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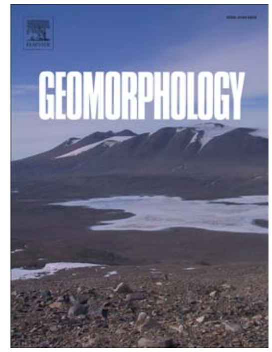

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Geomorphological record of extreme wave events during Roman times in the Guadalquivir estuary (Gulf of Cadiz, SW Spain): an archaeological and paleogeographical approach

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Abstract

Analysis of the geological record has made it possible to delimit for the Guadalquivir estuary the traces of extreme wave events (EWEs) during the Roman period in the Iberian Peninsula (218 BC to AD 476). The largest event occurred in the 2nd-3rd century AD. It generated clearly visible erosive effects in the coastal barriers, including washover fans and erosional scarps. In the inner estuary, however, the effects were minor: crevasse splays that broke levees and cheniers, as well as a residual sedimentary lag. The significant development of the spits protected the inner estuary from the marine incursion, which only caused a water level rise with low-regime waves. Correlation of the geomorphological and sedimentary marks left by this event with the archaeological and geological evidence of other events recognized elsewhere in the Gulf of Cadiz effectively argues for a tsunami as to the nature of the 2nd-3rd century AD event. Yet this and the other identified EWEs in the Guadalquivir estuary during the pre-Roman and the Roman period all fit a model of paleogeographic evolution dominated by processes of coastal progradation and estuarine infilling. Radiocarbon dating, geomorphological analysis, and historical references fail to warrant the so-called '218-209 BC' Atlantic tsunami, as hypothesized in the received scientific literature. In pre-Roman and Roman times, human occupation at the mouth of the Guadalquivir River was strongly influenced by various geodynamic processes, the location of the settlements being contingent upon dependable, fast communication with the sea and, above all, upon adequate protection from EWEs, on the leeward side of spits. Progressive progradation of these coastal barriers combined with the gradual infilling of the estuary to make navigation to open sea increasingly difficult and, eventually, to result in the abandonment of settlements.

Keywords: Extreme wave events (EWEs), Coastal Geomorphology, Roman period, Southwest Spain.

1. Introduction

Coastal environments are highly dynamic; they undergo significant evolutionary changes in short periods of time. This dynamism results largely from the interaction between waves, tides, and fluvial inputs, in their turn modified by relative sea-level changes, climatic setting, and neo-tectonic processes (Pethick, 1984). A mechanism that triggers an especially rapid development is an extreme wave event (hereinafter, EWE). Within hours it can generate a complex sedimentary record that has significant morphological and environmental effects in low-energy coastal environments such as lagoons and estuaries (Sawai, 2002). The EWE may severely hit human settlements as well (Goff et al., 2012). Two of the most dangerous and yet most common EWEs violently impinging upon coastal locations are tsunamis and storm surges (Morton et al., 2011). The combined analyses of geology, archaeology, and history may thus be necessary to determine past environmental scenarios and changes. Numerous studies have recently been carried out from an interdisciplinary perspective, e.g. to identify and assess the imprint of tsunamis in the record of archaeological sites (McFadgen and Goff, 2007; Bruins et al., 2008).

The marks of tsunamis in coastal sediments, however, are difficult to distinguish from those of violent storm surges as both tsunamis and violent storms are high-energy marine events that result in similar deposits. Many studies have been undertaken with the aim of establishing diagnostic criteria with which to tell the traces of one type of event from those of the other (Fujiwara et al., 2000; Goff et al., 2004, 2012; Morton et al., 2007; Ramírez-Herrera et al., 2012). It is precisely because both tsunamis and severe storms strike similarly in littoral areas and cause inundation of extensive surfaces by sea-water that both have been referred to as ‘extreme wave events’ or EWEs (Kortekaas and Dawson, 2007; Switzer, 2008).

Geomorphological and sedimentary features generated by EWEs are well known along the coasts of SW Iberia; such events having been attributed to tsunamis or storm surges, or both (Lario et al., 2010; Rodríguez-Ramírez et al., 2015). At present, damaging storms occur in the Gulf of Cadiz with a periodicity regulated by the North Atlantic Oscillation (NAO; periodicity of c. 6-7 years) as well as by solar irradiation (sunspot cycles) (periodicity of c. 11 years) (Rodríguez-Ramírez et al., 2003). Although storm surges are known to wreak havoc in littoral areas, the sedimentary record left by them in the Gulf of Cadiz has been scarcely studied. Pollen studies, nonetheless, have enabled researchers to confirm the already well documented Roman Humid Period in the southwestern Mediterranean region (Martín-Puertas et al., 2010). Such humid conditions at the time may have consisted of persistent storm activity resulting from a negative NAO index (Fletcher et al., 2012). As to tsunamis hitting the Gulf of Cadiz, they have drawn increasing interest in the wake of the recent tsunamis that have devastated the coasts of the Pacific Ocean. The southwestern Spanish coast is a low-probability tsunamigenic area (Reicherter, 2001), yet for decades it has been assumed that as many as sixteen tsunamis are historically documented for the time-period between 218 BC and AD 1900 (Campos, 1991), four of which dating to the years 218-

216 BC, 210-209 BC, 60 BC, and AD 382, in the Roman period (Galbis-Rodríguez, 1932-1940). Such an historical record must be revised, however, insofar as clear evidence from writers of Antiquity as well as from the archaeological record is uncertain (Gómez et al., 2015).

The sedimentary record in the Gulf of Cadiz has been investigated for traces of some of these events (Andrade, 1992; Dabrio et al., 1999b; Luque et al., 2002; Whelan and Kelletat, 2003; Alonso et al., 2004; Gracia et al., 2006; Morales et al., 2008; Gutiérrez-Mas et al., 2009; Baptista and Miranda, 2009). Archaeological indications of natural destructions in the Roman period recognized in the Gulf (Sillières, 2006; Campos, 2011; Alonso et al., 2015) would be related to some of these events. The epicenters of the corresponding earthquakes have commonly been placed at some 200 km southwest of Cape Sâo Vicente, near the Gorringe Bank (Martínez-Solares et al., 1979). Current analyses, however, point to movements along the Azores-Gibraltar Fault or along associated minor faults such as the Marques de Pombal Fault (Terrinha et al., 2003). Still other likely epicenters can be posited in connection with movements of faults that are even closer to the coasts of the Gulf (Silva et al., 2005).

The largest estuary in the Gulf is, by far, the Guadalquivir estuary (Fig. 1). Flanked on both sides by spits, known as Doñana and La Algaida, the estuary is a particularly interesting area with respect to both the intensity of its geomorphological dynamics and the large number of archaeological sites in it that date to Classical Antiquity and earlier periods in history and prehistory (Carriazo, 1975; Bellido and Pérez, 1985). The geodynamic evolution has drawn a great deal of scientific attention over the past few decades (Zazo et al., 1994; Rodríguez-Ramírez et al., 1996, 2014; Rodríguez-Ramírez and Yáñez, 2008; Dabrio et al., 1999a; Jiménez-Moreno et al., 2015). Archaeologists, for their part, have focused on the Roman period. The Doñana spit houses one of the most salient sites in the Gulf of Cadiz dating from this period, the well-known Cerro del Trigo site, with remains of a fishing-and-salting industry town from the 2nd to the 6th century AD (Bonsor, 1922, 1928; Schulten, 1924; Campos et al., 2002). The La Algaida spit hosts the El Tesorillo site; located upon the eastern bank of the spit, it includes remains of a carpentry workshop for repairing boats that date from the middle of the 1st century BC to the 4th century AD (Esteve-Guerrero, 1952; Blanco and Corzo, 1982; Corzo, 1984). East of La Algaida, on hilly terrain on the left side of the Guadalquivir estuary, stand the ruins of the ancient city of Ebora, much vandalized and still awaiting thorough, systematic study (Carriazo, 1970) (see Fig. 1).

The main objective of this paper is to furnish geomorphological and sedimentary evidence of EWEs having occurred in the lower Guadalquivir estuary during Roman times as expressions of the paleogeographic evolution of this estuary. Such evidence is the result of a multidisciplinary study of data obtained from boreholes in the upper sedimentary record which revealed shell-rich and sand facies. These facies were approached from the points of view of geomorphology, sedimentology, paleontology, history, and chronological assessment.

