

THE GEOLOGICAL RECORD OF THE OLDEST HISTORICAL TSUNAMIS IN SOUTHWESTERN SPAIN

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Abstract. A regressive sequence was determined in the late Holocene evolution of the southwestern Doñana National Park (SW Spain), based on a multidisciplinary study of sediments obtained in a drill core. In an initial phase (> cal. 2400 years BP), a shallow coastal lagoon with a partial marine connection occupied this area, with a progressive transition from subtidal to supratidal conditions. The following phase (cal. 2400-2350 years BP) is characterized by a tsunami, with the deposition of an upper chenier. This sedimentological layer is characterized by a ridge morphology, an erosive base, high bioclastic contents and the introduction of marine species toward the inner areas of this old lagoon. This tsunami may be assimilated to one of the historical tsunamis that occurred between 218 and 209 BC. A comparison with other deposits derived from these high-energy events permits to draw the differential effects produced along the western Iberian coasts.

Riassunto. Viene analizzata una sequenza regressiva del tardo Olocene nella parte sudoccidentale del Parco Nazionale di Doñana (SO della Spagna), con lo studio multidisciplinare dei sedimenti ottenuti mediante carotaggio. In una fase iniziale (> cal. 2400 anni BP), una laguna costiera poco profonda con parziali connessioni marine occupò quest'area con progressiva transizione da condizioni subtidali a supratidali. La fase successiva (cal. 2400-2350 anni BP) fu caratterizzata da uno tsunami, con la deposizione di una cresta bioclastica (chenier). Questo livello sedimentologico è caratterizzato da una morfologia con creste a base erosiva, un elevato contenuto in bioclasti e l'entrata di specie marine nelle aree interne della vecchia laguna. Questo tsunami può venire riferito ad uno degli tsunami storici che avvennero tra il 218 e il 209 AC. Il confronto con altri depositi dovuti a questi eventi ad elevata energia consente di illustrare i differenti effetti che si produssero lungo le coste iberiche occidentali.

Introduction

In the last years, numerous investigations were focused on the geological record of past high-energy events (tsunamis, storms) around the world, with the inclusion of lithostratigraphical, sedimentological, faunal and geochemical features, and radiocarbon datings (i.e., Clague et al. 2000; Goff & McFadgen 2002; Smith et al. 2004; Andrade et al. 2006). The southwestern Spanish coast is a low-probability tsunamigenic zone, according to the historical record of tsunamis (Galbis 1932; Campos 1991; Reicherter 2001). These authors have documented sixteen tsunamis between 218 BC and 1900 AC (Tab. 1). Nevertheless, the geological record of these high-energy events is still poorly known (Luque et al. 2002; Ruiz et al. 2004; 2005).

In this report, we make a multidisciplinary geological analysis of a short core collected in the Doñana National Park (SW Spain). The aim of this research is the reconstruction of the Late Holocene environmental changes of this area and to compare them with the historical record of tsunamis in the southwestern Iberian coasts.

The Doñana National Park

The southwestern Spanish coast includes four estuaries (Guadiana, Piedras, Tinto-Odiel, Guadalquivir)

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HISTORICAL TSUNAMIS	ZONE
218 BC-216 BC	Cádiz
210 BC - 209 BC	Cádiz
60 BC	Portugal and Galicia
382 AD	Portugal
881 AD	Cádiz
949 AD	Portugal
1531 AD	Lisbon-Southern Portugal
1722 AD	Southern Portugal
1731 AD	Cádiz
1755 AD	Portugal-Southern Spain
1756 AD	Portugal
1761 AD	Lisbon-Galicia
1816 AD	Portugal
1848 AD	Portugal

Tab. 1 - Historical tsunamis in Portugal and southern Spain (from Galbis 1932; Campos 1991).

partly enclosed by sandy barriers. The Guadalquivir River (560 km long) drains a catchment area of 57,000 km², comprising mainly Tertiary sedimentary rocks (Fig. 1). This river is partly blocked in the lower reach by sandy barriers, resulting in a large estuary (1800 km²). On the southwestern sector, this estuary includes the Doñana National Park, a UNESCO-MAB Biosphere Reserve. This site is one of the largest wetlands (50,720 ha) in Europe and represents the last tract of relatively undisturbed marshes in this system.

The hydrodynamic processes of this area are controlled by fluvial regime, tidal flux, wave action and drift currents. The Guadalquivir River has a mean annual water discharge of 164 m³s⁻¹, with the highest run-offs (> 1000 m³s⁻¹) from January to February (Menanteau 1979). The tidal regime is mesotidal and semidiurnal, with an average tidal range of approximately 3.6 m (Borrego et al. 1993). Dominant waves associated with the Atlantic circulation come from the southwest, whereas the main littoral drift currents transport sand-size sediments from the Portugal coast to the Spanish nearshore zone (Cuenca 1991) and contribute to the growth of sandy barriers or spits.

A number of studies have concentrated on the Holocene evolution of this littoral area, suggesting a chronology of events of progradation and erosion based on the radiocarbon dating of shells collected from these sandy barriers. Two major Holocene phases of coastal

progradation have been recognized after the transgressive maximum (6500 cal. yr BP; Zazo et al. 1994), including four sandy barrier systems: H₁ (6500-4400 cal. yr BP), H₂ (4200-2550 cal. yr BP), H₃ (2300-800 cal. yr BP) and H₄ (500 cal. yr BP to the present). These phases are divided by erosive events at 4500-4200 cal. yr BP, 2600-2300 cal. yr BP and 1100-1000 cal. yr BP.

