

Recent and active faults and folds in the central-eastern Internal Zones of the Betic Cordillera

Las fallas y pliegues recientes y activos de la parte centro-oriental de las
Zonas Internas de la Cordillera Bética

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Abstract

The most recent tectonic structures of the central-eastern Internal Zones of the Betic Cordillera (from 3.1°W to 1.7°W and to the south of 37.525°N) include fault and folds developed from the Late Miocene onwards, which are related to N-S/NW-SE directed continental collision and moderate thickening of a crust that is relatively hot at depth. In this setting, E-W to WSW-ESE folds, with locally associated E-W transpressive right-lateral and reverse faults, favoured the emersion of the northern Alborán basin palaeomargin and the progressive intramontane basin disconnection. The NNE-SSW to NE-SW trending regional left-lateral Palomares and Carboneras fault zones are dominant structures in the easternmost part of the cordillera. In addition, NW-SE to WNW-ESE trending normal and oblique-slip normal faults are widespread. The collision is still active and continues to drive active folds and faults, some probably being the likely source of moderate-sized earthquakes. The Campo de Dalías and surrounding sectors, deformed by active ENE-WSW folds and NW-SE to WNW-ESE oblique-slip normal faults, are probably the sites with the largest concentration of significant earthquakes during recent years. Moderate-magnitude earthquakes (Mw 5.0 to 6.5) have occurred there at fairly regular intervals, in 1804, 1910, and 1994. Toward the east, NW-SE trending normal faults extending from Almería to the Tabernas basin deform the Quaternary rocks with associated moderate seismicity (the 2002 Gergal Mw 4.7 earthquake, and possibly the 1894 Nacimiento earthquake, felt with intensity VII). In the Sorbas-Vera basin, the Palomares fault zone is also responsible for moderate-sized earthquakes (1518 Vera earthquake). In the Almanzora corridor, NW-SE to WNW-ESE trending Lúcar-Somontín faults also could be considered one of the possible source of moderate-magnitude seismicity (1932 Lúcar, Mw 4.8 earthquake felt

with intensity VIII). Toward the east, between Albox and Partalao, several small reverse faults and associated compressive structures deform Quaternary alluvial and fluvial sediments. Although some of these folds reveal a slow and progressive deformation from the Middle Pleistocene onwards, some of these reverse fault segments that deform the western Huércal-Overa basin could host the 1972 NW Partalao, mbLg 4.8 earthquake, felt with intensity VII.

Keywords: Active Tectonics; Earthquakes; Tectonic Evolution; Gibraltar Arc.

Resumen

Las estructuras tectónicas más recientes que deforman la parte centro-oriental de las Zonas Internas de Cordillera Bética (entre 3.1° y 1.7°O y al sur de 37.525°N) son fallas y pliegues que comenzaron a formarse aproximadamente en el Mioceno superior en un contexto de colisión continental N-S/NO-SE y moderado engrosamiento cortical. En este marco tectónico, pliegues y fallas transpresivas dexas e inversas de direcciones E-O/OSO-ENE favorecieron la emersión del borde norte de la paleocuenca de Alborán y la progresiva desconexión de pequeñas cuencas intramontañosas. Además, comenzaron a formarse las grandes zonas de falla de Palomares y Carboneras, con direcciones NNE-SSO y NE-SO respectivamente y movimientos sinistros, que también han condicionado la evolución de la Cordillera Bética oriental desde el Mioceno superior. Algunas fallas con salto normal/normal-oblicuo y trazas NO-SE/ONO-ESE también se han desarrollado ampliamente en toda la zona de estudio. La colisión, aún activa, permite que algunos pliegues y fallas continúen propagándose en la actualidad, eventualmente causando terremotos con magnitudes moderadas. El Campo de Dalías y los sectores adyacentes, deformados por pliegues activos de direcciones ENE-OSO y fallas NO-SE/ONO-ESE normales-oblicuas, probablemente representan la zona con mayor concentración de terremotos importantes (Mw 5.0-6.5) con eventos recurrentes en 1804, 1910 y 1994. Al este del Campo de Dalías, una amplia zona de falla normal se extiende en dirección NO-SE desde Almería hasta la cuenca de Tabernas. Esta zona de falla muestra evidencias de funcionamiento durante el Cuaternario y tiene sismicidad moderada asociada a su terminación septentrional (el terremoto de Gergal en 2002 con Mw 4.7; y posiblemente el terremoto de Nacimiento en 1894 con intensidad VII). La zona de falla de Palomares es también responsable de terremotos moderados en la Cuenca de Sorbas-Vera (terremoto de Vera en 1518). En la parte central del corredor del Almanzora, alguno de los segmentos de falla normal que se extienden entre Lúcar y Somontín podría ser responsable del terremoto de Lúcar, en 1932 (Mw 4.8 e intensidad VIII). Al este, entre Albox y Partalao, se han descrito fallas inversas y pliegues asociados que deforman sedimentos cuaternarios. Aunque algunas de estas estructuras muestran evidencias de funcionamiento lento y progresivo durante el Cuaternario, el terremoto de Partalao en 1972 (mbLg 4.8 e intensidad VII) pudo ser causado por la actividad de cualquiera de estos segmentos de falla inversa que deforman la parte occidental de la cuenca de Huércal-Overa.

Palabras clave: Sismicidad, Tectónica Activa; Terremotos; Evolución Tectónica; Arco de Gibraltar.

1. Introduction

The recent and active tectonic structures of the Betic Cordillera have attracted attention of Earth scientists since the 1970s (Andrieux *et al.*, 1971; Biju Duval *et al.*, 1977; Groupe de Recherche Neotectonique, 1977; Bousquet and Montecat, 1974; Bousquet and Phillip, 1976; Bousquet, 1979), and since then, much geological and geomorphological research has been focused on their identification in order to establish the mechanisms responsible for the tectonic evolution of the orogen (*e.g.*, Sanz de Galdeano, 1983; Ott d'Estevou and Montecat, 1985; Sanz de Galdeano, 1990) and to estimate their seismogenic potential (*e.g.*, Sanz de Galdeano and López Casado, 1988; Sanz de Galdeano *et al.*, 1995). While the location, geometry, and kinematics of the main structures are well established, the processes involved in their development and the present-day activity of some of these structures are still under debate. It is widely accepted that compressional and extensional structures have deformed the Internal Zones of the Betic Cordillera since the Late Miocene. This region exhibits a variety of deformational

styles, dominated by folds, right-lateral and normal faults in the central Betics (*e.g.*, Galindo-Zaldívar *et al.*, 2003), and by large left-lateral strike-slip faults in the eastern sector of the cordillera that also interact with folds and normal/normal-oblique faults (*e.g.*, Martínez-Díaz, 2002; Masana *et al.*, 2004; Booth-Rea *et al.*, 2003; Pedrera *et al.*, 2010a). The present study attempts to sketch a coherent picture of these recent tectonic structures that deform the central-eastern (from the longitude 3.1°W to 1.7°W and to the south of 37.525°N) Internal Zones of the Betic Cordillera (Fig. 1). Special attention is placed on the faults and folds that have been active during Quaternary times, which are potential sources of future earthquakes.

2. Geological setting

The Betic Cordillera, together with the Rif, constitutes the westernmost part of the Alpine Mediterranean belt in the convergent Eurasian and African plate boundary (Fig. 1A). The Alpine evolution of the orogen is determined by the interaction between the two major plates and the intermediate placed Alborán Domain (Internal

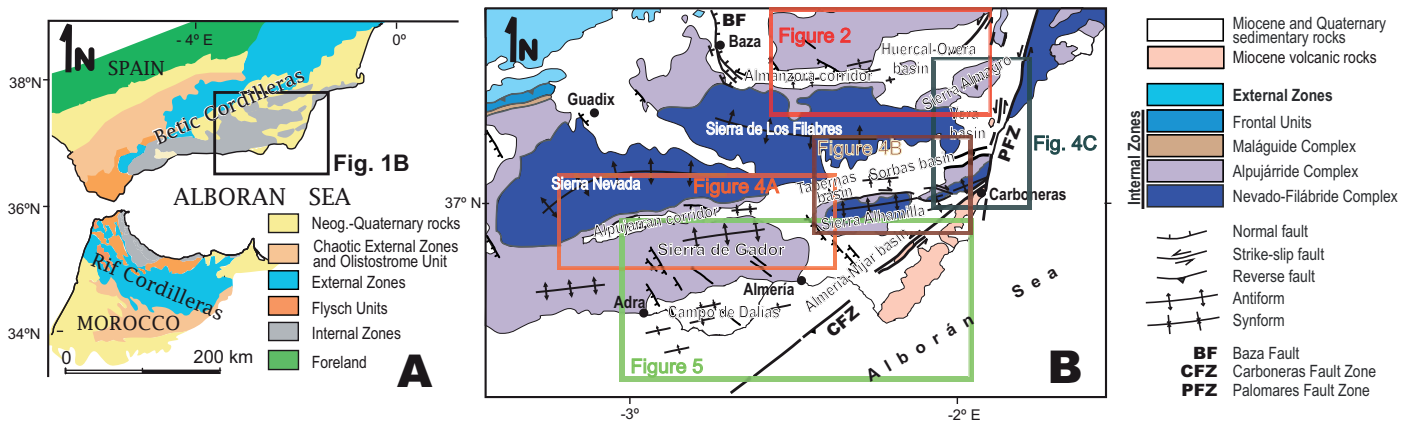


Fig. 1.- (A) Simplified geological map of the Betic and Rif Cordilleras including the location of figure 1B. (B) Geological sketch map of the central-eastern Betic Cordillera with the positions of the neotectonic maps of figures 2, 4A, 4B, 4C, 5.

