Establishment of a non-permanent GPS network to monitor deformations in Zafarraya Fault and Sierra Tejeda Antiform (Spain)

María Jesús BORQUE ARANCÓN[1], Jesús GALINDO-ZALDÍVAR[2],
Antonio J. GIL CRUZ[1], Antonio JABALOY SÁNCHEZ[2],
M. Clara de LACY PÉREZ DE LOS COBOS[1],
Ángel Carlos LÓPEZ GARRIDO[3], Gracia RODRÍGUEZ CADEROT[4],
Antonio RUIZ ARMENTEROS[1], Carlos SANZ DE GALDEANO EQUIZA[3]

[1]Dept. Ing. Cartográfica, Geodésica y Fotogrametría.
E.P.S. Universidad de Jaén, Spain. Campus Las Lagunillas, 23071 Jaén, Spain
(e-mail: mjborque@ujaen.es; ajgil@ujaen.es; mclacy@ujaen.es, amr@ujaen.es).

[2]Dept. Geodinámica, Universidad de Granada. 18071 Granada, Spain
(e-mail: jgalindo@ugr.es; jabaloy@ugr.es).

[3]Instituto Andaluz de Ciencias de la Tierra CSIC- Universidad de Granada. 18071 Granada, Spain
(e-mail: aclopez@ugr.es; csanz@ugr.es).

[4]Sec. Dptal. Astronomía y Geodesia. Facultad de CC Matemáticas.
Universidad Complutense de Madrid (e-mail: grc@mat.ucm.es).

ABSTRACT

The NW-SE to NNW-SSE convergence between the African and Eurasian plates in the western Mediterranean has developed the recent relief of the Betic-Rif Cordilleras. The central part of the Internal Zones of the Betic Cordilleras is deformed by large open folds and faults, mainly with normal character. The Zafarraya fault, located to the N of the Sierra Tejeda antiform, was active during the 1884 Andalusia earthquake of 6.7 estimated magnitude. In the framework of an interdisciplinary research project, a non-permanent GPS-network has been established at Zafarraya Fault and Sierra Tejeda antiform to monitor deformations related to these active tectonic structures.

Keywords: Active Tectonics, GPS Network, Zafarraya Fault, Sierra Tejeda Antiform, Betic Cordillera.

ISSN: 0214-4557

1. INTRODUCTION

The Betic-Rif cordilleras are build-up in the western Mediterranean by the deformations related to the Eurasian-African plate boundary. The recent NW-SE convergence (De Mets et al. 1990) produces the simultaneous development of large folds and faults in the central part of the Internal Zones of the Betic Cordilleras, which continues active up to Present (Galindo-Zaldívar et al. 2003). The uplift of the mountain ranges is mainly related to the development of folds in this regional compressive setting (Sanz de Galdeano & Alfaro 2004). The most abundant faults recognised in surface along the central part of the Cordillera show normal slip, sometimes with dextral or sinistral components.

Sierra Tejeda (Fig. 1) 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 Cordilleras. Along the northern limb of Sierra Tejeda is located the contact between the Internal and External zones. Geomorphologic evidences, like the important incision of the fluvial network or the cliff development along the coast line, indicate its recent uplift. At the northern limb of Sierra Tejeda is located the Zafarraya fault, 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 1980).

In this paper the first non-permanent GPS network devoted to quantify the present-day deformation in the Zafarraya Fault and the Sierra Tejeda antiform is presented. 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. In Section 2 the Zafarraya Fault and the Sierra Tejeda antiform are presented in the frame of the active tectonic structures of the central Betic Cordillera. In Section 3 both regional and local GPS networks are described. The first GPS survey has been carried out in September 2004 and the results relative to the regional network are presented in this work.

