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Evidence for the activity and paleoseismicity of the Padul fault (Betic Cordillera, southern Spain)

Evidencias de actividad y paleosismicidad de la falla de Padul (Cordillera Bética, sur de España)

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ABSTRACT

There is evidence of recent tectonic activity in the proximity of Padul, in the central sector of the Betic Cordillera. The principal active fault in this region is the Padul normal fault, running NW-SE, which displays spectacular geomorphological and structural features owing to its recent activity. However, there is no evidence of earthquakes of moderate-high magnitude occurring in this area during the historical or the instrumental period. In the vicinity of Padul we identified various soft-sediment deformation structures produced by liquefaction which we attributed to seismic shocks of a moderate-high magnitude. These structures are situated in detritic sediments, intercalated with layers of peat, which have enabled dating of these paleoearthquakes to the late Pleistocene (approx. 30,000 to 35,000 yr BP). Moreover, field observations in sediments of alluvial fans in the vicinity of the Padul fault, together with a retrodeformation analysis of an outcrop, enabled various deformation events to be dated to the recent Quaternary period.

Keywords: Paleoseismicity. Paleoliquefaction. Granada basin. Padul normal fault.

RESUMEN

En el área de Padul, localizada en el sector central de la Cordillera Bética, existen numerosas evidencias de actividad tectónica reciente. La principal falla activa de la región es la falla normal de Padul, de dirección NW-SE, que presenta evidencias geomorfológicas y estructurales espectaculares de su actividad reciente. Sin embargo, no se tiene constancia de la ocurrencia de terremotos de magnitud moderada-alta en el área de Padul ni durante el periodo histórico ni el instrumental. En este sector hemos identificado varias estructuras sedimentarias de deformación producidas por licuefacción que interpretamos como resultado de sacudidas sísmicas de magnitud moderada-alta. Estas estructuras se localizan en sedimentos detríticos intercalados con niveles de turba que han permitido datar estos paleoterremotos como Pleistoceno superior (aproximadamente entre 30.000 y 35.000 años B.P.). Por otra parte, las observaciones de campo realizadas en algunos sedimentos de los abanicos aluviales de la zona de falla de Padul y el análisis de retrodeformación en un afloramiento han permitido identificar varios eventos de deformación durante el Cuaternario reciente.

Palabras clave: Paleosismicidad. Paleolicuefacción. Cuenca de Granada. Falla normal de Padul.

INTRODUCTION

The Granada basin, which is situated in the central sector of the Betic Cordillera, is one of the most seismically-active areas in the Iberian Peninsula (Fig. 1). Small-magnitude earthquakes characterize the instrumental seismic activity documented in the region; data have been recorded since 1983 by the Andalusian Seismic Network (Alguacil et al., 1990). Occasionally there have been seismic series and seismic swarms, characterized by small-magnitude earthquakes, none of which has been related to a large earthquake (Galindo-Zaldívar et al., 1999). In the Granada basin, the earthquakes have been mainly distributed in the upper crust, between 9 and 16 km depth in the eastern part, and between 9 and 25 km in the western part (Morales et al., 1997). Although no seismic event of a moderate-high magnitude has been recorded in the Granada basin during the instrumental period, such occurrences should not be ruled out given the existence of various historical earthquakes (Vidal, 1986). The Andalusian earthquake (1884) stands out amongst these historical earthquakes. This was the most recent catastrophic earthquake recorded in the Iberian Peninsula, with a maximum M.S.K. intensity of X and an estimated magnitude of 6.5-6.7 (Muñoz and Udías, 1991). In addition to this historical earthquake, there is also evidence of similar moderate to high-magnitude earthquakes in the basin since at least the late Miocene. This has been deduced by the presence of various upper Miocene-Pliocene layers of seismites in the sedimentary fill of the Granada basin (Rodríguez-Fernández, 1982).

Seismic activity in the Granada depression has been linked to the convergence of the Eurasian and African plates (Argus et al., 1989). From a geodynamic point of view the basin is currently subject to a compressive stress field running NW-SE with an associated NE-SW extension (Galindo-Zaldívar et al., 1999). Since the late Miocene, σ_1 and σ_2 have exchanged positions on repeated occasions, accounting for the spatial and temporal coexistence of compression and extension running NW-SE. Both the geological structures and the analysis of focal mechanisms highlight the complex regional stress field in the upper crust of the central Betic Cordillera.

The extension is produced by normal faults with various orientations, but particularly with a NW-SE strike (the Granada, Dílar and Padul faults, amongst others). These NW-SE faults exhibit numerous signs of recent activity (fault scarps, triangular facets, deformed alluvial fans, fractured pebbles on fault planes, etc.) (Fig. 2) (Lhénaff, 1965; Estévez and Sanz de Galdeano, 1983; Riley and Moore, 1993; Calvache et al., 1997; Sanz de Galdeano and López Garrido, 1999), especially in the neighborhood of Padul (in the south-eastern part of the Granada basin), which is the area considered in this study. In this sector, which is located on the western edge of the Sierra Nevada, Sanz de Galdeano (1996) and Keller et al. (1996) estimated a mean uplift of 0.4 mm/yr, occasionally rising to 0.84 mm/yr, by comparing the different heights of Pleistocene rocks affected by faults. According to these authors, the age of the displacement of the Quaternary Alhambra formation, which crops out in the vicinity of the city of Granada, is not older than 0.5 Ma.

Of the various NW-SE active normal faults in the region, the Padul fault, which is also known as the Padul-Nigüelas fault (Doblas et al., 1997), stands out (Figs. 2 and 3). Despite ample geological evidence of recent tectonic activity in this part of the Granada basin, there is no evidence of moderate to high-magnitude earthquakes. Nor have any studies on the paleoseismology of the region been carried out.

