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Evidence for a 4700–2100 BC palaeoearthquake recorded in a fluvial-archaeological sequence of the Segura River, SE Spain

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ABSTRACT

The archaeological excavation of a rock shelter (Abrigo del Pozo) in one of the slopes of the Segura River (SE Spain) has revealed a exceptionally preserved sedimentary record spanning from the Paleolithic to the present-day, which includes an anomalous layer of stones (RFB) fallen from the roof. The sedimentary analysis of the stratigraphic sequence exhumed by the excavation indicates that human occupation of the rock shelter was controlled by fluvial environmental evolution. However, the RFB level resulted in a disturbance of human occupation and normal fluvial sedimentation. From the sedimentary and archaeological pieces of evidence, the RFB level has been interpreted as related to a palaeoearthquake responsible for the collapse of the roof and walls of the rock shelter. The palaeoearthquake has been dated between 5820 ± 50 BP, the ^{14}C age of the Neolithic occupation level directly below the RFB, and 3710 ± 40 BP, the ^{14}C age of the Chalcolithic level above the RFB. A nearby earthquake of M 5.5–6.5 appears as the most plausible cause for the shelter collapse. These data suggest that the seismic activity of this sector in the eastern Betics has been continuous during the Holocene, but with larger magnitudes than the ones instrumentally recorded nowadays. More palaeoseismic data are required to determine whether or not regional faults, such as the nearby Socovos Fault, are silent faults with a discontinuous seismic behaviour that could modify the current hazard assessment.

1. Introduction

Areas with low to moderate seismic hazard, such as SE Spain (Peláez and López Casado, 2002), are exposed to moderate earthquakes with a return period usually exceeding a few thousand years (e.g. Amit et al., 2002; Galadini et al., 2003; Pantosti et al., 2004). Thus, the instrumental record is obviously insufficient to characterize seismic activity of a region. Although some historical evidence reaches to 2000 years in areas of the Iberian Peninsula, where Roman information is most complete (Silva et al., 2005), a good knowledge of the seismic behaviour of a region implies extending the period of study as far back as possible through palaeoseismology and archaeoseismology.

The Betic Cordillera is the Spanish region with the highest seismic hazard (Peláez and López Casado, 2002). Various studies have started to show the effects of palaeoearthquakes in the area (e.g. Silva et al., 1997; Reicherter et al., 2003; Masana et al., 2004; Rodriguez-Pascua et al., 2008). Among them, trench studies constitute one of the most effective tools to establish the seismic history of a fault, but they need to have previously identified the fault at least as potentially active. The Betic Cordillera has a composite tectonic history (Sánchez-Gómez et al., 2002; Platt et al., 2003) with a large number of mapped faults, most of them being at present inactive. Therefore, one of the main tasks in the region is to recognize large palaeoearthquakes in the geological and archaeological records as well as to identify the associated faults.

When areas have been inhabited for a long time, archaeological sites could provide useful information on size and age of past earthquakes (Berberian and Yeats, 2001), usually drawing on damage of complex buildings such as palaces, city walls or fortresses (Reches and Hoexter, 1981; Ellenblum et al., 1998; Monaco and Tortorici, 2004). SE Spain has an ancient human occupation (Walker et al., 1999), but masonry constructions started only after 2000 BC (Muñoz-Amilibia, 1993). Thus, Palaeolithic and most of the Neolithic settlements are not suitable for palaeoseismic studies,

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except in caves and rock shelters, which constitute a common place of prehistoric habitat in SE Spain (Martínez-Andreu, 1999). Rock shelters and caves are susceptible to rock falls, one of the most sensitive geological secondary effects of earthquakes (Wieczorek and Jäger, 1996; Kagan et al., 2005; Matmon et al., 2005; Michetti et al., 2005), but which are usually difficult to identify as distinct events and date. The study of rock shelters could extend the seismic knowledge of the region back by some thousands of years.

This work analyzes the sedimentary infilling of a cave, adjacent to the Segura River in SE Spain. This cave has recorded almost continuous human presence and evidence of a catastrophic breakdown. This paper proposes that this collapse was caused by a seismic event, and then examines the implications of the earthquake in the area, where no other significant Holocene earthquake is known. This study highlights the potential of archaeological shelters for identifying and dating earthquakes, if they are revisited from a palaeoseismic point of view.

2. Geological and seismological setting

The Abrigo del Pozo (Pozo Rock Shelter) is located in a carbonate massif belonging to the Prebetic Zone of the Betic Cordillera (Fig. 1; Jerez-Mir, 1973; Jerez-Mir et al., 1973). The Prebetic and Subbetic Zone correspond respectively to the proximal and distal area of the South Iberian Palaeomargin during the Mesozoic (García-Hernández et al., 1980). In the Prebetic Zone, two domains have been distinguished based on different stratigraphic and tectonic features: External Prebetic and Internal Prebetic (Foucault, 1971; Jerez Mir, 1973), which can be correlated with proximal and distal areas inside of the Prebetic Zone.