2. THE ZAFARRAYA FAULT AND THE SIERRA TEJEDA ANTIFORM

In the central part of the Betic Cordillera, the Zafarraya fault constitutes one of the structures with evidence of very recent tectonic activity. There are reports of displacements along this fault during the 1884 Andalusia earthquake that destroyed part of the villages of the region (Zafarraya, Ventas de Zafarraya and Alhama de Granada, among others). Muñoz and Udías (1981) consider this earthquake to have been of a magnitude between 6.5 and 7. Field studies determine that the fault has a total length of more than 15 km. Its trend varies along the strike, approximately E-W to the south of Zafarraya and curves to a NW-SE orientation at its western end, where deformed rocks of the External Zones are found. The fault plane in the Zafarraya region dips 60º northwards, and its striae indicate that it is a normal fault (Fig. 1). Fault slip is of several hundred of meters. There, the fault develops in its hanging wall an endorreic related basin, the Zafarraya Depression, filled by sediments that range in age from Tortonian up to the Present. The basin is asymmetrical, and probably the main depocenter is located at the southern border, near the fault.

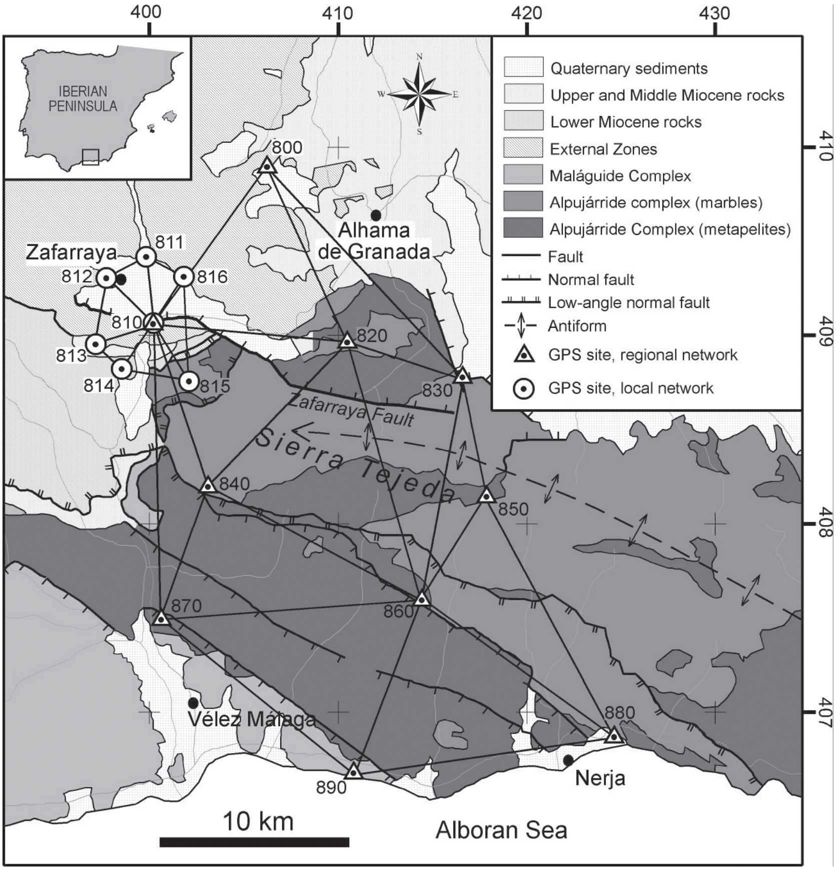

Figure 1. GPS network in Zafarraya Fault and Sierra Tejeda antiform.

Southeast and South of the Zafarraya Fault, also called N of Sierra Tejeda Fault, (Sanz de Galdeano et al. 2003) is the Sierra Tejeda, constituting a great radius antiform with an E-W to ESE-WNW oriented axis (superposed to a previous complicated alpine structure) and a periclinal end towards the west. This antiform is associated with a positive elongated relief parallel to the fold axis. The southern limb of the antiform is deformed by a set of WNW-ESE oriented faults dipping towards the SW and with a normal and transcurrent regime; although they developed during the Miocene, there is no clear evidences of very recent activity as the present-day coast line is not deformed (Fig. 1).

