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Sedimentary record of a tsunami during Roman times, Bay of Cadiz, Spain

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ABSTRACT: Historical data show that the Gulf of Cadiz has been exposed to destructive tsunamis during at least the past 2000 yr. The last tsunami was generated by the AD 1755 Lisbon earthquake, which affected the Atlantic coasts of Spain, Portugal and Morocco. Today, these littoral areas are intensely populated and the expected damage could be much greater. Tsunami studies are of great importance in helping to determine the recurrence interval of these events.

The presence of washover fan deposits on the inland margin of the Valdelagrana Spit bar (Cadiz, Spain) indicates the occurrence of a high energy marine event ca. 2300 cal. yr BP. Historical, geomorphological, sedimentological, palaeontological and geochronological data suggest that a tsunami could have affected the area during Roman times. Copyright © 2002 John Wiley & Sons, Ltd.

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KEYWORDS: tsunami deposits; grain size; palaeontology; Gulf of Cadiz; South Spain.

Introduction

Investigations of the geological records of past tsunamis are an important tool in helping to determine the recurrence interval of such events in a region. These investigations are also the only way of determining the prehistoric occurrence and tsunami hazard in areas of infrequent seismic activity. However, at present it is difficult to distinguish between tsunami deposits and those laid down by other high-energy events, such as a storm surge or hurricane. Recent work by Goff *et al.* (2001) has helped to identify a series of diagnostic criteria for tsunami deposits, and research is underway to highlight the differences between these and other high-energy events (Goff and Chagué-Goff, in preparation; J. Goff, personal communication, 2002). Wave hydrodynamics, the specific coastal setting (morphology, orientation, availability and type of sediments, depositional environments), tsunami magnitude and tidal range are all factors that help to define the type and preservation of tsunami deposits. Furthermore, the ability to determine the tsunamigenic source largely depends upon the palaeoseismic and historical record (e.g. Goff *et al.*, 2001).

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Studies of the sedimentary records of tsunamis started only a few years ago (Atwater, 1987; Dawson *et al.*, 1988) but there is already an extensive record of tsunami erosion and deposition, such as erosive escarpment formation on sandy beaches and dunes; and sand sheets covering the backshore on sandy coasts (Minoura and Nakaya, 1991; Bourgeois and Reinhart, 1993; Shi, 1993; Shi *et al.*, 1995; Goff *et al.*, 1998a; McSaveney *et al.*, 2000). The thickness of a deposit is usually less than 0.5 m and this thins, fines and rises in altitude landward (e.g. Goff *et al.*, 2001). Although sediment content depends upon the littoral lithology, it is frequently composed of sand and includes some blocks, reef fragments, rip-up clasts and plant remains (Sato *et al.*, 1995; Dawson *et al.*, 1996; Goff *et al.*, 1998b). However, clast size can vary from boulder to fine silt (Goff *et al.*, 2001). Structurally, the sand can vary from massive to graded and may be laminated or stratified (Minoura and Nakaya, 1991; Bourgeois *et al.*, 1993; Shi, 1993; Sato *et al.*, 1995; Dawson *et al.*, 1996; Goff *et al.*, 1998b), with coarse lithic components and shells frequently recorded at the lower part of the deposit. Shells are also often found 'rafted' in the upper parts of the deposit (Goff *et al.*, 2001). Marine microfauna such as diatoms are often present (Tsuji *et al.*, 1995; Dawson *et al.*, 1995; Dawson, 1996). Buried plant remains are frequently found and are often reworked by wave action during backwash. In some cases grass and leaves are orientated in the direction of flow (Nishimura and Miyaji, 1995). Sedimentological differences in tsunami deposits can also indicate the runup and backwash of the waves (Shi *et al.*, 1993, 1995; Nishimura and Miyaji, 1995; Sato *et al.*, 1995; Goff *et al.*, 1998b). Tsunami deposits are often well preserved in low-energy environments such as wetlands and coastal lagoons. These deposits are often used to determine fault rupture recurrence intervals in areas of high seismic activity (Atwater, 1987; Minoura and Nakaya, 1991; Shennan *et al.*, 1996; Nelson *et al.*, 1997; Fujiwara *et al.*, 1998).

The aim of this work is to determine palaeotsunami prior to the AD 1755 Lisbon earthquake and tsunami in the Gulf of Cadiz. Past seismic and tsunami activity have been reported in the area (Galbis, 1932, 1940; Campos, 1991, 1992) and some AD 1755 Lisbon tsunami deposits have been reported along the Algarve coast (Portugal) (Andrade, 1992; Andrade *et al.*, 1994, 1997, 1998; Dawson *et al.*, 1995; Hindson *et al.*, 1996; Kortekaas *et al.*, 1998a, b) and Cadiz province (Spain) (Dabrio *et al.*, 1998; Lario *et al.*, 2001a; Luque *et al.*, 1999, 2001). Seismic activity in the Gulf of Cadiz seems to be related to Azores–Gibraltar transform fault zone (Gloria Fault). The tectonic pattern of this area operates as a strike-slip movement in the western part (Azores) and as a north–south compression to the east (Gibraltar) (Udías *et al.*, 1976; Buforn *et al.*, 1988). Commonly, the AD 1755 Lisbon earthquake epicentre has been located 200 km southwest of St Vincent Cape (Fukao, 1973; Martínez Solares *et al.*, 1979). Recently though, drill core and seismic profile data suggests an incipient subduction area west of Portugal where the tsunami origin may possibly have been located (Baptista *et al.*, 1996, 1998; Zitellini *et al.*, 1999, 2001). In this work we analyse cores taken through washover fan deposits located in the Valdelagrana Holocene spit–barrier (Cadiz, Spain).