Fig. 1.- (A) Mapa geológico simplificado de las Cordilleras Bético-Rifeñas con la posición de la figura 1B. (B) Mapa geológico simplificado del sector central y oriental de la Cordillera Bética con la localización de los mapas neotectónicos de las figuras 2, 4A, 4B, 4C, 5.

Zones of the Betic and Rif Cordillera) (e.g., Andrieux *et al.*, 1971; Sanz de Galdeano, 1990). In a framework of continuous N-S to NW-SE convergence, subduction and subsequent collision, with the destruction of Mesozoic oceanic basins (e.g., Martín-Algarra, 1987) and slab roll-back, reasonably explain the latest Oligocene to middle Miocene evolution of the Betic-Rif cordilleras and the development of the large Alborán basin (e.g., Lonergan and White, 1997). Therefore, during the early and middle Miocene the metamorphic rocks of the Alborán Domain were exhumed at the footwall of extensional brittle-ductile detachments (Aldaya *et al.*, 1984; Galindo-Zaldívar, 1986; García-Dueñas and Martínez-Martínez, 1988; Jabaloy *et al.*, 1993) and the Alborán basin was formed, floored by thinned continental crust, exhibiting a large arched sedimentary depocenter: the West Alborán basin (Comas *et al.*, 1992, 1999; Soto *et al.*, 1996; Chalouan and Michard, 2004). Roughly since the late Miocene, the subduction shifted to N-S/NW-SE continental collision, the crust started to thicken, and the northern margin of the Alborán basin progressively emerged. Consequently, intramontane sedimentary basins gradually became isolated from the original Alborán basin, some completely emerging (e.g., Braga *et al.*, 2003). This continent collision is still active at a rate of 4-5 mm/yr (Argus *et al.*, 1989; DeMets *et al.*, 1990, 1994) and continues driving the development of active folds and faults (e.g., Sanz de Galdeano *et al.*, 1995; Galindo-Zaldívar *et al.*, 2003). Therefore, current displacement of the Earth's surface reveals the oblique convergence between the Iberian and African plates, showing a movement of the Eurasian plate and the Betic Cordillera toward the SSW/SW with respect to the African plate (Stich *et al.*, 2006; Fadil *et al.*,

2006; Tahayt *et al.*, 2008; Vernant *et al.*, 2010), which is roughly in accordance with the present-day stress setting (e.g., Fernández-Ibáñez *et al.*, 2007; Pedreira *et al.*, 2011).

In the Betic Cordillera, the structures that formed since the late Miocene up to now have been classically designated as recent or neotectonic. These structures determine the spatial distribution of the uplifted areas subjected to erosion and the sedimentary basins. Below, we describe the recent and active structures that, from north to south, deform the Almanzora corridor and the Huércal-Overa basin, the Alpujarran corridor and the Tabernas, Sorbas, and Vera basins, and the Campo de Dalías and the Almería-Níjar basin (Fig. 1B).

3. The Almanzora corridor and the Huércal-Overa basin

The Almanzora corridor and the Huércal-Overa basin are located between the Sierra de Los Filabres and Sierra de Las Estancias (Figs 1 and 2). Both basins are essentially filled by Serravallian-lower Tortonian continental/fluvial-deltaic sediments, and became a marine realm during the late Tortonian. The marine-continental transition started in Messinian times. Continental sedimentation along rivers and alluvial fans together with erosion occurred during the Pliocene and Quaternary.

3.1. Late Miocene tectonic structures

Compressive and extensional structures deformed the late Miocene-Quaternary sediments of the Almanzora corridor and the Huércal-Overa basin (Briend, 1981; Briend *et al.*, 1990; Mora-Gluckstadt, 1993; Poisson *et al.*, 1999;

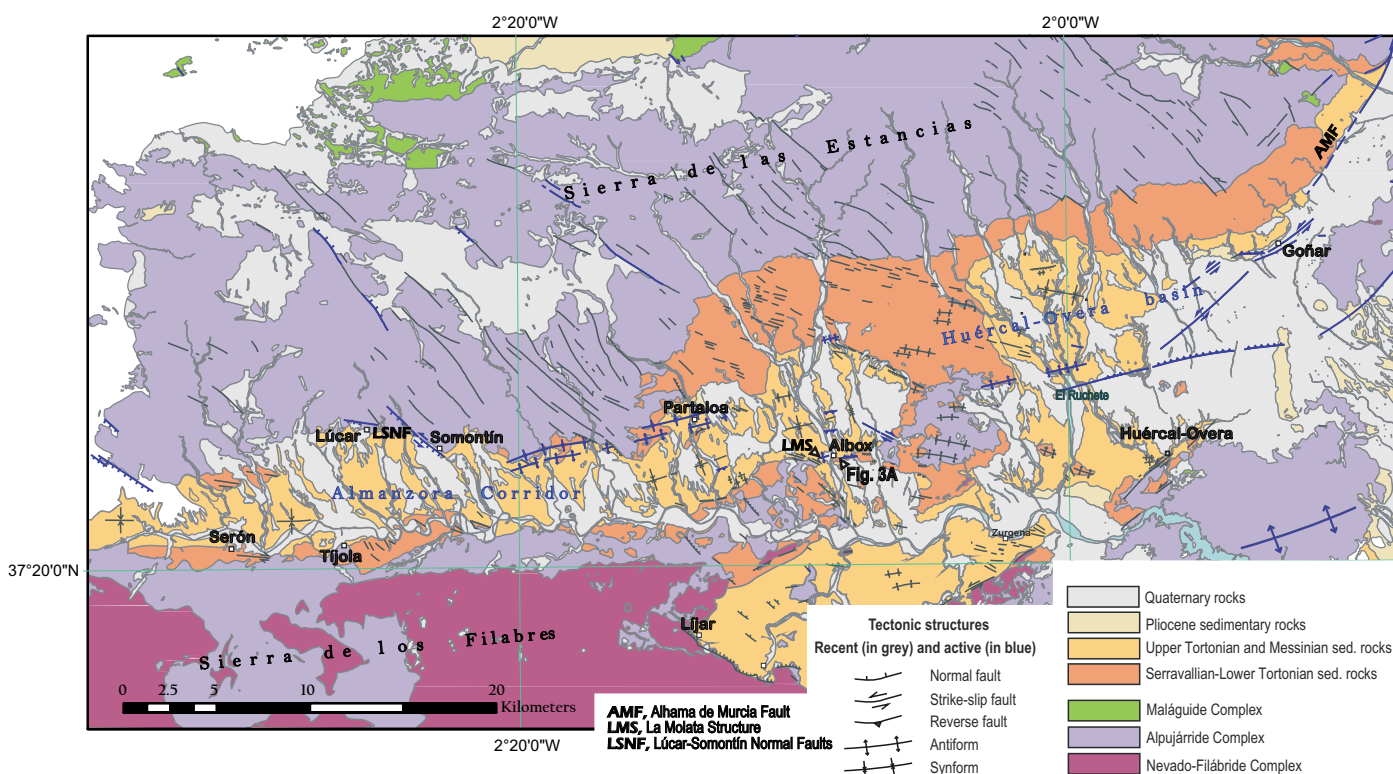


Fig. 2.- Geological map of the Almanzora corridor and the Huércal-Overa basin with traces of the recent (in grey) and active (blue) tectonic structures. The location of figure 3A is marked.

Fig. 2.- Mapa geológico del Corredor del Almanzora y la Cuenca de Huércal-Overa que incluye las trazas de las estructuras tectónicas recientes (en gris) y activas (en azul). La posición de la figura 3A está indicada.

Augier, 2004; Augier *et al.*, 2005; Meijninger and Visers, 2006; Pedrera *et al.*, 2007; Pedrera *et al.*, 2010a). The study area was deformed by a succession of kilometric scale 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 (Booth-Rea *et al.*, 2003, 2004; Pedrera *et al.*, 2007, 2009b). The antiforms coincide with the ranges where the metamorphic rocks crop out, while the synforms correspond to the sedimentary basins. Folding started there with the Sierra de los Filabres antiform nucleation during Serravallian-early Tortonian, as revealed by the syntectonic angular unconformities founded in its northern limb (Pedrera *et al.*, 2007). Large-scale folds continued growing and propagating to the north, forming the Almanzora corridor in the late Tortonian (Pedrera *et al.*, 2007). Moreover, the sedimentary rocks have been deformed since late Tortonian by ENE-WSW minor folds (Pedrera *et al.*, 2007; Pedrera *et al.*, 2010a). To the east, these minor folds progressively change their trend from ENE-WSW to WNW-ESE (Pedrera *et al.*, 2010a). In addition, the late Miocene sediments are quite deformed by several sets of faults. The most abundant set is formed by WNW-ESE to NW-SE normal faults that show a wi-

despread distribution in the basins (Briend, 1981; Briend *et al.*, 1990; Mora-Gluckstadt, 1993; Poisson *et al.*, 1999; Augier, 2004; Augier *et al.*, 2005; Meijninger and Visers, 2006; Pedrera *et al.*, 2007; Pedrera *et al.*, 2010a). Subvertical strike-slip dextral faults, E-W to ESE-WNW oriented, deformed the Tortonian sediments that crop out mainly in the southern Almanzora corridor boundary (Fig. 2; Poisson *et al.*, 1999; Pedrera *et al.*, 2007).

