Active rollback in the Gibraltar Arc: evidences from CGPS data in the Western Betic Cordillera

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Abstract

The Gibraltar Arc, located in the western Mediterranean Sea, is an arcuate Alpine orogen formed by the Betic and Rif Cordilleras, separated by the Alboran Sea. New continuous GPS data (2008-2013) obtained in the Topo-Iberia stations of the western Betic Cordillera allow us to improve the present-day deformation pattern related to active tectonics in this collision area between the Eurasian and African plates. These data indicate a very consistent westward motion of the Betic Cordillera with respect to the relatively stable Iberian Massif foreland. The displacement in the Betics increases towards the south and west, reaching maximum values in the Gibraltar Strait area (4.27 mm/yr in Ceuta, CEU1, and 4.06 mm/yr in San Fernando, SFER), then progressively decreasing towards the northwestern mountain front. The recent geological structures and seismicity evidence moderate deformation in a roughly NW-SE to WNW-ESE compressional stress setting in the mountain frontal areas, and moderate extension towards the internal part of the cordillera. The mountain front undergoes progressive development of folds affecting at least up to Pliocene deposits, with similar recent geological and geodetical rates. This folded strip helps to accommodate the active deformation with scarce associated seismicity. The displacement pattern is in agreement with the present-day clockwise rotation of the tectonic units in the northern branch of the Gibraltar Arc. Our data support that the westward emplacement of the Betic Cordillera continues to be active in a rollback tectonic scenario.

Hightlights

- New CGPS stations support fast westwards displacements of the Western Betics.
- Active dextral rotations are in agreement with the tectonic arc development.
- A folded strip of several tens of km accommodates the frontal deformations.
- Integration of CGPS and geological data supports active rollback in the Betics.

Key Words

CGPS stations; Western Mediterranean; active deformations; present-day rollback; tectonic rotation.

1. Introduction

The geodetical networks based on GPS observations provide new insights to constrain the pattern of active motion and rotation in oroclinals, as the Bolivian oroclinal (Allmendinger et al., 2005), St. Elias orogen in Alaska (Elliot et al., 2013) and central Anatolia (Aktug et al., 2013). The Betic-Rif cordillera, connected through the Gibraltar Arc (Fig.1), is a strongly curved oroclinal. New accurate GPS geodetical data are essential to constrain the active tectonic deformations.

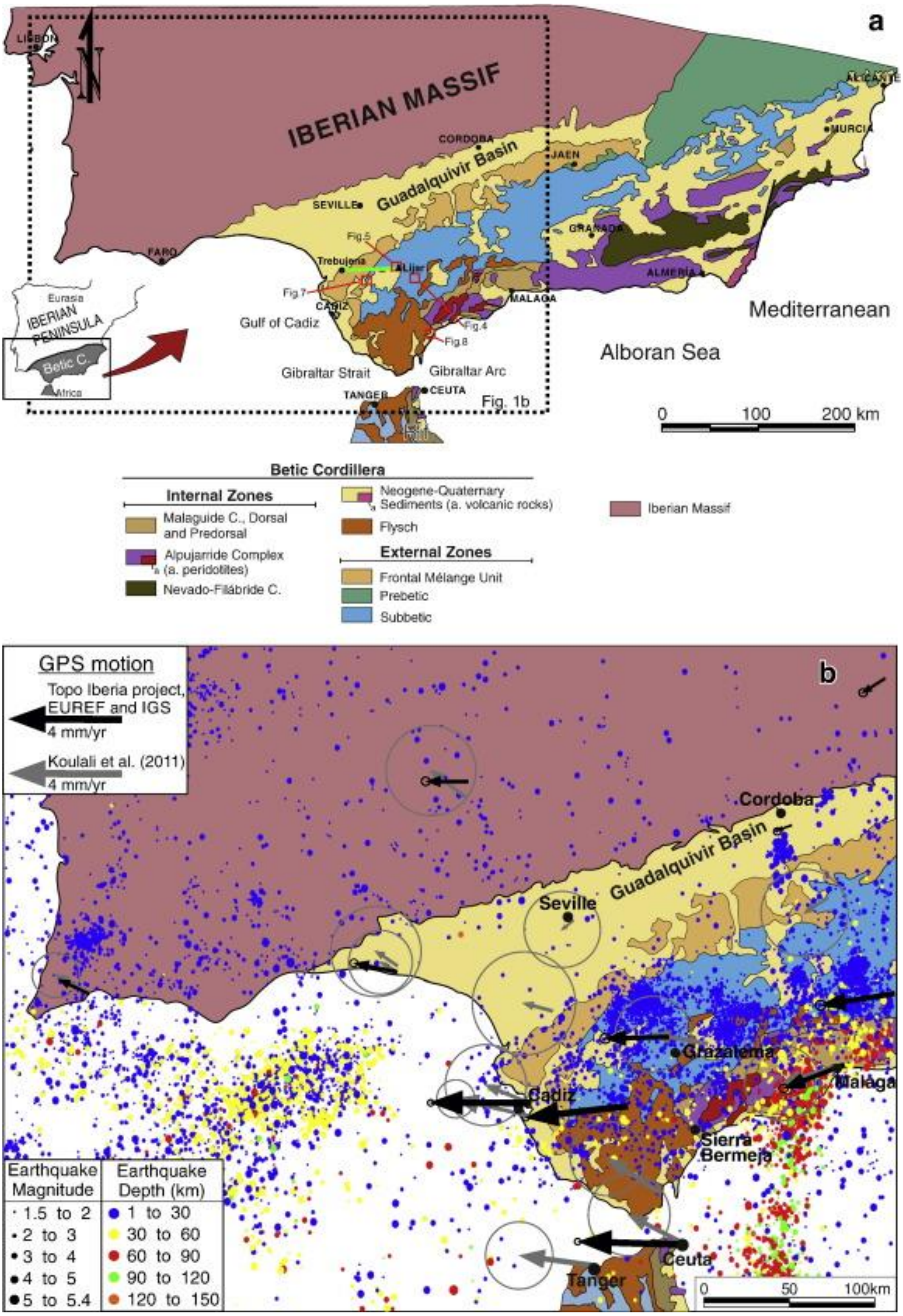

Fig. 1. The western Betic Cordillera and its foreland. (a) Geological setting of the western Betic Cordillera and its foreland. Dashed rectangle highlights the area studied. Small squares locate Fig. 4, Fig. 5, Fig. 7, Fig. 8. Green line indicates the Trebujena–Líjar cross-section. (b) Tectonic sketch of the area studied including seismicity (database of Instituto Geográfico Nacional, www.ign.es) and CGPS data. Residual velocity field is referred to Eurasia and 95% confidence ellipses.

In the western Mediterranean, NW-SE convergence of 4 to 5 mm/yr, depending on different geodynamics models, occurs in-between the major Eurasian and African plates (DeMets et al., 1994, Nocquet, 2012). Geodetic networks provide deformation patterns that show the activity of geological structures and eventually reveal the general deformation pattern. Up to now, GPS data from continuously recording GPS stations (CGPS) and survey-mode GPS sites show a roughly NW-WNW displacement in the western part of the Betic Cordillera (Serpelloni et al., 2007; Vernant et al., 2010; Koulali et al., 2011) with respect to the Iberian Massif. These data demonstrate that the building up of this Alpine cordillera continues at present, in agreement with the regional seismicity related to the plate boundary. However, models based on these studies generally aim to trace sharp rectilinear Eurasian-African plate boundaries, without integrating the widespread active tectonic structures observed in these Cordilleras.