This paper presents the results of a study undertaken in the Padul area to identify possible moderate to high-magnitude paleoearthquakes which may have occurred during the Quaternary. Part of the study was an analysis of the most recent, Holocene deposits, which are exposed in excavations currently being dug in the peat beds of Padul. Another part of the study was focussed on various sections of Quaternary sediments in the vicinity of the

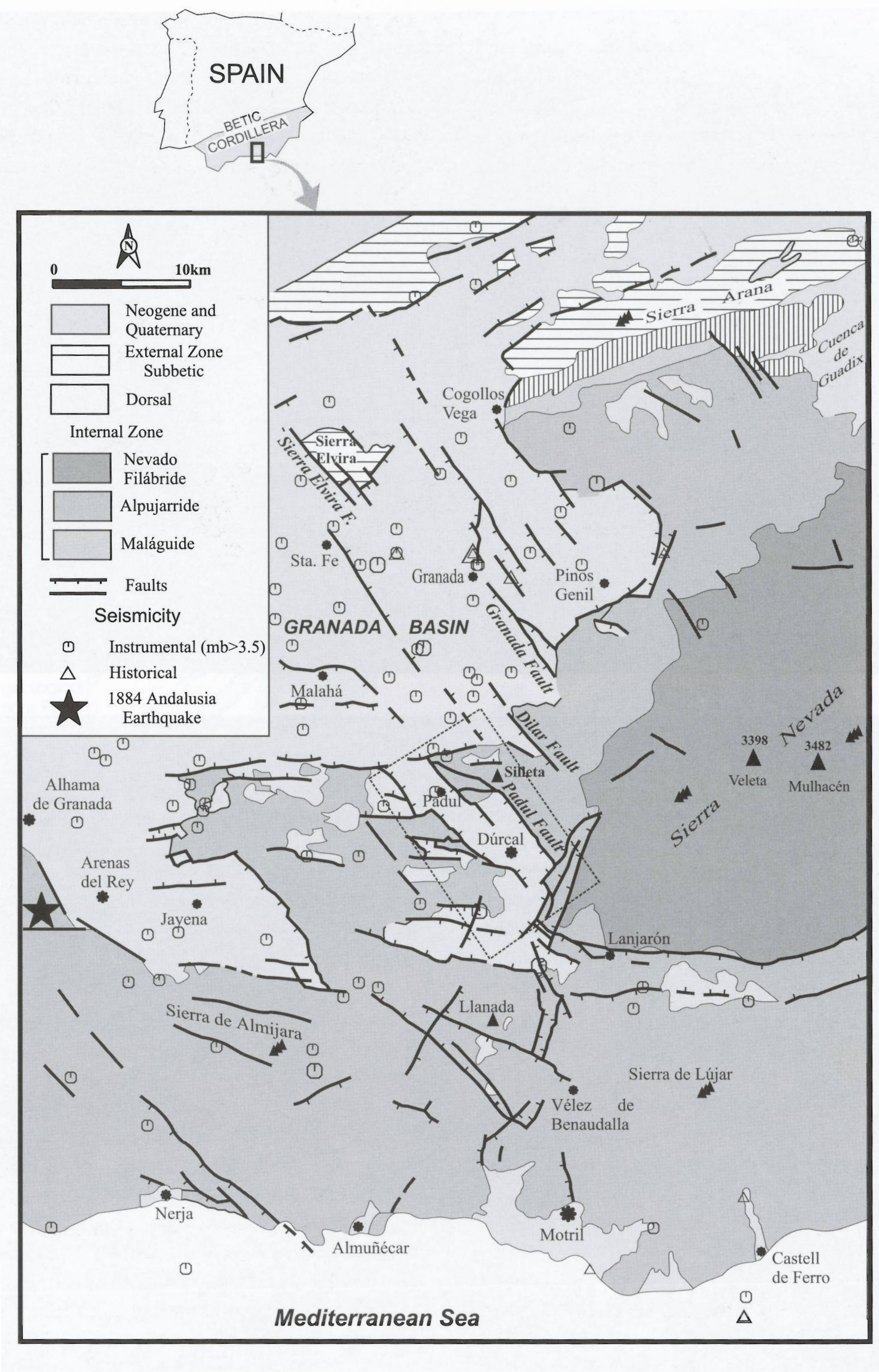

Figure 1. Geological map of the western sector of Sierra Nevada (Betic Cordillera, southern Spain). The rectangle with dashed line indicates position of Fig. 2. Historical (I>VII) and instrumental (mb>3.5) seismicity is also represented.

Figura 1. Mapa geológico del sector occidental de Sierra Nevada (Cordillera Bética, sur de España). La localización de la Fig. 2 se ha representado con un rectángulo de línea discontínua. También se ha representado la sismicidad histórica (I>VII) e instrumental (mb>3,5).