3.2. Active tectonic structures

The westernmost part of the Almanzora corridor is affected by a set of NW-SE faults that deform up to the Quaternary glacia and constitute the western end of the corridor. These fault segments are related to the normal Baza fault (Alfaro *et al.*, 2008; García-Tortosa *et al.*, 2008; Sanz de Galdeano *et al.*, this volume), which extends more than 30 km along the Baza basin, showing a N-S to NW-SE variable strike, and dipping to the NE (Fig. 1B). In the central part of the corridor, the Lúcar fault — formed by a set of ENE-WSW oriented and 40°-75° south dipping normal faults — locally deforms the Quaternary sediments. Close to Somontín, the 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 sense of motion overprinted on the normal striation. The eastern Almanzora corridor (Somontín-Partaloo sector) and the western Huércal-Overa basin are both deformed by widespread small-scale contractional tectonic structures, which include WNW-ESE trending dextral faults and ENE-WSW oriented open folds, fault-propagation folds, and reverse faults (Figs. 2 and 3A; Briend *et al.*, 1990; Pedrera *et al.*, 2009a and 2009b). Using a geomorphological approach, García-Meléndez (2000) and García-Meléndez *et al.* (2004) defined the Albox fault as an ENE-WSW to E-W fault zone with reverse-dextral kinematics that runs from the eastern Huércal-Overa basin as far as the Almanzora corridor to the west. The La Molata fault-propagation fold is one of the best-exposed outcrops (Fig. 2, Pedrera *et al.*, 2009a). This fold and its related faults have 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 to the present (Pedrera *et al.*, 2009a). The central and eastern part of the Huércal-Overa basin is deformed by ENE-WSW trending reverse faults with a splay geometry, belonging to the southern end of the Alhama de Murcia left-lateral transcurrent fault (AMF) (Martínez-Díaz *et al.*, this volume). These faults deform the Quaternary alluvial fan deposits in the eastern Huércal-Overa basin (Groupe de Recherche Néotectonique, 1977; Briend, 1981) and have been recently characterized with geomorphological, structural, and paleoseismologic studies (García-Meléndez *et al.*, 2003; Soler *et al.*, 2003; Masana *et al.*, 2005; Meijninger and Vissers, 2006; Ortuño *et al.*, 2009). Thus, paleoseismologic studies near Goñar (Fig. 2) in the eastern Huércal-Overa basin, identify at least two paleoearthquakes associated with the AMF during the last 150 ka and estimate a minimum vertical slip rate of ~ 0.02 mm/yr in the southern fault termination since the Middle Pleistocene (Ortuño *et al.*, 2009). In addition, a palaeoseismologic study in El Ruchete sector (Fig. 2) identified fault segments with short-term slip-rates ranging from 0.01 to 0.4 mm/yr and two possible paleoearthquakes deposits associated with them (Masana *et al.*, 2005). This reverse fault segment probably belongs to the horsetail reverse splay of the AMF (Fig. 2).

The drainage network of the Almanzora River, highly controlled by the above structures, reflects the activity of the faults and folds since the Messinian (Stokes, 2008; Stokes and Mather, 2000, 2003; Pedrera *et al.*, 2009c). The presence of normal faults condition small changes in the direction of the north Almanzora River tributary

stream. In addition, the role of the above-described active folds in the landscape evolution and drainage development was characterized in the folded eastern Almanzora corridor and western Huércal-Overa basin (Pedrera *et al.*, 2009c).

4. The Alpujarran corridor, the Tabernas basin, and the Sorbas-Vera basin

The Alpujarran corridor is an E-W elongated valley formed by a roughly synformal structure located between the Sierra Nevada to the north and the Sierras Lújar-Contraviesa-Gádor to the south. Eastwards the corridor extends to the Tabernas basin, which continues into the Sorbas-Vera basin, between Sierra de Los Filabres to the north and Sierra Alhamilla and Sierra Cabrera to the south (Figs. 1 and 4). These basins are partially filled with lower Miocene to Quaternary deposits and constitute a zone of crustal weakness where recent and active deformation structures are nucleated (Ott d'Estevou *et al.*, 1990; Rodríguez-Fernández, 1982). Researchers agree on the presence throughout this area of a main right-lateral fault zone (*e.g.*, Sanz de Galdeano *et al.*, 1985; Galindo-Zaldívar, 1986; Sanz de Galdeano, 1989; Jabaloy *et al.*, 1992; Galindo-Zaldívar *et al.*, 2003; Martínez-Díaz and Hernández-Enrile, 2004; Martínez-Martínez, 2006; Martínez-Martínez *et al.*, 2006; Sanz de Galdeano *et al.*, 2010). However, controversy persists concerning the deep continuity of the structures, the relationships of the exposed faults with seismicity, the driving mechanisms, and in some cases the age of fault activity. On the other hand, there is a general consensus regarding the features of the major left-lateral Palomares fault zone (PFZ), which developed since the late Tortonian in the eastern part of the Sorbas-Vera basin (*e.g.*, Bousquet and Phillip, 1976; Bousquet, 1979; Montenat *et al.*, 1987; Weijermars, 1987; Ott d'Estevou *et al.*, 1990; Silva *et al.*, 1993; Booth-Rea *et al.*, 2003).

4.1. Miocene tectonic structures

After the end of metamorphism in the Internal Zones, a set of top-to-the west low-angle normal faults thinned the crust and exhumed the Nevado-Filábride complex, up to the middle Miocene (*e.g.*, Aldaya *et al.*, 1984; Galindo Zaldívar, 1986; García-Dueñas and Martínez-Martínez, 1988; Jabaloy *et al.*, 1993). Afterwards, the crustal-thinning process shifted to crustal thickening and relief formation, when the Sierra Nevada and Sierra de los Filabres started to emerge (Braga *et al.*, 2003) as large antiforms that folded the extensional detachments

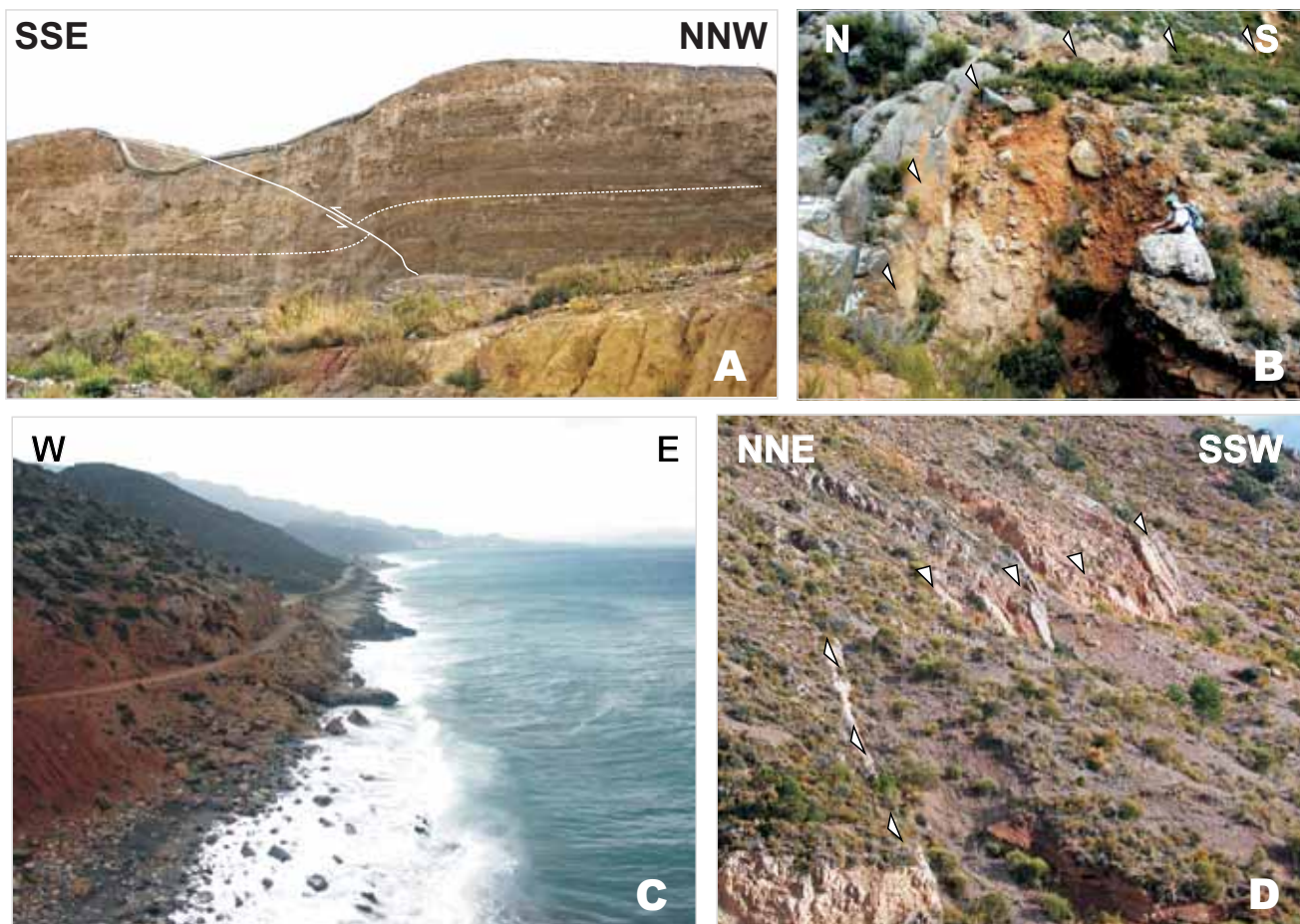


Fig. 3.- Field view of several active tectonic structures placed in the central-eastern Betic Cordillera. (A) ENE-WSW trending reverse fault and associated antiform that deform Quaternary conglomerates near Albox in the Huércal-Overa basin. (B) Laujar de Andarax normal fault: E-W oriented normal fault dipping toward the south affecting Quaternary sedimentary rocks in the northern Alpujarran corridor margin. (C) Rectilinear coast line that coincides with a fault segment of the left-lateral Palomares fault zone, which controls the eastern termination of the Sierra Cabrera. (D) Balanegra fault zone: NW-SE oriented normal fault segment that deforms Quaternary sediments in the western termination of the Sierra de Gádor, close to the village of Berja.