Different models have been proposed for the development of the Gibraltar Arc, based on the presence of subduction structures (Araña and Vegas, 1974; Torres-Roldán et al., 1986; De Jong, 1991 and 1993; Wortel and Spakman, 1992; Zeck et al., 1992 and Zeck,1996, Pedrera et al., 2011; Ruiz-Constán et al., 2011), lithospheric delamination (Houseman et al., 1981; Platt and Vissers, 1989; García-Dueñas et al., 1992; Seber et al., 1996; Calvert et al., 2000; de Lis Mancilla et al., 2013) or slab rollback (Blanco and Spakman, 1993; Morley, 1993; Royden, 1993; Lonergan and White, 1997; Hoernle et al., 1999; Wortel and Spakman, 2000; Gill et al. 2004; Thiebot and Gutscher, 2006; Brun and Faccena, 2008). Although most of them focus on the Miocene evolution, Gutscher et al. (2002), Thiebot and Gutscher (2006), Pedrera et al. (2011) and Ruiz-Constán et al. (2012) suggest that the subduction is still active at present. In addition, slab rollback models have been proposed based on GPS data from the Rif (Fadil et al., 2006; Pérouse et al., 2010). Its origin and recent evolution are still controversial due to a lack of accurate data on its structure at depth, as well as the superposition of deformations and the variable features of the recent tectonic movements.

The aim of this paper is to present the results of new CGPS data from some stations (Fig.1) that belonged to the Topo-Iberia research. As part of this project, a network of 26 CGPS stations covering the Spanish part of the Iberian Peninsula and Northern Morocco were set (Lacy et al., 2012; Gárate et al., 2014). These new data for the period between March 2008 and December 2013 attest a westward displacement of the Betic-Rif Cordillera, reaching maximum values toward the south, near Gibraltar Strait area. Given their high quality and novelty, the data presented here shed light on the active tectonic structures of the western Betic Cordillera.

2. Geological Setting

The Betic-Rif Cordillera constitutes an arcuate Alpine orogeny, connected through the Gibraltar Arc, formed by the interaction of the Eurasian-African plates in the Western Mediterranean (Fig.1). The Betic Cordillera is divided into the Internal Zones (Alboran Domain), Flysch Units and External Zones (South Iberian Domain) located over the Iberian Massif foreland. The internal zones are formed by metamorphic complexes that include Paleozoic rocks. They comprise three main complexes: from bottom to top, the Nevado-Filabride, Alpujarride and Malaguide, in addition to the Dorsal and Predorsal. The most complete Alpujarride units have a sequence of metamorphic rocks with peridotites at the base. The Flysch Units correspond to an accretionary wedge constituted by Early Cretaceous to Lower Miocene siliciclastic deposits, located between the External and Internal Zones (Luján et al., 2006). The External zones represent a thin-skinned fold and thrust belt formed by Mesozoic and Cenozoic carbonate and detritic deposits (e.g. Crespo-Blanc et al., 2012). Furthermore, there is widespread development of intramontane basins which, together with the Guadalquivir foreland basin, are filled by sedimentary rocks from Miocene to Quaternary ages (Roldán, 1995; Riaza and Martínez del Olmo, 1996; Salvany et al., 2011, Rodríguez-Ramírez et al., 2014). The frontal area of the Betic Cordillerra, located along the mountain front that bounds to the south the Guadalquivir basin, features a synorogenic early Miocene to early Serravallian Olisthostromic unit of the Guadalquivir (Perconig, 1960-1962) also called Mélange Unit (Bourgois, 1978; Pérez-López and Sanz de Galdeano, 1994; Pedrera et al., 2012; Roldan et al., 2012). The activity of this arcuate orogen (Balanyá et al., 2007, 2012; Expósito et al., 2012) has determined a clockwise rotation of tectonic units in the Betics and counter-clockwise in the Rif, as evidenced by paleomagnetic data (Platzman, 1990; Platzman and Lowrie, 1992; Platt et al., 2003). In the western Betics, rotation varies in every unit probably reaching as much as 60ºsince Cretaceous time. The present day relief has developed during the last 10 Ma (Braga et al., 2003) in a roughly NW-SE to WNW-ESE compressional setting (Pedrera et al., 2011; Palano et al., 2013).

The widespread seismicity in the region (Buforn et al., 1995 and database of the Instituto Geográfico Nacional, www.ign.es) is associated with the tectonic activity (Ruiz-Constán et al., 2012) and related to the Eurasian-Africa oblique collision. Most of the western Betic Cordillera is affected by compressional deformations related to the overthrusting of its tectonic units onto the Iberian Massif foreland (Ruiz-Constán et al., 2012). However, the eastern part of the Betics has mainly undergone extensional tectonics since Middle Miocene (Galindo-Zaldivar et al., 2003), although the transition from extensional to compressional deformations related to top-to-the west displacements and its timing are under discussion (Galindo-Zaldívar et al., 2000). Although most of the earthquakes are shallow nearby the Betic Cordillera mountain front, they are deeper toward the western Alboran Sea, reaching 120 km deep along an arcuate band related to active subduction processes (Buforn et al., 1995; Morales et al., 1999; Pedrera et al., 2011; Ruiz-Constán et al., 2011).

GPS research in the Betic-Rif Cordillera is based on the installation of survey-mode GPS networks to study local structures such as the Zafarraya fault (Galindo-Zaldívar et al., 2003), Balanegra Fault (Marín-Lechado et al., 2010), CuaTeNeo GPS network in the eastern Betic Cordillera (Echeverría et al., 2013) and Granada Basin (Gil et al., 2002; Ruiz et al., 2003). CGPS data —often combined with GPS campaign observations— have allowed researchers to determine the general deformation pattern of the Betic-Rif Cordillera with respect to the Iberian foreland, which represents the stable Eurasian plate. Most GPS contributions are aimed to distinguish different crustal blocks along the plate boundary (Fadil et al., 2006; Serpelloni et al., 2007; Vernant et al., 2010; Koulali et al., 2011), generally lacking interpretation of particular active structures. Serpelloni et al. (2007) derived a relative westward motion of the Betic-Rif Cordillera based on very scarce data. Fadil et al. (2006) focus on the

Rif, proposing rollback of a delaminated subcontinental lithospheric slab, while Tahayt (2008) evidenced westward motion in the Gibraltar Strait area with respect to Eurasia. Perez-Peña et al. (2010) studied the Betics and northern Rif, supporting roughly NW motion (ranging from N to W) and relating the displacement to several major faults and seismicity. Pérouse et al. (2010) use a GPS displacement model to propose a local detached slab in the Rif. Vernant et al. (2010) and De Lis Mancilla et al. (2013) also present scarce data in the Betics, with motions ranging from WSW in the eastern Betics to WNW in the western Betics. Koulali et al. (2011) present campaign GPS data between 1999 and 2009, showing the arcuate displacement pattern in greater detail (Fig. 1b). These results contrast with the current and innovative results presented in this paper, based on recent data (2008-2013) from the Topo-Iberia stations, which show a roughly westward motion of the western Betics.

