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Active faulting in the internal zones of the central Betic Cordilleras (SE, Spain)

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Abstract

The internal zones of the Betic Cordilleras show a present-day relief that is mainly controlled by kilometre-size, symmetrical or north-vergent folds which developed mostly since Middle Miocene times. The Sierra Nevada, Sierra Alhamilla, Sierra de Los Filabres, Sierra Tejeda and Sierra de Gádor, among others, are roughly E–W trending high mountain ranges, corresponding to antiforms where metamorphic rocks crop out. The surrounding depressions are located in synforms, where Neogene rocks are preserved from erosion. Field evidence shows that the growth of the folds is coeval with fault development, and that at least three of them, i.e. the Padul Fault, the Zafarraya Fault, and the Balanegra Fault, may be considered to be active seismogenetic structures. The Zafarraya Fault, in particular, is thought to be responsible for the 1884 Andalucía Earthquake. The fault is located at the northern limb of the Sierra Tejeda antiform, and could be interpreted as a collapse structure developed along the external arch of the uplifted fold. The Padul and Balanegra faults are located at the southeastern border of the Granada Basin and south of the Sierra de Gádor, respectively. They belong to a set of NW–SE oriented faults that are mainly normal in character and indicate NE–SW extension. The set up, since 1999, of a GPS network within and around the Granada Basin and the planed installation of a new network in the Sierra Tejeda, will give us new insights on the present-day deformation behaviour of both folds and faults in the area.

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1. Introduction

The internal zones of the Betic Cordilleras (Figs. 1 and 2) are characterized by a tectonic setting where compressional structures developed simultaneously with the extensional ones, in response to the present-day motion between Iberia and Africa (4 mm/year in a NW–SE direction; De Mets et al., 1990). Recent and active deformation, however, are distributed heterogeneously along the plate boundary. In the central sector of the Cordilleras, folds growth (Weijermars et al., 1985;