In the central Betic Cordilleras, folds and faults developed together since Middle Miocene. Reverse blind faults —probably located at depth— and large folds are responsible for the relief uplift, and are directly associated with the oblique convergent character of the plate boundary. However the active faults that are recognised in the upper part of the crust in this transect of the Cordilleras are mainly normal and have large vertical displacements. They are grouped into two main sets. The E-W oriented faults, like the active Zafarraya Fault, are parallel to kilometre-sized fold axes. The NW-SE oriented fault set is orthogonal to the main trend of extension undergone the area.

3. GPS NETWORK FOR DEFORMATION MONITORING

In order to quantify the deformation that is currently occurring in the Zafarraya Fault and Sierra Tejeda antiform, the first non-permanent GPS network of this area has been established (Fig.1).

The network design and the individual site selection take into account geological, logistical and observational aspects. As a very long-term project should guarantee the reoccupation after a time span. This network is made up of sixteen reinforced concrete pillars anchored to rock. Moreover, to assure that the antennas will be placed exactly at the same position in different reoccupations, the pillars have an embedded forced centring system.

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 located on the hanging wall of the fault. Most of them are build up on Jurassic limestones of the External Zones. The sites 810, 813, 814 and 815, located in the footwall, are build-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 (Fig. 2) 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 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 constellation 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 antenna.

Table 1. Minimum constrained adjustment parameters.

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

Ses: sessions, Eq: Number of equations, Unk: unknown parameters, Red: redundancy, s_0^2: unit weight variance; c^2_{exp}: experimental c^2 with «redundancy» degrees of freedom; c^2_{teo} theoretical c^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.

Figure 2. Reinforced concrete pillar anchored to rock in site 800.

The network was tied to Almería, Lagos and San Fernando sites. The first ones 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. 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 (Beutler et al. 2000) 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.

Table 2. Cartesian Coordinates at epoch 2004.6 in 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

Table 3. Geodetic Coordinates at epoch 2004.6 in ITRF00.

Point	latitude (º ' ")	rms (m)	longitude (º ' ")	rms (m)	height (m)	rms (m)
800	37 1 25.61975	0.001	-4 3 27.11380	0.001	984.065	0.003
810	36 57 22.10226	0.001	-4 7 14.66435	0.001	971.200	0.003
820	36 57 5.49199	0.001	-4 0 27.52066	0.001	1088.537	0.003
830	36 56 8.96438	0.001	-3 56 14.02907	0.001	1135.760	0.003
840	36 52 47.00435	0.001	-4 5 15.98891	0.001	786.601	0.002
850	36 52 44.06439	0.001	-3 55 27.49854	0.001	1598.260	0.002
860	36 49 44.51913		-3 57 34.08023		908.992	
870	36 49 32.35890	0.001	-4 5 49.57749	0.001	623.190	0.002
880	36 45 45.71781	0.001	-3 50 43.61178	0.001	217.396	0.002
890	36 44 27.20083	0.001	-3 59 54.35134	0.001	85.877	0.002

Table 1 shows the minimum constrained adjustment parameters and Fig. 3 shows the 99% confidence regions of the minimum constrained network. The adjusted coordinates can be seen in Table 2.

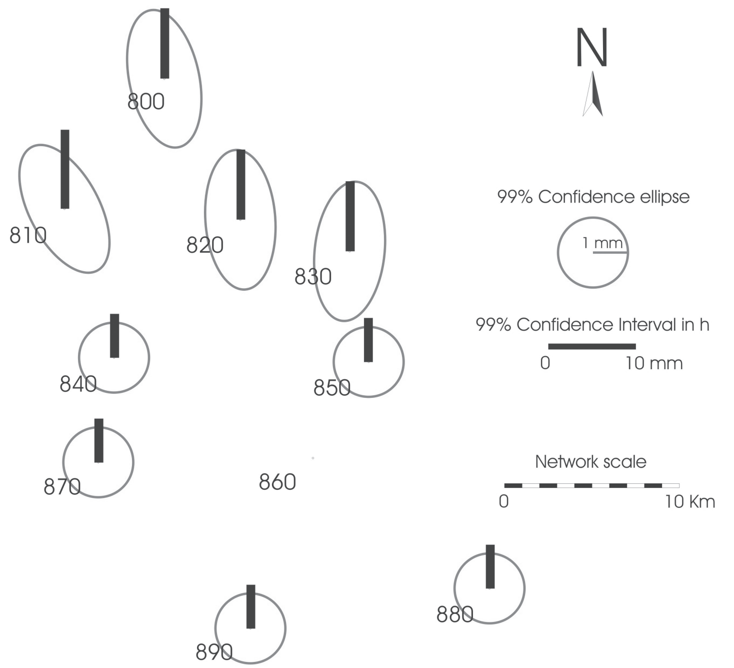

Figure 3. Confidence regions from network adjustment.

