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Tsunami deposits as paleoseismic indicators: examples from the Spanish coast

Los depósitos de tsunamis como indicadores paleosísmicos: ejemplos en el litoral español

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ABSTRACT

Tsunamis are usually associated with submarine tectonic activity. Tsunamis transform the shore owing to their erosive and sedimentary capacity. Evidence of tsunamis can be preserved in the geological record for millions of years. The tsunami sedimentary record is a useful tool for obtaining paleoseismic information since it is the only record available that allows us to detect and to analyze ancient offshore seismicity. Three examples of tsunami deposits which contribute to the knowledge of the paleoseismicity in the Gulf of Cádiz are presented. The study of sedimentary deposits of the Valdelagrana spit barrier (Cádiz, Spain) suggests that an event such as the 1755 Lisbon earthquake (Ms 8,5-9) might have occurred ca. 216-218 BC. This is the first time data on the return period of these high magnitude events have been provided.

Keywords: Paleoseismicity. Geological signature. 1755 Lisbon earthquake. Gulf of Cádiz records.

RESUMEN

Los tsunamis se generan, en la mayoría de los casos, como consecuencia de la actividad tectónica submarina. El efecto de los tsunamis sobre la costa transforma el paisaje debido tanto a su capacidad erosiva como sedimentaria. Dichas transformaciones pueden conservarse en el registro geológico durante millones de años. El análisis de los depósitos sedimentarios generados por tsunamis puede aportar valiosa información paleosísmica, ya que es el único registro disponible que permite descubrir e interpretar la sismicidad ocurrida en el fondo oceánico. Se presentan 3 ejemplos de depósitos atribuidos a la acción de tsunamis en las costas del sudoeste de España y su análisis, interpretación y aportación al estudio de la paleosismicidad del Golfo de Cádiz. La interpretación de un tsunami ocurrido, posiblemente, en el año 216-218 AC detectado en depósitos sedimentarios de la flecha litoral de Valdelagrana (Cádiz) y las marismas de Doñana (Huelva) aportan, por primera vez en este trabajo, información acerca del período de recurrencia de un evento como el terremoto de Lisboa de 1755 (Ms 8,5-9).

Palabras clave: Paleosismicidad. Registro geológico. Terremoto de Lisboa de 1755. Registro Golfo de Cádiz.

TSUNAMIS

A tsunami is a set of gravity waves produced by a displacement of the seafloor, and is characterized by a long wave-length and a long period. The waves move at a high speed across the ocean without significant loss of energy before finally breaking over the coast. The height of tsunami waves scarcely exceeds one meter in deep oceanic waters, but when they approach the continental shelf the shoaling effects become important, causing a reduction in phase velocity and a piling-up of water. The waves transform into enormous water-walls reaching 10, 20 or even 30 m in height when breaking over the coast. This often occurs at some distance from the source area.

Although most tsunamis are caused by sudden displacements of the ocean floor on account of earthquakes, they can also be caused by large-scale submarine landslides, major avalanches, volcanic eruptions and meteoritic impacts. At present, there is no way of knowing whether a tsunami that had occurred prior to historical times was triggered by an earthquake or by some other cause.

The size and pattern of a breaking tsunami wave on reaching the coast is variable and difficult to predict mainly because of local resonance, refraction and dissipation phenomena related to offshore topography, configuration of the coast, occurrence of reefs or sand bars, tidal elevation and quake magnitude. Tsunami waves may occur as breaking waves, water bores or as fast tides (González, 1999), and the wave run-up and inland penetration distance of a given event may vary along the coast (Imamura et al., 1995).

Although the coasts of the Iberian Peninsula cannot be regarded as very tsunamigenic, up to 27 tsunamis have been documented between the 3rd century BC and AD 1900. Of these, 18 struck the Spanish and Portuguese Atlantic coasts (Galbis, 1932, 1940, Campos, 1991, 1992) (Table 1). Despite their scarcity and usually limited coastal impact, the recurrence of particularly intense earthquakes capable of inducing large, catastrophic tsunamis is possible. This was the case of the 1755 Lisbon tsunami, which was associated with an earthquake of an estimated Ms of 8,5-9 (Udías et al., 1976, Campos, 1992). The main seismic area capable of generating such tsunamis is the Azores-Gibraltar transform fault, along the Africa-Iberian plate boundary. The North-South compression in the Cádiz-Gibraltar zone induces vertical movements that can produce large tsunamis such as the AD 1755 one (Udías et al., 1976, Catalán et al., 1979, Buforn et al., 1988, Campos, 1991, 1992).

TSUNAMIS AS PALAEOSEISMIC INDICATORS

In the case of seismic-induced tsunamis it has been empirically demonstrated that the magnitude of a tsunami depends considerably on the magnitude of the triggering earthquake and on the focal depth (Iida, 1963 in Catalán et al., 1979). Most tsunamis are produced by earthquakes with a magnitude higher than 6.5 and a focal depth between 20 and 40 km -never reaching 80 km (Fig. 1a, Iida, 1963). Additional controls of tsunami magnitude include the fault type, the aftershock area and the distance between the epicenter and the coast (cf. Ben-Menahen and Rosenman, 1972, Abe, 1973, Catalán et al., 1979, Hatori, 1995). Active dip-slip faults are potentially more dangerous than strike-slip structures because they move the ocean floor and the overlying water column vertically.

The magnitude of a tsunami (which is proportional to its energy) can be calculated from the height of the breaking wave crest above the still water level and from the length of the run-up (Iida, 1963) (Fig. 1b). Iida (1963) found a direct relationship between earthquake and tsunami magnitudes (Fig. 1c) and Hatori (1995) demonstrated that the magnitude of tsunamis decreases with increasing distance from the source area.

However, the application of these concepts to the geological and historical records is a complex task, and

Table 1: Historical record of tsunamis from 2300 BP until AD 1900 along the Spanish and Portuguese coasts (Galbis, 1932, 1940, Campos, 1991).

Tabla 1: Registro histórico de tsunamis ocurridos en el litoral español y portugués entre los años 2300 BC y 1900 AD (Galbis, 1932, 1940, Campos, 1991).