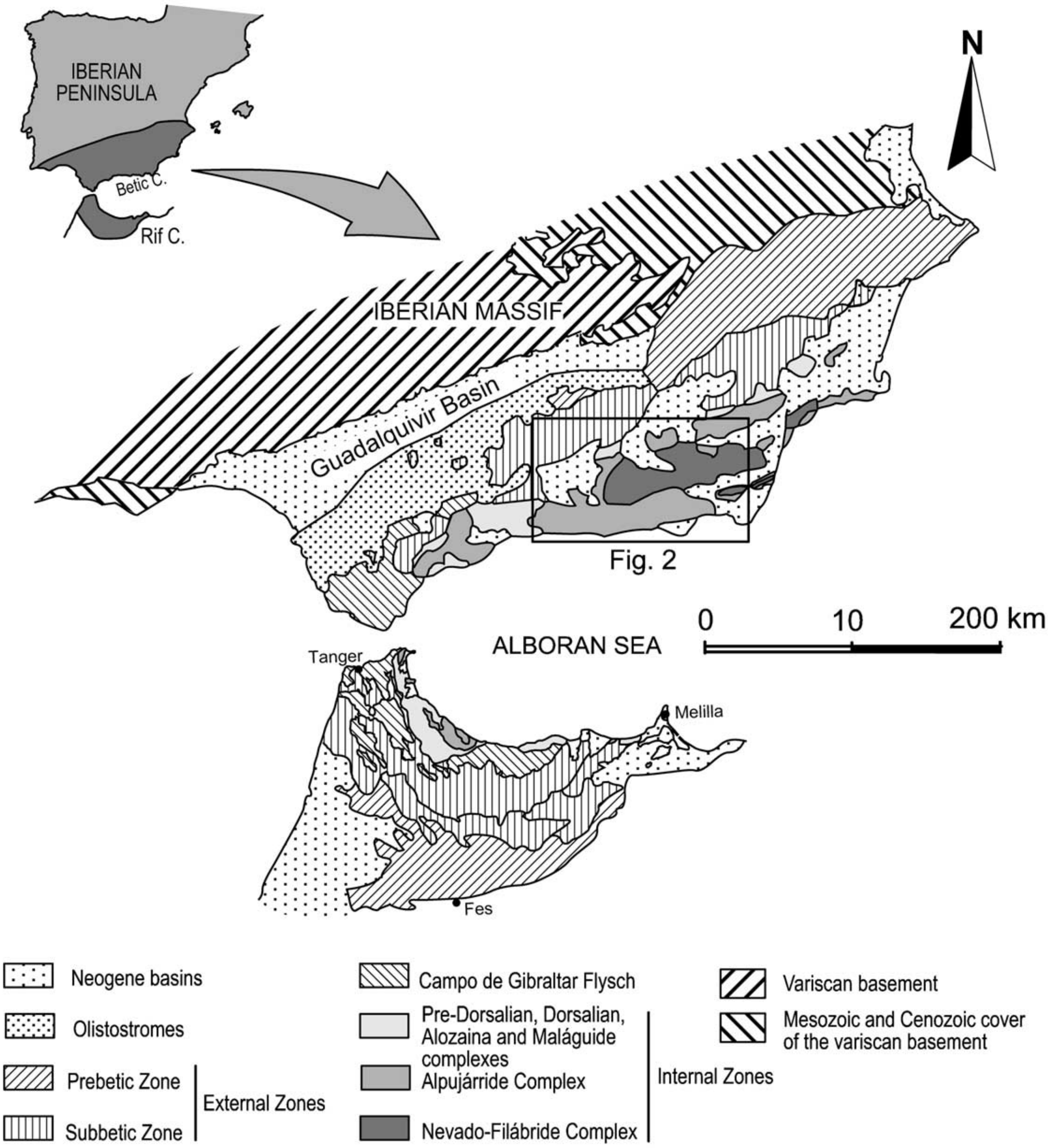

Fig. 1. Geological setting of the Betic and Rif Cordilleras in the frame of the western Mediterranean.

