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# Paleoseismologic advances in the Granada basin (Betic Cordilleras, southern Spain)

## Progresos paleosismológicos en la cuenca de Granada (Cordilleras Béticas, sur de España)

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## ABSTRACT

The Betic Cordilleras in southern Spain have experienced a number of moderate to strong seismic events during the last 2000 years of reported historical earthquakes. These earthquakes are distributed along the southern margin of Spain from Cádiz to Alicante, and offshore in the Alborán sea, reaching the island of Mallorca. Pliocene to Holocene alluvial and colluvial sediments in Neogene basins and adjacent smaller basins in the Betic Cordilleras display a broad range of faults and structures presumably related to coseismic surface deformation. A number of historical earthquakes capable of producing surface ruptures are presented. This study is focussed on reported ruptures and fault scarps, e.g., those of the Christmas event of 1884 (M 6.5-7) near Ventas de Zafarraya, in the southwestern and northeastern parts of the Granada basin. Displaced and buried paleosols and colluvial wedges in the hanging wall suggest multiple fault reactivation. AMS $^{14}$C-dating indicates at least three strong events along the Ventas de Zafarraya fault during the last 9 ka. Active faults, and hence seismogenic deformation, are distributed in the Betics, which considerably hinders the calculation of recurrence rates of strong earthquakes along discrete faults. The maximum expectable events for the study area are in the order of M 7.

*Keywords:* Paleoseismology. Earthquakes. Recurrence rates. Ground penetrating radar. Recent stress. Neotectonics. Active faults. Granada basin.

## RESUMEN

Se tiene registro histórico de que las Cordilleras Béticas, en el sur de España, han experimentado varios eventos sísmicos moderados a fuertes durante los últimos 2000 años. Estos terremotos se distribuyen a lo largo del margen meridional de España, desde Cádiz hasta Alicante, en el mar de Alborán, y continuan hasta la isla de Mallorca. Ciertos depósitos coluviales y aluviales, de edad pliocena a holocena, de las cuencas neógenas de las Cordilleras Béticas presentan un amplio rango de fallas y estructuras relacionadas, presumiblemente, con la deformación cosísmica de la superficie. Se presentan varios terremotos históricos capaces de producir rupturas de la superficie. Este estudio se centra en las rupturas y escarpes de falla descritos en las partes suroccidental y nororiental de la cuenca de Granada, como por ejemplo, los del terremoto de Navidad de 1884 (M 6,5-7) cerca de Ventas de Zafarraya. Paleosuelos enterrados y desplazados, así como cuñas coluviales en el bloque superior sugieren una reactivación múltiple de la falla. Las dataciones realizadas (AMS $^{14}$C) indican que durante los últimos 9 ka se han producido al menos tres eventos fuertes a lo largo de la falla de Ventas de Zafarraya. Las fallas activas, y por consiguiente la deformación sismogénica, están ampliamente distribuidas en las Béticas, hecho que dificulta considerablemente el cálculo de los períodos de recurrencia de los terremotos fuertes producidos por fallas discretas. Los máximos eventos esperables en la región estudiada son del orden de M 7.

*Palabras clave:* Paleosismología. Terremotos. Tasas de recurrencia. *Ground penetrating radar*. Esfuerzos recientes. Neotectónica. Fallas activas. Cuenca de Granada.

## INTRODUCTION

The Betic Cordilleras of southern Spain form the westernmost part of the Alpine orogenic belt of Europe, the Gibraltar arch. The Betics are divided into an Internal Zone consisting of a complex stack of nappes with a different metamorphic overprint, and an External Zone. These two zones are traditionally regarded as a thin-skinned fold and thrust belt of Mesozoic to lower Neogene sediments of southern Iberia, the Alborán microcontinent and northern Africa (Fig. 1A). Studies on the regional geology and paleogeography of the External Zones and on the structure of the Internal Zones have been published by García-Hernández et al. (1980) and Weijermars (1991), respectively. During the Oligocene and Miocene, compressional and extensional deformation occurred simultaneously in the Betics with nappe stacking and onset of basin formation in the Alborán region (e.g., Dewey et al., 1989). In the Afro-European convergence zone, oblique convergence rates are in the order of 4 mm/yr (Argus et al., 1989) to 5.6 mm/yr (Jolivet et al., 1999). The earthquake distribution along the southern margin of Spain and the southward increasing depth of the foci have been variously interpreted as an intracontinental subduction zone: Vegas (1991) has proposed a subduction of Africa below Iberia, whereas Morales et al., (1999) have interpreted this as a subduction of the Eurasian plate below Africa. The general plate boundary setting has been interpreted as a dextral transpressional zone (Morel and Meghraoui, 1996), where Neogene intramontane basins formed along strike-slip faults (Lonergan and White, 1997) and along major normal faults (e.g., Jabaloy et al., 1992).

The Granada basin in the central Betic Cordilleras is one of these Neogene-Quaternary intramontane basins under study (Fig. 1B). The sedimentary infill of the Granada basin documents various Neogene-Quaternary tectonic and sedimentary phases. Shallow marine Tortonian-Messinian carbonate and evaporite facies are overlain by terrigenous and lacustrine sediments, which, in turn, are succeeded by Pliocene to Quaternary alluvial and colluvial sediments with numerous paleosols and caliches. A northward tilt of the Neogene sediments is accompanied by a shift of the Quaternary depocenters, which subside close to the northern border of the basin along the NW-SE striking structures during the Holocene (Lhenaff, 1979). Other parts of the basin, the sierra Elvira, and the surrounding mountain ranges (sierra Gorda, sierra Nevada) are subject to uplift (Fig. 1B).

The main aim of this work is to study the behavior of discrete faults and to estimate return periods of moderate and large earthquakes in the Granada basin. Another objective is to present a selection of prehistoric earthquakes which occurred in the Betic Cordilleras and adjacent regions during the last 2000 years, and which are thought to have been strong enough to produce surface ruptures. The threshold of coseismic surface deformation is commonly considered to be $M \geq 5.5$ (Bonilla, 1988) and to have an MSK intensity exceeding 7-8 (Levret et al., 1994), bearing in mind the distance from the epicenter. The methods applied were the classic ones such as microgeomorphic studies, structural geology, stratigraphy of displaced paleosols including $^{14}$C-dating, aerial photos and satellite images and Ground Penetrating Radar studies. These methods were supplemented by archeological and historical studies. Secondary evidence for large earthquakes such as landslides and tsunami deposits was also taken into account.

The outcrop conditions of remnant surface faulting in southern Spain demand a neotectonic analysis based on new approaches to fault studies. A number of studies concerning the neotectonic evolution (e.g., Sanz de Galdeano, 1990; Galindo-Zaldívar et al., 1993, 1999; Jabaloy et al., 1992; Reicherter and Michel, 1993; Reicherter, 1999, 2000) have been carried out in the