Tsunami year	Atlantic coast	Mediterranean coast
218-216 BC	Cádiz	
210-209 BC	Cádiz	
60 BC	Portugal and Galicia	
365 AD		Málaga and Almería
382	Portugal	
881	Cádiz	
949	Portugal	
1504	Andalucía ?	Andalucía ?
1522		Almería
1531	Lisbon and S Portugal	
1680		Málaga
1722	Algarve (Portugal)	
1731	Cádiz	
1755 (Different months)	Portugal, Morocco and Andalucía	
1756 (Different months)	Portugal	Balearic islands
1761	Lisbon and Galicia	
1790		Murcia
1804		Málaga and Almería
1816	Portugal	
1829		Murcia and Alicante
1848	Portugal	
1860		Alicante
1875		Valencia and Cataluña

the main application to paleoseismic research is the determination of potential tsunamigenic areas that can affect a given coastal area.

Historical data allow a relatively precise estimation of wave parameters and effects such as height, number of waves, frequency, run-up and penetration and nature of flooding and, in the case of seismic origin, time, earthquake intensity and location. Geological data include geomorphological and sedimentary evidence of the erosion and deposits related to the tsunami. However, it is not easy to distinguish these signs from evidence of similar deposits generated by other catastrophic events of higher frequency such as storms and hurricane surges, and river floods. There are no quantitative or qualitative criteria for an accurate differentiation.

GEOLOGICAL SIGNATURES OF TSUNAMIS ON THE COAST

The geomorphological and sedimentological impact of tsunamis on the coast are poorly understood because of the high turbulence involved in this process, which has not been adequately described by any deterministic theory (Dawson et al., 1991, Dawson 1994, 1996, 1999).

Investigation of current tsunamis shows that run-up and swash cause material from the bottom of the sea to be transported landwards and deposited some distance inland as sand sheets forming washover fans with variable textures and grain sizes. In contrast, the backwash is usually associated with erosion. As a result,

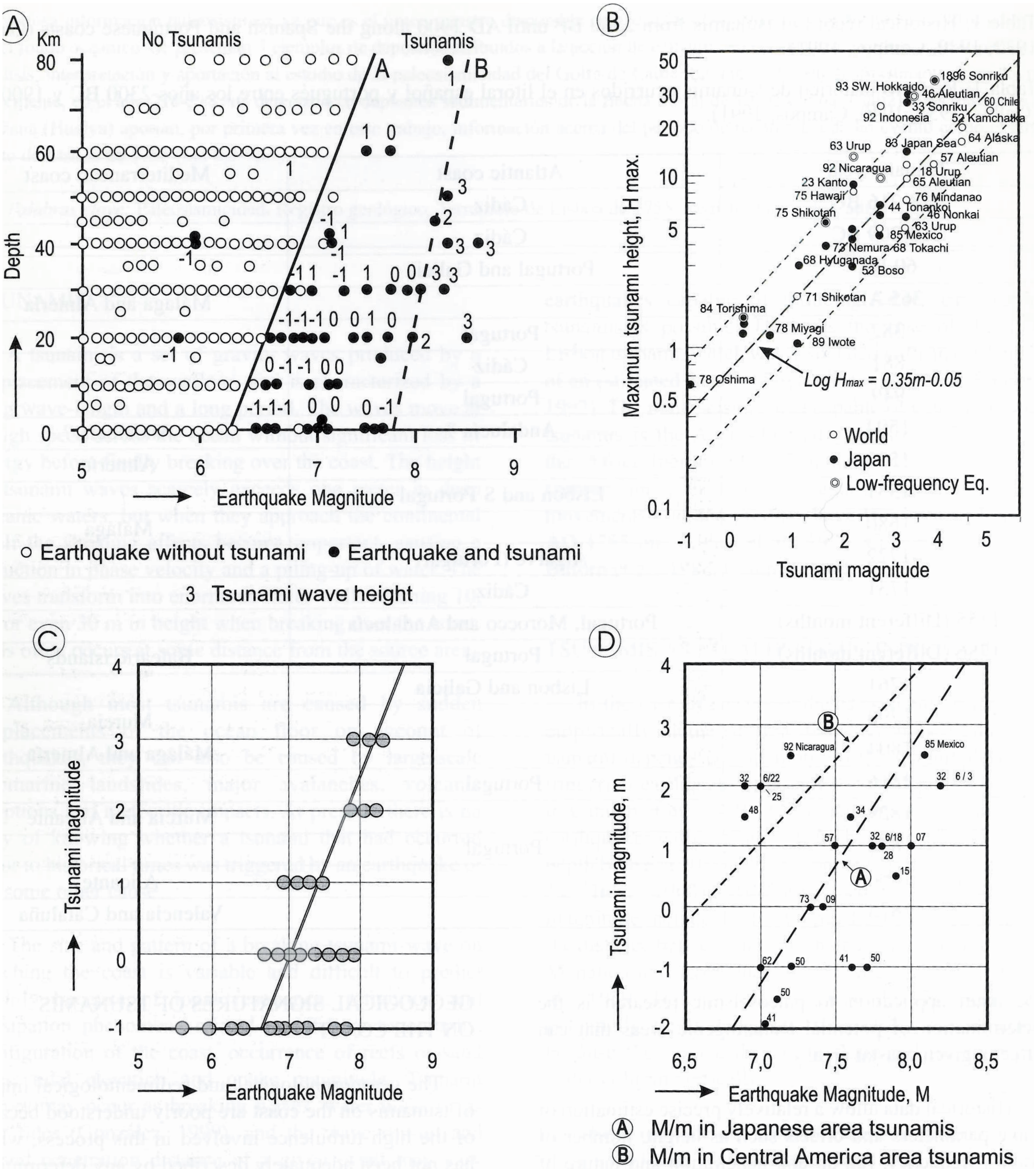

Figure 1. A) Relations between earthquake magnitude, focal depth and tsunami wave height (after Iida, 1963 in Catalán et al., 1979). B) Empirically obtained relationship between maximum tsunami height and tsunami magnitude (Hatori, 1995). C) Earthquake/tsunami magnitudes (Iida, 1963 in Catalán et al., 1979). D) Relationship between earthquake and tsunami magnitudes in different tsunamigenic areas (Hatori, 1995).