Fig. 3.- Ejemplos de algunas estructuras activas situadas en el área de estudio. (A) Falla inversa y pliegue asociado de direcciones ENE-OSO que deforman conglomerados cuaternarios en las proximidades de Albox, en la Cuenca de Huércal-Overa. (B) Falla normal de Laujar de Andarax: segmento que afecta a sedimentos cuaternarios con dirección aproximada E-O y buzamiento hacia el Sur. (C) Tramo de costa rectilínea asociado a un segmento de la Falla de Palomares que controla la terminación oriental de Sierra Cabrera. (D) Zona de falla de Balanegra: segmento de dirección NO-SE que deforma sedimentos cuaternarios en la terminación occidental de la Sierra de Gador, cerca de Berja.

(Martínez-Martínez *et al.*, 1995; Martínez-Martínez and Azañón, 1997; Galindo-Zaldívar *et al.*, 2003; Pedrera *et al.*, 2009b). The deformation also propagated southward since the late Tortonian with the development of E-W kilometre-sized folds (Weijermars, 1985) that determined the isolation of the Alpujarra-Tabernas-Sorbas corridor (Fig. 4). A major E-W right-lateral fault zone composed by subvertical fault segments runs within the corridor (Sanz de Galdeano *et al.*, 1985), developing foliated cataclases and fault-bound lenses (Sanz de Galdeano *et al.*, 1985). Faults segments with intermediate to low dips and oblique-slip including normal and reverse components have been also described, as in the Ugijar area (Fig. 4A; Galindo-Zaldívar, 1986).

Eastwards, E-W strike-slip faults segments are also well developed running along the southern part of the western Tabernas basin (Sanz de Galdeano *et al.*, 2010) and the northern boundary of Sierra Alhamilla antiform, the so-called Lucainena fault (Sanz de Galdeano, 1989) (Fig. 4A, B). The Lucainena fault branches into two segments to the east (Sanz de Galdeano, 1989). The northern segment, which runs near Gafarillos village, changes its orientation from E-W to NW-SE and cross-cut upper Tortonian sediments and the metamorphic rocks of the Sierra Cabrera (Sanz de Galdeano, 1989). This fault segment is usually called the **Gafarillos fault** (Stapel, 1996; Huijbregtse *et al.*, 1998; Jonk and Bierman, 2002) or North Gafarillos fault (Giaconia *et al.*, 2012). The southern

fault segment runs from Los Guardianes, near Polopos village, to the southern boundary of Sierra Cabrera anti-form with an ENE-WSW trend, being called the Polopos fault (Keller *et al.*, 1995) or the South Gafarillos fault (Fig. 4; Giaconia *et al.*, 2012).

The E-W right-lateral faults along the Alpujarras, the E-W oriented right-lateral faults of the southern Tabernas basin, and the dextral-reverse faults in the southern Sorbas basin have been traditionally interpreted as transpressive faults developed under N/S to NNW/SSE compression (*e.g.*, Sanz de Galdeano *et al.*, 1985, 1989; Stapel, 1996; Huibregtse *et al.*, 1998; Jonk and Bierman, 2002). However, Martínez-Martínez (2006) and Martínez-Martínez *et al.* (2006) propose a different interpretation for the Alpujarra right-lateral faults. They consider this fault zone to be part of a WSW-directed extensional system connecting two normal fault systems that thinned the Betic hinterland since the middle Miocene to the present.

In the absence of accurate, deep geophysical data, the deep continuity of the right-lateral faults has been considered to have a crustal (Sanz de Galdeano *et al.*, 1985) or at least shallow crustal character (Martínez-Díaz and Hernández-Enrile, 2004; Martínez-Martínez *et al.*, 2006), although Galindo-Zaldívar (1986) suggests that fault structures of the central Alpujarras corridor are restricted to the shallowest part of the crust.

Toward the east, the Palomares fault zone (PFZ), which is formed by several N10°E to N20°E left-lateral fault segments, deforms the eastern sector of the Vera basin (Fig. 4C) (Bousquet and Phillip, 1976; Bousquet, 1979; Weijermars, 1987). The Miocene sediments of the Vera basin are involved within the fault zone. Therefore, two depocenters filled by latest Tortonian to Quaternary sediments are linked to the movement of Arteal and Palomares fault segments (Fig. 4C; Booth-Rea *et al.*, 2003). Thus, the PFZ is considered a transcurrent deformation zone

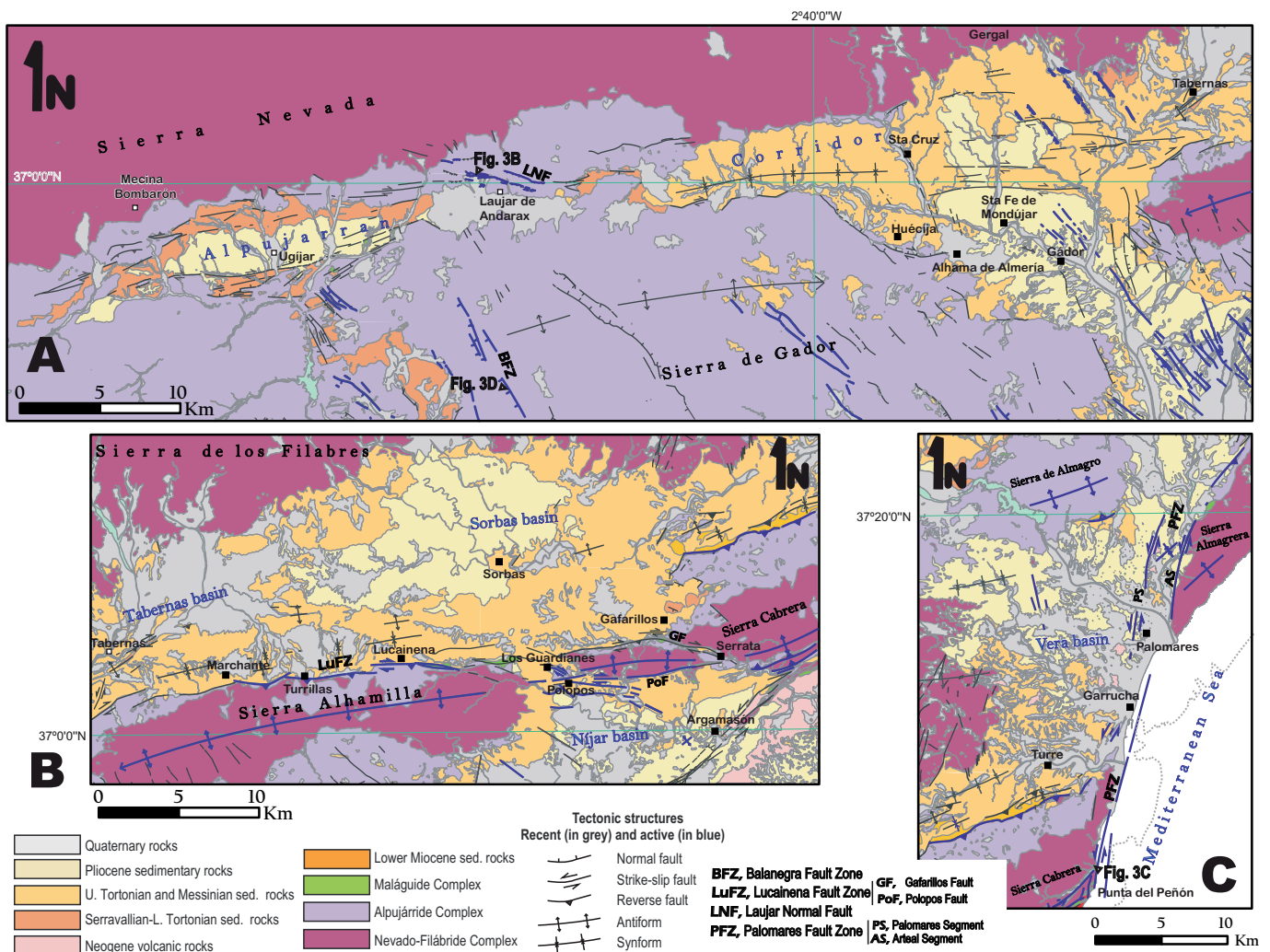


Fig. 4.- (A) Geological map of the Alpujarran corridor, (B) Tabernas/Sorbas basin, and (C) Vera basin showing traces of the recent (in grey) and active (blue) tectonic structures. The locations of figures 3B and C are marked.