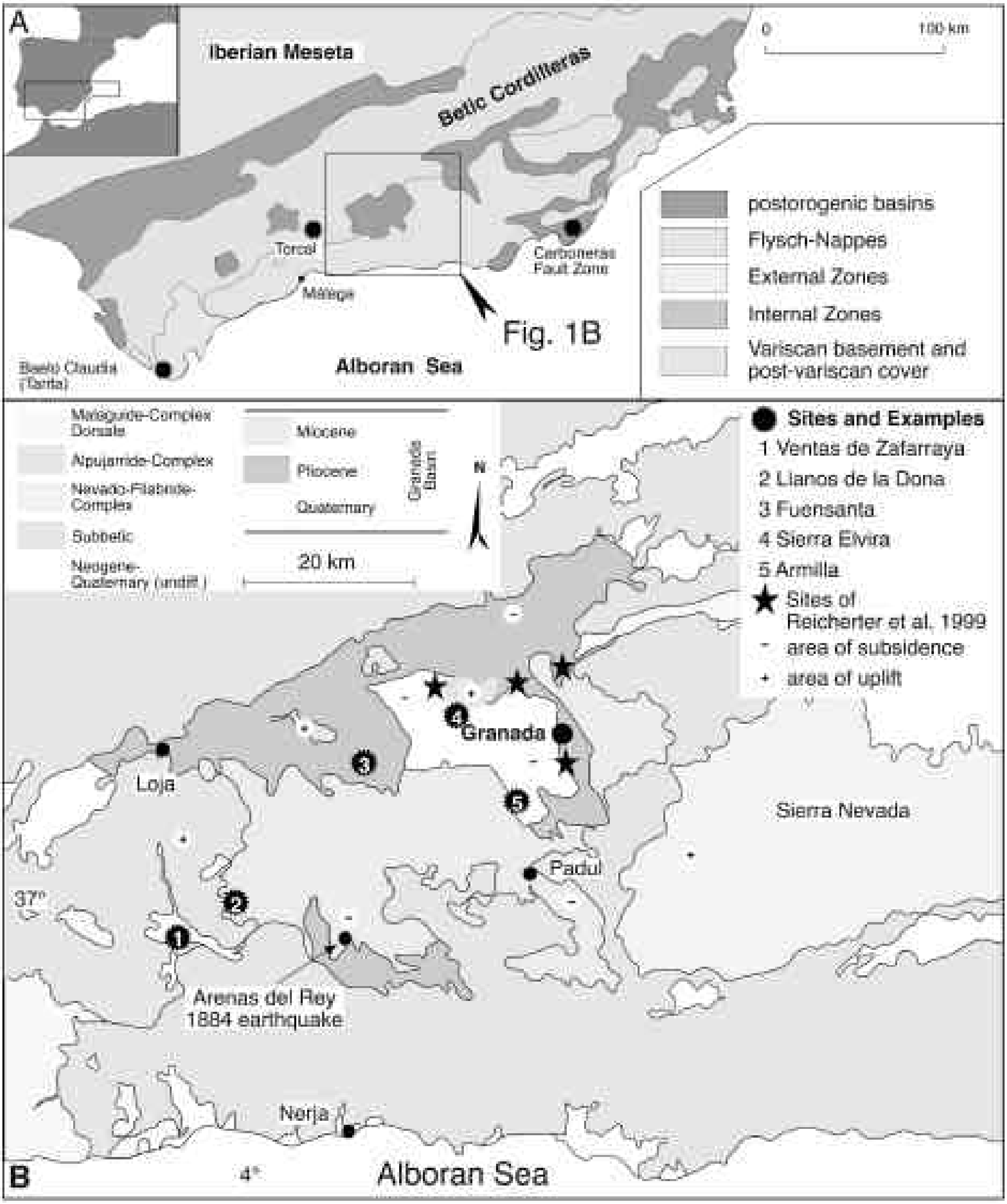

Figure 1. A) Geological sketch map of southern Spain, indicating the study areas. B) Sites in the Granada depression with evidence of coseismic ruptures (stars). Modified from Reicherter et al. (1999).

Figura 1. A) Esquema geológico del sur de España con indicación de las áreas estudiadas. B) Localidades de la depresión de Granada con pruebas de rupturas cosísmicas (estrellas). Modificado de Reicherter et al. (1999).

central part of the Betic mountain range, the Subbetic Zone and the adjacent Neogene basins. The data obtained have been used to establish models for the distribution of recent stresses in the central Betic Cordilleras, which point to a (N)NW-(S)SE-directed maximum horizontal compression (e.g., Galindo-Zaldívar et al., 1993, 1999; Reicherter, 1999). The temporal gap existing between neotectonic observations and recent seismic earthquake data must be bridged by paleoseismology. Relatively few and local paleoseismic studies in southern Spain have so far dealt with tsunami deposits in the Gulf of Cádiz (Dabrio et al., 1998), where spit-bar sediments in the Guadalquivir estuary have been attributed to the 1755 Lisbon earthquake. Further evidence for prehistorical coseismic faulting along an aseismic fault has been found in the Guadalentín depression near Murcia (Silva et al., 1996, 1997). In the eastern Betic Cordilleras, the Adra region (W of Almería) and parts of the province of Murcia, coseismic deformation linked to active faulting and its neotectonic implications have been fully described by Martínez-Díaz and Hernández-Enrile (1996) and Martínez-Díaz (1998). Bell et al. (1997) studied the recent movement history of the Carboneras fault system in the eastern part of the province of Almería. Quaternary reverse faulting, which is thought to have induced during past earthquakes (1851 Mallorca earthquake, MSK VIII), has been investigated on the island of Mallorca at the eastern end of the Alpine Betic orogen (Silva et al., 1999). The coastal zones of the Atlantic (Coto de Doñana by Rodríguez-Ramírez et al., 1997) and the Mediterranean sea (Valencia by Rey and Fumanal, 1997) show a pronounced neotectonically induced uplift. The northern border of the Guadalquivir depression and the seismicity along the Variscan Meseta have been investigated by Herraiz et al. (1996). These authors interpret the northern limit of the Guadalquivir depression as an active crustal flexure characterized by low to moderate seismicity accompanied by neoformed fractures.

Given that the Betics lack dating of prehistorical paleo-events, it is necessary to assess the recent faulting activity and the long-term seismic hazard in the Betic Cordilleras, especially in highly populated i.e. vulnerable areas.

## HISTORICAL AND PRESENT SEISMICITY

The Betic Cordilleras, the Guadalquivir basin, the Alborán sea and the Açores-Gibraltar zone represent the most seismically active zone in Spain, delineated by the Afro-European convergence zone. Available earthquake data indicate that in the last 2000 years different parts of the zone have been affected by major earthquakes with MSK intensities from VII to X (Appendix, Table 1). It must be emphasized that the available catalogues date back to the year 1300 AD. Earthquake information from the time of the Moors, western Goths, Romans or Greeks is scant. Where available such information is difficult to interpret given the translation of the Islamic calendar and vague, often exaggerated reports (Gentil and Justo, 1983; López Marinas, 1983). The "Christmas event" of 1884 (e.g., MacPherson, 1885; Fernández de Castro, 1885; Taramelli and Mercalli, 1885; Douvillé, 1906; Muñoz and Udías, 1980) was the last strong earthquake that produced major casualties in Andalucía. In recent years a number of geophysical studies on present-day seismicity have been published. They provide different or even contradictory solutions to focal mechanisms for the same earthquakes (e.g., Fonseca and Long, 1991; Buforn et al., 1995; Morales et al., 1996; Lonergan and White, 1997; Galindo-Zaldívar et al., 1993, 1999). An extensive seismic network has recently been established by the Instituto de Geofísica/Granada to monitor the area regionally. Further earthquake data on the Iberian Peninsula are gathered by the Instituto Geográfico Nacional/Madrid. An earlier assessment of the spatial distribution of microquakes during 1998-2000 in southern Spain (Fig. 2) reveals several maxima within and around the Granada basin (Morales et al., 1996, 1997; Reicherter et al., 1999), and to the West in the vicinity of Ventas de Zafarraya and the Torcal massif (Reicherter et al., 2000). Present-day activity in the Granada basin is related to E-W and NW-SE oriented faults (Galindo-Zaldívar et al., 1999). The strongest instrumentally recorded earthquakes in this area have been moderate (M < 5). In general, earthquake foci in this area are shallow and their depths range between 10 and 20 km within the seismogenic layer (Galindo-Zaldívar et al., 1999). Other seismically active zones in the Betics are located along large strike-slip faults between Almería and Murcia (e.g., Martínez-Díaz and Hernández-Enrile, 1996; Silva et al., 1997; Martínez-Díaz, 1998), in the Alborán sea, and along the eastern and northern borders of the province of Cádiz.