Figura. A) Relación entre la magnitud del terremoto, la profundidad del foco sísmico y la altura del tsunami (Iida, 1963, en Catalán et al., 1979). B) Relación empírica entre la altura máxima de diferentes tsunamis y su magnitud (Hatori, 1995). C). Relación Magnitud del terremoto / Magnitud del tsunami (Iida, 1963). D). Relación entre la magnitud del terremoto y la magnitud del tsunami en diferentes regiones del Planeta (Hatori, 1995).

the drainage network of the backshore may be dramatically changed. Tsunami deposits usually display multiple sedimentary sequences that fine both upwards and landwards. The maximum elevation reached by the deposit is usually less than the upper limit of the tsunami run-up (Dawson, 1999). The internal structure of the sandy deposits can be a horizontal lamination that is massive or parallel.

A good knowledge of the local dynamics and background processes influencing sedimentation in the studied area is essential as it is not possible to define unequivocally the signature of tsunami deposits owing to the diversity of controls involved in sedimentation (cf. Dawson et al., 1991, 1996, Foster et al., 1991, Minoura and Nakaya, 1991, Bourgeois and Reinhart, 1993, Dawson, 1994, 1996 and 1999, Nishimura and Miyaji, 1995, Sato et al., 1995, Shi et al., 1995, Synolakis et al., 1995, Minoura et al., 1996 or Goff et al., 1998).

There is agreement on 1) the marine origin of the tsunami deposits and associated fossil content, 2) the high energy involved in the event, 3) the geological position and (in some cases) morphology, and 4) on the topographic elevation reached in coastal settings (higher, and further inland than the highest storm surges). Tsunamis are also very rare, or at least occur with a low frequency in the sedimentary record (except in areas of great seismic activity). The deposit of a single event may include several sequences or episodes generated by swash and backwash of the same wave or by successive tsunami waves. Tsunami-related layers can be continuous laterally and can occur in very distant basins or basin margins as synchronous deposits.

Macrofauna, microfauna and diatom have been used to identify and interpret some deposits as tsunamigenic, and also to detect coseismic or postseismic vertical changes (subsidence or elevation) in the substratum (Dawson et al., 1996, Dominey-Howes, 1996, Guibault et al., 1996, Shennan et al., 1996, Kortekaas et al., 1998 a).

The application of these criteria to the sedimentary record is not easy given that some criteria are absent or ambiguous. Nevertheless, there is abundant literature on the interpretation of tsunamigenic deposits both of Holocene and older ages. Some of the most representative studies on Holocene tsunami deposits concern: the Storegga megaslide, which occurred ca. 7000 BP (Dawson et al., 1988, Long et al., 1989a, 1989b, Bondevik et al., 1997, Dawson, 1998); the slide deposits (homogenite) in the Mediterranean abyssal area related to the collapse of the Santorini volcano ca. 3500 BP (Kastens and Cita, 1981, Cita and Rimoldi, 1997); the tsunami deposits in the salt marshes and estuaries of western North-America which has permitted evaluation of local uplift or subsidence rates (Atwater, 1987, Clague and Bobrovsky, 1994, Darienzo et al., 1994, Nelson et al., 1996, Benson et al., 1997); and the Japanese coastal areas where it has been possible to correlate high energy deposits with recent and historically recorded tsunamis (Minoura and Nakaya, 1991, Minoura et al., 1994).

EXAMPLES FROM THE IBERIAN COAST

The tsunami generated by the 1755 Lisbon earthquake

The 1755 Lisbon earthquake is the best documented earthquake in history since it resulted in more than ten thousand deaths and caused considerable damage in Europe and North Africa. Galbis (1940) and Martínez Solares et al. (1979) used historical documents to reconstruct the isoseismal map of the earthquake and deduced a magnitude between 8,5 and 9. Some authors place the epicenter 200 km SW of cabo Sao Vicente (Portugal), to the North of the Gorringe Bank at the intersection of the Azores-Gibraltar transcurrent fault and the Messejana/Plasencia-Alentejo fault (Machado, 1966, Martínez Solares et al., 1979, Moreira, 1985, Buforn et al., 1988). Other authors invoke subduction at the Gorringe Bank or suggest an epicenter closer to Lisbon (Ribeiro, 1995, Baptista et al., 1996).

The 1755 Lisbon earthquake generated several tsunami waves that struck the coasts of Portugal, North Morocco and Spain, and even the Scilly Islands (SW UK) as has been demonstrated by distal deposits interbedded with lagoonal and coastal shallow-lacustrine peat sequences (Foster et al., 1991). Tsunami waves attained the maximum registered height along the Portuguese coast (Pereira de Sousa, 1919), leaving deposits in estuarine outlets and breaching barrier islands whose associated surficial forms are still preserved in many cases. Most Portuguese studies concern the remobilization of sand from the beach barriers and the re-deposition of sand, cobbles and boulders on the sheltered muddy intertidal salt marsh of Boca do Rio, Martinhal, and Ria Formosa (Andrade,1992, Andrade et al., 1994, 1997, 1998, Dawson et al., 1995, Hindson et al., 1996, Kortekaas et al., 1998a, 1998b, Hindson and Andrade, 1999).

Approximately one hour after the earthquake, the coasts of Cádiz and Huelva in Spain were also affected by three tsunami waves. In some places the number rose to approximately 20, and the irregular movement of water surface lasted for 24 hours (Real Academia de la Historia, 1756). Wave heights varied along the coast, with the most frequently reported values between 3 and 4 m. Nevertheless, although they rarely exceeded 6 m the waves attained 10 m at some sites. Despite not being very impressive, the waves reached the coast at high tide during a time of considerable fishing activity, taking the lives of more than one thousand people.

The 1755 tsunami deposits in the South of Spain

Several washover fans at the Valdelagrana barrier spit complex in the bay of Cádiz (southern Spain) have been related to the action of the 1755 Lisbon tsunami by Dabrio et al. (1998, 1999, 2000) and Luque et al. (1999). The barrier spit is located on the Atlantic side of the Gibraltar strait (Fig. 2), and extends in a north-south strike closing off the almost filled Guadalete estuary. The spit is crossed by the tide-dominated channels of the Guadalete and San Pedro rivers. The barrier spit includes three (H2 to H4) of the four sedimentary prograding morphosedimentary units (H1 to H4) separated by large swales formed by erosion or absence of deposition described by Zazo et al. (1994). The ages of these units are: H2 4400-2700 yr BP; H3 2400-700 yr BP and H4 500 yr BP-Present. Each H-unit consists of a set of prograding beach ridges. The sedimentary filling of the estuary has been studied by Zazo et al. (1994), Lario (1996), Borja et al. (1999), and Dabrio et al. (1999, 2000).