3. Methodology

This study presents the current GPS velocity field in the western Betic Cordillera derived from CGPS observations from March 2008 up to December 2013. The sub-network used in this paper consists of 10 sites (Figs. 1 and 2) which are operated by different Institutions: ALJI, LOJA, CAST, LIJA (Topo-Iberia research project), COBA, HUEL, MALA, CEU1, LAGO (EUREF Permanent Network, a science-driven network of continuously operating GPS reference stations of the International Association of Geodesy) and SFER (International GNSS Service, IGS). It is very important to emphasize that the locations of the Topo-Iberia sites are in the field (not on buildings) and founded on bedrock, implying a high stability of the concrete pillars and a high quality of the observations. Firstly, a previous quality check of CGPS data was carried out using the TEQC software developed by UNAVCO (Estey and Meertens 1999). Secondly, data processing was performed using the Bernesse software (Dach et al. 2007). A daily GPS network solution in a loosely constrained reference frame was estimated. The GPS observable is formed by double-differencing the L1 and L2 phase observations. GPS orbits and Earth's orientation parameters were held fixed to the combined IGS products and a priori error of 10 m is assigned to all site coordinates in order to get the loosely constrained coordinates. These solutions could be combined regardless of the datum definition of each contributing solution. The solution reference frame is defined stochastically by the input data and is basically unknown, though the estimation of relative rigid transformations (rotation-translation scale) between reference frames becomes necessary; this naturally leads to a combined solution not distorted by any constraint or transformation. Then, the daily network solutions were minimally constrained and transformed into EPN_A_IGb08 (EUREF Permanent Network station Positions in IGb08 reference frame) estimating translations and scale parameters. Finally, the velocity field was estimated by means of the NEVE software, which manages the complete stochastic model (Devoti et al. 2008). Velocities were estimated simultaneously, together with annual signals and sporadic offsets at epochs of instrumental changes. Velocity errors were derived from the direct propagation of the daily covariance matrix.

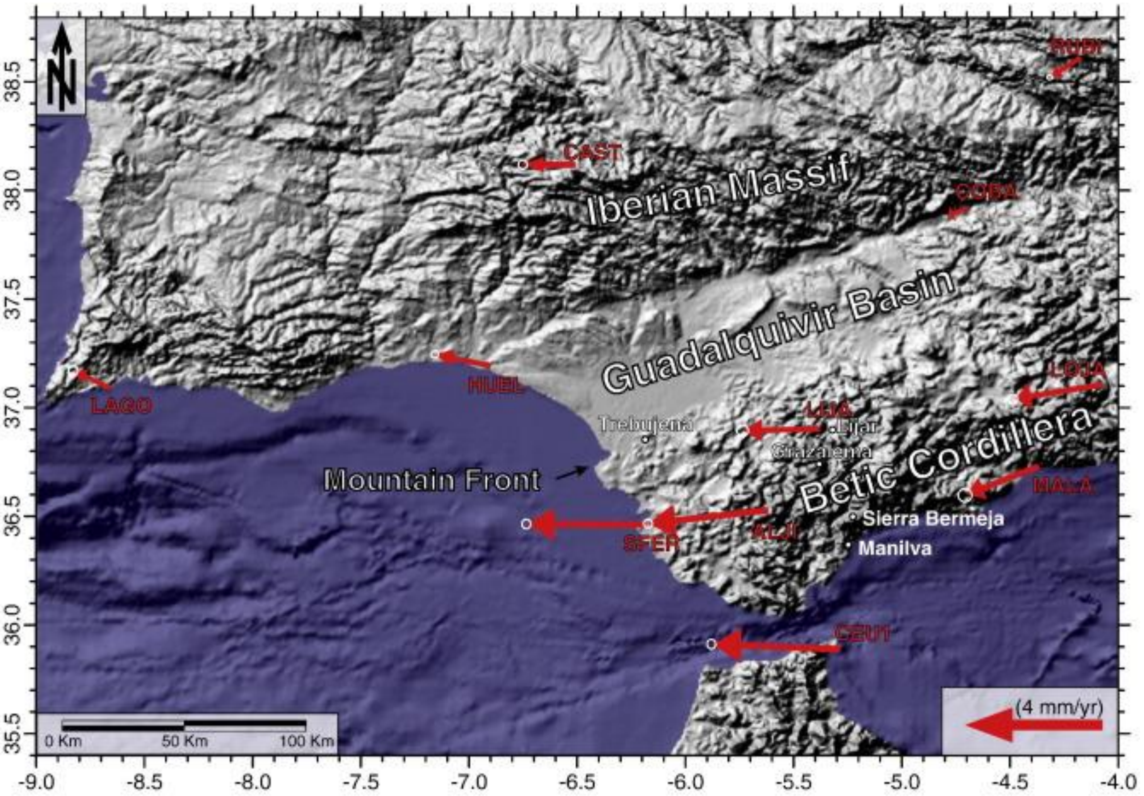

Fig. 2. Topography and CGPS data of the area studied. Residual velocity field is referred to Eurasia and 95% confidence ellipses.

Geological field observations involved recent and active structures that could accommodate the present day deformation field of the western Betic

Cordillera. Field research included observation of recent faults (fault surfaces and regime) and folds (orientation, dip of the limbs), as well as reviewing and improving the previous geological maps in areas of poor outcropping.

4. Displacements from GPS data in the western Betic Cordillera and its foreland

The CGPS-derived absolute velocities and associated errors in the IGb08 reference frame are given in Table 1 and Figure 3. A more effective representation of the estimated velocity field can be attained by presenting the residual velocities with respect to stable Eurasia, whose kinematics is defined through the rotation pole and rate. Figures 1 and 2 show the residual velocities at 95 % of conficence with respect to the Eurasia fixed reference frame. These new GPS results provide a highly consistent displacement pattern of the western Betic Cordillera with respect to its foreland.

Site	Coordinates		Absolute velocities (mm/yr)				Residual velocities (mm/yr)			
	Lat. (°N)	Long. (°E)	VE	σE	VN	σN	VE	σE	VN	σN
CAST	38.1227	− 6.5321	17.55	± 0.03	17.17	± 0.04	− 1.60	± 0.05	− 0.01	± 0.05
ALJI	36.5299	− 5.6494	15.67	± 0.05	16.72	± 0.06	− 4.00	± 0.07	− 0.44	± 0.07
LIJA	36.9062	− 5.4038	17.07	± 0.04	17.06	± 0.05	− 2.56	± 0.06	− 0.09	± 0.06
LOJA	37.1073	− 4.1064	17.01	± 0.04	16.67	± 0.04	− 2.81	± 0.05	− 0.44	± 0.05
LAGO	37.0989	− 8.6684	17.89	± 0.03	17.71	± 0.03	− 1.11	± 0.05	0.5	± 0.05
COBA	37.9156	− 4.7211	19.08	± 0.03	16.99	± 0.03	− 0.45	± 0.05	− 0.14	± 0.05
HUEL	37.2	− 6.9203	17.54	± 0.03	17.49	± 0.04	− 1.75	± 0.05	0.31	± 0.05
MALA	36.7261	− 4.3935	17.52	± 0.04	16.14	± 0.05	− 2.33	± 0.06	− 0.99	± 0.06
CEU1	35.892	− 5.3064	15.6	± 0.04	17.36	± 0.04	− 4.26	± 0.06	0.21	± 0.05
SFER	36.4643	− 6.2056	15.57	± 0.01	17.16	± 0.01	− 4.01	± 0.04	− 0.01	± 0.04

Table 1. CGPS-derived absolute velocities and associated errors in IGb08 reference frame and residual velocities with respect to Eurasia fixed.