Seismic risk studies of the early 80s by Muñoz and Udías (1983) presented long-term earthquake probabilities for Murcia, Alicante, and the major Andalucian capitals. The return periods for Granada, Murcia and Alicante are in the order of 2000 years for intensity X events, and 100 years for events of an

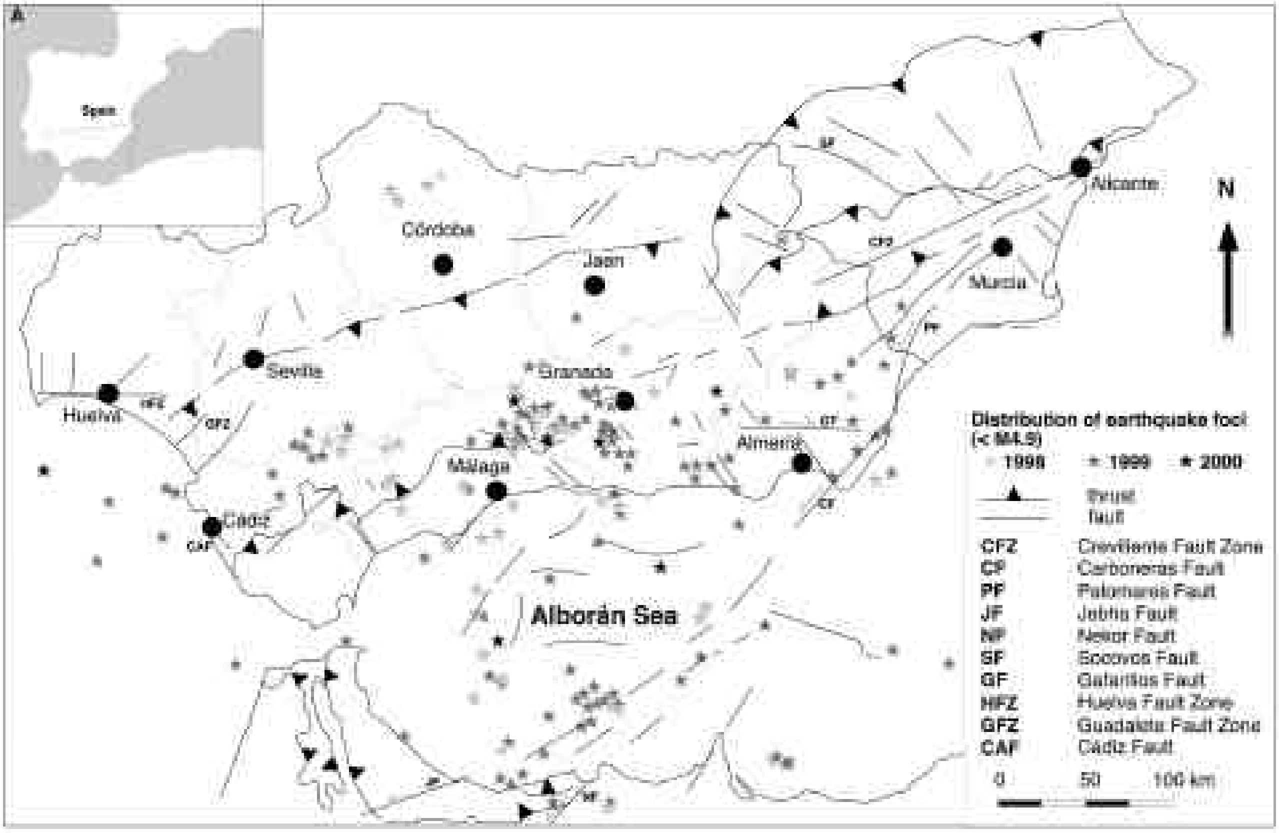

Figure 2. Micro-earthquake distribution (< M 4.9) during the 1998-2000 period in the Betic Cordilleras. Note maxima of seismicity around the Granada basin, the Alborán sea, the cabo de Gata region and along the northern border of the province of Cádiz. Data selection and compilation from the Instituto Andaluz de Geofísica (Universidad de Granada) web site.

Figura 2. Distribución de los microsismos (< M 4,9) en las Cordilleras Béticas durante el período 1998-2000. Nótense los máximos de sismicidad alrededor de la cuenca de Granada, el mar de Alborán, la región del cabo de Gata y a lo largo del borde norte de la provincia de Cádiz. Compilación y selección de los datos de la página web del Instituto Andaluz de Geofísica (Universidad de Granada).

intensity between VII and VIII, respectively. For the cities of Málaga and Almería, return periods for intensity X earthquakes of about 10,000 years, and approx. 400 years for events of an intensity between VII and VIII have been calculated. The possibility for moderate to strong earthquakes in Sevilla is even lower. This seismic risk assessment (Muñoz and Udías, 1983) is based on historical earthquakes and probably contains large errors (the Arenas del Rey and Torrevieja earthquakes of the 19th century, see Table 1). Comparable results have been obtained by Martín and García (1983), who subdivided the Betic Cordilleras into 11 seismogenic provinces (see also López Casado et al., 1995), excluding the Balearic islands. These provinces are largely defined on the basis of the geological structures, e.g., the Internal-External boundary zone, the Guadalquivir basin, or the Carboneras and Palomares fault zones. Estimates for the Granada basin based on instrumental records and interpolations using earthquakes with $M \leq 4.9$ are in the order of one M 6 event every 100 years, and one M 7 event every 1000 years (Morales et al., 1996). In the light of paleoseismological investigations, this risk assessment must be verified and recalculated for individual fault zones situated in these highly vulnerable regions.

## PALEOSEISMOLOGICAL INVESTIGATIONS

Late Pleistocene and Holocene alluvial, colluvial and marine deposits display a wide range of geomorphic features which are diagnostic criteria of coseismic surface ruptures in the Betic Cordilleras. NW-SE and E-W striking normal or dextral strike-slip faults concentrate along the seismically most active eastern and southern margins of the

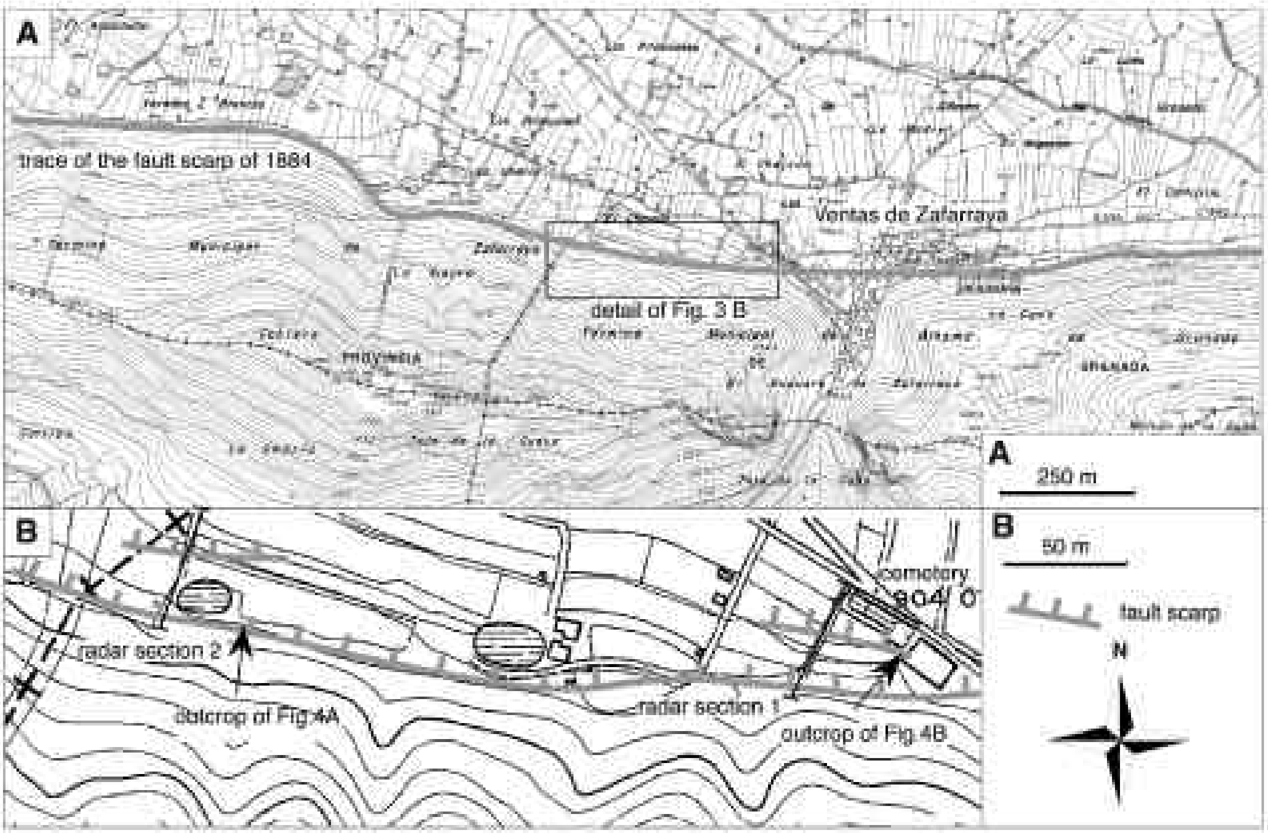

Figure 3. A) Trace of the fault scarp and topography of Ventas de Zafarraya; B) magnification of the study region, outcrops and georadar section are indicated.

