.012-0.013 mm/yr uplift and ~0.006 mm/yr horizontal shortening rates. The rate deduced for the fault slip is ~0.014-0.016 mm/yr. These deformation rates are similar to the rates suggested for the eastern Albox fault: 0.01-0.02 mm/y uplift rate and a 0.03 mm/y fault slip-rate last for the 63.3 ky (Masana et al., 2005).

4.4. Stress and paleostress analysis

The stress and paleostress ellipsoids were determined from microfault and mesofault data using the method of Galindo-Zaldívar and González-Lodeiro (1988). This method provides data on the main stress axes orientations and the axial ratio ($R = (\sigma_2 - \sigma_3)/(\sigma_1 - \sigma_3)$) of the overprinted deviatory stress ellipsoids. The fault surface and the striae orientation were determined in two outcrops related to the La Molata structure. The regime was established on the basis of displaced beds, steps on fault surfaces, and tails of microcrushed fault gouges. The paleostress ellipsoids determined evidence for a main tectonic event characterized by a horizontal N150ºE maximum stress axis, a subvertical minimum stress axis and low-to-medium axial ratios (Fig. 7.9). These solutions are compatible with the development of compressive structures during the Late Miocene (E-W to ESE-WNW dextral and dextral-reverse faults, in some cases sealed by most recent sediments) and during the Quaternary (ENE-WSW reverse faults and folds).

In addition, we calculated the average stress tensors and the axial ratio from the nine earthquake focal mechanisms plotted in Figure 7.1 (Stich et al., 2003, 2006; IGN website) using a grid-search approach (FMSI software, Gephart, 1990). The best-fit stress ellipsoid has a subhorizontal minimum stress axis that is N60ºE oriented, a maximum stress axis N150ºE oriented, and medium to high axial ratio (Fig. 7.9).

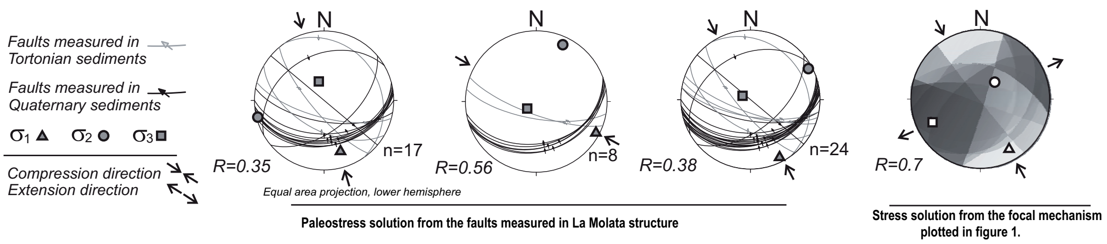

Fig. 7.9. Paleostress solution for the faults measured in La Molata structure and present-day stress from Earthquake focal mechanisms.

5. Discussion

In this manuscript we describe small-scale field examples of compressive Quaternary structures. We present the analysis of growth strata in a specific fault-related fold that reveals the fold development and evolution of deformation in an active compressive structure. The results allow us to discuss the role of small-scale tectonic structures located close to large seismogenic zones during the plate convergence process.

Data collected in the western Huércal-Overa basin suggest that compressive structures were active at least since the mid-Pleistocene, and probably from the Late Tortonian, accommodating a NW-SE shortening. These results are in agreement with recent studies in the nearby Almanzora basin that point to the activity of large folds and other compressive structures during the Tortonian (Pedrera et al., 2007). Some of these recent structures are small-scale ones and are located over previous faults that deform Tortonian sediments, such as the La Molata structure. In this outcrop, both Quaternary and Neogene faults were active under a similar stress ellipsoid, as deduced from the paleostress study. However in other outcrops, the compressive structures are located over WNW-ESE normal faults that were sometimes reactivated as dextral faults (e.g., El Romeral outcrop, Fig. 7.3D).

An open question remaining is the continuity in the deformation rate from the mid-Pleistocene up to now. Paleoseismological studies in the eastern Albox fault suggest a 0.01-0.02 mm/yr uplift rate and a 0.03 mm/yr fault-slip rate for the last 63.3 ky (Masana et al., 2005). These results are equivalent to the rates obtained for the La Molata structure for the last 0.95-0.83 Ma (~0.014 mm/yr uplift and ~0.015 mm/yr slip rate). Therefore, we can assume a continuous moderate activity of the reverse faults, probably related to a constant shortening rate from the mid-Pleistocene to present. The Quaternary structures and seismicity distribution in the western Huércal-Overa basin suggest that this shortening is accommodated along a broad area several kilometers wide that features open folds, fault-propagation folding and widespread small reverse and strike-slip faults.

The syn-folding fan geometry observed in La Molata structure point out a slow and progressive deformation from the mid-Pleistocene onward. We did not find sealed scarps or erosive deposits, such as clastic wedges, indicative of abrupt deformation events related to earthquakes. The outcropping fault zone is constituted by a gouge formed by crushed sedimentary rocks, but it may change its properties at depth, where the fault deforms the metamorphic rocks in the basement. In any case, all the evidence seen would indicate that the La Molata structure is most likely connected with aseismic ductile flow during the Quaternary fault-related fold growth.

The presence of pebbles cut by fault planes is indicative of the seismogenic character of the faulting (e.g. Azañón et al., 2004). In the Western Huércal-Overa, the Quaternary fault rocks are commonly developed on conglomerates. The pebbles located on fault planes are only reoriented according to the fault slip, but are never fractured, indicating an aseismic faulting behavior, also supported by the analysis of the La Molata fault-related-fold growth.

The Betics are subjected to a slow convergence that has produced the activity of some large tectonic structures during the Quaternary including folds and faults. Therefore, numerous paleoseismological studies have focused on individual faults. Such studies provide very important information about the timing, frequency, and size of prehistoric earthquakes. However, these large faults are frequently linked in space and in time with widespread small-scale active structures. In the Huércal-Overa basin, these minor structures accommodate part of the shortening and impede the increasing of elastic strain in the host rocks located close to the major faults, thus contributing to a decreased magnitude of seismicity in the area. Indeed, during the instrumental period no earthquakes of magnitudes higher than 4.4 were recorded. The integration of paleoseismological, seismological data and detailed geological observations in a region can therefore enhance our comprehension of its seismogenic potential.

6. Conclusions

The western Huércal-Overa basin is subjected to an active NW-SE shortening by the African and the Eurasian plate convergence, accommodated along a broad area several kilometers wide. Large structures are N-vergent folds and kilometric NE-SW to ENE-WSW sinistral strike-slip faults. In addition, widespread small-scale tectonic structures include ENE-WSW oriented open folds, fault-propagation folds and reverse faults, and WNW-ESE dextral faults. Some small-scale active compressive structures are mainly nucleated over previous WNW-ESE fault zones.

La Molata fault-propagation fold is one of the best examples. Paleostress ellipsoids determined in this structure, obtained from Neogene and Quaternary faults, evidence a tectonic event characterized by a horizontal NW-SE maximum stress axis compatible with Late Miocene (E-W to ESE-WNW dextral and dextral-reverse faults) and Quaternary deformations (ENE-WSW reverse faults and folds). The fold and the related faults propagated continuously, as evidenced the syn-tectonic geometry of the growth strata. Strain rates calculated across the structure give a constant ~0.007 mm/yr horizontal shortening and ~0.014 mm/yr vertical displacement from the mid-Pleistocene up to now, within the range of other structures. These structures contribute to the 4-5 mm/yr accommodation of present-day NW-SE plate convergence.

Small-scale structures play an important role during elastic energy dissipation around large seismogenic zones in diffuse plate boundaries, reducing the accumulation of elastic energy and decreasing the highest magnitudes reached by the related seismicity. This process may favor the development of recent folds and aseismic faults over previous fault zones.

Acknowledgements

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8. Testing the sensitivity of geomorphic indices in areas of low-rate active folding (eastern Betic Cordillera, Spain)

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Active deformation structures have an incidence in topography that can be quantified by using geomorphic indices. Most of these indices have been checked in faulted regions with high-deformation rates. The application of several geomorphic indices (hypsometric curve analysis, normalized stream-length gradient, and valley width-to-valley height ratio) to the drainage network of the southern limb of the Sierra de Las Estancias antiform (Internal Zones, eastern Betic Cordillera), where low-rate active folding has been recognized, allows us to investigate the suitability of these indices to identify active structures in such a scenario. Hypsometric curves clearly identify regions with recent uplift and young topography, but they do not provide any constraint on the location of active folds. Local valley width-to-valley height index variations have been detected just coinciding whit the position of ENE-WSW active folds. Normalized stream-length gradient index serves to locate active folds in areas of hard rock substratum, but not in those areas with soft sediments (Neogene-Quaternary sedimentary basins). This is most likely due to the fact that in the basins erosion is much more intense than in the hard rock sectors. In view of these results, we consider that geomorphic indices constitute a valuable tool for identifying sectors affected by low-rate uplift related to active folding, with the best results obtained in hard rock areas.

Keywords
Active and recent tectonics, low-rate folding, river incision, alluvial fan, SLk index, Vf index, hypsometric curve, Betic Cordillera

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1. Introduction

Recent and active tectonic structures may affect the topographic surface, interacting with geomorphic processes during landscape evolution. Geomorphic indices are indicators capable to detect landform responses to recent deformation processes and therefore have been broadly used as a recognition tool to characterize sectors deformed by active faults (e.g., Seeber and Gornitz, 1983; Brookfield, 1998; Keller and Pinter, 2002; Chen et al., 2003; Kobor and Roering, 2004). In areas subjected to active shortening, the relief is mainly controlled by reverse faults and folds that generate straight mountain fronts, with antiforms producing surface uplift. Fluvial and alluvial fan systems are very sensitive to uplift due to base-level lowering, resulting in complex changes in the sedimentation/denudation pattern (e.g., Mather, 1993; Mather 2000; Mather et al., 2000; Mather et al., 2002; Stokes et al., 2008). Erosion usually turns into the main process producing channel incision, river deflection, headward erosion, and eventually piracy processes (Holbrook and Schumm 1999; Burbank and Anderson, 2000; Lavé and Avouac, 2001; Snyder et al., 2000; Hilley and Arrowsmith, 2008). Normalized stream length-gradient index (SLk), valley floor-to-valley height ratio (Vf) and hypsometry curves have been previously demonstrated as useful geomorphic indices to successfully evaluate relative tectonic activity in high-rate folded areas, such as Taiwan (Delcaillau et al., 1998; Chen et al., 2003), the Himalaya fault-and-thrust belt (Seeber and Gornitz, 1983; Brookfield, 1998; Delcaillau et al., 2006; Malik and Mohanty, 2007), and some sector of the California coastal ranges (Medwedeff, 1992; Mueller and Talling, 1997; Keller et al., 1998; Azor et al., 2002). These regions are subjected to high convergence rates (more than 10 mm/y), reaching up to 7.1 cm/y in Taiwan (Seno et al., 1993), 14 mm/y to 21 mm/y in the Himalaya, (Lyon-Caen et al., 1985; Wesnousky et al. 1999; Larson et al., 1999), and 10.4 mm/y in the Pacific-North America margin (Hammond and Thatcher, 2004).

To the contrary, in active regions with low to very low convergence rates (less than 5 mm/y), folds grow slowly and high erosion rates may suppress the effects of active tectonics on present-day topography, thus questioning the suitability of geomorphic indices to characterize recent and active tectonics.

The aim of this contribution is to test the application of different geomorphic indices in an area of low-tectonic rates where the deformation is characterized by folding. To do so, we propose the assessment of SLk, Vf and hypsometry curve analysis in an area of the eastern Betic Cordillera (SE Spain) deformed by active folds affecting basement rocks of the southern slope of the Sierra de Las Estancias antiform and Neogene-Quaternary basin sediments that fill the Almanzora and the western Huércal-Overa basins. Despite the fact that regions of crustal shortening generally show high variable rates of convergence and uplift (spatially and temporally), recent studies have confirm the low-deformation rate of specific structures in this sector of the cordillera

(Masana et al., 2004 and 2005). This area is included in the 300-km-wide zone between Eurasia and Africa, which accommodates a present-day convergence rate of 4.5 mm/y (DeMets et al., 1990, 1994). The medium-scale recent and active folds are difficult to characterize in Sierra de Las Estancias due to the absence of sedimentary cover. Such metamorphic rocks are generally affected by previous polyphasic ductile and brittle deformations, which may complicate the characterization of recent and active folds.

2. Geological and geomorphical setting

The Betic Cordillera is part of the westernmost Alpine mountain belt formed by the relative convergence between Eurasia and Africa (Fig. 8.1). This cordillera has been traditionally subdivided into the External and the Internal Zones (Fallot, 1948) (Fig. 8.1A). The External Zones include rocks deposited in the southern boundary of the Iberian Massif in Mesozoic-Cenozoic times, which were deformed during the Neogene as a thin-skinned fold-and-thrust belt (Jabaloy-Sánchez et al., 2007). The Internal Zones comprise Palaeozoic and Mesozoic rocks metamorphosed and highly deformed during the Alpine orogeny.

The present-day relief of the Betic Cordillera started to develop in Tortonian times (e.g., Braga et al., 2003) (Figs. 8.1B, C). Topography is strongly conditioned by the presence of kilometre -scale folds, which mark the main ranges (antiforms) and basins (synforms) (Martínez-Martínez and Azañón, 1997; Crespo-Blanc and Campos, 2001; Galindo-Zaldívar et al., 2003; Sanz de Galdeano and Alfaro, 2004; Marín-Lechado et al., 2006; Ruiz-Constán et al., in press). In the eastern sector of the cordillera, these kilometre-scale folds interact with sinistral strike-slip faults NE-SW to NNE-SSW oriented (Weijermars et al., 1985; Montenat and D'Estevou, 1999; Booth-Rea et al., 2004). Sedimentary basin development was partially simultaneous to this folding and faulting (García-Meléndez et al., 2003; Pedrera et al., 2006). These major tectonic structures are still active and interact with other minor structures to accommodate the NW-SE 4.5 mm/y convergence rate between the Eurasian and African plates (DeMets et al., 1990, 1994). Seismological data reveal a low to moderate seismicity with diffuse distribution (e.g., IGN 2008). Earthquake focal solutions obtained in the Eastern Betics also support the NW-SE compression (Stich et al., 2003, 2006; Fernández-Ibáñez et al., 2007).

