Active faults in the Granada Depression and Zafarraya areas (Betic Cordilleras)

Fallas activas en las áreas de la Depresión de Granada y Zafarraya (Cordilleras Béticas)

K.R. Reicherter (*), A. Jabaloy (**), J. Galindo-Zaldívar (**), P. Ruano (**)

(*) Geologisch-Paläontologisches Institut und Museum, Universität Hamburg, Bundesstr. 55, D-20146 Hamburg, Germany; Email: reicherter@geowiss.uni-hamburg.de
(**) Dpto. de Geodinamica, Fac. de Ciencias, Campus Fuentenueva s/n, Universidad de Granada, 18071 Granada, España; Email: (jabaloy@goliat.ugr.es)

ABSTRACT

Pliocene to Holocene alluvial and colluvial deposits in the Granada Depression and surrounding areas display a wide range of features of recent faulting related to coseismic ruptures. The majority of the faults studied are normal. Secondary dextral strike-slip faults have also been observed North of Granada city (the Cubillas reservoir and Víznar areas). The most significant faults are the Ventas de Zafarraya fault scarp, that was activated during the 1884 earthquake of Arenas del Rey, and reactivated fault scarps in Pinos Puente. It has been observed an active faults concentration along the eastern and southwestern border of the depression.

Key words: *paleoseismology, Granada Depression, recent stress field, recurrence rates*

RESUMEN

Los depósitos aluviales y coluviales pliocenos a holocenos en la Depresión de Granada y áreas cercanas, contienen un amplio conjunto de rasgos asociados a fallas recientes relacionadas con rupturas cosísmicas. La mayoría de las fallas estudiadas son normales. También se observan fallas de salto en dirección dextras secundarias al norte de la ciudad de Granada (áreas del embalse de Cubillas y Víznar). Las fallas estudiadas más significativas son el escarpe de falla de Ventas de Zafarraya, que fue activado durante el terremoto de 1884 de Arenas del Rey, y los escarpes de fallas reactivadas en Pinos Puente. Las fallas activas observadas se concentran en dos áreas, una es el borde oriental de la depresión y la otra su borde sudoeste.

Geogaceta, 27 (1999), 135-138
ISSN: 0213683X

Introduction

The central and eastern Betic Cordilleras, including their Neogene intramontane basins, are the seismically most active zones in Spain with several moderate earthquakes reported during the last years (Morales *et al.*, 1996, 1997). Available earthquake data indicate, that in the last 600 years different parts of the Cordillera were shook by major earthquakes with MSK intensities VII - X. Several works concerning the neotectonic evolution (e.g., Sanz de Galdeano, 1980, 1985, 1990; Sanz de Galdeano and Estevez, 1981; Galindo-Zaldívar *et al.*, 1993, 1999; Ruano, 1998; Pistre *et al.*, 1999; Reicherter, 1999) were carried out in the Granada Depression. Paleoseismic studies in southern Spain concerned up to now Tsunami deposits in the Gulf of Cádiz (Dabrio *et al.*, 1998), the Guadalentín Depression near Murcia (Silva *et al.*, 1997) and in the Guadix-Baza Depression (Alfaro *et al.*, 1997). Near Carboneras/Almería further paleoseismic evidence was documented by Bell *et al.* (1997). The Granada Depression lacks of paleoseismic studies of all kind.

The main aim of this work is to present major evidence of paleoseismological events and to study the main features of active faults or faults with very recent activity in the Granada Depression.

Geological and seismological setting

During the Oligocene and Miocene coupled compression and extension occurred in the Betic Cordilleras, which are situated in the northern part of the Afro-European convergence zone. Present day kinematic data point to an NW-SE oblique convergence along the Afro-European plate boundary of about 4 mm/y (e.g., Morel and Meghraoui, 1996). Neogene intramontane basins formed during this period in a generally extensional context. The Granada Depression (Fig.1) is mainly filled with Upper Miocene to Pliocene calcarenites, marls, evaporites, terrigenous clastics and, occasionally, lacustrine limestone intervals, which are finally topped by fluvial, colluvial and alluvial Quaternary deposits. Simultaneously, normal faults and scarce strike-slip faults developed along some of the borders and inside the basin, affecting the basin evolution, among them the Padul fault in the SE part of the depression (Keller *et al.*, 1996).