Most of the sites located in the Iberian Massif have very low relative displacement with respect to stable Eurasia, and all of them have a roughly westward component. HUEL and CAST, are faster than COBA and RUBI (Fig. 2). Moreover, the stations in the western Gibraltar Arc (CEU1, LIJA, SFER) show a westward motion relative to its foreland (HUEL) (Figs. 1 and 2), the values reaching a maximum in the Gibraltar Strait (CEU1, 4.26 mm/yr) and its

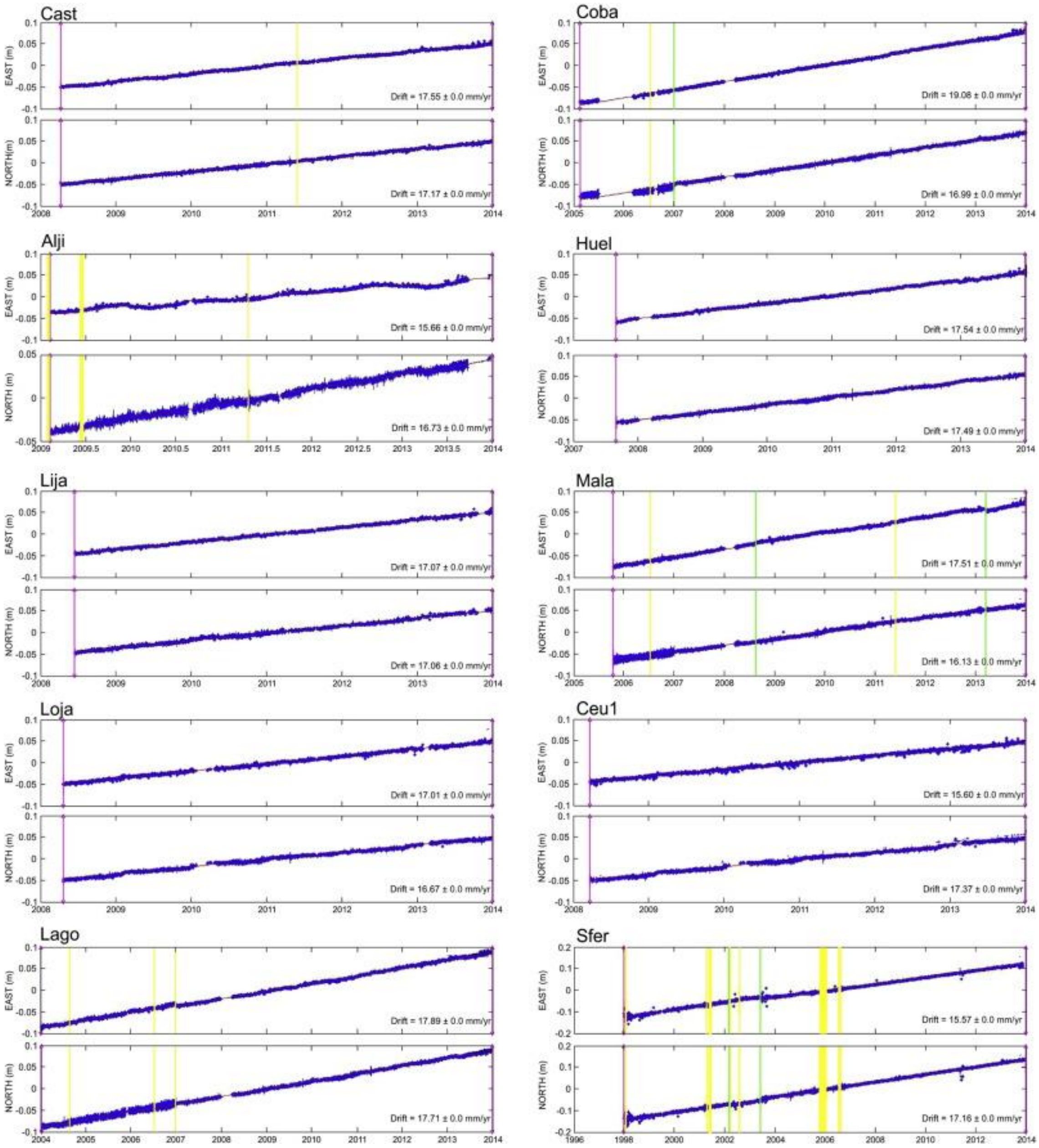

Fig. 3. Position time series of the network stations (North and East components in meters). Yellow lines are considered outliers according to the software applied. Absolute velocities are included in Table 1.

northern nearby region (ALJI 4.00 mm/yr), as well as in the area to the northwest (SFER site, 4.01 mm/yr). This displacement (Figs. 1 and 2) slightly decreases towards the north (LIJA, 2.56 mm/yr) and east (MALA, 2.33 mm/yr and LOJA, 2.81 mm/yr). Further eastward, the relative displacement has a minor WSW component (LOJA and MALA) in contrast to the purely westward motion of the LIJA, SFER and CEU1 stations.

In the northwestern front of the Betic Cordillera there is a high gradient of progressively decreasing displacement, up to the foreland located towards the

NW, evidencing oblique contraction. Moreover, the moderate difference of the displacements between LOJA and MALA with respect to ALJI (Figs.1 and 2) supports the occurrence of a low intensity widespread extension in the southeastern part of the study area.

5. Recent, active and other relevant structures

Field observations reveal the main features of the geological structures that may accommodate the present-day westward displacement of the western Betics with respect to its foreland. Most of the frontal area is formed by soft rocks of Miocene to Quaternary ages (Fig. 1), with scarce reference horizons. They unconformably lies over Cretaceous to Jurassic carbonate series. There are also olisthostromic masses mainly formed by Triassic sediments (Figs. 4, 5, and 6).

