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Paleoliquefaction in the Bajo Segura basin (eastern Betic Cordillera)

Paleolicuefacción en la cuenca del Bajo Segura (Cordillera Bética oriental)

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ABSTRACT

The Bajo Segura basin, in the eastern Betic Cordillera, displays a seismic activity characterized by small-magnitude earthquakes (1.5-4.5 mb), with some occasional moderate to high-magnitude events (> 5.0 mb). These earthquakes are produced by the activity of blind faults without surface ruptures. For this reason, the detection of paleoearthquakes in the geological record is limited to indirect evidence of paleoseismicity, mainly liquefaction features. Moreover, such evidence is abundant in the historical record of the 1829 Torrevieja earthquake, in some of its aftershocks and in the 1919 Jacarilla earthquake. In this study several layers of Holocene seismites previously described in the basin were analyzed, and correlated with various radiometric ^{14}C datings. This analysis enabled a recurrence period of approx. 1000 yr to be established for the moderate to high-magnitude earthquakes in the Bajo Segura basin.

Keywords: Paleoliquefaction. Paleoseismology. Betic Cordillera. Bajo Segura basin.

RESUMEN

La cuenca del Bajo Segura, localizada en la Cordillera Bética oriental, tiene una actividad sísmica caracterizada principalmente por terremotos de pequeña magnitud (1.5-4.5 mb), aunque ocasionalmente han ocurrido terremotos de magnitud moderada-alta (> 5 mb). Estos terremotos están producidos por la actividad de fallas que no presentan ruptura en superficie (fallas ciegas). Por este motivo, el reconocimiento de paleoterremotos en el registro geológico se limita a las evidencias indirectas de paleosismicidad entre las que destacan las estructuras de licuefacción sísmica. Además se tiene constancia de numerosas manifestaciones de licuefacción en el terremoto histórico de Torrevieja de 1829, en alguna de sus réplicas y en el terremoto de Jacarilla de 1919. En este trabajo se han analizado varios niveles de sismitas holocenas descritos previamente en la cuenca, y se han correlacionado con varias dataciones radiométricas de ^{14}C.

Este análisis ha permitido establecer un periodo de recurrencia de terremotos de magnitud moderada-alta en la cuenca del Bajo Segura, de aproximadamente 1000 años.

Palabras clave: Paleolicuefacción. Paleosismicidad. Cordillera Bética. Cuenca del Bajo Segura.

INTRODUCTION

The Bajo Segura basin, situated in the eastern Betic Cordillera, displays seismic activity characterized by small-magnitude earthquakes despite the occurrence of occasional catastrophic events such as the 1829 Torrevieja earthquake. Based on the damage caused by this earthquake, it has been estimated that the intensity at the epicenter reached the degree X (Muñoz et al., 1984). Other authors, on the basis of the spatial distribution of the damage, have estimated its magnitude as being between 6.3 and 6.9 Ms (Muñoz and Udías, 1991; Delgado et al., 1993). Other historical earthquakes, reaching an intensity of VIII, occurred at Guardamar del Segura (1523) and Jacarilla (1919). Given this low-moderate seismic activity, the information available for evaluating the regional seismic hazard is scarce. For this reason, there is considerable interest in any study of paleoseismicity which expands the seismic catalog and allows the recurrence period of large earthquakes to be established with greater precision.

In the Bajo Segura basin, the principal active faults are blind with the result that they do not rupture the ground surface. In this region, the only information available to date about paleoearthquakes is provided by seismic liquefaction features.

Obermeier (1996) made a detailed analysis of the current state of knowledge of the use of coseismic liquefaction features in studies of paleoseismology. These data can provide information about the position of the epicenter, the magnitude of the paleoseismic event and the recurrence period of earthquakes of moderate-high magnitude. Paleoliquefaction studies have identified several paleoearthquakes that occurred during the Holocene in different regions of the United States, such as the New Madrid seismic zone (Saucier, 1991; Tuttle and Schweig, 1995) and the South Carolina coast (Obermeier et al., 1987; Amick et al., 1990; Amick and Gelinas, 1991). Based on dating of some paleoearthquakes, recurrence times of moderate to high-magnitude earthquakes in the New Madrid seismic zone have been established (Russ, 1979; Saucier, 1991). In addition, it is possible to determine the epicentral region provided that the information available on the seismic liquefaction structures is sufficiently detailed. Munson et al. (1995) gave an approximate location for this based on the size of these structures. Estimating the magnitude of paleo-earthquakes, Ambraseys (1988) suggested that a minimum magnitude of 5 is required to trigger liquefaction, and above 5.5, their effects are relatively widespread. Recently, various methods have been used to estimate the magnitude of paleoearthquakes (see discussion in Obermeier, 1996).

The Bajo Segura basin contains sediments that are highly susceptible to liquefaction. Seismites (*sensu* Seilacher, 1969) have been identified in the upper Miocene (Montenat, 1980; Estévez et al., 1994) and Quaternary deposits (Alfaro et al., 1996, 1999). Moreover, liquefaction occurred during the 1829 Torrevieja and 1919 Jacarilla earthquakes. This study analyses the susceptibility of the upper Pleistocene and Holocene sediments filling the basin to liquefaction. In addition, several layers of Holocene seismites, previously described by Alfaro et al. (1996), together with various radiometric ^{14}C datings of the Holocene sediments (Soria et al., 1999), were used to establish the recurrence period for the moderate to high-magnitude earthquakes.

