Shallow frontal deformation related to active continental subduction: structure and recent stresses in the westernmost Betic Cordillera

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Abstract

The westernmost Betic Cordillera front is located along the arcuate alpine belt formed by the interaction of the Eurasian-African plate boundary and the Alboran continental domain in between. Although classical geological data suggest that the western Cordillera front is inactive, recent GPS data show a westward–north-westward motion of up to 3.4 mm a−1 with respect to the foreland. In addition, the increasing thickness of Guadalquivir sedimentary infill towards the Cordillera, and the rectilinear character of the front formed by soft sediments, suggest that the Cordillera is still active. Large ENE–WSW-oriented open folds detected in the field, seismic reflection profiles and new audiomagnetotellurics data are consistent with active deformation. Fracture analysis in Quaternary deposits evidences recent NW–SE horizontal compression. The GPS motion and maximum stress orientation may be due to north-westward tectonic collision of the westernmost Betic Cordillera, accommodated at depth by active continental subduction of the Iberian lithosphere.

1. Introduction

The transition from oceanic subduction to continental collision contributes to the development of orogenic belts in two main end-member geodynamic settings. (i) When continental lithosphere keeps subducting, aided by the pull down of the nearby oceanic lithosphere (Chemenda et al., 2001), its detachment produces uplift and a contractional deformation front (Gerya et al., 2004). (ii) If decoupling or delamination of the mantle lithosphere occurs, uplift, high heat flow, uncompensated high elevation and significant magmatic activity can be expected (Wortel and Spakman, 2000). The Eurasian-African plate boundary is associated with a broad band of continental deformation and seismicity in the westernmost Mediterranean (Buforn et al., 2004; Stich et al., 2010; Billi et al., 2011; Palano et al., 2013). In this region, the interaction of the roughly westward motion of the Alboran continental domain with this major plate boundary, since the late Oligocene, has created the Betic and Rif cordilleras. They surround the continental Alboran Neogene basin (Fig. 1).