Recent and active tectonics in the eastern Betic Cordillera have a direct incidence on landscape evolution (e.g., Silva et al., 1993, 2003; García-Meléndez et al., 2003; Sanz de Galdeano and Alfaro, 2004; García-Tortosa et al., 2008). In this respect, differential uplift, deformation of present-day fluvial profiles, fast headward erosion, and stream piracy are described (Calvache and Viseras, 1997; Calvache et al., 1997; Azañón et al., 2005; Stokes and Mather, 2003; Booth-Rea et al., 2004; El Hamdouni et al., 2008;

Stokes, 2008). Nevertheless, regional long-term uplift rates in the Betic Cordillera can be said to be low to moderate —as compared to more active regions in the earth— with values in the range 0.05 to 0.28 mm/y (Braga et al., 2003; Silva et al., 2003). Recent studies focused on this sector of the Betic Cordillera estimate deformation rates at a more local-scale and related to fault-activity (Fig. 8.1B). La Molata fault-propagation fold give a ~0.014-0.016 mm/yr slip-rate from mid-Pleistocene (Pedrera et al., 2008a, accepted). In the reverse Albox fault, located in the Huércal-Overa basin, uplift rates of 0.01-0.02 mm/y and fault slip-rates of 0.03 mm/y for the last 63.3 ky have been estimated using geochronological data (Masana et al., 2005). In the Alhama de Murcia Fault, geochronological studies reveal vertical slip-rate values of 0.10-0.35 mm/y during the last 30 ky (Masana et al., 2004). These uplift rates are also very similar to the 0.12 to 0.33 mm/y obtained for the active Baza fault since the Late Tortonian (Alfaro et al., 2007; García-Tortosa et al., 2008).

The area studied, located in the Internal Zones of the Eastern Betic Cordillera, comprises metamorphic rocks of the southern flank of Sierra de Las Estancias late antiform, as well as Neogene-Quaternary sediments of the adjacent Almanzora and Huércal-Overa sedimentary Basin, belonging to the Almanzora drainage system (Fig. 8.1C). This sector of Sierra de Las Estancias comprises several Alpujárride nappes formed by marbles, schists, and phyllites. These rocks were deformed during the Early and Middle Miocene by N-vergent kilometre-scale recumbent folds with associated foliations and low-angle normal faults (Lonergan and Platt, 1995). Since the Early Tortonian, sedimentary basins mainly filled by detritic rocks (Briend, 1981; Guerra-Merchán, 1992; Montentat and Ott D'Estevou 1999, Meijninger, 2006) started to develop in association with the kilometre-scale folds and oblique-slip NW-SE oriented normal faults (Pedrera et al., 2007) (Fig. 8.1).

2.1. The Almanzora River drainage system

The Almanzora River has a catchment area of ca. 2600 km^2 (Stokes and Mather, 2003) and extends 100 km from the southernmost part of the Baza basin (1000 m avobe sea level) to the Mediterranean Sea. It crosses the so-called Almanzora Corridor along its southern boundary, the western Huércal-Overa and the Vera basins (Fig. 8.1C).

At present, the Almanzora River has an ephemeral flood hydrology and a coarse-grained bed-load that is determined by the rain-fall cycle. The region is semi-arid (210–500 mm annual precipitation, Stokes and Mather, 2003) with rainy events concentrated in short-time periods, usually with very high intensity (Volk, 1973; Thornes, 1974; Esteban-Parra et al., 1998).

Climate-related factors interacted with long-term tectonics during the river evolution. Short-term climatic oscillations related to glacial/interglacial periods favored an episodic fluvial behaviour during the Quaternary (Harvey, 1987). Thus, glacial episodes enhanced sediment production, resulting in depositional landforms such as river terraces and alluvial fans. River incision was dominant during interglacial periods, when increased vegetation cover and associated hillslope stability produced a reduction in the sediment supply to river systems (Harvey, 1987; Harvey et al., 1995).

In the upper part of the Almanzora catchment, the tributary rivers flow from the two nearby ranges, Sierra de Las Estancias to the north and Sierra de Los Filabres to the south. This study is focused on the northern tributary streams. Some of these tributary rivers sharply change their direction from E-W to NNW-SSE near the river heads (Fig. 8.2). NW-SE normal faults determine small (1-2 km) changes in the direction of these tributary streams (Pedrera et al., 2007).

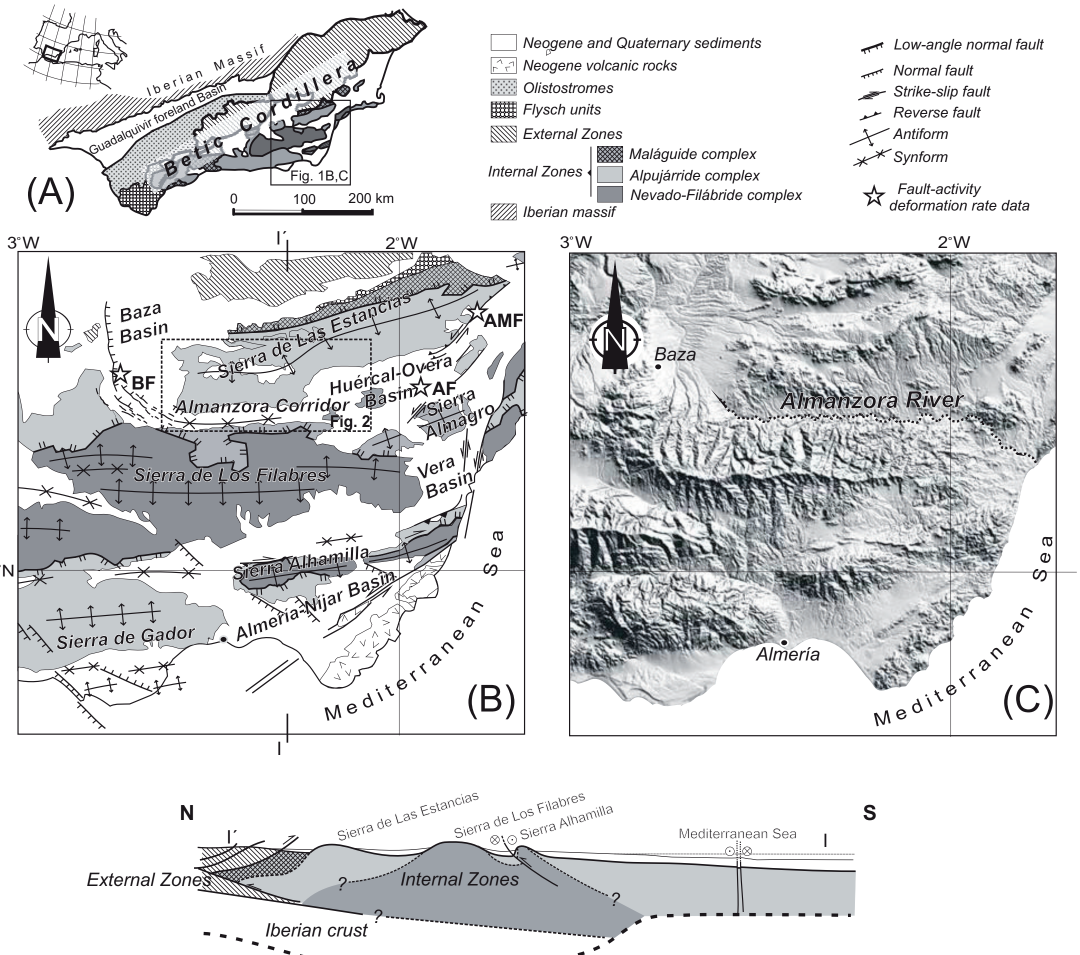

Fig. 8.1. Geological map of the Betic Cordillera showing the different domains (A), enlarged detail of the eastern sector showing the main active folds and faults (B) and digital elevation model of the eastern sector (C). BF: Baza Fault; AF: Albox Fault; AMF: Alhama de Murcia Fault.

All the tributary streams studied flow over the metamorphic rocks of the Sierra de Las Estancias and then incise into the Neogene-Quaternary sediments of the Almanzora and Huércal-Overa basins. These sediments are deformed by ENE-WSW trending folds in the eastern sector of the Almanzora Corridor (Fig. 8.2). In the margin of the Almanzora basin, coarse-grained deposits crop out related to Plio-Quaternary alluvial fans (Harvey, 1984, 1990).

2.2. Alluvial fans

Tectonic activity usually generates alluvial fans at the foot of the developed mountain fronts. In the Betic Cordillera, large alluvial fan systems developed during the Quaternary (Harvey, 1987, 1990; Silva et al., 1992; Viseras et al., 2003) associated with fault-bounded mountain fronts (Calvache et al., 1997) and folds bounded mountain fronts (Marín-Lechado et al., 2006).

Several generations of alluvial fans have developed along the southern limb of the Sierra de Las Estancias antiform and along the Almanzora Corridor basin. They were formed by sediment transport along feeder channels located in the Sierra de Las Estancias range. The configuration of the Almanzora Corridor and the western Huércal-Overa basin is clearly asymmetric. The position of the trunk Almanzora River, close to the southern boundary of both basins, implies the development of alluvial fans only on the north margin of the river system. These alluvial fans run from north to south with a telescopic geometry (elongated and with low thickness). Their age is not well constrained, though a mid-Pleistocene to late-Pleistocene age has been attributed for their growth (Guerra-Merchán, 1992), subjected to erosion since then.

2.3. Little dissected plains

The E-W to ENE-WSW direction of the Sierra de Las Estancias tectonic structures, together with the differential erosion degree of its metamorphic rocks, determines the presence of two elongated plain areas (Oria and Los Alamos plains, Fig. 8.2). These flat areas are located over the easily erodible phyllites and schists and have a gently concave shape, low slope, and a thin sedimentary cover —only small alluvial fans are found here close to the topographic highs—.

These flat, weakly dissected areas were recently captured by incision and headward erosion of the Almanzora north tributary rivers, cutting resistant carbonate lithological sequence, which can be considered as a hard barrier between the Neogene-Quaternary basins and the soft schist and phyllite rocks. This capture developed right-angle river diversions and prominent V-shaped gorges cut into the carbonates (Fig. 8.2).

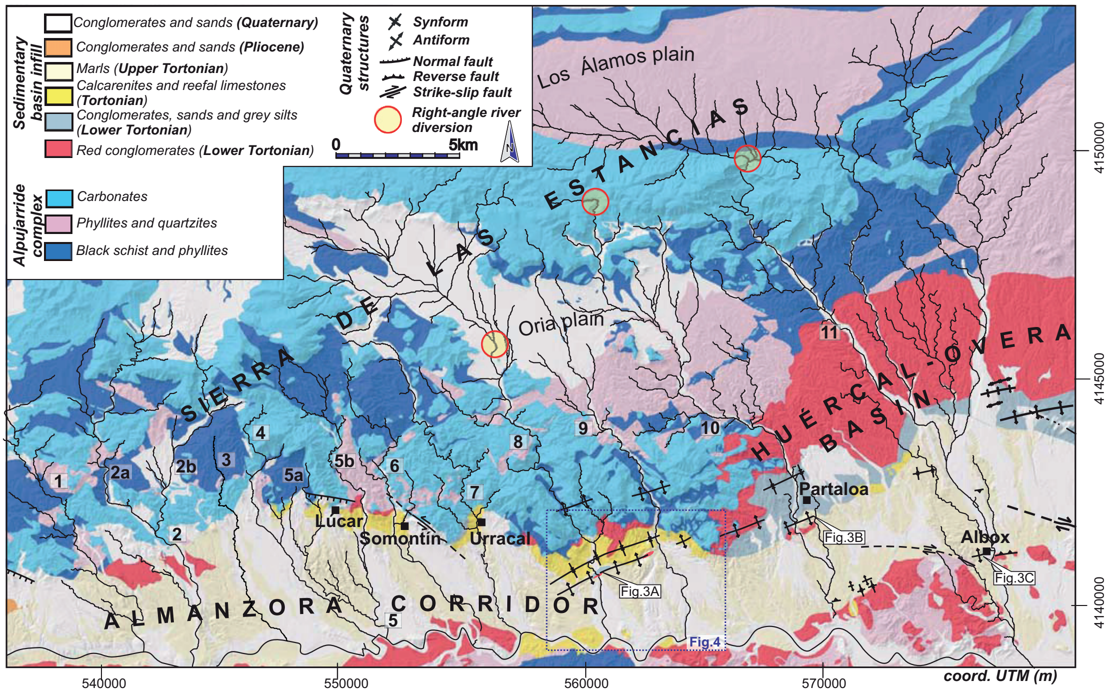

Fig. 8.2. Geological map of the studied area where are marked the active tectonic structures and the fluvial network. The position of the outcrops showed in the fig. 3 (chapter 8) is marked. Modified from: Baena et al., (1978a,b), Voermans et al., (1979 and 1980), Pedrera et al. (2007).

3. Approach

Geomorphic indices provide a tool for characterized recent and active structures (Keller and Pinter, 2002). In order to assess their suitability to detect recent and active low-rate folds the Sierra de Las Estancias-Almanzora and Huércal-Overa basin sector have been selected. We have used as starting point a detailed field work, which included kinematical analysis and spatial mapping of the tectonic structures (Pedrera et al., 2007). In order to elucidate the effect of the minor folds in the sediment infilling, we also have made several topographic profiles over three alluvial fans developed on the northern margin of the Almanzora basin. These profiles allow us to infer the Quaternary fold activity by analyzing their slope and the differential erosion degree.

Due to the configuration of the drainage network, with the main rivers being orthogonal to the tectonic structures, we have selected the normalized stream-length index (SLk) and the hypsometric curves as geomorphic indicators of possible recent and present-day tectonic activity. These geomorphic indexes are useful in such conditions, since they underline changes in river gradient and erosion pattern along river profiles (Seeber and Gornitz, 1983; Brookfield, 1998; Chen et al., 2003; Pérez-Peña et al., 2008b, in press). We have also calculated the valley width-to-valley height ratio (Vf) in order to quantify differences in erosion pattern between the different valley rivers.

To extract the drainage network, the drainage basins and the geomorphic analysis, a Digital Elevation Model with 10 m of pixel resolution has been used. In addition, topographic maps at a scale 1:25000 and 1:10000 from the Spanish military service, colour aerial photographs at a scale 1:10000 obtained in 1998/1999, and black and white aerial photographs at a scale 1:5000 obtained in 2001/2003 were used to check the validity of the drainage network and drainage basins. The drainage network has been obtained by computing a single flow drainage direction using the D8 (eight directions) method (O'Callaghan and Mark, 1984) on each cell of a Digital Elevation Model with 10 m of pixel resolution. This method assigns flow from each grid cell to one of its eight neighbours, either adjacent or diagonal, in the direction of steepest downward slope. The results were compared with topographic maps and aerial photographs in order to correct anomalous drainage flows. The main rivers were selected and their catchment areas obtained by identifying pour points in river mouths and using the flow direction previously calculated.