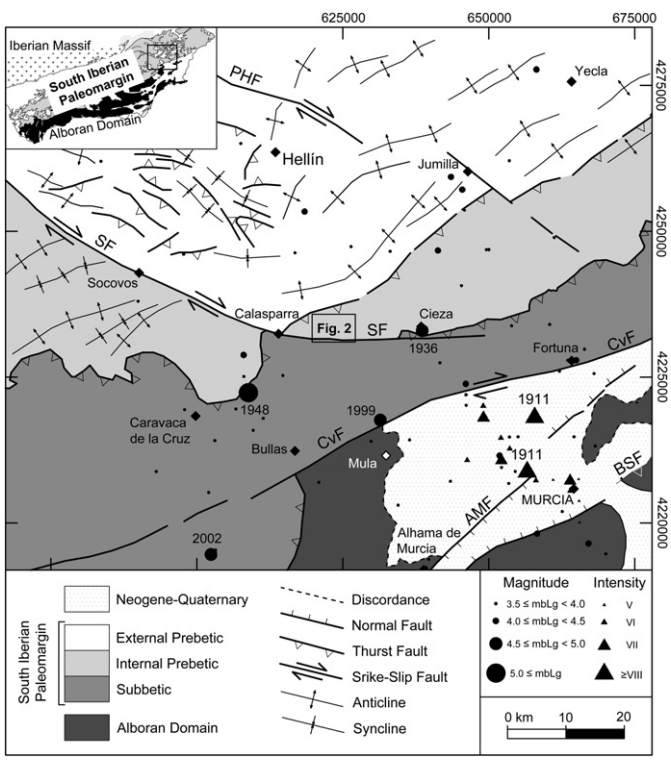

Fig. 1. Seismotectonic map of the region around the Abrigo del Pozo, at the marked location on Fig. 2 (displayed rectangle). Historical and instrumental recorded earthquakes of intensity > V and magnitude >3.5 has been represented. Geological units have been simplified to the main domains and zones of distinctive crustal structure. Major faults with evidences of recent seismicity and/or Quaternary activity are denoted: PHF = Pozohondo Fault (Rodriguez-Pascua et al., 2008, 2009); SF = Socovos Fault (Rodríguez-Pascua, 2001); CvF = Crevillente fault (Alfaro and Estévez, 2004; Sanz de Galdeano and Buforn, 2005); AMF = Alhama de Murcia Fault (Silva et al., 1997; Masana et al., 2004); BSF = Bajo Segura Fault (Alfaro et al., 2002).

The Abrigo del Pozo is situated in the Sierra del Molino that coincides with a large anticline, bounded towards the south by the Socovos Fault (SF, Fig. 2). SF is only 1.5 km from the Abrigo del Pozo, and constitutes a major regional structure that extends more than 80 km with an accumulated right-lateral displacement of 35 km (Fig. 1; Jerez Mir, 1973). In other sectors of the Socovos Fault, geomorphologic evidence of Quaternary displacements has been described (Rodríguez-Pascua, 2001). In the neighbourhood of the shelter, the Socovos Fault is depicted by parallel narrow mountain ranges that correspond to a positive flower structure, along the main fault zone (Section A–A′ of Fig. 2; Valera et al., 2010), and a south-verging recumbent fold at Sierra del Molino. The cave is placed at the foot of a cliff in a canyon-shaped valley incised by the Segura River (Figs. 2 and 3). There are no studies on the origin of this "Los Almadenes" canyon, but the general incision of the stream network with fluvial terraces 100 m above the present flood plain and presence of faulted scree cones (Fig. 2) suggest that the relief was tectonically active at least during part of the Quaternary. Thus, the shelter is within an active tectonic scenario that steers the geomorphic processes.

However, the known historic and instrumental seismicity in this region is very scarce. It appears as a dispersed seismicity, with little activity to the north of the SF (Fig. 1) that correspond with the foreland area of the Betic Cordillera. Most of the known earthquakes and seismic swarms are not clearly associated with the major exposed geological structures. The larger earthquakes recorded are Cehegín (mb 5.0 and intensity VIII), on June 23, 1948; and SW Bullas (Mw 5.0, V), on August 6, 2002, followed by a large seismic swarm (Fig. 1). Not recorded instrumentally, two earthquakes with intensity VIII, associated with a seismic swarm, were felt in Las Torres de Cotillas and Lorquí, on March 21 and April 3, 1911, 40–43 km to the SE. Related to major faults, a mb 4.5 small earthquake (Cieza, June 13th, 1936) has been located at the eastern end of the SF. A mb 5.5 earthquake (N of Mula, February 2, 1999) was associated with the movement of the Crevillente Fault Zone (Fig. 1; Buforn et al., 2005; Sanz de Galdeano and Buforn, 2005), the other important structure in the region.

Considering this short temporal window of seismic observations, the region is characterized by low-probability events with moderate impact. Nevertheless, palaeosesimic studies carried out on lacustrine sediments have shown that the region has had an intense seismic activity since Late Miocene (Rodriguez-Pascua et al., 2000, 2003). In this sense, recent investigations (Rodriguez-Pascua et al., 2008, 2009) have found evidence of an Mw 6–7 palaeoearthquake at 1–2 ka, along the Pozohondo Fault (Fig. 1). This works point out that the region could be affected by destructive earthquakes with large period of recurrence produced by faults not considered previously as seismic.

3. Cave description

The Abrigo del Pozo is carved in Upper Cretaceous sandy dolostones, with a thickness of more than 400 m. It is located in the Internal Prebetic (Fig. 1). These rocks are poorly stratified and structureless, with a very sparse fossil content. They show two penetrative sets of joints with a spacing ranging from 15 to 30 cm, which do not endanger the stability of the roof cave.