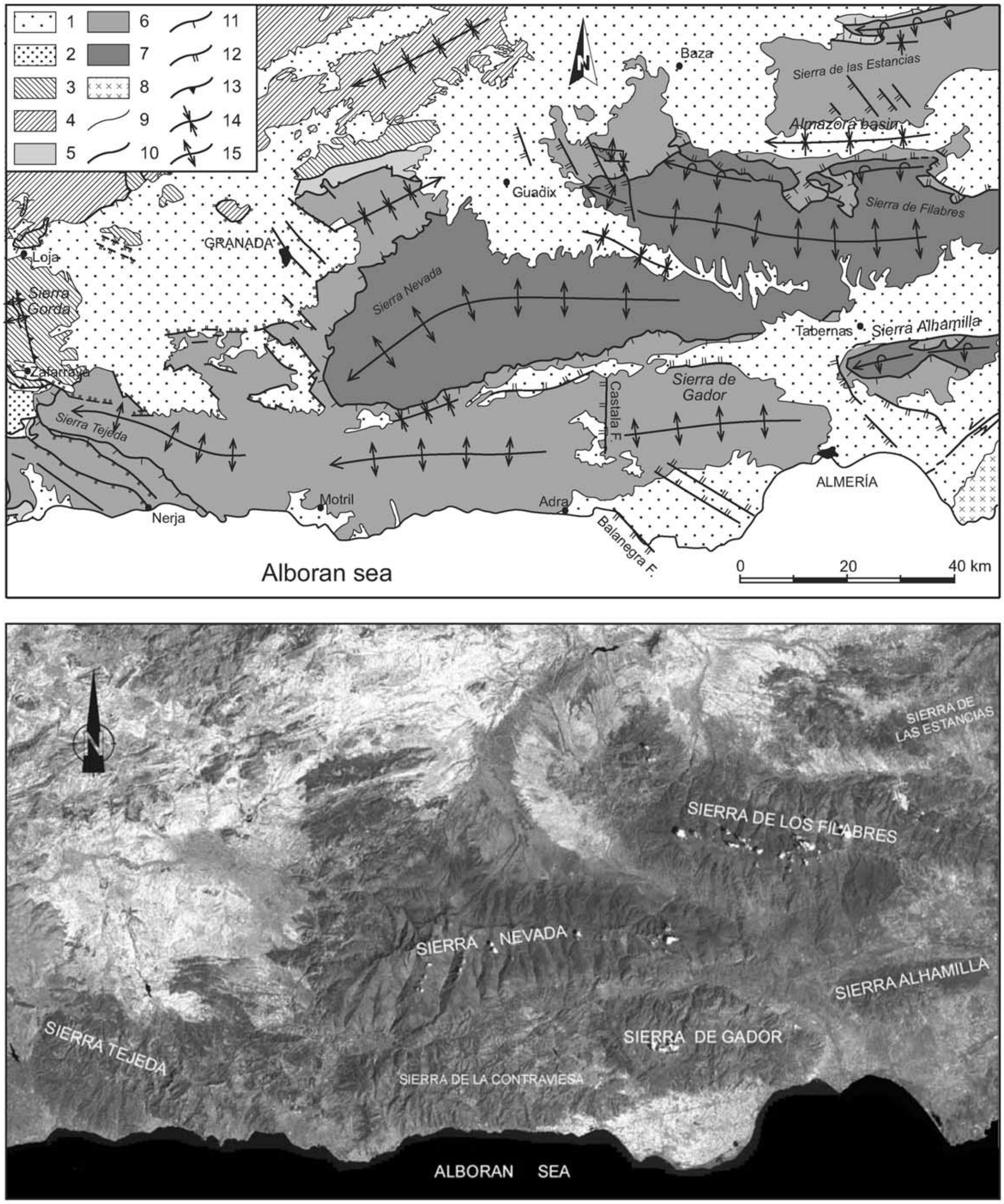

Fig. 2. Location of main folds in the central sector of the Internal Zones of the Betic Cordillera. (A) Tectonic sketch map; and (B) satellite view of the region. 1, Upper Miocene, and Plio-Quaternary rocks. 2, Middle and Lower Miocene rocks. 3, Upper Subbetic Unit. 4, Intermediate Subbetic Unit. 5, Maláguide Complex. 6, Alpujárride Complex. 7, Nevado-Filábride Complex. 8, Neogene volcanic rocks. 9, unconformity. 10, fault. 11, low-angle normal fault. 12, high-angle normal fault. 13, low-angle reverse fault. 14, syncline. 15, anticline.

Johnson, 1997) is simultaneous with the faults and some of them, like the Zafarraya Fault, are also responsible for the genesis of destructive historical earthquakes. On the other hand, in the eastern sector of the Cordilleras, mainly strike slip faults occur (Groupe de Recherche Neotectonique, 1977; Bousquet, 1979; Sanz de Galdeano, 1983; Montenat et al., 1987, among others).

In the last few years, geophysical and geological studies in the area have been focused on the recognition of distinctive active structures and seismogenic areas. As a result of geophysical investigations (including seismicity, seismic tomography, deep seismic reflection profiles, gravity and magnetics) it has been assessed that some of the most active features in the area are related to the subduction of the continental crust of the Iberian Massif below the Betic Cordilleras (Morales et al., 1999). Furthermore, in the central sector of the Cordilleras, a detachment horizon detected between 10 and 15 km depth (Galindo-Zaldívar et al., 1997; Ruano et al., in press), is considered to be the base of the seismogenic crust.

Tectonic and geomorphological studies carried out in different sectors around the Granada Basin and the Sierra Tejeda (Sanz de Galdeano, 1976; Galindo-Zaldívar et al., 1999; Sanz de Galdeano and López-Garrido, 1999, Ruano et al., 2000; Alfaro et al., 2001; Reicherter et al., 2002, submitted for publication; Ruano et al., in press, among others) show that, here, faulting was active since the Tortonian and up to the present. The main active faults in the area are the Padul and Zafarraya faults. They show a roughly NW–SE and E–W trend, respectively, and are predominantly normal faults with some strike-slip components. In order to determine the present-day deformation rates of these structures, a GPS regional network with 16 observation sites located within and around the Granada Basin was installed in 1999 (Gil et al., 2002). In addition, another local GPS network is being set up in the Sierra Tejeda, for monitoring the Zafarraya fault.

The aim of this paper is that of discussing the coeval development of recent and active folds and faults in the central sector of the internal zones of the Betic Cordilleras, and reviewing available results from the operating GPS network.

2. Recent and active faults and folds in the Betic Cordilleras

The internal zones of the Betic Cordilleras show a relief that is mainly due to the occurrence of kilometre-size fold, which locally are modified or bordered by high angle faults (Fig. 2). The faults showing recent activity are located mainly along the borders of the mountain ranges (Sierras), and display tectonic, geomorphological, and seismological evidence of recent motion. In the following sections, we present several case studies with the aim of assessing the appropriate relationships between folding and faulting in the area.

2.1. The Zafarraya Fault

The Zafarraya Fault is part of a range-bounding, roughly E–W trending fault system (Type I, faults), which is generally located at the northern border of the ridges (Fig. 3). This fault is one of the few structures, in the central part of the Betic Cordilleras, with historical evidence of tectonic activity. There are reports of ground breaks, along this normal fault, during the 1884 Andalucía Earthquake, with an estimated magnitude between 6.5 and 7 (Muñoz and Udías, 1981). This