4. Recent folds

Prior to the geomorphic analysis, the recent folds in the study area have been mapped and described from a tectonic point of view. We need to constrain the position and geometry of these recent structures in order to check the sensitivity of the different geomorphic indices.

The selected area is characterized by several recent N-vergent kilometre-scale folds with an orientation ranging from E-W to ENE-WSW, namely the Sierra de Los Filabres antiform, the Sierra Almagro antiform, the Almanzora Corridor synform, and the Sierra de Las Estancias antiform (Fig. 8.1B). These antiforms coincide with the ranges where the metamorphic complexes are exposed, affecting all of the previous structures, including the Early-Middle Miocene low-angle normal faults and related structures. These folds are furthermore identified by a tilting of the bedding in Neogene sediments located along their limbs. Syn-sedimentary unconformities are located in both the northern and southern boundaries of the Almanzora basin (Pedrera et al., 2007), as well as in the Sierra de Almagro open antiform, which deforms both the sediments of the Vera and Huércal-Overa basins (Booth-Rea et al., 2003b, 2004).

The sedimentary infill of the easternmost Almanzora Corridor and the western Huércal-Overa basin is deformed by ENE-WSW trending folds that sometimes affect the Quaternary sediments (e.g., Briend, 1981; Soler et al., 2003; Masana et al., 2005; Pedrera et al., 2007) (Fig. 8.2, 8.3). These folds have variable wavelengths (from meters to hundreds of meters) and geometries ranging from open to tight N-vergent with a minimum interlimb angle of 50º. A succession of folds, affecting a broad band of basement rocks in the eastern Almanzora Corridor (Figs. 8.2, 8.3A, B), must have involved basement rocks, as deduced from gravimetric data (Pedrera et al., 2008b, in press). In some cases, these folds are related to reverse fault growth and interpreted as fold-propagation faults (La Molata structure, Fig. 8.3C). The timing of these folds is deduced from the progressive unconformities in the sediments of the limbs. The dip increase from lower to upper Tortonian sediments is indicative of syn-tectonic sedimentation (Fig. 8.3A). Fold development continues during the Pliocene and Quaternary, as recognized in a few outcrops where the exposure conditions are exceptional (Figs. 8.2, and 8.3C).

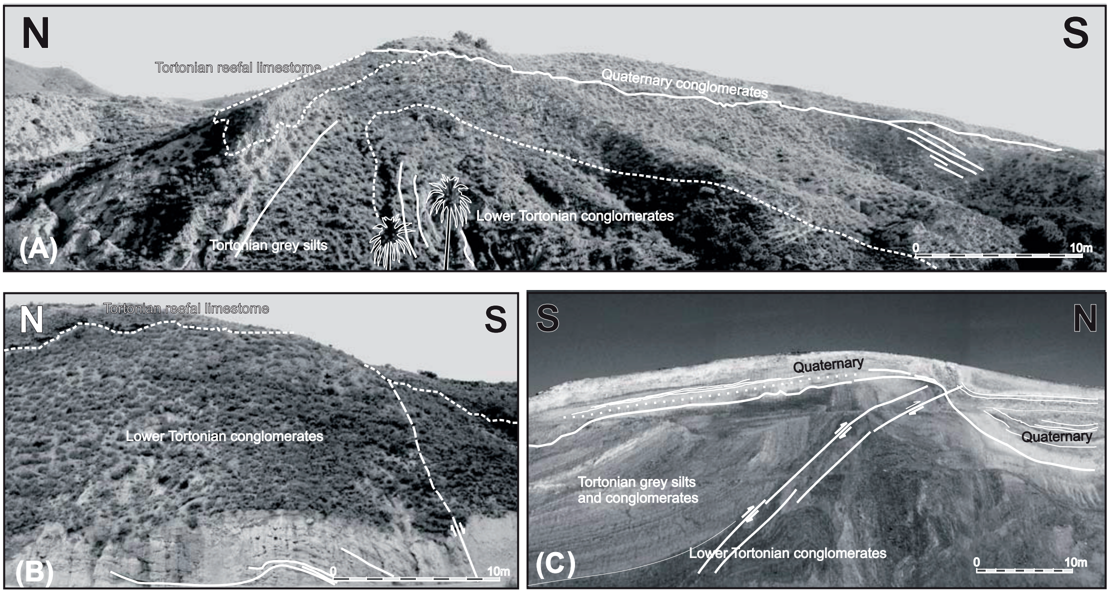

Fig. 8.3. Field examples of ENE-WSW folds. Position of the outcrops is marked in fig. 2 (chapter 8).

4.1. Topographic profiles

The minor folds observed in the field between Partaloa and Urracal clearly deform the Late Miocene sediments, sometimes showing progressive growth strata (Fig. 8.3). The alluvial fan deposits unconformably overlie the Miocene folded sequence, making it difficult to discern whether or not the folds affect or not the Quaternary rocks. This is due to the open geometry of the folds and the erosion in the alluvial fans by river incision. Six longitudinal topographic profiles made along three alluvial fans developed on the northern Almanzora basin (A, B, and C, in Fig. 8.4) allow us to infer the Quaternary folds activity. We analyzed the slope and differential erosion degree of alluvial fans A and B, located just over the folded Upper Miocene sediments, as well as the alluvial fan C, which is undisturbed by minor folds. The profiles were obtained picking the fan surfaces. Since the fans are highly dissected, we have generated profiles envelopes by taking the topographic highs along the profiles that are related to the

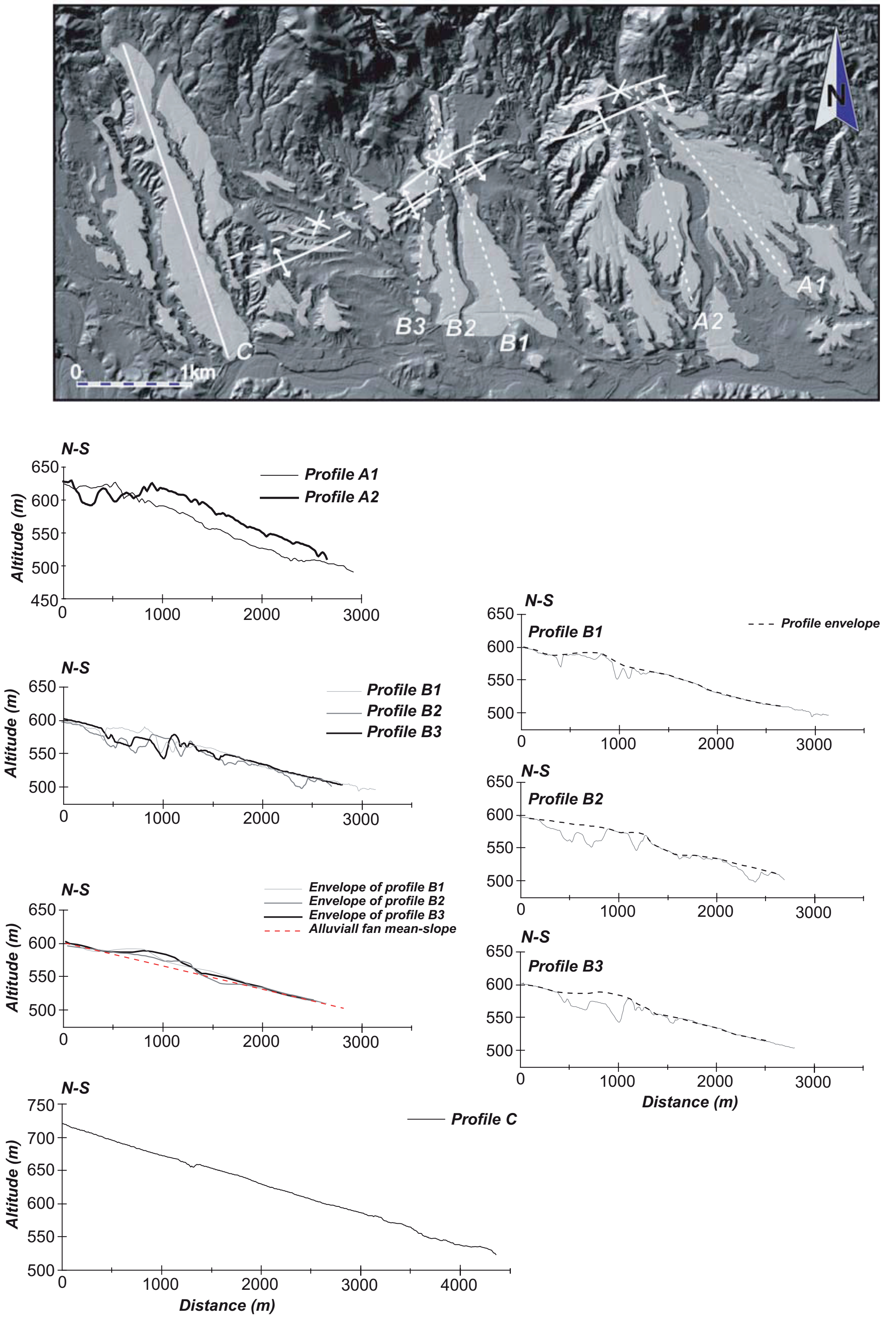

Fig. 8.4. Enlarged image of the DEM (10-m grid) where is plotted the position of the alluvial fan and the topographic profiles (A and B). In order to better interpret the alluvial fan morphologies, we draw the envelope for the fan topographic profiles that show a clear elevated area in the three profiles that coincided to an antiform trace.

deformation caused by folds.

The two longitudinal profiles constructed along the alluvial fan A reveal two sectors. In the upper sector close to the apex, a flat partially eroded zone just coincides precisely with the antiform hinge (profile A2 in Fig. 8.4). Farther down, the fan reaches a normal and constant gradient (0.064). The three radial profiles made along the alluvial fan B show three different sectors: less-eroded upper and lower parts with a constant gradient (~ 0.033 for the three profiles) and a prominent more-eroded middle part. The same gradient is seen in the upper and the lower part of the alluvial fan, indicateing a single fan generation. The elevated middle part of the profiles outlines the trace of the antiform. The profiles located over the alluvial fan C maintain a regular and constant gradient (0.044) throughout the profile and lacking any signs of deformation by folding.

5. Strength of the lithological sequence

In order to qualitatively characterize the behavior of the different rocks in the studied area with respect to the weathering and runoff erosion we used a lithological map (Baena et al., 1978a,b; Voermans et al., 1979, 1980; Pedrera et al., 2007) representing the fluvial network (Fig. 8.2). Unconfined compressive strength field tests have been used to quantify rock strength (Mining Life, 2005).

In the Sierra de Las Estancias, the Alpujárride Complex include several thrust sheets with very similar lithological sequences. They are made up of Paleozoic to Mesozoic metamorphic rocks with several overprinted foliations and, sometimes, with stretching lineation. The lowest lithological unit is formed by weak to medium strong black schist with thin quartzite intercalations. The intermediate unit is composed of phyllites and fine-grained light schists, which also have weak to medium strong. The topmost unit is made up of very to extremely strong marbles, which are responsible for the main relieves of the region.

In the Almanzora and Huércal-Overa basins, the sedimentary sequence is essentially detritic (Briend, 1981; Guerra-Merchán, 1992; Montentat and Ott D'Estevou 1999, Meijninger, 2006) and starts with a strong to very strong thick continental red conglomerate formation of Early Tortonian age. These continental deposits contain coarse to very coarse clasts of metamorphic rock embedded in a red sandy clay matrix. The clasts show a close packing and are occasionally cemented. These conglomerates gradually change upwards into a succession of strong conglomerates, medium strong sands, weak silts, and weak gypsum. At the top, an angular unconformity separated the previous formation from strong Tortonian bioclastic reefal limestones and well-packed strong calcarenites, which change to yellow marls toward the center of the basin that have a very weak to weak behaviour. Weak Messinian marls crop out in the easternmost part of the study area. During the Pliocene and Quaternary, detrital alluvial fans and river deposits were unconformably placed over the Miocene rocks. These sediments often show groundwater cementation at the bottom and pedogenic calcretes at the top (Stokes et al., 2007); they have numerous open joints, though they constitute a strong lithology.

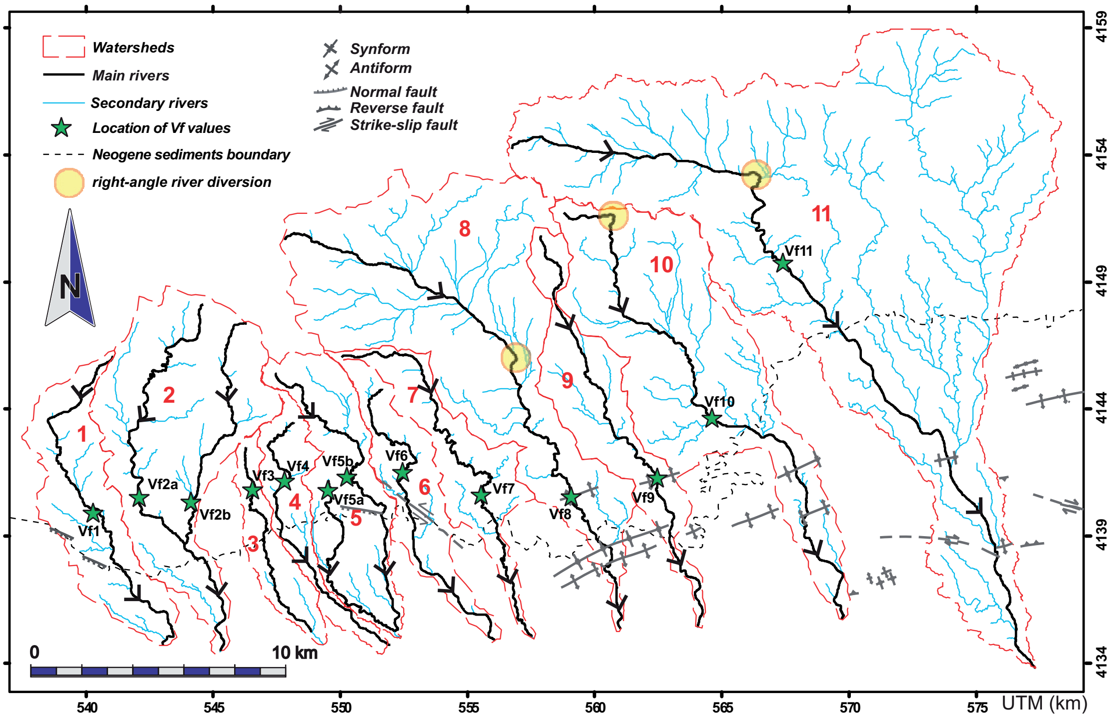

Fig. 8.5. Position of the analyzed drainage network, the drainage basins, and the sectors where the Vf have been calculated. The main active folds and faults are marked.