2. Geographical and morphodynamic setting

Located in the Gulf of Cadiz under the influence of the Atlantic Ocean (Fig. 1), the Guadalquivir estuary contains a wide freshwater marshland of 180,000 ha that includes Doñana National Park, a UNESCOMAB Biosphere Reserve. The enclosing spits, Doñana and La Algaida, both partly covered by active dunes, make up the largest spit system of the Gulf of Cadiz, which extends toward the E and SE. The wide marshland located behind the system grew out of the sediment contributions of the Guadalquivir and convergent rivers as they filled in the formerly marine estuary in the form of ever extensive finger deltas in a low-energy environment. The process was favored by the growth of the large littoral spits that isolated the estuary from the sea as well as by the development toward the center of a spacious chenier plain (Rodríguez-Ramírez and Yáñez, 2008).

Hydrodynamics in the estuary are controlled by the fluvial regime, the tidal inflow, wave action, and drift currents. The largest river draining the Spanish southwest and the main source for fluvial sediments in the entire southwestern coastline, the Guadalquivir has a mean annual discharge of 164 m^3/s, even though winter spates can easily exceed 5000 m^3/s (Vanney, 1970). The highest runoff (>1000 m^3/s) takes place from January to February, with fluvial current velocities of up to 1 m/s (Vanney, 1970; Menanteau, 1979). The maximum tidal range observed at the river mouth is 3.86 m (period from 1997 to 2003), the average range being some 2 m (Spanish Ministry of Fomento, 2005). The coastline can be described as mesotidal, semi-diurnal.

The wave regime depends directly upon the prevailing SW winds, with 22.5% of the days of the year blowing in this direction (data of Spain's Instituto Nacional de Meteorología, I.N.M, for the city of Huelva between 1960 and 1990). In the wintertime Atlantic cyclones are common, giving rise to strong SW winds that generate 'sea-type' waves more than 6-8 m high (H_{smax}; data of Spain's Departamento de Clima Marítimo of Organismo Autónomo Puertos del Estado, OAPE). Although these waves cause significant erosion in the littoral zone (Rodríguez-Ramírez et al., 2003), they represent only around 3–5% of the total annual waves. In general, the wave regime in the Gulf of Cadiz is a medium-to-low energy one, with waves usually smaller than 0.6 m high (data of Departamento de Clima Marítimo). Most of the wave fronts approach the coast obliquely and induce littoral currents that transport sand from the Portuguese coast to Spanish nearshore areas.

3. Methodology

3.1. Geomorphology

As a first step in the investigation, the geomorphology of the Guadalquivir river mouth was mapped from 1:33,000 aerial photographs taken in 1956, checked with satellite images of 2012 commissioned by Servicio Cartográfico of the regional government of Andalusia in Spain. The initial cartography of the fluvial and littoral elements (i.e., levees, fluvial channels, spits, cheniers, littoral strands) was partly modified after direct observation in the field. The Topographic Map of Andalusia (1:10,000) was used as a base document for the geomorphological mapping. All of this information was integrated and analyzed into the *gvSIG* GIS program.

3.2. Lithostratigraphy

We examined the sedimentary sequence and facies obtained from shallow drillings (< 3 m) in surface formations (Figs. 1, 2), for which we used a 2 cm diameter Eijkelkamp gouge, an 8 cm diameter helicoidal drill, and trenches. Our aim was to identify depositional features through small variations in the textural and compositional characteristics of the deposits. Grain-size analyses were conducted at different levels of the sedimentary sequences by means of a Malvern Mastersizer 2000 laser diffraction particle analyzer, which makes it possible to determine precise particle distributions for sizes between 2 mm and 2 μm. For sizes larger than 2 mm, a conventional sieving method was employed. We looked for morphological, geometrical, and extension marks of EWE deposits, as well as for relations of these deposits with underlying and overlying sediments if they existed.

3.3. Paleontology

Macrofossil analysis from sediment samples was performed to identify types and diversity of species (faunal composition and shell taphonomy) (Fig. 2). Several samples were collected from different cores, and the bulk sediment of each (12 cm^3) was washed through a 1 mm sieve. Bivalves and gastropods were identified to the species level and then counted in order to determine the semi-quantitative distribution of species in each core. The presence and relative abundance of other groups (such as scaphopods, barnacles and bryozoans) were also noted.

3.4. Dating

Nine dates resulted from radiocarbon determinations at the laboratories of Centro Nacional of Aceleradores (Seville, Spain) and Accium BioSciences Accelerator Mass Spectrometry Lab (Seattle, USA) from mollusc shells (Table 1, Fig. 3). The shells selected were those that showed no or low degree of transport and were preserved as articulated valves in the lag deposit. Published radiocarbon data were also used (Rodríguez-Ramírez et al., 1996; Dabrio et al., 1999a; Ruiz et al., 2004; Rodríguez-Ramírez and Yáñez, 2008). Radiocarbon data were calibrated by using CALIB 7.0 (Stuiver and Reimer, 1993) and the Reimer et al. (2013) calibration dataset. The final results correspond to calibrated ages (cal.) with 2σ uncertainty, corrected for the reservoir effect in this area as measured by Soares & Martins (2010). For the Late Holocene on the Andalusian coast of the Gulf of Cadiz, Soares (2015) has recommended a ΔR value of -108 ± 31 ^{14}C yr.

4. The historical references to tsunamis during the Roman Period

All references in the current scientific literature to historical tsunamis hitting SW Iberia and the Gulf of Cadiz in pre-Roman and Roman times cite the chronology of José Galbis-Rodríguez (1932-1940), which lists events in the years 218, 216, 210, 209, and 60 BC, and AD 382. Galbis-Rodríguez's sources for such events, however, can no longer be accepted with confidence.

For the event of 218 BC, Galbis-Rodríguez's source is 16th-century Spanish historian Florián de Ocampo (1578, first edition in 1544). For the event of 216 BC, the source is early 20th-century Spanish geologist M. M. S. Navarro-Neumann (1920), whose source was, again, Ocampo. The 16th-century historian mentions but one tsunami rather than two, however. He wrote (1578: 174r-174v) that this event occurred in the year 216 BC, early during the Second Punic War, when the Carthaginian army led by Hannibal marched from eastern Iberia across southern France and the Alps to invade Italy and attack Rome—a development, it is known today (Bordet, 2000: 71-72), that took place in 218 BC. Ocampo's words call to mind some of the defining features of a large seismic crisis that includes a tsunami: "*grandes terremotos o temblores que derrocaron edificios y mataron gentes... Y la mar anegó muchos lugares que primero fueron descubiertos; lanzó fuera de sí multitud de pescados, dellos comunes y conocidos y dellos nunca vistos...*" ("large earthquakes or tremors that tore down buildings and killed people… And the sea flooded many places that had first been exposed, throwing out of itself a multitude of fish, some of them commonplace and known, yet others not seen before….")

As his own sources for this information, Ocampo vaguely refers to "some Spanish chronicles" ("*memorias españolas*"), which he fails to cite, plus two authors whom he calls "the two Julians" ("los dos Julianos") and includes in the list of references for his work (1578: 4r-5v). One is a Julian who late in the 7th century AD was archbishop of Toledo and allegedly wrote a major chronicle on early Spanish history. This chronicle, however, was actually the work of a shadowy contemporary of his by the name of "Wulsa" and is known to contain no more than a chronology of kings of Iberia during the Visigothic Period (AD 415-711) (Antonio, 1998: I, 374-375, 461-473). The other Julian is Juliano Luca Diácono, who according to Ocampo was a Greek national and also lived in the latter years of the Visigothic kingdom in Iberia. But the work of this second Julian, *Comentarii hispanicarum antiquitatum*, has escaped scholars entirely;

including Ambrosio de Morales, Ocampo's close friend, colleague, and editor (Antonio, 1998: I, 488-489; Pellicer de Ossau in Antonio, 1799: 680).

Revealingly enough, neither *Primera Crónica General de España*, by 13th-century King of Castile Alphonsus X, nor the 7th-century writings of Isidorus Hispalensis, arguably the most authoritative sources in the Middle Ages for the ancient history of Iberia which Ocampo cites, makes any reference whatsoever to the event of 218 BC. In the 18th century, the Portuguese historian J. J. Moreira de Mendonça, an early enquirer into the cataclysmic Lisbon earthquake of 1755, does make reference (1758: 16) to a large seismic event in 216 BC, yet he cites as sources Spanish historian Juan de Mariana (1852-1853, first edition in 1601), who relied on Ocampo, and Portuguese historian Amador Patricio (1739: 116), who referred to an earthquake-cum-tsunami in 217 BC in Italy rather than Western Iberia at the time of Hannibal's victory at the battle of Lake Trasumennus, north of Rome. Patricio's source was Roman historian Livy (in Foster et al., 1919-1959: V, 216-218).