Study area

The Valdelagrana spit–barrier system is located in the inner part of Cadiz Bay (Fig. 1). It is a mesotidal area with moderate wave action, and an easterly wind predominates. The spit–barrier system partially encloses the Guadalete estuary forming an extensive wetland area. Previous geomorphological and sedimentological studies show that the Valdelagrana spit–barrier system is composed of at least three of the four Holocene morphosedimentary units (H) defined by Zazo *et al.* (1994) (Fig. 1). The age of these units (H_2, H_3 and H_4) range from 4400 cal. yr BP to present (Lario, 1996; Borja *et al.*, 1999). These morphosedimentary units grow from east to the west. The washover fan deposits are located close to the northeastern part of the H_3 progradational unit (2400–700 cal. yr BP, Borja *et al.*, 1999), to the east of which are salt pools and the Guadalete marshes (Fig. 2).

During this stage the spit was growing from north to south partially closing a tidal flat and estuary environment (Dabrio *et al.*, 2000). Other larger washover fans further south and west (Fig. 1), orientated in a similar direction to the earliest fan (from west to east), have been laid down as a result of the AD 1755 Lisbon tsunami (Dabrio *et al.*, 1998; Luque *et al.*, 2001; Fig. 1). Human activities in the area have modified the washover fan shape and size and it is now difficult to know their original extent. Cores CIS-98 and TAP-98 taken along the Valdelagrana spit–barrier shows that units H_2 and H_3 are composed of 1–2.5 m thick sands overlying a clay-rich high marsh facies. These overlying deposits are believed to constitute the last stage of Holocene spit and estuary formation.

Methods

Geomorphological studies were carried out based on aerial photograph interpretation and field work. Core sites were selected following the mapping and identification of washover fan deposits. Three cores (TAP-01-01, TAP-01-02 and

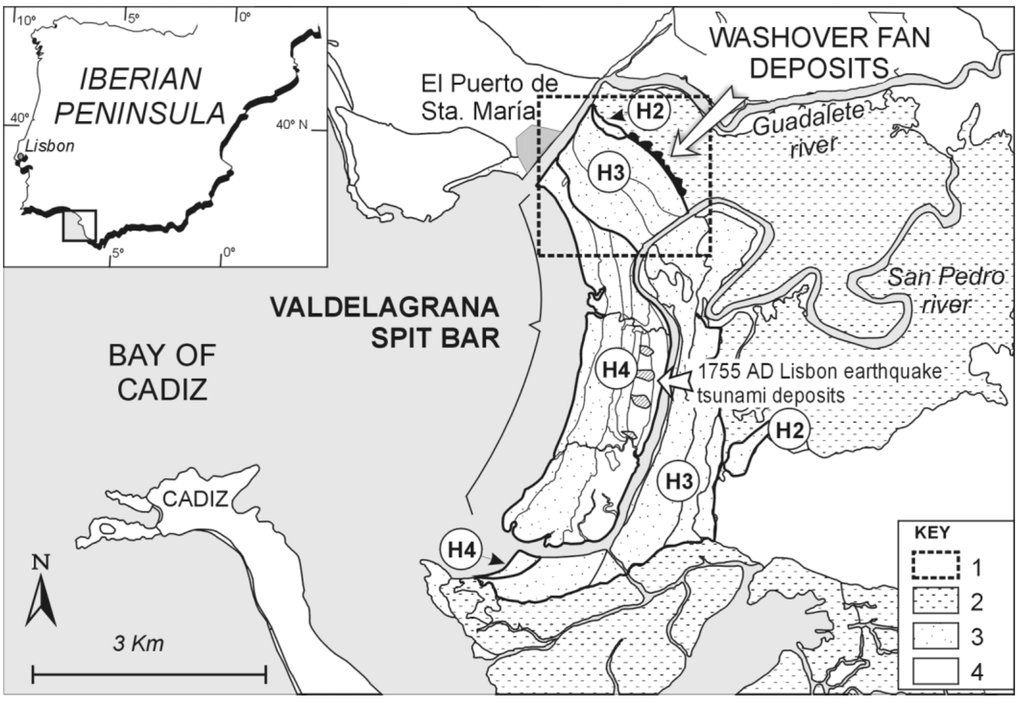

Figure 1 Location map of the Valdelagrana spit–barrier system and H_2, H_3 and H_4 morphosedimentary units described by Zazo *et al.* (1994). It also includes the position of washover fan deposits under study and those previously attributed to AD 1755 tsunami (Dabrio *et al.*, 1998). Key: 1, area shown in Fig. 2; 2, Holocene intertidal clays and silts; 3, Holocene sandy beaches and beach ridges; 4, Pre-Holocene substratum