6. Geomorphic analysis

We analyzed two geomorphic indices [valley floor-to-valley height ratio (Vf) and normalized stream-length gradient (SLk)], together with topographic river profiles and hypsometric curves in areas affected by the active folds previously described.

6.1. SLk index

River systems attain an erosion/sedimentation equilibrium characterized by slightly concave longitudinal profiles (Mackin, 1948; Schumm et al., 2000). Deviation from this river equilibrium profile may be induced by tectonic, lithological and/or climatic factors (Burbank and Anderson, 2000). The SLk index highlights anomalies in river longitudinal profiles, providing criteria to evaluate and quantify these slope

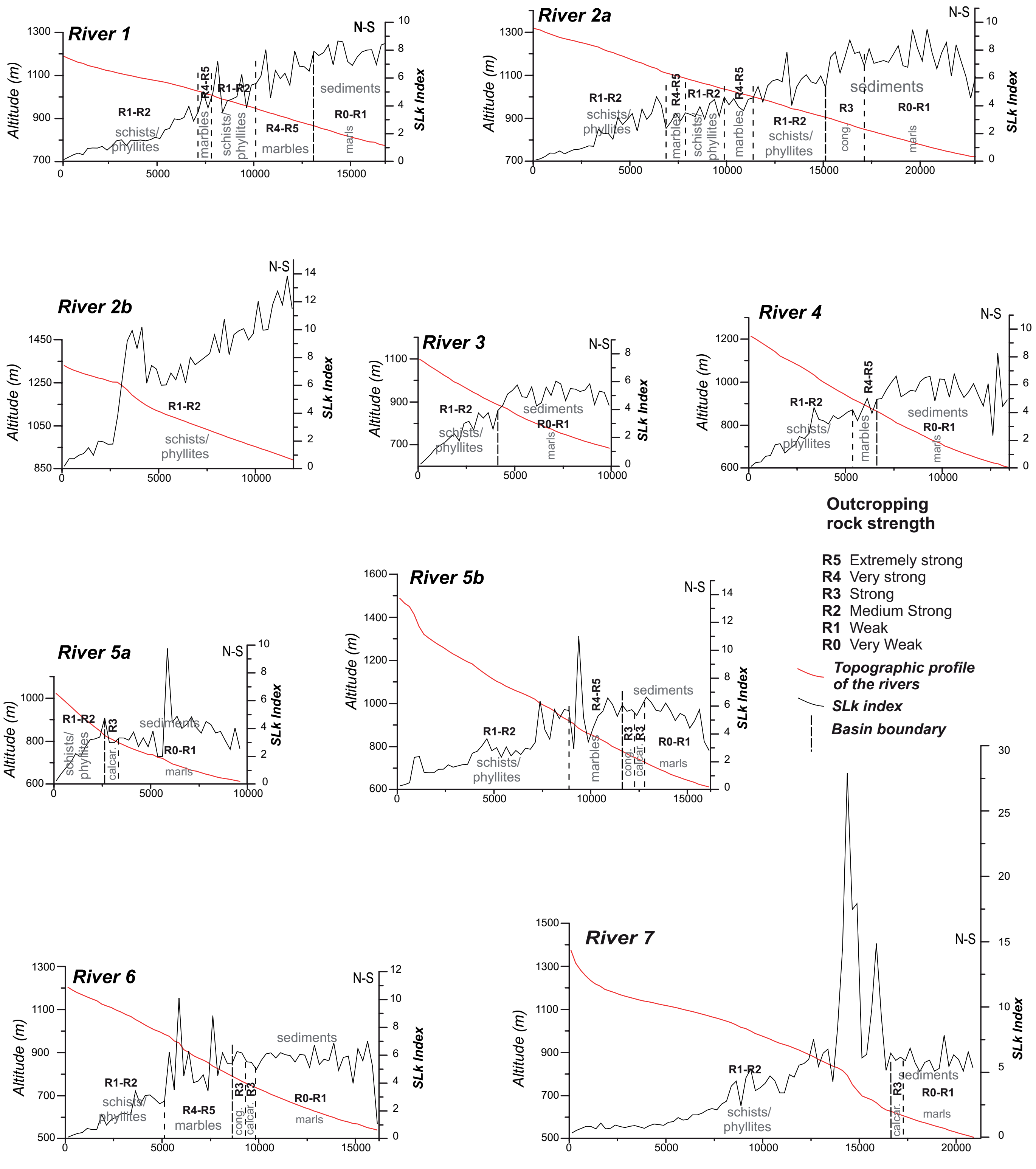

Fig. 8.6. River topographic and SLk profiles. The lithological changes are marked.

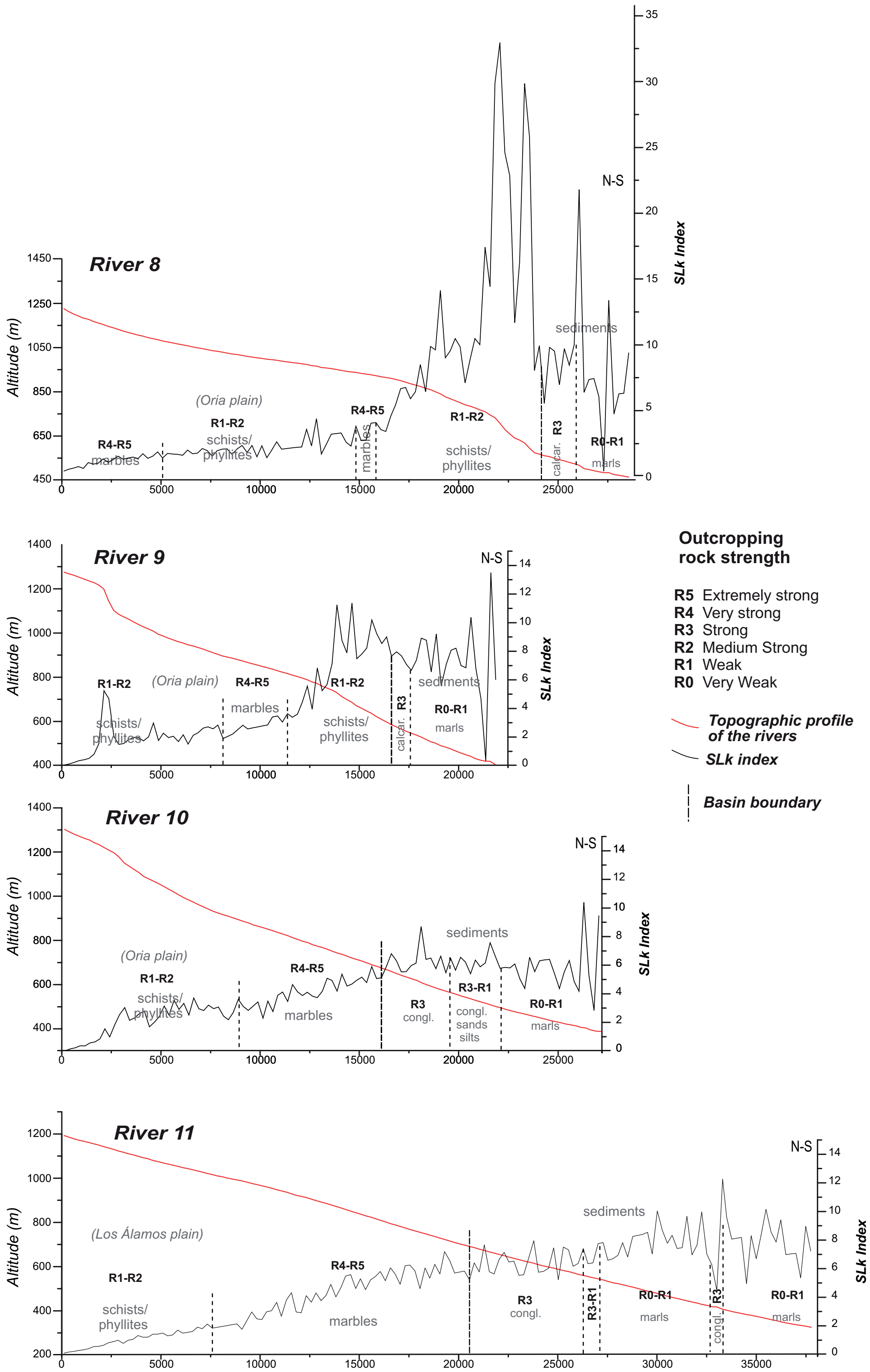

Fig. 8.6. (Continuation)

changes (Hack, 1973; Keller and Pinter, 2002; Pérez-Peña et al., 2008b, in press).

The topographic profiles of the rivers feature prominent steps when cutting the metamorphic rocks of the Sierra de Las Estancias (rivers 7, 8, 9 in Figs. 8.5 and 8.6). In order to assess the incidence of low-rate active folds on channel equilibrium parameters we have performed stream-length gradient index (SLk) on the main tributary streams rivers. We considered SLk points a value of 250 m as a calculation for fixing interval, yielding 1019 points for the analysis. The 250 m distance was assumed by following the methodology proposed by Perez-Peña et al. (in press-b) in the nearby Granada basin. Our study area presents similar climate and relief conditions. From these SLk values, an anomaly map was generated by using a krigging statistic method based on a variogram model (Fig. 8.7). The anomaly map shows a local maximum over the metamorphic rocks of the Sierra de Las Estancias, which is detected on three rivers (rivers 7, 8, and 9 in Figs. 8.5 and 8.6). This maximum is elongated with an ENE-WSW trend, running parallel and coincident with the folds traces identified on the sediments. The Slk profiles of these rivers present two maximum values, which are displaced downstream from the topographic steps. In the other rivers studied, such SLk anomalies have were not detected, even though the rivers run from the hard metamorphic rocks of the Sierra de Las Estancias to the softer and more erodible Neogene sediments of the Almanzora Corridor (Figs. 8.2, 8.5, and 8.7). Finally, in the sedimentary basin, despite the presence of active folds with associate topographic highs, no SLk maximum was detected.

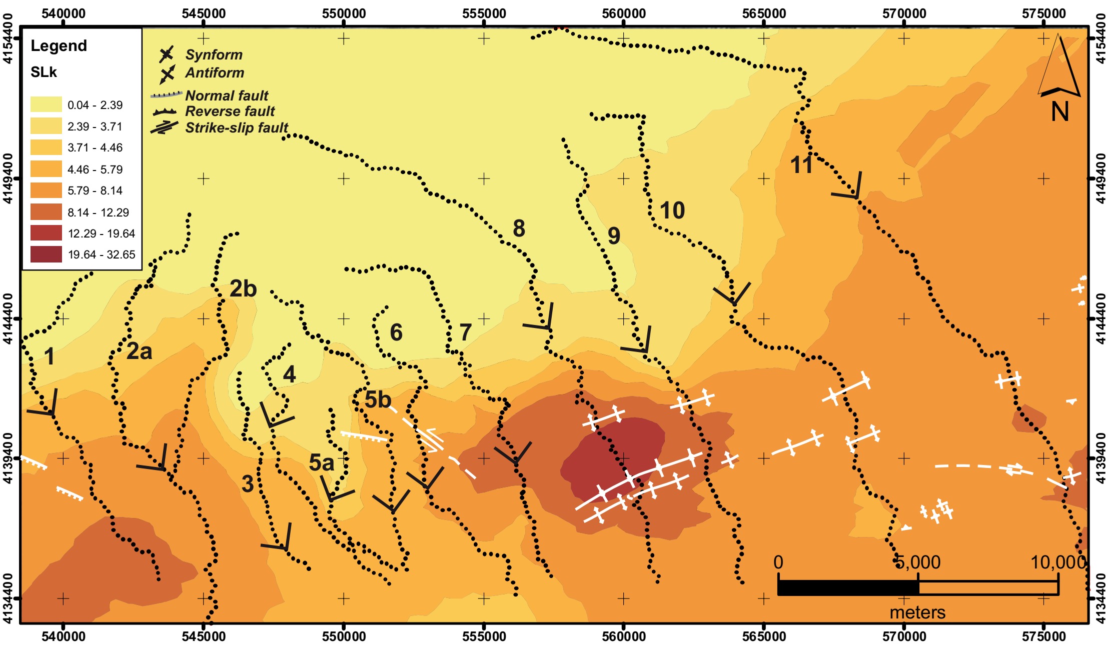

Fig.8.7. SLk anomaly map. The active tectonic structures are marked

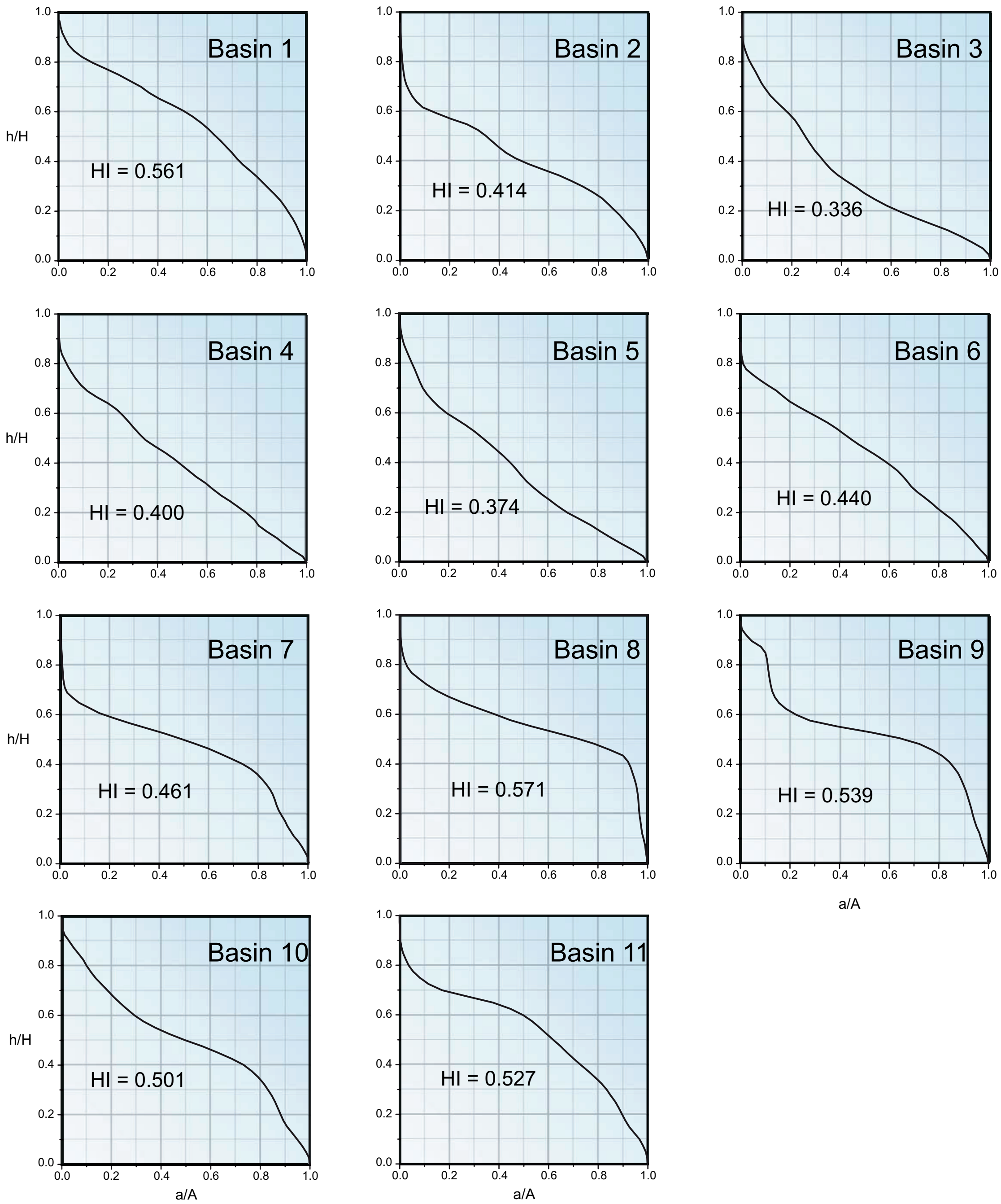

Fig. 8.8. Hypsometric curves analyzed.