The rock shelter is about 30 m long, with a maximum depth of 9 m and an average height ≥2 m (Fig. 3). The present-day height of the cave floor above the average stream level is about 4 m. The Segura River (main channel) describes a convex arc towards the northeast (Fig. 2). The cave is located on the southwest bank, its entrance oriented towards the NE. Therefore, the shelter is located in the accretion margin of the meander, where processes of lateral

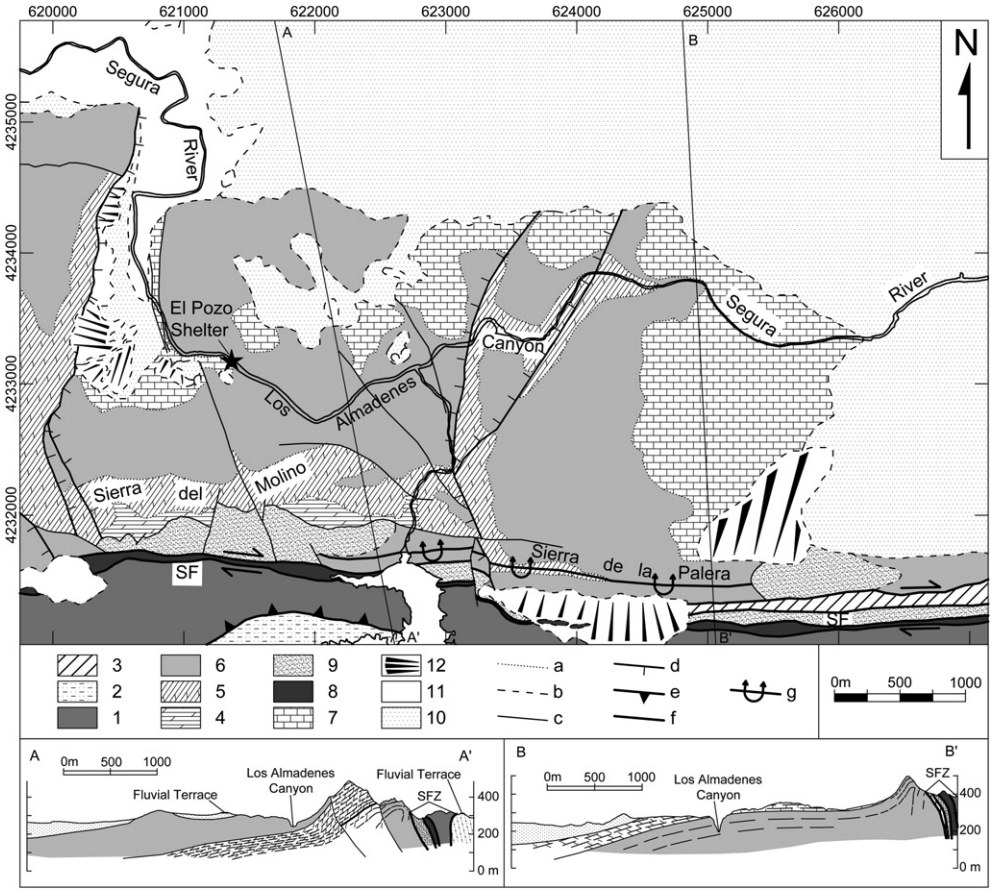

Fig. 2. Geological sketch of the surrounding area of the Abrigo del Pozo (Pozo Rock Shelter). Two topographic profiles show the relationship between the topography and the main structures described in the text. Note the presence of fluvial terraces 100 m above the present fluvial level (vertical scale of profile is exaggerated 2:1). Legend: (1) Triassic gypsum, sandstone, siltstone and limestone; Lower Cretaceous (2) marl, (3) sand and conglomerate; Upper Cretaceous (4) structureless dolostone, (5) stratified dolostone, (6) structureless dolostone, (7) limestone; (8) Eocene limestone; (9) Middle Miocene conglomerate, bioclastic limestone and marl; (10) Upper Miocene bioclastic limestone and marl; Quaternary (11) conglomerate, (12) Scree cone. (a) Stratigraphic contact, (b) unconformity, (c) minor faults, (d) normal faults, (e) thrust faults, (d) strike-slip faults; SF = Socovos Fault, SFZ = Socovos Fault Zone.

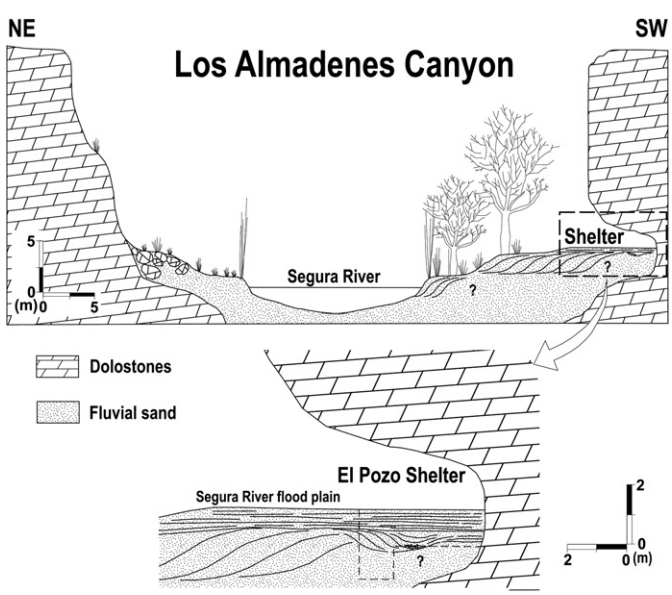

Fig. 3. Segura River and "Los Almadenes" canyon cross-section showing the rock shelter and an outline of the hypothetical meander sedimentary body.

accretion linked to helicoidal flow predominates in the channel. The cave itself must have been excavated in an initial stage of canyon incision, probably karstic, and later was filled with fluvial sediments in a meander bar subenvironment.