Figura 3. A) Traza del escarpe de falla y topografía en Ventas de Zafarraya; B) ampliación de la zona estudiada con indicación de los afloramientos y la sección de georadar.

Granada depression (Galindo-Zaldivar et al., 1999; Reicherter, 1999; Reicherter et al., 1999). However, fault scarps are often difficult to detect because of land-use and rapid erosion. In the regions where moderate or strong earthquakes were described in the catalog, we concentrated our studies on artificial exposures such as road and railway cuttings (Reicherter et al., 1999, 2000). It should be pointed out that since only a limited number of fault scarps have been studied, the number of large earthquakes during the Quaternary could be significantly higher. Our data base is complemented by studies of the local Neogene and Quaternary tectonic evolution and by remote sensing data such as U.S. aerial photos from 1956/57, which predate the use of modern agricultural machines. During recent field campaigns we investigated several outcrops, some of which have already been described in Reicherter et al. (1999, 2000). The preliminary results of additional outcrops with coseismic indications and rupturing will be described in the following section.

### Ventas de Zafarraya scarp (N 36° 57´ 700, W 4° 07´ 500)

A detailed description of the geological evidence and damage after the "Christmas event" (25.12.1884) close to Arenas del Rey in the Granada basin has been provided by a number of authors. Douvillé (1906) described two major "open fractures" with lengths of 8 and 7 km close to Ventas de Zafarraya along the contact between Jurassic limestone and Quaternary sediments (Fig. 3A and B). Large landslides have been reported in Periana (Guaro, Prov. of Málaga) and Guevejar, situated to the North of Granada. Numerous springs underwent a change in water discharge and chemistry. Douvillé (1906) also mentioned E-W striking active structures from El Chorro (Prov. of Málaga) to Ventas de Zafarraya, accompanied by NW-SE structures along the NE flank of the Torcal massif. The E-W striking and N-dipping normal fault scarp is exposed near the cemetery (Fig. 4A). Fault slip data (kinematic criteria of slickensides) suggest a multiple reactivation of the fault plane. Normal dip-slip faulting was followed by a transtensive dextral period and rejuvenation as a normal fault during the last event.

The footwall of the fault is made up of lower Jurassic limestone. Occasionally, upper Cretaceous marly limestones, reddish in color, crop out along the fault scarp (Fig. 4A). The hanging wall consists of Quaternary colluvial, sands and paleosols (Fig. 5B). At least five different paleosols are cut and displaced by the normal fault accompanied by liquefaction such as sand blows and craters (Fig. 5A). Three scarp-derived colluvial wedges consisting of coarse limestone debris, each forming a fining-upward sequence, were employed to interpret the faulting history. The colluvial wedges are overlain by wash-element colluvium and brownish and reddish paleosols, whose radiocarbon ages range between 15,900 and 10,100 yr BP. Two paleosol samples yielded AMS-$^{14}$C ages of 2315 ± 30 yr BP (ZAF 1) and 2940 ± 140 yr BP (ZAF 2), and the lower colluvial wedge had an uncalibrated $^{14}$C age of 8720 ±130 yr BP. We sampled the soils above the lower colluvial wedge (Fig. 5A) and the last paleosol below the second wedge in order to bracket the seismic quiescence period of > 600 years of soil formation and accumulation. The distances between the bases of the three wedges were 150 cm from the lower to the middle wedge, and 90 cm from the middle to the upper wedge. The thicknesses of the lower and middle wedges were approx. 50 cm, whilst the upper one was 35 cm thick. A preliminary interpretation of geological trench mapping and dating resulted in the detection of three paleoseismic events during the last 9000 years. Displacement estimates based on the wedge thickness and on the "rule of thumb" of McCalpin (1966) "initial scarp height = 2 x maximum colluvial thickness" provided evidence for three steps of about 100 cm per event, the last event being about 70 cm. According to Bonilla et al. (1984) and Wells and Coppersmith (1994), all three events are related to a coseismic maximum displacement induced by an M > 6 (6.5) earthquake. Similarly, the rupture length (15 km) suggests a magnitude around 6.5 for the 1884 earthquake in accordance with the empirical relations of Wells and Coppersmith (1994). The results are consistent and reflect multiple Holocene activity along one major fault in the central Betics.

### *Ground Penetrating Radar (GPR) Studies*

The Ground Penetrating Radar (GPR) technique is a geophysical tool used in pre-trenching studies. GPR surveys are non-intrusive, rapid, reliable and cheap for mapping of shallow subsurface sediments, hydrologic conditions, and potential geologic hazards (e.g., active faults or groundwater pollution). Neotectonic and paleoseismic investigations combined with GPR studies have been carried out successfully in different climatic and geologic settings. Penetration depth is strongly dependent on the antenna frequency applied, the geophysical parameters of the material studied (permitivity and conductivity), the presence of water-saturated sediments (shallow ground water tables) and on the weather conditions during the investigation. The double channel SIR-10 B system (GSSI) was employed, using 200 MHz

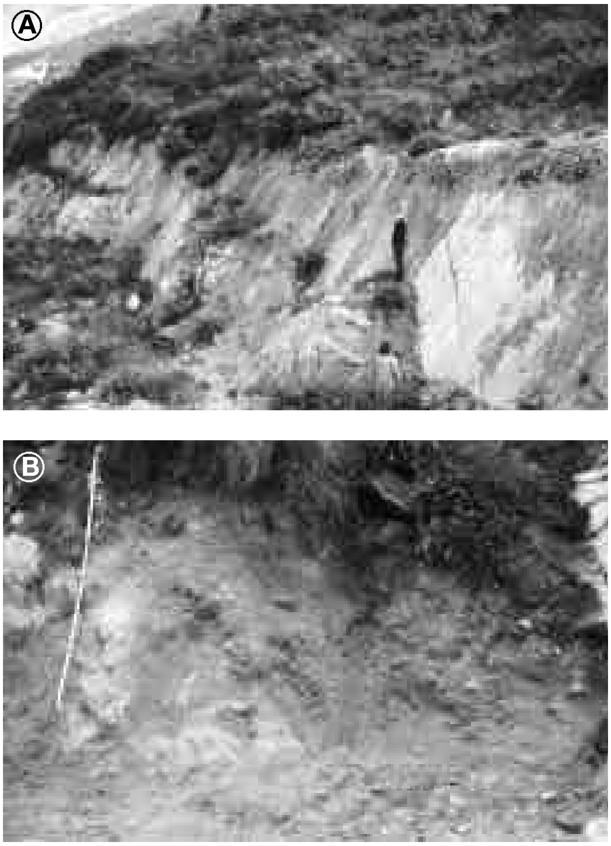

Figure 4. A) Photograph of the Ventas de Zafarraya escarpment of 1884; note intensive human modification on the right side (left is approx. East); B) photograph of the exposure at the cemetery of Ventas de Zafarraya; note fault plane and warped paleosols in the hanging wall (left is approx. East).

Figura 4. A) Fotografía del escarpe de 1884 en Ventas de Zafarraya; nótese las intensas modificaciones debidas a la acción humana en la parte derecha (la izquierda es aprox. el este); B) fotografía del afloramiento junto al cementerio de Ventas de Zafarraya; nótese el plano de falla y los paleosuelos arrastrados en el bloque superior (la izquierda es aprox. el este).

antenna for obtaining sub-surface information of the Ventas de Zafarraya scarp (Fig. 6). No filtering tools were applied. The raw data were interpreted as seismic sections (Meschede et al., 1997). Geological structures in Quaternary and Jurassic limestone deposits across the fault scarp in Ventas de Zafarraya revealed high-resolution data sets which permit interpretation up to a depth of 5m.