Fig. 4.- Mapa geológico del Corredor de las Alpujarras, (B) la Cuenca de Tabernas/Sorbas y (C) la Cuenca de Vera con las trazas de las estructuras tectónicas recientes (en gris) y activas (en azul). La posición de la figuras 3B y C están indicadas.

active during most of the Neogene and Quaternary (e.g., Montenat *et al.*, 1987; Ott d'Estevou *et al.* 1990; Silva *et al.*, 1993; Ruano *et al.*, 2007). Both ends are characterized by a change in the fault segments direction, which acquire a splay geometry that may be consistent with the development of reverse faults and antiforms since upper Miocene (Sierra Cabrera and Sierra Almagrera).

4.2. Active tectonic structures

The major dextral fault zone of the Alpujarra-Tabernas-Sorbas basins may have continued its activity up to the Quaternary (Sanz de Galdeano *et al.*, 1985; Martínez-Díaz and Hernández-Enrile, 2004; Martínez-Martínez *et al.*, 2006). Moreover, most of the dextral faults appear to be covered by the thin Plio-Quaternary sediments in the western Ugijar basin (Galindo-Zaldívar, 1986). Eastwards, the southern border of the Sorbas basin shows evidence of recent dextral oblique-reverse faulting (Sanz de Galdeano, 1989; Martínez-Díaz and Hernández-Enrile, 2004; Giaconia *et al.*, 2012).

A clear evidence of Quaternary faulting is found in the eastern Alpujarran corridor, in the Laujar de Andarax zone (García-Tortosa and Sanz de Galdeano, 2007). This consists of an E-W trending fault zone formed by southward-dipping normal faults segments affecting Quaternary deposits (Fig. 3B and 4A). Quaternary faults with related seismic activity are also found along a NW-SE zone that stretches from Almería to the Tabernas basin and separates Sierra Alhamilla from Sierra de Gádor (Sanz de Galdeano *et al.*, 2010). Seismicity is concentrated in the basement at the north-western edge, near Gergal, and this may correspond to the area of propagation of the fault zone.

The dextral-reverse Polopos fault deforms the Mesinian and locally Quaternary sedimentary rocks of the Níjar basin with (Sanz de Galdeano, 1989). A recent geomorphic analysis confirms that active tectonics influences the streams and hillslopes of the Sierra Alhamilla antiform related to the Polopos fault and identify Quaternary contractional deformation associated to the Lucainena fault zone to the east of Marchante (the North Alhamilla Reverse Fault of Giaconia *et al.*, 2012).

The PFZ deforms Pleistocene conglomerates, close to Palomares village, developing an impressive fault-mirror with subhorizontal striations (Bousquet and Phillip, 1976). Pliocene-Quaternary sedimentary depocenters reveal that deformation along the PFZ fault zone migrated towards the eastern Arteal fault segment, which bounds the western mountain front of Sierra Almagrera (Booth-Rea *et al.*, 2003). In addition, the Quaternary activity of

the PFZ favoured stream dissection, headward erosion of streams transverse to the active fault segments, and the asymmetry of the drainage network (Booth-Rea *et al.*, 2004; Stokes, 2008). The almost straight coastline from Palomares to Punta del Peñón is controlled by the PFZ (Figs. 3C and 4C), therefore the Late Pleistocene-Holocene marine terraces are uplifted along the coast (Goy and Zazo, 1986). In addition, Pleistocene conglomerates located in the Punta del Peñón contain numerous pebbles striated under the left-lateral shear of the PFZ. At its southern end, the PFZ splays into a horsetail formed by ENE-WSW reverse faults (Fig. 3C and 4C). South-dipping reverse faults form the north boundary of the Sierra Cabrera (Booth-Rea *et al.*, 2004), locally affecting Quaternary sediments (Sanz de Galdeano, 1987), and north-dipping reverse faults constitute the southern edge of the Sierra (Keller *et al.*, 1995). The CuaTeNeo (Cuantificación de la Tectónica actual y Neotectónica) GPS non-permanent network was installed in 1996 to quantify the deformation in the Eastern Betic Cordillera. The network consists of 15 monuments covering an area of 120x50 km in Murcia and Almería (Colomina *et al.*, 1998; Khazaradze *et al.*, 2007 and 2008). In the northern part of the GPS network, the stations placed westward of the AMF and the PFZ show insignificant motions with respect to the stable part of the Eurasian plate. The GPS sites placed close to coast, eastward of the AMF and the PFZ, move 1-1.5 mm/yr toward the NNW revealing a strain accumulation (Echeverría *et al.*, 2011; Frontera *et al.*, 2011).

5. The Campo de Dalías and the Almería-Níjar basin

The Campo de Dalías and the Almería-Níjar basin are located at the boundary between the Alborán Sea and the Betic Cordillera. In both basins, the Tortonian and Pliocene marine sedimentary rocks, which belonged to the Northern Alborán basin, have emerged in Quaternary times (Fig. 5).

5.1. Late Miocene tectonic structures

The Carboneras fault zone (CFZ) is a major regional left-lateral fault that extends onshore along the Almería-Níjar basin (Bousquet and Montenant 1974; Ott d'Estevou and Montenant; 1985, Keller *et al.*, 1995; Scotney *et al.*, 2000; Faulkner *et al.*, 2003) and continues offshore along the Almería Gulf in a NE-SW direction (Fig. 5; De Larouzière *et al.*, 1988; Gràcia *et al.*, 2006). The upper Miocene sediments, together with metamorphic and volcanic basement rocks, crop out along the highly deformed CFZ (Bousquet and Montenant 1974; Rutter *et al.*, 1986;

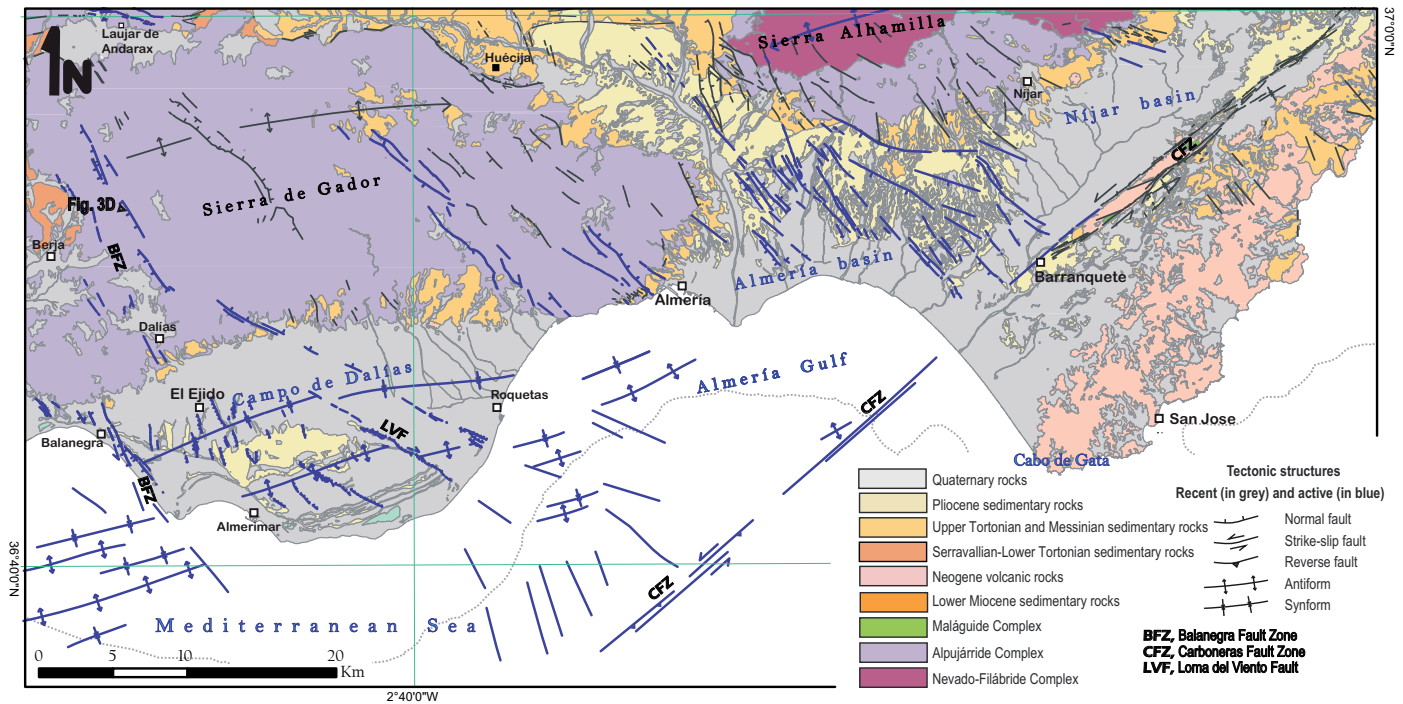


Fig. 5.- Geological map of the Campo de Dalías and the Almería/Níjar Basin with the traces of the recent (in grey) and active (blue) tectonic structures. The location of figure 3D is marked.

Fig. 5.- Mapa geológico del Campo de Dalías y de la Cuenca de Almería/Níjar con las trazas de las estructuras tectónicas recientes (en gris) y activas (en azul). La posición de la figura 3D está indicada.

Van de Poel, 1991; Keller *et al.*, 1995). The nucleation of the crustal-scale CFZ is closely linked to the Miocene volcanism, which modified the thermal structure and the strength of the lithosphere (Pedrera *et al.*, 2010b). Northwards of the CFZ, the sedimentary rocks are widely deformed by folds with a hundreds of meters amplitude and consistently showing an ENE-WSW strike onshore and offshore (Figs. 4B and 5). These folds deformed the sediments before the Messinian generating a cartographic unconformity between the highly folded upper Tortonian rocks and the less deformed post-Messinian sediments (Weijermars *et al.*, 1985).