The cave section and position in relation to the fluvial channel (Fig. 3) provides a comfortable and secure habitat. Rock paintings and abundant archaeological remains reveal a reiterated use as prehistoric residence, refuge or sanctuary (San Nicolás, 1986; Martínez Sánchez; 1994). Nevertheless, the access is difficult due to its location amidst the canyon, this fact having preserved the rock shelter from later alterations and vandalism. The archaeological site and rock painting on the cave walls are now protected by an artificial entrance along the cliffs.

4. Sedimentary and archaeological record

The archaeological excavation of the cave has revealed the upper part (up to 2 m depth) of a sequence of fluvial sediments along two main perpendicular sections, which delimitate an area of approximately 14 m^2. Unfortunately, the accretion margin deposits of the main channel are not exposed in the archaeological excavation (Fig. 3). The section with a trend N40E is 4.5 m long best exposes the deeper parts of the sedimentary infilling of the cave. The other (N130E) is 7 m long, showing only the upper part. The good exposure of the excavation walls has made it possible to draw up several detailed stratigraphic logs, presented here in a synthetic log

(Fig. 4). Fig. 4 establishes a direct correlation between the lithofacies and the 3D geometry of the sedimentary bodies, interpreted following Miall (1985, 1996). The general succession of the site consists of a fining-upward cycle, basically beginning with gravels and/or sands of a meandering channel and concluding with slackwater fine-grained deposits (Fig. 4). The cycle consists of three intervals, which correspond to fluvial subenvironments as determined by sedimentological analysis. The facies associations at the site are described below and their significance is discussed in terms of subenvironments and sedimentary processes.

4.1. Facies association A (chute-channel filling)

This facies is located at the base of this cycle, where the bottom is visible, appearing as an erosive surface on the fine facies of the underlying sequence (2–3 m-wide and 30–40 cm-deep). This facies association has the coarsest sediment. These sediments are represented by normally-graded sands/gravels lithofacies, described in the literature as coarse sand to granules with epsilon cross-bedding constructing sigmoidal shaped beds (lithofacies Sla of Viseras et al., 2006; Pla-Pueyo et al., 2009). It varies in thickness from 25 to 35 cm. Palaeocurrent data suggest a southward main flow direction.

Following interpretations of other examples (Allen, 1970; Bluck, 1971; Nijnman and Puigdefábregas, 1978), this assemblage association represents the lateral accretion of a minor sinuous channel. The margin accretion occurred at the opposite direction (towards the southwest) of the main channel. It presumably represents a chute channel (a minor channel at the top of the inner bank of the meander) filled during periods of high-stage-flow.