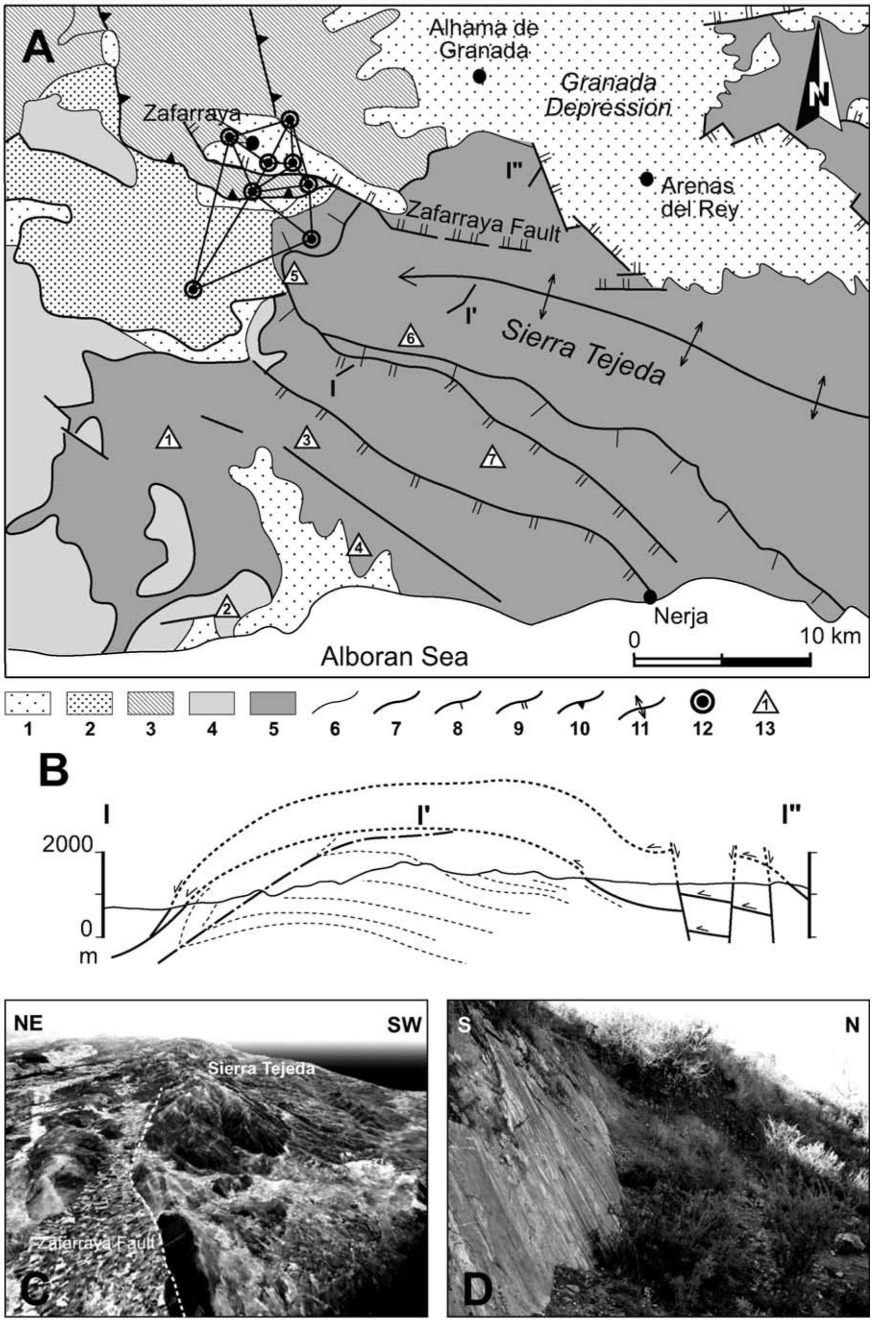

Fig. 3. Sierra Tejeda and Zafarraya fault. (A) Tectonic sketch map; including the scheduled GPS network. 1, Upper Miocene, and Plio-Quaternary rocks. 2, Middle and Lower Miocene rocks. 3, Upper Subbetic Unit. 4, Maláguide Complex. 5, Alpujarride Complex. 6, unconformity. 7, fault. 8, low-angle normal fault. 9, high-angle normal fault. 10, low-angle reverse fault. 11, anticline. 12, GPS site, local network. 13, GPS site, regional network. (B) Cross section along the trace I, I′,I″, of the Sierra Tejeda antiform; simplified from Fernández-Fernández et al. (1992). (C) Satellite restituted image of the Sierra Tejeda fold and Zafarraya fault. (D) Field evidence of the Zafarraya fault.

