MORPHO-SEDIMENTARY EVIDENCE OF HOLOCENE TSUNAMIS IN SOUTHWESTERN SPANISH ESTUARIES: A SUMMARY

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***Resumen* (*Evidencias morfosedimentarias de tsunamis holocenos en los estuarios del Suroeste de España*):** *Los estuarios constituyen sistemas costeros excelentes para registrar tsunamis a través de un amplio tipo de evidencias geológicas. Este trabajo revisa y resume las evidencias de tsunamis prehistóricos e históricos en los cuatro principales estuarios del suroeste de España. Las más frecuentes son erosión de playas y retroceso del litoral, ruptura y desbordamiento de flechas arenosas y depósito de capas bioclásticas. En la actualidad, estas características se encuentran particularmente bien estudiadas en los estuarios del Tinto-Odiel, Guadalquivir y Guadalete, mientras que son necesarios trabajos más detallados en el sector de influencia marina del estuario del Río Guadiana.*

Palabras clave: Geomorfología, tsunami, estuario, SO España
Key words: *Geomorphology, tsunami, estuary, SW Spain*

INTRODUCTION

In recent years, numerous researches have focused on the geomorphic evidence of the 2004 Indian Ocean tsunami along the coasts of Indonesia, Thailand, India or Sri Lanka. These imprints include the formation of new inlets and the breaching of barrier islands, extensive erosion in river mouths and tidal channels, return channels or area reduction in reef islands (e.g., Kench et al., 2008). In this sense, the post-tsunami effects have been extensively analyzed comparing pre- and post-tsunami data and satellite imagery in order to calculate coastal recovery (Liew et al., 2010) or bathymetric changes in the nearshore zone. The general conclusion is that this event caused a strong geomorphic crisis, which played a determinant role in the afterwards development of these areas. Lessons from this tsunami applied to the geological record have resulted in interesting findings. In this paper, we summarize the main geomorphological imprints of Holocene tsunamis in four estuaries of southwestern Spain.

STUDY AREA

In the southwestern Spanish coast (Fig. 1), five main estuaries may be differentiated on a clastic Plio–Pleistocene substrate: (1) Guadiana Estuary, composed by a main channel (5–15 m depth) and the so-called Carreras subsystem, characterized by marsh deposits protected by sandy barriers and separated by distributary channels; (2) Piedras Estuary, a small bar-built estuary protected by an elongated spit near the mouth; (3) Tinto-Odiel Estuary, with a marine sector constituted by a braided channel system that separate salt-marsh deposits; (4) Guadalquivir Estuary, partially closed by two spits (Doñana and La Algaida) that protect the Doñana National Park, a Biosphere Reserve (>50,000 ha) with a complex sedimentary record from the Lower Pliocene to the Late Holocene; and (5) the wave-dominated Guadalete Estuary, roughly circular and separated from the sea by a complex sedimentary spit (Dabrio et al., 2000). These and other minor estuaries are separated by sandy beaches and Pleistocene cliffs in interfluvial areas. In this work, we focus in the analysis of the main four, i.e. Guadiana, Tinto-Odiel, Guadalquivir and Guadalete estuaries.

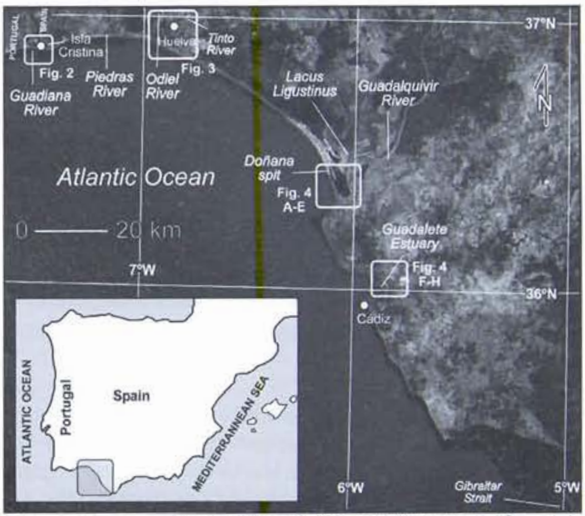

Fig. 1: Geographical map of the southwestern Spanish coast, with location of the four estuaries studied.