TECTONIC SETTING

Regional seismotectonic studies show that the Bajo Segura basin (Fig. 1) is currently subject to a compressive stress field with a maximum horizontal stress, trending NNW-SSE (Alfaro, 1995). This stress field, which is linked to the convergence of the African and Eurasian plates, is consistent with the recent stress tensor obtained by the SIGMA project corresponding to the eastern part of the Betic Cordillera (Herraiz et al., 2000).

Compression has been active since at least the late Miocene, and has deformed both the basement of the Internal and External Zones of the Cordillera and the Neogene-Quaternary sedimentary cover. A number of folds formed in the Neogene-Quaternary sediments. Some of these are associated at depth with various blind

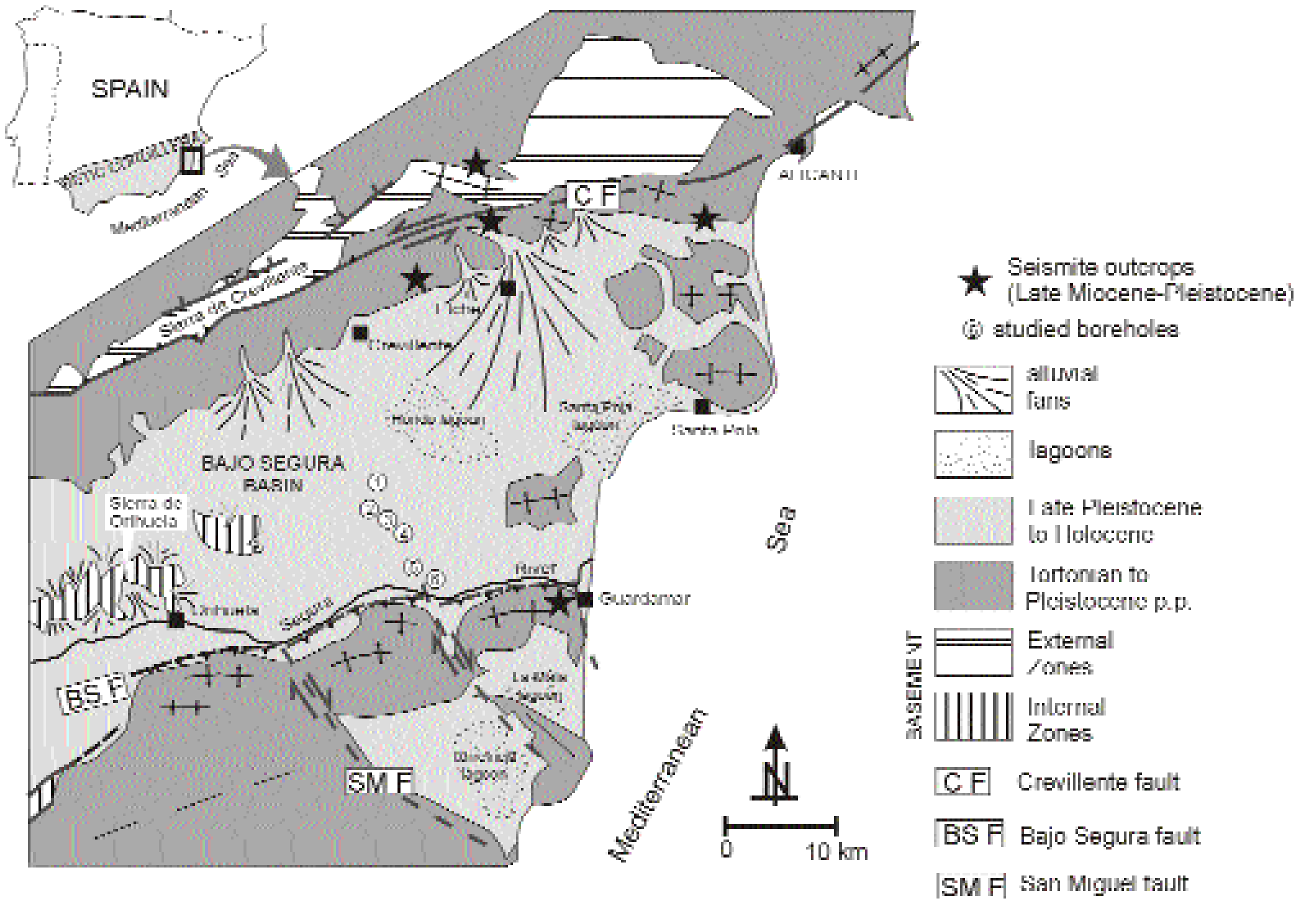

Figure 1. Geological map of the study area showing location of boreholes and the main outcrops where seismites were observed.

Figura 1. Mapa de localización geológica del área de estudio, en el que se han situado los principales afloramientos de sismitas y los sondeos estudiados.

reverse faults and strike-slip faults. On the basis of the neotectonic and seismotectonic studies in the Bajo Segura basin and in adjacent sectors (Montenat, 1977; Bousquet, 1979; López Casado et al., 1987; Somoza, 1993; Taboada et al., 1993; Alfaro, 1995), the following faults stand out as the most active: the Bajo Segura fault, the Crevillente fault and the faults running NW-SE, particularly the San Miguel de Salinas fault (Fig. 1).