earthquake heavily damaged several villages in the region (Arenas del Rey, Zafarraya, Ventas de Zafarraya and Alhama de Granada, among others). The causative fault has a total length of over 15 km, and its trend varies along strike approximately from E–W (to the south) to NW–SE, at its western termination. The occurrence of colluvial wedges with preserved soils near the fault indicates that the area has undergone several seismic events during the Holocene (Reicherter et al., 2002, submitted for publication). Cumulative fault displacements across the Zafarraya fault are in the order of several hundred meters (Reicherter et al., 2002, submitted for publication). The fault borders to the south an endorheic basin, the Zafarraya Depression, filled with sediments that range in age from Tortonian to Present (López-Chicano et al., 2002). The basin is asymmetric, and probably one of the main depocenters is located at its southern border, near the fault. To the southeast of the Zafarraya fault, the Sierra Tejeda antiform shows a periclinal termination towards the west (Fig. 3b). Here, antiform uplift must be still occurring, since very steep slopes with a fluvial network deeply cutting through its limbs are distinctive features in the area (Fig. 3). Furthermore, several unconformities related to the fold uplift are observed in Pliocene rocks exposed at the southern limb of the structure (Guerra-Merchán and Serrano, 1993; Ruano et al., in press), where a set of WNW–ESE oriented faults, with both normal and trascurrent components, occur. These faults are of Neogene age, but do not show evidence of recent activity.

2.2. The Padul Fault

The Padul Fault (Fig. 4) belongs to a system of NW-SE trending normal faults mainly dipping towards the SW. These faults (Type II faults) are often associated to asymmetric basins filled with sedimentary wedges of Tortonian and younger ages (Galindo-Zaldívar et al., 1996). Type II faults show intermediate features between a listric fan and a domino-like system (Galindo-Zaldívar et al., 1996).

The Padul Fault borders to the east an asymmetric basin that, at least during the Quaternary, constituted an endorheic depression filled with detritic sediments and peat (Sanz de Galdeano, 1976; Galindo-Zaldívar et al., 1996). This fault consists of two connected segments showing clear evidence of recent activity as a seismic source (Alfaro et al., 2001). In detail, the fault geometry is quite complex and display both low and high angle surfaces; furthermore, there is evidence of progressive rotation of the fault during its evolutionary history (Alfaro et al., 2001). The cumulative vertical displacement associated to the Padul Fault is greater than 800 m (Sanz de Galdeano, 1976), and the uplift rate is about 0.4 mm/year (Sanz de Galdeano, 1996; Keller et al., 1996).

The Padul Fault is located at the westernmost termination of the Sierra Nevada (Figs. 2 and 4), the highest mountain range in the Betic Cordilleras, which includes the Mulhacén peak, where the maximum altitude (3482 m a.s.l.) of the entire Iberian Peninsula occur. The Sierra Nevada Range includes a major antiform and several minor folds (Fig. 4) affecting mainly pre-Miocene rocks, whereas the surrounding depressions are mostly filled with sediments deposited since the initial stages of fold development (i.e. during the Tortonian) and up to the Present. Fission track studies (Johnson, 1997) indicate that these structures underwent a fast uplift during the Pliocene.

2.3. Other fold- related faults

In addition to the Padul and Zafarraya faults, other faults associated with folds are exposed in the mountain ranges of the Internal Zones of the Betic Cordilleras. South of the Sierra Nevada,