From a tectonic point of view, the southwestern coast of Spain is located near the Africa-Eurasia plate boundary. This tectonic boundary extends from the Azores archipelago to the Gibraltar Strait, with a complex interplate domain characterized by different ridges, seamounts (e.g. Gorringe Bank) and depressions (e.g. Horseshoe abyssal plain). This boundary is the source area of different magnitude earthquakes, some of them tsunami-causing, during pre-historical and historical times (Campos, 1992).

Sixteen tsunamis have been recorded during the last 2300 years (Campos, 1991) including the Great Lisbon earthquake (MSK intensity: VIII–IX; Mw: 8.5±0.3; Solares and Arroyo, 2004) and tsunami (run-up: 3–15 m asl; Lima et al., 2010) of AD 1755, one of the most devastating phenomena ever occurred in this area.

METHODOLOGY

Numerous historical maps and references were reviewed to deduce the palaeogeographical changes derived from the AD 1755 tsunami, with special attention to the Guadiana River mouth. These maps were selected from the General Archives of Seville and Simancas (Spain). In addition, the available literature on tsunamis affecting southwestern Spain and Portugal was analyzed.

GEOMORPHOLOGICAL IMPRINTS OF PAST TSUNAMIS: HUMAN IMPLICATIONS

- **Guadiana River mouth:** at present, the main channel of the Guadiana River marks the border between Spain and Portugal, as happened in 1750 (Vaugondy and Vaugondy, 1750) (Fig. 2). In the Portuguese bank, a large spit with a long jetty protects the town of Vila Real do Santo Antonio. In the Spanish side, the Carreras subsystem presents several elongated, sandy barriers that protect numerous marsh bodies crossed by a main channel (Carreras Channel) and numerous distributaries and ebb-tide channels. This general pattern is derived from a progressive infilling of the innermost areas due to the growing of an initial barrier-island system in a W–E direction during the last 3000 years (Morales, 1997).

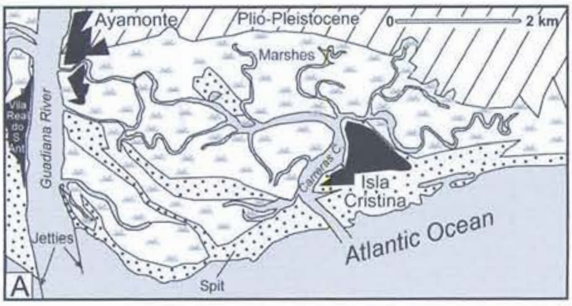

Fig. 2: Main geomorphological features of the Guadiana River mouth (Morales, 1997).

Available historical maps only provide a general perspective on the geomorphological effects of the AD 1755 earthquake and tsunami (General Archive of Simancas). In the Guadiana River mouth, the old channel was partially filled, whereas a new channel was created on the Portuguese side (Gozálvez, 2002). These geomorphic changes might be due to the rupture of sand bars and spits on the Portuguese side, the subsequent sediment redistribution, and the emersion of new sand bars above the swash platform in the open intertidal zones close to the Carreras subsystem (see Morales et al., 2008 for a more detailed description of these beds in recent environments). Consequently, the geomorphic changes derived from this tsunami 'redrew' an international border.

In addition, this disaster caused more than 1000 fatalities in this area and the transfer of fishing activities in 1756 to the Higuerita Island, a more protected environment that coincides with the present-day Isla Cristina village (Fig. 1 in Gozálvez, 1988). Some channels located near this island were filled and several small islands disappeared (Ménanteau et al., 2006). In 1775, the external spits of the Carreras subsystem showed a remarkable expansion and the barrier island located on the western bank of the present-day Carreras channel was attached to the western spit. This growth was clearly controlled by the W–E littoral drift currents and the Guadiana sediment supplies, not repressed at this time.

- **Tinto-Odiel Estuary:** This estuary is a 25 km long incised valley underlain by Plio–Pleistocene marine and fluvial sediments (Fig. 3A). A cross-section of the outer zone shows two main sandy spits (Punta Umbria and Punta Arenilla) separated by the Saltés Island, an intermediate salt-marsh body that includes old spits. This central island delineates the deeper Padre Santo channel, which is the main passage to the Huelva harbour, and the narrower Punta Umbria channel (Fig. 3).