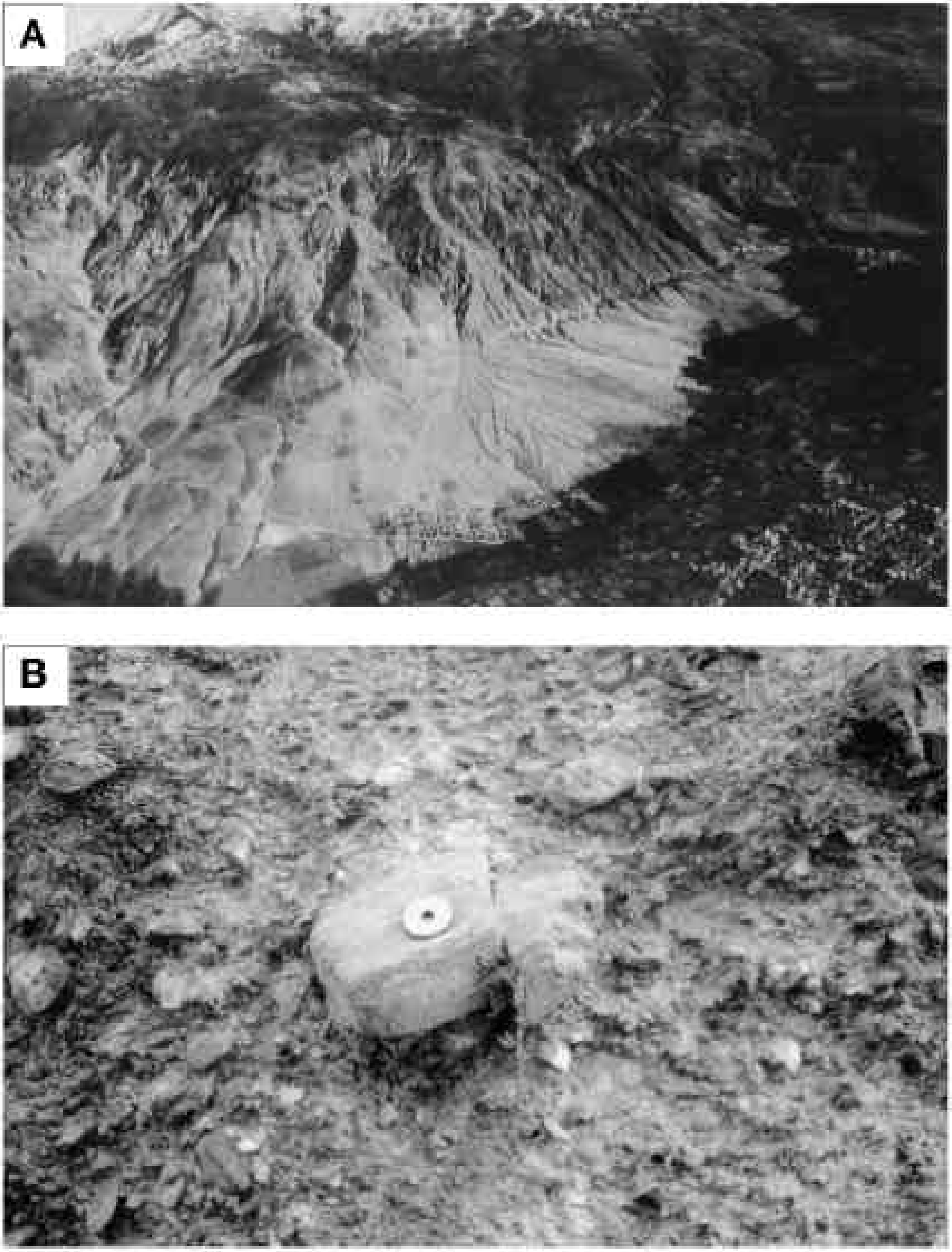

Figure 2. A. Panorama of the Padul fault. Courtesy of F. Aldaya. B. Pebble fractured by a normal fault situated to the SE of the Padul fault.

Figura 2. A. Panorámica de la falla de Padul. Cortesía de F. Aldaya. B. Canto fracturado por una falla normal situada al SE de la falla de Padul.

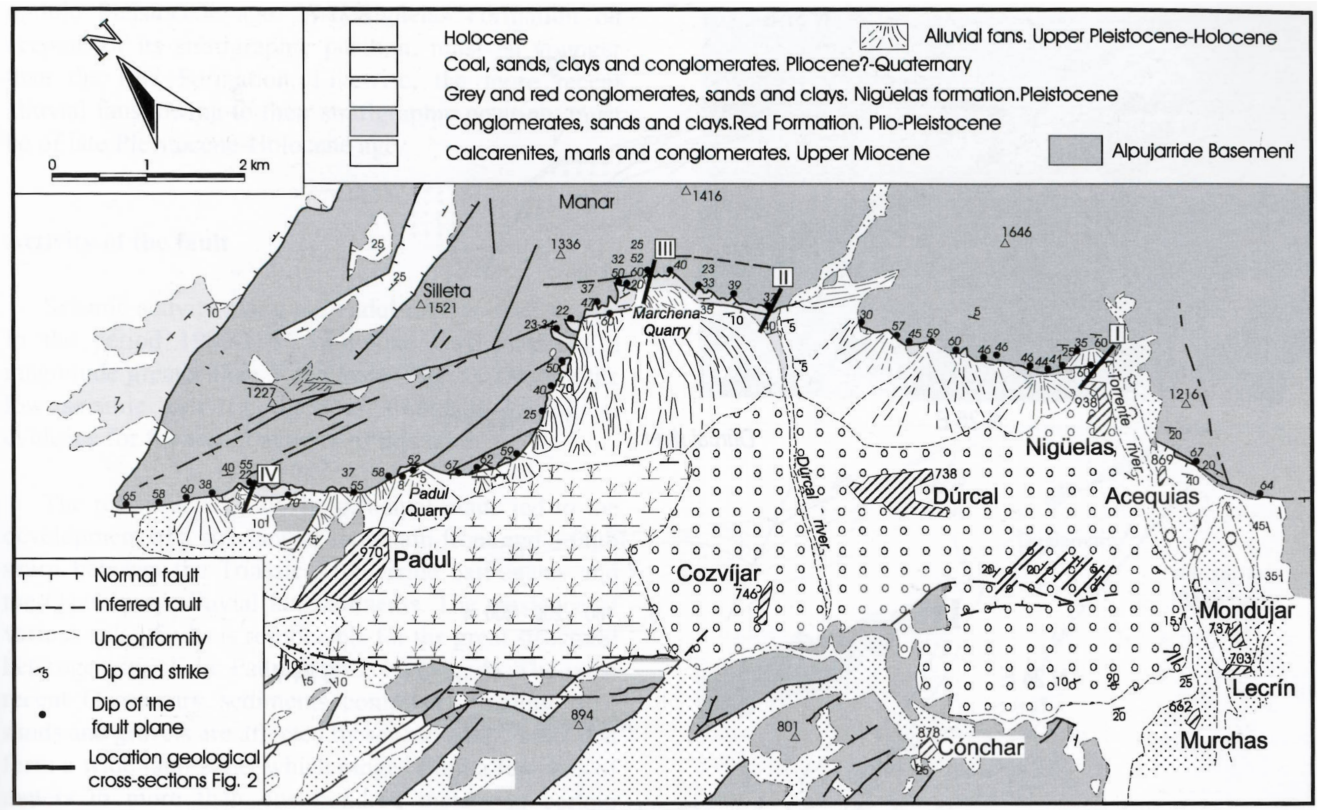

Figure 3. Geological map of the study area, showing the extensional Padul-Nigüelas basin and the Padul fault.