One of the first historical descriptions of this littoral was made by the Roman chronicler Estrabon in his work *Geographica*, written between 29 and 7 BC. He referred to the southern part of the Guadalquivir estuary as an inland lagoon (*Lacus Ligustinus*), a palaeogeography confirmed 40 years later by Mela, a Spanish chronicler, in his work *De Chorographia* (García Bellido 1987).

Methodology

A short core (147 cm long) was collected with a 20 mm diameter vibrocore, which was divided in thirty-three samples (Fig. 1: HR/1 to HR/33). The lithology of each core was described during field sampling, whereas the mineralogical analysis of 10 samples was studied by X-ray diffraction applied to the whole sample (Fig. 2). The equipment used was a Philips PW 1130/90, with an automatic slit, using Ka radiation of Cu and a Ni filter at 20 mA and 20 kv. The < 2 µm was separated by a standard sedimentation method (Barahona 1974). Before the separation, carbonates were eliminated using 0.6 N acetic acid. Moreover, a dating was carried out at Beta Analytic Laboratories (Miami, USA) by radiocarbon methods applied to mollusk shells (sample S-29; laboratory reference Beta-228880; AMS-Standard). Data were calibrated using CALIB version 5.1 (Stuiver & Reimer 1993) and the Stuiver et al. (1998) calibration dataset. The final results correspond to calibrated ages (cal.) using 2s intervals, with the reservoir correction suggested in Lario (1996) for this area. Ages discussed below will be expressed as the highest probable age of the 2s calibrated range (e.g., Van der Kaars et al. 2001).

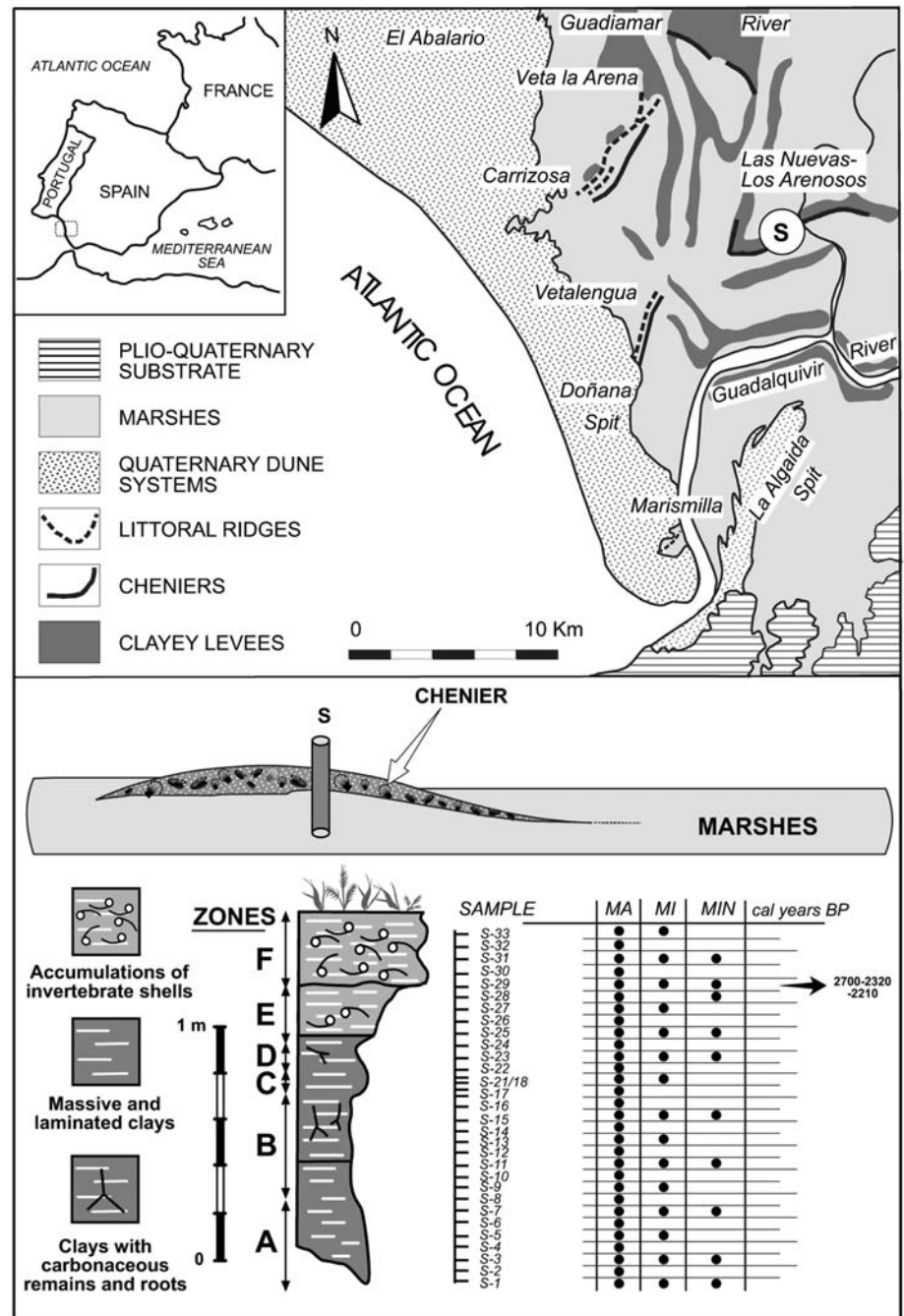
All samples were analyzed for macrofossil analysis. These sub-samples were collected and prepared by washing the bulk sediment (12 cm³) through a 1-mm sieve. Bivalves and gastropods were identified to the species level and counted to study the semi-quantitative distribution in the core. Due to the reduced amount of sediment studied, the abundance of a species in each sample was described as follows: rare (one specimen), frequent (2-5 specimens) and abundant (> 5 specimens). In addition, the relative abundance of other groups (scaphopods, echinoderms, charophytes, bryozoans, sponges, remains of plants) was also tested. In addition, eighteen sub-samples of approximately 15 g were taken for microfossil analysis, which were washed through a 63-µm sieve to remove the mud fraction and then dried. If possible, more than 300 ostracode valves and carapaces from each sample were picked onto faunal microscope slides. The abundance of a species in each sample was described as follows: rare (< 10 specimens), frequent (10-100 specimens), abundant (101-1000 specimens) and very abundant (> 1000 specimens).