Most historical data on the effects of the tsunami in this coastal zone concern the village of El Puerto de Santa María, located on the northern side of the bay of Cádiz. A report of the Real Academia de la Historia cites waves of up to 8 m in height which destroyed the harbour and scattered numerous boats in the village and in the surrounding fields.

Aerial photographs and historical maps show that the sand ridges of the spit barrier grew from North to South, prograding successively to the western (seaward) side of the spit. Although the youngest progradation unit (H4) began to grow approximately 500 years ago, it was relatively small at the start of the XVIII century. There are several washover fans connected to the eastern (inland) side of the oldest H4 beach-ridge, which was active in 1755. The sandy washover fans record an event of exceptionally high energy. This event has been related to the tsunami triggered by the Lisbon earthquake (Dabrio et al., 1998, 1999, 2000).

The dimensions of the washover fans are 350-400 m long and 200-300 m wide (Fig. 2). At this locality, beach ridges rise 3-4 m above the high tide level and the fans, which are partially covered with aeolian sand dunes, almost attained the same height. Their margins have been covered with recent muddy sediments from the San Pedro tidal channel (Fig. 3).

Nowadays, storm surges inside the bay of Cádiz do not breach the outer sandy beach-ridges which locally rise 1.5 m above the high tide level. Some storms modify the beach profile and erode the clayey substratum (Reyes et al., 1996). This suggests that the waves that breached the 3 m-high beach ridges of the spit bar, which was active in 1755, were not caused by an average storm event. Rather, they should be attributed to an extreme episode of flooding.

The thickness of the sand units range between 1.2 and 0.5 m but they wedge out landwards. The marine origin of these deposits is demonstrated by the faunal content (besides macrofauna, there are also Ostracoda and foraminifers typical of marine and estuarine environments) and the morphology of the fans.

Luque et al. (1999) cored the fans at 19 localities to study the composition and internal structure of these deposits. These deposits consist of fine quartz sands, similar to the sediments of coastal ridges and aeolian dunes. They are arranged in irregularly-represented fining upwards sequences that occur three or four times in each fan. Each sequence includes up to 4 units (informally named Ato D) that could reflect the different conditions during the run-up and backwash of several tsunami waves (Fig. 3):

A: Basal unit, with an average thickness of 5 cm (values ranging between 3 and 12 cm) composed of a chaotic mass of fine sand and pebbles, complete and fragmented shells, and wood fragments, arranged chaotically. Although *Glycymeris* is the dominant genus, there are also ostreids (*Mactra* and *Cerastoderma*), and fragments of echinoids.

B: Fine sands with brown spots, 3 to 30 cm thick, with small scattered shell fragments and some plant remains.

C: 1 to 7 cm of homogeneous white fine sands that occasionally include a thin basal layer of fine shells in some cores.

D: (top). 1 to 11 cm of fine sand with interbedded irregular layers of silty clay, often with a wavy structure. The contact between sands and clays may be sharp or diffuse. The clays contain small fragments of shells and conspicuous plant remains.

The sand grain-size distribution is very similar to the underlying beach-ridge sands, but poorly sorted. Unit D and A are bimodally distributed because of the increase in the fraction finer than 0.063 mm, in the gravel sized clasts and in the fossil remains.