Available earthquake data indicate, that in the last 600 years of cataloguing different parts of the southern Spain were place of major earthquakes with MSK intensities VII - X. The Christmas event of 1884 (M~7) was one of the most destructive that affected Andalucia (e.g., MacPherson, 1885; Taramelli and Mercalli, 1886; Muñoz and Udías, 1980; Sanz de Galdeano, 1985). The epicenter was supposed to be close to Arenas del Rey in the southern Granada Depression. Since then, no larger earthquakes occurred. Moderate

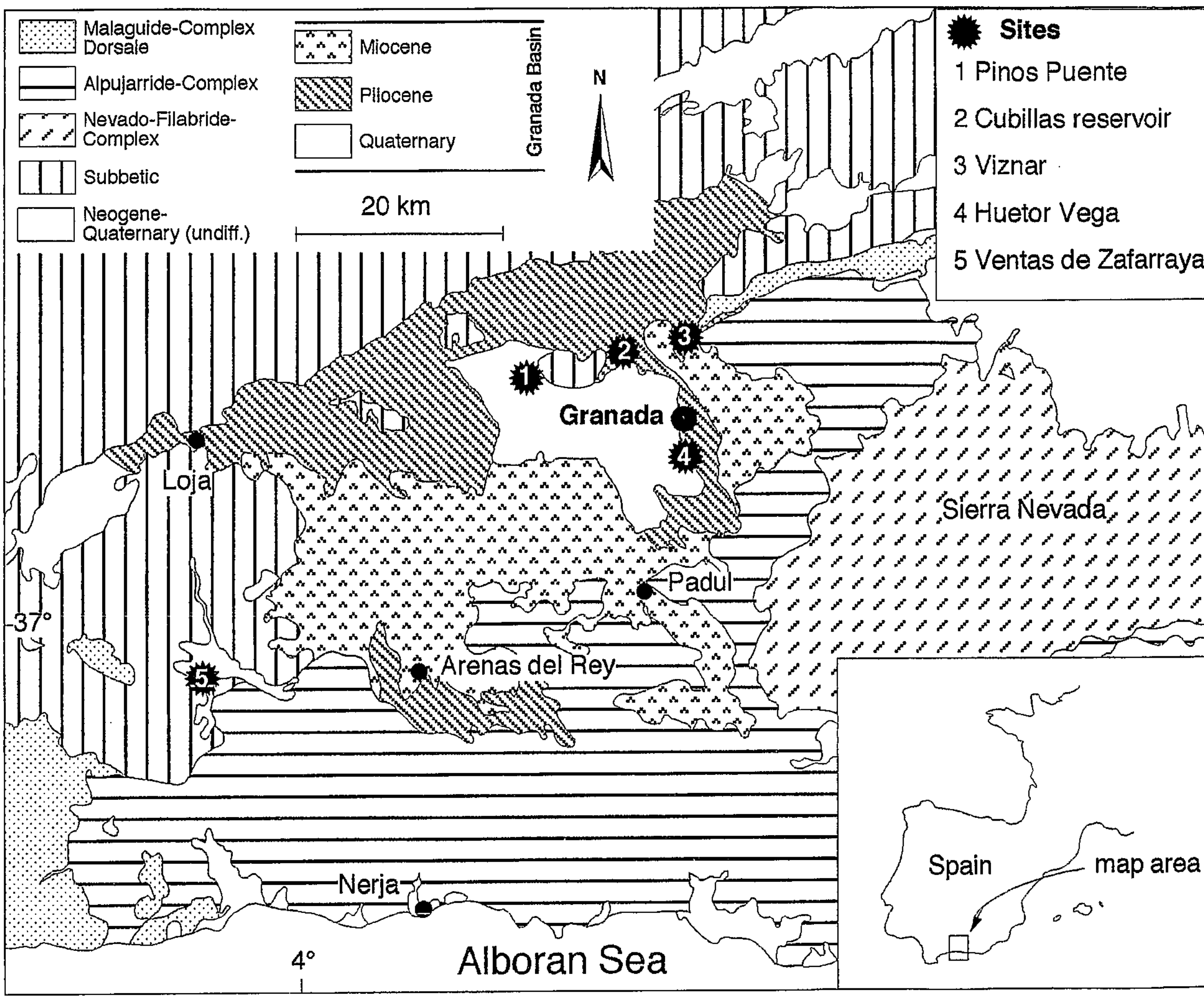

Figure 1: Studied locations in the Granada Depression

Figura 1: Mapa geológico simplificado de la Depresión de Granada y localidades estudiadas