A 95 m long profile covers the entire faulted zone (limestone in the SW and Quaternary sediments in the NE), including the studied outcrop section along the western wall of the Ventas de Zafarraya cemetery. Continuous reflectors were interpreted as bedding planes (Fig. 6A). The individual fault planes and associated minor faults were characterized by continuous reflector

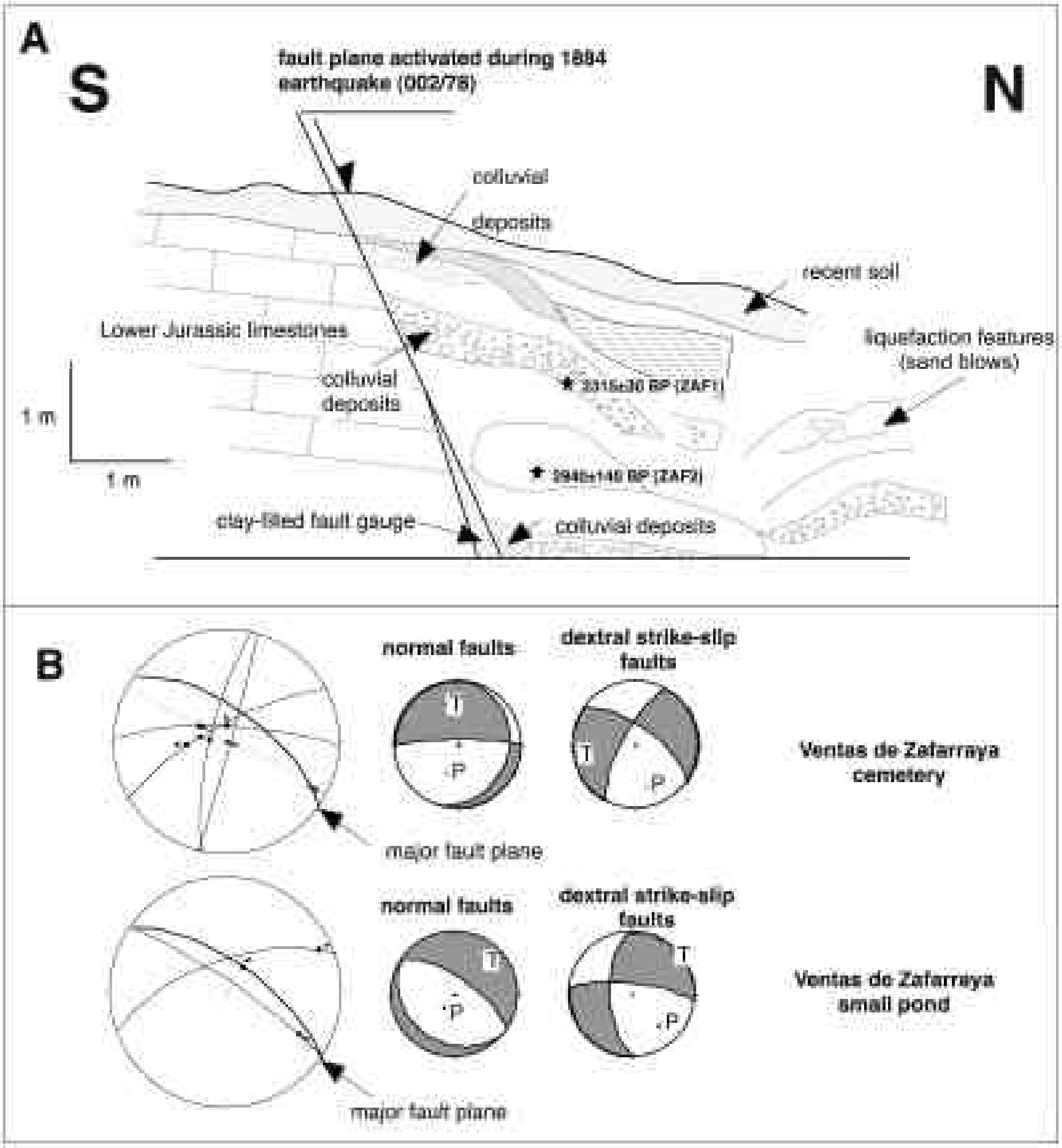

Figure 5. A) Geological field sketch of the Ventas de Zafarraya fault scarp. Asterisks indicate dated paleosol samples above the basal colluvial wedge. B) Stereoplots of the fault planes with multiple slip vectors on the scarp plane, and pseudo-fault plane solutions in accordance with fault-slip data.

Figura 5. A) Esquema geológico de campo del escarpe de falla en Ventas de Zafarraya. Los asteriscos indican las muestras de paleosuelo datadas por encima de la cuña coluvial basal. B) Proyección estereográfica de los planos de falla del escarpe de falla con vectores de deslizamiento múltiples y soluciones de pseudoplanos de falla coherentes con los datos de deslizamiento.

terminations. Varying intensities were attributed to higher water and clay mineral contents, e.g., in the man-made terraces between 45 and 55 m of the section, which produce a multiple that masks deeper signals. The radar patterns in the hanging wall show a significant change in a concave-up pattern, which is interpreted as fault-related half graben sediments. Three major normal faults dipping to the N(E) were identified in the radargram.

A clearer GPR section was obtained approx. 250 m to the west of the cemetery (Fig. 3B), close to a small pond with 200 MHz antenna (Fig. 6B). Twenty-seven meters were screened along this line in the same direction as in profile 1. The major fault was detected and traceable at depth. Concave-upward patterns indicate the half graben filling of the hanging wall.

Briefly, important sub-surface information was obtained. The studied fault scarp and associated minor faults are traceable at depth and distance. The faults truncate and warp the reflections, and juxtapose strata with different dips and contrasting intensities. Diverse reflection patterns suggest a multiple faulting history along the Ventas de Zafarraya fault. Additional evidence will be obtained from a trench section.

### Further paleoseismic evidence in the Granada basin and adjacent areas - a perspective

*Llanos de la Dona*
*(Alhama de Granada, N 37° 01′ 401, W 4° 03′ 490)*

An example of potential coseismic faulting is exposed at Llanos de la Dona, N of Ventas de Zafarraya, and west of Alhama de Granada. A segmented and polished normal fault plane with an approx. 50 cm thick cataclastic fault gouge dipping to the S is traceable for 500-1000 m. The scarp shows no evidence of karstification. The hanging wall exhibits different periods of sudden relief changes, i.e. the formation of colluvial wedges and a paleosol. The outcrop displays two major coarse-grained and fining-upward tapering deposits which are separated by a reddish paleosol, which could provide a reliable age for soil formation.

*Fuensanta (N 37° 10′ 728, W 3° 54′ 825)*

The anticline deforming marls and clays of the upper Messinian to the lower Pliocene (Turolian) located close to Fuensanta (along the national road 342 is affected by domino-style high-angle normal faulting. Reicherter and Michel (1993) ascribed this normal faulting to a basin-wide extension. In a more recent interpretation, these normal faults formed along the outer hinge of an anticline in an overall compressive stress regime (pers. comm. J. Galindo-Zaldívar). In earlier interpretations, the Quaternary sediments sealed the faults (Reicherter and Michel, 1993; pers. comm. P. Ruano). By contrast, our investigations show that some of the normal faults continue in the Quaternary sediments with vertical displacements of up to 45 cm. Georadar investigations and paleosol sampling are currently in progress.

*Sierra Elvira*
*(Tajo Colorado, N 36° 45′ 623, W 3° 43′ 000)*

Other seismogenic faults have been found between Pinos Puente and Atarfe along the NW-SE striking fault scarp of the sierra Elvira. Moderate and major earthquakes occurred in this area (Table 1). A dip-slip fault with a recent scarp is crossed by the main road and used for agriculture. In the "Tajo Colorado" quarry, the steeply dipping to vertical fault plane is exposed, separating lower Liassic limestone in the footwall from Quaternary colluvial deposits in the hanging wall. A section perpendicular to the scarp exhibits several fining-up cycles in the coarse grained colluvial debris of the hanging wall. Dating of intercalated soils is currently in progress.