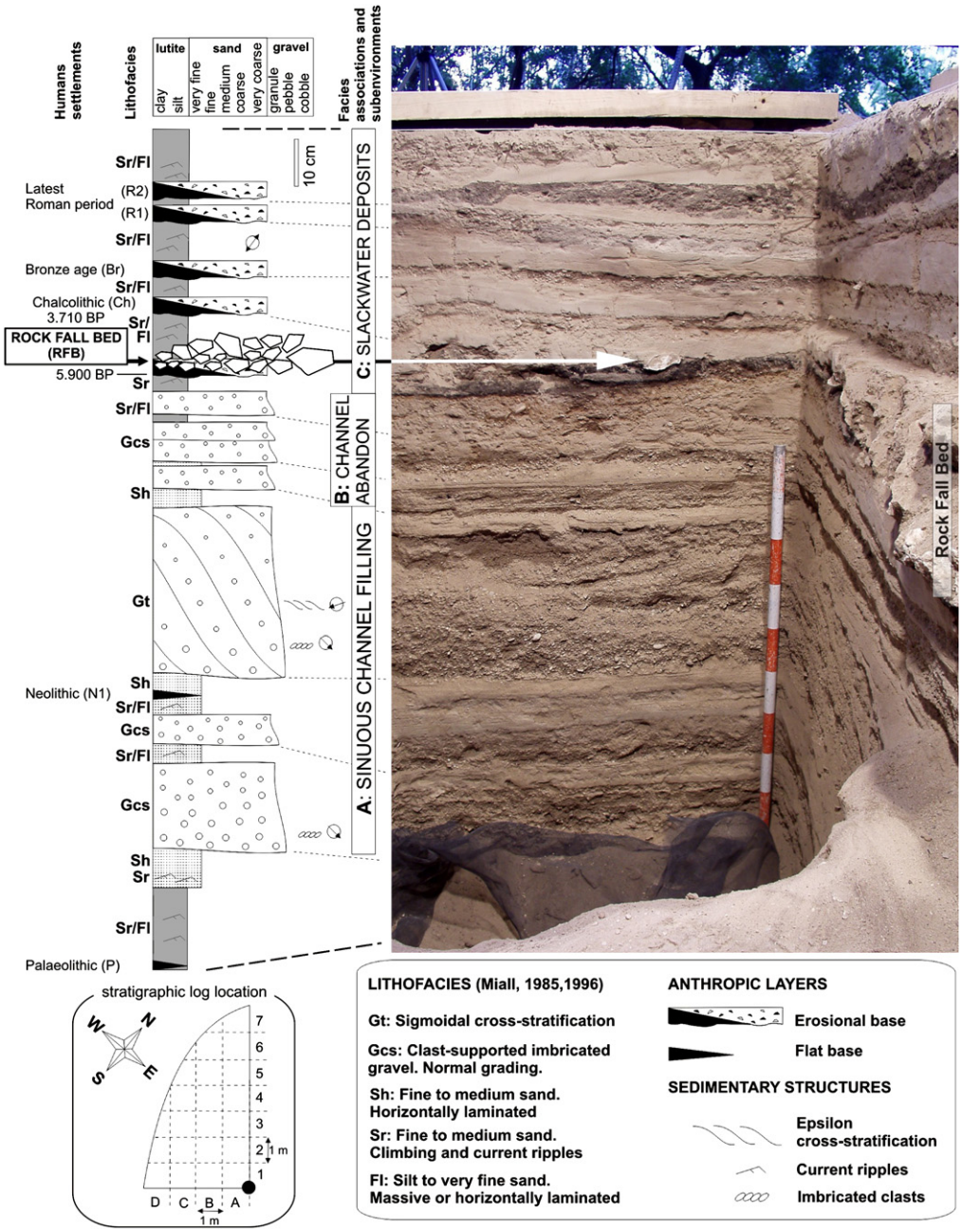

Fig. 4. Detailed stratigraphic column (see location in the excavation plan sketch at the left-down corner) and archaeological section photograph. Lithofacies and facies associations (A–C) are described in the text.

4.2. Facies association B (channel abandonment)

This facies overlies the assemblage association A by means of a gradual change. The section consists of alternating westward gently dipping layers of granules (Gcs) and sands from 5 to 10 cm thick and several metrrs wide, but no bigger than the channel where facies association A developed. In the fine sandy layers, current ripples can be distinguished (lithofacies Sr) as well as horizontal lamination (Sh).

According to the types of lithofacies and the shapes of the sedimentary bodies, facies association B can be interpreted as the filling of a channel in a stage of gradual abandonment. During this process of abandonment, periods of high energy traction flow (development of granule layers) alternated with low energy traction flow (development of sandy layers with current ripples) that gradually filled and softened the topographical depression of the old channel, as described by Guccione et al. (2001).

4.3. Facies association C (slackwater deposits)

This facies association is located in gradual transition above the facies association B. It is represented by four horizontally-bedded couplets of climbing ripple-laminated fine sand with humans reworked land surface (footprints and other bioturbation marks) and a fifth climbing ripple-laminated sand bed at the top (Sr, Fl). Sands show an upstream ripple-migration direction.

This facies is interpreted as slackwater deposits as described by Woodward et al., (2000), Thorndycraft et al. (2005) and Xiaochun et al. (2009). The deposition occurred in an eddy (ripple-migration direction is consistent with upstream flow in the eddy return current) during palaeoflood events in the Segura River. Human reworking of the top of flood beds indicates the subaerial exposition of the sedimentary surface.

The particular sedimentary conditions occurred here have preserved very well seven anthropic layers intercalated with the fluvial deposits (Fig. 4). Each one was covered by a fluvial flow that sealed the archaeological record, separating one anthropic level from the other and avoiding the alteration of the remains of human activity during the subsequent period.

The archaeological excavation was stopped at a Palaeolithic level (P), identified by artefacts (Martínez Sánchez, 1994). Within the sedimentary cycle A, a thin level with Neolithic artefacts and fire pits has been recognized (N1, Fig. 4). The next Neolithic level (N2) is located 70 cm upwards, at the end of the sedimentary cycle B. N2 level consists of an almost continuous layer 4–6 cm thick, with plenty of artefacts, ashes and bone remains of food. Platy-shaped smoked rock fragments, up to 6 cm length, are abundant in ash accumulation places. Charcoal from N2 yielded a ^{14}C uncalibrated age of 6260 ± 120 BP (Martínez Sánchez, 1994).

A bed with outsized clasts (RFB level, Fig. 4) appears intercalated in fine sands and lutites of the facies association C, overlying the N2 anthropogenic layer. The bed consists of very angular and scattered cobbles and boulders of sandy dolostones lacking internal organization (Figs. 4 and 5). The grain size and the textural maturity of the clasts are genetically independent of facies association C, deposited at lower regime flow in a flood plain where the bed intercalates. Thus, the RFB level is unconnected with purely fluvial processes. This level directly overlies the N2 level, sealing fire and bone-food remains. Scarce artefacts have been found among the stones of the RFB. The RFB level and the scarce anthropogenic remains are completely covered by the next flood sand level.

Over RFB, four more anthropogenic layers are separated by flood sand layers (Fig. 4). Each one of these levels has been relatively dated by artefacts and pottery (Martínez Sánchez, 1994), showing an ascending younger age: Chalcolithic (Ch level), Bronze (Br) and latest Roman (R1 and R2). All these levels, ranging from 2 to 10 cm thick, show an erosive bottom with human and livestock footprints and other bioturbation marks in the lower sand layer.

