MONITORING OF ACTIVE TECTONIC STRUCTURES IN CENTRAL BETIC CORDILLERA (SOUTHERN SPAIN)

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ABSTRACT
The Betic Cordillera, located at the westernmost end of the Mediterranean alpine belt, is deformed by overprinted folds and faults that produced the present-day relief since the Tortonian. In the frame of the COST 625 action, four sectors have been studied in the central part of the cordillera. In the Granada Depression, the large NW-SE Padul normal fault deforms the SW periclinal end of the Sierra Nevada antiform. MT surveys indicate the continuity in depth of high and low angle normal seismogenic faults and the presence of active detachment faults. In Tabernas region a good example of interaction between a NW-SE propagating normal fault, E-W strike-slip faults and the fold system is studied. In the Sierra Tejeda-Zafarraya and in the Balanegra-Sierra de Gádor areas, two new GPS networks have been installed to determine the interaction and the development of large antiformal structures and normal faults with E-W and NW-SE orientations. However, taking into account the low tectonic activity of the studied region, a period of more than 5 year could be needed to determine with enough accuracy the development rate of the structures.

KEYWORDS: Betic Cordillera, crustal structure, active faults, fault and fold interaction, GPS networks

INTRODUCTION

The Betic-Rif cordilleras are build-up in the western Mediterranean by the deformations related to the Eurasian-African plate boundary. The recent and present-day NW-SE convergence (De Mets et al. 1990) produces the simultaneous development of large folds and faults, which continues active up to Present (Galindo-Zaldívar et al., 2003). These active structures are responsible of the moderate seismicity of the region (Fig. 1).

One of the sectors with most intense tectonic activity in this region is located in the Betic Cordillera, in the central part of the Internal Zone (Fig. 2). The uplift of the mountain ranges is mainly related to the development of folds in this regional compressive setting (Sanz de Galdeano and Alfaro, 2004). However, the most abundant faults recognised in surface along the central part of the Cordillera show normal slip, sometimes with dextral or sinistral components.

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 research (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 contact detected between 10 and 15 km depth (Galindo-Zaldívar et al., 1997; Ruano et al., 2004), is considered to be the base of the seismogenic crust.

The activities developed during the 625 COST action, aims in a first step to recognise the location of the main active structures, folds and faults, and to install GPS networks to quantify the present-day deformation rates. The activities may be grouped into two main items (Fig. 3):

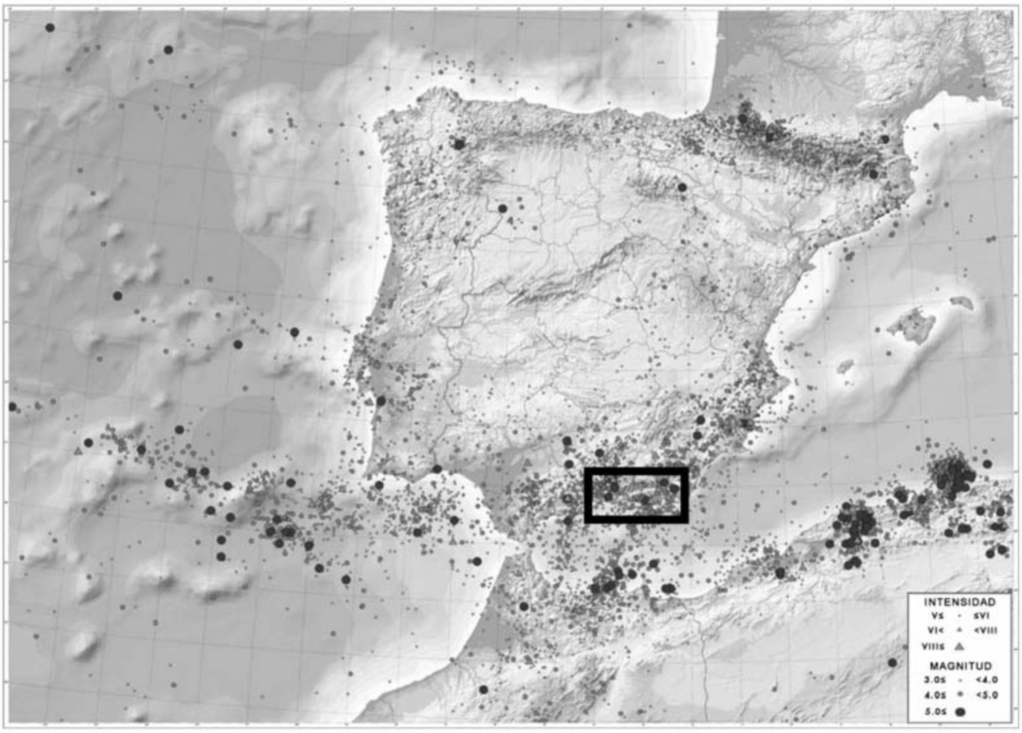

Fig. 1 Seismicity in the western Mediterranean (1920-2003). Instituto Geográfico Nacional de España. Square indicates the location of central Betic Cordilleras studied during the 625 COST action. The distributed seismicity is related to the Eurasian-African plate boundary.