Figura 3. Mapa geológico del área de estudio, en el que están representados la cuenca extensional de Padul-Nigüelas y la falla de Padul.

Padul fault; in particular, two sections situated in the abandoned quarry at Marchena (Fig. 3). A retrodeformation analysis was made in one of these sections.

THE PADUL FAULT

Geological context

The normal fault of Padul is situated on the western edge of the Sierra Nevada in the Internal Zone of the Betic Cordillera (Fig. 3) which, in this sector, is made up of metamorphic Triassic dolomites, from the Alpujarride Complex. The Padul fault is approximately 12 km long with an average NW-SE strike and has various segments which dip towards the SW and S.

On the surface, the main fault plane separates the Alpujarride basement from detritic sediments Quaternary and Plio-Quaternary in age. On the hanging wall, the activity of this fault gave rise to the Padul-Nigüelas extensional basin (Sanz de Galdeano, 1976; Santanach et al., 1980) (Fig. 3). The most recent alluvial sediments that fill the basin, dating from the Pliocene to Holocene, can be grouped into various formations which lie over the late Miocene sedimentary rocks and the Alpujarride basement (Sanz de Galdeano, 1996) (Fig. 3). The base consists of reddish-brown alluvial clays, sands and conglomerates which make up the Red Formation. Above these rocks are conglomerates containing large gray and reddish boulders whose deposition is related to drainage of the Torrente river (Nigüelas Formation). In the uppermost part are the most recent alluvial fans which developed along the north-eastern edge of the basin. All the alluvial deposits change laterally to lacustrine and marsh deposits which crop out in the north-western sector close to Padul.

Except for the upper Miocene rocks and the upper layers of peat which have been dated using ^{14}C, direct ages are not available for the materials that fill the basin. The Red Formation correlates with the Alhambra Formation, to which Aguirre (1957) assigned an early-

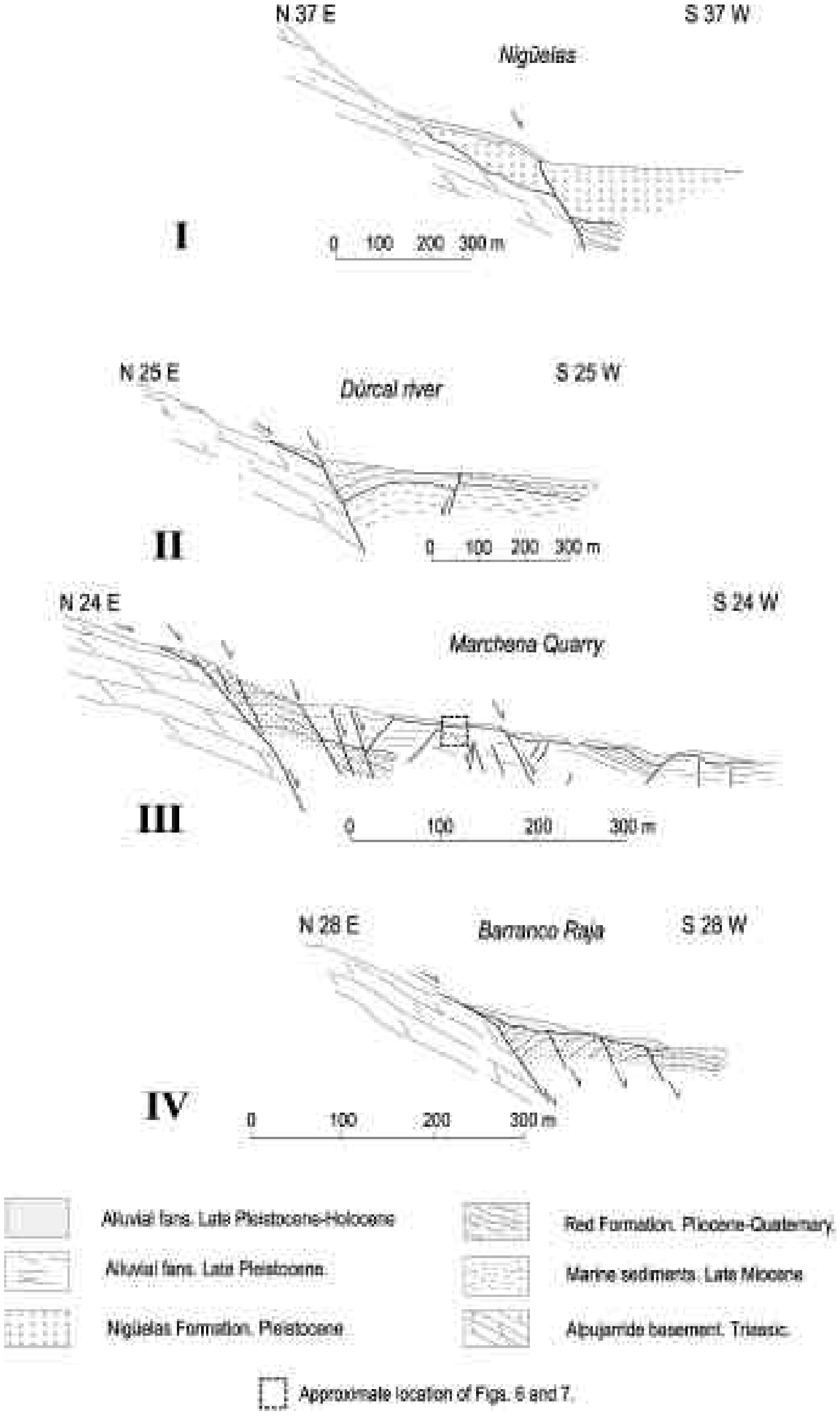

Figure 4. Geological cross-sections from the Padul fault zone. For location, see Fig. 3.

Figura 4. Cortes geológicos de la zona de falla de Padul. Están localizados en la Fig. 3.

middle Pleistocene age. The Nigüelas Formation on account of its stratigraphic position, must be younger than the Red Formation. Likewise, the more recent alluvial fans, owing to their stratigraphic position, must be of late Pleistocene-Holocene age.