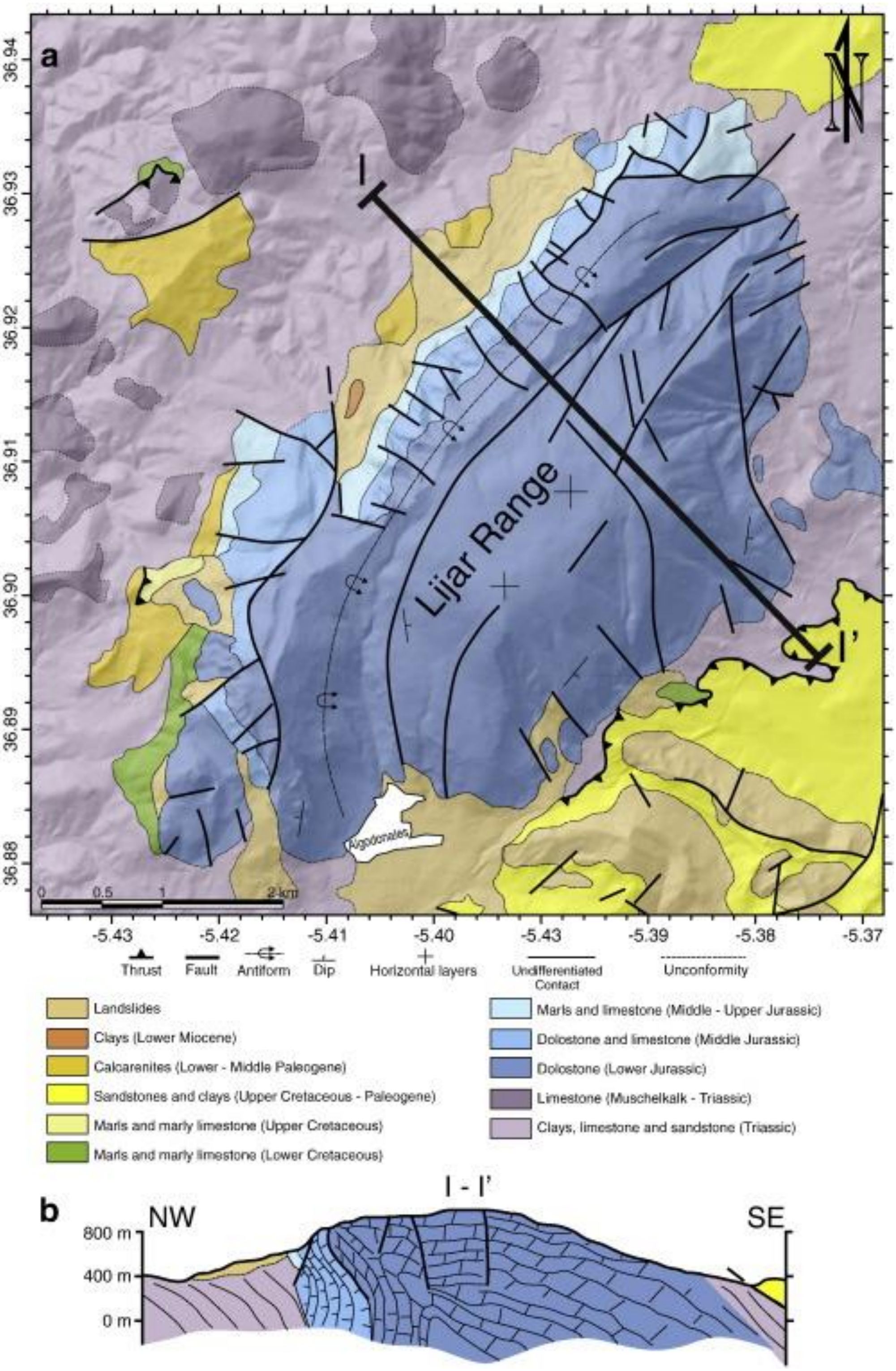

Fig. 4. Structure of the Líjar range. (a) Geological map. (b) Cross-section. See regional location in Fig. 1a. Modified from Cano-Medina (1981).

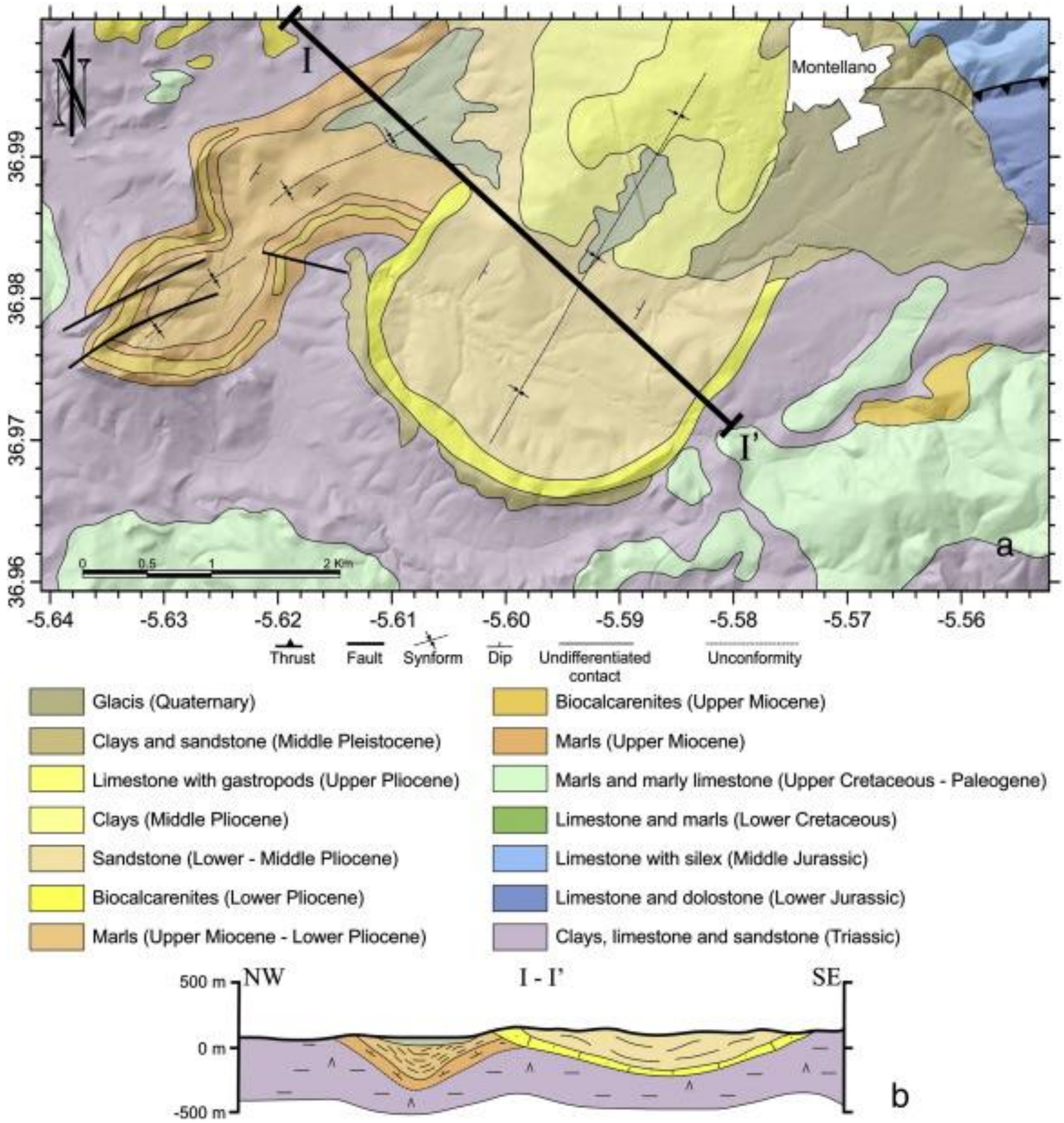

Fig. 5. Structure of the Montellano area. (a) Geological map. (b) Cross-section. See regional location in Fig. 1a. Modified from de Domingo (1985).