Results

The multivariate analysis of this core permits to define seven zones (Fig. 1):

Zone A (samples S-1 to S-7). The lower 30 cm of this core are represented by massive, green to grayish

Fig. 1 - Geographical and geological setting of the southwestern Doñana National Park. S: core. ^{14}C age calibration: minimum calibrated age-highest probability age-maximum calibrated age (yr BP). MA: macrofauna; MI: microfauna; MIN: mineralogy.



clays with scattered fragments of bivalves. The mineralogical composition consists of phyllosilicates (47-51%), calcite (19-32%) and quartz (13-16%), with decreasing contents of feldspars toward the top and minor quantities of dolomite and halite (<3%; see Fig. 2). The ostracode faunas are dominated by *Cyprideis torosa*, *Loxoconcha elliptica*, *Leptocythere castanea* and *Leptocythere tenera*. This basal zone ends with a thin layer (sample S-7) of silty clays with frequent valves of bivalves (Fig. 3: *Cerastoderma edule*) and gastropods (*Rissoa* sp.). This layer includes also numerous fragments of sponges, bryozoans and echinoderms.

Zone B (samples S-8 to S-17). This zone presents lithological features similar to Zone A, although the

main characteristic is the abundance of roots and fragments of plants. Other differences are a small increase in the phyllosilicate percentages (55-58%) and minor quartz contents (10-12%). Moreover, the macrofaunal components are almost absent. Ostracodes show a remarkable decrease, being represented by rare or frequent individuals of *C. torosa*.

Zone C (samples S-18 to S-20). The following upper 12 cm consists of silty clays with numerous roots and without macrofauna. Two levels may be differentiated according to the ostracode content: a) C1 (S-18 and S-19), with rare to frequent individuals of high brackish (*C. torosa*) and marine ostracodes (Fig. 4: *Cytheretta adriatica*, *Semicytherura incongruens*, *Uro-*

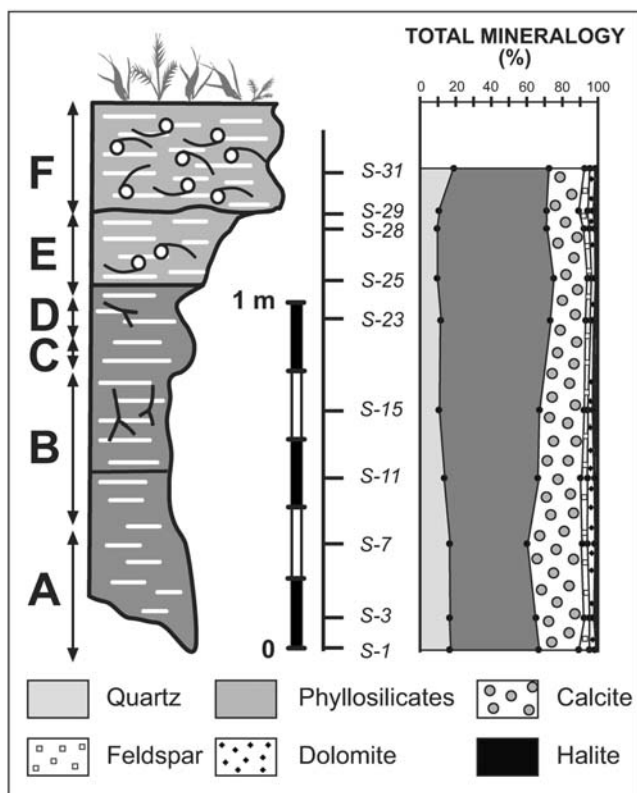


Fig. 2 - Results of the mineralogical (XRD) analysis (%).

cythereis britannica); and b) C2 (S-20), with a high diversity (16 species) and a remarkable abundance of the former high brackish assemblage and frequent valves of marine species (*Callistocythere rastrifera*, *Neocytherideis subulata*, *Paracytheridea depressa*, *S. incongruens*, *U. britannica*).