The ENE-WSW Bajo Segura fault is situated in the southern part of the Bajo Segura basin. It is a blind reverse fault which dips towards the South and is related, on the surface, to several asymmetrical anticlines in the Neogene and Quaternary rocks. These folds include the Guardamar-El Moncayo, Benejúzar and Hurchillo folds (Montenat, 1977; Taboada et al., 1993; Alfaro, 1995). On both sides of the anticlines lie two subsiding sectors represented by the flood plain of the river Segura to the North, which is characterized by a more marked subsidence, and by the La Mata-Torrevieja lagoons to the South.

The Crevillente reverse fault, which runs N070E and dips northwards, is situated in the northern sector of the basin. The hanging wall is mainly composed of rocks from the basement of the External Zones of the Betic Cordillera, whereas the footwall comprises sedimentary rocks from the late Miocene-Quaternary which show a progressive unconformity. Several anticlines which continued to fold during the Quaternary occur along this fault (Alfaro, 1995).

In the Bajo Segura basin there are several NW-SE running faults, such as the Torrevieja, Guardamar and San Miguel de Salinas faults. These right-lateral faults displaced several of the anticlines of the Bajo Segura.

SUSCEPTIBILITY OF HOLOCENE AND UPPER PLEISTOCENE SEDIMENTS TO LIQUEFACTION

Liquefaction occurred on repeated occasions in the Bajo Segura basin. The historical cases of liquefaction always took place in the fluvial and coastal sediments which lie close to the present-day course of the river. This is a consequence of the susceptibility of these sediments to liquefaction.

This susceptibility to liquefaction is due to a combination of a number of factors (Seed and Idriss, 1971; Youd and Perkins, 1978): (1) the presence of the water table close to the surface, which saturates the materials, (2) the fact that the sediments are fine-grained and non-cohesive, and exhibit a reduced permeability (fine or silty sand although recent data show that coarser sediments may also liquefy, Obermeier et al., 1993), and (3) the fact that these sediments are situated close to the surface (between 0 and -15 m), and, hence, are poorly compacted.

The water table in this valley is very shallow and linked to the river. Frequently, its maximum depth is less than 2 m although it increases towards the edges of the valley because of the rise in the topography (depths greater than 10 m). Since the aquifer is characterized by its poor quality (high salinity), it is scarcely exploited with the result that it undergoes only small variations in level with time (Excma. Dip. Prov. Alicante and I.T.G.E., 1982).

The most recent sediments filling the basin belong to a unit of late Pleistocene-Holocene age. This unit consists of three different facies: (1) alluvial fan facies, (2) fluvial and lagoon facies and (3) littoral facies. Given the nature of the sedimentary environments in the valley (mainly alluvial, fluvial and littoral), fine sands frequently occur. Youd and Perkins (1978) analyzed the influence of the sedimentary environment on liquefaction, noting that it is limited to certain environments, whilst absent in others. Considering the data compiled by these authors, the susceptibility to liquefaction of the Segura valley sediments is high for fluvial and littoral environments, and moderate for alluvial fan sediments. It should also be pointed out that, in alluvial fan sediments, the water table is at a greater depth with the result that no cases of liquefaction have been documented for these sediments.

The age of the sediments is also a very important factor given that the susceptibility to liquefaction decreases with age (Youd and Perkins, 1978). Kramer and Arango (1998) quantified this and demonstrated that, all other factors being equal (geological, geotechnical etc.), the strength of sediments doubles at 0.1 Ma (Table 1). Given that the surficial sediments (0-15 m) of the river Segura valley are between 0 and 6000 years old (Alfaro, 1995; Soria et al., 1999), this effect is negligible. Consequently, from a strictly geological point of view, the susceptibility of these sediments to liquefaction is high.

The last factor which defines the susceptibility of sediments to liquefaction is their mechanical properties. The granulometric curve of the sediment and its resistance to penetration (SPT) are particularly useful. The results of this test are related to the degree of sediment compaction and cementation, which is a direct indicator of the susceptibility of the sediment to liquefaction. More than 70% of the SPT carried out in sediments from the Segura valley gave less than 10 blows, and SPT was similar to the rest of the valley. Fig. 2 shows the results of the SPT tests carried out in sandy sediments (fluvial and littoral) in the valley. The number of blows in this test increases owing to the existence of a greater confining pressure with depth. Likewise, the number of blows varies depending on the energy efficiency of the equipment used (energy losses due to friction of the test rods). In accordance with Seed and Idriss (1982), it is necessary to correct the result of the

Table 1. Liquefaction strength increase in relation to age increase (after Kramer and Arango, 1998). Quantities indicate the number of times soil strength increases with respect to strength of current sediments.

Tabla 1. Aumento de la resistencia a la licuefacción con el aumento de la edad del sedimento (según Kramer y Arango, 1998). Las cantidades indican el número de veces que se incrementa la resistencia del terreno en comparación con sedimentos actuales.

Age (years)	0-1000	10,000	100,000	1,000,000
Strength	1	1.42	2	2.45

SPT test for these two factors in order to obtain a correct evaluation of the strength of the sediment.