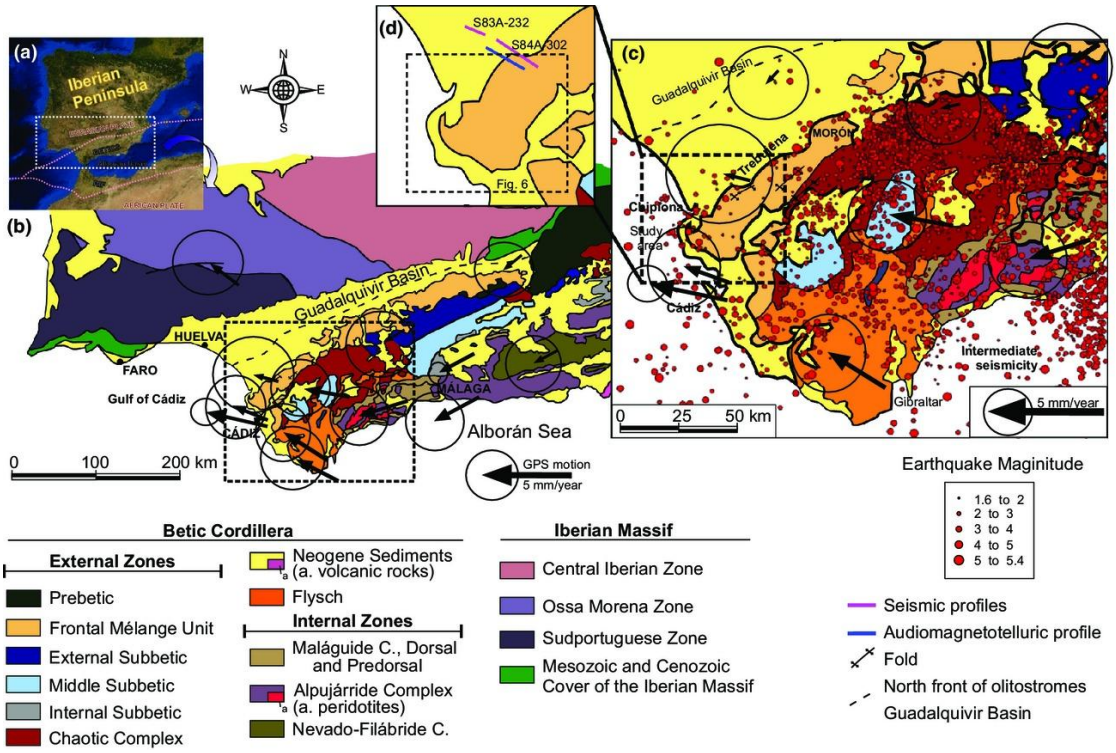


Figure 1: Geological Setting. (a) The Betic-Rif Cordillera in the Western Mediterranean Sea. The boundaries of this alpine belt are indicated by the white dashed lines. (b) The main tectonic units of the Betic Cordillera and its foreland, including GPS motion and 95% confidence ellipses (Koulali et al., 2011). (c) Detail of the Western Betic Cordillera, including seismicity, GPS motions and 95% confidence ellipses (Koulali et al., 2011). (d) Detailed location of seismic and audiomagnetotelluric lines. Dashed lines indicates the area covered in Fig. 6.

Some authors propose delamination and mantle lithosphere detachment below the Alboran Domain (Docherty and Banda, 1995; Seber et al., 1996; De Lis Mancilla et al., 2013). However, other researchers support subduction models (Doglioni et al., 1999a,b) – based on seismic tomography studies that imaged an oceanic subducted slab with SW–NE to N–S orientation (Blanco and Spakman, 1993; Gutscher et al., 2002, 2012; Piromallo and Morelli, 2003; Spakman and Wortel, 2004; Bezada et al., 2013; Palomeras et al., 2014) and E to SE-dip – including slab roll-back (Lonergan and White, 1997; Pedrera et al., 2011) with partial or total slab break off and/or tearing (Blanco and Spakman, 1993; Spakman and Wortel, 2004; Garcia-Castellanos and Villaseñor, 2011; van Hinsbergen et al., 2014). Eastward (Gutscher et al., 2002, 2012) and south-eastward (Ruiz-Constán et al., 2009, 2011, 2012a) dipping slabs have been considered. The Alboran Basin may be interpreted as a backarc basin, although related to different proposed subduction slabs (Doglioni et al., 1997; Gueguen et al., 1997; Galindo-Zaldivar et al., 1998; Gueguen et al., 1998; Doglioni et al., 1999a,b; Pedrera et al., 2011; Carminati et al., 2012; van Hinsbergen et al., 2014).

The major lithosphere-scale fault along the boundary between the external and internal zones was active during the westward motion of the Alboran domain before the contact was covered by Tortonian marine sediments (Martín-Algarra, 1987). Yet GPS data in the central and western Betics indicate a relative westward displacement of the internal zones with respect to Eurasia of up to 3.4 mm a−1 (Fig. 1; Koulali et al., 2011). At present, the eastern part of the cordillera mountain front seems to be scarcely active (Ruano et al., 2004). However, late Miocene faults located within the Iberian basement have been reactivated under the present-day NW–SE convergence, often leading to shallow seismicity (Pedrera et al., 2013). To the west, however, there is widespread shallow seismicity in the Iberian basement beneath the Morón de la Frontera area (Fig. 1; Ruiz-Constán et al., 2009, 2012b). Farther west, seismic reflection profiles and bathymetry in the Gulf of Cadiz (Gutscher et al., 2002, 2012) suggest thrust activity on the front offshore. To date, there are no studies of the activity and structures related to the westernmost part of the onshore Betic cordillera front.

The aim of this study was to characterize the westernmost Betic cordillera front to determine the recent and present-day tectonic activity. A combination of geological and geophysical observations supported by available GPS data provides new results that enrich discussion of the present-day setting of this key area.

2. Geological setting

The westernmost part of the Betic Cordillera and the Guadalquivir Neogene foreland basin are located above the Iberian Massif (Fig. 1). The Betic Cordillera is traditionally divided into three main zones. The Alboran Domain (internal zones) and the South Iberian Domain (external zones) are separated by a Flysch Complex. The South Iberian Domain represents the Mesozoic to Paleogene cover of the former South Iberian margin, deformed as a thin-skinned fold-and-thrust belt between the latest Oligocene and late Miocene, and consists of carbonates with intercalated marls, along with siliciclastic and, locally, volcanic rocks. A synorogenic mélange unit (Bourgois, 1973; Pedrera et al., 2012; Roldán et al., 2012) occurs in the frontal area of the Cordillera, formed during the early Miocene to early Serravallian. The Guadalquivir foreland basin has an ENE–WSW elongated triangular shape, opening towards the Gulf of Cadiz. It developed as a consequence of flexure of the Variscan lithosphere by the load of the Alboran Domain during its emplacement (Garcia-Castellanos et al., 2002). Stratigraphic studies (Martínez del Olmo et al., 1984; Sierro et al., 1990; Roldán, 1995; Riaza and Martinez del Olmo, 1996; Salvany et al., 2011; Rodríguez-Ramírez et al., 2014) as well as several boreholes and seismic reflection profiles (Fernàndez et al., 1998) have determined the pattern of the sedimentary infill, whose thickness at some points is greater than 5 km.