Zone D (samples S-21 to S-24). This zone consists of greenish clays with numerous roots and may be differentiated from Zone B by the higher phyllosilicate percentages (61%), lower calcite contents (21%) and even more scattered individuals of *C. torosa*.

Zone E (samples S-25 to S-29). The following 18 cm are formed by accumulations of invertebrate shells, with a ridge morphology and an unconformable disposition over the lower clays. This zone contains frequent bioclasts (15-20% dry weight) within a silty-clayey matrix and low percentages of sands (10-15%). The mineralogical composition is dominated by phyllosilicates (60-65%), calcite (19-21%) and quartz (9-10%). Macrofauna includes frequent disarticulated valves of estuarine (*C. edule*) and marine (*Acanthocardia tuberculata*, *Diluvvarca diluvii*, *Spisula solida*) bivalves, together with freshwater (*Gyraulus albus*) and marine (*Rissoa* sp.) gastropods. The ostracode faunas present frequent specimens of *C. torosa* and a sparse although well diversified marine assemblage (e.g., *Callistocythere rastrifera*, *Hiltermannicythere emaciata*, *Pontocythere elongata*).

Zone F (samples S-30 to S-33). The upper part (37 cm thickness) presents a new accumulation of invertebrates within a silty matrix, with an erosive base in relation to the lower bioclastic level. Bioclasts are very abundant (30-50% dry weight), being composed by both marine and estuarine bivalves, together with freshwater and marine gastropods. This macrofauna presents a distinctive "rafted" disposition. In addition, remains of other marine faunas (scaphopods, echinoderms,

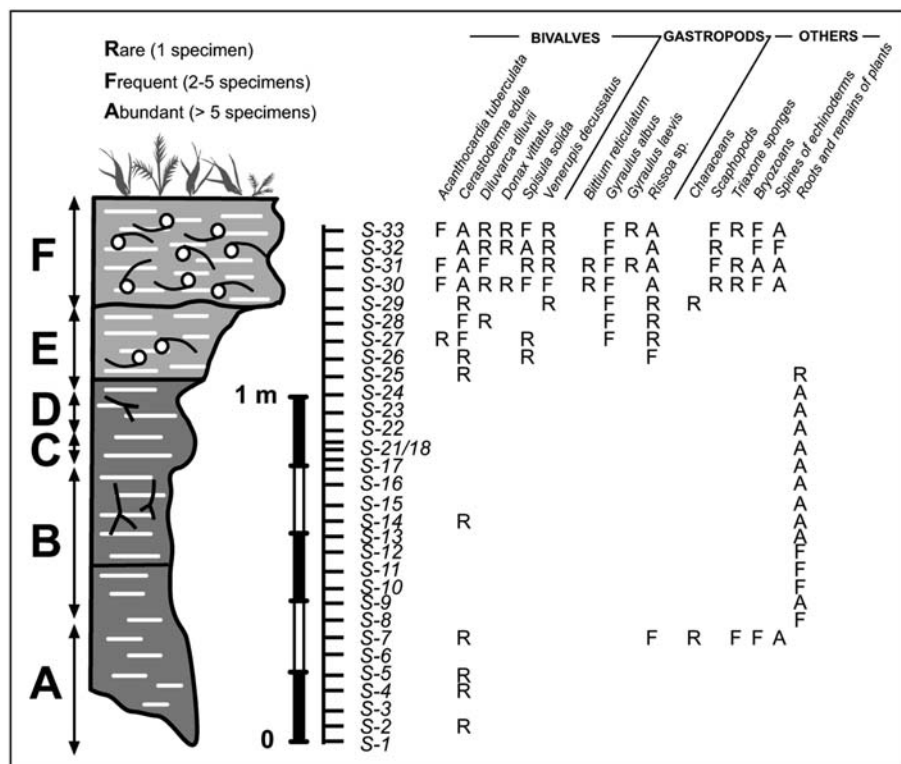


Fig. 3 - Macrofaunal distribution. Abundance: rare (R: one specimen); frequent (F: 2-5 specimens); abundant (A: > 5 specimens).