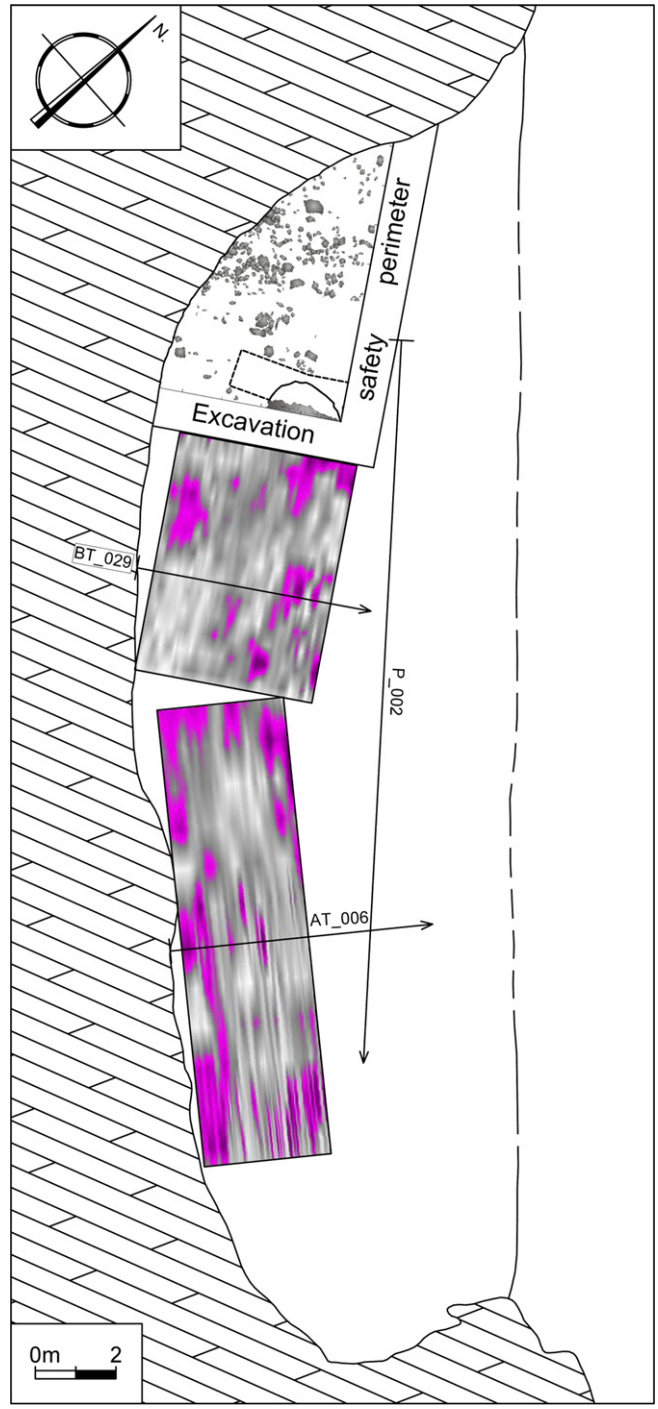

Fig. 5. Abrigo del Pozo archaeological site showing excavation and GPR surveyed areas. The excavation (north sector) shows the distribution of the fallen roof stones from the RFB level. Oblique void in the east corner corresponds to an initial preliminary excavation where stone level data were mislaid. Outline simplified from the original archaeological work drawing at scale 1:20. The central and south rectangles correspond to GPR depth-slices at 0.4 m from a 400 MHz 3D subsurface-image acquired by means of a 1 × 0.5 m profile grid. Darker (coloured) areas indicate high amplitude subhorizontal electromagnetic reflections that are interpreted as stones from the RFB. Positions of the GPR profiles shown in Fig. 6 are represented (sense of the arrow point to the direction in which GPR data was acquired). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Three samples of charcoal beneath and above RFB have been dated by AMS radiocarbon dating. Two samples below RFB have been selected from those directly in contact with the bottom of large rocks. They consist of remains of *Olea* sp. (*europaea*) and *Pistacia terebinthus* that yield an age of 5980 ± 50 BP and 5820 ± 50 BP respectively (Cal BC 4840 and Cal BC 4700). The sample above RFB belongs to the lower layers of the Chalcolithic level (Ch). It consists of fragments of *Rosmarinus* sp. (*oficinalis*) and *Retama* sp. (*sphaerocarpa*) that yield an age of 3710 ± 40 BP (Cal BC 2130–2060).

5. Interactions between fluvial sedimentation and human activity

Fluvial deposition (point bar) at the inner bank of a bend of the Segura main channel (non-outcropping deposits) created the basement of the rock shelter. Then, the top of the inner bank was only flooded during periods of fluvial high-stage-flow, encouraging human occupation during periods of fluvial low-stage-flow. Lithology, facies associations, stratigraphic architecture and timing and features of the anthropogenic layers intercalated within the fluvial deposits (Fig. 4) distinguish two stages in the interaction of fluvial dynamic and human occupation.

5.1. Stage 1 (Paleolithic to 5900 BP)

This site was a casual habitat as indicated by the scarce remains found, which did not disturb the sedimentary bodies. The fluvial activity during periods of high-stage-flow, represented by a sinuous chute-channel cutting the inner bank into the shelter, presumably conditioned the ephemeral human occupation. Neolithic humans (N1) occupied a slight topographic depression caused by the chute channel in the process of abandonment.

5.2. Stage 2 (5900 BP to present-day)

Before N2 level, a decrease in the energy of the sedimentary processes in the secondary channel (facies association B) can be noted. After complete filling of this channel, the topography would have been homogenized at the level of the flood plain of the main channel. Overflow from the laterally migrating active main channel began to bury the secondary channel deposits with flood-plain sediments. This is why the particular location of the site at study here became a preferential occupation zone for humans (from 3710 BP to the Roman period), just at the beginning of the development of facies association C (slackwater deposits). The long history of human occupation of this period occurred during the slackwater deposits sedimentary cycle when only occasional floods deposited sediments into the shelter. The high sedimentation rate in the cave, resulting from the local concentration of detrital sediments from overflow of the main channel, led to the burial of the anthropogenic layers. This genetic context, characterizing the site, remained outside the erosive influence of the fluvial channel, the cave having been thus an area protected from fluvial erosion.