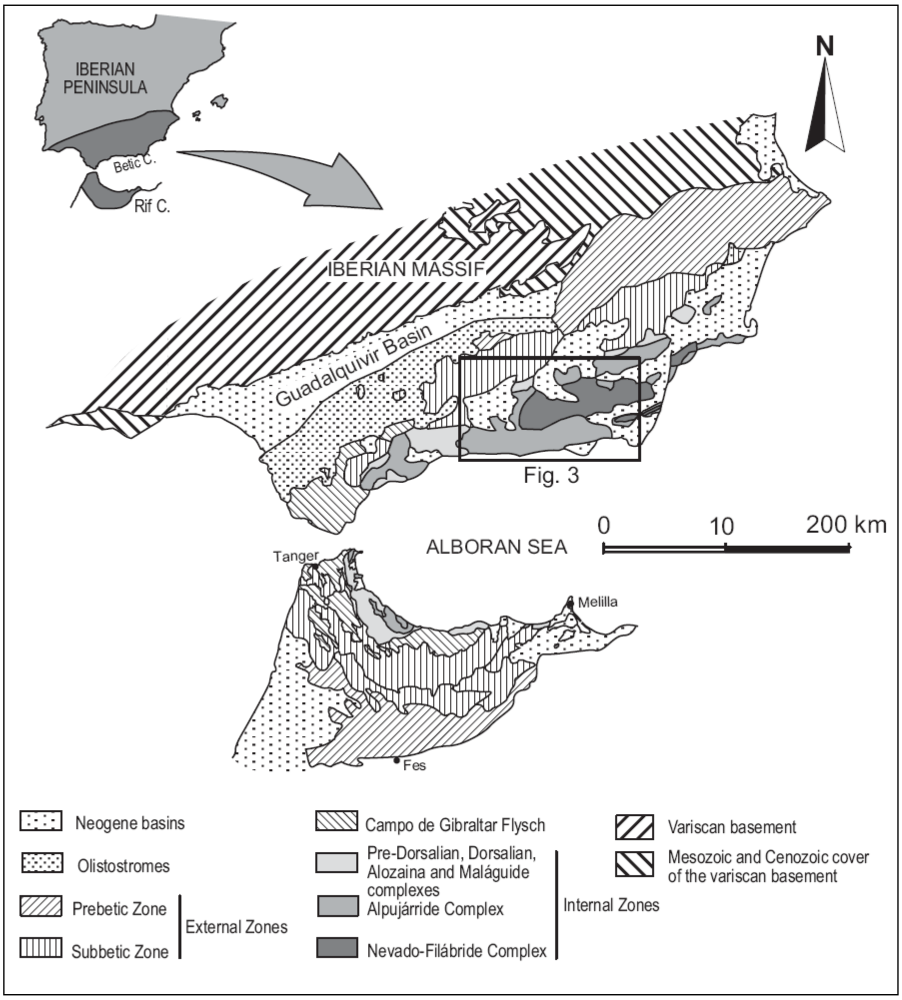

Fig. 2 Geological setting of the Betic and Rif Cordilleras in the frame of the western Mediterranean.