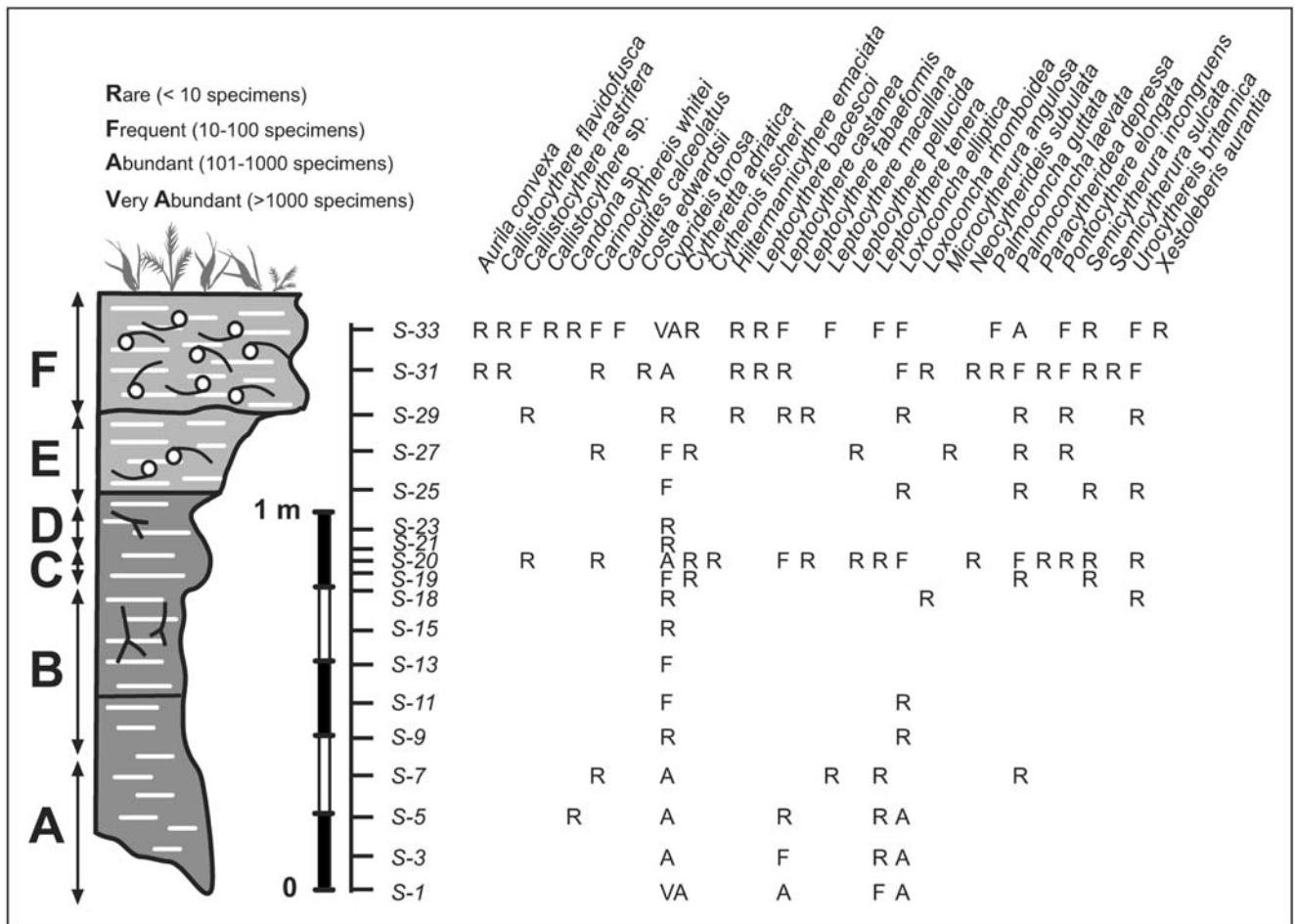


Fig. 4 - Ostracode distribution in the core. Abundance: rare (R: < 10 specimens); frequent (F: 10-100 specimens); abundant (A: 101-1000 specimens); very abundant (VA: > 1000 specimens).

bryozoans, and sponges) are very abundant. This zone is characterized by the highest ostracode densities and diversities, with abundant individuals of high brackish (*C. torosa*, *L. elliptica*, *L. castanea*) and marine (*C. rastriifera*, *Palmoconcha guttata*, *P. elongata*, *Urocythereis britannica*) species.

Discussion: Palaeoenvironmental interpretation

The ostracode assemblage of Zone A characterizes the inner, shallow areas (< 1 m depth) of recent lagoons with marine connection, located near the lagoon shore and close to a river mouth (Athersuch et al. 1989; Marocco et al. 1996; Montenegro & Pugliese, 1996; Ruiz et al. 2000a). This lagoon (Fig. 5) may be assimilated to the *Lacus Ligustinus* described by the chroniclers Estrabon and Mela. This palaeoenvironmental interpretation is also consistent with the presence of scarce transported specimens of marine species (e.g., *Carinocythereis whitei*), well represented in the infralittoral areas of the Cadiz Gulf (Ruiz et al. 2000b). In the upper layer, the accumulation of small

fragments of marine faunas indicates a limited transport from the adjacent nearshore palaeoenvironments, with the introduction of fragments of marine species probably due to the action of a small storm or a high astronomical tide.

The main features of Zone B would indicate a transition toward intertidal-supratidal conditions, with a progressive decrease of the marine tidal inputs. This progressive emersion is accompanied by an important drop in the ostracode populations, because a high sub-aerial exposure is an unfavorable factor for these microcrustaceans (Carbonel 1980; Ruiz et al. 2000b).

Zone C is characterized by an introduction of marine and brackish ostracode species over the underlying sediments. This zone may be interpreted as a consequence of a storm or a high tidal flux, which cause the transport of suspended material (including ostracodes) toward the inner low marshes of the lagoon.