In Fig. 3 the granulometric curves of sandy sediments are given for several zones within the valley (the alluvial sediment tests were excluded). The curves were obtained using granulometric analyses of numerous samples taken from more than 100 boreholes. This figure shows that the particle-size distribution is not uniform: at the river mouth the fine content of the sand is very low (10%); close to the channel the fine content is 20-40% (although it can reach up to 60%); in the center and NW of the valley the fine content is 30-50%, and can reach 60-70%; lastly, in the NE of the valley the sand content is generally less than 30%, despite the existence of very localized pockets of very clean, fine sand (hence the wide range of particle size in this area, see Fig. 3). Bearing in mind that the normalized SPT does not vary significantly, it can be deduced that the present-day river mouth and the areas close to the channel are most susceptible to liquefaction (high or very high), whereas the rest of the valley is somewhat less susceptible (moderate to high) given that these sediments have a high silt and clay content, which confers cohesive properties upon the sediment and makes liquefaction more difficult. These results are consistent with the historical data on liquefaction during the 1829 Torrevieja earthquake (Larramendi, 1829).

LIQUEFACTION DURING THE 1829 TORREVIEJA EARTHQUAKE

The violence of the Torrevieja earthquake led to the liquefaction of recent sandy sediments, with frequent surface manifestations (Rodríguez de la Torre, 1984), such as sand volcanoes, with craters of up to 12 cm in diameter, from which there was a prolonged and abundant flow of water and sand. Similarly, there are reports of numerous cases of cracks on the ground surface, with lateral spreading of blocks, from which, again, there was an abundant flow of water and sand. River banks underwent numerous breaks and collapses, probably related to the liquefaction of deep levels of sand and lateral spreading of the non-liquefied part of the ground. The collapse of four bridges was due to this phenomenon (Delgado et al., 1998).

According to the data compiled by Larramendi (1829), the total area covered by sand extruded from sand volcanoes and fissures was over 7 km^2 (Fig. 4). Most cases of liquefaction took place at the mouth of the Segura river, between Dolores, Benijófar and Guardamar.

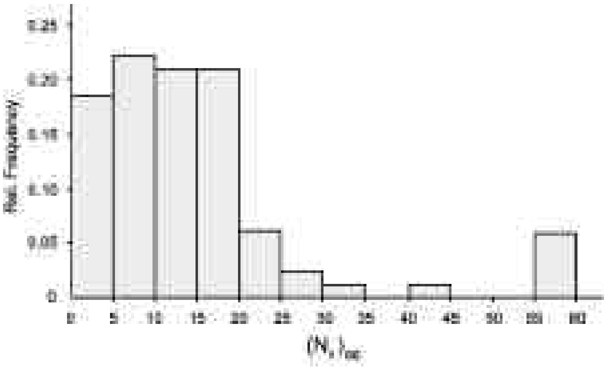

Figure 2. Normalized SPT distribution in the sandy sediments of the Vega Baja (Delgado, 1997).

Figura 2. Distribución del SPT normalizado en los sedimentos arenosos de la Vega Baja (Delgado, 1997).

The largest manifestations of liquefaction occurred in the immediate vicinity of San Fulgencio, being also abundant in Callosa del Segura (Larramendi, 1829). In the Callosa del Segura area, the seismic liquefaction processes were probably favored by the existing artesian conditions. In the vicinity of Callosa is a superficial sandy aquifer whose sands are colloquially known as *arenas brujas* because of the frequent artesian processes. The remainder of the Bajo Segura basin comprises a multilayered aquifer, and there is only evidence of small artesian aquifers at more than 40 m depth.

Despite the extent of liquefaction processes in the past, there is currently no evidence on the surface probably because of the small size of these liquefaction features and the intense anthropogenic activity. In addition, historical documents describe the rapid removal of the remains of sand volcanoes immediately after the earthquake (Rodríguez de la Torre, 1984).

The earthquake was followed by a number of large aftershocks, some of which were large enough to trigger liquefaction. Based on historical documents, therefore, we know that the aftershock of the 18/04/1829 event (I_o = VII) led to the formation of nine sand volcanoes in the vicinity of Orihuela (Rodríguez de la Torre, 1984).

More recently, the 1919 Jacarilla earthquake (I_o= VIII; mb = 5.2; Mezcua and Martínez Solares, 1983) also caused liquefaction (Kindelán and Gorostízaga, 1920). Although the information available does not allow the geographical areas affected to be determined with certainty, modeling of the soil behavior suggests that the