Activity of the fault

Seismic activity along the Padul fault is very scarce. In the period 1980-1996 only one earthquake of a magnitude greater than 3 occurred (Fig. 1). Despite the low seismic activity, there is abundant geological evidence for the recent activity of this fault.

The recent activity of the principal plane led to the development of a spectacular mountain front and a fault scarp between the Triassic Alpujarride carbonates and the Quaternary alluvial fan sediments. The existence of various splay faults is responsible for the great structural heterogeneity of the Padul fault zone (Fig. 4). The most recent Quaternary sediments comprising mainly silts, sands and gravels are affected by several splay faults that form a wide fault zone, which ranges from a few tens of meters to more than one hundred meters in certain sectors, such as the Marchena quarry. The majority of the fractures observed in the immediate vicinity of the principal fault form a system of normal conjugate faults with a NW-SE strike. Moreover, subvertical open fractures running in the same direction can be recognized. These faults can have vertical displacements of several meters, with openings between the blocks of several centimeters.

The main active scarps are not situated at the lithological contact between the basement and the Quaternary sediments, but in the alluvial sediments of the hanging wall (Fig. 5). They are generally located less than 20 m from the principal plane but are occasionally found at a distance of more than 100 m (Marchena quarry). These active scarps related to splay faults are common in normal active faults. In addition to the fault scarps, the splays have generated anomalous inflections of the topographic surface of the alluvial fans and drag folds in the most recent sediments, which are late Pleistocene–Holocene in age.

Another feature is that all the boreholes and geophysical studies undertaken in this sector of the basin indicate that the greatest thickness of sediments dating from the Holocene and late Pleistocene is located close to the fault. This asymmetrical geometry of the basin in the Padul sector, with recent peat layers tilted towards the fault, is related to the recent activity of this fault.

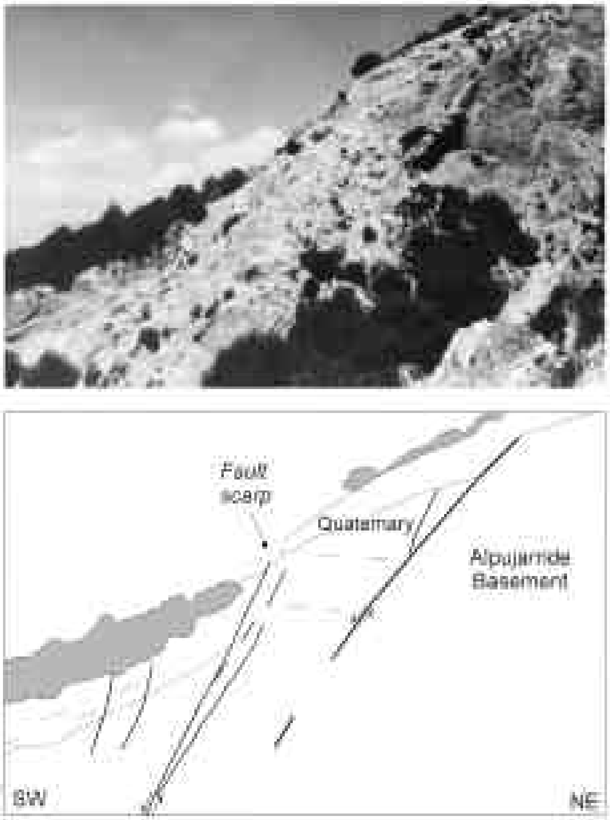

Figure 5. Detail of the Padul fault. A high-angle splay fault deforms the alluvial sediments of late Pleistocene-Holocene age forming a scarp several meters high.

Figura 5. Detalle de la falla de Padul. Un plano de falla ramificado de la falla principal corta los depósitos aluviales de edad Pleistoceno superior-Holoceno formando un escarpe de varios metros.

Paleoseismology

In this study we made a detailed analysis of two subvertical sections, Marchena 1 (Fig. 6) and Marchena 2 (Fig. 7), in alluvial fan sediments in the abandoned quarry at Marchena. The two sections, separated from each other by about 100 m, cut through part of the fault zone in a NE-SW orientation, perpendicular to the principal trace of the fault. These two sections at Marchena are located in cross section III of Fig. 4.

The effects of one of the main splay faults on the most recent alluvial fan deposits were observed in both

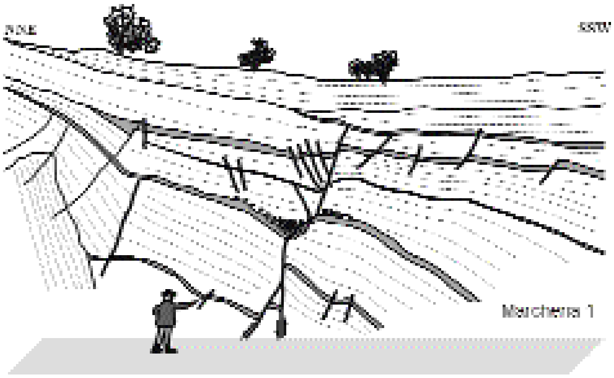

Figure 6. Geological cross-section of Marchena 1. For approximate location, see Fig. 4.

Figura 6. Corte geológico detallado de la trinchera Marchena 1. Su localización aproximada está representada en la Fig. 4.

sections. Based on their stratigraphic and geomorphic position, these alluvial deposits are attributed to the late Pleistocene and Holocene (Fig. 3). They consist of silts, sands and gravels and show a progressive unconformity, with dips varying between 10º and 70º.

Although the main fault is not visible in these sections, we were able to identify various events related to the activity of this fault based on geomorphological, stratigraphical and structural evidence (including differences in the dip between successive layers, internal unconformities, paleosols and colluvial wedges in relation to antithetic scarps) found in the two sections.