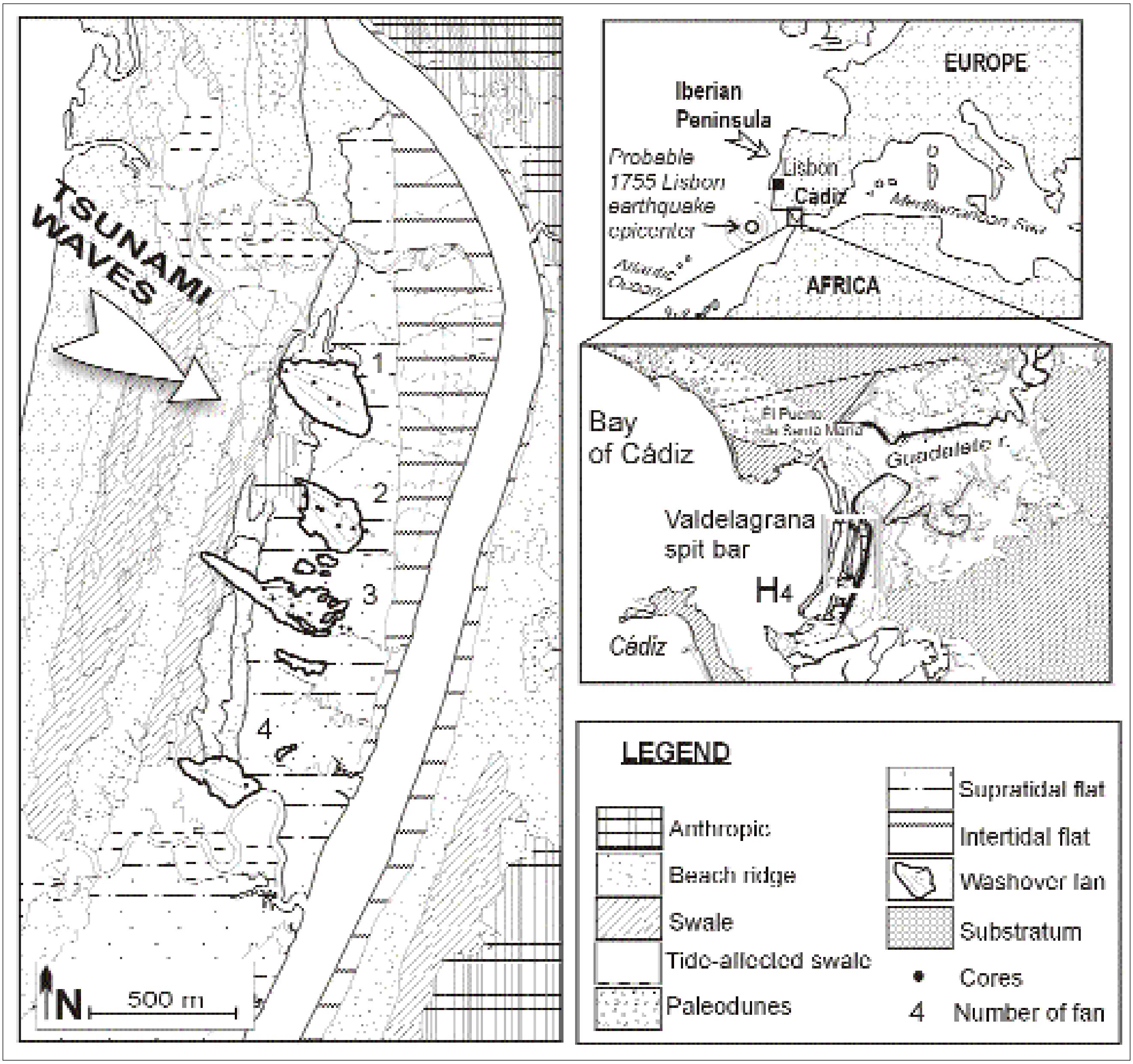

Figure 2. Location of the H4 progradation Unit at the Valdelagrana Spit Bar (Cádiz, Spain) and geomorphological map showing the 1755 Lisbon earthquake tsunami generated washover fan deposits (modified from Dabrio et al., 1999a, 1999b, 2000, Gómez Ponce et al., 1999, Luque et al., 1999).

Figura 2. Situación de la unidad progradante H4 en la flecha litoral de Valdelagrana (Cádiz, España) y mapa geomorfológico en el que se localizan los abanicos de derrame originados por el tsunami de 1755 (modificado de Dabrio et al., 1999 a, 1999 b, 2000, Gómez Ponce et al., 1999, Luque et al., 1999).

The internal structure of the deposits is evidence of the complex hydrodynamics and sedimentation, and can be attributed either to the cumulative effect of several flooding events repeated in time or to several tsunami wave penetration during a single event. These interpretations have been applied to recent and fossil tsunami deposits (Dawson et al., 1988, 1991, Long et al., 1989 a, 1989 b, Shi et al., 1995). Other possibilities are the occurrence of several tsunamis in a short time span, such as four smaller tsunamis documented in this area

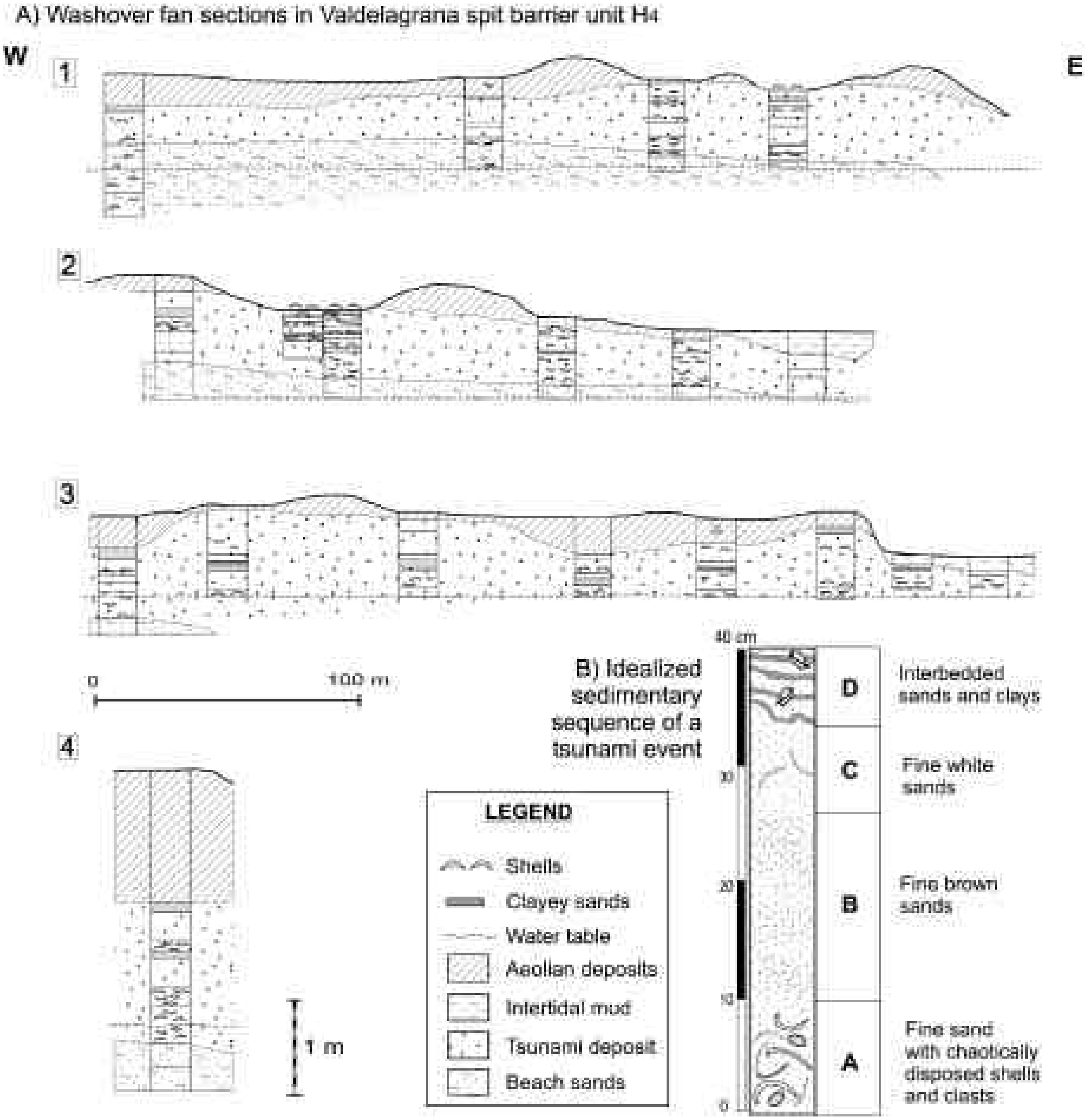

Figure 3. A) Stratigraphical section deduced from cores in the Valdelagrana washover fans. B) Ideal sequence of deposits related to a tsunami event (after Luque et al., 1999).