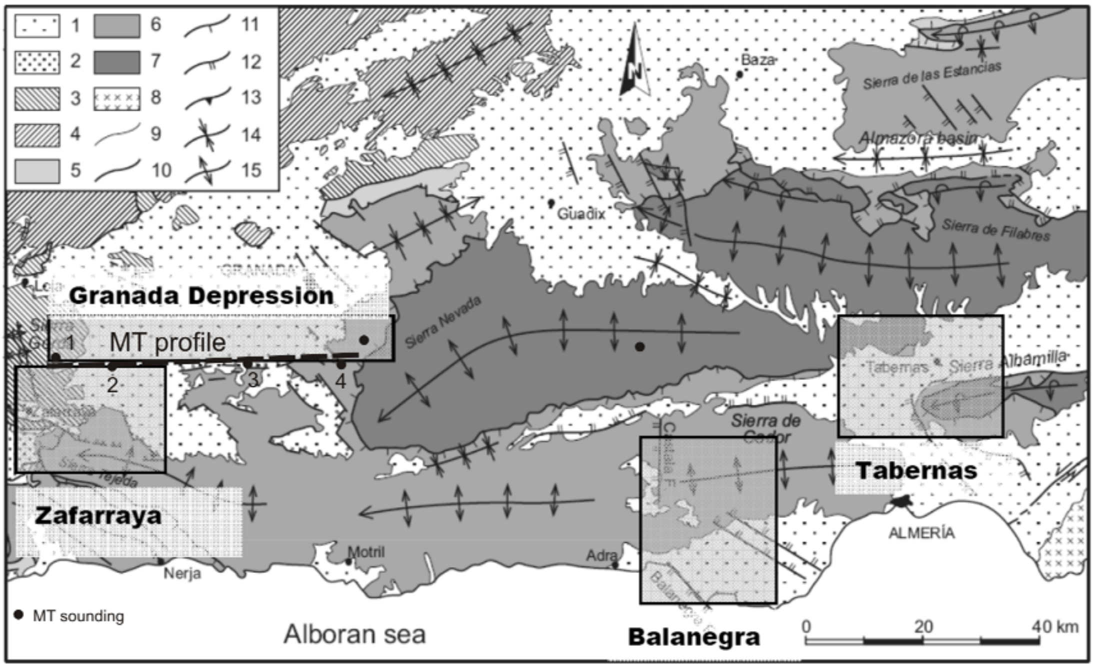

Fig. 3 Location of four main areas studied during the COST 625 action in a tectonic sketch of the central sector of the Internal Zones of the Betic Cordillera. 1, Upper Miocene, and Plio-Quaternary rocks. 2, Middle and Lower Miocene rocks. 3, Upper Subbetic Unit. 4, Intermediate Subbetic Unit. 5, Maláguide Complex. 6, Alpujarride Complex. 7, Nevado-Filabride 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. Location of MT soundings (dots) and MT profile are indicated.

1. Identification of active structures and geological studies. In addition to the previously known active faults and folds, during the 625 COST action additional studies have been developed to identify new active faults in two areas: Granada Depression and Tabernas region.
2. Installation and measurement of GPS geodetic networks on the main active structures. Most of the faults that are identified in the region generally separate hard rocks in the footwall, mainly limestones, and soft rocks in the hanging wall. This geological setting avoids the installation of extensiometers, like the TM-71, because there are no appropriate stable sites in the soft rocks of hanging walls. In this setting, the best cost-effective results will be obtained by non permanent GPS networks.

New measures have been performed in the Granada Depression- Padul fault GPS network that was installed before this COST action (Gil et al., 2002). In addition, two new GPS networks have been installed in the region, in the two more active faults of the area: Sierra Tejeda - Zafarraya Fault and Balanegra Fault.

IDENTIFICATION OF ACTIVE STRUCTURES AND GEOLOGICAL STUDIES IN CENTRAL BETIC CORDILLERA

1- GRANADA DEPRESSION

The Granada Depression is filled by Neogene-Quaternary sediments located on the contact between the Internal and External Zones of the Betic Cordillera. This basin is largely deformed by different sets of active normal and strike-slip faults. In the Granada Depression the recent segmentation of the fault system that is located in its eastern border, have been studied in collaboration with Italian (V. Spina; Galindo-Zaldívar et al., 2006) and Bulgarian (Radulov et al., 2006) researchers in the frame of the 625 COST activities. Although the segmentation of the fault system reduces the seismic hazard of the region, the activation of some of the faults may be responsible of a change of stresses in the area that selectively active other faults of the system.

The crustal structure of the region was poorly known up to date. Although there is seismic activity at different depths, most of the earthquakes are located at 10-15 km depth. MT sounding, in collaboration with Dr. Dumitru Stanica and Dr. Maria Stanica (Romania)

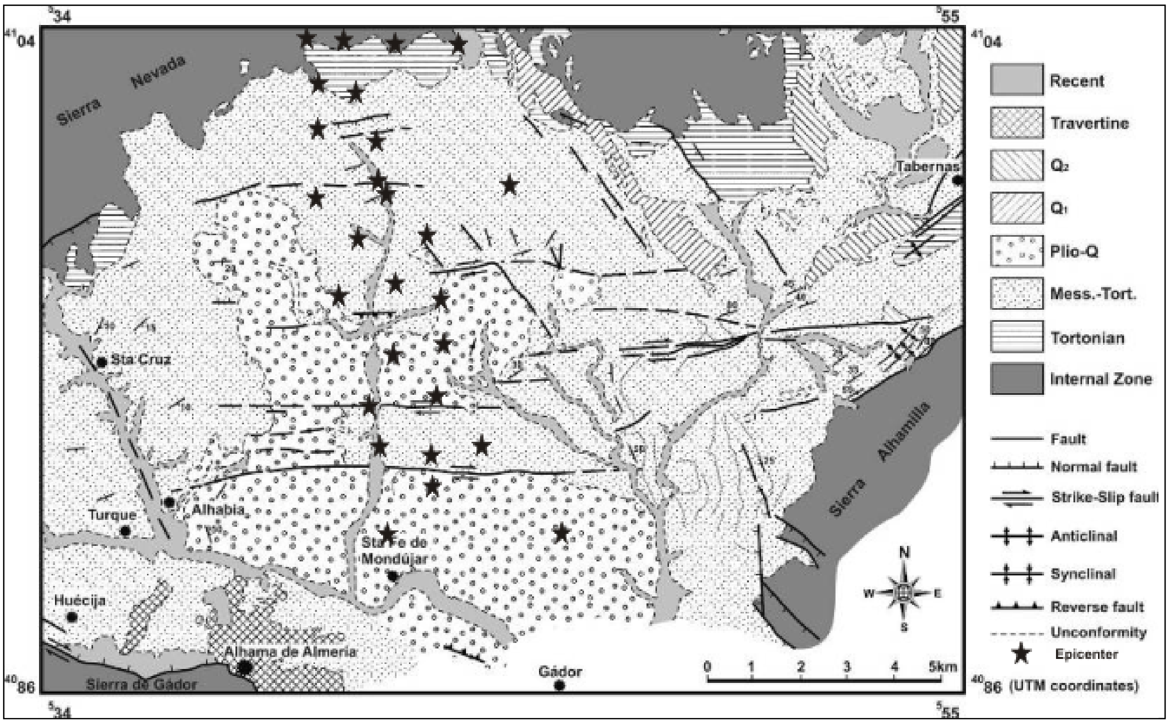

Fig. 5 Epicenter location and geological map of the Tabernas Area.

have been developed for the first time in the region and show the deep resistivity structure (Figs. 3 and 4).