To the north, the highest reliefs in the area are linked to culminations on the hinge line of the Sierra Alhamilla and Sierra de Gador antiforms, which have an ENE-WSW orientation, 10 km of maximum amplitude, and are 25 to 30 km long respectively, and more than 1300 m high. The lower Tortonian-Serravallian conglomerates and the upper Tortonian sediments that surround the ranges are folded, revealing the fold geometry and the age of the deformation. In the Sierra Alhamilla, the late Tortonian rocks dip 20° in the southern slopes, yet are vertical or even overturned on the northern slopes as a consequence of the northward fold vergence and the activity of the E-W oriented high-angle reverse to right-lateral Lucainena fault zone (Weijermars *et al.*, 1985; Sanz de Galdeano, 1989).

The Níjar basin is intensely deformed by high-angle dipping normal faults since the Late Miocene (Martínez-Díaz and Hernández-Enrile, 2004; Marín-Lechado *et al.*, 2005; Pedrera *et al.*, 2006; Sanz de Galdeano *et al.*, 2010). They have a consistent NNW-SSE to NW-SE strike. Although the normal faults have a widespread distribution, their presence predominates in western Níjar, extending toward the Tabernas basins and very locally toward the Sorbas basin. The Níjar basin depocenter is associated with this NW-SE oriented normal fault activity. The maximum sedimentary thickness, established from gravity data, reaches more than 1 km in the western sector of the basin (Pedrera *et al.*, 2006). The fault surfaces dip towards the SW and usually deform the Tortonian and Messinian sediments, showing variable geometries from listric to domino-like systems. To the south-eastern part of the Almería Níjar basin, NW-SE normal faults dipping mainly to the NE deform the Pliocene sediments, sometimes showing syn-sedimentary features (Marín-Lechado *et al.*, 2005; Pedrera *et al.*, 2006).

5.2. Active tectonic structures

ENE-WSW open to gentle N-vergent folds affect the Pliocene and Quaternary sediments that extend along the continental shelf of the Almería Gulf, the Campo de

Dalías (Marín-Lechado *et al.*, 2006) and the Níjar basin (Fig. 5; Sanz de Galdeano, 1989; Huibregtse *et al.*, 1998; Pedrera *et al.*, 2006). These folds indicate the continuity of the contractional deformation after the major Messinian unconformity. In addition, normal to normal-oblique faults deform alluvial sediments up to the Pliocene and the Quaternary, generating fault scarps. In the Almería-Níjar basin, NNW-SSE to NW-SE normal faults are responsible for high slopes and sharp topography in the western part of the Sierra Alhamilla antiform and deform its southern limb. Therefore, from Gergal to Cabo de Gata, they control the Andarax valley geometry and the rectilinear coast line (*e.g.*, Martínez-Díaz and Hernández-Enrile, 2004; Marín-Lechado *et al.*, 2005; Pedrera *et al.*, 2006; Sanz de Galdeano *et al.*, 2010). From a geomorphological point of view, abrupt changes in the channels slope are probably associated to the activity of these normal faults (Giaconia, 2012).

Onshore recent tectonic activity of the CFZ is well observed near Barranquete, in the SW sector, where N30°-45°E subvertical left-lateral fault surfaces deform Quaternary sediments (*e.g.*, Boorsma, 1992; Pedrera *et al.*, 2006). There, detailed geochronological and paleoseismic studies have been carried out (Moreno, 2011). Slip-rates, paleoseismologic, and seismic potential behaviour of the CFZ derived from onshore-offshore results have been recently described in detail by Moreno (2011). A GPS station on the southern fault block is moving 1.5 ± 0.7 mm/yr toward the NNE with respect to northward stations. This can be interpreted as being mainly caused by the left-lateral strike slip motion along the CFZ (Khazaradze *et al.*, 2010).

The Campo de Dalías is widely deformed by subvertical oblique-slip faults that have directions between NW-SE and WNW-ESE and that have been active since the Pleistocene (Martínez-Díaz, 1998; Martínez-Díaz and Hernández-Enrile, 2004; Marín-Lechado *et al.*, 2004, 2005; Pedrera *et al.*, 2012). The Balanegra fault zone extends from the western end of the Sierra de Gádor toward the Alborán Sea, controlling the western termination of the Sierra de Gádor antiform and the NW-SE oriented straight morphology of the coast line (Figs. 3D and 5; Martínez-Díaz and Hernández-Enrile, 2004; Marín-Lechado *et al.*, 2005 and 2010; Fernández-Ibáñez *et al.*, 2006). Other prominent fault is the WNW-ESE oriented Loma del Viento fault (Figs. 3D and 5), which deforms the central part of the Campo de Dalías with dextral-normal kinematics since Pleistocene (Marín-Lechado *et al.*, 2004; Martínez-Díaz and Hernández-Enrile, 2004; Pedrera *et al.*, 2012). The Loma del Viento fault is formed by six onshore segments and some of them are hard-linked

(Pedrera *et al.*, 2012). Fault slip enhances toward the linkage sectors with an estimated long-term slip rate of 0.07 ± 0.03 mm/yr since the Pleistocene (Fig. 5; Pedrera *et al.*, 2012). The normal to normal-oblique faults continue toward the Alborán Sea, as deduced from NW-SE trending lineaments detected by bathymetric studies (Fig. 5; Gràcia *et al.*, 2006).

A non-permanent GPS network was installed in the Campo de Dalías to control the crustal deformation associated with active folds and faults. GPS measurements were made in 2006 and 2011, and the data are being processed. In addition, two precision levelling profiles were installed along the southern part of the Balanegra fault zone and measured in 2006, 2007, 2009, and 2010 to estimate the short-term fault-slip rate (Marín-Lechado *et al.*, 2010).

6. Seismicity and Earthquake Sources

The sector of the Betic Cordillera addressed in this paper is affected by distributed seismicity of low to moderate magnitude, which is limited to the upper crust (*e.g.*, Stich *et al.*, 2003, 2010; Fernández-Ibáñez and Soto, 2008). Earthquakes larger than Mw 5 rarely occur (Table 1). These major earthquakes can cautiously be associated with possible source faults, on the basis of damage descriptions in the cases of pre-instrumentally registered events and the estimated location and source analysis derived from the moment tensor solution in the case of the most recent earthquakes (Table 1). In the Campo de Dalías and surrounding sectors, large events occurred close to the village of Dalías (August 25, 1804, with felt intensity VIII-IX in the scale EMS-98 used throughout this paper, and Mw 6.4 macroseismic magnitude) and close to Adra, where a Mw 6.1 earthquake and Mw 5.5 aftershock occurred on June 16, 1910. The source parameters of the main Adra shock was established after analysing six analogue seismogram recordings ($M_0 = 1.50 \cdot 10^{18}$ Nm, Mw=6.1, oblique strike-slip event at 16 km in depth; Stich *et al.*, 2003). Recently, two related events occurred to the south of Berja (December 23, 1993, Mw 5.3, m_{bLg}), and of Guardias Viejas (January 4, 1994, Mw 4.9). Both reveal strike-slip, slightly oblique fault plane solutions with a N120°E oriented dextral nodal plane (Stich *et al.*, 2001), very similar to that found for the June 16, 1910 Adra earthquake. Stich *et al.* (2001) analysed the complete 1993-1994 seismic series and later seismicity in the area up to 1998, recognizing 39 multiplet clusters with N120-130°E and N60-70°E lineaments. These earthquakes could be assigned to the Balanegra fault zone (Marín-Lechado *et al.*, 2005), which is formed by N120°E

Date	Latitude (N)	Longitude (W)	Intensity (EMS-98 scale)	Magnitude	Location	Possible source
01/01/1406	37.25	1.87	VII-VIII	M _s 5.0 ¹	Vera. Al	Palomares Fault
01/11/1487	36.83	2.47	VIII	M _s 5.4 ¹	Almería	NW-SE normal faults
09/11/1518	37.23	1.87	VIII-IX	M _s 6.0 ¹	Vera. Al	Palomares Fault
22/09/1522	36.97	2.67	VIII-IX	M _w 6.5 ²	W Alhama de Almería. Al	Carboneras Fault; NW-SE normal faults
31/12/1658	36.83	2.47	VIII	M _s 5.4 ¹	Almería	NW-SE normal faults
---/---/1686	36.85	2.95	VI-VII	M _s 4.5 ¹	Berja. Al	Balanegra Fault Zone -western Gádor
25/08/1804	36.77	2.83	VIII-IX	M _w 6.4 ²	Dalías. Al	Balanegra or Loma del Viento Fault
25/08/1804*	36.77	2.83	VII	M _s 4.7 ¹	Dalías. Al	Balanegra or Loma del Viento Fault
29/08/1804*	36.77	2.83	VII	M _s 4.7 ¹	Dalías. Al	Balanegra or Loma del Viento Fault
10/06/1863	37.37	1.93	VI-VII	M _s 4.5 ¹	Huércal-Overa	Reverse faults Huércal Overa (South termination AMF)
11/06/1894	37.12	2.67	VII	M _s 4.7 ¹	Nacimiento. Al	NW-SE normal faults
13/05/1895	37.00	1.90	VI-VII	M _s 4.5 ¹	Carboneras. Al	Palomares Fault
16/06/1910	36.67 36.84 ²	3.37 3.00 ²	VIII	M _w 6.1 ³ M _w 6.7 ²	Adra. Al	Balanegra Fault Zone
16/06/1910*	36.67	3.37	VII	M _w 5.5 ³	Adra. Al	Balanegra Fault Zone
22/04/1912	37.03	2.95	VII	M _s 4.7 ¹	Ocaña. Al	
05/03/1932	37.42 37.51 ²	2.45 2.45 ²	VIII	m _D 4.8 M _w 5.7 ²	Lúcar. Al	Lúcar-Somontín Faults
16/03/1972	37.42	2.24	VII	m _{blg} 4.8	NW Partalooa. Al	Reverse faults eastern Almanzora
13/09/1984	36.98	2.34	V	m _{blg} 5.0	SE Tabernas. Al	
23/12/1993	36.78	2.94	VII	m _{blg} 5.0	S Berja	Strike-slip, slightly oblique Balanegra Fault
04/01/1994*	36.57	2.82	VII	m _{blg} 4.9	N Alborán	Strike-slip slightly oblique Balanegra Fault
04/02/2002	37.09	2.53	V	m _{blg} 5.1 M _w 4.6	S Gergal. Al	NW-SE normal faults.