Plate relative angular velocities reveal a NW–SE convergence between the African and European plates in the western Mediterranean (Argus et al., 1989; DeMets et al., 1994). Stresses characterized by brittle deformation and earthquake focal mechanisms show a regional NW–SE compression, subparallel to the relative major plate motion, as well as variable to NE–SW tension in the internal zones of the Betic Cordillera (Galindo-Zaldívar et al., 1993; De Vicente et al., 2008; Pedrera et al., 2011; Palano et al., 2013). In the western Betics, large E–W and ENE–WSW folds have been observed, deforming late Tortonian to Pliocene rocks (Balanyá et al., 2007; Ruiz-Constán et al., 2009, 2012b).

In the western part of the Betic Cordillera, the depth of earthquakes progressively increases towards the south–south-east – from shallow seismicity at the Morón mountain front segment (Ruiz-Constán et al., 2009) to events at approximately 120 km depth beneath the western Alboran Sea, where an arc is traced south of the Malaga coast (Buforn et al., 1995; Morales et al., 1999; Pedrera et al., 2011; Ruiz-Constán et al., 2011). In contrast, seismicity is very scarce in the westernmost part of the mountain front, the sector studied here.

GPS research (McClusky et al., 2000; Vernant et al., 2010; Koulali et al., 2011) shows regional westward movement of the Betic Cordillera with respect to the Iberian Massif. In the central Betics the displacement is roughly to the WSW, but further west the largest velocities are reached in a WNW direction, even affecting the external zones (Fig. 1). The movement progressively decreases towards the mountain front and is practically absent in the Guadalquivir Basin.

3. Morphology of the westernmost Betic Cordillera mountain front

The Betic Cordillera relief developed in stages, as evidenced by continental deposits since the Aquitanian (Martín-Algarra, 1987). The north-western limit of the Betic Cordillera front was traditionally considered to be an inactive thrust. Onshore, the westernmost mountain front in south-west Spain draws a linear step along the Gulf of Cadiz coastline between the towns of Chipiona and Sanlucar de Barrameda (Figs 1 and 2). To the east, the lower Guadalquivir Basin is characterized by a large flat marsh area in sharp contact with the mountain area. The rectilinear front continues along the southern boundary of the Guadalquivir Basin, at least as far as Cabezas de San Juan, with discontinuous segments corresponding to elongated hills with steep NW rectilinear boundaries (Fig. 2). The sinuosity mountain front index (Bull and McFadden, 1977; SMF = length of the mountain front/length of straight line of the mountain front) of 1.13 indicates its active character.