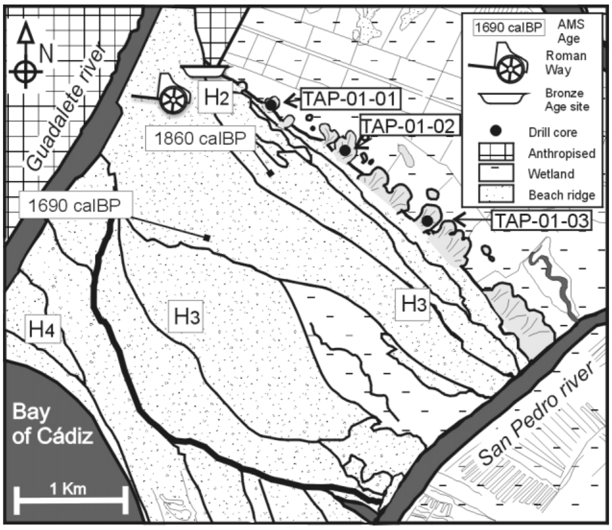

Figure 2 Detailed map of washover fan deposits, cores and archaeological remains related to these deposits

TAP-01-03) were taken using an Eijelkamp corer (Fig. 2). Cores were subsampled at approximately 5 cm intervals for particle size, sedimentological and micropalaeontological analyses.

Particle-size analysis was undertaken using an Analyssette 22 Fritsch laser granulometer. The associated software was used to calculate the statistical parameters of mean, mode and median using the arithmetic method. Measurements in micrometres were converted into the equivalent phi (ϕ) value (Krumbein, 1934). Skewness, kurtosis and standard deviation (sorting), were calculated using the graphic expressions of Folk and Ward (1957) once the percentiles given by the laser granulometer had been converted to phi values. Samples were taken from all the major sedimentary units within the cores and, where appropriate, sampling intervals were varied in order to characterise the upper, middle and lower sections of particularly thick units.

In interpreting particle size data, a number of approaches have been utilised, for example the use of summary statistics (mean grain size, sorting, skewness and kurtosis) of particle-size distributions (Folk and Ward, 1957; Folk, 1974). These may be plotted on bivariate scattergrams, for which a number of workers have identified graphic envelopes within which deposits of particular environments are plotted (Mason and Folk, 1958; Freidmann, 1961, 1967; Moiola and Weiser, 1968; Buller and McManus, 1972; Tanner, 1991a, b; Duck, 1994). However, particle-size data should be used only in conjunction with other evidence to determine the environment of deposition of a sediment.

Micropalaeontological and macropalaeontological analyses were undertaken using standard techniques; washing and sieving of samples (0.063 mm diameter) and systematic identification using binocular microscope.

Results

Cores taken along the washover fans (TAP-01-01, TAP-01-02 and TAP-01-03) have similar lithological characteristics. We identify three different sedimentary units (Fig. 3):

Level a: the lowest unit in all cores, it comprises compact brown clays that grade to grey with increasing depth. Pedogenic processes and intensive bioturbation are evident. Rare carbonate and manganese nodules are present.

Level b: this is a yellowish, matrix-poor unit that overlies level a. It is approximately 1 m thick, and contains quartz and bioclastic particles with possible subhorizontal laminations. The basal contact with level a is sharp.

Level c: this is the uppermost unit. It is of variable thickness (0.4–1 m) and is composed of grey to brown, fine and medium sands with a silty–clayey matrix. The basal contact with level b is gradational. Rare rock fragments and flint are present. There is some evidence of soil-forming processes.