6.2. Hypsometric curves

The hypsometric curve of a catchment represents the relative area below (or above) a given altitude (Strahler, 1952). These curves have been used to infer the stage of development of the drainage network, i.e., the erosional stage of the catchment (Keller and Pinter, 2002). Convex hypsometric curves characterize young slightly eroded regions; S-shaped curves characterize moderately eroded regions; concave curves point to old, highly eroded regions. The area below the hypsometric curve is known as the hypsometric integral (HI), varying from 0 to 1 (with values close to 0 in highly eroded regions and values close to 1 in slightly eroded regions). The shape of the hypsometric curves —and the HI values— provide valuable information not only on the erosional stage of the basin, but also on the tectonic, climatic, and lithological factors controlling it (e.g., Moglen and Bras, 1995; Willgoose and Hancock, 1998; Huang and Niemann, 2006). The area below the hypsometric curve portrays the amount of material left after erosion, as the curve gradient becomes sharper in its left-initial section (that represent the river-head) the amount of material left after erosion is smaller (Strahler, 1952; Harlin, 1978; Luo 2000; Pérez-Peña et al., 2008a, in press). That can be considered a sign of maturity of the basin, since indicates that the lateral erosion has been intensive in river head (Ohmori 1993; Keller and Pinter, 2002). It is clear, that a piracy process or differential uplift would have an influence in the shape of an hypsometric curve of a basin. Such processes would increase erosion in the basin and it would be reflected in the hypsometric curve as a progressive increase in convexity. To draw the hypsometric curves, we have used an extension (Pérez-Peña et al., 2008a, in press) of the software ArcGIS 9.1 and a DEM with 10 m of pixel resolution.

The hypsometric curves obtained for the 11 selected basins are shown in Figs. 8.5 and 8.8. We distinguished two groups with a particular curve shape. The basins located in the western sector (1, 2, 3, 4, 5, and 6) and the easternmost basins (10 and 11) constitute the first group, characterized by a general subrectilinear to very smooth concave-convex shapes. The second group corresponds to the basins in the eastern sector (basins 7, 8, and 9), featuring convex shapes in the middle-mouth basin parts.

6.3. Valley width to valley height ratio (Vf)

Valley width to valley height ratio (Vf) (Bull and McFadden, 1977) is a geomorphic index conceived to discriminate between V-shaped valleys (Vf values close to 0) and U-shaped, flat-floored valleys (high Vf values). Deep V-shaped valleys are associated with linear active incision, distinctive of areas subjected to active tectonics; while flat-floored valleys are characteristic of sectors with less river incision, where lateral erosion predominates in response to constant base levels and low tectonic activity (Keller and Pinter, 2002). This index has been applied to evaluate the relative degree of tectonic activity of several mountain fronts located in the eastern and central Betic Cordillera (Silva et al., 2003).

The Vf values were obtained in the river reaches located above the rocks in order to avoid lithological controls, at a distance of ~1 km upstream from the contact between the basement and the sedimentary basins. We have calculated Vf with a view to evaluate the differential uplift across the valleys of the northern tributary streams of the Almanzora River. We want to check whether or not the Vf index of rivers cutting across the recent folds is sensitive to local variations associated to folding.

The heights of the river valley and the local divides were obtained from the DEM. Most of the valley floors are narrow (less than 50m wide, Table 1), the resolution of the DEM being insufficient for accurate measurement of their widths; for this reason, widths were measured using high resolution aerial photographs, satellite images and topographic maps (1:10000). At first sight, all of the selected valleys show regular V shapes with maximum linear incision in V_7, V_8, and V_9 (Fig. 8.5; table 8.1). Hence, all of the Vf values obtained are low, ranging from 0.05 to 1.395. However, three valley classes might be distinguished on the basis of the Vf values: class 1 (Vf < 0.2), class 2 (0.2 < Vf < 1), and class 3 (Vf > 1). The spatial distribution of the class 1 valleys is again coincident with the ENE-WSW trending recent folds affecting the basement rocks.

	Erd (m)	Hld (m)	Erd (m)	Vfw (m)	Vf
V_1	1053	1018	968	37	0.548
V_{2A}	1083	1134	978	164	1.257
V_{2B}	1000	1072	960	106	1.395
V_3	1087	1048	990	52	0.498
V_4	1055	1089	993	42	0.532
V_{5A}	1183	1110	1040	76	0.714
V_{5B}	887	952	785	35	0.260
V_6	1094	1027	946	30	0.262
V_7	1000	1014	875	14	0.106
V_8	1054	1120	790	15	0.050
V_9	1050	1075	769	20	0.068
V_{10}	860	779	713	95	0.892
V_{11}	919	859	746	105	0.734

Table 8.1. Vf values. Vfw is the width of the valley, Eld and Erd are respectively the elevations of the left and right valleys divides, and Esc is the elevation of the valley floor.

7. Discussion

Active folded areas formed at high convergence rates have been extensively studied using geomorphic indices (Delcaillau et al., 1998 and 2006; Chen et al., 2003). These regions register earthquakes of maximal magnitudes around 8, sometimes with associated coseismic surface ruptures affecting river systems (e.g., Cheng et al., 1999). The Betic Cordillera is quite a different scenario, subjected to a low convergence rate, responsible for low to moderate magnitude earthquakes (M < 5, Buforn et al., 2004; Stich et al., 2003 and 2006). Moreover, the seismicity shows a very diffuse distribution, making it difficult to associate specific earthquakes with the outcropping faults. In the eastern Betic Cordillera, the tectonic structures accommodating this convergence are folds and strike-slip faults, with very low regional long-term uplift rates (Braga et al., 2003; Booth-Rea et al., 2004; Sanz de Galdeano and Alfaro, 2004; Stokes, 2008). This tectonic scenario is a good one to explore whether or not geomorphic analysis in these areas is worthy to detect slow-motion active tectonic structures.

The present-day river incision pattern observed in the eastern Betic Cordillera can be attributed to tectonics and associated base-level lowering (Harvey, 1987; Mather and Harvey, 1995). Previous studies have proposed tilting because of differential uplift and subsidence related to normal faults as the factors responsible for river incision and headward erosion since the Pleistocene (Stokes and Mather, 2003). Yet compression (rather than extension) has been active since the Tortonian in this part of the Betic Cordillera producing crustal thickening and mountain building related to ENE-WSW folds and NNE-WSW sinistral strike-slip faults (Weijermars et al., 1985; Montenat and D'Estevou, 1999; Pedrera et al., 2007). Small normal faults with downthrows of a few centimetres locally deform the Quaternary sediments in the central and westernmost Almanzora Corridor (Pedrera et al., 2007) (Figs. 8.2 and 8.5). Nevertheless, no major normal faults are observed in the area studied. The landscape evolution and the drainage pattern development must therefore be explained as a consequence of the NW-SE oriented horizontal shortening, which in turn is responsible for fold development. These folds play an important role controlling the location of sedimentation (basins) and denudation areas (ranges).

In the sector of the eastern Betic Cordillera studied here, the presence of kilometre-scale folds controls the slope of the Sierra de las Estancias flanks, the asymmetrical southwards position of the Almanzora axial river, the basin size and the alluvial fan morphology. Since the Pleistocene, the folding process has induced progressive southward migration of the alluvial fans. The associated regional uplift and eastward line-coast migration produced a headward incision of the main rivers. In the easternmost sector studied here, headward erosion connected the Huércal-Overa basin to the Vera basin, cutting across the Sierra de Almagro (Stokes and Mather, 2003). Furthermore, the progressive growth of small-scale folds favoured the connection of the alluvial fan feeder channels to the Almanzora axial river via headward erosion. This process produced the shift of the locus of active sedimentation, while the fan systems became inactive. Finally, the northern tributaries of the Almanzora River captured the plains located in the Sierra de Las Estancias, as suggested by the right-angle river diversions and V-shaped gorges in the hard carbonate rocks.

7.1. Quantitative geomorphic analysis

The SLk index would seem to be insensitive to the low-rate uplift from the ENE-WSW oriented small-scale active folds identified in the Almanzora and Huércal-Overa sedimentary basins; that is, this geomorphic index and the topographic profile of Rambla de Albox do not show remarkable anomalies coincident with the active folds (Fig. 8.7). This fact can be explained because the incision rate in these soft rocks exceeds the uplift rate related to the folds. Contrarywise, the SLk index is sensitive to the active folds in those areas where hard rock crop out, such as the Alpujárride carbonate rocks. Active folds are difficult to recognize in the metamorphic rocks, owing to the absence of recent sediments that might provide deformation markers. In this context, the SLk index could be used as a tool to discern recent folds developed on resistant metamorphic rocks at low deformation rates.

Because of the size of the studied area (~1200 km^2), we may assume one same climatic history for all the studied rivers. Morphology of the hypsometric curve is very sensitive to recent and active folding, which would have favoured elevation and denudation that cause distinctive changes in the drainage basins (Fig. 8.8). The hypsometric curves that belong to the first group (1, 2, 3, 4, 5, 6, 10, and 11) differ from the curves located on the folded sector (8 and 9), characterized by a strong convex shape in middle-mouth parts. The landscape in the eastern sector is clearly conditioned by the presence of recent folds that produced a differential uplift and higher vertical erosion; this area is characterized by a plain located in the upper part and large V-shaped valleys in the lower sector. However, hypsometric curves do not allow us to determine the position of the folded sectors along the main stream, as they take into account the whole subbasin.

In order to avoid lithological controls, the Vf value was obtained systematically for valleys developed upon Alpujárride marbles. Therefore, geomorphologic differences could be assigned to local tectonic variations. As might be expected in an active tectonic setting linked to regional uplift and base level lowering all the valleys present a regular V-shape (relatively low Vf values). However, local variations can be detected, coinciding precisely with the position of the ENE-WSW active folds (Partaloa–Urracal sector): in this sector we found the maximum linear incision for the V_7, V_8, and V_9 that give class 1 Vf values (Fig. 8.5).

8. Conclusions

In convergence settings, fold development plays an important role in landscape evolution and drainage development. The analysis of the tributary streams of the Almanzora River at the southern limb of the Sierra de Las Estancias antiform (eastern

Betics), in a region affected by low-rate active folding accompanied by river incision and erosional denudation, allows us to evaluate the suitability of geomorphic indices to properly characterize recent and active tectonics in such a situation.

The SLk index, which mainly reflects local river gradient variation, seems to be sensitive to low-rate slow active folding in hard (very to extremely strong marbles) basement rocks. To the contrary, the same index on easily erodible Neogene-Quaternary sediments does not show any significant anomaly, probably because of erosional processes keeping pace with tectonic uplift. Therefore, in regions affected by low-rate uplift, the SLk index may serve to find active folds, but only in those sectors where the outcropping rocks are highly resistant and erosion is, in turn, quite slow. Notwithstanding, other geological evidence, such as folded recent sediments, must be considered in order to discard the presence of previously developed folds, which might have favoured the exposure of hard rocks resistant to erosion.

The shape of the hypsometric curve also varies from catchments affected by active folding to those unaffected, though the precise location of the folds cannot be established. The hypsometric curves of the catchments located in the folded sectors of the Sierra de Las Estancias-Almanzora basin are characterized by marked convex shapes in their middle-mouth sectors. These convex shapes are the result of the relative uplift caused by the folds.

The Vf ratio, once lithological and climatic factors are discounted, can also prove valuable for detecting low-rate active folding. In our case, Vf values obtained on the hard carbonate rocks of the Alpujárride complex are very low (< 0.2), and spatially coincident with the ENE-WSW active folds.

Our main conclusion is that sectors subjected to low-rate active folding can be reasonably distinguished by means of a combined morphometric (topographic profiles of recent alluvial fans, SLk index, hypsometric curves, and Vf ratio) and geologic study, mainly when resistant rocks are exposed.

Acknowledgements

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PART THREE

9. The Almanzora Corridor and the Huércal-Overa basin in the framework of the recent Betic Cordillera geodynamic evolution

10. Conclusions

11. Futures perspectives

9. The Almanzora Corridor and the Huércal-Overa basin in the framework of the recent Betic Cordillera geodynamics evolution

The previous chapters have expounded new data that will enrich discussions and considerations regarding the structures and tectonic evolution proposed to date for the Eastern Betic Cordillera, from a regional and sometimes methodological standpoint. In this chapter we integrate the results of such contributions so as to present a comprehensive model for the tectonic evolution of the Almanzora Corridor and the Huércal-Overa basin, well within the general Miocene geodynamic evolution of the Betic Cordillera and the western Mediterranean context. Taking into account the new geological, geophysical and geomorphological data, several remarks may be highlighted to decide between the different models put forth to explain the recent evolution of the cordillera.