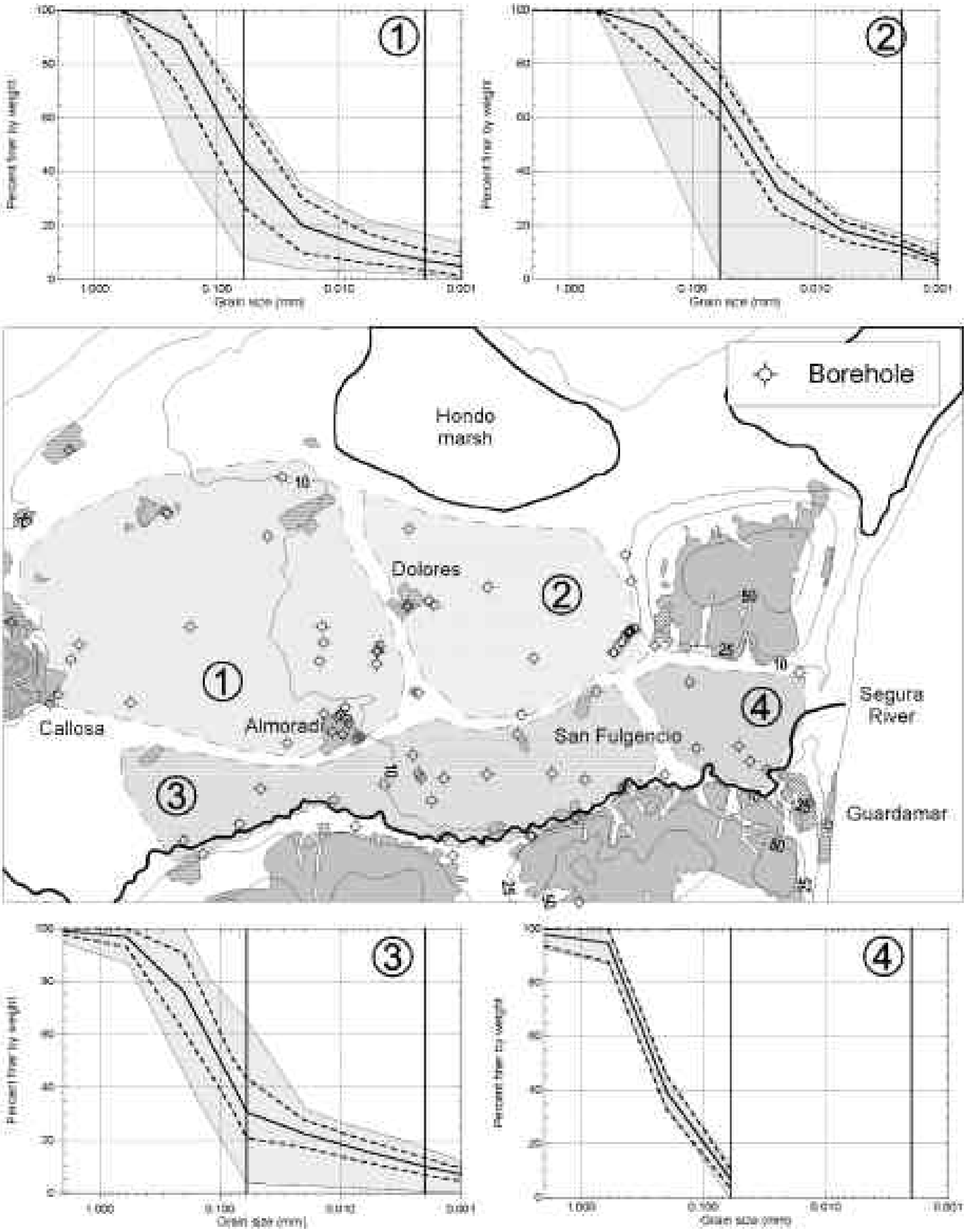

Figure 3. Fine grained content (f<0.072 mm) variation in the sandy sediments from the Segura valley.

Figura 3. Variación del contenido en finos (f<0.072 mm) en los sedimentos arenosos del Valle del río Segura.