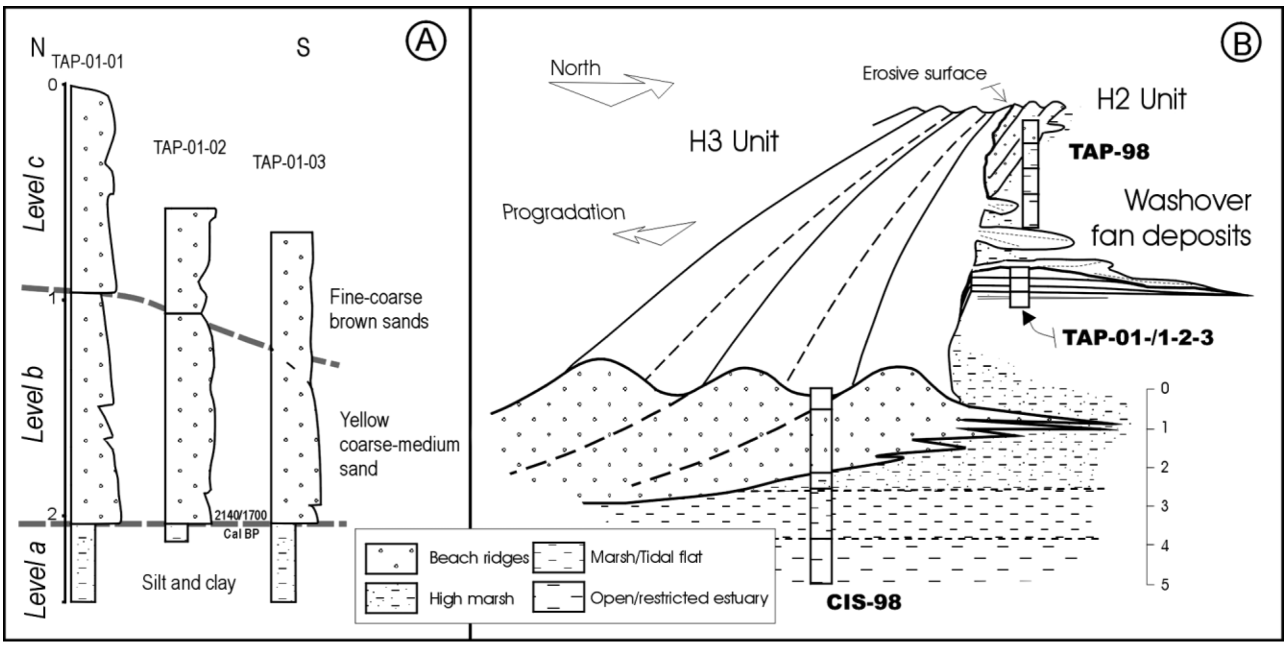

Figure 3 (A) Core logs and startigraphical units of the washover fan deposits. (B) Diagrammatic interpretation of the spatial relationship between units H_2, H_3, underlying marshes and washover fan deposits

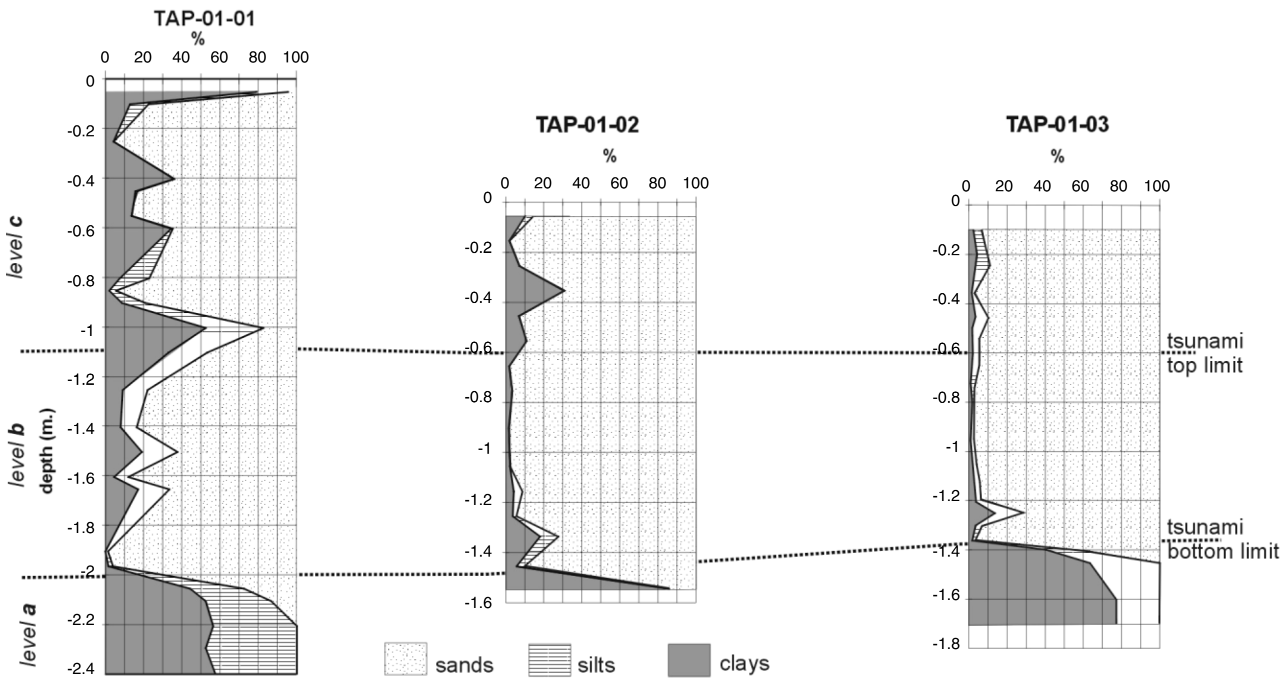

Figure 4 Grain-size distribution of cores TAP-01-01, TAP-01-02 and TAP-01-03

Particle size

Changes in mean grain size are evident between levels a and b in all cores. Level a is dominated by silts and clays whereas level b is composed mainly of sand (Fig. 4). Furthermore, the abrupt contact between levels a and b indicates a marked change in hydrodynamic conditions. Grain-size differences between levels b and c are less clear. Grain-size changes in Level b are marked by at least one (two in TAP-01-01) fining upwards sub unit, whereas Level c has even greater variations in grain size, with finer material dominating the uppermost sediments.

Palaeontology

Palaeontological data also serve to define the three different levels discussed above, based upon biotic component, faunal association and taphonomy (Fig. 6).