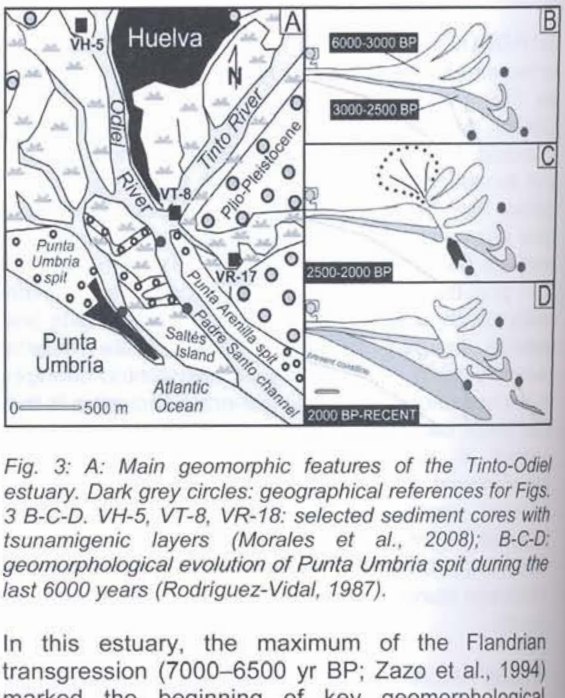

Fig. 3: A: Main geomorphic features of the Tinto-Odiel estuary. Dark grey circles: geographical references for Figs. 3 B-C-D. VH-5, VT-8, VR-18: selected sediment cores with tsunamigenic layers (Morales et al., 2008); B-C-D: geomorphological evolution of Punta Umbria spit during the last 6000 years (Rodriguez-Vidal, 1987).

In this estuary, the maximum of the Flandrian transgression (7000–6500 yr BP; Zazo et al., 1994) marked the beginning of key geomorphological structures (e.g. Punta Umbria spit) that help to understand its subsequent evolution. In an early stage (6000–2500 yr BP), the spit emerges and progrades southeastward with the progressive addition of attached beach berms (Fig. 3B). In this phase, several curved spits were created near the end of this main spit, the current Saltés Island. The intermediate stage (Fig. 3C: 2500–2000 yr BP) is characterized by the breakdown of this spit, with the generation of an inner washover fan and the appearance of the Punta Umbria inlet. These geomorphic changes could be induced by the 218-209 BC tsunami, the only high-energy event that occurred during this period (Lario et al., 2011). In a final stage (Fig. 3D; 2000 yr BP–Recent), the littoral drift currents caused the progradation of beaches attached to the southeastern corner of the spit, whereas the tidal fluxes associated to the new inlet generated small spits linked to Saltés Island. These spits are partially preserved nowadays.

Other tsunamigenic imprints have been found in the innermost areas of this estuary. Numerous sediment cores collected across the different estuarine environments (marsh, channel margin, channel, spit) contain bioclastic layers with different ages agreeing with historical tsunamis (VH-5: 218–209 BC tsunami; VT-8: AD 395 tsunami; VR-17: AD 1531 tsunami). These beds present an erosional base, a fining-upwards sequence and a mixing of both estuarine and marine faunas (Morales et al., 2008). The inner location of some of them (e.g. VH-5) indicates a complete propagation of the tsunami waves along the whole estuary during these events.

- **Guadalquivir Estuary:** The Guadalquivir River (560 km long) is partly blocked by the Doñana (Fig. 4A) and La Algaida sandy spits, resulting in a large estuary (1800 km^2). Four spit regional systems have been defined in the Holocene (H1: 6900–4500 cal. yr BP; H2: 4200–2600 cal. yr BP; H3: 2300–1100 cal. yr BP; H4: 1000 cal. yr BP to the Present) divided by erosional phases at 4500–4200 cal. yr BP, 2600–2300 cal. yr BP and 1100–1000 cal. yr BP (Zazo et al., 1994). The end of the intermediate erosional phase H2–H3 coincides with the 218–209 BC tsunami, which caused a strong geomorphological disturbance (Ruiz et al., 2004) in both former spits and the adjacent *Lacus Ligustinus*, a brackish lagoon detailed by the Roman chroniclers Strabo and Mela in the first historical descriptions of this estuary (García Bellido, 1987). Several geomorphological imprints are linked to this high-energy event:

a) Beach erosion and shoreline retreat in the external side of the Doñana spit, with the presence of a distinctive erosional surface along the southeastern part of this bed (Rodríguez-Ramirez et al., 1996).