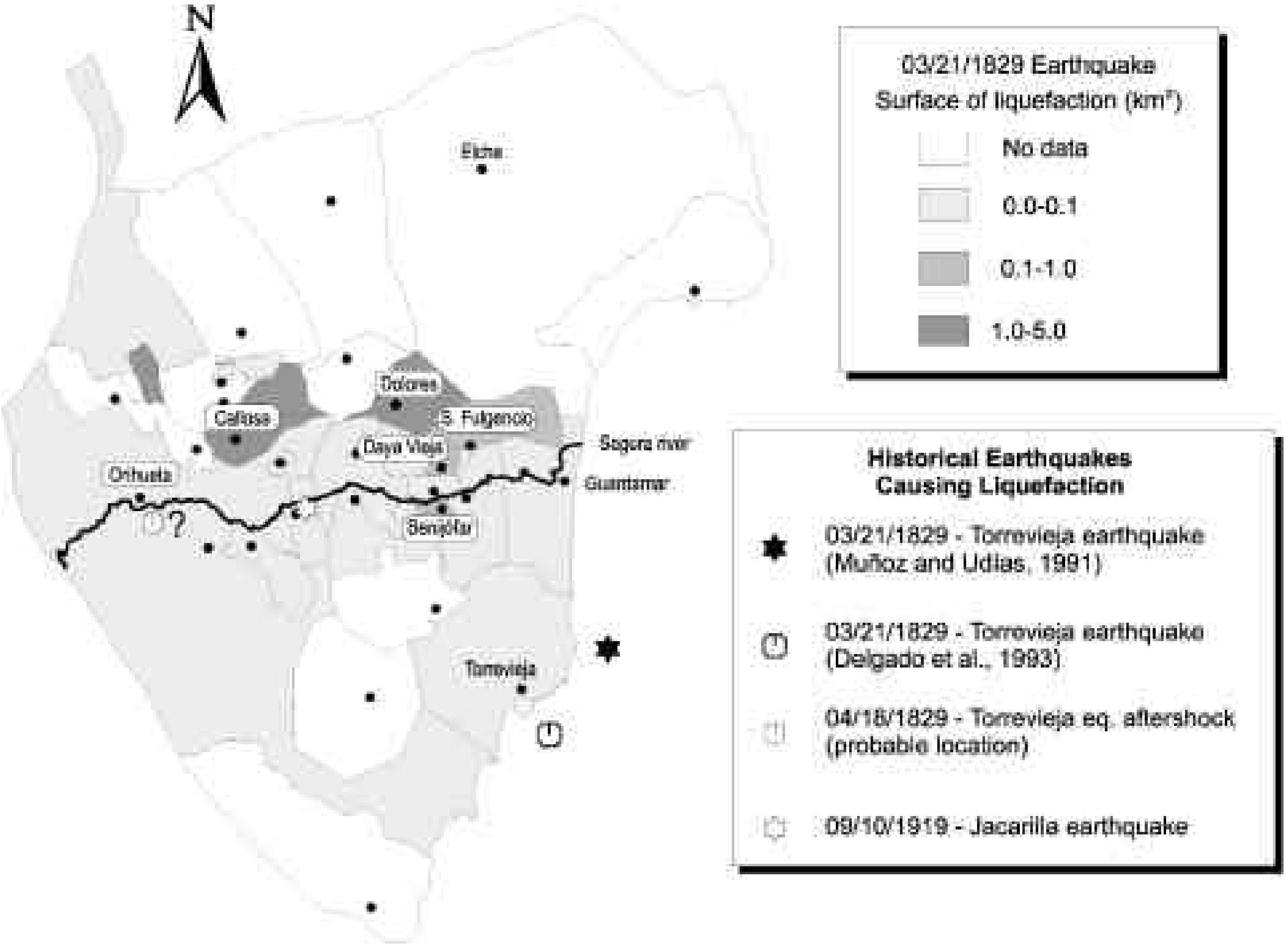

Figure 4. Map showing the distribution of historical liquefaction during the Torrevieja earthquake (1829).

Figura 4. Mapa en el que se muestra la distribución de la licuefacción histórica durante el terremoto de Torrevieja de 1829.

phenomena only occurred close to Jacarilla (Delgado et al., 1996).

PALEOLIQUEFACTION IN THE BAJO SEGURA BASIN

Some of the effects of paleoliquefaction processes may be preserved in the geological record, displaying a series of sediment deformation structures called seismites (Seilacher, 1969). Estévez et al. (1994) describe soft-sediment deformation structures named detritic wedges and interpret them as seismites in the Tortonian deltaic sediments, outcropping between Crevillente and Elche. Montenat (1980) mentions the presence of seismites in Messinian shallow marine sediments, close to San Miguel de Salinas. Finally, Alfaro et al. (1999) have attributed several soft-sediment deformation structures observed in the fluvial and littoral early Pleistocene sediments of Alicante and Guardamar del Segura to seismic shocks. All these soft-sediment deformation structures, interpreted as seismites, indicate the occurrence of earthquakes of moderate-high magnitude in the Bajo Segura basin, from the late Miocene to the early Pleistocene. However, these seismites should not be used to establish the recurrence of moderate-large paleoearthquakes in the region. In most cases, more recent sediments are employed to establish these recurrence intervals.

To this end, the last sediments (late Pleistocene-Holocene) to fill the Bajo Segura basin were analyzed. Several trenches, which were excavated for the construction of the Crevillente-Cartagena motorway, were examined. Unfortunately, the reliance on observation of trenches for paleoliquefaction studies constitutes a serious limitation in most of the basin. The water table is very shallow in the area where the sediments are highly susceptible to the production of seismites. Only 1 to 2 m of sediments are exposed above the water table; and the top meter or so has been reworked by agricultural activity. Despite several hundred meters of trenches analyzed, no paleoseismic evidence was found.

In the study area, the only available evidence for recent paleoearthquakes is provided by several seismite layers identified in boreholes (Alfaro et al., 1996). Based on the analysis of core samples from various boreholes drilled into the most recent sediments filling the Bajo Segura basin, these authors reported the presence of at least 25 liquefaction features interpreted