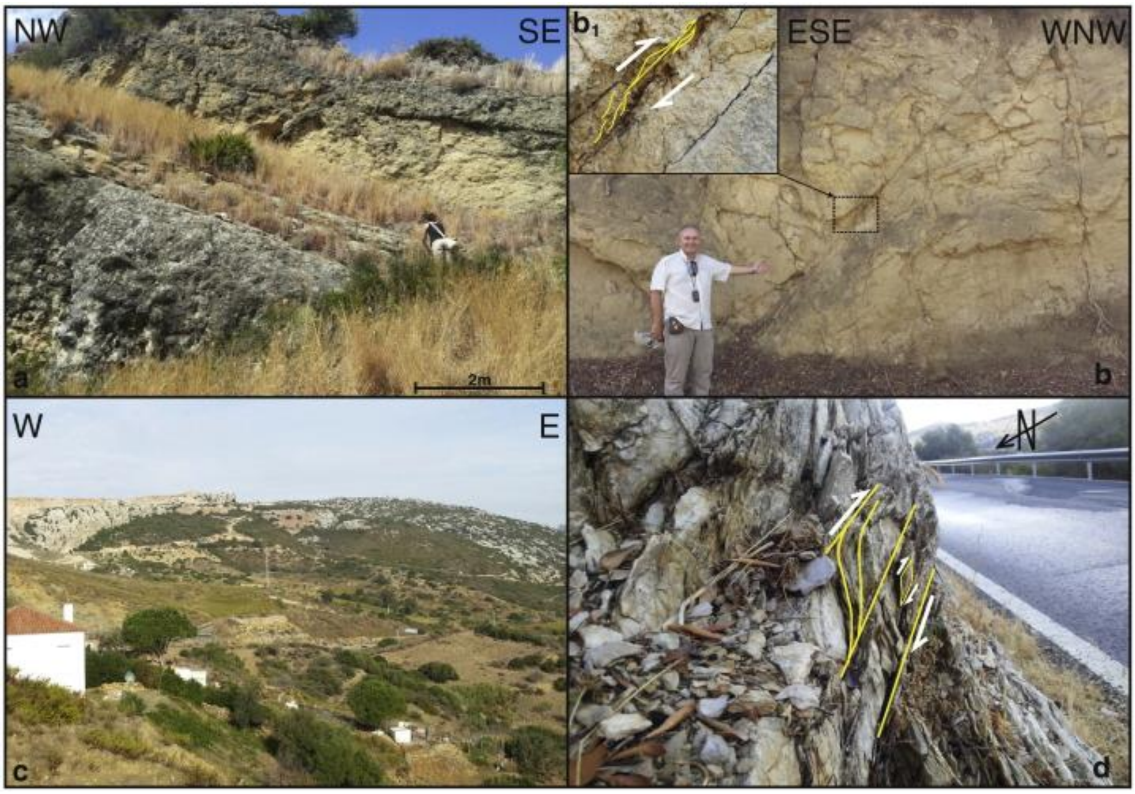

Fig. 6. Field structures. (a) Dipping Upper Miocene biocalcarenite layer in the western limb of the Montellano synform. (b) Reverse fault in the Espera area. (b1) Detailed view of fault gauge fabric. (c) Manilva N–S oriented antiform. (d) E–W oriented fault in Grazalema area with expected strike-slip but which only shows S–C structures of reverse fault.

The westernmost front of the Cordillera (Figs. 1 and 2) constitutes a thin-skinned fold and thrust belt and huge olisthostromic masses derived from the External Zones. Folds affecting Jurassic and Cretaceous rocks (Sierra de Líjar, Fig. 4), as well as Upper Miocene sediments (Montellano area, Figs. 5 and 6), generally have NE-SW orientations ranging from N45ºE to N50ºE. More recent folds affect Pliocene sediments in the Montellano area (Fig. 5) and have axes N20ºE to N40ºE. The geometry of these folds varies from NW vergent moderately inclined (Sierra de Lijar, Fig. 4) to upright (Espera, Fig. 7). Southward along the Gibraltar Arc, folds also affect the inner sector of the Cordillera, as evidenced by the N-S oriented Manilva antiform (Figs. 6 and 8) formed in early-middle Miocene, but also affecting upper Miocene rocks (Balanyá et al., 2012) and Pliocene sediments (Durand-Delga, 2006). Although the main structures observed are recent folds, scarce recent reverse faults can also be identified, for instance near Espera (Figs. 6 and 7). These structures are responsible for accommodating recent shortening in the western Betics.

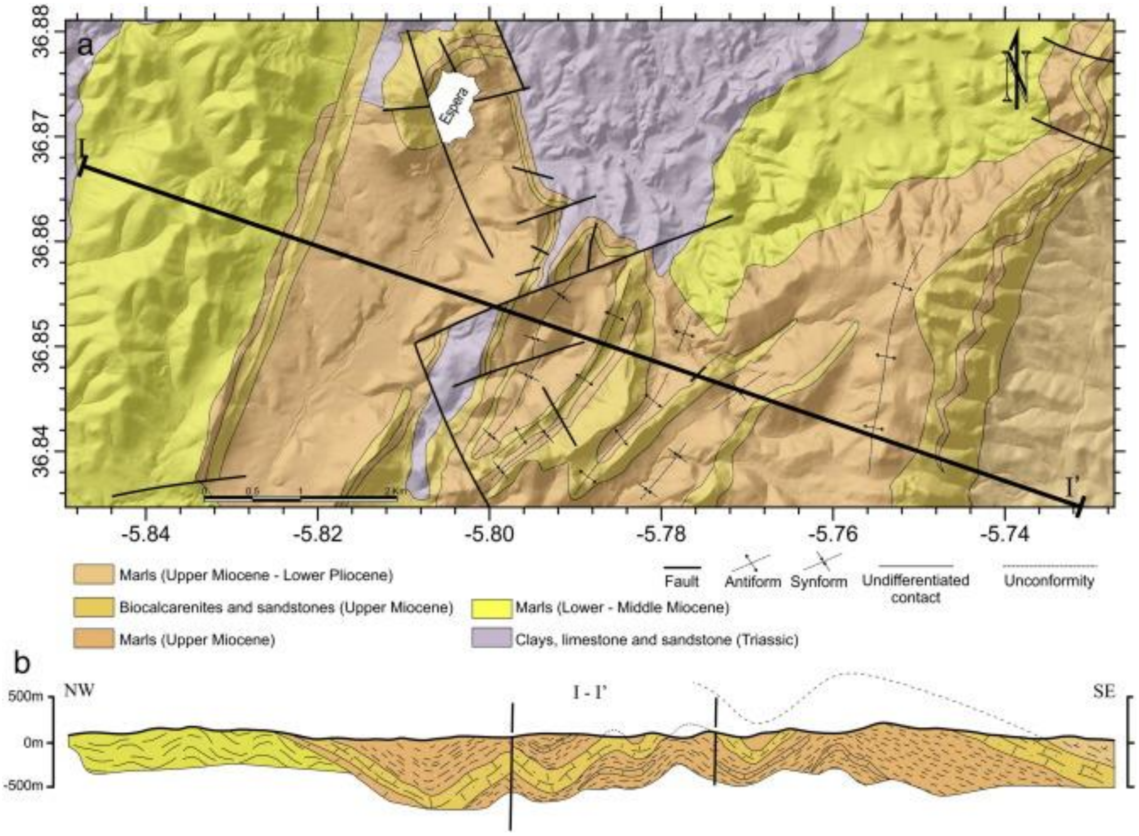

Fig. 7. Folds affecting up to Pliocene sediments in the Espera area. (a) Geological map. (b) Cross-section. See regional location in Fig. 1a. Modified from de Domingo (1985).

Several E-W oriented faults occur in the Grazalema area (Figs. 1 and 6), separating sectors with different westward displacements. Despite the expected dextral kinematics, a detailed analysis of striae and S-C structures reveals that these faults have reverse kinematics and are inactive at present. Thus, we have not identified any remarkable tectonic structure that would justify the different displacement observed between LIJA and ALJI sites (Figs. 1 and 2). Therefore, the strong N-S gradient inferred might be due to the poor velocity estimation at ALJI station, which, in turn, could be related to a site effect (see time series; Fig. 3). Alternatively, these data may evidence a fast present-day block rotation. In addition, the N-S oriented faults between ALJI and MALA sites should have a normal regime, though they don't show typical features of active faults.