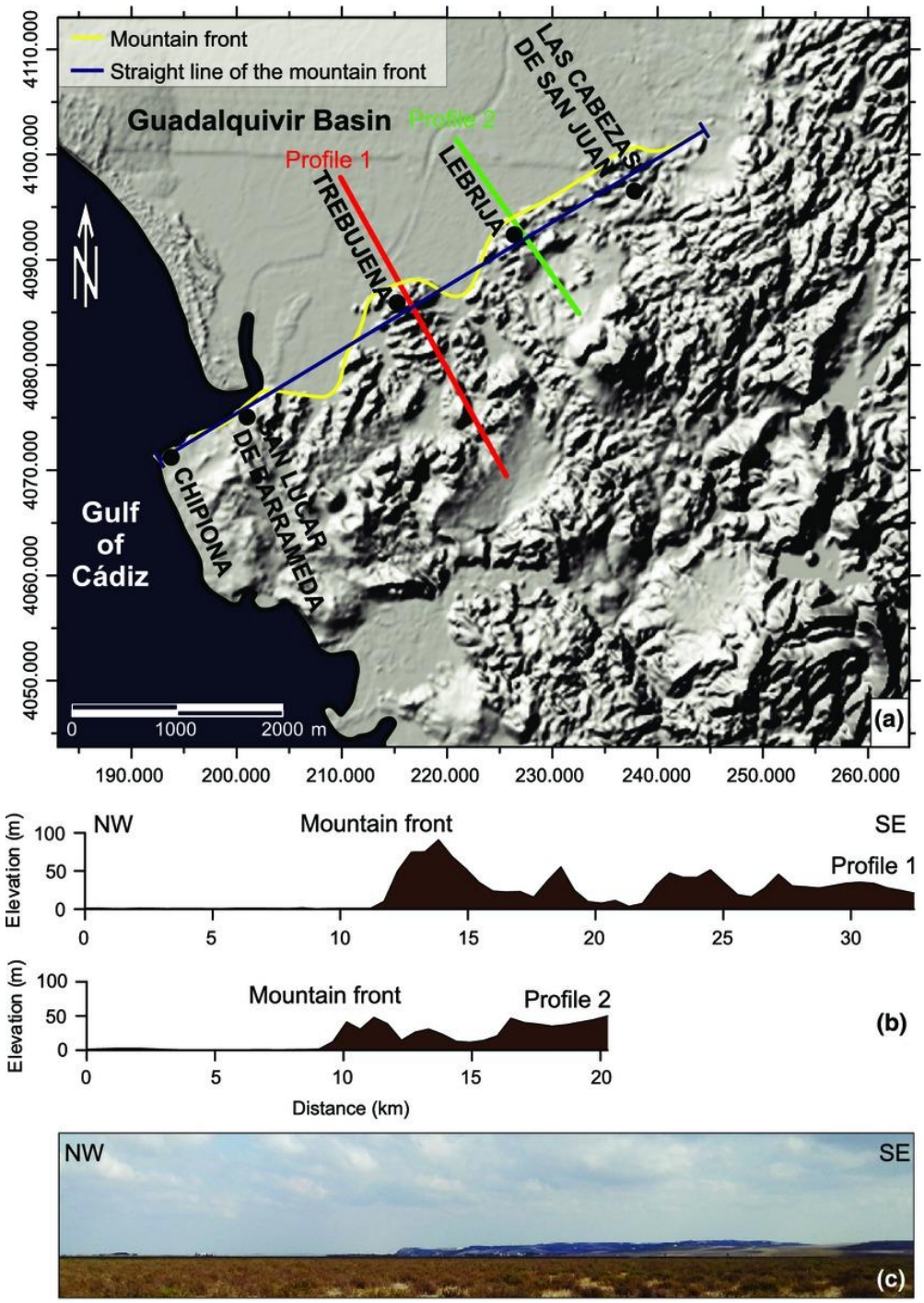


Figure 2: The relief of the western mountain front. (a) Shadow relief image of the western mountain front. (b) Topographic profiles. (c) Field panoramic. SMF index = 1.13.

4. Structure of the mountain front

The mountain front is formed mainly by folds with ENE–WSW axes (Fig. 1). Antiform culminations consist of Tortonian moronite formations. There is no surface field evidence of recent sediment deformation. In contrast, borehole data (Salvany et al., 2011) indicate

progressive thickening towards the south-east up to Holocene of the Guadalquivir deposits.

4.1 Seismic reflection profiles

Multichannel seismic reflection profiles (Fig. 3) were processed by means of a standard sequence including migration.