The 2D resistivity model indicates that the shallow low-angle normal faults that are recognised from field geological studies in the region separating Nevado-Filábride and Alpujarride metamorphic complexes (Figs. 3 and 4), extends in depth along the upper crust (FP) and join a basal detachment (D). MT sounding (Fig. 4) suggest that detachment is located at about 15-20 km, where most of the seismicity is concentrated. High-angle surface faults may join these major crustal low-angle faults. Although in this region it is difficult to relate the surface motion to the seismic activity at depth.

2- TABERNAS REGION

The Tabernas region (Fig. 5) is located in the relay between the major antiforms of Sierra Nevada, Sierra de Gádor and Sierra Alhamilla (Fig. 3). In this area, there are exceptional outcrops of Neogene and Quaternary sediments that fill the Sorbas-Tabernas basin and connected through the Almeria basin to the Alboran Sea. Alignement of recent epicentres in this region (Fig. 5) suggest the presence of an active N-S fault. This area has been mapped by a Bulgarian-Spanish team (Sanz de Galdeano et al., 2006) (Fig. 5). Most of the faults observed on the surface are strike-slip dextral faults in addition to more scarce NNW-SSE oriented normal faults. However, the prolongation in depth of NNW-SSE faults should be the most active and in recent times should be associated to a significant part of the observed seismicity.

GPS NETWORKS IN BETIC CORDILLERAS

The three GPS networks that are related to the COST activities in the Betic Cordilleras are non-permanent. The network designs and the individual site selection take into account geological, logistical and observational aspects. As a very long-term project, these constructions should guarantee the reoccupation after a long time span. These networks are made up of reinforced concrete pillars anchored to rock (Fig. 6). Moreover, to assure that the antennas

Fig. 6 Concrete pillar for GPS measurement at site 800 of the Zafarraya network.

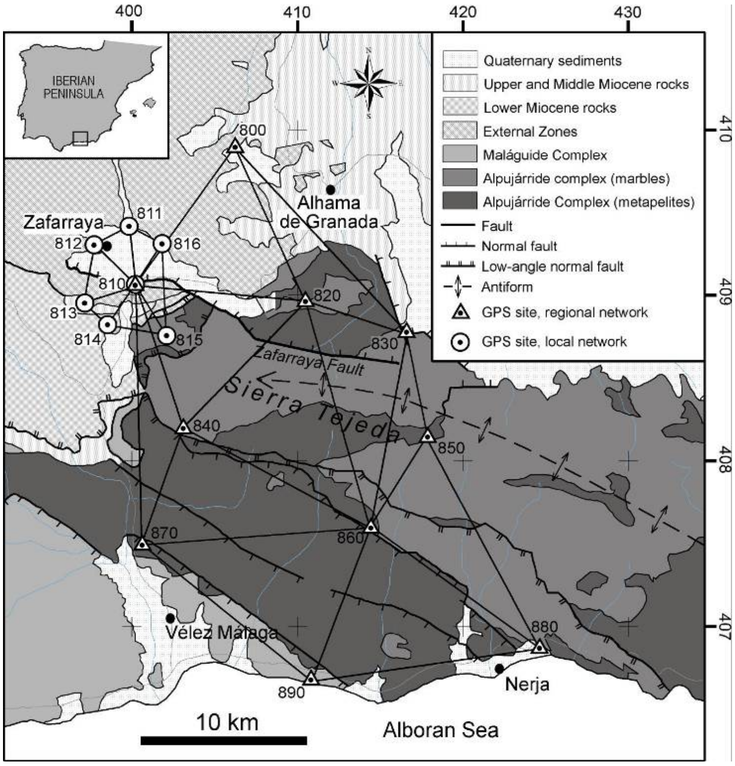

Fig. 7 Zafarraya GPS network.

will be placed exactly at the same position in different reoccupations, the pillars have an embedded forced centring system.

1-SIERRA TEJEDA AND ZAFARRAYA FAULT

Sierra Tejeda (Fig. 7) constitutes a relief related to the development of a complex shaped recent antiform that is located near the coast line, overprinted on previous folded Alpujarride rocks belonging to the Internal Zones of the Betic Cordillera. Geomorphologic evidences, like the important incision of the fluvial network or the cliff development along the coast line, indicate its recent uplift. The Zafarraya fault is located at the northern limb of Sierra Tejeda, a high-angle northwards dipping normal fault, which produces the development of a half graben in its hanging wall filled by Miocene-to-Quaternary sediments. This fault shows evidences of activity during the 1884 Christmas Andalusia earthquake with an estimated magnitude near 6.7 (Muñoz and Udías, 1981; Reicherter et al., 2003; Galindo-Zaldívar et al., 2004).