Further paleoseismic evidence has been found in the Torcal massif along the NW-SE trending border fault (N 36° 58′ 599, W 4° 30′ 178). Here, Jurassic limestone, occasionally overlain by upper Cretaceous marly limestone, reddish in color, forms the footwall. The hanging wall is made up of coarse grained red debris without paleosols. The relatively fresh and unkarstified fault plane was reactivated, as is evidenced by various generations of calcite fibers on slickensides. A sinistral strike-slip period was followed by oblique normal faulting. No exact timing of the faulting events is currently available. Douvillé (1906) suggested that the prolongation of the Ventas de Zafarraya fault could be found in the Torcal-El Chorro corridor.

## DISCUSSION AND CONCLUSIONS

Our paleoseismic studies in the Betics are currently focused on (1) the Granada basin and on several minor

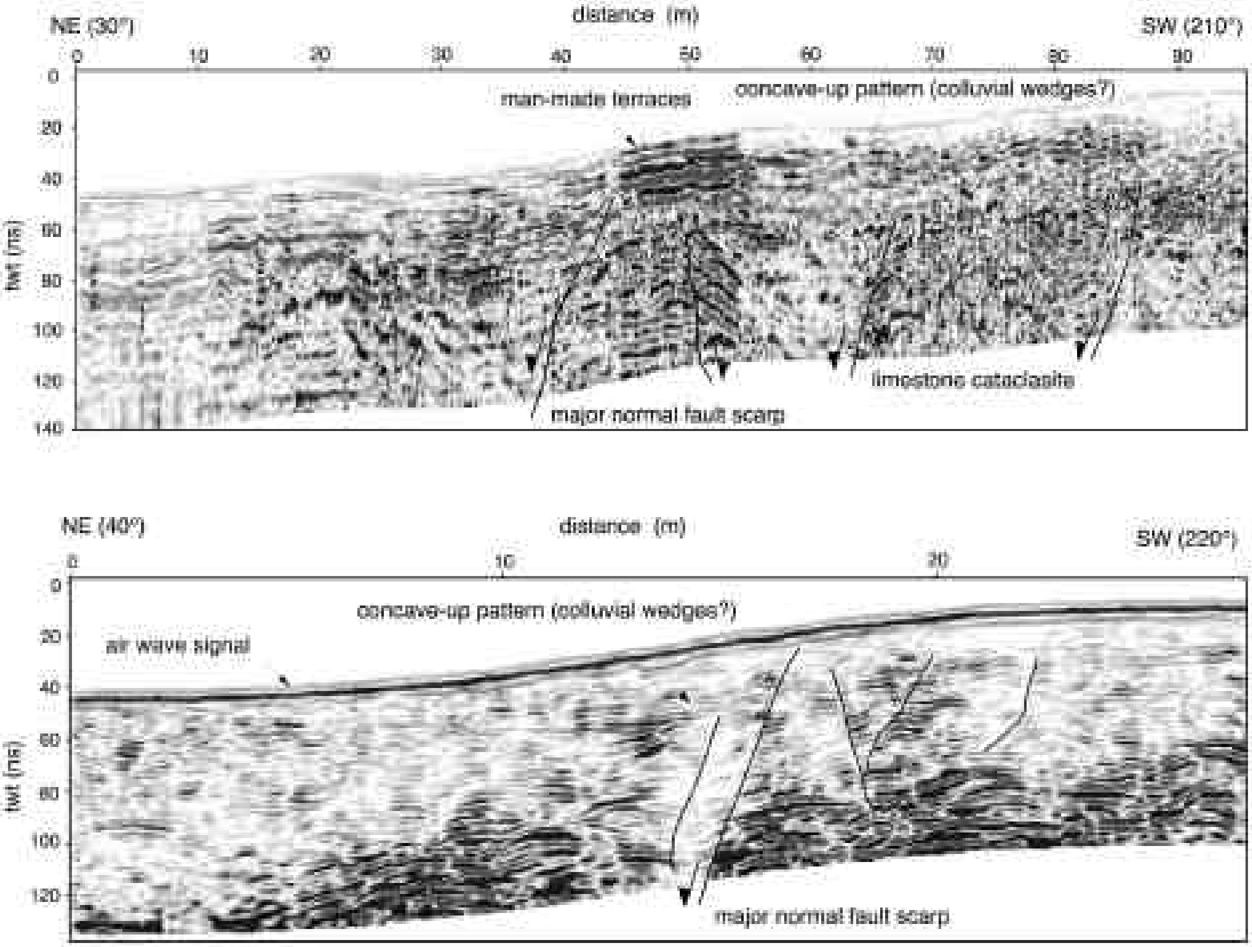

Figure 6. A) Ground penetrating radar (GPR) section of the Ventas de Zafarraya fault scarp with 200 MHz antenna, located at the cemetery (see Fig. 3). Section is topographically restored. Vertical exaggeration (20 ns TWT refers to approx. 1 m) and penetration depth is around 5 m. Multiple faults in limestone bedrocks and halfgraben filling (concave-up patterns). B) GPR section of the Ventas de Zafarraya fault scarp with 200 MHz antenna; locality is approx. 250 m west of cemetery (see Fig. 3B). Section is topographically restored. Note vertical exaggeration. Penetration depth is around 5 m.

Figura 6. A) Sección de georradar (GPR), con una antena de 200 MHz, del escarpe de falla en Ventas de Zafarraya junto al cementerio (véase Fig. 3). La sección ha sido restituidada topográficamente. Exageración vertical (20 ns TWT corresponden aprox. a 1 m) y la profundidad de penetración es de unos 5 m. Múltiples fallas en las calizas del sustrato y relleno de semifosa (patrones cóncavos hacia arriba). B) Sección GPR, con antena de 200 MHz, del escarpe de falla de Ventas de Zafarraya, localizado aprox. a unos 250 m al oeste del cementerio (véase Fig. 3B). La sección ha sido restituida topográficamente. Nótese la exageración vertical. La profundidad de penetración es de unos 5 m.

outcrops in the adjacent Neogene basins (Fig. 1 A and B), (2) the Campo de Gibraltar, (3) the Carboneras fault zone (Prov. of Almería) and (4) the Roman ruins of Baelo Claudia close to Tarifa (Prov. of Cádiz). The Ventas de Zafarraya fault is one of the major E-W-trending faults and has produced at least three strong events in the last 9000 years. GPR profiling across active faults constitutes an additional tool for detecting and tracing sub-surface structures related to coseismic faulting. The colluvial wedges exposed in several hanging walls of faults may provide solid evidence of seismic activity. However, these findings must be viewed with caution and supplementary data besides rupture length, liquefaction and ruptured pebbles should also be taken into account. The results of Ventas de Zafarraya show an important correlation with the Holocene climate. The interval of soil formation found in the Ventas de Zafarraya scarp between 3000 and 2000 yr BP correlates with a period of a moderately

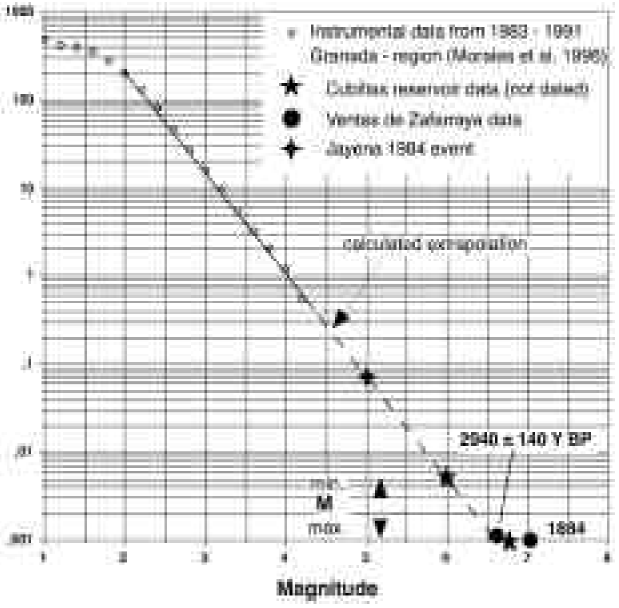

Figure 7. Annual cumulative frequency-magnitude for the Granada basin derived from instrumental data (Morales et al., 1996), supplemented by the 1884 event of Arenas del Rey and the Jayena 1984 event. The paleoseismologically investigated Ventas de Zafarraya and Cubillas fault data (Reicherter et al., 1999) are plotted on the calculated extrapolation and show that the seismic cycle for the study region is incomplete.