Level a: there is a high abundance and diversity of fauna. The dominant taxa are *Ammonia beccarii*, *Elphidium crispum* and *Haynesina germanica*, together with some porcellanoid foraminifera such as *Quinqueloculina* and *Triloculina* genera. Other less abundant genera are *Elphidium*, *Lobatula*, *Cibicidoides* and Discorbiacea. This assemblage is a typical association of a high, vegetated marsh (Murray, 1991). The Ostracoda assemblage is composed of *Leptocythere castanea* with rare *Leptocythere porcellanea.* This ostracod assemblage also represents brackish water conditions associated with estuaries and marshlands (Athersuch *et al.*, 1989; Ruiz *et al.*, 1997; 2000). There are many gastropoda of the *Hydrobia* genus. These are frequently found in low salinity, high marsh environments.

The upper section of Level a in two of the cores (TAP-01-02 and TAP-01-03) lack microfaunal remains, which we believe represents either unstable or limiting conditions.

Level b: bioclastic grains are common, consisting primarily of fragments of molluscs, echinoid and briozoans. The foraminiferal assemblage includes a great number of reworked Cretaceous to Pliocene forms.

Autochthonous foraminifera (no abrasion or size sorting) are represented by an assemblage of *Ammonia beccarii*, *Quinqueloculina seminula*, *Triloculina trigonula*, *Triloculina oblonga* and *Elphidium crispum* forms. Less abundant forms include *Lobatula lobatula*, *Eponides concameratus*, *Elphidium advenum*, *E. macellum*, and some discorbids such as genera *Asterigerinata* and *Rosalina* and *Planorbulina mediterranensis*. This latter assemblage is not always present and represents a small percentage of the total count. The palaeoenvironmental conditions would have been that of a low salinity, low marsh or estuary. Ostracoda are scarce, with several reworked remains. The species identified are indicative of a shallow marine environment. These include *Palmoconcha guttata*, *Xestoleberis* sp., *Loxoconcha rhomboidea*, *Semicytherura sulcata*, *Semicytherura incongruens*, *Pontocythere elongata*, *Carinocythereis carinata* and *Callistocythere flavidofusca*. Some subunits contain a large number of well-sorted bioclasts, most of which contain reworked macro- and microfossils.

Level c is characterised by a high degree of fragmentation and abrasion of both the macro and micro-organisms. The macrobiota include mollusc fragments (both gastropods and bivalvia), branching briozoa, echinoids, and *in situ* terrestrial helicaceous gastropod shells. There are few foraminifera, mainly *Ammonia beccarii* and *Elphidium crispum* with some porcellanoids; *Quinqueloculina seminula* and *Triloculina* spp. All tests show evidence of transport (abrasion and sorting).

Age of the deposit

Previous radiocarbon dating and geomorphological studies show that unit H_3 covers a period from 2400 cal. yr BP to 700 cal. yr BP (Zazo *et al.*, 1994; Lario *et al.*, 1995; Lario, 1996). This unit is composed of a set of beach ridges bounded by swales or erosional surfaces. The washover fan deposits were laid down during the earliest phase of beach ridge