* Foreshock;

1 From maximum intensity, using the D'Amico et al. (1999) relationship; 2 Mezcuca et al. (2004), using the procedure by Bakun and Wentworth (1997); 3 Stich et al. (2003a)

Table 1.- Significant historic and instrumental earthquakes in the study area.

Tabla 1.- Terremotos históricos e instrumentales en la zona de estudio.

to N160°E trending oblique-slip segments. Instrumental seismicity is concentrated in the basement at the north-western end of the fault zone, where the 2002 Gergal earthquake Mw 4.7 was located (Sanz de Galdeano *et al.*, 2010). In addition, the 1894 Nacimiento earthquake (VII) could be tentatively associated with these normal faults. The 1522 Almería earthquake (VIII-IX), for which the exact epicentre is unknown, has been associated with the offshore segment of the CFZ (Reicherter and Hübscher, 2006). Vera was destroyed in 1518 (VIII-IX) by an earthquake that could be hosted by the left-lateral Palomares fault (Bousquet, 1979; Weijermars, 1987). Toward the north, two moderate earthquakes were registered in the Almanzora corridor: the April 5, 1932 Lúcar earthquake (VIII, m_D 4.8) and the April 16, 1972 NW Partalooa earthquake (VII, m_{blg} 4.8). The Lúcar earthquake could tentatively be associated with the Lúcar and Somontín fault zone, which extends from the Almanzora basin towards

the Sierra de la Estancias, crossing the village of Lúcar. The village of Partalooa is located above a sector deformed by active ENE-WSW reverse faults and associated folds (Pedrera *et al.*, 2007, 2009a, 2009c).

7. Discussion and Conclusions

This work compiles the available information on the late Miocene to Quaternary faults and folds in the central-eastern Internal Zones of the Betic Cordillera. Some of these features have probably been the source of moderate-sized earthquakes throughout history and therefore are potential sources of future earthquakes.

7.1. Late Miocene geodynamic evolution

Regarding the evolution of the tectonic structures over time, folding started in the present position of the Sierra

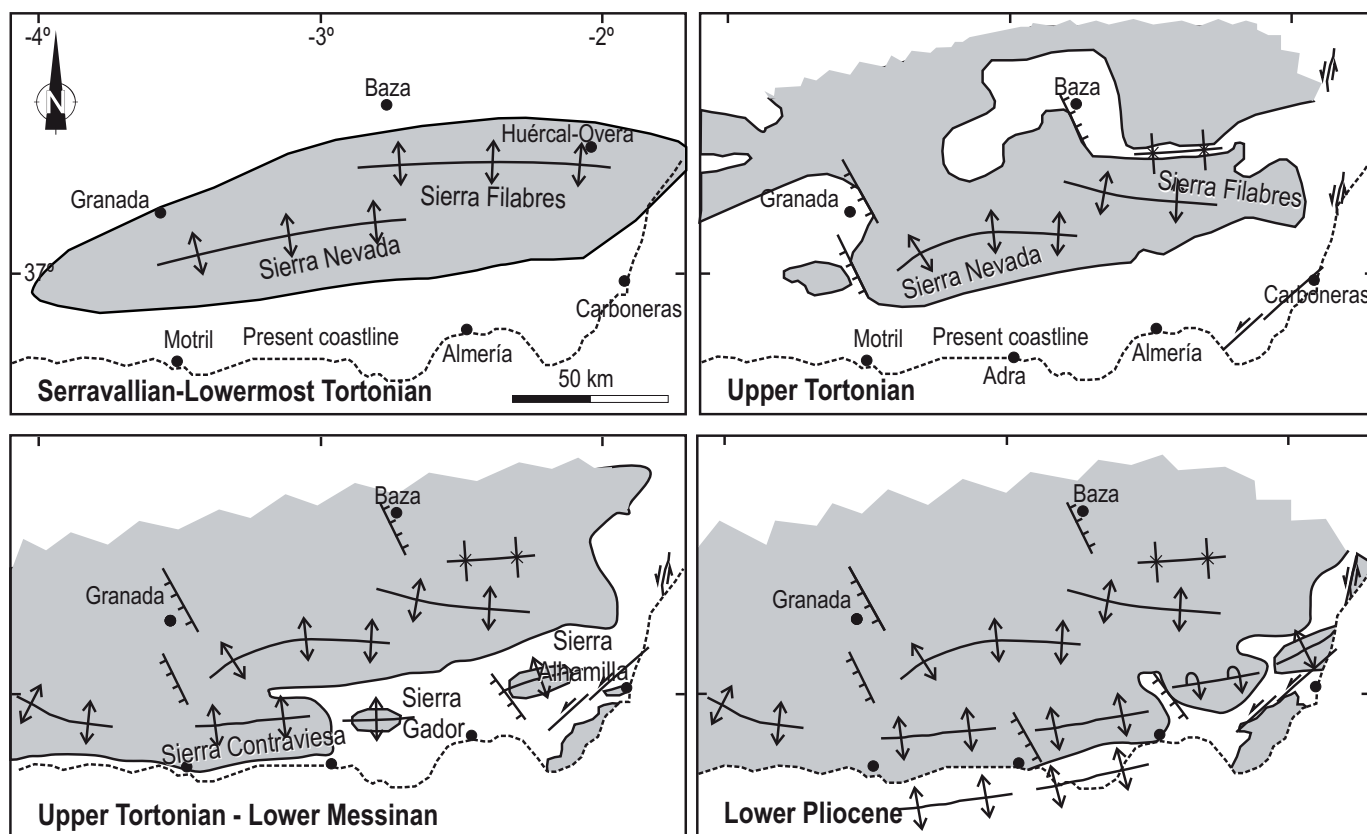


Fig. 6.- Paleogeographic and tectonic evolution of the central-eastern Betic Cordillera from the Serravallian-lowermost Tortonian onward. Evolution of the emergent land reconstructed from the facies distributions in the Neogene basins (Braga *et al.*, 2003). Note that the progressive emergence of the sierras coincides with the traces of the antiformal folds.

Fig. 6.- Reconstrucción paleogeográfica y evolución tectónica del sector central y oriental de la Cordillera Bética desde el Serravaliense-Tortoniano inferior. La distribución espacial y temporal de tierras emergidas/sumergidas se estableció a partir del análisis de facies (modificado de Braga *et al.*, 2003). Es preciso remarcar la coincidencia entre la posición de las sierras y la traza de las antiformas.

Nevada and Sierra de Los Filabres during the Serravallian-early Tortonian (Fig. 6). Therefore, stratigraphic and sedimentological studies indicate that a large E-W island started to emerge there at this time (Braga *et al.*, 2003). These large-scale antiformal folds underwent progressive lateral growth from east to west, folding the previous extensional detachments and therefore favouring the final exhumation of the Nevado-Filábride rocks. Fission-track analyses revealed that cooling to nearly surface temperatures occurred first in the Sierra de Los Filabres during the mid-Serravallian (12 Ma) and later in Sierra Nevada, located to the west (9-8 Ma; Johnson *et al.* 1997). The erosion of these ranges supplied sediments to the nearby basins. Progressive unconformities found in the Serravallian-lower Tortonian conglomerate formation located in the Almanzora corridor are coeval with the Sierra de Los Filabres antiformal fold growth. Since the late Tortonian, folding continues and propagates northwards (Sierra de Las Estancias) and southwards (the Sierra de Gádor, the Sierra Alhamilla and the Sierra Cabrera). In addition, the Almanzora corridor, the Huércal-Overa basin, the Al-

pujarran corridor, and the Tabernas basin acquired their elongate shape.

The origin of the E-W to ENE-WSW trending large-scale open folds is still under debate. The folds have been interpreted as caused by isostatic rebound in response to extensional denudation along the regional extensional detachments (*e.g.*, Martínez-Martínez *et al.*, 2002; Augier *et al.*, 2005; Meiginger and Vissers, 2006). Alternatively, we consider them as contractional folds developed above upper-crustal detachments developed in a collisional framework (*e.g.*, Weijermars *et al.*, 1985; Montecat and Ott d'Estevou, 1990; Sanz de Galdeano and Vera, 1992; Martínez-Martínez *et al.*, 1995; Galindo-Zaldívar *et al.*, 2003; Sanz de Galdeano and Alfaro, 2004; Pedrera *et al.*, 2009b). In any case, these folds contribute to the uplift of the northern boundary of the Alborán Basin gradually disconnecting the now emerged intramontane basins (Comas *et al.*, 1992, 1999) and inducing the development of the present-day relief (Fig. 6; Braga *et al.*, 2003; Sanz de Galdeano and Alfaro, 2004). In addition, melts in the deep crust and middle to upper Miocene volcanism also

conditioned the relief and the deformation mode (Duggen et al., 2008; Soto et al., 2008).