Possibly because of this flimsy evidence, the Official Register of Historical Earthquakes and Tsunamis in Spain (before 1370) by Instituto Geografico Nacional (Madrid) (www.ign.es/resources/sismologia/pdfTerremotos/Catalogohasta1370.pdf; last accessed January 2016) assesses the 218 BC event in SW Iberia as historically ill-founded (see also Udías 2015: 1003; electronic supplement: 9). The shaky documentary grounds on which it rests stand in stark paradoxical contrast with Ocampo's dramatic though accurate rendition of the event. This puzzle might perhaps be solved by establishing that Ocampo recorded the tradition of an actual event in the Gulf of Cadiz, albeit a more recent one such as the tsunami of AD 881 (Guidoboni et al., 1994: 388) or the tsunami of AD 1356 (Pemán, 1941: 31; Bosch Vilá, 1984: 260, 270).

A similar situation obtains for the events reported for 210 and 209 BC. Galbis-Rodríguez's chronology includes a tsunami in 210 BC and another one in 209 BC. For the former event his source is, again, Ocampo. For the latter, the source is Navarro-Neumann, who cited Ocampo's narrative. Yet, as for the previous juncture, Ocampo told of only one tsunami rather than two (1578: 213v) which he dated to 210 BC. The crisis was vivid in the city of Cadiz: "*Los vecinos de Cádiz padecieron algunos terremotos y la mar anduvo muchos días tan gruesa, con bravezas y corrientes* *excesivas que pasó harto adelante de donde solía...*" ("The residents of Cadiz suffered a number of earthquakes and the sea surged so much for many days, with such fury and excessive flows, that it advanced far ahead of where it used to"). Ocampo failed to mention his own source for this information. This event also appears marked down by the Official Register of Historical Earthquakes and Tsunamis in Spain as unlikely to have actually occurred.

As to the tsunami of 60 BC, the source of Galbis-Rodríguez is Navarro-Neumann, who relied on Moreira de Mendonça. Moreira, in turn, had trusted the 17th-century treatise *Europa portuguesa*, by Portuguese historian and poet Manuel Faria y Sousa. The event ("*en la costa de Portugal y Galicia un terremoto... horrible y peligroso…, el mar excediendo de sus ordinarios límites ganó campos, descubriéndolos también en otras partes…*") ("on the coast of Portugal and Galicia there happened an earthquake…; it was horrible and dangerous… The sea trespassed its ordinary limits to flood spaces in some areas while exposing other spaces elsewhere…") Faria y Sousa (1680: 203) dated to sometime in the years from 68 to 60 BC, upon the assassination of Roman opposition leader Quintus Sertorius. Faria failed to cite his source. The event is not mentioned by Ambrosio de Morales in his extension of Ocampo's chronicle of ancient Iberia (Morales, 1574-1586). The Official Register of Historical Earthquakes and Tsunamis in Spain also lists this event as unlikely to have actually taken place. Perhaps Faria learnt of the information, recorded fragmentarily by Roman historian Caius Sallustius Crispus (Sallust in Maurenbrecher, 1893: I, 70), that a large earthquake had been felt in Cordova about the time of the war waged by the Roman Senate against Sertorius. An army sent by the Senate was stationed in Cordova when that happened. The event, it is now established, occurred in the winter of 77-76 BC. Sallust wrote about it in his *Historiae*, just a few decades after the event. Because this work has come down to us incomplete, it is uncertain whether he specified that the earthquake was part of a larger seismic context that also included a tsunami in SW Iberia and the Gulf of Cadiz.

Finally, with respect to the tsunami of AD 382, which allegedly struck the Portuguese littoral zone, the sources of Galbis-Rodríguez are, again, Navarro-Neumann and Moreira de Mendonça. Moreira wrote: "*subverterâo-se ilhas, de que ainda ao presente apparecen algumas eminencias defronte do cabo de S. Vicente*" ("a number of isles were submerged, the tops of which still to be seen in front of Cape S. Vicente") (1758:

26). Moreira relied on *Monarchia lusytana* by Frey Bernardo de Britto, a 16th-century Portuguese chronicler whom Faria often read for his own work. De Britto cited as his source *Antiguidades lusytanas* by a Portuguese author from the late Visigothic Period to whom he refers as “Laymundo Ortega” or “Laymundus” (1597: 4v; 1609: 124v). The actual existence of this author has been seriously doubted, however, and *Antiguidades lusytanas* has been considered a 16th-century forgery (Antonio, 1998: I, 504-509). De Britto also made reference (1609: 124v) to the large earthquake-cum-tsunami that ravaged the central and eastern Mediterranean in AD 21 July 365, reported by Ammianus Marcellinus, Paulus Orosius, and other authors of Antiquity. De Britto may have meant this event and no other when he cited “Laymundus” for its effects in the Portuguese littoral. The Official Register of Historical Earthquakes and Tsunamis in Spain lists no event for the year AD 382.

5. The Geological evidence

5.1. The geomorphology of the marshland

The geomorphology of the marshland is characterized by fluvial levees on both sides of the Guadalquivir River, in addition to ancient courses of the river and the inter-levee areas. The clay-rich fluvial levees have a variable width (300–2000 m) and great length, reaching heights of 0.5–1.5 m above the adjacent inter-levee marshes which are the zones that get flooded the most. These levees are part of a deltaic system that has been filling the old estuary; topographically, the levees diminish progressively in height, from 2 m high to the north to 0.5–1 m near the mouth of the river, with a slight slope on the order of 0.004%.

Beach ridges of sandy and shelly deposits with a littoral strand morphology, known as ‘cheniers’, overlie the clayey infilling of the marshland (Rodríguez-Ramírez and Yáñez, 2008). Cheniers signal the location of ancient shorelines and are evidence of changes in paleoenvironmental conditions, specifically changes in sediment supply, river discharge, sea level, and the frequency of storms, among others (Augustinus, 1989). These formations, found on top of the different fluvial levees of the Guadalquivir marshes, were part of a wider chenier plain. Chenier plains consist of two or more parallel to subparallel ridges (the cheniers), separated from one another by progradational littoral muddy deposits; in the Guadalquivir marshes, the original extension of the chenier plain has been eroded by both fluvial-tidal activity and EWEs during relative sea-level highstands, generating crevasse-splays and washover fans at some locations (Figs. 4, 5). The age of these crevasse splays and washover fans may be gathered from the chronology of the affected chenier.

The sandy chenier systems are 50 to 100 m wide and 2.00 to 2.25 m high above sea level. They consist of overlapped strands associated with the two ancient inlet channels (paleo-mouths) of the Guadalquivir River. The first, westernmost paleo-mouth, defined by the littoral strands of Vetalengua (VL1), was flanked on the right side of the estuary by the Doñana spit and on the left side by the La Algaida spit. On the right side the Vetalengua strands are distally attached to the Doñana spit and oriented toward the NE over long distances; on the left side, the strands are attached to the La Algaida spit, though over less geographical extent (Q4 to Q9). The second paleo-mouth, to the east of the first one and defined by the littoral strands of Los Prados (LP), was flanked on the right side by the La Algaida spit and on the left side by the hills of Sanlúcar de Barrameda. The geomorphological evidence and the dates obtained indicate that VL1 and LP remained active up to the 1st century AD (Table 1, Fig. 3), while Q4 to Q9 represent stages of a progressive migration of the Guadalquivir River toward the west (Fig. 1).

The main shelly chenier systems are located in Las Nuevas and Vetalengua. Geomorphological analysis of the cheniers in Las Nuevas revealed a progressive growth of the system toward the west and south in the form of successive ridges (VAT, AA, AR, LV, and PB), ridges AA and AR overlapping toward the east. Ridge LV exhibits the bulkiest morphological development, including beach ridge morphology of narrow (5-15 m), small ridges and landward-dipping crests which rise some 1.75 to 1.95 m in height above sea level. Ridges VAT, AA, AR, and PB, of lesser morphological build and partly buried by estuarine deposits, reach heights of 1.30 to 1.50 m above sea level. The oldest ridges are in the east, as the dates range from the 7th century BC in VAT through the 4th century BC in AA to the 3rd century BC in AR (Figs. 1, 3, 5, and Table 1). The growth of Ridge LV started in the 2nd and continued on to the 4th century AD and beyond (Table 1), not counting two dates that are older but concern samples that have been subject to reworking (B-145202 and GX-21825) (Fig. 3 and Table 1). It was precisely from the 2nd to the 4th century AD that this ridge experienced its largest morphological development, like a transgressive shelly chenier. The most recent shelly cheniers—VL2, in Vetalengua, and PB, in Las Nuevas—would have resulted from the last phases in the accumulation process during the 6th and 7th centuries AD (Figs. 1, 3, 4, 5) and would have been affected by the unremitting evolution of the fluvial levees. Eventually, all these cheniers would turn into the thin layers of residual shell that one finds embedded in the fluvial levees, especially at locations that are the farthest from the present-day mouth of the river.