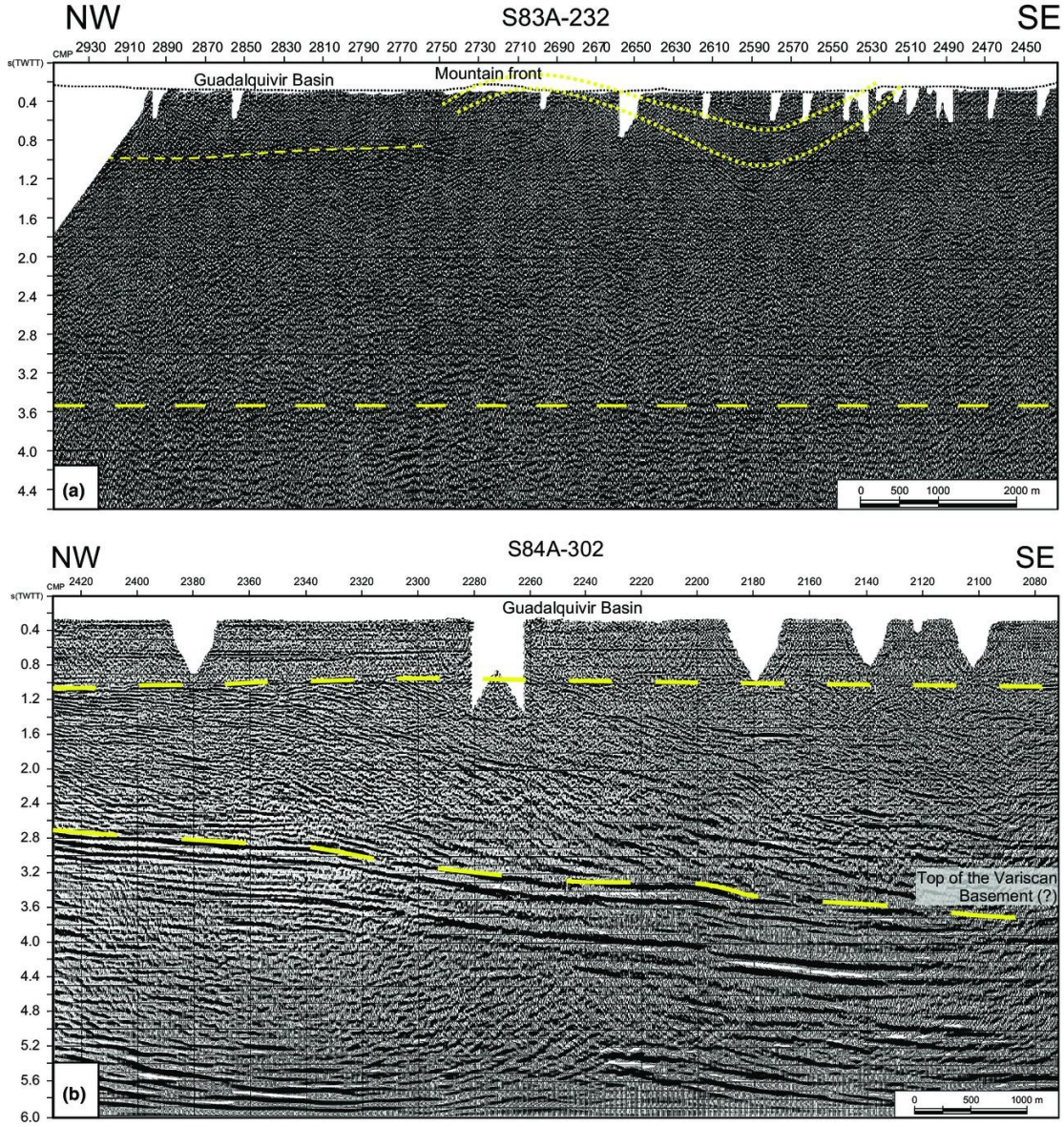


Figure 3: Multichannel seismic profiles. SIGECO database (http://cuarzo.igme.es/sigeco) Location in Fig. 1d.

The S83A-232 profile has a NW–SE orientation and crosses the mountain front orthogonally, near Trebujena (Fig. 1). A roughly continuous subhorizontal deep reflector is recognized at about 3.6 s TWT and may represent the top of the Variscan basement.

Horizontal reflectors belonging to the sedimentary infill of the Guadalquivir basin contrast with the folds in the Betic Cordillera Front, where antiforms determine the main hills of the area and the varying reflector curvature along synforms supports a synsedimentary character. No surface faults are recognized, suggesting that the mountain front formed mainly as a consequence of fold activity above a detachment level.

The S84A-302 profile, in the Guadalquivir basin, shows a SE-ward dipping reflector corresponding to the top of the Variscan basement below the cross-bedding, thus indicating SE progradation of the sedimentary infill. Subhorizontal layers correspond to the top of the sedimentary sequence.

4.2 Audiomagnetotelluric data

A detailed audiomagnetotellurics profile orthogonal to the mountain front was recorded with Strata Gem EH4 equipment, in a frequency range from 70 kHz to 10 Hz, reaching depths of tens to hundreds of meters. A transmitter antenna was used to enhance the natural electromagnetic field from 1 kHz to 5 kHz, where the natural signal decreases. Geoelectric dimensionality was analysed by means of Bahr decomposition (Bahr, 1988, 1991). The curves show a general 1D behaviour up to 10−1 s and a 2D structure from 10−1 to 10 s with a N70-90°E strike. We checked the internal consistency of the rho and phase estimated at each site (Parker and Booker, 1996) and corrected static shift problems in some of the curves. A joint 2D inversion of resistivities and phases was carried out integrating all the data (Rodi and Mackie, 2001). An error floor of 3% for the apparent resistivities and the phases was selected.

The north-western part of the profile (Fig. 4) is characterized by a low-resistivity sector, extending from the surface down to 300 m (~1 ohm·m), corresponding to the sedimentary Guadalquivir basin infill, made up of saturated clays and silts. To the south-east, uplift of the resistive layer is related to an antiformal structure that reaches the surface along an elongated hill, determining a sharp mountain front extending down the basin sediments.