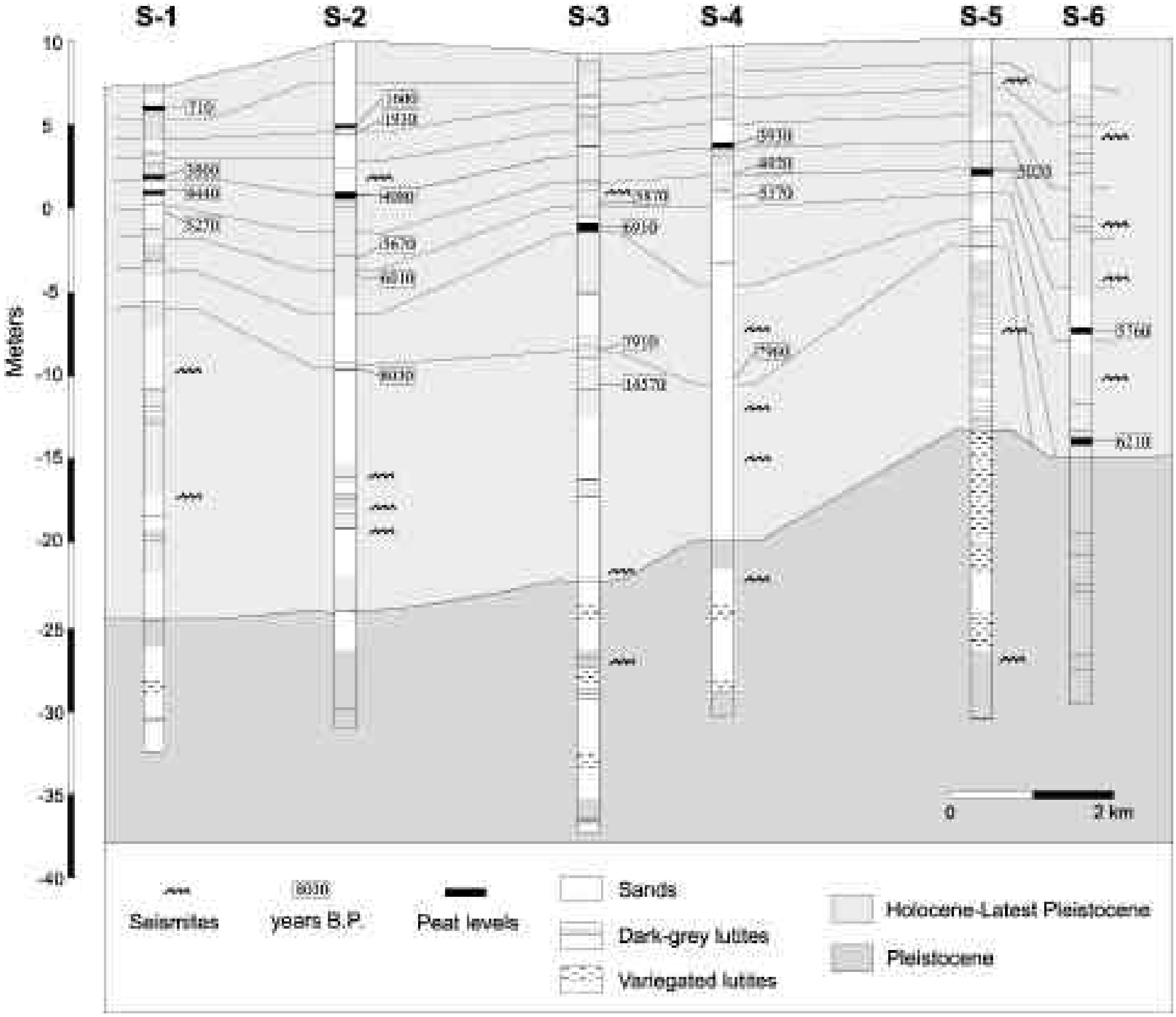

Figure 5. NW-SE simplified geological cross-section showing the morphology of the uppermost fill of the Bajo Segura basin (latest Pleistocene-Holocene), with location of boreholes, soft-sediment deformation structures interpreted as seismites (Alfaro et al., 1996), and the ^{14}C datings (after Soria et al., 1999).

Figura 5. Corte geológico NW-SE esquemático en el que se muestra la morfología del relleno más superficial de la cuenca del Bajo Segura (Pleistoceno terminal-Holoceno). Se han situado las columnas de los sondeos estudiados, las estructuras de deformación interpretadas como sismitas por Alfaro et al. (1996) y las dataciones radiométricas de ^{14}C (según Soria et al., 1999).

as seismites. These seismites belong to the last unit filling the Bajo Segura basin, dating from the late Pleistocene-Holocene (Soria et al., 1999). These authors used 30 radiometric ^{14}C datings obtained in layers rich in organic material and shells (Quaternary Dating Research Center, Australian National University) to calculate the recent sedimentation rates in the basin and to establish the position of the isochrones over the last 8000 years at intervals of 1000 years. The young age of the latest sediments filling the basin, with a mean thickness of 30 m, is due to the high rate of sedimentation during the Holocene, varying between 3.7 mm/yr and 1.9 mm/yr, which is related to the last eustatic rise in the Mediterranean Sea (Soria et al., 1999).

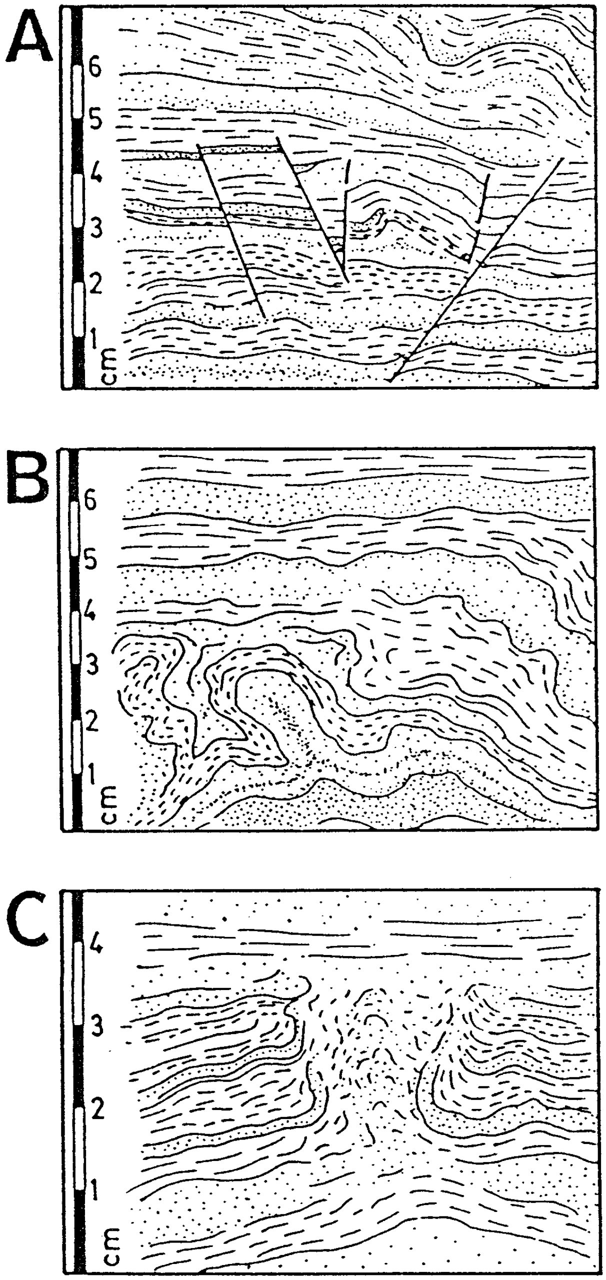

Figure 6. Soft-sediment deformation structures observed in the cores of boreholes. A. Microfaults. B. Convolute lamination. C. Fluid escape structure.