The Marchena 1 section, which is situated in the SE of the quarry, is 15 m long and 10 m high. A retrodeformation analysis was made in this section. Difficulties were caused by the curved shape of some of the fault surfaces, resulting in gaps when the slip is restored, and by the presence of folds the mechanism of which could not be established. Although Fig. 8 shows an approximate retrodeformation analysis of this section, it does not illustrate the evolution of the deformations with precision. The slope on which the alluvial fan materials were deposited must have resembled the most recent one given the similarity of the lithology. The evolution consists (Fig. 8-I) of the deposition of an initial layer of sediments (layer 1) followed by a 40º tilt towards the SW (Fig. 8-II). Subsequently, another layer of sediments was deposited (2 and 3) and a reverse fault formed simultaneously, producing variations in the thickness of the deposits in both fault walls, and a topographical scarp. This reverse displacement between blocks could also be linked to a strike-slip fault since it was not possible to observe striations in this high-angle reverse fault.

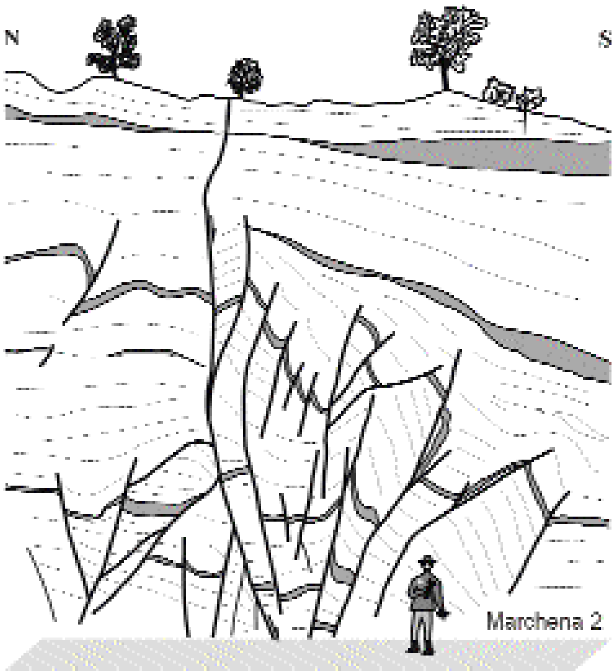

Figure 7. Geological cross-section of Marchena 2. For approximate location, see Fig. 4.

Figura 7. Corte geológico detallado de la trinchera Marchena 2. Su localización aproximada está representada en la Fig. 4.

Subsequently (Fig. 8-III), the zone of the reverse fault was reworked by normal faults and a colluvial wedge was deposited along the fault scarp. Then, another layer of sediments (4) was deposited with a wedge-shaped geometry, indicating a progressive tilt of approximately 7º towards the SW. Next, (Fig. 8-IV), a further tilt of 6º towards the SW occurred, with the deposition of a new wedge of sediments that ended at level 5. This layer was deformed by small normal faults, with dips towards the NE as well as to the SW (Fig. 8-V). A further deposit of materials (Figs. 8-VI and 8-VII) sealed these normal faults and a further tilting of nearly 6º occurred. Finally (Fig. 8-VIII), the last sediment layer was deposited (8). Thus, the section shows a complex history of the progressive activity of the fault, with alternating episodes of deposition and fracturing and tilting.

Amongst the various events that can be recognized in the Marchena 1 section, one notable feature is the