4. CONCLUSIONS AND OUTLOOKS

In the central part of the Betic Cordillera, the Zafarraya fault constitutes one of the structures with evidence of very recent tectonic activity. Southeast of the Zafarraya Fault is the Sierra Tejeda, constituting a great radius antiform with an E-W to ESE-WNW oriented axis and a periclinal end towards the west. A GPS monitoring network has been established in Sierra Tejeda antiform and Zafarraya fault. The first campaign has been carried out in September 2004. This GPS network is composed by a regional and a local network. The results corresponding to the regional network are presented. From Table 2 we can conclude the rms of the cartesian coordinates is an average at 1 mm level in planimetry and under 3 mm in altimetry. In the near future the local network data will be processed.

The reoccupation campaign will be carried out two years after the first campaign and it will allow confirming that the 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.

5. REFERENCES

BEUTLER, G., E. BROCKMANN, R. DACH, P. FRIDEZ, W. GURTNER, U. HUGENTOBLER, J. JOHNSON, L. MERVANT, M. ROTHACHER, S. SCHAER, T. SPRINGER & R. WEBER, 2000. *BERNESE GPS software version 4.2*. Astronomical Institute University of Berna.

CRESPI, M., 1996. Software Package for the Adjustment and the Analysis of GPS Control Networks. *Reports on Survey and Geodesy in memoria of Proff. A. Gubellini and G. Folloni.* (Ed. M. Unguendoli), Edizione Nautilus, Bologna, 237-264.

DE METS, C., R. G. GORDON, D. ARGUS, S. STEIN, 1990. Current plate motions. *Geophysical Journal International,* 101, 425-478.

GALINDO-ZALDÍVAR, J., A. J. GIL, M.J. BORQUE, F. GONZÁLEZ-LODEIRO, A. JABALOY, C. MARÍN-LECHADO, P. RUANO & C. SANZ DE GALDEANO, 2003. Active faulting in the internal zones of the central Betic Cordilleras (SE, Spain), Journal of Geodynamics 36, 239–250.

JOHNSON C., 1997. Resolving denudational histories in orogenic belts with apatite fission-track thermochronology and structural data: an example from southern Spain. *Geology*, 25, 623-626.

MUÑOZ M. & UDÍAS A., 1980, Estudio de los Parámetros y Serie de Réplicas del Terremoto de Andalucía del 25 de Diciembre de 1884 y de la Sismicidad de la Región Málaga-Granada. In: *El Terremoto de Andalucía de 1884,* Instituto Geográfico Nacional (ed.), Madrid, 95-139.

MUÑOZ D. & UDÍAS A., 1981. *El Terremoto de Andalucía del 25 de Diciembre de 1884*. Instituto Geográfico Nacional, Madrid.

SANZ DE GALDEANO C. & ALFARO P., 2004. Tectonic significance of the present relief of the Betic cordillera. *Geomorphlogy*, 63, 178-190.

SANZ DE GALDEANO C., PÉLAEZ J. A., LÓPEZ C., 2003. Seismic potentiality of the main faults in the Granada Basin (South of Spain), *Pure and Applied Geophysics*, 160, 1537-1556.

WEIJERMARS R., TH.B. ROEP, B. VAN DEN EECKHOUT, G. POSTMA & K. KLEVERLAAN, 1985. Uplift history of a Betic fold nappe inferred from Neogene-Quaternary sedimentation and tectonics (in the Sierra Alhamilla and Almeria, Sorbas and Tabernas Basins of the Betic Cordilleras, SE Spain). *Geol. Mijnb.*, 64, 397-411.