The first non-permanent GPS network devoted to quantify the present-day deformation in the Zafarraya Fault and the Sierra Tejeda antiform has been installed in relation to this 625 COST action (Gil et al., 2005). This GPS network actually consists of a local network in the Zafarraya area and a regional network that extends up to the coast line. The aim of the local network is to characterize the slip in the Zafarraya fault and to determine if there is a tectonic creep component. These data may help to relate the fault and the fold activity with the relief building in the region.

The GPS sites are located in a local and a regional network in order to study the local motion along the Zafarraya fault and the regional development of the Sierra Tejeda antiform. In the local network, the sites 811, 812 and 816 are situated on the hanging wall of the fault. Most of them are built up on Jurassic limestones of the External Zones. The sites 810, 813, 814 and 815, located in the footwall, are built up mainly on limestones and marbles. Although these sites are located across the contact between External and Internal Zones, this contact is inactive at Present, and the southern part of the network may constitute a reference for the activity of the most recent Zafarraya Fault. The site 800 is in the northern boundary of the regional network on Jurassic limestones of the External Zones. Southwards, the network crosses the Zafarraya Fault and the contact between External and Internal Zones and reaches the uppermost part of Sierra Tejeda in the site 850, located on Triassic Alpujarride marbles. The southern part of the network is located along the southern limb of Sierra Tejeda, deformed by NW-SE oriented normal faults, and reaches the coast line with sites 890 and 880, build up respectively on Alpujarride metapelites and marbles. The regional network also covers the WNW periclinal end of the

Table 1 Zafarraya GPS network. Minimum constrained adjustment parameters.
Ses: sessions, Eq: Number of equations, Unk: unknown parameters, Red: redundancy, σ_0^2: unit weight variance; χ^2_{exp}: experimental χ^2 with "redundancy" degrees of freedom; χ^2_{teo} theoretical χ^2 with "redundancy" degrees of freedom at the 99% confidence level; rms: average SQM values in mm, Smaj: semimajor axis of the 99% confidence ellipse in mm. Smin: semiminor axis at the 99% confidence level in mm; CI: 99% confidence height interval in mm.

Ses	Eq	Unk	Red	σ_0^2	χ^2_{exp}	χ^2_{teo}	rms X	rms Y	rms Z	S_{min}	S_{maj}	*CI*
4	57	27	30	1.28	49.52	50.89	2	0.1	1	1	2	6

Table 2 Zafarraya GPS network. Cartesian Coordinates, 2004.6,ITRF00 [m].

Point	X	rms X	Y	rms Y	Z	rms Z
800	5086408.803	0.003	-360809.032	0.001	3820093.313	0.002
810	5090503.164	0.003	-366743.996	0.001	3814088.558	0.002
820	5091617.818	0.002	-356723.274	0.001	3813749.847	0.002
830	5093135.071	0.002	-350540.119	0.001	3812385.280	0.002
840	5095647.763	0.002	-364167.736	0.001	3807196.718	0.001
850	5097368.020	0.002	-349676.130	0.001	3807611.313	0.001
860	5099914.591		-352995.427		3802768.328	
870	5099047.856	0.001	-365245.318	0.001	3802296.930	0.001
880	5104454.023	0.002	-343104.455	0.001	3796458.819	0.001
890	5104859.323	0.002	-356826.056	0.001	3794440.807	0.001

Sierra Tejeda antiform. All sites meet the following requirements: no obstruction above 10 degrees; no high power lines nearby; easily accessible, etc.

The first survey has been carried out in September 2004. The GPS constellations have been tracked during five-day campaigns with eight-hour sessions over baseline lengths ranging from 2 km to 20 km. In the local network the observation period was divided into two sessions of four hours. The equipment used was 6 Leica GX1230 dual frequency carrier phase GPS receivers with LEIAX1202 antennas.

The network was tied to Almería, Lagos and San Fernando sites. The first two belong to the EUREF (EUropean REFerence) network and the last one belongs to the IGS (International GPS Service) network. From these stations the coordinates of the regional central point 860 were computed.

After the regional network adjustment the coordinates of the local central point (810) were obtained. In the following, the results of the regional network are presented (Tables 1 and 2). The length of the baselines belonging to the regional GPS network ranges from 6 to 25 km and GPS data processing was performed by using Bernese 4.2 software (Hugentobler et al., 2001) in the following way: single sessions were computed in multibaseline mode. The first step (pre-processing) 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 fixed solution of the coordinates was estimated using the sigma method to fix integer ambiguities. Troposphere parameters every two hours were estimated. From these results we used an intermediate program to produce GPS baselines with their covariance matrixes. Using the NETGPS program (Crespi, 1996) that performs the adjustment of GPS baselines accounting for their full covariance matrixes, the minimal-constrained network adjustment was done.