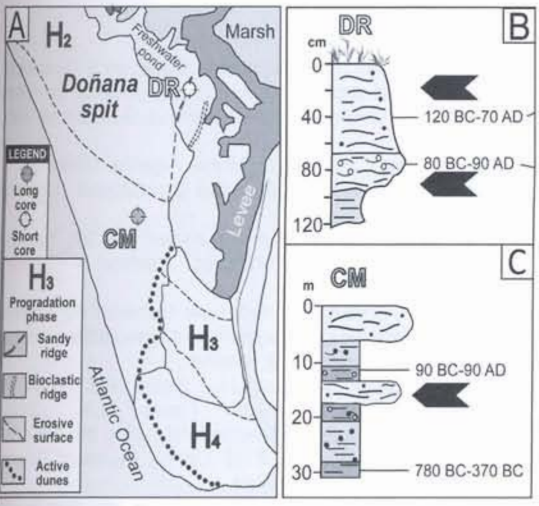

Fig. 4: A: Main geomorphological characteristics of the Doñana Spit bar at Guadalquivir river mouth. B: Lithological features of short sediment core DR, including the calibrated ages of two tsunamigenic layers (Ruiz et al., 2004). C: Lithological features of the long sediment core CM, including two calibrates ages (Rodríguez-Vidal et al., 2011).

b) Accumulation of bioclastic ridges along or very close to the lagoon margins (Fig 4B, lower arrow) by tsunami waves or post-tsunami tidal fluxes. These ridges were also deposited by this tsunami and other older high-energy events in the innermost areas of the lagoon (Pozo et al., 2010). They are elongated (3–6 km), with a narrow width (20–30 m) and thickness (0.5–0.7 m). These bioclastic silts and sands present an erosional base and a bimodal grain size distribution. Both macrofauna and microfauna include estuarine and marine, reworked species.

c) Deposit of reworked sandy ridges (Fig. 4B: upper arrow), derived from the direct erosion of the Doñana spit, a posterior tidal redistribution and the final deposit close to the *Lacus Ligustinus* margin. These spit-like beds are formed by fine to medium sands very rich in quartz, with very scarce fauna. Other sandy ridges have been observed in the northwestern part of the *Lacus Ligustinus*, with ages that coincide with oldest tsunamis and erosional phases. Both bioclastic and sandy ridges occupy the 'hills' (2–2.5 m above the marsh level; Ruiz et al., 2004) of this area. They remain emerged during the fluvial flood episodes suffered by the estuary, with the presence of numerous freshwater ponds so-called 'lucios'.

d) Deposit of subtidal sandy layers (Fig 4C: arrow) in infralittoral environments located near the lagoon mouth. These layers (>3 m thickness) present very similar features to the previous sandy ridges, indicating a common origin (e.g., the erosion of the Doñana spit).

e) The pre-218 BC eastern ridges of Doñana and La Algaida spit-barriers (Rodríguez-Vidal et al., 2011) were suddenly eroded by incoming tsunami waves and mainly by the backwash currents. This action created a channelled morphology, with small cliffs at right angles to the coastline, which are partially preserved today. Relict high-energy beaches were attached to the new cliff morphologies composed of fine sands with numerous bioclasts, rock fragments and pebbles.

f) The great sand barrier of Doñana protected the coastal and tidal lowlands from erosion, although the first line of foredune and former dune ridges were eroded. Accordingly, transgressive dunes were reactivated and migrated inland, toward the inner estuary, as large parabolic sand sheets.

g) The palaeogeographical and geomorphological reconstruction of the post-tsunami littoral landscape (Rodríguez-Vidal et al., 2011) coincides with the earliest historical description of the estuary, made by the Roman chronicler Strabo in his work Geographica, written between 29 and 7 years BC. The spit-barrier of La Algaida records the unique pre-Roman settlement (sanctuary) documented in this coastal area (7th–3rd centuries BC: Blanco and Corzo, 1983). This ancient settlement was abandoned approximately at the date of the tsunami, when this sandy barrier became an island (Rodríguez-Ramírez et al., 1996). Later, in the 1st century AD, and when the connection with the continent was re-established, the Romans installed a saltworks on the eastern coast, sheltered from wave action (Esteve Guerrero, 1952).