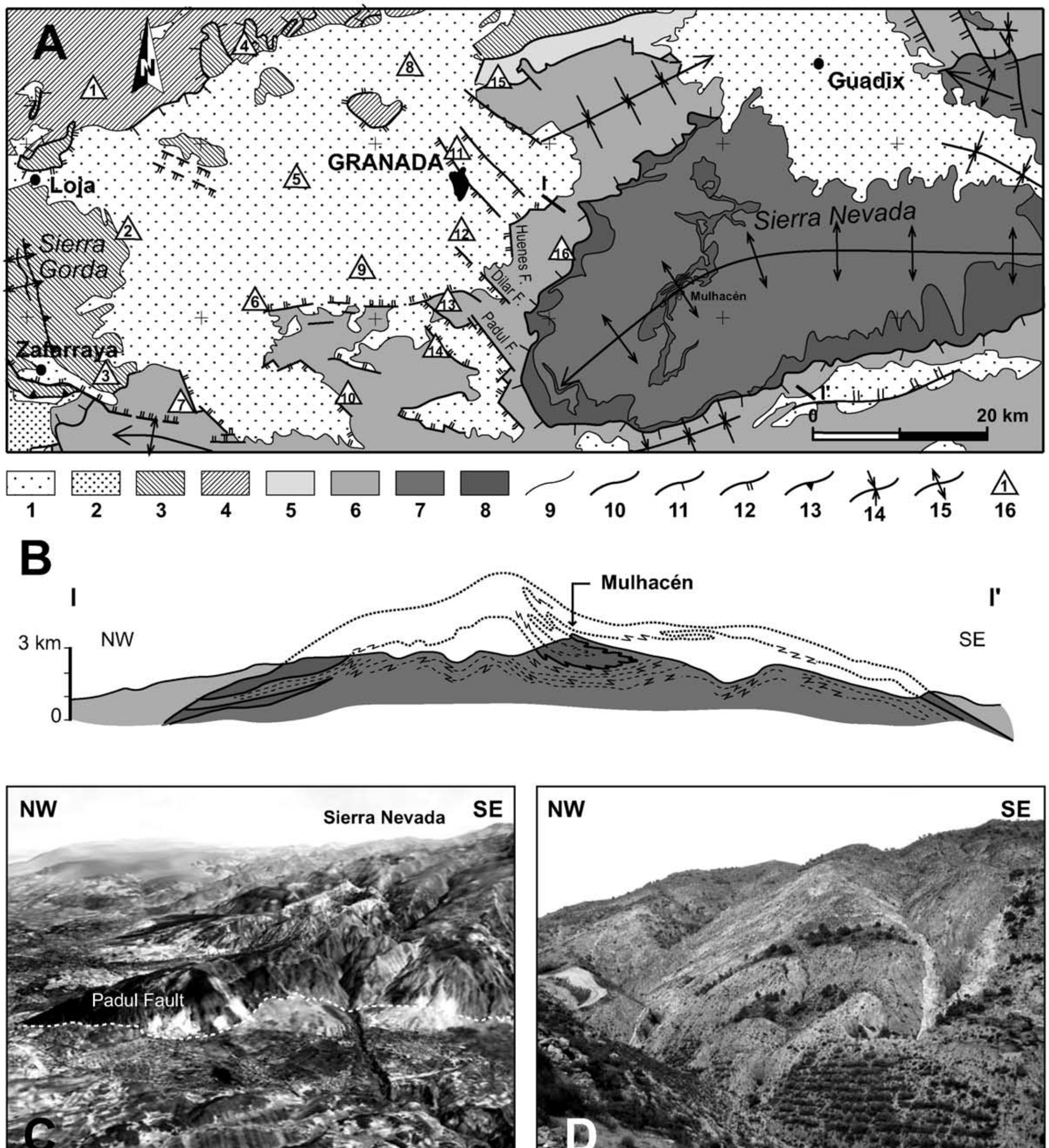

Fig. 4. Sierra Nevada and Granada Basin. (A) Tectonic sketch map including the GPS network operating in the area since 1999. 1, Upper Miocene, and Plio-Quaternary rocks. 2, Middle and Lower Miocene rocks. 3, Upper Subbetic Unit. 4, Intermediate Subbetic Unit. 5, Maláguide Complex. 6, Alpujárride Complex. 7, Nevado-Filábride Complex, lower series. 8, Nevado-Filábride Complex, upper series and tectonic intercalations of upper and lower series. 9, unconformity. 10, fault. 11, low-angle normal fault. 12, high-angle normal fault. 13, low-angle reverse fault. 14, syncline. 15, anticline. 16, GPS site. (B) Cross section of the western Sierra Nevada showing fold geometry. (C) Satellite restituted image of the Padul fault. (D) Triangular facets along the Padul Fault.

roughly E–W oriented structures including normal (Fig. 2), dextral and reverse faults can be observed, whereas in the Sierra Alhamilla (Fig. 2), a mountain range displaying a structure that resembles that of the Sierra Nevada, several NNW–SSE trending, mostly normal, faults are nicely exposed to the south and west of the main antiform. Although some of these faults were active since the Early Miocene (Martínez-Martínez and Azañón, 1997), it must be emphasized that most of them also cut through sediments of Plio-Quaternary age. On the other hand, at the northern termination of Sierra Alhamilla, trascurrent (dextral) and reverse high angle faults with a roughly E–W orientation dissect rocks of up to Messinian age (Sanz de Galdeano, 1989). Field evidence suggests that the uplift of the Sierra Alhamilla antiform started at the end of the Tortonian (Weijermars et al., 1985), when deformation in the surrounding Neogene sediments occurred in response to forced uprising.

The Sierra de Los Filabres (Fig. 2) is made up of a north-vergent antiform (Jabaloy et al., 1993) bordered to the north and northwest by roughly NNW–SSE oriented normal faults (Type II faults) cutting through Neogene deposits. Most of these faults do not show evidence of recent activity, except for that exposed in the Guadix-Baza Basin (Fig. 2).

The Sierra de Gádor (Fig. 2) is another example of associated faults and folds. Here, Tortonian marine calcarenites are found at the top of the structure, thus indicating that folding developed after Tortonian times. To the west of the Sierra de Gádor, the zone around the N–S Castala Fault, which was already active in the Early Miocene (Jabaloy et al., 1992), display some evidence of recent activity as shown by radar interferometry analysis performed on images obtained before and after the 1993 Adra earthquake (Romero et al., 2001). The best evidence of an active fault in this area is found, however, to the south of Sierra de Gador, where the roughly NW-SE oriented Balanegra Fault (Fig. 2) controls the position and setting of the coast line and may be associated to the 1993–1994 seismic sequence described by Stich et al. (2001).