First and foremost, it appears necessary to discuss the metamorphic rock exhumation and basin formation during the Late Miocene, because most recent models consider this aspect to be related with simultaneous processes developed in an extensional setting. In the second section, we take a look at the studied basins in the recent evolution of the cordillera, underlining the most significant geological events and their relevance on a regional scale.

9.1. Relationship between metamorphic rock exhumation and Late Miocene basin development

Given the interpretation of the main low-angle contacts between the metamorphic complexes of the Betic Cordillera as normal faults, many mechanisms have been proposed to explain the origin of extension. Further information about these extensional models can be found in the introductory chapter. Although there is no consensus with regards to the different models that account for a fast metamorphic rock exhumation during the Alborán basin development, all the proposed models establish a main phase of widespread extension as the central driving mechanism. This extension was accommodated along ductile to ductile-brittle structures, causing the collapse in the Early to Middle Miocene of a previously over-thickened orogen. The roughly E-W trend of the maximum horizontal extension is deduced from stretching lineations, extensional crenulation cleavages and striations during the ductile-to-brittle deformation evolution (e.g., Galindo-Zaldívar, 1989; Jabaloy et al., 1992). Assuming that extension was the driving exhumation mechanism active during the Early to Middle Miocene, some open questions can be raised here: Was this extensional mechanism active during the Late Miocene basin infill? And therefore, is there any relationship between the Early Miocene and the Late Miocene causes behind extension? Some authors propose core complex models and Basin and Range relief type in the Betic Cordillera during the Late Miocene, coetaneous to basin development (e.g. Augier et al., 2005b; Meininger and Vissers, 2006). Some keys to the answer would be: (a) the precise age of the low-angle normal faults, (b) a strict definition of the relation between the kinematics of the low-angle normal faults and those of the high-angle normal faults, which develop mainly in the hanging-wall and broadly deform the Late Miocene sediments of the basins, (c) an understanding of the role of contractional structures and their relation with the sedimentation, (d) accounting for the profuse geophysical information, and (e) comprehending the information coming from volcanic rocks.

Focusing in the Nevado-Filábride Complex exhumation —although no doubt the extension during the Early to Middle Miocene pushed these rocks toward the surface— total exhumation was probably produced by the late folding. A single dome usually develops in the classic core complex models (Spencer, 1984; Werneke 1985; Werneke and Axen, 1988) (Fig. 8.1), though the low angle normal faults in the hanging wall of the main detachment would produce a succession of asymmetric basin and ranges. The Betic Cordillera, however, features several consecutive ranges where the Nevado-Filábride rocks crop out: Sierra Alhamilla, Sierra Nevada and Sierra de Los Filabres (as a continuous outcrop), and Sierra Almenara-Almagrera. In addition, most of these ranges (Sierra de Nevada, Sierra de Los Filabres and Sierra Alhamilla) have been largely interpreted as antiforms (Weijermars, 1985; Martínez-Martínez and Azañón, 1997). It is possible to state with certainty that these folds were growing during Tortonian times, as confirmed by the folded sediment age and fission-track analysis in Sierra Nevada and Sierra de Los Filabres (Johnson, 1994; Johnson et al., 1997a, 1997b). Yet we would extend the onset of folding up to the Serravallian (12 Ma), simultaneous to the red conglomerate sedimentation in the Eastern Cordillera (based on data from Johnson et al. 1997b and Guerra-Merchán et al., 2001). The studied basins have exceptional outcrops of this conglomerate unit, showing syn-folding fan structures. In addition, these rocks cover the Alpujarride/Nevado Filábride low-angle normal fault in the Sierra de Los Filabres and some impressive detachments that crop out in Sierra Limaria.

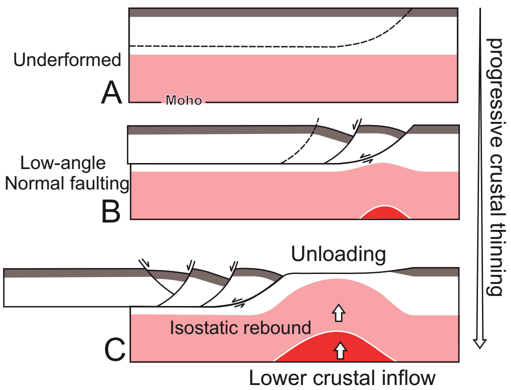

Fig. 9.1. Core complex model involving progressive crustal thinning, the unloading of the upper crust, lower crustal inflow, doming and metamorphic rocks exhumation.

It is necessary to point out that, since the Tortonian, some high-angle normal faults developed in the hanging wall of the Alpujárride/Nevado-Filabride contact (and locally) contributed to the metamorphic rock exhumation. For example, those occurring in the westernmost outcrop of the Nevado-Filábride/Alpujárride contact, just at the western periclinal termination of the Sierra Nevada antiform (Galindo-Zaldívar et al., 1996). This major low-angle normal fault, which was active during the Early-Middle Miocene, was most likely reactivated in depth since the Late Miocene, having related high-angle normal faults (like the active Padul-Nigüelas fault) in its hanging wall. Sanz de Galdeano and López Garrido (1999) point out that these high-angle normal faults contributed to a rapid uplift of the Sierra Nevada since Tortonian times. Martínez-Martínez et al. (2002) interpreted the NW-SE oriented antiform located in the western Sierra Nevada as an isostatic fold, developed in response to a progressive unloading of the extensional detachment footwalls that may have induced ductile flow in the middle crust from Serravallian to Pliocene times (Reinhardt et al., 2006, and 2007). However, this local framework can not be extrapolated to the whole cordillera.

Focusing on the studied sector, the Alpujárride/Nevado-Filábride contact —which was interpreted by Augier et al. (2005b) as the fault responsible for the Huércal-Overa and Almanzora Corridor formation— is buried in some sectors under sediments from the Serravallian-Early Tortonian. This fact suggests that the fault was active mainly prior to basin development. In addition, the sub-horizontal NNE-SSW to NE-SW extension direction deduced from the measured high-angle normal fault kinematics deforming the studied basins does not coincide with the top-to-the-W/NW sense of movement deduced from the Alpujárride/Nevado-Filábride contact (Jabaloy et al., 1992). This could indicate that the phase of widespread extension responsible for the low-angle normal fault development in the Internal Zones of the Betic Cordillera was inactive during this high-normal fault activity. Therefore, the proposal put forth here is that the studied basins developed under the progressive crustal thickening process. Although a significant component of the deformation can be found on many faults, sedimentary basins are generally located between the ranges, where synclines control the spatial distribution of erosion and sedimentation sectors. The progressive unconformities of folds in the sediments, as well as the association between synform and depocenter locations, detected by gravity, point to a coexistence of fold growth and sedimentation. Nevertheless, some high-angle normal faults condition the basin shape and the sedimentation (e.g., in the northern Almanzora Corridor boundary and in the Líjar-Albanchez sector). The crustal thickening process, active since Tortonian, is also in agreement with the generally accepted active plate convergence, as well as with results obtained from geophysical methods that indicate a crust over 35 km thick below the Internal Zones, sharply thinned toward the Alborán Sea (Torné et al., 1992; Banda et al., 1993; Fernández-Ibáñez and Soto, 2008). The high-angle normal faults, then, would have developed during the relief growth related to this crustal thickening.

In sum, the extension affecting the Internal Zones of the cordillera contributed decisively to the exhumation of Nevado-Filábride metamorphic rocks. However, the last stage of this process during the Serravallian-Early Tortonian was mainly controlled by the Eurasian–African plate convergence: a setting that determines compression, crustal shortening and thickening. At this stage, large scale folds represent a significant component of surface deformation and are probably the main structure responsible for the final exhumation of Nevado-Filábride rocks. The array of proposed models based on sub-lithospheric processes that took place during this evolution could hardly be checked.

9.2. Basin and relief development in the geodynamic evolution of the Betic Cordillera

In the Betic Cordillera Internal Zones, paleogeographic reconstructions on the basis of facies distribution information, together with our data and a comprehensive revision of the available tectonic data, led us to reconstruct the evolution of the relief and to correlate it with the recent tectonic structures.

The paleogeography of the Betic Cordillera during the Early and Middle Miocene is not well established, though there are good indications of the presence of a large Alborán basin with small isolated emerged ridges (Alvinerie et al., 1992) and an important sedimentary depocenter fitting the arc shape (West Alborán basin, Comas et al., 1999). During the Early-Middle Miocene, the convergence between the Internal and External Zones is well constrained (Lonergan and Platt 1995; Jabaloy-Sanchez et al., 2007). This important compressive deformation affected the flysch units, and a large olistostromic unit began to develop at the mountain front. Meanwhile, the Internal Zones were extending at all structural levels. Extensional activity on the Maláguide/Alpujárride contact finished earlier than that by the Alpujárride/Nevado Filábride contact (Platt and Vissers 1989; Galindo-Zaldívar et al. 1989; Jabaloy et al. 1993; Lonergan and Platt, 1995; González-Lodeiro et al., 1996). Recent tomographic models (Gutcher et al., 2002) show a high velocity body that dips eastward and reaches up to 660 km, from the Strait of Gibraltar to below the Alborán Sea. All these data, together with the presence of a few deep earthquakes below the central Betic Cordillera (~600 km, Buforn et al., 1991) would incline one to support the Royden (1993) and Lonergan and White (1997) models. These models propose a subducting slab and westward rollback as the main cause of extension and orogenic collapse in the westernmost Mediterranean (Fig. 8.2). In this sense, some authors consider the deep seismicity (~600 km) to be produced by an ancient slab of oceanic crust, whose subduction started prior to the Early to Middle Miocene (Lonergan and White, 1997). Tentative estimations of ~26-46 mm/yr sinking rates can be evoked, considering the presence on the surface of this hypothetical oceanic crust during the Early Miocene (23–13 Ma). This sinking rate is similar to those calculated by GPS in the Eastern Mediterranean subduction zone (35–45 mm/yr at the Hellenic subduction zone, Ring and Reischmann, 2002).

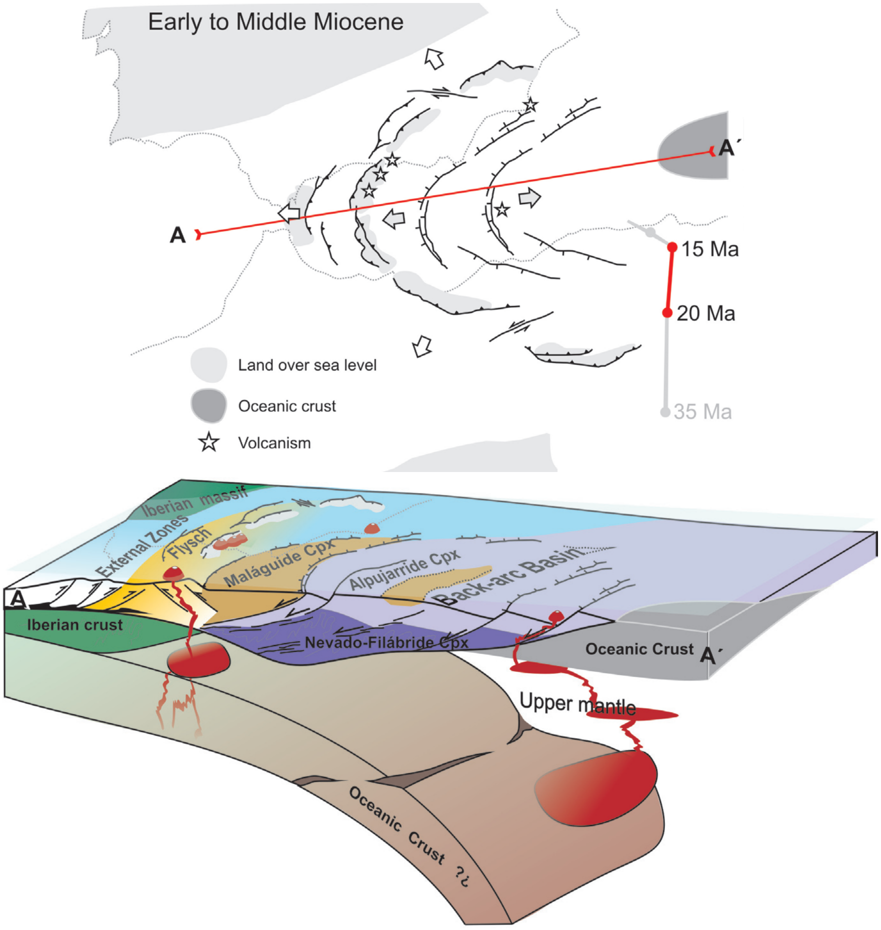

Fig. 9.2. Early to Middle Miocene paleogeographic reconstruction. The block diagram shows the relation between the different paleogeographic domain, the subduction of the African crust bellow the Iberian crust, and the volcanism.

However, the activity of this subduction zone decreased at the end of the Middle Miocene, enhancing the convergence between the Eurasian and African plates, as deduced from the following data. Sedimentological analyses indicate that from the Serravallian to the Early Tortonian a large E-W island started to emerge in the present position of the Sierra Nevada and Sierra de Los Filabres ranges (Braga et al., 2003). According to the fission data of Johnson et al. (1997), cooling near surface temperature first occurred in the Sierra de Los Filabres during the mid-Serravallian (12 Ma) and later in the Sierra de Los Filabres, located to the west (9-8 Ma). The erosion of these ranges supplies sediments to the nearby basins. Progressive unconformities found in the conglomerates located in the Almanzora Corridor are interpreted as being coetaneous with the Sierra de Los Filabres antiform growth, probably under N-S convergence. The N-S shortening is in agreement with the proposed direction of the plate convergence (Dewey et al., 1989). Our geophysical data point out that the Sierra de Los Filabres antiform nucleation was favoured by the presence of basic rocks at depth (Fig. 8.3A). Crustal anatexis processes occurred between 12 and 9 Ma at depth, deduced from the mineral age of enclaves located in the high-calalkaline volcanic rocks cropping out in the Eastern Betics (Álvarez-Valero and Kriegsma, 2007; Cesare et al., 2008). This crustal melting coincided with the extrusion of calkalcaline lavas in the Cabo de Gata region (11.78-6.57 Ma), and in the Alborán Sea (Fig. 8.3A).