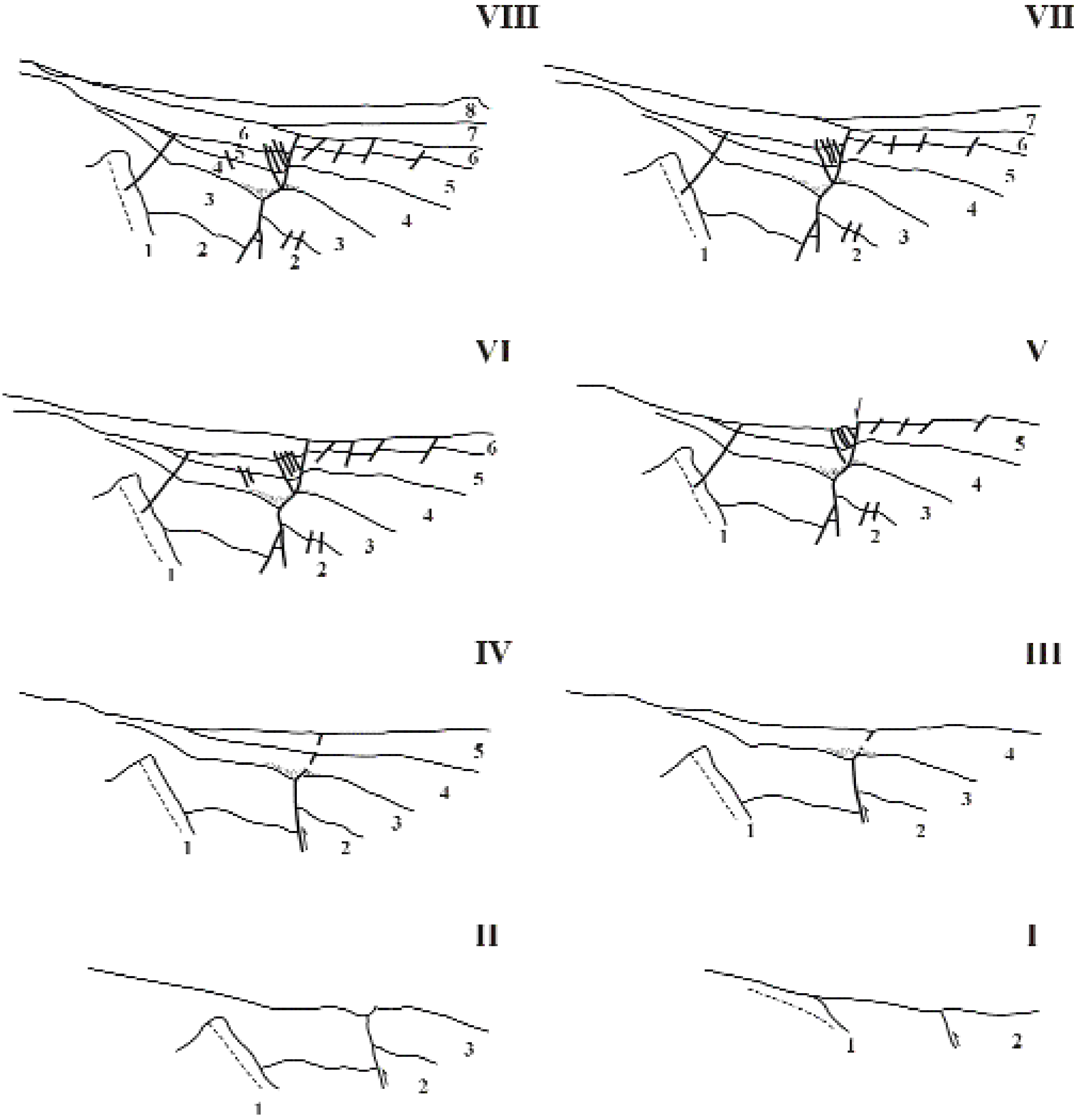

Figure 8. Retrodeformation scheme for Marchena 1 section.

Figura 8. Esquema de retrodeformación de la trinchera Marchena 1.

fault scarp that dips towards the NE in contrast to the principal fault. Associated with this antithetic fault scarp, which in this case is also an upslope-facing scarp (*sensu* McCalpin, 1996), is a deposit of decimetric blocks contained within a heterometric matrix of gravel and sand, which suggests a coseismic deformation.

Situated to the NW of the quarry is the other section, Marchena 2, which is about 10 m long and 10 m high. The alluvial sediments display complex fracturing in this section and, as in the Marchena 1 section, the most recent layers are the least deformed. Only one of the faults, a curve-shaped fault, whose dip changes from 70º at depth to subvertical on the surface, affects the most recent sediments. The retrodeformation in this section is not very reliable because the geometry of the deformation structures is very complex. No attempt was made to restore this section because of the presence of curved and folded fault surfaces and the impossibility of determining their folding mechanisms. This section also confirms the recent activity of the Padul fault given the existence of various events during the late Pleistocene and the Holocene.

THE PADUL PEAT DEPOSITS

Geological context

The Padul peat deposits are located in an endorheic area measuring approximately 4 km^2 in the Padul-Nigüelas basin (Fig. 3). Historically, this was a small lake and a number of channels were cut to cultivate and exploit the peat. These channels now drain the area and prevent it from becoming waterlogged.

The boreholes drilled into the peat and various electrical logs and gravimetric data show that these peat deposits attain a thickness of nearly one hundred

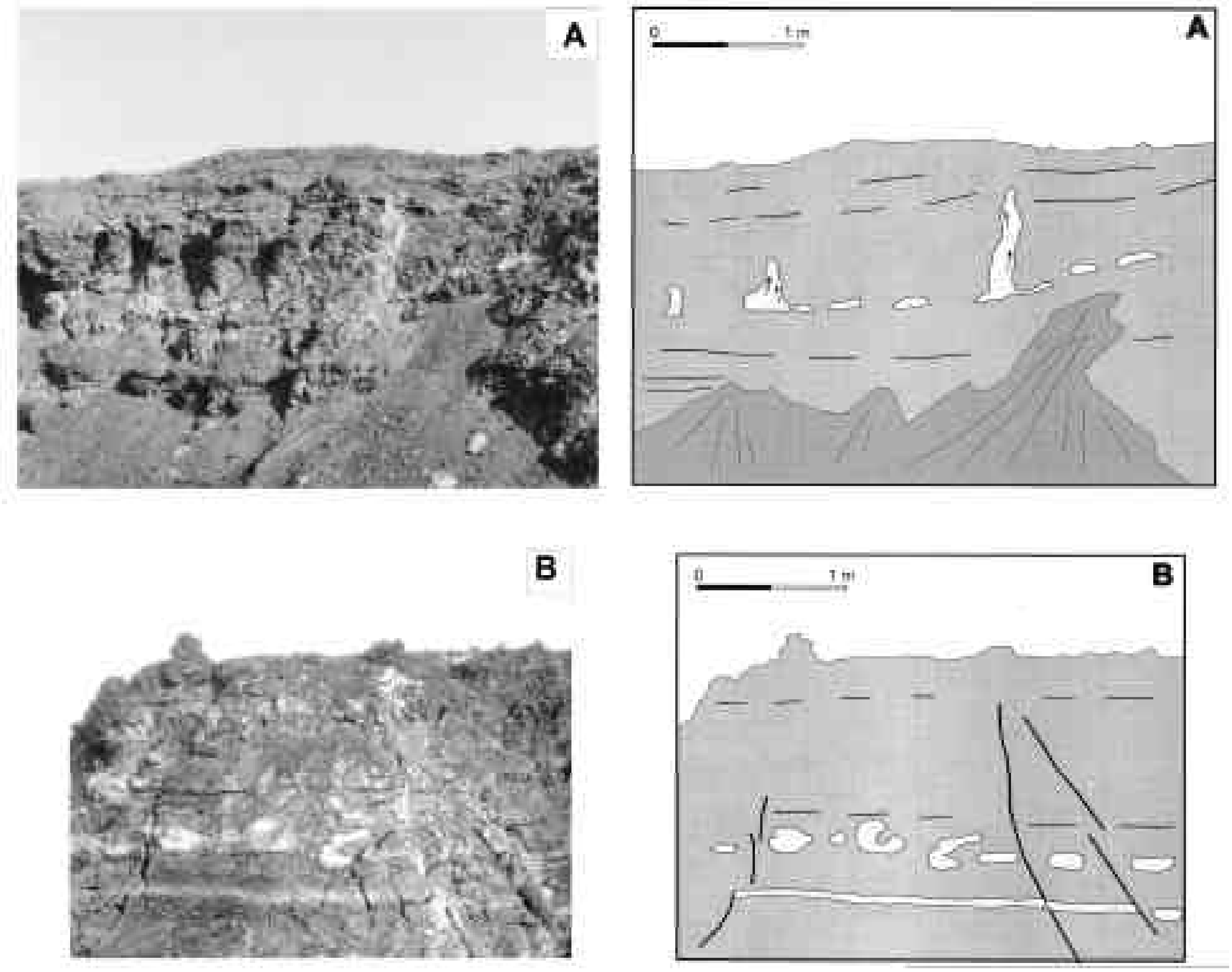

Figure 9. Photographs of various soft-sediment deformation structures in the peat beds of Padul. A. Fluid escape structure. B. Ball-and-pillow deformation structure.