Figura 3. A) Sección estratigráfica de los abanicos de derrame de Valdelagrana descritos en base al estudio de los sondeos realizados. B) Esquema sintético de cada secuencia sedimentaria originada por un evento de tsunami (Luque et al., 1999).

between 1755 and 1761 (Galbis, 1932), or the swash of storm surges through the breaches in the sand barrier caused by the tsunamis.

The structure of the first three fining upward sequences at Valdelagrana resembles unit B of the Boca do Rio (Portugal) tsunami deposit, which Hindson et al. (1996) attributed to the 1755 event. The Boca do Rio tsunami deposits also include a subunit similar to our clayey unit D, with fining upward sequences, which Hindson et al. (1996) ascribed to repeated waves of tsunami or to wave reflection or backwash.

Luque et al. (1999) linked the sedimentary sequence of the Valdelagrana washover fans to the three consecutive waves that breached the sandy ridge, flooding the marshes inland. During the initial run-up a chaotic shelly basal level was deposited by turbulent water flowing inland. After inundation by a relatively still body of water of the area landwards of the spit, the continued run-up and the deceleration of the flow were recorded by units B and C. Amore accurate interpretation of the complex hydrodynamics of the process is not possible owing to the scarce data available. Unit D was deposited essentially by suspension during the high water level period following the passage of the large wave. Reflection of waves trapped inland of the barrier account for the wave-rippled structure.

Records of other pre-1755 tsunamis in the Gulf of Cádiz

Geomorphological and sedimentological data strongly suggest the occurrence of other tsunamis along the gulf of Cádiz during the late Holocene, as reported in historical documents (Galbis, 1932). Tsumani-generated deposits can be observed in two places: (1) the pre-H4 units of the Valdelagrana barrier spit, first described in this paper, and (2) the Doñana National Park in the Guadalquivir marshlands (Huelva, SW Spain).

Tsunami records in Doñana drill cores

The Doñana National Park occupies a wide marshland area near the mouth of the river Guadalquivir. Marshlands result from the progressive Holocene infilling of the Guadalquivir estuary, which has been associated with the progradation of a large barrier spit system, partly covered by a large dune field, to the southeast. The geomorphology of the area and the late Pleistocene and Holocene sedimentary evolution have been studied by Zazo et al. (1994, 1999 a, b), Lario et al. (1995), Goy et al. (1996), Lario (1996), Rodríguez-Ramírez et al. (1996), Rodríguez-Ramírez (1998), Cáceres (1999) and Dabrio et al. (1999).

Analysis of particle-size and environmental magnetic properties of two cores from the internal part of the muddy Holocene marshlands of Doñana (Lucio del Pescador and Lucio del Lobo, Lario, 1996) showed two episodes of an abrupt input of coarser sediment to the backbarrier muddy area (Fig. 4), which Lario et al. (2000) have attributed to tsunamis.

The 7.6 m deep Lucio del Pescador core (LP) was drilled 21 km from the coast, less than one meter above high-tide level. Despite the fact that the core consists of clayey silts, it contains two sandy intervals between 0.65-0.75 m and 7.10-7.20 m depth. The highest interval is made up of millimeter-thick layers of poorly sorted sands with shell fragments, with a small variation in grain size in the mean and median values. The lowermost layer is marked by an increase in sand content and by laminae of bivalve bioclasts and foraminifera, interbedded with clays; the increase in the mean grain size produces bimodal and multimodal distributions. Magnetic properties show an increase in the concentration of magnetic minerals which can reflect a change in the dynamics of the depositional environments and/or the provenance of sediments (Lario et al., 2000).

The 7.3 m-deep Lucio del Lobo (LL) core was drilled 18 km inland, less than one meter above high tide level. The dominant lithology is clayey silts. Near the base (7.00 to 7.10 m), a coarser-grained, bioclastic-rich layer records an increase in the hydrodynamic energy of the depositional environment. There are two other layers of poorly sorted coarser sediments that record events of increased energy. The environmental interpretation of the relatively-coarser sediment input and the change in the magnetic properties between 6.50 and 7.00 m suggest a possible fluvial contribution and/or high energy episodes which remobilized sediments towards a partially open estuarine environment.

The high-energy episode, which is well marked in the Lucio del Pescador core, was probably caused by a tsunami. By contrast, this can only be inferred at Lucio del Lobo since it lacks the required resolution (Fig. 4). This episode marks an increase in the hydraulic energy