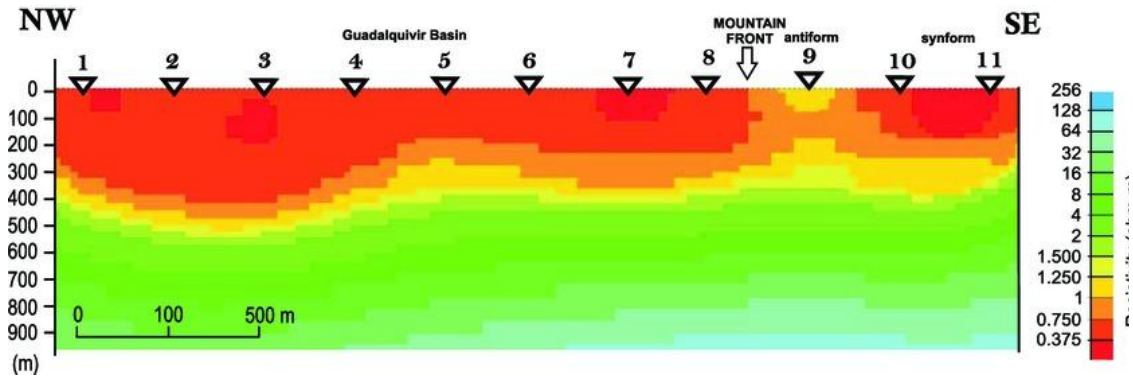


Figure 4: Audiomagnetotelluric profile across the mountain front. Location in Fig. 1d. Root-mean-square-misfit between the data and the synthetic response was 4.1.

5. Brittle deformation and stresses

In order to characterize the recent palaeostress pattern in this region, microtectonic measurements were made in a wide zone along the mountain front. According to Hancock (1985), the main joint system (Figs 5 and 6) consists of a NW–SE tensional set or two hybrid sets forming an acute angle, suggesting that the mountain front underwent NW–SE compression and orthogonal NE–SW tension. This stress field is recognized all along the mountain front and is well constrained in the Chipiona sector, where the coastal area is formed from Quaternary consolidated beach deposits. Faults are scarce, with normal regime and restricted to antiformal areas (Fig. 5).

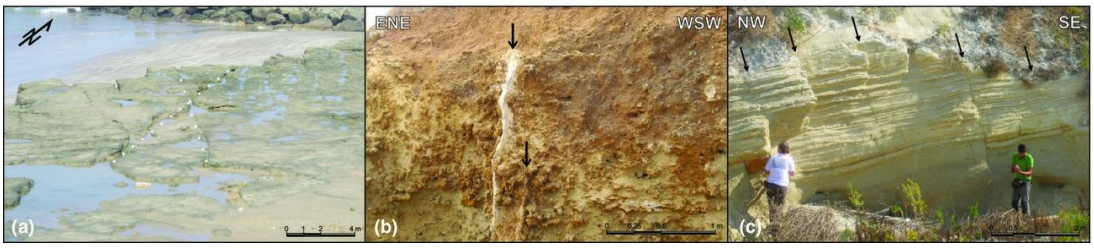


Figure 5: Field examples of fractures. (a) Conjugate fractures in Quaternary beach deposits (‘Corrales de Peces’, Chipiona). (b) Vertical tension joints. (c) Normal faults in antiformal areas.