The presence of abundant remains of plants, high phyllosilicate contents and the almost disappearance of ostracodes observed in Zone D will indicate a final transition toward almost supratidal, high salt marsh condi-

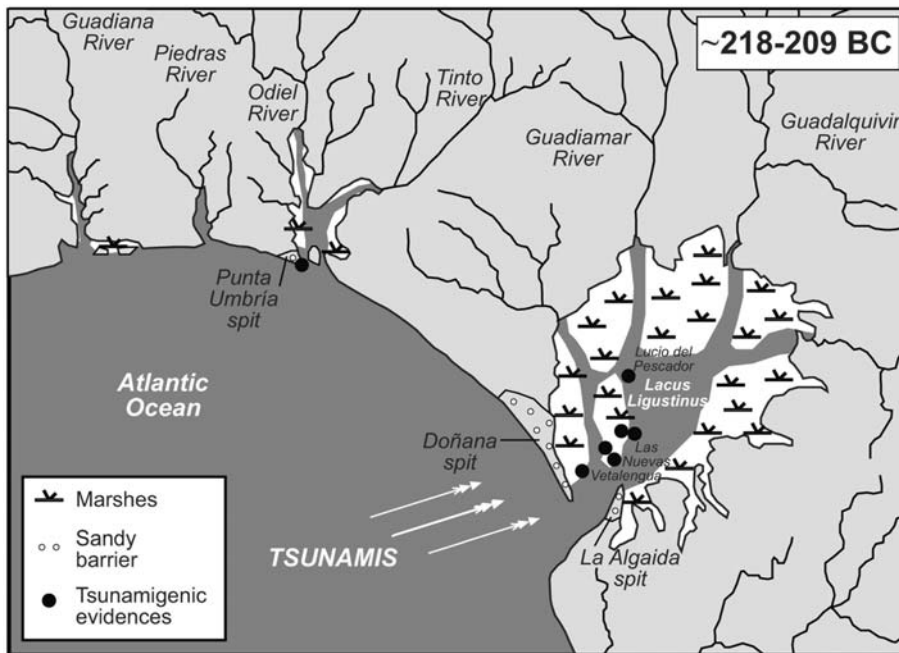


Fig. 5 - Tentative palaeogeographical reconstruction of the Huelva coast (218-209 BC).

tions. In these environments, ostracodes are generally absent (Ruiz et al. 2000b).

The following bioclastic ridge or chenier (Zone E) is usually produced by tsunamis, storms, sea-level changes, tidal fluxes, drift currents or biological crisis (Augustinus 1989). In the Doñana National Park, similar high-energy episodes have been found within clayey sequences and have been interpreted as tsunamigenic deposits (Lario et al. 2000, 2002). This ridge is overlain by an upper bioclastic ridge (Zone F) that may be attributed to a new tsunami, which caused higher wave heights than the previous one. The co-occurrence of species indicative of different palaeoenvironments may be explained by an important sedimentary transport (saltation and suspension) from the infralittoral areas and a strong erosion of the lagoon bottom. A date was obtained on the estuarine bivalve *C. edule*, indicating the calibrated age of this event (sample S-29; Beta-228880; 2700-2320-2210 yr BP or 750-370-260 yr BC).

This vertical evolution suggests a progressive emersion from an initial very shallow, high brackish lagoon to a final, supratidal high marsh. The fine to very fine sediments observed indicate a calm environment dominated by suspension processes, with Na-Cl rich waters as evidenced by the smooth-shelled *Cyprideis torosa* (Anadón et al. 1986). This quiet scenario is slightly altered by periodical storms or high tidal fluxes that introduce small-sized marine ostracode species landward. The final part of the core comprises two tsunamigenic deposits, with a “rafted” disposition of shells very similar to other tsunami-induced layers (e.g., Goff et al. 2001).

Geological evidences of the 218-209 BC tsunamis

Between 218 and 209 BC, the western coasts of Iberian suffered the impacts of four historical tsunamis, with epicenters located between 36° 00'N-36° 50'N and 7° 40'W-10° 30'W (Campos 1991). These high-energy events caused different consequences in each coastal stretch due to the littoral morphology.

A reconstruction of the tsunami effects in the Doñana National Park

A comparison of these data with those indicated by previous investigations allows us to reconstruct the main geological effects of these tsunamis in the different areas of the Doñana National Park. This spatial reconstruction is rare in the scientific literature over tsunamis (e.g., Dawson et al. 1995), focused mainly in a single core or the external areas of coastal environments.

These high-energy events caused the partial rupture of the Doñana spit near Vetaleña (Fig. 5), with the presence of an erosive surface that crosses the adjacent dune systems (Rodríguez-Ramírez et al. 1995). A washover fan was generated probably in the inner side of this spit, with a later reworking of its sandy sediments by the tidal fluxes. The final result was the formation of a sandy ridge (Vetaleña), with a quartz-rich composition and the absence of palaeontological remains. These features coincide with those observed by Flor (1990) in the adjacent dune systems of the Doñana spit.