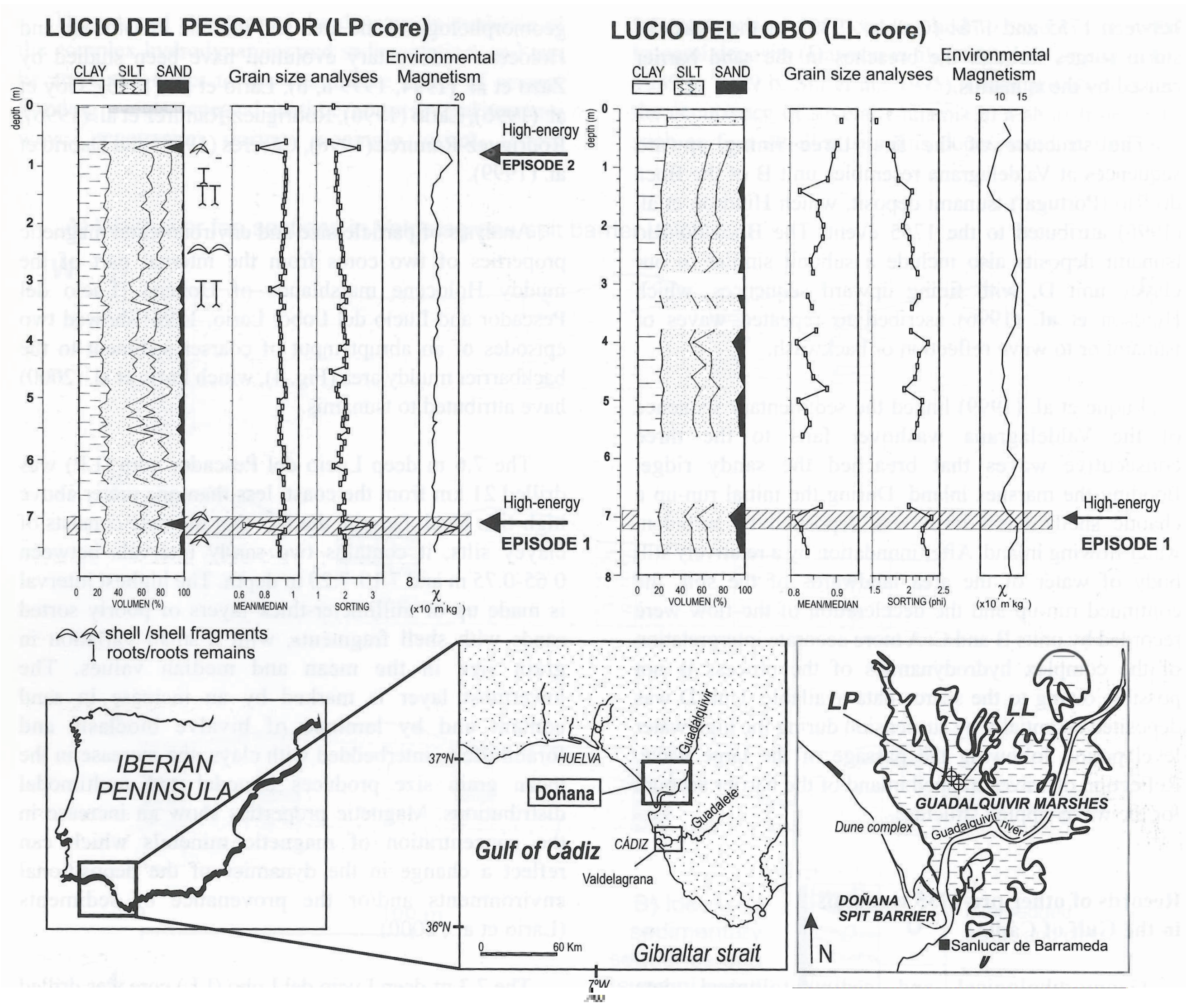

Figure 4. Grain size and environmental magnetism properties of the Lucio del Pescador (LP) and Lucio del Lobo (LL) cores (Guadalquivir marshlands) (Lario, 1996, Lario et al., 2000).

Figura 4. Análisis granulométrico y de magnetismo ambiental de los sondeos Lucio del Pescador (LP) y Lucio del Lobo (LL) (marismas del Guadalquivir) (Lario, 1996, Lario et al., 2000).

and in the size of the sediments. Magnetic properties, which also reflect a change, were re-established after the high-energy episode. This suggests a sporadic event that was probably unrelated to changes in sea-level or sediment budget.

Paleontological evidence (mollusc and echinoid bioclasts) indicate a marine provenance for these deposits. After this episode, brackish species of foraminifera and diatoms provide evidence of renewed communication with the sea (Lario, 1996). The event is therefore of marine origin, and Lario et al. (2000) correlated this with the gap separating the prograding morphosedimentary units H2 and H3 dated as 2550-2300 yr BP. Lario (1996) and Rodríguez-Ramírez et al. (1996) interpreted the gap as a time of widespread erosion at the Doñana barrier spit, but found no evidence of erosion in the marshland cores. As a result, Lario et al. (2000) suggest that the coarser-grained layers at the base of the cores represent a period of increased storminess, perhaps coeval with a very rapid high-energy episode such as a tsunami. Explanations for the origin of the gap include a

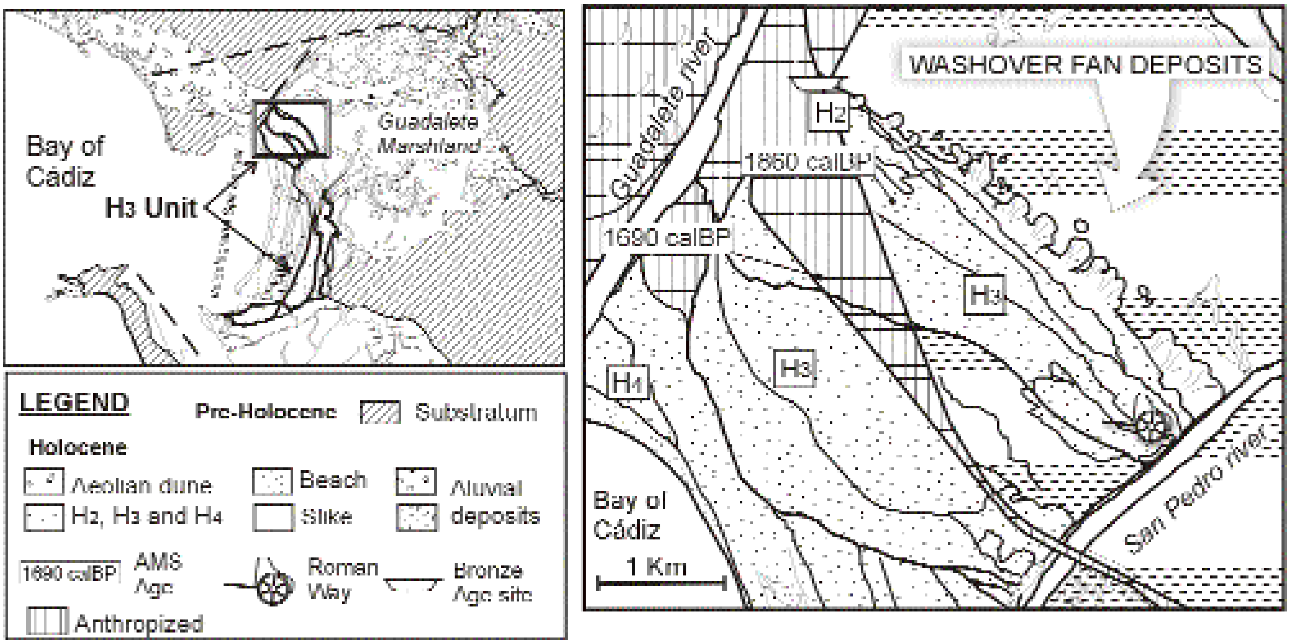

Figure 5. Washover fans associated with the prograding H3 unit at the Valdelagrana barrier spit, and at archeological sites cited in Borja et al. (1999).