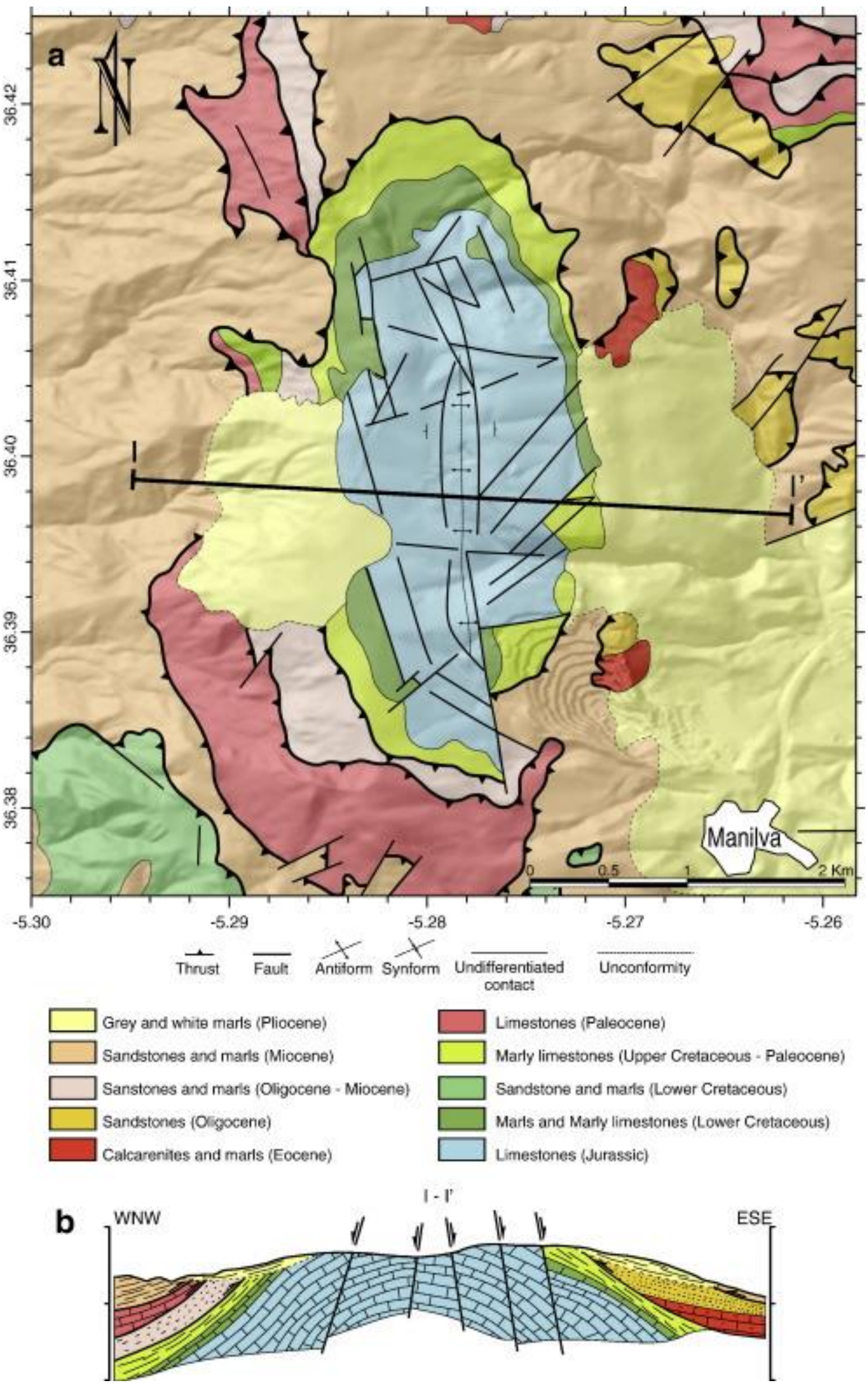

Fig. 8. N–S oriented antiform in the Manilva area. This fold mainly developed during Miocene, though also affects Pliocene deposits. (a) Geological map. (b) Cross-section. See regional location in Fig. 1a. Modified from Cano Medina and Torres-Roldán (1980).

6. Shortening in the western Betic mountain front and clockwise rotation

The cross-section of the Espera region (Fig. 7) allows us to derive a mean value of WNW-ESE to W-E shortening that may be taken into account for the whole frontal area. Considering the Messinian calcarenites as a reference level affected by Early Pliocene (5.3 to 3.6 Ma) folds, an average shortening of 16.1 % is estimated to have occurred. LIJA site and the westward Betic Cordillera mountain front in the direction of Trebujena are 61 km apart. Bearing in mind a roughly homogeneous shortening, folding has accommodated 11.70 km of deformation at a geological rate between 2.2 and 3.25 mm/yr, while the CGPS observations determine a present-day rate of 2.6 mm/yr.

The clockwise rotation of the western Betic units is of 60º (Platzman, 1990; Platzman and Lowrie, 1992; Platt et al., 2003) since Cretaceous times (145.5 to 65.5 Ma). Considering that rotation started at 65.5 Ma, on average a rate of 0.916º/Ma can be inferred. If we take into account the different displacement rates at LIJA and ALJI stations, as well as the distance and angle between them, a clockwise block rotation of 2.06º/Ma would have been occurring at present, i.e. approximately twice the long-term geological rates but in agreement with the sense of rotation.

7. Discussion

We have analyzed data and used velocities from 10 CGPS Topo-Iberia and EUREF stations acquired in the period 2008-2013 to investigate present day deformation in the Western Betic Cordillera. These new data provide very detailed information on deformation in the area.

The new data depict a more consistent pattern of roughly parallel westward displacements that reach maximum values in the central part of the Gibraltar Arc (ALJI, CEU1) and decrease towards the NW Betic mountain front.. This pattern contrasts with the previous marked arcuated patterns proposed by Vernant et al. (2010), Koulali et al. (2011), Palano et al. (2013) and De Lis Mancilla et al. (2013), being however in agreement with the simpler patterns of Serpelloni et al. (2007).

The above deformation pattern agrees with an active westward displacement of the western Betics in the northern branch of the Gibraltar Arc. Towards the NW mountain front, a fold belt with scarce reverse faults accommodates the deformation over a basal detachment. The folds in the Montellano area (Fig. 5) evidence active deformation at least since the late Miocene. While the oldest folds have NE-SW trends, the most recent folds have a NNE-SSW orientation, closer to N-S. Although this setting may have been a consequence of changing stresses or convergence trends, it is more likely due to progressive clockwise rotation during oblique convergence in agreement with regional clockwise block rotations (Fig. 9). The N-S oriented antiform mainly developed during Miocene (Balanyá et al., 2012) and affecting Pliocene sediments nearby Manilva (Durand-Delga, 2006) is compatible with the westward present-day displacement recorded in the westernmost part of the Gibraltar Arc.