Figura 6. Esquemas de varias estructuras de deformación observadas en los testigos de los sondeos. A. Microfallas. B. Laminación distorsionada. C. Estructura de escape de fluidos.

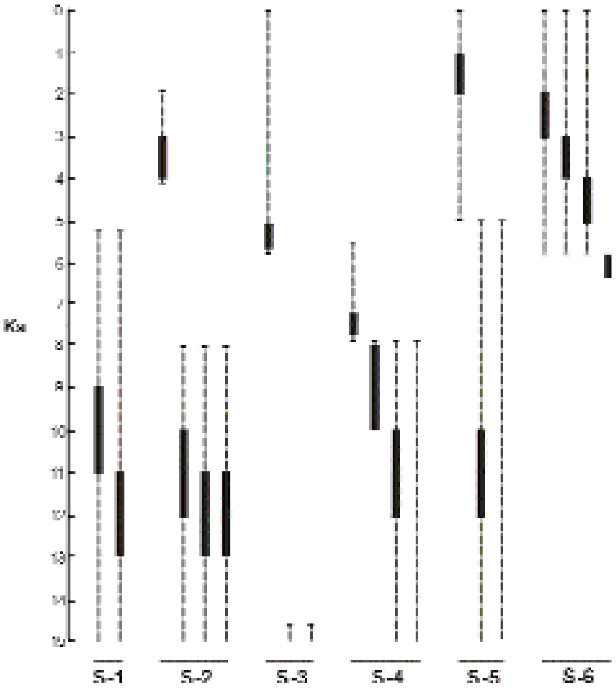

Figure 7. Age of soft-sediment deformation structures interpreted as seismites from ^{14}C datings. The solid line indicates the time interval in which seismites could have developed. The black solid rectangle indicates the most probable age deduced from isochrones.

Figura 7. Edad de las estructuras sedimentarias de deformación interpretadas como sismitas, deducida de las dataciones de ^{14}C. La línea continua indica el intervalo de tiempo en el que se han podido originar cada una de las sismitas. El rectángulo negro indica la edad más probable deducida a partir de las isocronas.

We selected six of these boreholes (Fig. 5), where the majority of these seismites were located and for which 17 ^{14}C radiocarbon datings were available in an attempt to establish the recurrence intervals for earthquakes of moderate-high magnitude in the study area. These coseismic liquefaction features, which liquefied when located at the surface, are found at a depth of nearly 40 m. The main types of seismites, limited above and below by non-deformed beds, are microfaults, convolute lamination and fluid escape structures (pillars) (Fig. 6).

The possible age intervals for all of the seismites, based on the radiometric ^{14}C datings, are shown in Fig. 7. The most probable age for each of the liquefaction features was established using the isochrones defined by Soria et al. (1999). Based on the most probable age of each seismite, we identified at least seven paleoearthquakes over the last 8000 years. From these paleoearthquakes and the 1829 Torrevieja earthquake, we established a minimum recurrence interval of earthquakes of moderate-high magnitude in the study area of approximately 1000 years. Although this methodology has certain limitations because of the small size of the core samples (only 15 cm in diameter) (Alfaro, 1996), it allows the identification of, at least, eight moderate to high-magnitude earthquakes in the Bajo Segura Basin during the last 8000 years. Seismites are also present below the 8000 yr isochrone and below one sample dated at 14,500 years, but the scarcity of datings prevents us from making a reliable estimate for the recurrence interval in these older deposits.

CONCLUSIONS

In the Bajo Segura basin, situated in the eastern part of the Betic Cordillera, no direct evidence of paleoearthquakes is available since the principal active faults are blind thrusts and blind strike-slip faults. Evidence of paleoseismicity is restricted to coseismic liquefaction features with the result that indirect evidence of paleoearthquakes is of particular interest in this region where surface fault ruptures are not visible. Such references to paleoliquefaction have been reported during various historical earthquakes, especially, in the case of the 1829 Torrevieja earthquake.

In the Bajo Segura basin, analysis of trenches in the most recent Holocene sediments filling the basin is limited by the shallowness of the water table between 1 and 2 m in depth. It should also be pointed out that these sediments have been reworked by agricultural activity.

The only available evidence for recent paleoearthquakes in the study area constitutes various layers of liquefaction features that were identified from core samples in sediments dating from the late Pleistocene-Holocene. Analysis of these seismite layers and the radiometric ^{14}C datings corresponding to the same boreholes enabled us to determine a recurrence interval of seismic events of moderate-high magnitude of approximately 1000 years. Despite its limitations, the method allowed us to assess the recurrence of moderate-high paleoearthquakes, using the information available to date.

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