In Las Nuevas, because of EWEs in the past, the chenier system exhibits a number of erosive incisions that resulted in crevasse splay formations over the marshland floodplain (crevasse splays A and B, Fig. 5). Because these incisions can be seen in chenier AA, they must date from the 4th to the 3rd century BC. Those on ridge LV date mostly from the 2nd to the 3th century AD; erosion there has been active until recently (Figs. 1, 5).

5.2. The geomorphology of the spits

Two dune systems lie over the spits' oldest section. The first extends from the shoreline toward the hinterland of the spit, displaying formations that range from foredunes to transversal bodies that can be as high as 35 m at Cerro de los Ánsares (Fig. 1). Below these bodies and extending further inland there spreads the second dune system, which consists of rather blurred parabolic dunes no more than 10 m high. The two systems are clearly discernible in the Doñana spit, but not so in the La Algaida spit.

Besides these dune systems, the spits include a number of littoral strands that represent intense coastal progradation (Figs. 1, 2). In the Doñana spit, these strands are divided into two sets, one separated from the other by a rectilinear cliff and a number of incisions (Figs. 1, 2). The strands of the first set slightly curve toward the west. Dates obtained at the oldest strand (M1) indicate a development from 188 cal. yr BC to 92 cal. yr AD. The second, more recent set of strands, subsequent to an erosional surface, exhibits a general development that includes ridges and swales progressively curving toward the east. Dates here range from 464-712 cal. yr AD (M2) to the Present, the most recent formations being covered by dunes. Because of the age of the strands extending in front of and behind the erosional surface, the event that caused this morphological anomaly can be dated to the 2nd or 3rd century AD.

As the oldest strand (M1) shows a number of washover fans (cf. washover fan A, Fig. 4) extending toward the marshland, they must date to around the 1st century BC. The erosion affected the oldest progradation phases during the early stages of spit growth. A more recent development, however, can be recognized on the leeward side of the erosional surface and must, therefore, be related to the event that generated this surface in the 2nd-3rd century AD. Though very blurred by the dunes and the vegetation, these washover fans partially reach the apical zone of the first set of littoral strands (cf. washover fan B, Fig. 4).

In the La Algaida spit the strands prograde toward the NNE as they surround the core of the formation, which is covered by dunes. A number of successive erosional surfaces can be recognized on such core in the form of rectilinear cliffs and incisions. Because these erosional surfaces break the geomorphological continuity of previous formations that resulted from progradation, they enable the observer to identify a number of progradation sets. The core of the spit is older than the 6th century BC (Rodríguez-Ramírez et al., 1996). Separated from it by an erosional incision, a subsequent system of littoral strands spreads out with dates ranging from 534 to 107 cal. yr BC (Q1) and from 142 cal. yr BC to 96 cal. yr AD (Q2). A second erosional incision separates this system from the most recent progradation formations. Generally speaking, the sedimentary process that resulted in the littoral strands of the spits of Doñana and La Algaida shows a marked alternation between ridges and swales.

5.3. Sedimentary lag of EWE (BT core)

Core BT revealed a layer of massive clayey silt with sand (2-5%) in the clayey deposits that have filled in the Guadalquivir paleoestuary at a depth of about -1 m under the topographical surface (Fig. 2), its thickness varying from 5 to 15 cm. The sedimentary succession built upon an erosional uncorformity with the underlying deposit, made of clayey silt. Substantial quantities of *Cerastoderma glaucum* and *Solen marginatus*, with articulated whole shells, appeared mixed in with sporadic fragments of other marine life forms (*Glycymeris* sp.). Overlying this shelly layer, more recent sedimentation, 10 to 25 cm thick, contained vertical burrows of *S. marginatus* and *C. glaucum*, starting from the lower shell level and finishing with the shell itself in life position. The dates obtained from the shells range from 9 cal. yr BC to 300 cal. yr AD and from 105 cal. yr BC to 292 cal. yr AD. These deposits can be interpreted as accumulated sedimentary lag caused by a EWE.

5.4. Littoral strands and washover fan (MW core)

Core MW was drilled in the littoral strands of the Doñana spit, where various sedimentary facies can be recognized (Fig. 1):

First, an aeolian facies, 1 to 2 m thick from the bottom of the core upwards (Fig. 2), made up of fine to medium sands (70-80% sand) with intense yellow shades and abundant quartz (66%-91%) which are well sorted and highly bioturbated by plants and roots without significant sedimentary structures. Up to 75% of the sediment presents a mean grain size between 500 and 125 mm. Macrofauna are virtually absent, with the exception of some fragmented, well spread out remains of continental gastropoda (*Helix* sp., *Otala* sp.). The facies, interpreted as aeolian sands, exhibits on the surface a blunt morphology of transversal dunes with sinuous crests.

Secondly, a high-energy facies: a layer of yellowish sands (70-80% quartz) within a matrix 0.3 to 0.7 m thick that contains little fine sediment (silt, clay) yet much, significant bioclastic material. The basal contact is erosive. The layer has no sedimentary structures. The abundant macrofauna, mixed in with rock fragments, consists almost exclusively of a bed of *Glycymeris glycymeris*. This second facies can be interpreted as a washover fan lying over the various littoral strands in connection with the erosive surface in the Doñana spit. The fan became fossilized by a more recent dune system eventually (Fig. 2).

Thirdly, a sandy beach facies made up of coarse grained sands (60-75% quartz) that are well sorted and mixed in with abundant remains of marine malacofauna (*Glycymeris*, *Clhamys*, *Mactra*) as well as some rocky fragments. It has a sedimentary structure, characterized by cross-bedding perpendicular to the shore. This facies can be interpreted as a foreshore depositional environment, in transition to the backshore from the top of the swash zone. It is an environment of intense wave energy and constant reworking of the sediments.

6. Discussion

6.1. The geological record of EWEs

The impact of EWEs on low-energy coastal environments such as estuaries and coastal lagoons generates characteristic sedimentation that may result in significant geomorphological changes (Goff et al., 2012). The mouth of the Guadalquivir River exhibits a number of geomorphological and sedimentary features that are evidence of EWEs (storm surges or tsunamis) having occurred in the Roman period. Geomorphological features include washover fans, paleocliffs or erosional scarps, coarse gravel deposits, and crevasse splays. Sedimentary features are sedimentary lags of sand and shells, as well as coarse deposits that are stratified with various types of facies (Morales et al., 2011).

Though largely blurred by more recent dynamics, paleocliffs or erosional scarps still border the littoral spits. The Doñana spit conspicuously displays one of these incisions in delineating two different phases of progradation, which are local instances of regional progradation phases known as H5 and H6 (Zazo et al., 2008). While in other spits in the Gulf of Cadiz interruptions in the progradation are marked by large swales or gaps that have been recognized in formations of the same kind elsewhere (Zazo, 2006), in the Guadalquivir estuary the H5-H6 interruption is due to an EWE. Clear signs of an EWE being the cause are the orientation of the incision toward the open sea and the presence nearby on the leeward side of the erosional surface—affecting older littoral strands—of a washover fan that contains a layer of shells (*G. glycymeris*) and interstratified pebbles (Fig. 2). Washover fans are numerous in the Gulf of Cadiz; they all have been related to tsunamis (Luque et al., 2002) as well as to storm surges (Morales et al., 2014). In addition, interstratified layers of *Glycymeris* sp. that have been studied in coastal formations in the Guadalete estuary, located no more than some 25 km to the south of the Guadalquivir estuary, have been related to tsunamis (Gutiérrez-Mas, 2011).

The La Algaida spit shows a number of erosional scarps that are superimposed on top of one another. Their origin owes much to an intense fluvial dynamics, however. There was a time when La Algaida was but an isle in the course of the lower Guadalquivir River and, therefore, was embraced by two branches of the river (Rodríguez-Ramírez et al., 1996). A complex tidal delta would cause the river beds to migrate cyclically, in a way similar to the dynamics which animates most other estuaries in the Gulf of Cadiz (Morales et al., 2006). Although tsunamis as well as storm surges may have eroded the boundaries of the isle, it is such periodic migration of the river branches which chiefly explains the erosive morphology that one finds in La Algaida (Fig. 6). In other words, marine events are not enough of a cause to account for all of the paleocliffs and incisions in La Algaida; the geographical and geodynamic context must be factored in as well. By way of illustration of the importance of this context, suffice it to say that the present-day dynamics of the Guadalquivir River is causing a large erosional scarp in the Doñana spit (Fig. 4).