During the Tortonian, large folds grew to the North, as in the Sierra de Las Estancias. The Almanzora Corridor and the Huércal-Overa basin acquired their narrow shape. Coetaneous to the fold growth was the onset of activity of the major sinistral faults of the Eastern Betic Cordillera under a NW-SE regional compression. Coeval to the relief growth, NW-SE to E-W normal faults developed, also suggesting active extension. Moreover, a transgressive event occured during the Tortonian. In the initial folding stages, synform development (including the Almanzora synform) would have favoured sea water penetration (Fig. 8.3B). The extrusion of calcalkaline and tholeitic volcanic rocks extends from Tortotian up to Messinian in the Eastern Betic, the Rif cordilleras and the Alborán Sea (see age data compilation in Duggen et al., 2008).

The paleostress setting remained stable during the Latest Tortonian, when large antiforms (the Sierra de la Contraviesa, the Sierra de Gádor, the Sierra Alhamilla and the Sierra Cabrera) began to rise to the South of the Sierra Nevada and Sierra de Los Filabres. This setting persisted during the Messinian, with the activity of these large folds, the large sinistral transcurrent faults in the Eastern cordillera, and widespread normal faults. Normal faults locally started to control the position of endorreic depressions (the Granada basin, and the Guadix-Baza basin) (Fig. 8.3C).

During the Pliocene and Quaternary, the continuity of compression contributed to the progression of crustal thickening, and to the regional progressive emersion of the marine basin and final capture by the drainage network of the endorreic basins. The location of main present-day folds in the Internal Zones produces emersion of the northern Alboran Sea (Marín-Lechado et al., 2006). In addition, there is continued activity of some segments of the NE-SW to NNE-SSW major sinistral fault located in the eastern sector of the cordillera (such as the Alhama de Murcia Fault and the Palomares Fault), and of associated structures mainly located in the fault terminations. Moreover, large normal faults remain active during the Quaternary and at present in the cordillera, with a main NE-SW to NNE-SSW to radial active extension in the upper crust, as deduced from Holocene sediment deformation and associated fault scarps (Granada/Padul-Nigüelas sector, Sanz de Galdeano, 1976; Galindo-Zaldívar et al., 1996; Alfaro et al., 2001; Baza Fault, Alfaro et al., 2007) and associated instrumental seismicity (Granada sector, Sanz de Galdeano et al., 1995; Galindo-Zaldívar et al., 1999; Sierra de Gador/Campo de Dalías sector, Marín-Lechado et al., 2005). Alkali basalts extrude in the Mazarrón-Cartagena area during the Pliocene, as occurs in other zones of the Betic-Rif forelands.

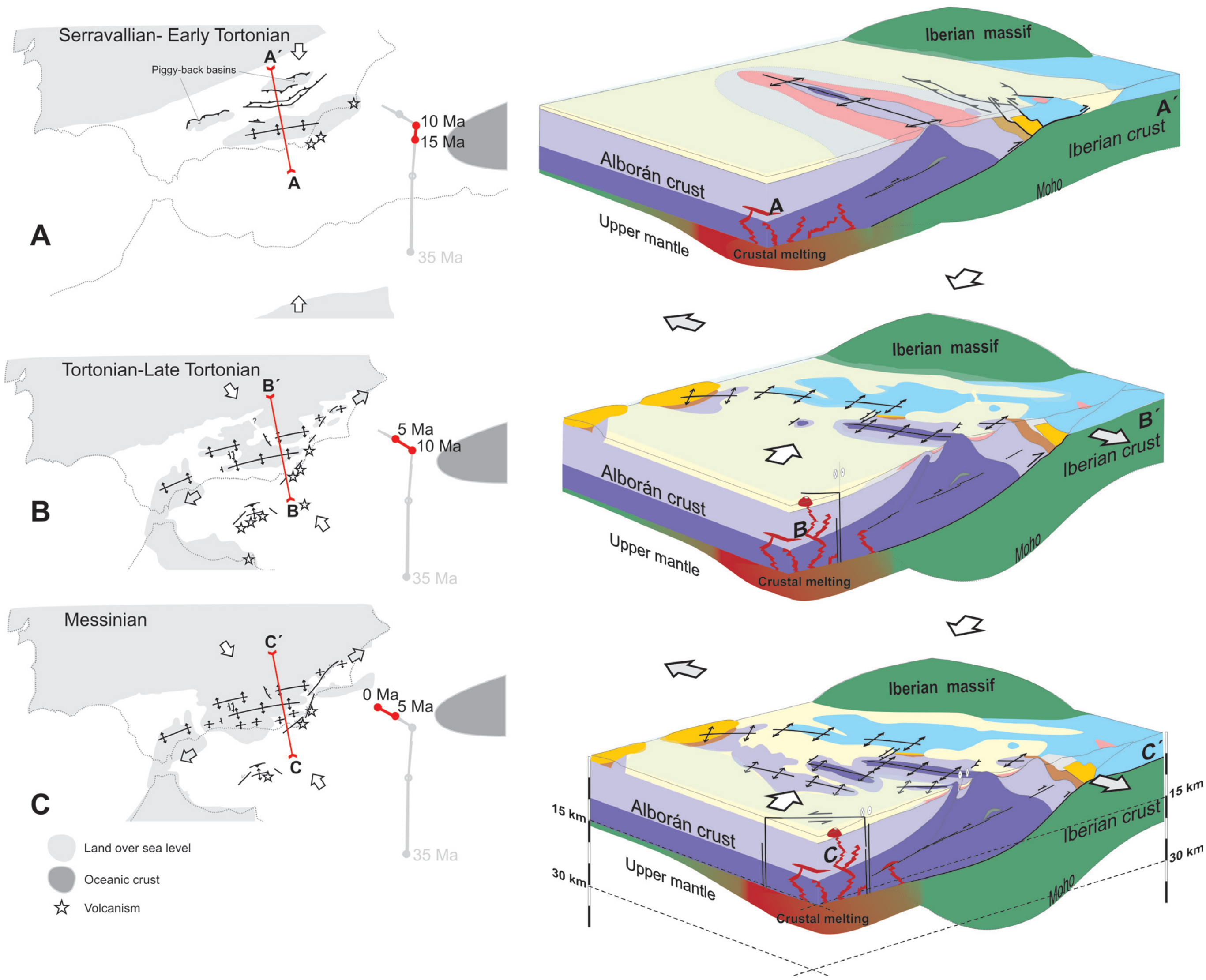

Fig. 9.3. Paleogeographic reconstructions and block diagrams showing the Serravallian-Messinian geodynamic evolution of the cordillera.

10. Conclusions

As a summary of the previous chapters, the conclusions related to the shallow geological research, deep structure and recent tectonic activity of the Almanzora Corridor and Huércal-Overa basin are presented in order to offer a full view of the tectonic evolution of this key region of the Eastern Betic Cordillera. In addition, results on geomorphological indices as applied to the study of active structures are included.

Surface and shallow crustal structure

Compressive and extensional structures deformed the Late Miocene-Quaternary sediments of the Almanzora Corridor and the Huércal-Overa basin. The studied area is deformed by a succession of kilometric amplitude folds with orientations ranging from E-W to ENE-WSW: the Sierra de Los Filabres and Sierra de Almagro antiforms, Almanzora Corridor synform and Sierra de Las Estancias antiform. The antiforms coincide with the ranges where the metamorphic rocks crop out, while the synforms correspond with the sedimentary basins developed since the Late Miocene. Sinsedimentary unconformities located in both boundaries of the Almanzora basin point to a Serravallian-Early Tortonian initial stage of fold development. Moreover, the Neogene sediments are deformed since Tortonian by ENE-WSW minor folds. To the East, these minor folds progressively change their trend from ENE-WSW to WNW-ESE, showing an increase of shear strain close to the Alhama de Murcia sinistral transcurrent fault.

In addition, the Late Miocene sediments are quite deformed by several set of faults. The most abundant set is formed by WNW-ESE to NW-SE normal faults that show a widespread distribution in the basins and evidence activity from the Early Tortonian. More scarce is the E-W to NE-SW oriented normal fault set. In addition, subvertical strike-slip dextral faults, E-W to ESE-WNW oriented, deform the Tortonian sediments that crop out mainly in the southern basin boundaries. The eastern Almanzora Corridor and the Huércal-Overa basin are deformed by reverse faults of E-W to ENE-WSW orientation that cut the Tortonian and, locally, the Quaternary sediments.

Deep crustal structure

New geophysical data, including gravity, magnetic, magnetotelluric and seismicity data, reveal the subsurface structure of the studied area. The geometry of the upper crust is constrained from the previously presented geological field data, 2D gravity models, 2D magnetic models and 2D MT resistivity model:

- In both basins, geological cross-sections determined from the structural data and gravity models indicate that there is no great depocenter linked to normal faults; rather, these are generally related to folds. The maximum sedimentary thickness reaches 1000 meters in the Huercal-Overa basin, associated with the eastern termination of Almanzora synform.
- The combination of magnetic, magnetotelluric and seismicity data allow us to propose that the Sierra de Los Filabres antiform core corresponds to a large basic rock body located at a depth between 4 and 9 km, evidenced by a low resistivity body (~0.5 Ω ·m) that produces a large total intensity dipole of magnetic field anomaly. This basic rock body would have determined the nucleation and development of the kilometric antiform.

Recent and present activity of tectonic structures

Evidence of present-day activity comes from detailed structures that affected Quaternary sediments, more difficult to trace and scarcer than the widespread brittle deformations seen in the Late Miocene sediments. The main evidence from West to East is detailed below:

The westernmost part of the Almanzora Corridor is affected by a set of NW-SE faults that deforms up to the Quaternary glacis and produces the Corridor's western termination. These fault segments are related to the Baza normal Fault, which extends more than 30 km along the Baza basin, showing a N-S to NW-SE variable strike, and dipping to the NE. In the central part of the Corridor, the Lúcar fault —formed by a set of E-W oriented and 40º-75º south dipping normal faults— locally deforms the Quaternary sediments. Close to Somontín, Quaternary sediments are deformed by a NW-SE oriented high-dipping fault that generates a steep scarp. The fault surface shows horizontal striation with a left-lateral regime overprinted on the normal old striae. The eastern Almanzora Corridor (Somontín-Partaloa sector) and the Huércal-Overa basin are both deformed by widespread small-scale contractional tectonic structures, which include ENE-WSW oriented open folds, fault-propagation folds, reverse faults, and WNW-ESE dextral faults. These small-scale active structures are sometimes nucleated over previous fault zones. The La Molata fault-propagation fold is one of the best exposed examples and has been studied in detail. This fold and its related faults propagated progressively, as evidenced by the syn-tectonic geometry of the growth strata. Strain rates calculated across the structure give a constant ~0.007 mm/yr horizontal shortening and ~0.014 mm/yr vertical displacement from the mid-Pleistocene up to now. These structures contribute to the 4-5 mm/yr accommodation of present-day NW-SE plate convergence.

In both studied basins, earthquake focal mechanisms suggest the presence in depth of a regional NW-SE compressive stress field. However, most of the seismogenetic structures do not extend up to the surface, where the NW-SE and WNW-ESE observed outcropping active normal faults indicate a NE-SW extension in the upper crust simultaneous to an orthogonal NW-SE compression, related to reverse faults and minor folds developed in the Eastern Almanzora Corridor and in the nearby Huércal-Overa basin. Therefore, the instrumental seismicity is probably concentrated along the deep detachments and minor faults related to fold growth that do not reach up to the surface.

Suitability of different geomorphic indexes as applied to the moderately active structures

The drainage network of the Almanzora River, highly controlled by tectonics, reflects recent activity of the faults and folds. The presence of normal faults determines small changes in the direction of the north Almanzora River tributary stream that might easily be detected from direct observations. However, the role of the previously recognized active folds in the landscape evolution and drainage development is not so obvious, and therefore has been analyzed in detail. We selected the tributary streams of the Almanzora River that cross the folded Eastern Almanzora Corridor and Western Huércal-Overa basin in order to evaluate the suitability of different geomorphic indices (SLk, hypsometric curve and Vf ratio):

- The SLk index, which mainly reflects local river gradient variation, appears to be sensitive to low-rate slow active folding in hard —resistant— basement rocks. Contrariwise, the same index on low resistant soft Neogene-Quaternary sediments does not show any significant anomaly, probably due to erosional processes keeping pace with tectonic uplift.
- The shape of the hypsometric curve also varies from catchments affected by active folding to those unaffected, though the precise location of the folds cannot be established. The hypsometric curves of the catchments located in the folded sectors of the Sierra de Las Estancias are characterized by marked convex shapes and HI values around 0.5. In those catchments not affected by the active folds, the hypsometric curves are rectilinear and HI values are slightly lower than in the folded catchments.
- The Vf values obtained on the hard marbles of the Alpujárride Complex are very low (< 0.2) and spatially coincident with the ENE-WSW active fold position.

Geodynamic evolution of the basins

The Almanzora Corridor and Huércal-Overa basin growth entails a complex structural interaction:

(a) During the Serravallian-Early Tortonian, N-S directed compression allows deformation to propagate northwards with a progressive fold growth, starting with the Sierra de Los Filabres antiform (12 Ma), followed by the Almanzora synform, and the Sierra de Las Estancias antiform.

(b) Since Tortonian times, counter-clockwise rotation in the stress field occurred, and the shortening direction changed to NW-SE, presenting an orthogonal associated extension (NNE-SSW to NE-SW) in a crustal thickening framework:

- In the Almanzora Corridor, the maximum stress axis became oblique to the previous E-W oriented Sierra de Los Filabres fold, producing dextral shear deformation along a wide band located to the North and determining the eastern Corridor narrowing. Deformation styles were clearly different in the Baza basin and western Almanzora Corridor (only extensional) as compared to the eastern part of the Almanzora Corridor and Huércal-Overa basin (extensional and compressional).
- To the east, contractive and extensional structures deformed the southern termination of the Alhama de Murcia sinistral fault (AMF), which began its activity in Tortonian times, and highly conditioned the Huércal-Overa basin development. The minor folds progressively grew and rotated from ENE-WSW up to WNW-ESE, with an increase in shear strain close to the transcurrent fault termination. Meanwhile, a sub-vertical maximum stress axis and sub-horizontal extension, NNE-SSW to NE-SW and E-W to NW-SE oriented, in transition to radial extension, is responsible for the normal fault development.

The study of these basins supports those regional models of the Betic-Rif Cordilleras that proposed a progressive crustal thickening since Tortonian, associated with the Eurasian and African plate convergence. In this framework, the development of large antiforms has contributed to the final exhumation of the metamorphic rocks, determining the position and geometry of the intramontane sedimentary basins, sometimes modified by faults. The extensional mechanism proposed to explain the Early to Middle Miocene metamorphic rock exhumation and the Alborán basin development are probably inactive during the Late Miocene, when high-angle normal faults are amply distributed in the shallow levels, probably related to the gravity effect linked to crustal thickening.