Figura 9. Fotografías de varias estructuras sedimentarias de deformación en la turbera de Padul. A. Estructura de escape de fluidos. B. Estructura de deformación almohadillada.

meters. Domingo-García et al. (1983) indicated the existence of sediments with intercalations of peat approx. 100 m thick. Recently, Nestares and Torres (1998) undertook a borehole survey during which they encountered peat layers as deep as 90 m or more. In the vicinity of the Padul fault, the peat fill is much thicker in the northern sector, forming a wedge which disappears towards the South. This asymmetric fill is related to the rotation of the hanging wall of the Padul fault.

The asymmetric sedimentary fill is characterized by an irregular sequence of peat layers with intercalations of clay, sand and gravel; these detritic deposits correspond to the distal facies of the alluvial fans which interfinger with the peat deposits. The radiometric ^{14}C dating of the peat layers has enabled the sectors with the most subsidence to be located; some of these contain Holocene sediments with a thickness exceeding 10 m. Florschütz et al. (1971) analyzed pollen of these lacustrine deposits chronostratigraphically, placing the Holstein base (ca. 300,000 yr) at a depth of 62 m.

Paleoseismology

Detailed analysis of these lacustrine deposits revealed the presence of various levels of soft-sediment deformation structures. In the southern part of the peat deposit at least two detritic layers of sandy silt were observed, with deformation structures that are intercalated with non-deformed peat layers (Fig. 9). These were load structures (load casts *s.s.* and ball-and-pillow structures, *sensu* Reineck and Singh, 1980; Allen, 1982) between 10 and 30 cm in length and 10 cm in width. These deformation structures are produced by liquefaction of the sediment. In addition, some fluid escape structures were also observed, particularly sandy silt dikes which cut the overlying peat layers. These vertical dikes, ranging between 5 and 10 cm width, were injected approximately 30-40 cm into the peat strata.

The sedimentary processes which could liquefy sediments in this type of lacustrine environment could be related to overloading or to artesian spring activity. The deformation structures described in this study are found in thin beds less than 10 cm thick. The sedimentological characteristics of these detritic deposits do not indicate sudden deposition of mass deposits of sufficient thickness to produce liquefaction of the underlying sediment. Therefore, it is unlikely that these structures were produced by overloading. In terms of artesian spring activity, this would produce sediment deformation structures with a morphology very different from that observed in the Padul peat deposits. The mechanism of deformation associated with artesian conditions produces very localized structures with a generally cylindrical morphology, unlike the load structures in this study which achieve a considerable lateral extension. Therefore, these deformation structures must have been triggered by a mechanism outside the sedimentary environment. We propose that the deformation is the result of earthquakes of moderate-high magnitude; the minimum magnitude required to trigger liquefaction processes is 5.0 and about 5.5 to produce widespread liquefaction structures (Ambraseys, 1988). These structures may have been produced by a moderate to high-magnitude earthquake due to the Padul fault, or by a larger earthquake caused by another fault in the vicinity.

Three peat samples were dated with the ^{14}C technique at Granada University, one above the liquefied layer and two below. The upper sample yielded an age of 34,590 ± 900 yr BP and the two lower samples gave ages of 33,010 ± 700 and 42,030 ± 2160 yr BP. Although, these ages are close to the resolution boundary of the ^{14}C technique, the liquefaction features (seismites *sensu* Seilacher, 1969) probably occurred during the late Pleistocene.

DISCUSSION AND CONCLUSIONS

Although the instrumental period in the Padul area (south of Granada) is characterized only by the occurrence of small-magnitude earthquakes, there is geological evidence of moderate to high-magnitude earthquakes during the Quaternary. In this study, we described various soft-sediment deformation structures produced by earthquakes, probably during the late Pleistocene. We identified, at least, two levels of seismites in detritic deposits which are intercalated with non-deformed peat layers. Although we cannot determine their exact magnitude, we can conclude that they were of a magnitude greater than 5, the minimum magnitude needed to trigger seismic liquefaction (Ambraseys, 1988). Despite their proximity to the Padul fault (less than 1 km), it cannot be confirmed that they were produced by an earthquake associated with this fault. The reason for this is that liquefaction can be induced at considerable distances (even greater than 100 km, Ambraseys, 1988) from the epicenter, and that there are numerous active faults within a few tens of kilometers of Padul.

The Padul fault appears to have been consistently active since the late Miocene. Our observations show that the fault may produce rare moderate to large-magnitude surface-faulting events. The scarps generated by the recent activity of the Padul fault are mainly situated in the alluvial materials of the hanging wall, related to splay faults, and are seldom on the principal plane that separates the Alpujarride basement from the Quaternary alluvial materials.

The analysis of the Padul fault zone enabled us to determine the probable occurrence of moderate to high-magnitude earthquakes associated with one of these splay faults. A number of deformation events associated with this fault were identified in the two sections studied in the Marchena quarry. Retrodeformation analysis in the Marchena 1 section allowed the identification of several significant deformation events which were probably related to earthquakes of moderate-high magnitude which occurred during the Pleistocene and Holocene.

The development of scarps in the recent alluvial sediments which are antithetic to the main fault is probably linked to coseismic deformation. The presence of pebbles in conglomerates cut by normal fault planes located in the vicinity of the Padul fault also supports the seismogenic character of these NW-SE faults. All things considered, the Padul fault, which has been active since the late Miocene, can account for some of background seismicity observed in the area, and also for infrequent large earthquakes.

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