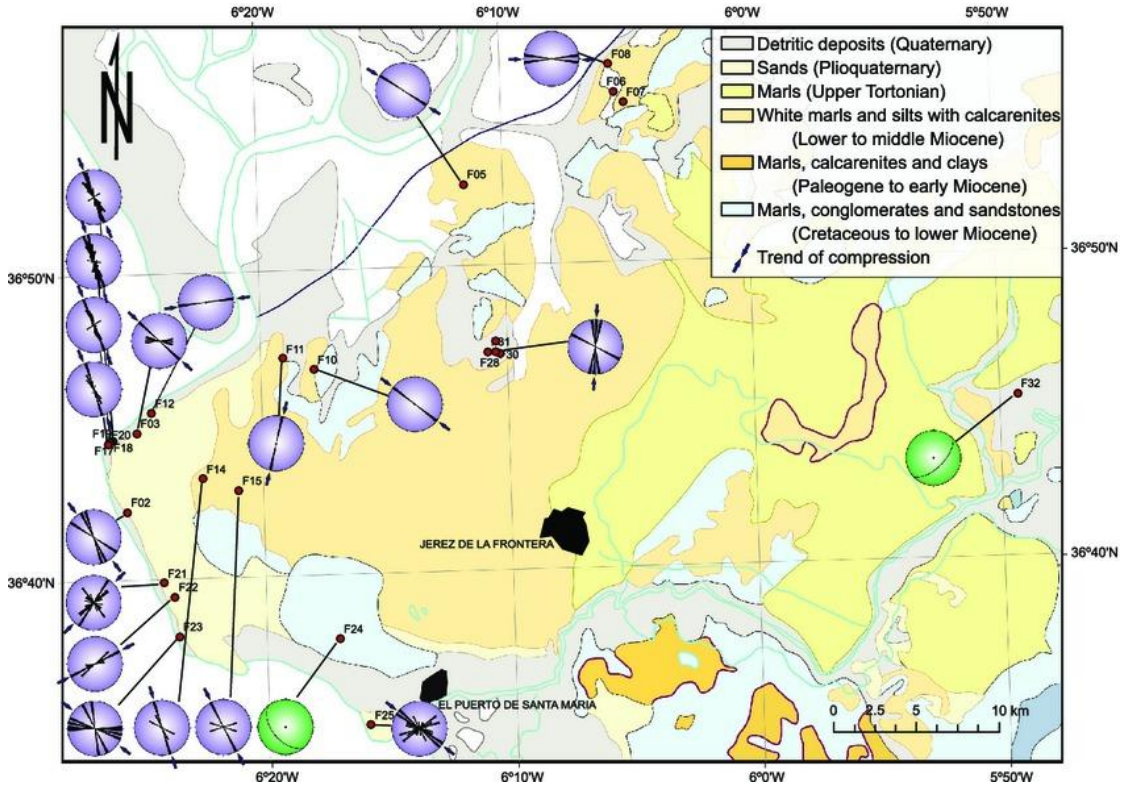


Figure 6: Fracture orientation and palaeostresses. Rose diagrams of main outcrops (purple plots); maximum horizontal stress corresponds to the orientation of the main extensional joint set or to the acute angle between the conjugate or hybrid joint sets according to Hancock (1985). Faults in stereographic projection (green plots), lower hemisphere.

7. Discussion

Although the major tectonic structures that accommodated the accretion of the external Betics appear to have been inactive since the late Miocene, the rectilinear character of the westernmost Betic Cordillera mountain front suggests that it is still affected by active deformation. Although no large faults are recognized, active folds affect the marine Tortonian rocks up to the Holocene deposits (Fig. 7). Normal faults along antiformal culminations reveal local shallow NW–SE to NNE–SSE extensional trends (Figs 5-7), which could be a consequence of the uplifted relief that developed as a result of deep compressional deformation.

The decreasing magnitude of the WNW GPS velocities (from 3.4 mm a−1) towards the western mountain front with respect to the roughly stable foreland basin agrees with active folding along a broad band. The progressive crustal thickening of the Betic Cordillera produces a load and flexure of the Guadalquivir Basin Variscan basement (Garcia-Castellanos et al., 2002); the thickness of sedimentary infill increases towards the mountain front (Salvany et al., 2011; Rodríguez-Ramírez et al., 2014).

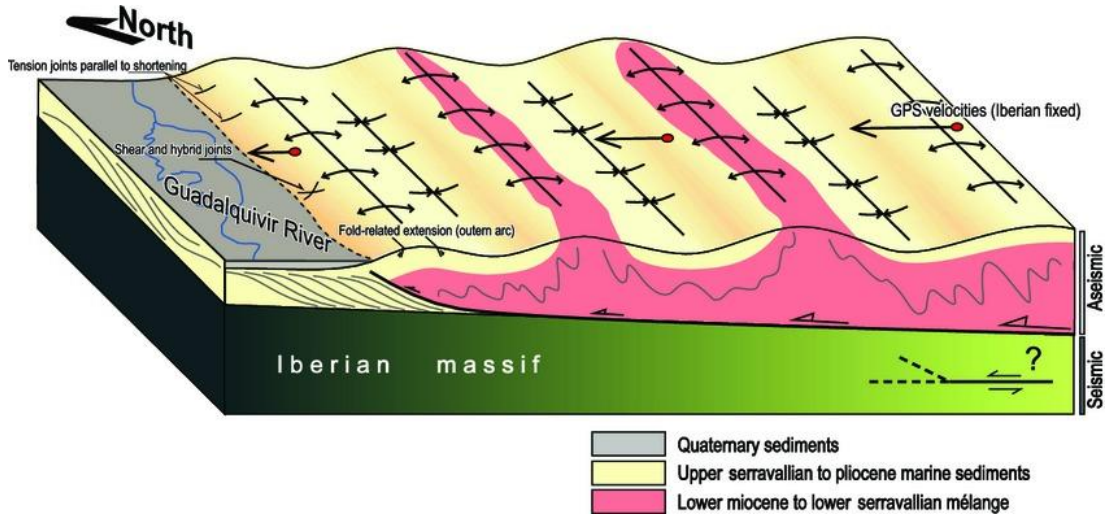


Figure 7: 3D model of the structures across the folded deformation front.