and small earthquakes (M = 5; Morales *et al.*, 1996) in the Betics and the Rif (Morocco) have been recorded. Galindo-Zaldívar *et al.* (1993, 1999) compared the present-day stresses deduced from earthquakes focal mechanisms with paleostress determined from micro-fault analysis. A concentration of earthquakes along the western and southern borders of the Granada Depression with shallow foci of ≤ 20 Km depth within the depression micro-earthquakes concentrate on four regions withe elevated activity. Based on these, Morales el al. (1996) suggest a period of recurrence of 10, 100, 1000 years for magnitudes 5, 6 and 7, respectively.

Paleoseismic evidence

Several outcrops in the Granada Depression are pointing to paleo-earthquake activity, and are described in the following section (Fig. 1). Fault scarps are often degraded due to intense land-use in the region and fast erosion. In general, (1) high angle NW-SE, E-W and NE-SW normal faults with displacements that may reach several hundreds of meters, and (2) WNW-ESE subvertical dextral strike-slip faults, with subhorizontal striae and average offsets ranging in the order 1 to 5 m were observed. Also high angle NW-SE faults with both oblique and strike-slip striae developed in the area.

Cubillas River and reservoir area (Northwest of Granada)

Along the E902 highway, several dextral strike-slip faults are beautifully exposed in piedmont and glacis sediments (Fig. 2A), which provide an example for a possible coseimic surface rupture. Paleosol 1 (Fig. 2A) exhibits the vertical displacement of the fault. The dextral sense of shear was determined using the fault gauge fabric and the vertical displacement of paleosol 1. Using the shallow dipping plunge of the striation (19°) and the throw, it is possible to calculate the maximum displacement D (Fig. 2B). Supposing that the whole displacement originated in a single event, then a first preliminary assessment of a paleo-magnitude related to this fault was calculated with the empirical formulae of Bonilla *et al.* (1984) and of Wells and Coppersmith (1994). Both formulae resulted in a quite similar paleo-magnitude (seismic moment and surface waves magnitude) of about M = 7, expecting the singularity of the event. Adjacent to this fault, a dextral extensional fault shows a vertical throw of approx. 4 m, and is capped and sealed by colluvial conglomerates. The