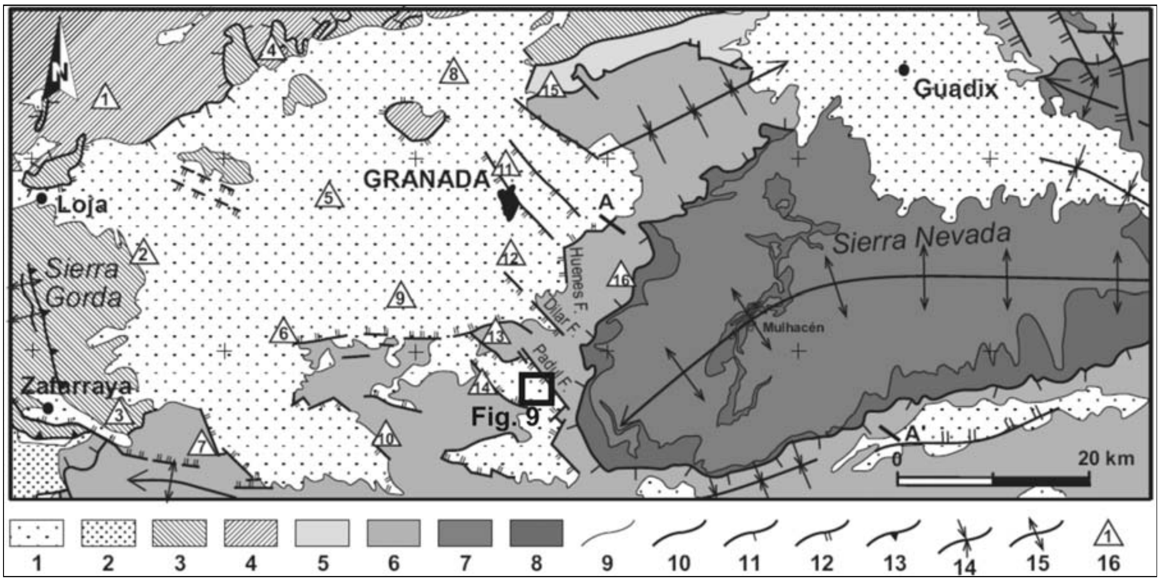

Fig. 8 Granada Depression GPS network and Padul fault area. Tectonic sketch map shows the GPS network installed in 1999. 1, Upper Miocene, and Plio-Quaternary rocks. 2, Middle and Lower Miocene rocks. 3, Upper Subbetic Unit. 4, Intermediate Subbetic Unit. 5, Maláguide Complex. 6, Alpujárride Complex. 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.

The reoccupation campaign will be carried out two years after the first campaign and it will allow confirming that the geological estimates of displacement rates are small. The DENETGPS program (Crespi, 1996) will be used to evaluate the significance of the coordinate differences without assuming any initial hypothesis on the point's behaviour or any geophysical constraint. This assumption corresponds to fix the centroid of the whole network. The movements are probably less than 1 mm per year and may have also a coseismic character. In order to detect such small rates, one will have to measure over a longer time span, probably a decade.

2-GRANADA DEPRESSION AND PADUL FAULT

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; Ruiz et al., 2003).

The installed network (Fig. 8) 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 February 27 to March 7, 1999, and the second one from June 18 to June 25, 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 km to 55 km. The network was tied to IGS sites. GPS data processing was performed using Bernese 4.2 software 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 performed 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.

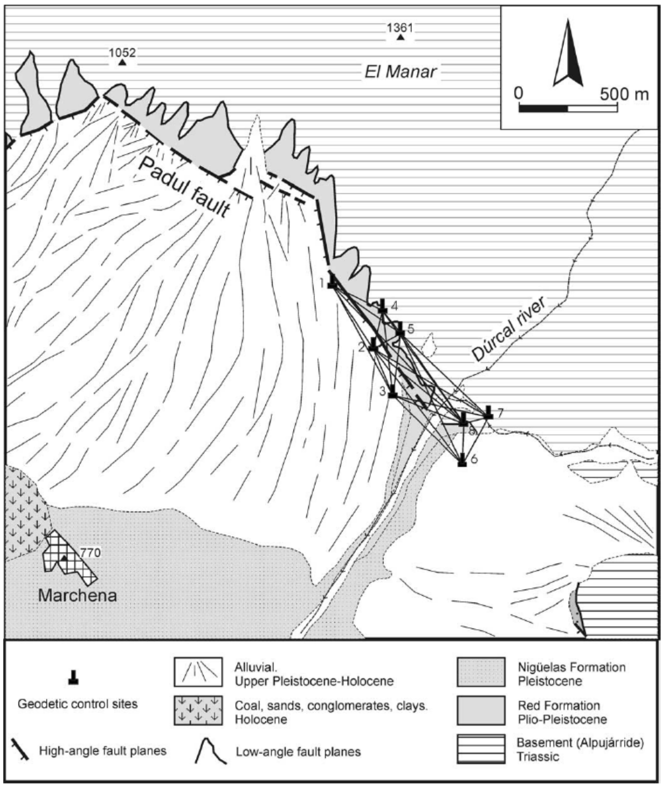

Fig. 9 Padul Fault GPS network.