In spite of the wide ellipse errors of the GPS measurements (Fig.1), WNW motion of the western Betic Cordillera with respect to the Eurasian plate is consistent with the NW-SE compression, underlining the relevance of present-day collision tectonics related to ongoing continental subduction, aided by the pull of the already subducted oceanic crust (Ruiz-Constán et al., 2011; Fig. 8).

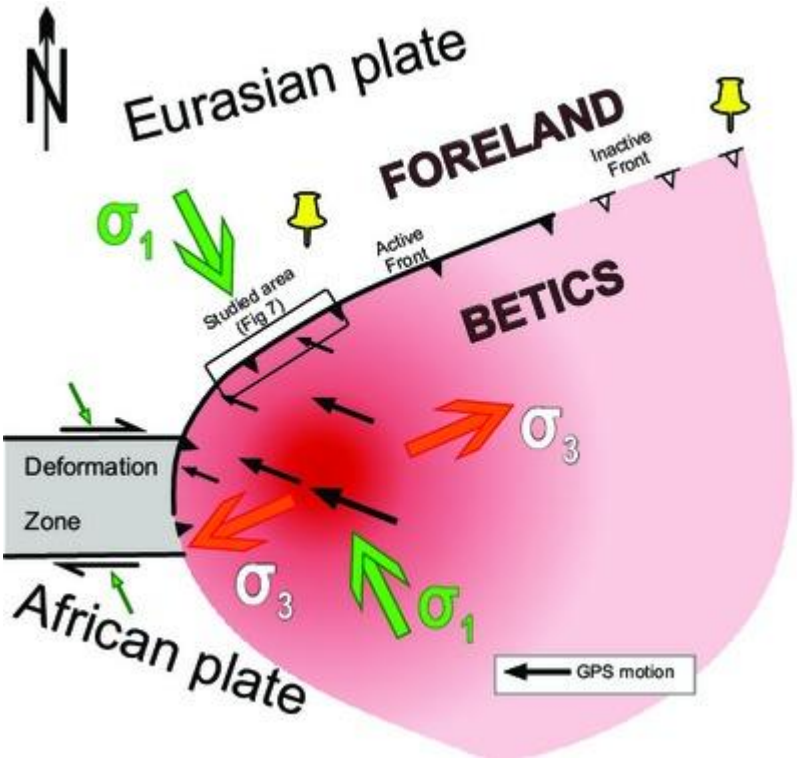


Figure 8: Tectonic model showing the GPS motion and compression trend. The regional NW–SE compression between the Eurasian and African plates together with the NE–SW extension in the Betic Cordillera determines the relatively westwards–north-westwards motion of the Alboran domain.

The active structures vary along the mountain front. The folds and soft rocks in the study area prevent the occurrence of shallow earthquakes. Coupling between the Alboran Domain and the Iberian massif promotes the occurrence of seismicity within the foreland. Westward, this area connects offshore in the Gulf of Cadiz, where Gutscher et al. (2002, 2012) documented present-day thrusting. Eastward, shallow earthquakes affect the Iberian crust in the Morón (Ruiz-Constán et al., 2009) and Torreperogil areas (Pedrera et al., 2013). In the central Betic Cordillera the front is essentially inactive, and deformation occurs towards the interior of the mountain belt (Ruano et al., 2004).

8. Conclusions

The compilation of geomorphic, field geological, geophysical and available GPS data provides evidence that the westernmost Betic Cordillera mountain front is active, and that it produced the south-eastward increase in the thickness of the sedimentary infill of the Guadalquivir Basin, which affects up to Holocene deposits. The mountain front has a variable character due to the different lithologies. Shallow seismicity related to reverse and strike-slip faults occurs in the Morón area; to the west, active folds accommodate the deformation along the westernmost mountain front in the Trebujena-Chipiona area (Fig. 7); finally, thrusts affect the Gulf of Cadiz.

The obliquity between the WNW-wards motion of the Cordillera with respect to the foreland, and the NW–SE trend of compression related to the Eurasian-African plate motion, may result from oblique collision (Fig. 8) related at depth to active continental subduction. These newly integrated results confirm that alpine compressional deformation continues in this sector of the western Mediterranean.

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