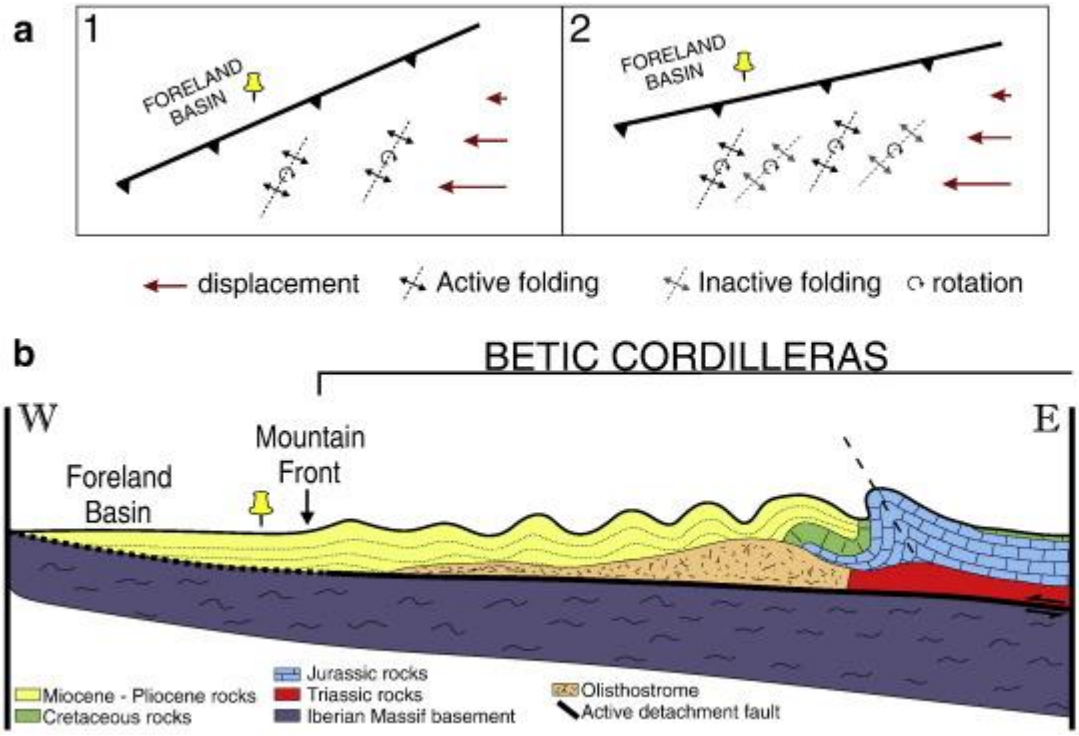

Fig. 9. 3D model of the folded belt in the NW frontal zone of the Betics. (a) Progressive dextral rotation of folds due to oblique convergence, which probably determines the end of their activity and the development of a new fold generation with orientation more close to N–S. (b) The asymmetrical vergent folds toward the inner zones become symmetrical and more open toward the NW mountain front in a thin skinned tectonic scenario.

The estimated values of geological shortening for the Líjar-Trebujena cross-section (2.2-3.25 mm/yr) are in line with the geodetic rates (2.6 mm/yr), thus supporting a continuous deformation in the western Betics since the Pliocene. Frontal folds accommodate most of the deformation and are responsible for the rectilinear character of the northwestern mountain front. The present-day clockwise rotation sense is also in agreement with paleomagnetic studies (Platzman, 1990; Platzman and Lowrie, 1992; Platt et al., 2003).

The displacement pattern points to an active westward motion of the mountain belt along the Gibraltar Arc (Figs.1, 2 and 10). Geodynamic models that involve only delamination would imply active extension in the whole orogeny. Therefore, our results don't give credit to delamination models. On the contrary, models that consider a simple orogenic wedge with a subduction zone, are compatible with a continuous compressive westward motion. However, these simple models do not agree with the moderately present-day extension evidenced by the larger westwards motion of LIJA and CEU1 sites with respect to MALA and LOJA. Finally, if subduction with related active slab rollback is considered (Fig. 10), the expected deformation pattern may fit quite well the obtained GPS results. This tectonic model determines, at surface, that the frontal compressive deformation area is related to an oblique dextral convergence mainly accommodated by folds. At a broader scale, this setting produces the progressive clockwise rotation of the more rigid tectonic blocks. The fact that subduction is active in the Betic Cordillera is evidenced by the intermediate deep seismicity along the arcuate band parallel to the western boundary of the Alboran Sea (Fig. 1). This model for the Betic Cordillera is also compatible with models proposed for the Rif Cordillera (Fadil et al., 2006; Pérouse et al., 2010) that envisage slab rollback.

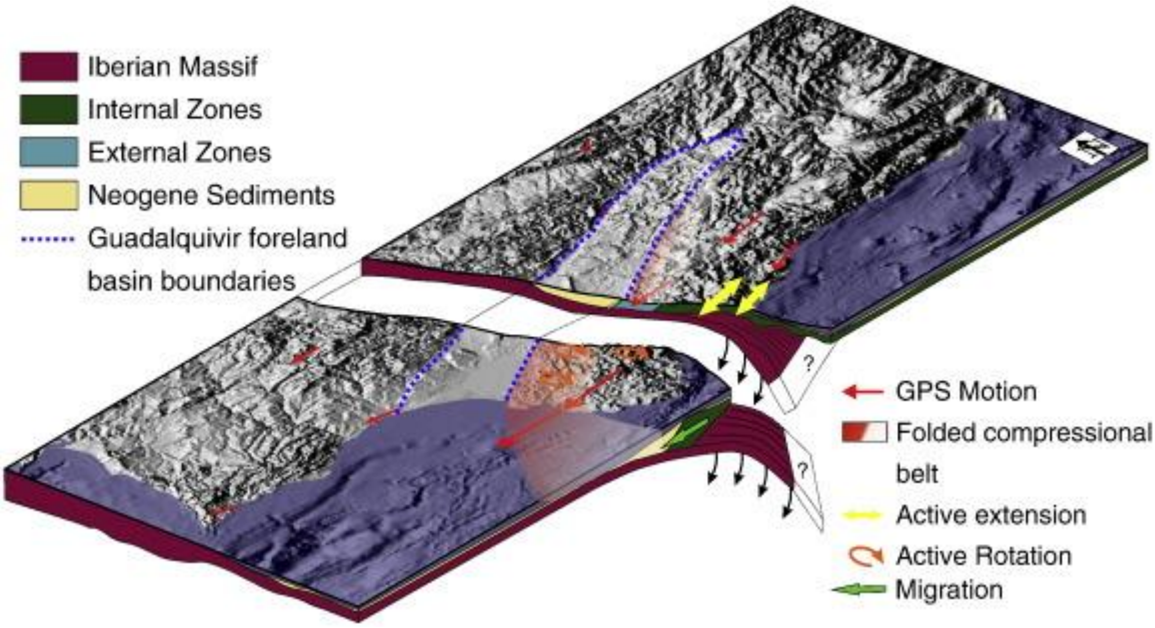

Fig. 10. Tectonic model for the westernmost Betic Cordillera integrating CGPS data. The slab rollback tectonics determines the faster westwards displacement of the westernmost portion of the orogen and the development of dextral rotations. At the same time, moderate E–W oriented extension occurs toward the southeastern sector of the region studied.

8. Conclusions

A CGPS monitoring by means of the Topo-Iberia stations has allowed us to determine the present-day deformation of the Western Betic Cordillera from recent data (2008-2013) affording higher detail and precision than previous assessments. Accordingly, the development of the Gibraltar Arc continues at present. Maximum relative westward displacements with respect to the foreland reach up to 4.27 mm/yr in the Gibraltar Strait. The rate of displacement decreases along a narrow band towards the northwest mountain front and towards the eastward internal zones of the arcuate orogen. Furthermore, present-day clockwise rotation of geological units in the western Betics is shown to be faster (2.06º/Ma) than long-term geological rotations (0.916º/Ma). Such displacement values are compatible with the presence of a region undergoing contraction in the frontal part of the Cordillera, while moderate extension takes place eastwards.

The oblique shortening of the Cordillera with respect to its foreland is accommodated by a deformation band affected mainly by folds, active at least since the Late Miocene. Local reverse faults have also been identified. While long-term WNW-ESE to W-E shortening rates from the LIJA station to the NW mountain front are of the order 2.2-3.25 mm/yr, present-day rates lie within this range, reaching 2.6 mm/yr. The presence of soft rocks and the thin-skinned tectonics characterizing most of the mountain front, would have concentrated the deformation along folds at shallow crustal levels, thus explaining the scarce seismicity in this region.

The new CGPS-derived velocity field for the Western Betic Cordillera, together with the intermediate-depth seismicity, is in agreement with active subduction and slab rollback.

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