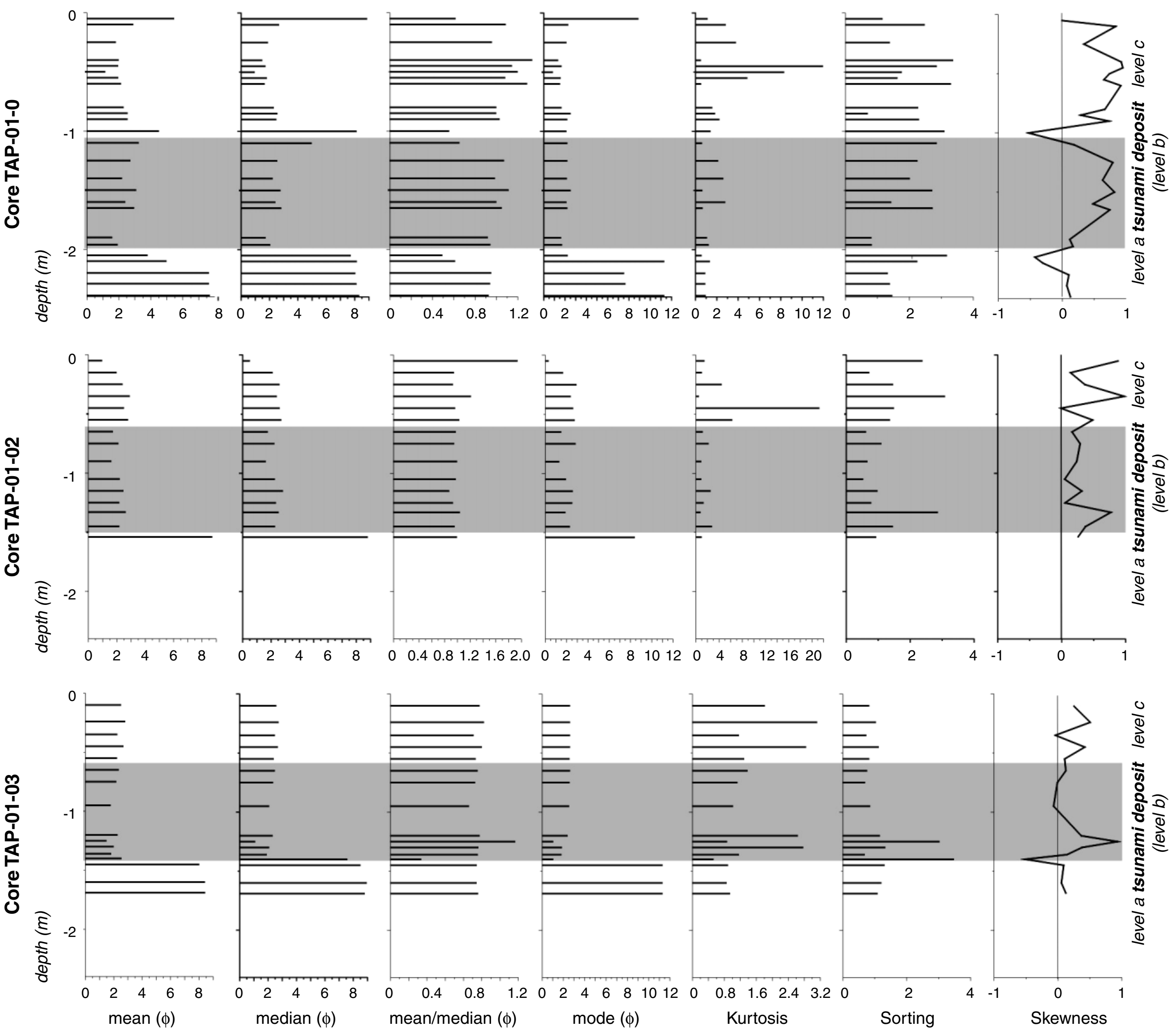

Figure 5 Grain-size properties of cores TAP-01-01, TAP-01-02 and TAP-01-03

formation. Radiocarbon dating indicates an age of between 2400 and 1860 cal. yr BP for the first stages of beach ridge (spit bar) formation (Zazo *et al.*, 1994; Lario, 1996). Complementary archaeological data show that the beach ridges were deposited on top of a Bronze Age site (3850–3860 cal. yr BP) and before the building of a Roman road (first century BC to second century AD) (Borja *et al.*, 1999) (Fig. 2).

An AMS radiocarbon age was obtained for a bivalve shell sample taken from the lowest part of level b (1.52 m) in core TAP-01-02 (Fig. 3). The shell has an age of 2340 ± 40 yr BP (sample GX-27986, Geochron Laboratory, USA). This produces a calibrated date of 2140–1700 cal. yr BP, or 190 BC to 250 AD, at the 2 sigma level (using the CALIB Program, version 4.2, Stuiver and Reimer, 1993; Stuiver *et al.*, 1998). This should be considered to be a maximum age for the event.

A comparison of these chronological data with the historical seismic catalogue (Galbis, 1932, 1940) indicates that these dates coincide with a tsunami that affected both Portugal and Galicia (northwest Spain) in approximately 60 BC. There are also two other tsunamis recorded that appear to have been of greater consequence for the Cadiz area. These occurred around 210 and 218 BC. Although these are slightly older than the calibrated AMS date they have been linked with high-energy marine deposits found in cores from the neighbouring wetlands of Guadalquivir (Lario *et al.*, 2001a) and should be considered as possible sources.

Discussion

From the particle-size data, there is evidence for the emplacement of coarse material into the tidal flat area, marking an abrupt change in all parameters. This episode corresponds with level b. This level is composed primarily of poorly sorted medium and coarse sands with abundant shells fragments and microfossils.

Previous studies have tried to interpret environmental conditions using bivariate plots of parameters that describe the sample size spectrum (Stewart, 1958; Friedman, 1961, 1967; Buller and McManus, 1972; Friedman and Sanders, 1978; Tanner, 1991a). Tanner (1991a), however, used bivariate plots of particle size data to investigate the environment of deposition by plotting mean grain size against sorting. As it is generally accepted that mean grain size and sorting are hydraulically controlled (Griffiths, 1967), these parameters can be positively correlated with the energy of the environment and the degree of sediment processing (Long *et al.*, 1996). Using

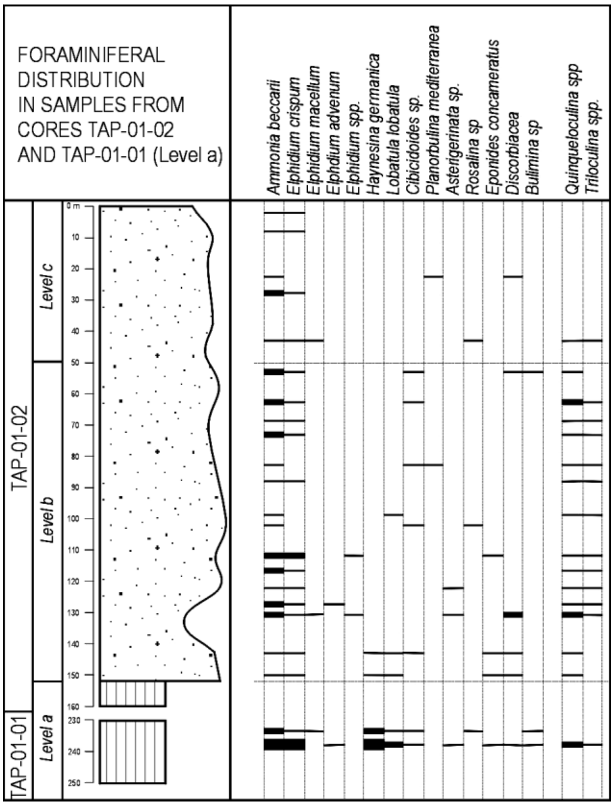

Figure 6 Foraminiferal species and genus identified in the samples from core TAP-01-02 and the basal level a in core TAP-01-01