Associated with these scarps and included in the sedimentary sequence of many littoral strands, in the present as well as from the past, are striking accumulations of pebbles, some of them large enough to be regarded as true beaches made of coarse gravel deposits. The presence of these formations in La Algaida has been interpreted as unequivocal signs of one or more of the alleged tsunamis of 218 to 209 BC (Rodríguez-Vidal et al., 2011). Yet these formations are commonplace in the study area. Some of them are even active at present; e.g., in the intertidal zone of the present-day mouth of the Guadalquivir River, where an increasingly extensive littoral platform bearing on rocky outcrops from the Pleistocene produces numerous pebbles and shells in the thunderstorm season, which are thereafter carried to the beaches and result in spectacular ridges made of loose coarse gravel deposits (Fig. 7). Indeed, these formations are far more related to storms than to any other kind of natural occurrence; they cannot be attributed to any specific tsunami.

As far as sedimentology is concerned, EWEs are known to feed a great sedimentary load to the inner estuary that includes significant amounts of fauna and a sandy facies (Fujiwara et al., 2000). Chronological evidence from archaeological remains as well as shell samples in the analyzed sedimentary formation (BT) indicates an EWE that took place in the 2nd or 3rd century AD. Similar formations have been studied in the Tinto-

Odiel estuary, north of the Guadalquivir estuary, in connection with tsunamis (Morales et al., 2008). Subsequent dynamics gradually built up the detrital deposits in the form of beach ridges lying over the fluvial levees, as in cheniers, which resulted in intense reworking and migration toward the hinterland (Narayana et al., 2007; Rodríguez-Ramírez and Yáñez, 2008).

As many as eight dates have been obtained from chenier LV of Las Nuevas (Rodríguez-Ramírez et al., 1996; Dabrio et al., 1999a; Ruiz et al., 2004; Rodríguez-Ramírez and Yáñez, 2008). Leaving aside the oldest determinations because of reworking of the samples, analysis of the reliable dates suggests the period from the 2nd to the 4th century AD as development for this chenier, the accumulation cresting about the 3rd century AD. Although some researchers (Rodríguez-Vidal et al., 2011; Ruiz et al., 2013) have attempted to relate this chenier also to one or more of the alleged tsunamis of 218 to 209 BC (so weakly anchored in historical evidence) they have failed to consider the whole panoply of dates that are available from protracted work in the area, which point to an EWE in the 3rd century AD or thereabouts instead. Insofar as this type of formation has been subject to much reworking, it is absolutely impossible to identify traces of some events in the sedimentary sequence (Rodríguez-Ramírez and Yáñez, 2008; Rodríguez-Ramírez, 2009).

The various levees and cheniers in the paleoestuary are also subject to erosive processes and even ruptures that result in crevasse splays by either storm surges or tsunamis, or fluvial flooding or high tides, or by a combination thereof. Similar processes have been identified in the Mississippi delta during tropical hurricanes (Cahoon et al., 2011). The chenier system of Las Nuevas shows the marks of two significant ruptures and their associated crevasse splays. Located in the front of the formation, where the waves hit most violently, these crevasse splays date from at least two periods: the 4th to 3rd century BC (crevasse splay A) and the 2nd to 3rd century AD (crevasse splay B) (Fig. 5).

The geomorphological and sedimentary evidence for the Guadalquivir estuary in the Roman period calls for a model of evolution punctuated by successive small EWEs, possibly storm surges, and disrupted by a considerably larger event, likely a tsunami, in the 2nd-3rd century AD.

6.2. The archaeological evidence

The record at archaeological sites on the coasts of the Gulf of Cadiz registers a turning point from the late 2nd to the middle 3rd century AD: the number of structures and the production and use of pottery vessels, including amphorae, declined dramatically at that time (Alonso et al., 2004, 2015; Campos et al., 2015). A downturn in economic activity between the late 2nd and the early 3rd century AD has been inferred for the remains found at the Roman site of Cerro del Trigo (Campos et al., 2002). Yet the record at the country houses and pottery workshops (*villae* and *figlinae*) in the hinterland registers no such turning point (Vidal and Campos, 2008; Campos, 2011), which suggests that the downturn was confined to littoral areas. It is rather telling in this regard that archaeologist G. Bonsor, who excavated at Cerro del Trigo in the early 1920s, hypothesized (1928) that the collapse and destruction of structures from the Roman imperial period that he had recognized at the site would have been caused by an earthquake. Likewise, the site of Bolonia (Roman *Baelo Claudia*), some 10 km north of the Strait of Gibraltar, upon the seashore of the province of Cadiz, registers a stratigraphic break represented by the collapse and subsequent sealing of structures from the Roman imperial period; for which development has been attributed to a seismic event that occurred sometime in the second half of the 2nd century AD (Alonso et al., 2004) or in the 3rd century AD (Sillières, 2006). It was not until the middle 4th century AD at the earliest that *Baelo Claudia* saw fresh urban developments (Sillières, 1995). The site of Bolonia stands out as one of the best studied ever in the history of archaeology in Spain. Previous earthquakes and possible tsunamis have been hypothesized for this area in the middle 1st century AD (Sillières, 1995; Alonso et al., 2004; Silva et al., 2005).

Comparable evidence of destruction has been identified at the site of Munigua (Roman *Mulva*), near Villanueva del Río, in the province of Seville (Sillières, 1995). Much the same is true regarding the record in the estuary of the Sado River, in southwestern Portugal; amphorae ceased to be made there in the 3rd century AD (Mayet and Tavares, 2002; Fabião, 2008).

These are probable instances of the cause-and-effect relationship between tsunamis and temporary abandonment of settlements hit by them. The relationship, by way of the wanton destruction of infrastructure and the high anxiety among the population that a tsunami brings about, is well known (Kremer et al., 2014). In effect, the solutions of continuity registered in the stratigraphy of the sites mentioned are congruous with the occurrence of some kind of extremely violent event in the Gulf of Cadiz in the time span from the late 2nd to the middle 3rd century AD that the data presented herein suggest. As waves generated by cyclonic phenomena do not seem to be destructive enough to result in such breaks in the archaeological record, a tsunamigenic process appears to be far more likely instead.

It may not be coincidental in this regard that Roman author Rufius F. Avienus, in his poem *Ora maritima* (1959), reported having seen clear evidence of widespread natural destruction in the city of Cadiz when he paid this city a visit in the middle 4th century AD: "*multa et opulens civitas aevo vetusto, nunc egena, nunc brevis, nunc destituta, nunc ruinarum agger est…*" ("a large, prosperous city in times past, it is nowadays impoverished, small, disfranchised, lying in ruins"). Although further research is necessary to ascertain it, one may well surmise that what Avieno saw was nothing but the devastation caused by the large tsunami in the Gulf of Cadiz in about the 3rd century AD that hit at least *Baelo Claudia* and Cerro del Trigo.

6.3. A paleogeographical approach

6.3.1. The inception of the progradation of the coast

The earliest commonly accepted reference to the mouth of the Guadalquivir River that has come down to us from Antiquity was written by the Greek geographer and ethnologist Strabo of Amasia around the beginning of the Christian era. Drawing from Greek authors who had been to southern Iberia, mostly in the 2nd and 1st centuries BC, Strabo wrote in Book III, Chapter 1 of his encyclopedic *Geographiká* (1966) that the Guadalquivir River, known as *Baetis* in Roman times, emptied itself into the Atlantic Ocean by means of two mouths. In the middle of the 1st century AD, the geographer Pomponius Mela of Tingentera, a native to southern Iberia, also wrote, in his *De chorographia* (1987: 8), that the *Baetis* River reached the sea in the form of two large streams, which flowed from a large lake that stood not far from the ocean. The geological evidence presented in this paper indicates that the estuary of the

Guadalquivir River bifurcated into two inlet channels until the 1st century AD. The main, larger channel would cover the distance between La Algaida and the Doñana spit; the smaller one would run between La Algaida and the hills of Sanlúcar de Barrameda (Fig. 8A). La Algaida, therefore, would have been an isle in that period, lying between the two channels. By way of both channels the fluvial current as well as the tidal flows would put the open sea in connection with *Lacus Ligustinus*, the lake referred to by Mela of Tingentera and so called by Avienus, doubtless a coastal lagoon (Fig. 8A). The evidence of the dynamics at work in such channels is, on the one side (that of the Doñana spit), the littoral strands of Vetalengua (V1) and, on the other side (that of La Algaida), the strands of Los Prados (LP).