In the central areas, this tsunami produced the deposition of a bioclastic ridge or chenier (Fig. 5: Las Nuevas), located over the silty levees of an old tidal channel. In the westernmost part of this ridge, an important proportion of the sandy sediments derived from

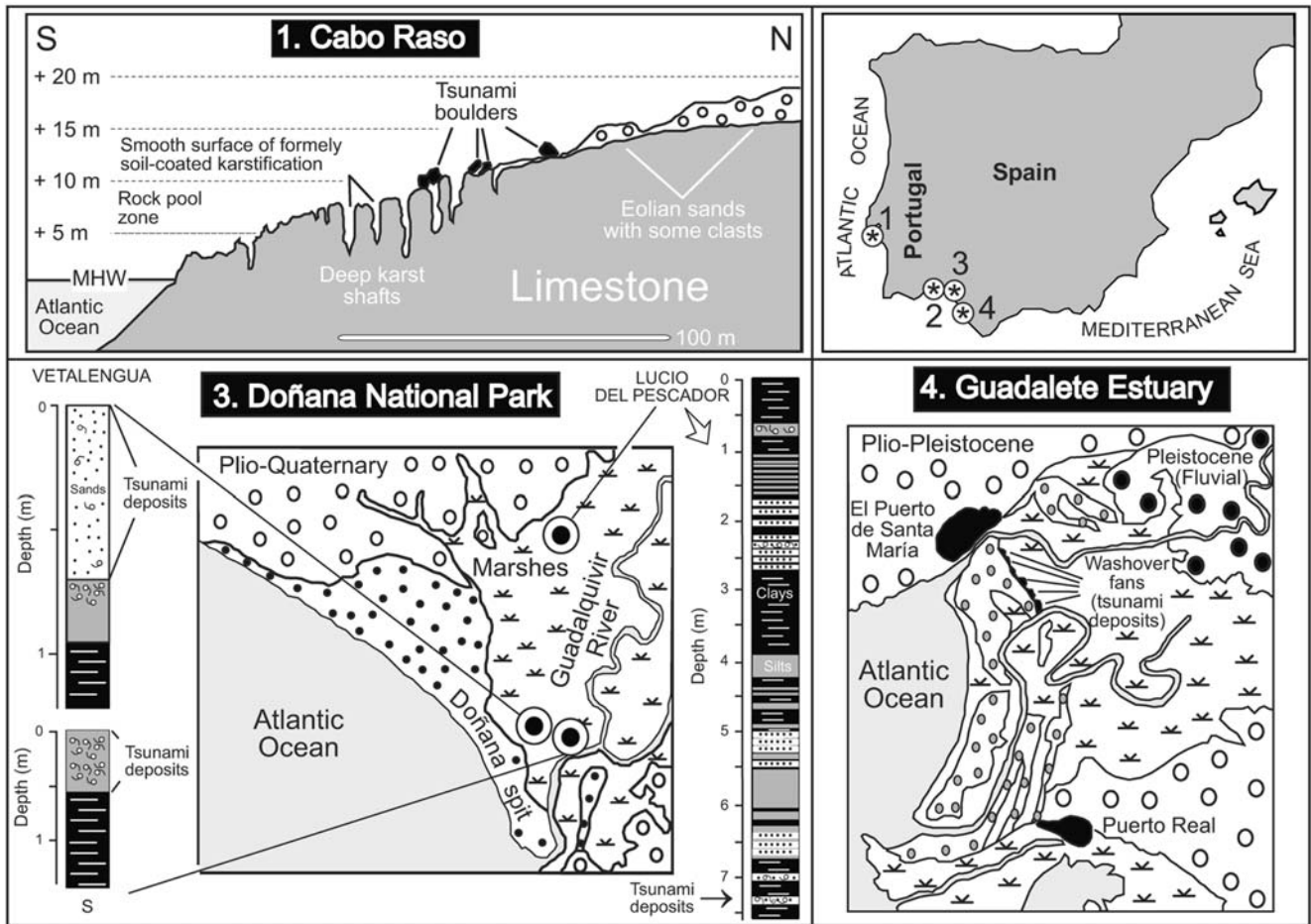


Fig. 6 - Coastal deposits derived from the 218-209 BC tsunamis along the western Iberian coasts. 1: Cabo Raso; 2: Tinto-Odiel Estuary; 3: Doñana National Park; 4: Guadalete estuary.

the spit erosion were reworked and constituted the westernmost part of Las Nuevas (Ruiz et al. 2004). This bed shows lower grain sizes toward the northeast (e.g., landward), with the presence of silty sediments in the inner part of this ridge (Zones E-F in this paper). This decrease of the mean grain sizes in a landward direction is a general feature of tsunamigenic deposits (e.g., Dawson & Stewart 2007).

In this bioclastic bed, the numerous specimens collected of both brackish and marine ostracodes indicates a strong erosion of the lagoon bottom, whereas the abundant marine macrofauna and microfauna proceed from the erosion of the adjacent shallow shelf (Ruiz et al. 1997). In addition, the rare individuals of freshwater ostracodes (Fig. 4: *Candona* sp.) collected in the upper part of Zone F may proceed from the tsunami retreat and the erosion of inner freshwater marshes. Altogether, this inclusion of macrofossils and microfossils in unusual concentrations and sourced from seaward or landward of the existing palaeoenvironments is a characteristic feature of these high-energy events (Cochran et al. 2005).

In the northern, more protected area of the *Lacus Ligustinus*, a bioclastic layer was deposited over the bottom sediments in the Lucio del Pescador area (Fig. 5). At present, this layer is located at 7.3 m depth near the Guadamar River mouth (see Fig. 1) and presents coarse sediments (coarse silts and sands) and numerous bioclastic remains (Lario 1996). Consequently, these tsunamis inundated almost completely this old lagoon.