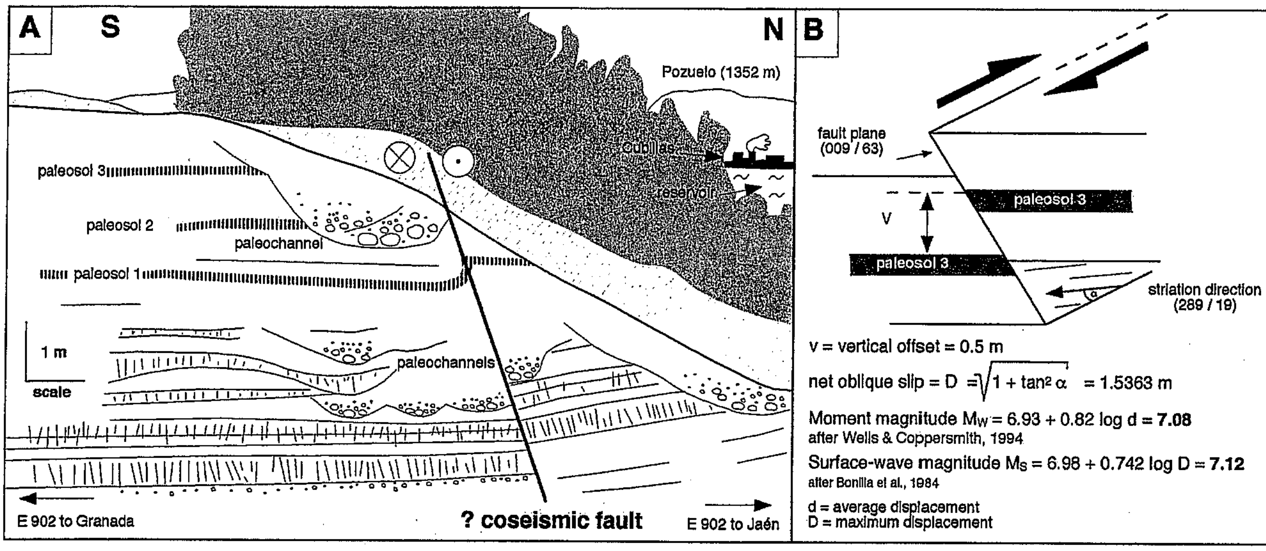

Figure 2: Dextral strike-slip fault in Pliocene sediments near the Cubillas reservoir north of Granada. Fig 2A: Sketch of the trench along the highway E 902 (redrawn from photograph, site 2 in Fig. 1). Fig.2B: Preliminary calculation of the fault depicted in Fig.2A

Figura 2. Falla de salto en dirección dextra en sedimentos pliocenos cerca del embalse de Cubillas, al norte de Granada. Fig. 2A: Esquema de la trinchera a lo largo de la autovía E 902 (dibujado de una fotografía, localidad 2 en Fig. 1). Fig.2B: Cálculo preliminar de la falla dibujada en la Fig.2A

preliminary age assessment of the sediments faulted is latest Pliocene (Günster, 1999).

Víznar (Northeast of Granada)

Several NW-SE normal, oblique and dextral strike-slip faults are exposed at km 252 of the A 92 highway (near exit Víznar), cut lower Messinian conglomerates and are sealed by recent soils. A fault plane exhibits two different striae: the older one has a normal sense of movement and a great dip-slip component. The younger one is subhorizontal and has a dextral strike-slip sense of movement (Reicherter, 1999). Conglomerate pebbles show surface striation and are cut by the faults. Striated pebbles indicate subhorizontal NW-SE compression. Crushed pebbles suggest high energy released during deformation, suggesting being produced during a seismic event. On NE-SW striking fault surfaces frequently sigmoidal gypsum fibres developed, indicating a progressive change of the stress field.

Huetor Vega (South of Granada)

NW-SE normal faults crop out in the Alhambra Conglomerate and are cut by the road towards Sierra Nevada South of Granada, close to the tunnel (Fig.3A). The faults displace the Plio-Pleistocene Alhambra Conglomerate and the Holocene deposits and have eroded topographic scarps. One of the main fault surfaces with a leached fault gauge displays several marked steps in intercalated calcrete horizons, and, associated drag folding. In the road trench one minor conjugate NW-SE striking normal fault with several meters of displacement are observable in paleosols (Fig. 3B). The leached fault gauges and degraded scarps suggest that these faults are presently not active.

Pinos Puente (Northwest of Granada)

In Pinos Puente, along the prolongation of the south-western Sierra Elvira normal fault scarp, intensely deformed Quaternary sediments with several displaced paleosols have been found. The paleosols define a NW-SE monoclinal fold cut by normal faults. The normal faults are associated with a marked topographic step and drag folds. Close to the cemetery, young N-S and E-W striking normal faults are exposed.

Ventas de Zafarraya (Southwest of Granada)

The Spanish commission that studied the earthquake of 1884 described two major “open fractures” of 8 and 7 km length in Ventas de Zafarraya, along the contact between the Jurassic limestones and Quaternary sediments (IGN, 1980). The E-W striking and N-dipping normal fault scarp is exposed near the new cemetery. In the hanging wall, several paleosols are cut and displaced by small normal faults parallel to the main fault accompanied with liquefaction, as sand blows. This fault was activated during the 1884 event and the length of the rupture (8 km) suggests a magnitude between 6 and 6.5 for this earthquake (Wells and Coppersmith, 1994).