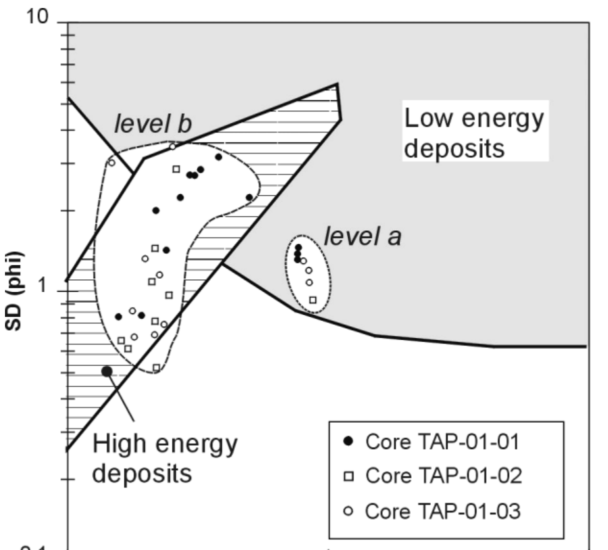

Figure 7 Bivariate plot of mean grain size against sorting for all cores (based on Tanner. 1991a and Lario *et al.*, 2001b)

the domains defined by Tanner (1991a) and modified in Lario *et al.* (2001a, b), the combined mean grain size and sorting plot (Fig. 7) shows that level a sediments were deposited under closed-basin conditions. This can be interpreted as representing the final stages of the evolution of the partially closed estuary into tidal flat and marshes once the barrier system was well developed. Level b sediments can be linked with high-energy conditions representing the input of coarse sediments into the inner estuary during this infilling phase. There is no gradual transition between the two grain-size groupings, suggesting that there was an abrupt change in hydrodynamic conditions. In Fig. 7, data from level c have not been included because they are scattered randomly through the whole diagram and therefore cannot be related to any of the represented depositional environments. This could be due either to a mixture of source areas of sediments or to the low maturity of the deposit.

The sedimentary and palaeontological content of the washover fan deposits in unit H_3 indicates that they were generated by a high-energy event of marine origin that broke through the barrier during the first phases of formation of the unit (Fig. 8). Washover fan formation is a typical product of the storm wave breaching of sandy, coastal barriers (Schwartz, 1982) and the preservation potential of such deposits is high because they are deposited in a low-energy environment and covered, at least temporarily, by water.

Sedimentological and palaeontological analyses of the cores show three distinct units, levels a, b and c. The first comprises the substrate over which the fans are deposited. In this case the fans overlie a high tidal flat, where pedogenic processes were taking place. The contact between the tidal flat facies and the basal sandy unit of the fans is sharp and probably erosional, implying an abrupt change in the depositional environment. In the lower part of the washover fan deposit (level b) the grain size is coarser and the microfauna of marine and estuarine origin are relatively abundant. The internal grain-size structure of level b shows marked variations that probably correspond to changes in hydrodynamic flow during their deposition. The overlying unit (level c) has finer sands with few microfauna present, and indications of stable, soil-forming processes.

Level b probably represents a deposit generated by a high-energy marine incursion that subsequently has been buried by aeolian sands. This sedimentary assemblage is similar to washover fans deposited by the tsunami generated by the AD 1755 Lisbon earthquake that affected unit H_4 of the same spit bar (Luque *et al.*, 1999, 2001). Given the absence of other similar sedimentary records along the rest of the spit–barrier, we surmise that these types of event are of a frequency far

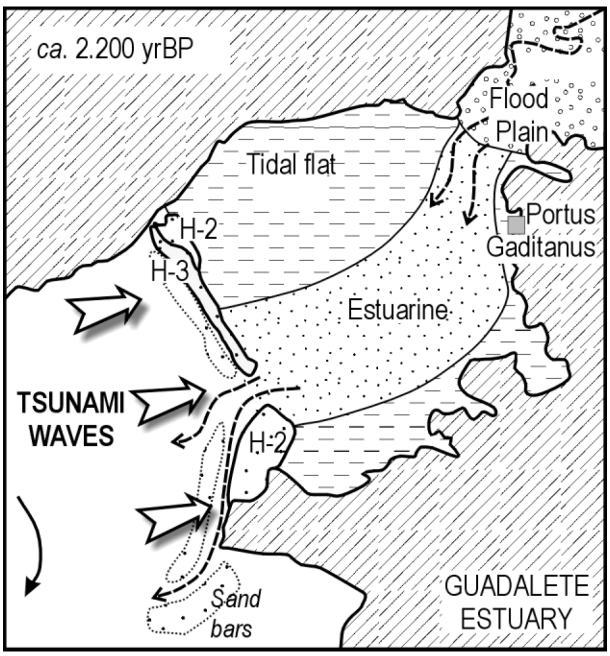

Figure 8 Palaeoenvironmental reconstruction of Guadalete estuary at ca. 2200 yr BP, during the tsunami event (palaeoenvironmental data modified from Dabrio *et al.*, 2000)

lower than that of storms along the same coast. We infer that this deposit (level b) was laid down as a result of a tsunami that broke through the spit–barrier flooding the tidal flats of the Guadalete marsh and splaying marine deposits in the form of washover fans.