Additional effects along the southwestern Iberian coasts

The tsunamigenic deposits derived from the 218-209 BC tsunamis have been detected in several coastal environments of Portugal and Spain (Fig. 6). Near the Cabo Raso promontory (Portugal), some huge boulders of limestones (up to 100 tons in some cases) are located from about +10 to +15 m asl over high cliffs. Scheffers & Kelletat (2005) attributed them to the effect of the 218-216 BC tsunami, according to a radiocarbon datum from *Patella* sp. at +12 m asl.

In the Tinto-Odiel estuary (S Spain), this tsunami caused the rupture of the Punta Umbría spit and the creation of a new tidal channel (Rodríguez Vidal 1987). Consequently, this tsunami created a new macrotopography in this coastal stretch.

In the Guadalete estuary (S Spain), a multivariate approach carried out by Luque et al. (2002) revealed the presence of numerous washover fans located close to the northeastern part of the H₃ progradational unit. According to datings of mollusk shells collected in several washover fans located near Puerto de Santa María and numerous textural analyses (Fig. 6), these authors inferred that a tsunami affected the southwestern Iberian littoral at cal. 2300 yr BP, with morphological and sedimentological changes in these coasts very similar to those derived from the tsunami associated to the AD 1755 Lisbon earthquake. This later shock was one of the most extraordinary earth events ever occurred, with a grade X-XI (MSK scale) or magnitude 8.5-9 (Richter scale) along the southwestern Spanish coasts (Ribeiro 1995; Reicherter 2001).

Radiocarbon chronology of tsunamis

Ages of tsunamis are obtained generally from radiocarbon datings of fossil remains included within the associated deposits. These remains proceed from the erosion of infralittoral sediments, sandy spits, cliffs, marshes or bottom sediments of coastal lagoons. Consequently, they are slightly older than the tsunami age and present a very broad range of ages, even in recent tsunami deposits.

Ages of mollusk shells obtained in Cabo Raso (2440 ± 50 BP), Lucio del Pescador (2490 ± 60 BP; 2490 ± 105 BP), Las Nuevas (2284 ± 39 BP), Vetalengua (2230 ± 60 BP; 2171 ± 36 BP), and Guadalete (2340 ± 40 BP) agreed with this general appreciation. For comparison, ages of deposits originated by the 1755 Lisbon earthquake-induced tsunamis in southern Portugal are 1801 ± 76 years (Hindson et al. 1998).

Tsunamis vs storms

This core is especially interesting because it contains storm layers and tsunami-induced deposits in the same vertical sequence. This coincidence is very unusual in coastal (palaeo-)environments (e.g., Costa & Leroy 2007) and permits to compare the sedimentary record of these high-energy events.

The main features of zones E and F are very similar to those observed in tsunamigenic layers located in the same zone, with calibrated ages comprised between cal. 5300 and 2000 yr BP (Ruiz et al. 2004, 2005). In this area, they may be differentiated from storm deposits in the following features:

a) An analysis of the winter storm record has revealed that these high-energy events cause a strong erosion of the littoral beaches in the last forty years. In the post-storm spring-summer, high volumes of the sediment eroded were transported toward the coast, causing the progradation of the littoral spits with a new beach ridge. Nevertheless, there are not sedimentary deposits derived from these events over the salt marshes protected by these spits, as is the case of zones E and F. Moreover, this bioclastic chevron ridge or chenier is clearly longer (up to 4 km) than those derived from the storm action (200-1000 m long; Rodríguez Ramirez et al. 2003).

b) Facies changes. In this area, past tsunamis have caused the deposition of sandy silts over salt marshes, with higher percentages of quartz and a bimodal grain size distribution (see Fig. 2), a typical feature of tsunamigenic deposits (Scheffers & Kelletat 2005). On the contrary, storms only increase the sand percentages (López-González et al. 2006).

c) Higher thickness and lateral extension. In the Holocene geological record of the southwestern Doñana National Park, the storm deposits consists of very thin layers (5-10 cm thickness) with limited lateral extension, in contrast with the tsunami deposits (0.4-1.5 m thickness; Ruiz et al. 2005).

d) Higher bioclastic contents (storm: 5-10 % in most cases; tsunamis: 20-50 %).

e) Higher percentages of marine species (mainly ostracodes or bivalves).

Conclusions

A multidisciplinary analysis (texture, color, mineralogy, paleontology, dating) of the sediments present in a drill core permits to delineate the Late Holocene evolution of the southwestern Doñana National Park. Before cal. 2400 years BP, the phyllosilicate-rich, clayey bottom sediments of the old *Lacus Ligustinus* contained a rich populations of ostracodes (*Cyprideis torosa*, *Loxoconcha elliptica*, *Leptocythere castanea*), which lived in a quiet environment that suffered the periodical actions of storms or high tides. The transition toward intertidal-supratidal conditions coincided with higher phyllosilicate contents, the disappearance of marine species, a remarkable decrease in both ostracode density and diversity and the presence of numerous fragments of plants and roots. Between cal. 2400 and 2350 years BP, a tsunami caused the deposition of bioclastic, silty cheniers over these clayey sediments near the Guadalquivir mouth.

Similar calibrated ages have been indicated for other tsunamigenic deposits present along the western Iberian coasts. These deposits (boulders up to 100 tn,

sandy ridges, cheniers, washover fans) have been attributed to several tsunamis that occurred between 218 and 209 BC, with similar magnitudes to the 1755 Lisbon earthquake-induced tsunami, one of the most destructive events in the historical record of this area.

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