The powerful hold of the drift currents, the extensive mesotidal range, and a fluvial current that depends upon wide seasonal fluctuations, all shaped a system of flood and ebb tidal deltas which resulted in river beds that were shifting and unstable (Fig. 8A). These environmental conditions in the Guadalquivir estuary have also governed other large estuaries in the Gulf of Cadiz in the course of the Holocene (Morales et al., 2001; 2006; Rodríguez-Ramírez et al., 2008). The dynamics of the deltaic systems in these estuaries is responsible for the periodic migration of the beds of the rivers. One especially clear illustration of such dynamics is La Algaida itself, where it has generated erosional scarps or paleocliffs (Fig. 6). Intense prograding processes would have begun before the 1st century BC.

From time to time the coastal progradation had to cope with storm surges, which generated washover fans in the Doñana spit in the 1st century BC and, before then, crevasse-splay developments in the levees of the inner side of the estuary in the 4th-3rd centuries BC (Figs. 2, 8A). Scant sedimentary evidence in the paleoestuary from these pre-Roman and early Roman periods leads us to consider that the deltaic systems limited the sedimentary contributions of the open sea to the inner estuary. The violent storms in the area in the wintertime and the numerous rocky pebbles available throughout explain the substantial presence of these pebbles in the littoral strands.

It was against this paleogeographical setting that a Roman settlement was established in the isle of La Algaida, at the site of El Tesorillo (Blanco and Corzo, 1982; Corzo, 1984). The place chosen for the settlement was the northernmost sector of the isle (Figs.

1, 8A), possibly because this location had easy access to the western mouth of the Baetis River—wider, deeper, and more stable than the eastern mouth—and also because the place was on the leeward side of the isle, which would shelter the inhabitants from the storm surges of the wintertime.

6.3.2. Intense progradation from the 1st century BC to the 2nd century AD

Coastal progradation would proceed, even more rapidly, after the 1st century BC. This acceleration may have resulted from either the slowing down or cessation of subsidence processes in the area from then on (Rodríguez-Ramírez et al., 2014) or the erosive consequences in the mainland of deforestation and agriculture over the past two millennia, or both. A comparable development of accelerated infilling of estuaries, wetlands, and lagoons has been recognized for the Mediterranean coasts of Iberia since Roman imperial times; this development was triggered by human encroachment upon the environment (Carmona and Pérez, 2011). Whatever the weight of their respective influence may have been, the combined effect of these processes was the beginning of the formation of successive littoral strands in Doñana and La Algaida and the inception of the closing of both the eastern channel of the river and the Vetalengua channel. Inside the estuary, the fluvial levees as well as chenier LV of Las Nuevas grew larger (Fig. 8B). The shelly chenier of Las Nuevas is the clearest sign that the estuary started to become progressively isolated from the sea as the growth of sandy coastal barriers caused ever lesser marine sedimentation to reach into the estuary (Rodríguez-Ramírez and Yáñez, 2008).

The formation of successive littoral strands in the two spits within the course of the 1st century BC onto the 2nd century AD generated a sequence therein of ridges and swales as well as a slight aeolian development. The Doñana spit grew some 5 km toward the SE. East of La Algaida, the channel that separated the isle from the mainland finally closed, which made the access of the nearby city of Ebora to the open sea difficult (Fig. 8B). A tombolo now connected the isle with the mainland north of Sanlúcar de Barrameda. West of La Algaida, the remaining inlet channel of the *Baetis* River moved further west and there narrowed considerably, inviting sustained infilling around La Algaida. This development may have brought about the premature abandonment of the settlement of El Tesorillo, its residents then moving to the settlement of Cerro del Trigo.

It is known that occupation there started in the middle 2nd century AD (Campos et al., 2002). Cerro del Trigo had easy access to the remaining channel of the river and, therefore, to the open sea; furthermore, as the site stands on the leeward side of the sandy barrier of Doñana it can avoid the wintertime storms coming from the west.

Such process of coastal progradation from the 1st century BC to the 2nd century AD would be the local manifestation in the Guadalquivir estuary of the H5 progradation phase defined by Zazo et al. (2008) for the Gulf of Cadiz.

6.3.3. The EWE of the 2nd-3rd century AD

The progradational process was interrupted by an EWE in the 2nd-3rd century AD. The geomorphological and sedimentary manifestations of this event are a significant erosive scar on the oldest littoral strands in Doñana spit and on the washover fans that had developed on the spit (Fig. 8C). In addition, the event left a striking sedimentary lag in the estuary containing abundant shells (Fig. 2). These are facies that closely resemble facies in the Tinto-Odiel estuary that have been recognized as signs of tsunamis (Morales et al., 2008). Furthermore, accumulation in the chenier of Las Nuevas crested between the 2nd and the 4th century AD, especially in the 3rd century AD; a development which can be explained as the result of the reworking and subsequent build-up of the basal residual lag in the estuary that the event had originated. Despite such geomorphological and sedimentary effects, however, the event failed to break through, by means of inlets, the Doñana spit as well as the tombolo that linked the mainland to La Algaida, thereby limiting the sedimentary contribution of the open sea. By contrast, some 2,250 years earlier, when the estuary was wider and the spits less developed, an EWE of comparable energy had destroyed such coastal barriers and pushed the sea several kilometers into the inner estuary, dragging with it large amounts of sand and marine fauna (Rodríguez-Ramírez et al., 2015).

These geomorphological and sedimentary characteristics, in the light of convergent yet independent evidence such as the chronological correlation of the event with comparable events elsewhere in the Gulf of Cadiz and the hiatuses in the archaeological record identified at a number of sites from the late 2nd century to the 3rd century AD

(Sillères, 1995, 2006; Campos et al., 2002), make us submit that this event was a tsunami.

6.3.4. The continuous progradation from the c. 3rd to the 6th centuries AD

Coastal progradation and estuary infilling processes resumed upon such EWE of the 2nd-3rd century AD, confining the estuary to a smaller area as a result (Fig. 8D). The first littoral strands after the EWE started to form immediately. They had ridges and swales clearly marked in them, while favoring substantial aeolian developments which have continued up to the present. The west, or remaining, inlet channel of the Guadalquivir River narrowed considerably as it migrated toward the south, away from the settlement by Cerro del Trigo. The onset of this progradation phase would be the same as that of Phase H6 for the Gulf of Cadiz as defined by Zazo et al. (2008). Although these researchers have attributed this morphological change to a shift in the patterns of the climate in the region, the new data presented here point to the effects of a EWE instead. As the successive phases of progradation identified in the sandy barriers of the nearby Guadalete estuary (Alonso et al., 2015) can be explained in the same manner, it can be inferred that successive morphological changes of first order brought about by coastal progradation in the Gulf of Cadiz during the Holocene were a direct consequence of events of very high energy rather than of climate changes. In contrast, second-order alterations in the barriers such as the generation of gaps can be attributed to storm surges and, therefore, to climate-related variables.

In the long run, the progradation in the Doñana littoral and the infilling of the Guadalquivir estuary would be detrimental to the fishing-and-salting industry of Cerro del Trigo insofar as both developments made commercial navigation to and from the sea increasingly difficult. In effect, the beginning of an economic decline has been recognized at this site for the 5th century AD. The decline turned into a complete halt and final abandonment of the settlement in the 6th century AD (Campos et al., 2002). An additional materialization of the new morphological conditions, specifically the gradual confinement of the estuary, are the shelly cheniers of Vetalengua (VL2) and Las Nuevas (PB) marking the progressive advance of the fluvial levees (Fig. 8D). Concerning La Algaida, this spit became ever more isolated from marine influence, as the Guadalquivir River moved its course farther and farther away from the west banks of the former isle and left marshes in its place. Eventually, successive trains of dunes would arrive in from the west, impinging upon such marshes and burying the abandoned settlements of Cerro del Trigo as well as La Algaida. Simultaneously, the evolution of the river and the gradual infilling of the estuary would turn *Lacus Ligustinus* into a tidal marsh and subsequently into a freshwater marsh.

7. Conclusions

The combined analyses of geology, archaeology, and history are necessarily called for in any scientific attempt to determine past geographies and environmental changes in areas with a rich history and a substantial archaeological record, such as the Guadalquivir estuary.

The chronology of tsunamis in the Gulf of Cadiz during the Roman period that Galbis-Rodríguez established (1932-1940) rests on feeble foundations and, therefore, should no longer be used for any scientifically rigorous paleogeographical project. Instead, evidence of tsunamis over such a period ought to be sought by means of geological probing and assays, archaeological investigations, and rigorous consideration of the written sources handed down from Antiquity.

The geological record of the Guadalquivir estuary presents a wide spectrum of geomorphological and sedimentary developments in connection with EWEs: washover fans, paleocliffs or erosional scarps, coarse gravel deposits, crevasse splays, and sedimentary lags of sand and shells. In trying to fathom the genesis of each and every one of these developments, researchers should adopt a holistic vision of the paleography of the estuary as well as of the various geodynamic processes involved in it.