Figura 7. Relación magnitud-frecuencia acumulativa anual, de la cuenca de Granada, basada en los datos instrumentales (Morales et al., 1996) complementados con los eventos de 1884 de Arenas del Rey y de 1984 de Jayena. Los datos paleosísmicos investigados referentes a las fallas de Ventas de Zafarraya y Cubillas se han representado junto con la extrapolación calculada, lo que muestra que el ciclo sísmico de la región estudiada es incompleto.

humid climate and with the start of an aridification phase (Jalut et al., 2000).

A preliminary frequency/magnitude distribution based on instrumental seismicity data (Morales et al., 1996) has been used to estimate the potential of large earthquakes in the area (Fig. 7). This distribution suggests recurrence rates for M 6 earthquakes in the Granada region in the order of 100 years, and for M 7 earthquakes in the order of 1000 years (Morales et al., 1996). This recurrence rate is significantly higher than earlier estimates (e.g., Muñoz and Udías, 1983). In summary, it is evident that (1) seismic deformation in the Granada basin and other parts of the Betics is distributed along a number of faults and (2) that the seismic cycle for the study area is incomplete. Further investigation will be focussed on the different segments along related fault zones and on their past and present activity.

A record of the moderate to strong earthquakes during the last 2000 years suggests the existence of even more active faults and coseismic ruptures in the Betic Cordilleras (Table 1). Clearly, the history of pre-historical earthquakes in southern Spain demands further scrutiny with particular emphasis on the secondary effects that are evidenced by diverse geological phenomena, such as tsunami deposits or paleo-landslides. Despite being well known in the Betic Cordillera (e.g., on Costa de la Luz), these features still await a systematic paleoseismic study. The bias that results from the sole consideration of strong earthquakes in the seismic catalogues and calculations distorts the risk assessment of this highly active seismic zone. Furthermore, active faults and their associated seismogenic deformation are distributed in the Betics, which hinders the calculation of recurrence rates of strong earthquake along discrete faults.

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## APPENDIX

Selected historical earthquakes which may have produced surface ruptures in the Betic Cordilleras. Data selection and compilation from: von Lasaulx (1885), Gentil and Justo (1983), Bisbal Cervelló (1984); Mezcua and Udías (1991, eds.); López Casado et al. (1995); in the web: Significant Earthquakes World Wide (NOAA); www.ign.es; www.ugr.es/iag; www.seismology.harvard. edu/CMT, www.ua.es/ursua/; www.galbis.org/sismicidad/. Note that pre-instrumental M* values were calculated after Karnik (1971); see also discussion in López Casado et al. (1995). Information on earthquakes which occurred in 1775, 1777, 1778, 1783, 1790, 1822, 1823, 1824, 1826, 1836 and 1841 in Andalucía (in: von Lasaulx, 1885; after Hoff and Perrey) is not available, and therefore not listed in Table 1.

Table 1. Historical earthquakes (MSK intensity > VII) in southern Spain and adjacent areas.

Tabla 1. Sismos históricos (Intensidad MSK >VII) del sur de España y áreas adyacentes.

| DATE | INTENSITY (MSK) | LOCALITY | REMARKS |
|---|---|---|---|
| 250 (?) | VII-?X | Cádiz, Bolonia (Tarifa) | Roman cities destroyed, gulf of Cádiz |
| 26.5.881 | X | unknown (near Córdoba?) | (?880) |
| 10.6.881 | IX-(XI) | unknown (near Córdoba?) | |

| DATE | INTENSITY (MSK) | LOCALITY | REMARKS |
|---|---|---|---|
| | | | |
| 881 | X-XI | | Gulf of Cádiz |
| 3.7.944 | VII | Córdoba | |
| 9.955 | VIII | Córdoba | |
| 957 | | Córdoba | |
| 971 | | Córdoba | |
| 20.5.973 | | Córdoba | |
| 9.11.974 | | Córdoba | |
| 1009 | | | Lisbon and S of Spain |
| 1013-1014 | | | E coast of Andalucía |
| ?1024-1025 | VII-IX? | Córdoba | between 15.3.1024-15.3.1025 |
| 1048-1049 | IX? | Vera (AL) | Vera basin, Neogene (N 37.2, W 1.9) |
| 1079-1080 | VIII-(X) | unknown (Sevilla?) | (Açores-Gibraltar fault?, Morocco?) |
| 1169-1170 | VII-VIII (IX-X?) | Andújar (J) | |
| 1356 (57) | VIII, M* 5.5 | Sevilla? | Andalucía |
| 18.12.1396 | IX, M* 6.2 | Tabernes (V) | (N 39.2, W 0.2) |
| 1406 | VIII-IX? | Vera (AL) | (N 37.3, W 1.9) |
| 24.4.1431 | VIII (IX), M* 5.5 | Atarfe (GR) | Granada basin, Neogene (N 37.2, W 3.6) |
| 1466 | VIII, M* 5.5 | Carmona | (N 37.4, W 5.6) |
| 10.10.1482 | IX | Orihuela (A) | (N 38.1, W 0.9) |
| 1484 | VIII | Orihuela (A) | (N 38.1, W 0.9) |
| 11.1487 | VIII-IX | Almería | Internal Zone (N 36.9, W 2.5) |
| 26.1.1494 | VIII-IX, M* 5.5 | Málaga | Internal Zone (N 36.7, W 4.4) |
| 5.4.1504 | IX, M* 6.2 | Carmona (SE) | (N 37.4, W 5.6) |
| 9.11.1518 | IX, M* 6.2 | Vera (AL) | Vera basin, Neogene (N 37.2, W 1.9) |
| 11.1519 | VIII, M* 5.5 | Játiva (V) | (N 37.2, W 0.5) |
| 22.9.1522 | IX, M* 6.2 | Almería | Alborán sea, Neogene (N 36.9, W 2.5) |
| 1523 | VIII, M* 5.5 | Guardamar (A) | (N 38.1, W 0.6) |
| 4.7.1526 | VII-VIII, M* 5.5 | Granada | Granada basin, Neogene (N 37.2, W 3.6) |
| 13.4.1529 | VI | Almería | (N 36.9, W 2.5) |
| 30.9.1531 | (VIII) IX, M* 5.5 | Baza (GR) | Baza basin, Neogene (N 37.5, W 2.8) |
| 22.6.1544 | VII | Guadalest (A) | (N 38.7, W 0.2) |
| 29.8.1547 | VIII | Concentaina (A) | (N 38.8, W 0.8) |
| 30.1.1579 | VIII, M* 5.5 | Lorca (MU) | (N 37.7, W 1.7) |
| 18.6.1581 | VII-VIII, M* 5.5 | Sierra de Alhama (MA) | Internal Zone (N 36.7, W 4.4) |
| 26.12.1598 | VIII | Oliva (V) | (N 38.9, W 1.1) |
| 1.1599 | VII | Gandia (V) | (N 39.0, W 0.1) |
| 21.3.1608 | VII-VIII, M* 5,5 | Sevilla | |
| 2.12.1620 | VIII, M* 5.5 | Alcoy (A) | (N 38.7, W 0.4) |
| 26.6.1644 | VIII (IX), M* 6.2 | Alcoy (A) | (N 38.7, W 0.4) 1645? |
| 7.6.1656 | VIII | Ademuz (V) | (N 40.1, W 1.2) |
| 31.12.1658 | VIII, M* 5.5 | Almería | (N 36.9, W 2.5) |
| 15.1.1673 | VIII | Orihuela (A) | (N 38.1, W 0.9) |
| 10.8.1674 | VII | Lorca (MU) | (N 37.7, W 1.7) |
| 28.8.1674 | VIII, M* 5.5 | Lorca (MU) | (N 37.7, W 1.7) |
| 29.8.1674 | VII | Lorca (MU) | (N 37.7, W 1.7) |
| 9.10.1680 | IX, M* 6.2 | Málaga, (Alhaurin) | Internal Zone, (N 36.7, W 4.4) |
| 1668 | VII-VIII | Alcalá La Real (J) | Subbetic (N 37.7, W 3.8) |
| 1724 | VIII, M* 5.5 | Sevilla | |
| 13.9.1724 | VII | Gandía (A) | (N 39.0, W 0.1) |
| 16.4.1730 | VII | Elche (A) | (N 38.5, W 0.7) |
| 9.3.1743 | VII | Murcia | (N 38.0, W 1.1) |
| 15.8.1746 | VII | Rojales (A) | (N 38.1, W 0.7) |
| 23.3.1748 | IX, M* 6.2 | Enguera (V) | (N 39.0, W 0.6) |
| 2.4.1748 | VIII, M* 5.5 | Enguera (V) | (N 39.0, W 0.6) |
| 4.3.1751 | VII | Vélez Rubio (AL) | (N 37.6, W 2.1) |
| 1.11.1755 | X-(XI) | Lisbon | E Atlantic, southern Spain |
| 17.7.1767 | VII | Málaga | (N 36.7, W 4.4) |
| 17.8.1787 | VII | Elche (A) | (N 38.5, W 0.7) |
| 31.8.1792 | VII-VIII | Melilla | (N 35.3, W 3.0) |
| 18.1.1802 | VII | Torrevieja (A) | (N 38.0, W 0.6) |
| 13.1.1804 | VIII | Motril (GR) | Internal Zone (N 36.7, W 3.5) |
| 25.8.1804 | IX, M* 6.2 | Dalías (AL) | (N 36.8, W 2.8) |
| 1804 | VIII, M* 5.5 | Dalías, Adra (AL) | (N 36.8, W 2.8) |