The palaeontological content also shows three levels. Level a microfauna indicate a marsh with a well-preserved autochthonous fauna. Level b microfauna indicate a marine origin. There are numerous reworked microfossils, probably derived from former deposits of the spit–barrier. Part of unit H_2 was eroded before unit H_3 was deposited, but also there are frequent outcrops of Miocene and Cretaceous deposits that act as possible sediment sources. Level c has few microfauna but shows an increase in allochthonous species.

The age proposed for the deposits (2200–2300 cal. yr BP) is in agreement with archaeological, sedimentological and radiometric dating. Reference to a seismic catalogue (Galbis, 1932, 1940) indicates that there are two historical tsunamis at 218–210 and 60 BC. The chronicles mention that the island of Cadiz and the coast of Andalusia suffered large earthquakes and the sea, after retreating, flooded many places leaving numerous fish on the ground. These data help identify a seismic origin for the tsunami, and indicate the level of risk posed by two events in 2000 yr in the area. Interestingly, the historic data base indicates that 18 tsunamis have occurred along the Spanish Atlantic coast between the third century BC and AD 1900. Bearing in mind the absence of other tsunami deposits along the coast, this would suggest that either most of the tsunamis were too small to generate any deposits, or that any deposits laid down have been subsequently reworked, or that the deposits are indistinguishable from other coastal sediments. Nevertheless, Ribeiro (1995) proposed a recurrence period of 300–1500 yr for a seismic event similar to the Lisbon earthquake (magnitude 8.5–9). The tsunami that deposited the sediments of level b must have had a minimum wave height of at least 1.5 m (over high tide level—local tidal range average 2.1 m, Dabrio *et al.*, 1998) to overtop the barrier, but the extent of deposition suggests that it was far larger.

Possible evidence of this tsunami also has been described around the Gulf of Cadiz. A high-energy, erosional episode, was recorded in several spit–barrier systems along the coast. In the nearby Guadalquivir spit–barrier and Doñana marshes Rodriguez Ramirez *et al.* (1996) described a phase of extensive erosion in the spit–barrier between units H_2 and H_3 described by Zazo *et al.* (1994). Furthermore, Lario *et al.* (2001a) describe episodes of high-energy hydrodynamic conditions in the Guadalquivir marshes, interpreted as tsunami deposits. This episode is accompanied not only by the input of silt and coarse sediments, as has been observed by Dawson *et al.* (1995) in the Algarve (south Portugal), but also by the presence of shell fragments. Moreover, in the nearby spit–barrier system of Punta Umbria a similar episode, linked with a large erosional event dated between 2700 and 2400 cal. yr BP was responsible for the dividing up of the spit and the initiation of a new drainage system (Punta Umbria ria) (Lario, 1996). Owing to the breaking up of the spit–barrier, marine conditions were re-established in the estuary with an increase in faunal diversity and abundance (Goy *et al.*, 1996). There is some evidence to suggest that large-scale tsunamis are often associated with the reorganisation of coastal barrier systems (Bourrouilh-Le Jan and Talandier, 1985; Dawson 1994). Andrade (1992) found that tsunami inundation in the Algarve region associated with the Lisbon earthquake of AD 1755, appears to have been accompanied by widespread submergence, barrier breaching and the deposition of a large washover fan, as well as the complete reorganisation of the back-barrier drainage system. Dabrio *et al.* (1998) found the same features affecting the Valdelagrana spit–barrier around the same time.

Conclusions

Lithological, sedimentological and palaeontological data have been used to identify a high-energy marine inundation (tsunami) that input coarse sands into the late Holocene Guadalete estuary. Locally, this episode broke through the spit–barrier and spread material over the tidal marsh deposits, forming a set of washover fans. Archaeological, morphological and radiocarbon data place this episode at ca. 2300–2000 cal. yr BP, during Roman times. This corresponds with several seismic events that affected southwest Iberia at about the same time (218–210 and 60 BC) and are recorded in contemporary chronicles.

From these data we infer that at ca. 2300 cal. yr BP a tsunami generated by local seismic activity in southwest Iberia, affected the coast of the Algarve and Gulf of Cadiz. Morphological and sedimentological changes in the coast triggered by this event were similar or greater than the changes in coastal features related to the AD 1755 Lisbon earthquake and tsunami that we recorded previously only in contemporary beach ridges and Guadalquivir marshes. These data show that large tsunamis are more common than currently assumed and that adequate calculations of the recurrence intervals of such events will be possible only after detailed analysis of all such deposits in the geological record.

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