- **Guadalete Estuary:** This estuary presents wide marsh bodies surrounded by Plio–Pleistocene marine and fluvial formations and protected by the Valdelagrana spit, a complex sedimentary system that includes three spit systems mentioned above (H2 to H4; Dabrio et al., 2000). Different geomorphological imprints of past tsunamis have been reported in this area (Fig. 5):

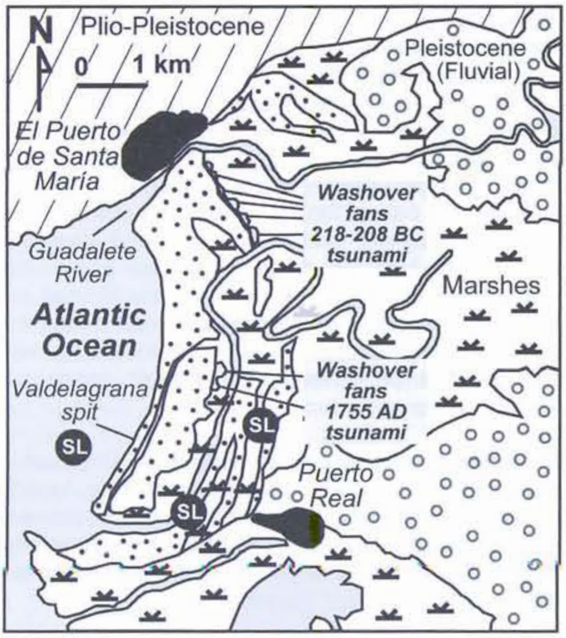

Fig. 5: Main geomorphological features of the Guadalete Estuary (Luque et al., 2002); SL: emerged trenchs or subtidal cores with tsunamigenic, shelly layers (data from Gutiérrez-Más, 2011).

a) Washover fans. These beds have limited length (350–400 m), width (200–300 m) and height (<4 m). The sedimentary units (<1.5 m thickness) are derived from the erosion of sandy spits and present a sharp, erosional contact with underlying flat facies (Luque, 2002). They are composed of yellow, poorly sorted coarse–medium sands with high percentages of quartz and bioclast fragments of molluscs, echinoids and briozoans. These washover fans were generated by the 218–209 BC and AD 1755 tsunamis.

b) Shelly sandy layers observed in both subtidal zones and emerged areas (Gutiérrez-Más, 2011). Biogenic clasts consist of bivalve shells (mainly *Glycymeris*), sometimes imbricated, with abrasion evidence, impact marks and dissolution. These medium to fine bioclastic sands are poorly sorted and can be arranged in surface bands (3–15 m long, 1–3 m wide). The application of new reservoir effect data (Soares, 2010) allow us to link most of these high-energy beds with prehistoric (~3.7–3.0 cal. kyr BP; Pozo et al., 2010) and historical tsunamis (AD 382–395).

c) Destruction of beaches connecting Cádiz with the mainland (Campos, 1992). The AD 1755 tsunami caused severe damages in this area, with run-ups up to 5 m (Blanc, 2008).

CONCLUSIONS

1) The southwestern Spanish estuaries are excellent geological reservoirs of both prehistoric and historical tsunamis, with a wide set of geomorphological imprints. The most frequent are beach erosion with shoreline retreat, breaking or overwash of sandy spits and deposition of bioclastic layers. At present, these features are particularly well studied in the Tinto-Odiel, Guadalquivir and Guadalete estuaries, whereas new studies are necessary in the marine domain of the Guadiana River.

2) In the last 4000 years, two historical tsunamis (218–209 BC and AD 1755) are revealed as extremely violent events and caused most of these geomorphological imprints. The geomorphological record of other probable local tsunamis (~4.0–3.8 cal. kyr BP, 3.2–3.0 cal. kyr BP, AD 382–395, AD 1531) is more restricted.

3) These two historical tsunamis caused substantial changes in the coastal settlements and their adjacent landscapes, with the creation of new waterways or the relocation of fishery activities. In addition, they clearly conditioned the further geographical development of these areas. In addition, the AD 1755 tsunami was likely accompanied by high mortality and injury among the exposed population. The economic impacts should have been also very important at the times.

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