In the southern Granada Depression is located the Padul Fault, where a local GPS network was installed (Fig. 9). The Padul normal fault offsets the metamorphic Triassic carbonates of the Betic Cordillera Internal Zone (Alpujarride Complex). This NW–SE fault (locally E–W) is approximately 15 km long and has various segments which dip towards the SW and S. The footwall is constituted of Alpujarride basement and the fault hanging wall is comprised of Quaternary and Plio-Quaternary sediments deposited above the Alpujarride basement and upperMiocene rocks. There is both geomorphological and tectonic evidence to indicate that this fault continues to be active at present (fault scarps, deformed Holocene alluvial fans, triangular facets, strong downcutting in the drainage network, Holocene peat deposits dipping against the fault plane, etc). Nevertheless, the level of seismic activity along the Padul fault is very low. No evidence of moderate or high magnitude historic earthquakes exists. In the period 1980–1996 only one earthquake of magnitude higher than 3.5 has occurred. In spite of this low recent seismic activity, there is geological evidence of moderate to high-magnitude earthquakes during the Quaternary (Alfaro et al., 2001).

Eighty horizontal angles among sites were measured with the Wild T3000 electronic theodolite and the TCA2003 total station applying the Schreiber method in three different campaigns, February 1999, February 2000 and February 2001. At the Padul fault geodetic network, in the planimetric position, displacement vectors are of similar magnitude as propagated errors, so the results show no significant movements in general.

3-BALANEGRA FAULT

South of Sierra de Gador antiform is found the NW-SE oriented Balanegra fault, that determines the position of the coast line (Fig. 3) and can be associated with the seismic series described by Stich et al. (2001). The Balanegra Fault zone (Marín-Lechado et al., 2004) is formed by several parallel faults with associated scarps of 1-10 m producing a staircase morphology. The maximum vertical slip is generally of several hundred of meters. At the southwestern border of the Sierra, other minor NW-SE oriented normal faults are found (Fig. 3) indicating an ENE-WSW oriented extension in the area.

In this region, a new non-permanent GPS network (Fig. 10) is being installed as one of the last activities developed in the frame of the 625 COST action. The aim of this GPS network is to study in detail the relationships between the development of large folds and faults because both structures seem to develop simultaneously in this region. For this purpose, in addition to measurement points installed in the fault zone, other points have been located in the Sierra de Gádor Antiform. After installation of all GPS points, a first measurement campaign was conducted during the spring-2006, but due to the low

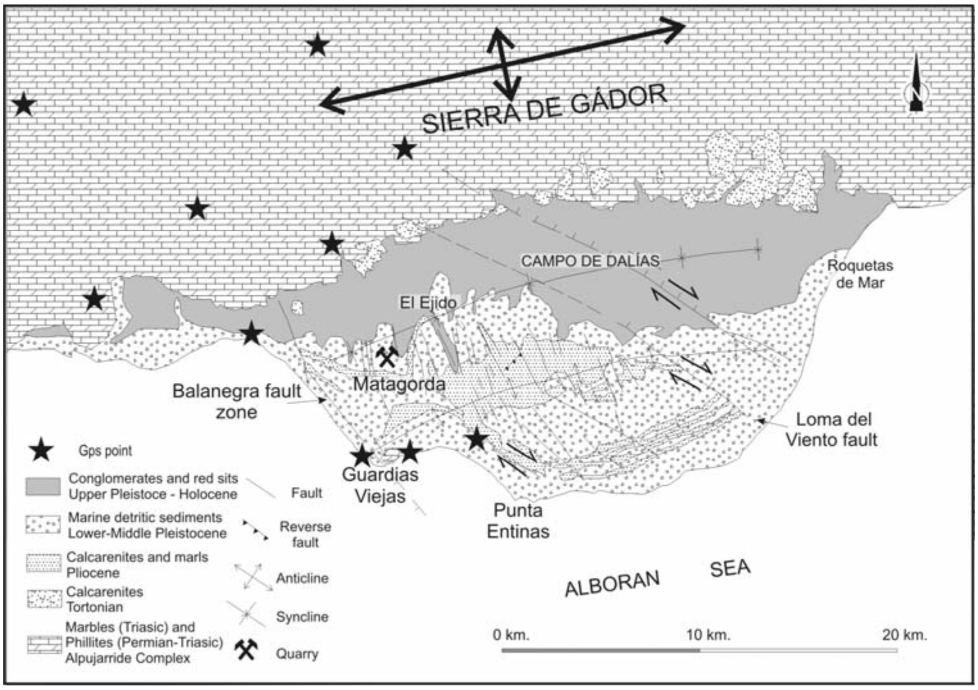

Fig. 10 Balanegra GPS network.

activity rates, the meaningful results cannot be expected after earlier than 5 years or in case of occurrence of new seismic series.

CONCLUDING REMARKS

The geological, geophysical and geodetical researches developed in the central Betic Cordilleras during the 625 COST action have improved the knowledge on the active tectonic structures of this region. Taking into account that the depth of seismicity, generally at about 10-15 km depth, is deeper than fault traces lengths, it is difficult to relate the epicentres to surface active faults. The magnetotelluric survey of the Granada Depression has demonstrated the continuity in depth of the active normal low angle and detachment faults that determined a layered crustal structure. In this setting, there is a lack of continuity of deep active seismogenic faults to surface.