Discussion and conclusions

The Granada Depression exhibits several localities with evidence of active faults and recent active faults, some of which with coseismic displacements. The sense of the active faults are basically normal ones, striking NW-SE and reflecting the overall NE-SW directed extensional setting. Minor E-W and NE-SW normal faults were also observed. Post-Pliocene dextral strike-slip faults occur mainly north of Granada. These active faults including the Padul fault concentrate along the eastern and south-western border of the depression. The active eastern and north-eastern border coincides with one of the areas of high micro-earthquake activity.

Our observations coincide with the present-day stresses determined from earthquakes focal mechanisms of the area (Galindo-Zaldívar *et al.*, 1999). The previous seismological studies and our data suggest different and complex active structures in the study area that may produce earthquakes with magnitudes between 6 and 7. Based on preliminary paleoseismological data, the Gutenberg-Richter relation

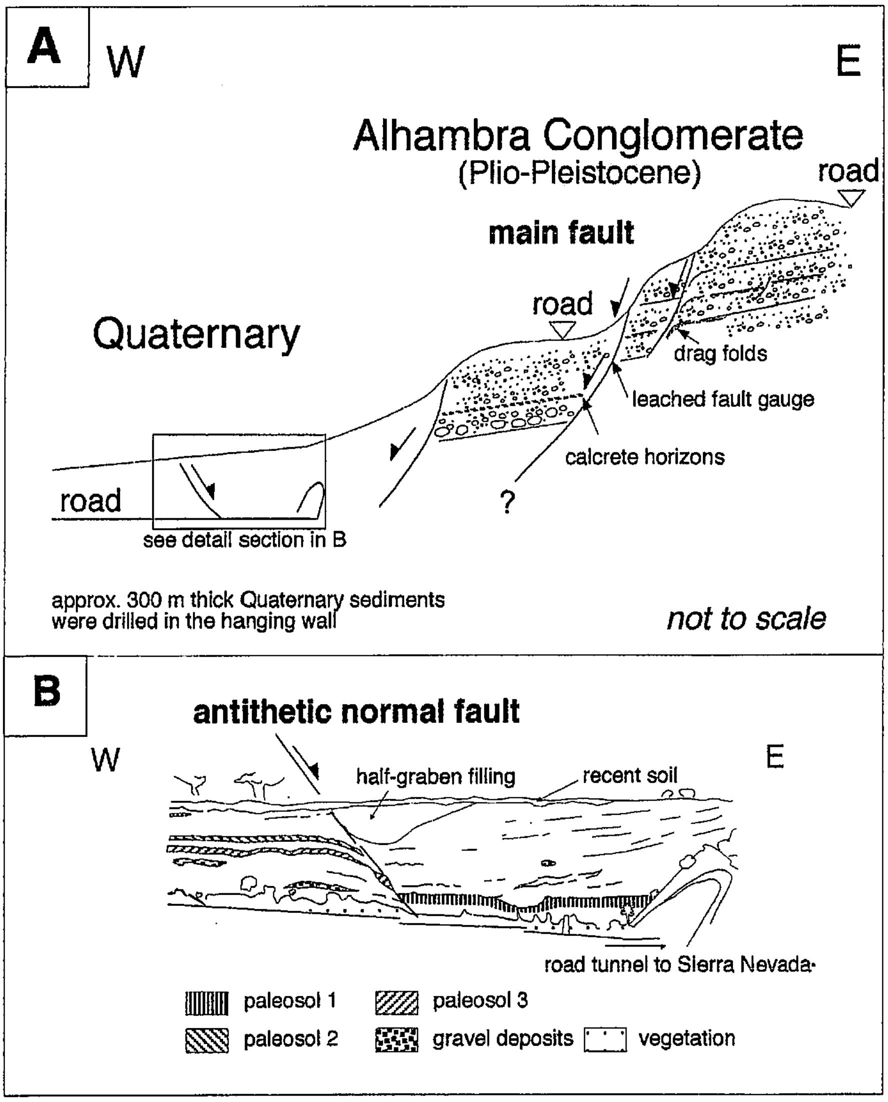

Figure 3. A: Schematic cross-section across a Quaternary fault scarp juxtaposing the Plio-Pleistocene Alhambra Conglomerate against Holocene south of Granada close to Huetor Vega (site 4 in Fig. 1). Note degraded scarps, minor syn- and antithetic faults.