6. Interpretation of the rock collapse

The RFB level is made up of fragmented sandy dolostones from the walls and roof of the rock shelter. Rock fragments appear in the excavation as isolated angular pieces of variable size with 5–50 cm maximum length and 15 cm maximum thickness (Figs. 4 and 5), except an outsized block that reaches 0.4 m^3 (2 × 1 × 0.2 m). Larger fragments are fractured, though they preserve most of the original joints between pieces. Fragments do not have faces altered by fire and only minor smoke imprint is observed in some of them. The horizontal distribution of the fragments is almost regular at the excavated area (Fig. 5), though in some places adjacent but separated stones can be fitted together reconstructing a former larger fragment. These larger fragments can be roughly coupled with hollows in the roof of the shelter.

The fluvial sediments have rounded particles with an average maximum size of coarse-grained gravel. Thus, the RFB level with pebble- and cobble-sized blocks represents an exceptionally coarse-grained layer. Blocks up to 20 cm also occur in the Chalcolithic anthropogenic layer (Ch level, Fig. 3) in a circle around a fireplace. These blocks, at variance from the RFB ones, are more heterogeneous and appear with a reddish patina as a consequence of the calcination.

The shelter was surveyed with GPR in order to establish the lateral continuity of the RFB along the shelter. GPR profiles were grouped in two grids with spaced cells of 0.5 × 1 m, plus an additional profile (Fig. 5). The profiles were obtained with 400 MHz antennas that provided in preliminary measurements optimal vertical and horizontal resolution as has been observed in other rock shelters (Porsani et al., 2010). Profile grids were designed to obtain a 3D subsurface-image. Vertical profiles (Fig. 6) show profuse hyperbolic reflections between 0.3 and 0.4 m deep, which can be observed in depth-slices as areas of high amplitude reflections (Fig. 5). Depths and estimated velocity of the anomalies (0.13 m/ns) fit with the presence of the dolostone fragments from the RFB level along all the shelter palaeo-floor.

All of the pieces of evidence described above suggest that rock fragments in the RFB fell from the roof of the shelter. The collapse must have occurred in a short interval of time, interrupting the routine use of the shelter by the Neolithic settlement. Abundant artefacts and bones were trapped under the RFB level, which, in turn, was buried by the next overflow level. The age of this collapse must be between 5900 BP, the age of the charcoal covered by the RFB stones, and 3700 BP, the age of the next occupation level (Ch, Fig. 4). Ch level is not directly over RFB because there is a flood sand level interposed (Fig. 4), and thus the age of the event that caused the rock fall should be closer to the first age.

An earthquake might account for such a sudden and general collapse. Palaeoseismic evidence in caves is mainly related to fallen or broken slender speleothems (seismothems) and soda straws (e.g. Carbonnel et al., 1999; Gilli and Serface, 1999; Cadorin et al., 2001; Delaby, 2001; Lacave et al., 2004; Kagan et al., 2005; Gilli, 2005). Nevertheless, rock falls are a common secondary effect in large (Owen et al., 2008) and moderate earthquakes (Beldjoudi et al., 2009). To allow the fall, the rock shelter roof, altered to a certain degree by weathering and/or anthropogenic processes, would stay metastable until the seismic shaking. Rock falls induced by

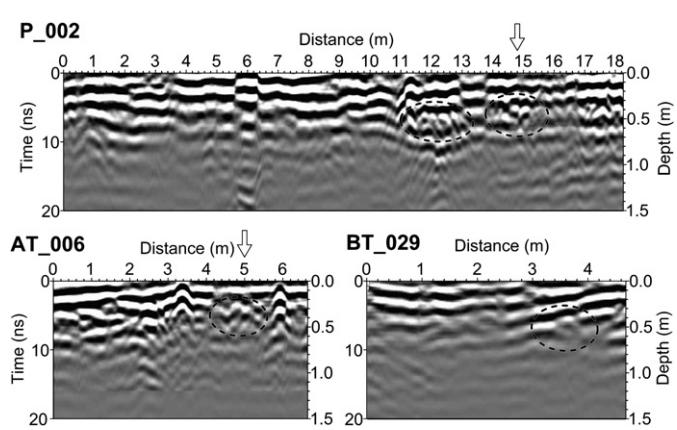

Fig. 6. Three examples of GPR profiles of 400 MHz taken on the Abrigo del Pozo. Location in Fig. 5. Some anomalies at 0.4 m deep are marked (dotted circle). Arrow indicates the crossing point between AT-006 and P-002 profiles.

earthquakes occur only when joints become large and well developed cracks (Matmon et al., 2005).

Large-scale rock collapses in karst environments are also associated with gravitational loads (White and White, 2003) or glacial intrusion (Gilli, 2005). However in the case at issue here, no glacial overload can be expected at this latitude and altitude in middle Holocene times. Cliff retreat, a normal process in the geomorphic evolution of these geomorphic features (Ahnert, 1996), would yield block accumulation at the entrance of the rock shelter, but not distributed below the protected area. Moreover, frost-wedging in rock shelters would produce small-sized rock fragments all along the sedimentary record, without concentration in a particular level. A hypothetical human devastating action could not explain the size and distribution of fragments. On the other hand, an earthquake could also produce major changes in the access or habitability of the shelter, thus shifting the use as permanent habitat towards a more sporadic one. The Almadenes Canyon and other nearby rock shelters also show recent large-scale rock falls and topples, which however cannot be properly dated, but might suggest the possibility of general modifications in the close environment. Rock fall events affecting broad areas have been associated with large palaeoearthquakes in arid and warm regions (Matmon et al., 2005), where climatic causes are less plausible.