Figura 5. Abanicos de derrame asociados a la unidad progradante H3 de la flecha litoral de Valdelagrana y situación de los yacimientos arqueológicos citados por Borja et al. (1999).

slight rise in sea-level, a change in the direction of prevailing winds (from WSW to SW) or storms, associated with low pressure cells (Zazo et al., 1994, 1999 a, Lario et al., 1995, Goy et al., 1996, Borja et al., 1999).

AMS radiocarbon dating of shells and plant remains in the event layers yielded ages ca. 2500 yr BP, which Lario et al. (2000) compare to the historical tsunami of BC 218 documented by Galbis (1932).

Washover fan deposits in Unit H3 of the Valdelagrana spit bar

The unit H3 at Valdelagrana (Fig. 5) began to accumulate after the erosional gap dated ca. 2550-2300 yr BP (Borja et al., 1999, see also Zazo et al., 1994, and Dabrio et al., 1999, 2000). In contrast to the younger unit H4, two spits grew from the northern and southern sides of the estuary meeting approximately at the center, almost closing off the estuary in the process. In this period there was a centripetal progradation of the tidal flats and a shift from intertidal to supratidal facies in the area. Unit H3 is divided into two large sets of sandy beach ridges separated by a minor gap of undefined age. In the zone studied, both sets are separated by alluvial flood-plain deposits which could be chronologically correlated with this gap.

At least ten washover fans are located at the inner edge of the 4.5 km-long northern segment of the spit, along the boundary with the tidal flats (Fig. 5). Human impact and salt-pan building have partially destroyed the fans. The fans cut across a sandy beach ridge that occupies the inner north-eastern end of the spit. Fans are lobate, and are raised one meter above high tide, extending 300 m inland and 200 m across. They are slightly smaller than the fans described in unit H4.

The formation of these fans requires a penetration of water that is strong enough to breach the spit and mobilize a large amount of sand. Arguments in favor of an ancient tsunami-related genesis include: (a) the uniform distribution of the fans along the edge of the spit, which is not consistent with periodical floods caused by storms or with tidal inlets; (b) the absence of washovers at other ridges of the same spit, which points to a single, catastrophic high-energy event, caused by either an extreme storm or a tsunami; this is particularly interesting because the maximum elevation of the beach crest (up to two meters above high-tide level) is not enough to prevent overwash during violent storms; and (c) the difficulty of invoking the 1755 tsunami since this did not affect the beach ridges located between this area and the sea front, which at that time was 2 km away. The Lisbon tsunami probably entered this area via the Guadalete river channel. It may, therefore, be assumed that the fans are connected to a marine event that overwashed the beach ridge shortly after its deposition.

The age of the spit has been deduced from both archeological and geochronological data. In the northern sector of the spit, spit unit H3 overlies a Bronze Age site (3850-3650 yr BP). Moreover, the Romans built a road between 1st century BC and 2nd century AD along the spit and this is exposed near the San Pedro River (Borja et al., 1999) (Fig. 5).

These data together with the age deduced for the erosional gap separating H2 and H3 suggest that sedimentation of the spit bar started ca. 2300 to 1800 BP. ^{14}C dating of shells from the sandy ridges of the eastern set of the unit (Zazo et al., 1994) yielded ages of 1860 yr BP for the oldest (easternmost ridge) and 1690 yr BP for the youngest western sand ridge (Fig. 5). The first age is consistent with archeological and geological data. Therefore, the washover fans may be coeval with the beginning of the development of unit H3, before 1800 BP but after 2300 BP. The geomorphological map shows that the youngest beach ridges have not been modified or eroded (Gómez Ponce et al., 1999). It may be assumed that the Roman road required a stable substratum, not only a couple of sand ridges, suggesting that the event generating the washover occurred between 2300 and 2000 BP, before the construction of the road.

Historical data (Galbis, 1932) document two tsunamis of seismic origin in 218 and 216 BC, although these dates probably correspond to the same tsunami. After the chronicler Florian de Ocampo *"The island of Cádiz and all the marine frontier of Andalusia suffered large earthquakes or shakings that caused considerable loss of life and damage to buildings: the sea flooded many previously-exposed places, throwing up multitudes of fishes, some of them known and others never seen before…"*. This description clearly refers to a seismogenic tsunami and the document includes data such as the previous retreat of the sea, or the occurrence of fish on the beach (confirming the description). This recurred at many localities affected by the 1755 Lisbon tsunami according to the historical chronicles.

Historically recorded tsunamis probably correspond to this high-energy marine event which overwashed the first sand ridges of the H3 prograding unit at the Valdelagrana spit barrier, leaving deposits landward.

CONCLUSIONS

Sediments generated by tsunamis can provide valuable paleoseismic information given that most of these events are caused by underwater earthquakes. Geomorphological and sedimentological analyses play a key role in the study of tsunami deposits although historical data also make a considerable contribution. A large variety of local and regional factors control the type of deposit. Direct data provided by these deposits include: the minimum tsunami wave height (magnitude), the wave orientation with respect to the coastline, the number of waves and the age of the event. Contemporaneous deposits in basins located further away can provide an approximate indication of the tsunamigenic area. A number of tsunami deposits within the same sedimentary sequence can yield information on the recurrence period of seismic events.

Geomorphological and sedimentological studies of the sedimentary record along the Spanish SW Atlantic littoral allowed identification of three tsunami-generated sediments. The most recent of these were deposited in unit H4 of the Valdelagrana spit bar (Cádiz, Spain) and were correlated with the 1755 tsunami. The oldest ones could be contemporaneous and were recorded in the H3 unit of the Valdelagrana spit bar and in drill holes in the Doñana National Park. According to the historical, archeological and radiometric records, these high-energy deposits were probably generated by a tsunami ca. 216-218 BC. The magnitude of this tsunamigenic seismic event was probably lower than the 1755 Lisbon earthquake since the height of the beach ridges breached by the tsunami was 2-3 m lower although the washover fans of both tsunamis were of similar size. These data are the first geological record of a high magnitude tsunami produced in the gulf of Cádiz prior to the 1755 event. Accordingly, an interval of about 2000 years between these two events was deduced. The absence of a sedimentary record of tsunamis during this time span can be attributed to the lower magnitude of the events or to paleogeographical changes. Subsequent erosional processes and the possible occurrence of tsunamis during low tide periods should also be borne in mind. Finally, the sedimentation in the Guadalquivir marshlands has not undergone large-magnitude changes during the last two thousand years, which results in a rather homogeneous record.

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