Such geomorphological and sedimentary evidence is consistent with a model of evolution that includes periodic small EWEs—possibly storm surges—during the 4^{th} and 3^{rd} centuries BC and the 1st century BC, on the one hand, and a considerably larger event—likely a tsunami—in the 2^{nd}-3^{rd} century AD, on the other hand. The geomorphological and sedimentary data analyzed are persuasive enough in this regard. Furthermore, the effects of the larger event were considerable: formation of an erosional surface and washover fans in the spits, and a crevasse splay and sedimentary lags in the estuary. This event, however, neither resulted in inlet channels in the Doñana spit nor ruptured the tombolo that connected La Algaida with the mainland. This succession of EWEs (storms surges and tsunamis) would be the cause of the clearly marked alternation between ridges and swales that one can observe in the various littoral spits of the Gulf of Cadiz.

From a regional perspective, the 2nd-3rd century AD EWE caused the end of 'Progradation Phase' H5 and prepared the ground for 'Progradation Phase' H6. The impact of this event in the Gulf of Cadiz was so extensive that its material signs can be chronologically correlated with comparable marks left in other estuaries of the Gulf that have been interpreted as evidence of a tsunami. This event can also explain the hiatus remarked upon in the archaeological record of Cerro del Trigo for the 2nd or 3rd century AD and the evidence of seismic destruction at Bolonia (Roman *Baelo Claudia*) and Munigua (Roman *Mulva*) somewhere between the 2nd and the 3rd century AD. Radiocarbon dating, geomorphological analysis, and historical references fail to support the so-called '218-209 BC' Atlantic tsunami in the Guadalquivir estuary, as hypothesized in the received literature.

The different geodynamic processes at work in the mouth of the Guadalquivir River and its vicinity conditioned to a large extent the peopling of the area. The settling communities in the spits always sought a rapid, dependable communication with the sea, preferably through the main inlet channel of the river, the west one. In addition, they were careful not to expose the settlement to EWEs, which necessarily meant settling on the leeward side. The slow and punctuated, yet unremitting growth of the sandy barriers and the infilling of the estuary were to result eventually in the gradual abandonment of the places that they chose.

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Figure captions

Figure 1. Study area and location of cores with dates. The Spanish local term 'caño' refers to a relict, fully filled-in tidal-fluvial channel.

Figure 2. Lithostratigraphy and paleontology of sedimentary sequence. Morphostratigraphic and geomorphological outline of Doñana spit and Guadalquivir estuary.

Figure 3. Graphical representation of dated samples (radiocarbon calibrated dataset) with respect to EWE. Rectangles indicate ^{14}C calibrated ages (cal.) with 2σ uncertainty.

Figure 4. Geomorphological elements of Doñana spit and chenier systems of Vetalengua (Left: aerial photograph of 1956; right: satellite images of 2012 commissioned by the regional government of Andalusia, Spain).

Figure 5. Oblique aerial view of chenier systems of Las Nuevas (2012 satellite image by Junta de Andalucía).

Figure 6. Evolution of ebb-tidal delta and inlet channels in Guadalquivir mouth in relation to erosional incisions in La Algaida spit.

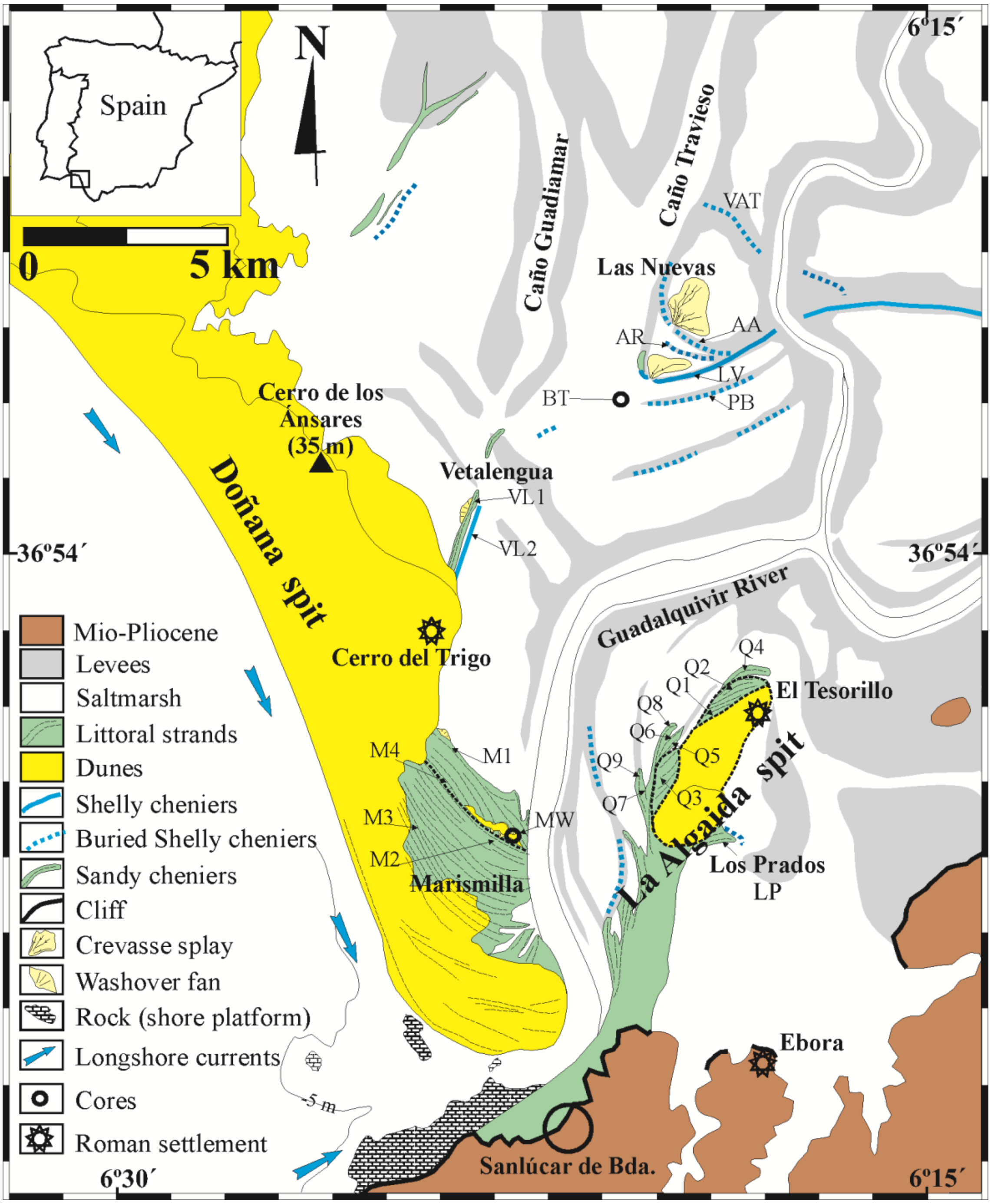
Figure 7. Present-day beach with coarse gravel deposit in Sanlúcar de Barrameda.

Figure 8. Paleogeographical approach of the Guadalquivir mouth in Roman times.

Table captions

Table 1.- Database of ^{14}C results after using the Marine13 curve (Reimer et al., 2013) and the program CALIB rev. 7.0 (Stuiver and Reimer, 1993). B.- Beta Analytic Laboratory (Miami, USA). CNA.- Centro Nacional de Aceleradores (Seville, Spain). DAMS.- Accium BioSciences Accelerator Mass Spectrometry Lab (Seattle, USA). GX.- Geochron Laboratories, Krueger Enterprises, Inc., (Cambridge, USA). R.- Centro

di Studio per il Quaternario e I'Evoluzione Ambientale de1 CNR-Dipartimento Science della Terra, Università La Sapienza (Rome, Italy). ([a])Rodríguez-Ramírez et al., 1996. ([b])Rodríguez-Ramírez and Yáñez, 2008. ([c])Dabrio et al., 1999a. ([d])Ruiz et al., 2004. In boldface, dates determined for the present paper.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Caño Guadiamar
Caño Travieso
VAT
Las Nuevas
AR
AA
LV
BT
PB
Cerro de los
Ánsares
(35 m)
Doñana spit
Vetalengua
VL1
VL2
36º54´
36º54´
Guadalquivir River
Cerro del Trigo
Q4
Q2
Q1
El Tesorillo
Q8
Q6
Q9
Q5
Q7
Q3
La Algaida spit
Los Prados
LP
M4
M1
M3
MW
M2
Marismilla
Ebora
-5 m
Sanlúcar de Bda.
6º30´
6º15´
Mio-Pliocene
Levees
Saltmarsh
Littoral strands
Dunes
Shelly cheniers
Buried Shelly cheniers
Sandy cheniers
Cliff
Crevasse splay
Washover fan
Rock (shore platform)
Longshore currents
Cores
Roman settlement