7. Earthquake size and regional implications

At this moment, one question remains: which ground motion might cause this breakdown? The answer is the same as for the generic question: which ground motions can cause collapses or falls? Without more related studies, this topic must be regarded as a typical landslide problem. Peak ground horizontal accelerations (PGA) values, used worldwide in seismic hazard, clearly are not a reliable measure for this type of study (Harp and Wilson, 1995). On the contrary, Arias intensity values, a measure of earthquake intensity based on instrumental records (Arias, 1970), claimed to be a measure of the total seismic energy absorbed by the ground, and is the most used intensity in earthquake triggered landslide investigations, firstly correlated with induced landslides by Wilson and Keefer (1985). Arias intensity considers the full range of frequencies recorded in an accelerogram, as well as the duration of the ground motion.

Using data from Californian earthquakes, Harp and Wilson (1995) proved that with horizontal Arias intensity values above 0.25–0.30 m/s, on average, seismically induced rock falls and rock slides can be observed. However, in several cases, values above 0.1 m/s were sufficient. Using the known relationship by Sabetta and Pugliese (1996) between horizontal Arias intensity, moment magnitude and rupture distance, a M 5.5 earthquake could provide expected Arias intensity values of the order of 0.4 m/s at the rupture, and above 0.1 m/s at distances to the rupture below 10 km, for stiff rocks. For an M 6.0 earthquake, Arias intensity values of the order of 1.2 m/s at the rupture, and values above 0.1 m/s at distances below 20 km, are expected. Finally, for an M 6.5 earthquake, the maximum magnitude that can be expected in the Betic Cordillera (Buforn et al., 1988; Peláez et al., 2005) and near to the magnitude limit for which the Sabetta and Pugliese relationship (1996) can be used, values above 0.1 m/s are obtained at distances bellow 37 km from the rupture. This relationship has been proposed as the most reliable one to be used in the Betic Cordillera (Peláez et al., 2005).

From a probabilistic point of view, the region is included in an area of low to moderate seismicity and seismic hazard. For example, mean PGA values of the order of 0.10 g must be expected for a return period of 975 years, that is, for a 5% probability of exceedance in 50 years (Peláez and López Casado, 2002). For a return period of 475 years, that is, for a 10% probability of exceedance in 50 years, mean PGA reaches values of the order of 0.08 g (Peláez and López Casado, 2002). For this last return period, horizontal Arias intensity values of the order of 0.1 m/s must be expected for stiff rocks, using the mean + σ attenuation curve (Peláez et al., 2005), and the attenuation relationship and geological conditions proposed by Sabetta and Pugliese (1996). Due to the lack of active fault data or palaeoseismic information, only the instrumental and historic seismicity was considered in these assessments, including the more energetic seismicity in the last 700 years.

The knowledge of the occurrence of this earthquake is important because it can be used to establish the seismic potential for this area. Instrumental and historic earthquakes, as has been pointed out above, showed a low to moderate seismically active region and seismic hazard. The plausible magnitude reached for this paleoearthquake is greater than probabilistic seismic hazard values, even for a return period of 975 years. Thereby, this information may be useful as complementary data in a future assessment of the seismic hazard of the region. This estimated magnitude could be a first and rough appraisal of the maximum potential earthquake or act as a characteristic earthquake for the candidate faults.

The most likely seismic sources, considering the known recent seismicity and tectonic information, are the Socovos (SF) and the Crevillente (CvF) faults, or one of the secondary faults in the nearby area between them. More palaeoseismic data are required to determinate whether SF, or other nearby fault, seem inactive for periods of a few thousand years with a discontinuous seismic behaviour, as happens with the so-called silent faults from other Mediterranean areas (Cinti et al., 1997, 2002; Galadini and Galli, 2003).

8. Conclusions

The Abrigo del Pozo archaeological site is located palaeogeographically on meander bars and flood-plain deposits of the Segura River. The rock shelter is partially filled with fluvial and anthropogenic sediments in an almost continuous sequence, at least since the Palaeolithic. The shelter usage shifted from sporadic refuge to permanent habitat during the Neolithic, when the fluvial environment changed from secondary channel to slackwater deposits, thus becoming more comfortable and secure. Archaeological excavations have shown the presence of a rock collapse level above the main Neolithic occupation level (N2), which interrupts the regular use of the shelter as habitat. This collapse is interpreted as a seismic event, dated between Cal BC 4670 $\pm$ 60, age of the underlying habitation level (N2) and Cal BC 2090 $\pm$ 60, age of the overlying anthropological level (Ch, Fig. 2).

The most plausible event causing this collapse is an M 5.5–6.5 earthquake with focus at 10–40 km, generating Arias intensity values above 0.1 ms^{-1}. More energetic earthquakes could be barely justified in basis of the present seismotectonic knowledge of the Betic Cordillera. This assumption, together with the regional tectonic context, points to a seismic source located to the south in a nearby area. One of the most reliable structures capable of producing such an earthquake is the Socovos fault (SF, Fig. 1), which, however, has no significant seismic activity in the instrumental record. In any case, this result shows a certain continuity of the tectonic activity in the region during the Holocene. Future regional palaeoseismic investigations should take into account the existence of more seismic evidence in the 4700–2100 BC interval in order to identify the earthquake source and improve the seismic hazard assessment.

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