Figure 3B: Detail of Fig. 3A, Quaternary section exposed at the entrance of the road tunnel close to Huetor Vega towards the Sierra Nevada. Note antithetic normal fault.

Figura.3A: Corte geológico esquemático del escarpe de falla que separa el Conglomerado Alhambra del Plio-Pleistoceno de los depósitos holocenos al sur de Granada, cerca de Huetor Vega (localidad 4 en la Fig.1). Obsérvense los escarpes degradados, y las fallas menores antitéticas y sintéticas.

Figura.3B: Detalle de la Fig. 3A, Corte del Cuaternario expuesto a la entrada del túnel de la carretera hacia Sierra Nevada cerca de Huetor Vega. Obsérvese la falla normal antitética.

corroborates recurrence rates proposed by Morales *et al.* (1997).

Acknowledgements

This work has been financially supported by the DAAD (Acciones Integradas project of the University of Hamburg with the University of Granada) and the Spanish CICYT project PB96-1452-C03-01. The help of Dr. G. Michel (Potsdam/Germany), G. Peters and U. Dyrssen (Hamburg/Germany) during field work is gratefully acknowledged.

References

Alfaro, P., Moretti, M. and Soria, J.M. (1997): *Eclogae Geologicae Helvetiae*, 90: 531-540

Bell, J. W., Amelung, F. and King, G.C.P. (1997): *J. Geodynamics*, 24: 51-66.

Bonilla, M.G., Mark, R.K. and Lienkaemper, J.J. (1984): *Bull. Seismol. Soc. America,* 74: 2379-2411

Dabrio, C.J., Goy, J.L. and Zazo, C. (1998): *Geogaceta,* 23: 31-34

Galindo-Zaldívar, J., González-Lodeiro, F. and Jabaloy, A. (1993): *Tectonophysics,* 227: 105-126

Galindo-Zaldívar, J., Jabaloy, A., Serrano, L., Morales, J., González-Lodeiro, F. and Torcal, F. (1999): *Tectonics*, 18: 686-702.

Günster, N. (1999): *Bonner Bodenkundl. Abh.*, 26: 238 pp.

Instituto Geografico National de España (1980): *Terremoto de Andalucia, Serie sismología*, A. López *et al.* (eds.)

Keller, E.A.; Sanz de Galdeano, C. and Chacón, J. (1996): *1ª Conferencia Internacional Sierra-Nevada,* Granada, Marzo, 1996: 201-218

MacPherson, J. (1885): Los terremotos de Andalucía. *Conferencia Ateneo de Madrid*

Morales, J., Singh, S.K. and Ordaz, M. (1996): *Tectonophysics,* 257, (2-4): 253-262

Morales, J., Serrano, I., Vidal, F. and Torcal F. (1997): *Geophys. Research Lett.*, 24 (24): 3289-3292

Morel, J.L. and Meghraoui, M. (1996): *Geology,* 24: 755-758

Muñoz, M. and Udias, A. (1980): "El Terremoto de Andalucía de 1884", *Inst. Geogr. Nac.:* 95-139

Pistre, S., López-Chicano, M., Pulido-Bosch, A. and Drogue, C. (1999): *Geodinamica Acta (Paris),* 12: 11-24.

Reicherter, K. (1999): *Mitt. Geol. Pal. Inst. Univ. Hamburg*, 83: 1-15.

Ruano, P. (1998): *Master-thesis*, Univ. of Oviedo: 70 pp.

Sanz de Galdeano, C. (1980): *Estudios Geol.,* 36: 255-261

Sanz de Galdeano, C. (1985): *Estudios Geol.,* 41: 59-68

Sanz de Galdeano, C. (1990): *Tectonophysics,* 172: 107-119

Sanz de Galdeano, C. and Estévez, A. (1981): *Estudios Geol.,* 37: 227-232

Silva, P.G., Goy, J.L., Zazo, C., Lario, J. and Bardají, T. (1997): *J. Geodynamics,* 24 (1-4): 105-115

Taramelli, T. and Mercalli, G. (1886): *Atti de la R. Accad. dei Lincei,* 83

Wells, D.L. and Coppersmith, K.L. (1994): *Bull. Seismol. Soc. America,* 84 (4): 974-1002.