| DATE | INTENSITY (MSK) | LOCALITY | REMARKS |
|---|---|---|---|
| 27.10.1806 | VIII-(IX?), M* 5.5 | Santa Fé (GR) | Granada basin, Neogene (N 37.2, W 3.7) |
| 20.12.1819 | VII | Lorca (MU) | Internal Zone, (N 37.7, W 1.6) |
| 8.4.-9.5.1821 | VII-VIII | Melilla | (N 36.5, W 3.0) |
| 15.9.1828 | VII | Torrevieja (A) | (N 38.0, W 0.6) |
| 21.3.1829 | X | Torrevieja (A) | (N 38.0, W 0.6), M = 7 event, NOAA |
| 18.4.1829 | VII | Torrevieja (A) | (N 38.0, W 0.6) |
| 31.10.1837 | VII | Torrevieja (A) | (N 38.0, W 0.6) |
| 3.10.1845 | VII | Tivisa (T) | (N 41.0, E 0.7) |
| 3.10.1848 | VII | Tramacastilla (Teruel) | (N 40.5, W 1.5) |
| 10.11.1852 | VII | Benigámin (V) | (N 38.9, W 0.4) |
| 10.6.1863 | VII | Huércal-Overa (AL) | (N 37.4, W 1.9) |
| 19.6.1863 | VII | Huércal-Overa (AL) | (N 37.4, W 1.9) |
| 3.2.1867 | VII | Torrevieja (A) | (N 38.0, W 0.6) |
| 19.5.1872 | VII | Carlet (V) | (N 39.2, W 0.5) |
| 8.1.1883 | VII | Archena (MU) | (N 38.1, W 1.3) |
| 16.1.1883 | VII | Ceuti (MU) | (N 38.0, W 0.6) |
| 14.4.1883 | VII | Villanueva (V) | (N 39.1, W 0.5) Villanueva de Castelló |
| 11.6.1883 | VII | Villanueva (V) | (N 39.1, W 0.5) Villanueva de Castelló |
| 25.12.1884 | X | Arenas del Rey (GR) | Granada basin, Neogene, M = 6,7 event, NOAA (N 36.9, W 4.0) |
| 29.12.1884 | VII-VIII | Arenas del Rey (GR) | (N 36.9, W 4.0) |
| 31.12.1884 | VIII | Torrox (MA) | (N 36.7, W 4.0) |
| 27.1.1885 | VII-VIII | Alhama de Granada (GR) | Granada basin, Neogene (N 37.0, W 4.0) |
| 14.3.1886 | VII-VIII | Loja (GR) | Granada basin, Neogene (N 37.2, W 4.1) |
| 5.5.1902 | VII | Murcia | (N 38.0, W 1.2) |
| 16.4.1907 | VII | Totana (MU) | (N 37.8, W 1.3) |
| 29.9.1908 | VII | Ojos (MU) | (N 38.1, W 1.2) |
| 21.2.1909 | VII | Crevillente (A) | (N 38.3, W 0.7) |
| 1.7.1909 | VII | Torrevieja (A) | (N 38.0, W 0.6) |
| 16.6.1910 | VIII, M 6.3, M* 5.5 | Adra (AL) | (N 36.7, W 3.1) |
| 21.3.1911 | VIII, M 5.5, M* 5.5 | Cotillas (MU) | (N 38.0, W 1.2) |
| 3.4.1911 | VIII, M* 5.5 | Lorqui (MU) | (N 38.1, W 1.1) |
| 10.5.1911 | VII | Lorqui (MU) | (N 38.1, W 1.1) |
| 16.5.1911 | VII | Lorqui (MU) | (N 38.1, W 1.1) |
| 31.5.1911 | VIII, M 4.9, M* 5.5 | Santa Fé (GR) | Granada basin, Neogene (N 37.2, W 3.7) |
| 25.11.1913 | VII | Huescar (GR) | (N 38.4, W 2.5) |
| 28.11.1916 | VII | Salinas (A) | (N 38.4, W 1.0) |
| 28.1.1917 | VII | Torres de Cotillas (MU) | (N 38.2, W 1.2) |
| 10.9.1919 | VIII, M 5,2, M* 5.5 | Almoradí, Jacarilla (A) | (N 38.1, W 0.9) |
| 1919 | VII, M 5.1 | Almoradí, Jacarilla (A) | (N 38.1, W 0.9) |
| 5.7.1930 | VIII, M 5.3, M* 5.5 | Montilla (CO) | (N 37.6, W 4.7) |
| 5.3.1932 | VII, M 4.7, M* 5.5 | Lúcar (AL) | (N 37.4, W 2.4) |
| 1935 | V, M 5.0 | Benamejí | |
| 1.7.1945 | VII | Onteniente (V) | (N 38.5, W 0.4) |
| 23.6.1948 | VIII, M 4.7, M* 5,5 | Cehegín (MU) | (N 38.1, W 1.9) |
| 10.3.1951 | VIII, M 5.0 | Bailén; Linares (J) | (N 38.1 W 3.8) |
| 19.5.1951 | VIII, M 5.5 (5.1) | Alcaudete (J) | (N 38.1 W 3.7) |
| 8.1.1954 | VII-VIII, M 4.2, M* 5.5 | Arenas del Rey (GR) | (N 36.9, W 4.0) |
| 29.3.1954 | VII-VIII, M 7.0 | Granada, Durcal (GR) | Granada basin, Neogene (N 37.2, W 3.6) |
| 1955 | VII, M 5,1 | La Zubia (GR) | |
| 19.4.1956 | VIII, M 5.0, M* 5,5 | Albolote (GR) | (N 37.2, W 3.7) |
| 9.6.1964 | VIII, M 4.8, M* 5,5 | Orce-Galera (GR) | (N 37.7, W 2.6) |
| 1976 | IV, M 5.4 | Alora (MA) | |
| 24.6.1984 | VII, M 5.2 | Jayena (GR) | (N 36.8, W 3.7) |
| 13.8.1984 | VII, M 5.0 | | (N 37.0, W 2.3) |
| 26.5.1985 | VII, M 5.0 | | (N 37.8, W 4.6) |
| 23.3.1993 | VII, M 5.0 | Berja (AL) | (N 36.7, W 3.1) |
| 4.1.1994 | VI-VII, M 4.9 | Costa de Balemra (AL) | (N 36.6, W 2.8) |
| 2.2.1999 | VII, M 5.0 | Mula (MU) | (N 38.8, W 1.2) |