3. Present day status of the GPS network

In the framework of a research project focused at quantifying the current deformation rates in the Central Sector of the Betic Cordilleras, a non-permanent GPS-network has been established in the Granada Basin area (Gil et al., 2002). In addition, a new network has been planned, and will be set up soon, for monitoring the Zafarraya Fault, in the Sierra Tejeda (Fig. 3). The installed network (Fig. 4) is made up of sixteen reinforced concrete pillars anchored to rock, with an embedded forced centring system to assure that the antennas are placed exactly at the same position in different reoccupations. Nine, out of the sixteen monitoring points, are located above basement rocks in the External and Internal Zones of the Cordilleras surrounding the Granada Basin. The remaining six points are located within the depression itself.

Two observation campaigns were performed in 1999 and 2000. The first survey was carried out from 27 February to 7 March 1999, and the second one from 18 to 25 June 2000. Five dual frequency carrier phase GPS receivers belonging to the University of Jaén were used to track the GPS constellation for eight-hour sessions over baseline lengths ranging from 10 to 55 km. The network was tied to IGS sites. GPS data processing was performed using Bernese 4.0 software (Rothacher et al., 1996) computing single sessions in multibaseline mode. The first step (preprocessing) related to receivers clocks calibration, performed by code pseudoranges, and detection and repair of cycle slips and removal of outliers, was carried out simultaneously for L1 and L2 data. The final solution for each session was obtained using the iono-free observable with precise ephemeris and antenna phase centre variation files. The station coordinates, apart from fixed reference site 5, were estimated in both campaigns. The significance of the coordinate differences was evaluated without assuming any initial hypothesis on the station behaviour or any geophysical constraint. This assumption corresponds to fixing the centroid of the whole network. No stations, except site 1, have significant coordinate changes at the 5% significance level, which agrees with the low rate of extension calculated from geological data. The reoccupation campaign run a year after the first campaign confirmed that deformation rates, in the area, are indeed very small. In order to detect such small rates, observations over a longer time span are necessary, probably over a decade.

4. Discussion

The Internal Zones of the Betic Cordilleras are a good example, in the Mediterranean region, of simultaneous development of faults and folds and relief uprising associated to the oblique convergent character of the Eurasian–African plate boundary, since the Tortonian. Field observations on recent/active structures constrain the relative position of the faults with respect to the folds. Type I faults, like the normal Zafarraya fault, are subparallel to the folds that accommodate a roughly N–S contraction. This apparent contradiction may be overcome if these fold-related faults are considered as collapse or extensional structures developed in response to thrust sheet emplacement resulting from cumulate displacement associated with a deep blind thrust