Coevally to large-scale open fold development, E-W transpressive right-lateral and reverse faults nucleated along the Alpujarra, the Tabernas, and the Sorbas basins while the NNE-SSW/NE-SW left-lateral Palomares and Carboneras fault zones occurred in the easternmost part of the cordillera (Fig. 6). Thus, the Polopos fault has been interpreted as a conjugate fault system to the Carboneras and Palomares left-lateral fault zones (Giaconia et al., 2012). Coeval to the relief growth, NW-SE to E-W normal and oblique slip normal faults developed.

During the Messinian, Pliocene and Quaternary, compression contributed to the progression of the moderate crustal thickening and to the regional progressive emersion of the marine basins with the final capture by the

drainage network of the endorheic basins. Active folds caused the emersion of the northern Alborán Sea (Marín-Lechado et al., 2006). In addition, there was continued activity of some segments of the strike-slip faults. Moreover, normal and normal-oblique faults have remained active during the Quaternary to the present in this part of the cordillera.

7.2. Active Tectonics

The present study summarized the most prominent active faults of the central-eastern Internal Zones of the Betic Cordillera (from 3.1°W to 1.7°W and to the south of 37.525°N) providing detailed maps of the fault and fold traces (Fig. 7). The Campo de Dalías and surrounding sectors are probably the sites with the greatest concentra-

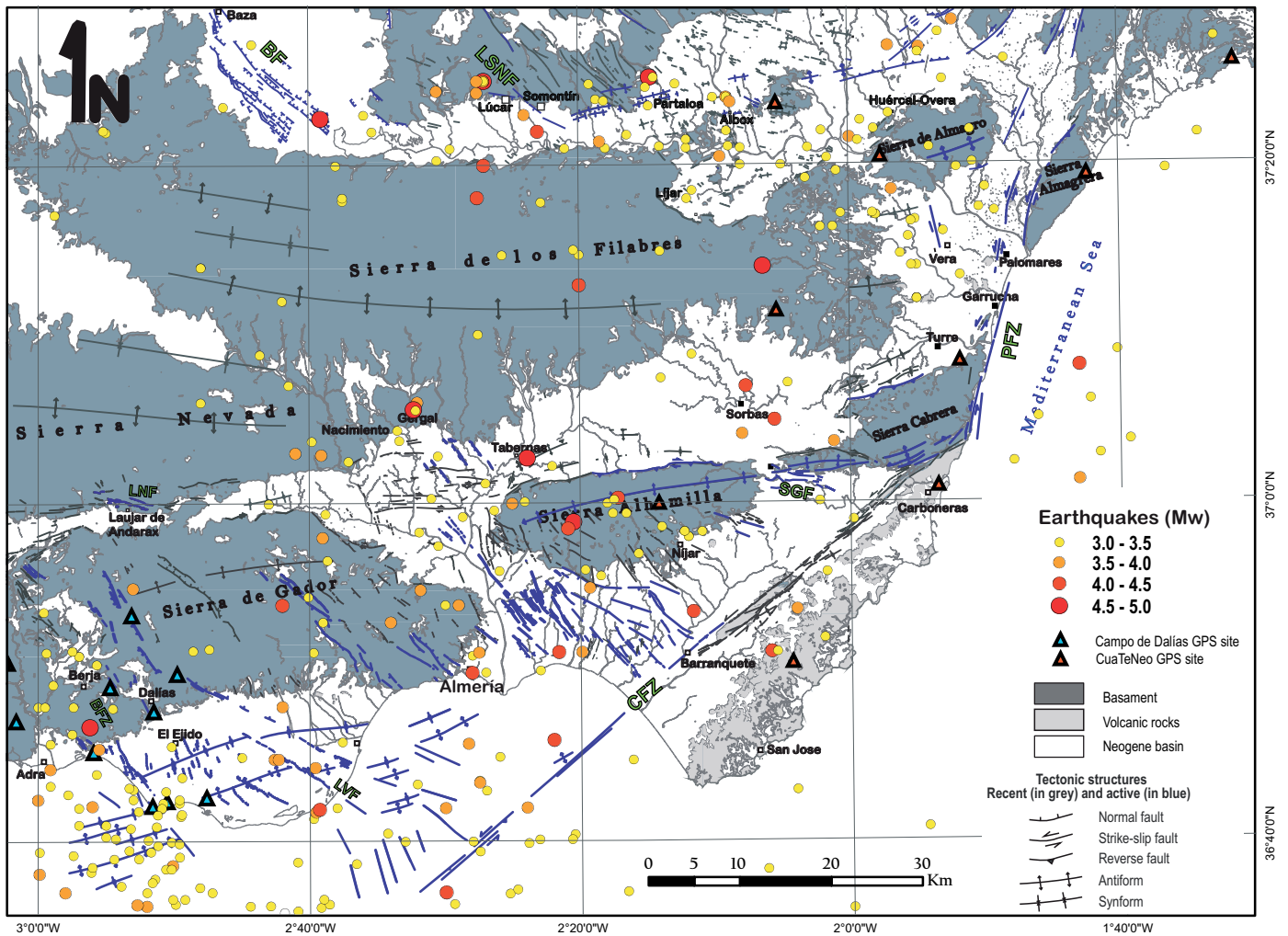


Fig. 7.- Seismotectonic map of the study area showing traces of recent and active tectonic structures and the location of the seismicity with $M_w \geq 3$ for the period 1926-2011 from the Instituto Geográfico Nacional catalogue (<http://www.ign.es>). The non-permanent GPS sites of the networks CuaTeNeo and Campo de Dalías are marked.

Fig. 7.- Mapa sismotectónico del área de estudio con la traza de las principales estructuras tectónicas (recientes y activas) y la posición de la sismicidad $M_w \geq 3$ comprendida entre 1926-2011 (catálogo del IGN, Instituto Geográfico Nacional, <http://www.ign.es>). Se ha incluido la posición (no permanente) de los GPS pertenecientes a las redes CuaTeNeo y Campo de Dalías.

tion of large earthquakes during the recent history. Moderate-sized earthquakes (Mw 5.0 to 6.0-6.5) have occurred in this area at fairly regular intervals, in 1804, 1910, and 1993 probably associated to the Balanegra fault zone activity (Marín-Lechado *et al.*, 2010). Despite the absence of clear historic earthquakes associated with the Loma del Viento fault, it is reasonable to consider it as a potential seismic fault (Pedrera *et al.*, 2012). There, we have designed a multidisciplinary control of the potential earthquakes sources. We have mapped the active faults and folds in detail. In addition, we performed a 3D geological model by incorporating borehole and geophysical data to establish the geometry of the tectonic structures. The sector is monitored with a non-permanent GPS network and high-precision levelling profiles (Fig. 7). The geometric knowledge of these structures combined with geodetic measurements of tectonic-strain accumulation yield improved models of nucleation, linkage, and propagation of active faults, as well as their seismic implications.

The NW-SE trending Quaternary faults extending from Almería to the Tabernas basin and separating Sierra Alhamilla from Sierra de Gádor have related seismicity (Fig. 7). These NW-SE normal faults have higher seismic potential than does the E-W dextral system (the 2002, Mw 4.7 Gergal earthquake and the 1894 Nacimiento earthquake, VII).

Toward the north in the Almanzora corridor, the Lúcar-Somontín NW-SE to WNW-ESE trending Quaternary faults could also cautiously be considered as possible sources of moderate-magnitude seismicity (the April 5, 1932 Lúcar m_d 4.8 earthquake, VIII). Toward the east, between Albox and Partalao, several small reverse faults and associated compressive structures deforming Quaternary alluvial and fluvial sediments (Fig. 7) have been described?. The syn-folding fan geometry observed in the one of these structures (La Molata structure, Pedrera *et al.*, 2009a) suggests a slow and progressive deformation from middle Pleistocene onward. They do not show scarps or erosive deposits, such as clastic wedges, indicative of abrupt deformation events related to earthquakes, suggesting that the La Molata structure is most likely connected with aseismic slip during Quaternary fault-related fold growth. Nevertheless, some of these reverse fault segments could have associated moderate-sized events such as the April 16, 1972 NW Partalao, m_{bLg} 4.8 earthquake (VII). Regarding the proximity between the villages Lúcar and Partalao, further seismic studies of the main shock parameters are necessary to identify viable source structures.

The PFZ is very favourably oriented (N10-20°E trend) with respect to the present-day stress field for left-lateral

strike-slip displacement. The angle between the fault strike and the maximum principal stress is around 30°. Therefore, this fault probably nucleates moderate-sized earthquakes (1518 Vera earthquake). Unlike the Palomares fault, the CFZ is almost orthogonal to the present-day maximum horizontal compressive stress. Although not very suitably oriented to act as a strike-slip fault, it could act as a high-angle reverse or reverse-oblique fault despite its sub-vertical geometry. Paleoseismic data, high resolution seismic profiles and sediment coring indicate Quaternary activity of some fault segments (Reicherter and Hübscher, 2006; Moreno *et al.*, 2009). The ongoing GPS results derived from the CuaTeNeo network will decisively contribute to understand the relationship between the strain accumulation and seismic potential of the Carboneras and Palomares fault zones (Fig. 7).

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