The surface active faults are generally normal with NW-SE orientations, like the Padul fault in the Granada Depression and the fault zone that now is propagating in the Tabernas region. These faults sometimes also show strike-slip type motions, mainly dextral. In addition, there are E-W oriented faults that may be normal (e.g. Zafarraya fault) or dextral (in Tabernas Area). Extensional faults are produced in shallow crustal levels by the uplift of the Cordillera due to the crustal thickening related to depth compressional structures. Strike-slip faults are formed as a consequence of the N-S to NW-SE successive compressive regional stresses related to the Euarasian-African convergence.

Most of the relief of the central part of the Betic Cordilleras has been built up since Tortonian by the development of kilometre-sized folds that developed simultaneously to the fault system. This setting is suitable to study the relationships between the simultaneous development of these tectonic structures. Three GPS networks are available. The Granada Depression GPS network was installed before the COST 625 action with the aim of studying the Padul fault activity in the frame of the western end of the Sierra Nevada antiform. The SierraTejeda-Zafarraya Fault GPS network, measured first time in 2004, aims to study the relationships between the development of Sierra Tejeda antiform and the Zafarraya fault, that was responsible of the 1884 Andalusian earthquake. Finally, the Balanegra fault GPS network, intalled in 2006, is located in the region were shallow seismic series occurred during 1994 and may help to characterise also the growth of the Sierra de Gador antiform.

The central part of the Betic Cordilleras is a region of moderate tectonic activity. The 625 COST have helped to install new GPS networks that will allow to characterise the fold and fault development.

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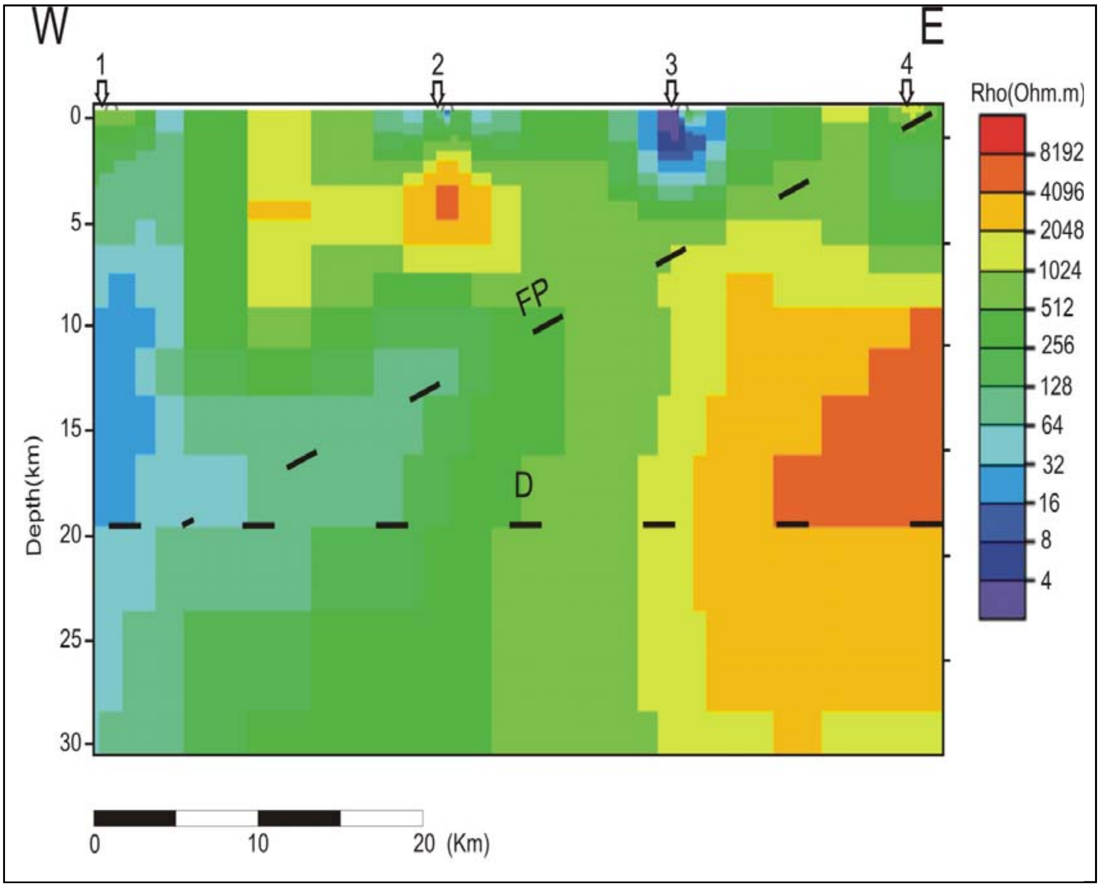

Fig. 4 MT 2D cross section model of resistivity in southern Granada Depression. FP, Low angle fault plane. D, Detachment.