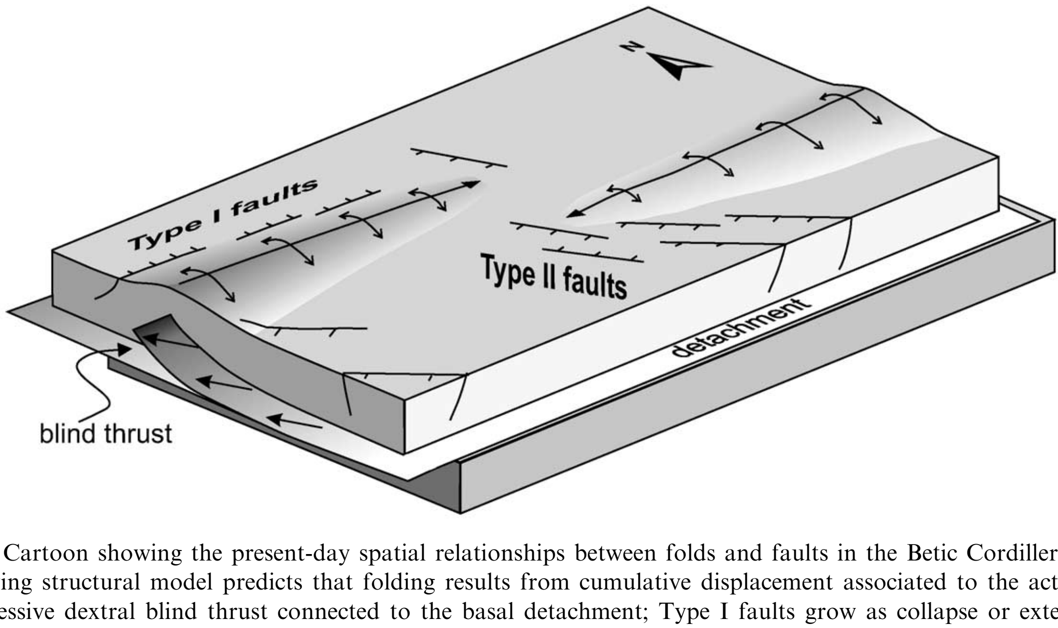

Fig. 5. Cartoon showing the present-day spatial relationships between folds and faults in the Betic Cordilleras. The underlying structural model predicts that folding results from cumulative displacement associated to the activity of transpressive dextral blind thrust connected to the basal detachment; Type I faults grow as collapse or extensional structures in response to the growth of the antiform; Type II faults develop as extensional features displaying a trend which is sub-parallel to the slip vector between Africa and Eurasia.

(Fig. 5) (Cello and Nur, 1988). Because the Zafarraya Fault is one of the few faults in the system that records a clear historical activity, associated with the 1884 Christmas Andalucía earthquake, a local GPS network will be installed near this fault and a regional network is located in the Granada Basin area with the aim of monitoring the present-day tectonic deformation.

A second type of relationship between folds and faults, observed in the area, is displayed by a set of NW–SE oriented faults that are preferentially located at the western periclinal terminations of the antiforms (in the Sierra Nevada, Sierra Alhamilla, Sierra Tejeda, Sierra de Gádor, Sierra de Los Filabres) or along their southern limbs (in the Sierra Tejeda, Sierra Alhamilla, Sierra de Gádor). These structures show mostly dip-slip (normal) kinematics, with minor strike-slip components, and variable displacements. In the Sierra Nevada, some of them, like the Padul Fault, display evidence of very recent activity (Alfaro et al., 2001; Sanz de Galdeano, 1976; Galindo-Zaldívar et al., 1996). In the Sierra de Gádor and in the Sierra Alhamilla, the structural setting is similar to that of the Sierra Nevada, but only a few faults, like the Balanegra fault, seem to be active. On the other hand, in the Sierra de Los Filabres, this fault system appears to be mainly inactive; the only active fault being that identified in the Guadix-Baza Basin, whereas in the Sierra Tejeda the whole fault system is inactive and sealed by Plio-Quaternary deposits.

As discussed above, the most active structures in the area (i.e. the Zafarraya, Padul and Balanegra faults) are mostly normal faults accommodating either roughly N–S or NE–SW extension. However, field evidence suggests that post-Tortonian folding and uplift of the Cordilleras indicating a N–S to NW–SE contraction were coeval with the development and evolution of normal faulting in the area. These observations pose some compatibility problems for interpreting the NW–SE trending structures (Type II faults) in relation to the evolution of the roughly E–W oriented folds. A possible interpretation may be that of considering these faults as extensional features developed in response to the current stress field in the area, and folds will be related to the blind thrusts with the dextral transpressive kinematics imposed by the oblique motion of Africa with respect to Eurasia (Fig. 5).

5. Conclusions

The central sector of the Internal Zones of the Betic Cordilleras constitutes a good example of the simultaneous development of kilometre-size folds and faults since Tortonian times. Most of the present-day relief of the Cordillera is directly related to active (Type I and Type II) faults and folds structures. The structural setting of the area is characterized by predominantly E–W oriented antiforms made of metamorphic rocks, which are surrounded by synform basins where Neogene rocks are preserved from erosion.

Type I faults are mainly normal faults located preferentially at the fold northern boundaries (Fig. 5); they are parallel to the fold axes, with a main E–W orientation like the Zafarraya Fault, and the fault zones located to the south of the Sierra Nevada and to the north of Sierra de Los Filabres and Sierra Alhamilla.

Type II faults are oriented roughly NW–SE and they too show a main dip-slip (normal) kinematics; type II faults are often found at the western periclinal terminations of the main folds (in the Sierra Nevada, Sierra Alhamilla, Sierra de Gádor, and Sierra Tejeda).

The Zafarraya Fault is thought to be responsible for the 1884 Andalucía earthquake (Muñoz and Udías, 1981); however, its long-term (post-Tortonian) history suggests that the fault is strictly related to the coeval development of the main folds, and that it can be interpreted as a collapse structure grown along the external arch of the fold.

The Padul fault, in the Sierra Nevada, and the Balanegra fault, in the Sierra de Gádor, also show clear evidence of recent activity. These structures (belonging to Type II faults) are interpreted as extensional features developed in response to the current stress field imposed by the oblique motion of Africa with respect to Eurasia.

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