10. Conclusiones

Los principales resultados obtenidos a partir de los datos de geología superficial y geofísicos permiten establecer la estructura y la actividad tectónica reciente del Corredor del Almanzora y la cuenca de Huércal-Overa que constituyen un sector clave para comprender la evolución de la Cordillera Bética oriental. Además, se han incluido los principales resultados obtenidos de un análisis morfométrico detallado aplicado al área de estudio.

Estructura cortical superficial

Numerosas estructuras compresivas y extensionales deforman los sedimentos que rellenan el Corredor del Almanzora y la cuenca de Huércal-Overa desde el Mioceno superior. El área estudiada está afectada por una sucesión de de pliegues con amplitud kilométrica y orientaciones comprendidas entre E-O y ENE-OSO: las antiformas de Sierra de Los Filabres y Sierra de Almagro, la sinforma del Corredor del Almanzora y la antiforma de Sierra de Las Estancias. La posición de las antiformas coincide con elevaciones topográficas donde afloran las rocas metamórficas y las sinformas corresponden con depresiones topográficas donde se han desarrollado cuencas sedimentarias desde Mioceno superior. La presencia de discordancias progresivas en los sedimentos localizados en los bordes del Corredor del Almanzora, indican que estos pliegues comenzaron su actividad en el Serravaliense-Tortoniense inferior. Además, otros pliegues con menor longitud de onda deforman los sedimentos desde el Tortoniense. Estos pliegues menores tienen una dirección preferente ENE-OSO. Hacia la zona oriental del sector estudiado, la orientación de estos pliegues cambia progresivamente hasta adquirir una dirección ONO-ESE que se puede asociar al aumento de la deformación por cizalla en las inmediaciones de la falla sinistra de Alhama de Murcia.

Numerosas fallas deforman los sedimentos desde el Tortoniense y se pueden agrupar en distintos grupos según su orientación y cinemática. El grupo más abundante está compuesto por fallas normales de dirección ONO-ESE a NO-SE. Estas fallas están ampliamente distribuidas en ambas cuencas y muestran evidencias de funcionamiento desde el Tortoniense inferior. Un segundo grupo está formado por fallas normales de dirección comprendida entre E-O y NE-SO. Los sedimentos de edad Tortoniense que afloran cerca del borde meridional de las cuencas están deformados por fallas dextras subverticales con dirección comprendida entre E-O y ESE-ONO. El último grupo está formado por fallas inversas de dirección E-O a ENE-OSO que deforman los sedimentos tortonienses y, localmente, cuaternarios de la parte oriental del Corredor del Almanzora y la cuenca de Huércal-Overa.

Estructura cortical profunda

Los nuevos datos geofísicos –gravimétricos, magnéticos, magnetotelúricos y de distribución de la sismicidad– revelan la estructura cortical de la zona de estudio. La geometría de la corteza está caracterizada a partir de los datos geológicos presentados anteriormente y nuevos modelos 2D gravimétricos, magnéticos y magnetotelúricos.

- Los cortes geológicos, construidos a partir de la combinación de los modelos gravimétricos y las observaciones de geología estructural, permiten establecer la estructura en ambas cuencas. Las mayores potencias sedimentarias están asociadas al funcionamiento de las sinformas y no hay grandes espesores de sedimentos relacionados con la actividad de las fallas normales. El depocentro se localiza en la cuenca de Huércal-Overa, donde se alcanzan 1000 metros de espesor de sedimentos, ligado al crecimiento de la parte oriental de la sinforma del Almanzora.

- La combinación de los modelos magnéticos, magnetotelúricos y los datos de sismicidad permiten detectar un cuerpo de rocas básicas en el núcleo de la antiforma de Los Filabres a una profundidad entre 4 y 9 km. Estas rocas producen una importante anomalía en el campo magnético total que ha sido modelizada y que coincide con un cuerpo de baja resistividad (~0.5 Ω·m) detectado en el modelo magnetotelúrico. La presencia de estas rocas básicas suponen un contraste reológico que probablemente condicionó la nucleación y el posterior desarrollo de la antiforma de Sierra de Los Filabres.

Actividad reciente y actual de las estructuras tectónicas

Localmente se observan estructuras que deforman los sedimentos cuaternarios y ponen de manifiesto la tectónica activa de la región. Estas deformaciones activas son mucho más escasas que las estructuras recientes desarrolladas desde el Mioceno superior y por lo tanto se detectan con más dificultad. Las principales estructuras activas que deforman el área de estudio se describen a continuación, de Oeste a Este:

La terminación occidental del Corredor del Almanzora está determinada por la presencia de fallas normales con dirección NO-SE que deforman el glacis cuaternario. Estos segmentos de fallas están relacionados con el funcionamiento de la Falla de Baza, que se extiende más de 30 km a lo largo de la cuenca de Baza con una orientación variable entre N-S y NO-E y buzamiento hacia el NE. En la parte central del Corredor del Almanzora, la Falla de Lúcar—formada por un conjunto de fallas normales de dirección E-O que buzan 40º-75º hacia el Sur— deforma localmente sedimentos cuaternarios. Cerca de Somontín, los sedimentos cuaternarios están afectados por fallas subverticales de dirección NO-SE, que generan un importante escarpe topográfico. La superficie de la falla principal tiene un juego de estrías horizontales sinistras superpuestas a estrías de falla normal más antiguas. La parte oriental del Corredor del Almanzora (sector

Somontín-Partaloa) y la cuenca de Huércal-Overa están deformados por estructuras compresivas de pequeña escala que incluyen pliegues abiertos, pliegues de propagación de falla, fallas inversas de orientación ENE-OSO y fallas dextras con dirección ONO-ESE. Ocasionalmente, estas estructuras están desarrolladas sobre zonas de falla previas. El pliegue de propagación de falla que aflora cerca de La Molata constituye el mejor ejemplo y ha sido estudiado en detalle. Este pliegue, así como las fallas relacionadas con su funcionamiento, se desarrolló de forma progresiva como se deduce de los sedimentos sintectónicos que tiene asociados. Las velocidades de deformación calculadas para esta estructura ponen de manifiesto ~0.007 mm/año de acortamiento horizontal y ~0.014 mm/año de desplazamiento vertical desde el Pleistoceno medio. La presencia de numerosas estructuras activas de pequeña escala contribuye a acomodar los 4-5 mm/año de convergencia NO-SE calculados para la cordillera.

En las dos cuencas estudiadas, los mecanismos focales de terremotos sugieren la presencia en profundidad de un elipsoide de esfuerzo compresivo NE-SO. En superficie, las fallas normales de dirección NO-SE y ONO-ESE, ponen de manifiesto una extensión NE-SO activa en la corteza superior. Esta extensión es coetánea de la compresión NO-SE que está relacionada con el desarrollo de fallas inversas y pliegues menores en la parte oriental del Corredor del Almanzora y en la cuenca de Huércal-Overa. La sismicidad instrumental no se correlaciona bien con las estructuras activas que afloran. Una posible explicación es que buena parte de esta sismicidad esté relacionada con despegues profundos y fallas menores que no llegan a aflorar en superficie.

Evaluación de la aplicación de índices geomorfológicos en áreas con actividad tectónica moderada

La red de drenaje del río Almanzora está controlada por la actividad reciente de de pliegues y fallas. La presencia de fallas normales determina pequeños cambios en la dirección de los afluentes situados al Norte del río Almanzora que pueden ser detectados mediante observaciones directas. Para cuantificar la influencia de los pliegues con velocidad de crecimiento lento previamente reconocidos mediante trabajo de campo, se han seleccionado los afluentes del río Almanzora que fluyen por su margen izquierdo. La comparación de índices en sectores plegados y no plegados tiene como objetivo evaluar su validez en cada tipo de entorno geológico (SLk, curvas hipsométricas y Vf):

- El índice SLk, que refleja variaciones locales en la pendiente del cauce del río, sólo es sensible a los pliegues activos con tasa de crecimiento lento que deforman la las rocas resistentes del basamento. Por el contrario cuando estos pliegues deforman los sedimentos neógenos y cuaternarios, más fácilmente erosionables, no se observa ninguna anomalía significativa en este índice.

- La forma de la curva hipsométrica muestra variaciones entre las cuencas de drenaje que están afectadas por pliegues activos y las que no lo están. Si embargo, este índice no permite establecer la posición exacta de los pliegues. Las curvas hipsométricas que pertenecen a cuencas de drenaje afectadas por pliegues en Sierra de Las Estancias están caracterizadas por morfologías convexas. Las cuencas no afectadas por pliegues tiene morfologías rectilíneas.

- Los valores de Vf obtenidos en los mármoles alpujárrides son muy bajos (< 0.2) y coinciden espacialmente con la posición de los pliegues activos.

Evolución geodinámica de las cuencas

El desarrollo del Corredor del Almanzora y la cuenca de Huércal-Overa está controlado por una compleja interacción de estructuras tectónicas:

(a) Durante el Serravaliense-Tortoniense inferior, la compresión N-S permitió que la deformación se propagase hacia el Norte con el desarrollo progresivo de pliegues kilométricos. En primer lugar se produjo la formación de la antiforma de la Sierra de Los Filabres (12 Ma), seguida del crecimiento del la sinforma del Almanzora y la antiforma de la Sierra de Las Estancias durante el Tortoniense.

(b) Durante el Tortoniense el eje de esfuerzos máximo sufrió una rotación antihoraria desde N-S hasta NO-SE, con una extensión perpendicular asociada (NNE-SSO a NE-SO), en un contexto de engrosamiento cortical.

- En el Corredor del Almanzora, la nueva dirección de compresión, oblicua a la dirección E-O de la Sierra de Los Filabres, favoreció una deformación por cizalla dextra que determinó el estrechamiento de la parte oriental del Corredor. Desde el Tortoniense, los estilos de deformación son considerablemente heterogéneos en el área de estudio. En la cuenca de Baza y la parte occidental del Corredor del Almanzora, sólo se detectan estructuras extensionales que contrastan con la presencia de estructuras compresivas y extensionales en la parte oriental del Corredor y la cuenca de Huércal-Overa.

- Hacia el Este, estas estructuras compresivas y extensionales están relacionadas con la terminación meridional de la Falla de Alhama de Murcia. Esta falla, activa desde el Tortoniense, ha condicionado el desarrollo de la cuenca de Huércal-Overa. Los pliegues menores que crecieron con una dirección inicial ENE-OSO, con el aumento de la deformación por cizalla en las inmediaciones de la terminación de la Falla de Alhama de Murcia, han rotado progresivamente hasta alcanzar una dirección ONO-ESE. Además del desarrollo de estructuras compresivas, numerosas fallas normales se formaron como consecuencia de elipsoide de esfuerzos caracterizado por un eje máximo de esfuerzo subvertical y una extensión subhorizontal de dirección, NNE-SSO a NE-SO y E-O a NO-SE, en transición con una extensión radial.

El estudio de estas cuencas confirma los modelos que proponen un desarrollo de la Cordillera Bético-Rifeña durante el engrosamiento cortical progresivo, activo desde el Tortoniense, asociado con la convergencia entre las placas Euroasiática y Africana. En este contexto, el desarrollo de grandes antiformas ha contribuido a la exhumación final de las rocas metamórficas y ha determinado la posición y geometría de las cuencas sedimentarias intramontañosas, ocasionalmente muy deformadas por fallas. Los mecanismos extensionales propuestos para explicar la exhumación de las rocas metamórficas y la formación del mar de Alborán durante el Mioceno inferior y medio, probablemente fueron inactivos durante el Mioceno superior, cuando fallas normales de alto ángulo deformaron ampliamente la corteza superior de la cordillera. El desarrollo de estas fallas está probablemente relacionado con inestabilidades gravitatorias asociadas con el proceso de engrosamiento cortical.

11. Future Perspectives

Despite the number of studies undertaken to date in the Betic and Rif cordilleras, the proposed geodynamic models for the orogen development still remain contradictory. One of the main sources of debate is that of the sub-crustal structure, composition and evolution, as well as its relationship with the upper crust deformation. The problem resides in the difficulties for direct testing and discrimination between these models on the basis of existing data, because the widespread recent brittle deformation interferes with deep interpretations from surface geological observations. In the near future, further geodynamic research will address this issue.

The integration of multidisciplinary research efforts involving geomorphology, geology, geophysics, and geodesy results will serve to shed light on neotectonic deformation models. These studies must include a detailed characterization of the outcropping structures, providing new data and new time constraints by geochronology, an assessment of the deeper structure through the acquisition of new geophysical data, a specific quantification of the tectonic incidence on land forms, and the rheological modelling of the crust. In this sense, two points can be emphasized here as especially relevant:

Up to now, all the acquired geophysical data used to explore the mantle below the Betic and Rif Cordilleras and the Alborán Sea are based on seismic sources, such as seismicity hypocenter distribution, seismic tomography, poorly detailed seismic refraction profiles and two deep seismic reflection profiles (ESCI-Béticas and ESCI-Alborán) that, even in conjunction, do not adequately constrain the deep structure. Several projects have been designed to clarify the dynamics of the lithospheric processes and their relation with the relief formation. Under a multidisciplinary approach, several geophysical methods are being used to constrain the deep structure of the lithosphere and upper mantle. To this end, broadband and long period magnetotelluric data will be acquired for assessing the resistivity structure of the mantle, which can then be compared with seismic data.

At the same time, the interaction between the compressive and extensional structures during the Late Miocene is not well constrained. The Betic Cordillera contains folds and normal faults that are still active and are now interacting. In order to pin down the distribution of the active deformation, several local GPS networks have been installed in collaboration with the University of Jaen (Sierra Tejeda antiform and Zafarraya normal fault, Western Sierra Nevada antiform and Padul-Nigüelas normal faults, Sierra de Gador antiform and Balanegra normal fault). The low deformation rate of these structures requires a long time period for obtaining results. However, the direct measurement of the compressive/extensional deformation interaction will contribute, in the future, to our understanding of the mechanism responsible for their coexistence.

Finally, in order to understand the Eurasian-African plate boundary as an integral deformation zone, it is necessary to follow those lines of research conducted in the Betic Cordillera in conjunction with a detailed study of the Rif Cordillera, and the integration of land surveys with marine data obtained from the Alborán Sea. Such research efforts will surely help to constrain the key seismogenic sources and will also enhance our knowledge of the overall geological hazards of the region.

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