Figure 1

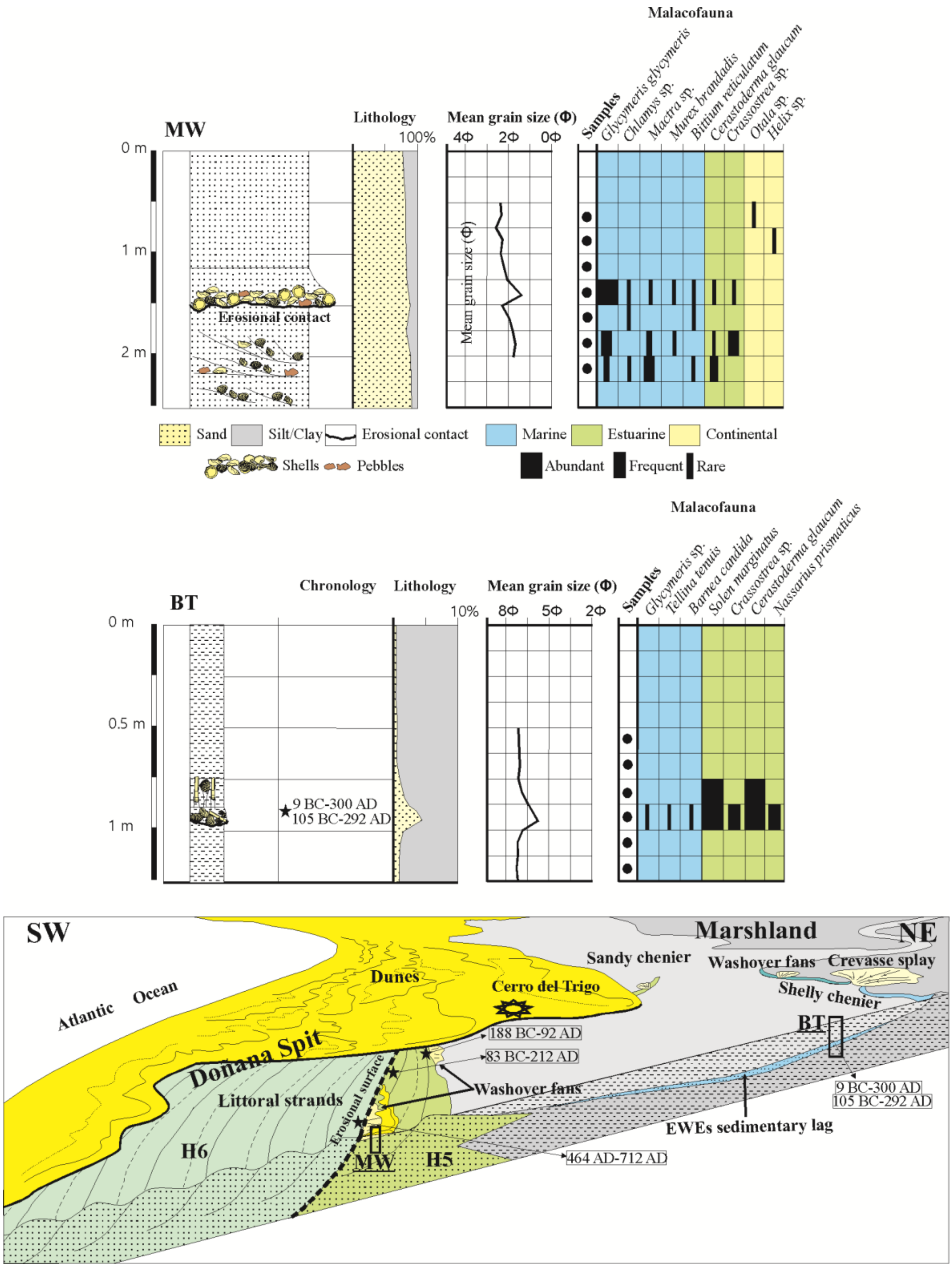

MW
Lithology
Mean grain size (Φ)
Malacofauna
Samples
Glycymeris glycymeris
Chlamys sp.
Mactra sp.
Murex brandadis
Bittium reticulatum
Cerastoderma glaucum
Crassostrea sp.
Otala sp.
Helix sp.
0 m
1 m
2 m
100%
4Φ
2Φ
0Φ
Erosional contact
Mean grain size (Φ)
Sand
Silt/Clay
Erosional contact
Marine
Estuarine
Continental
Shells
Pebbles
Abundant
Frequent
Rare
BT
Chronology
Lithology
Mean grain size (Φ)
Malacofauna
Samples
Glycymeris sp.
Tellina tenuis
Barnea candida
Solen marginatus
Crassostrea sp.
Cerastoderma glaucum
Nassarius prismaticus
0 m
0.5 m
1 m
10%
8Φ
5Φ
2Φ
9 BC-300 AD
105 BC-292 AD
SW
NE
Marshland
Atlantic Ocean
Dunes
Cerro del Trigo
Sandy chenier
Washover fans
Crevasse splay
Shelly chenier
Donana Spit
Littoral strands
Erosional surface
188 BC-92 AD
83 BC-212 AD
Washover fans
BT
9 BC-300 AD
105 BC-292 AD
EWEs sedimentary lag
H6
MW
H5
464 AD-712 AD

Figure 2

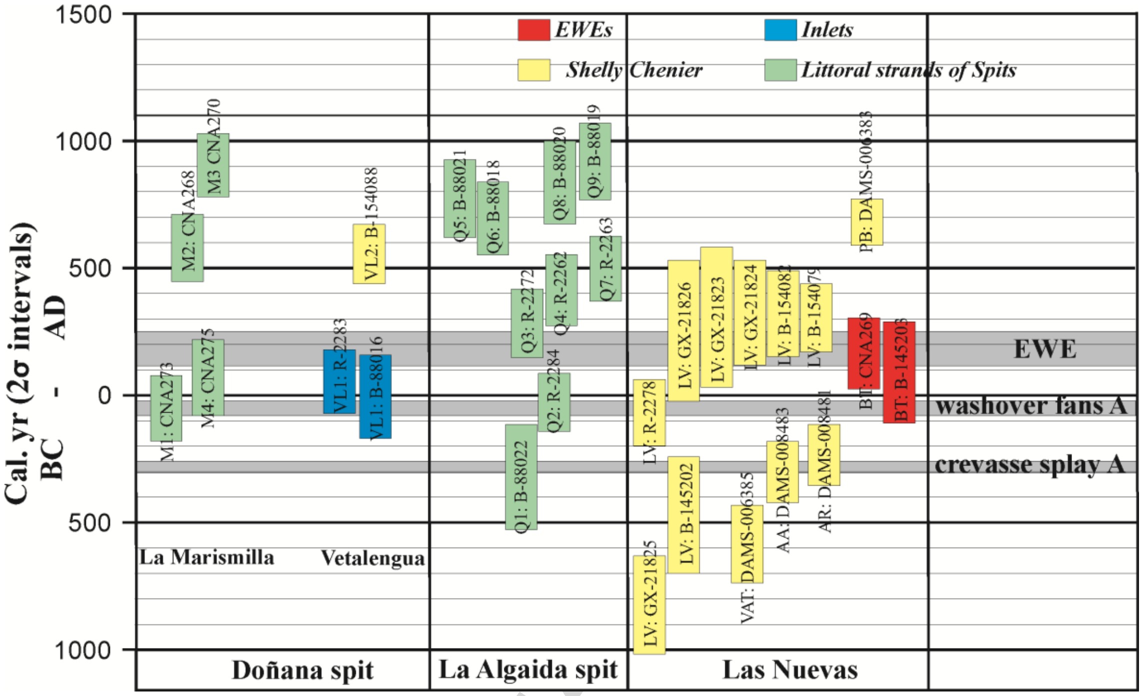

EWEs
Inlets
Shelly Chenier
Littoral strands of Spits
Cal. yr (2σ intervals)
BC - AD
1500
1000
500
0
500
1000
M1: CNA273
M2: CNA268
M3 CNA270
M4: CNA275
VL1: R-2283
VL1: B-88016
VL2: B-154088
Q1: B-88022
Q2: R-2284
Q3: R-2272
Q4: R-2262
Q5: B-88021
Q6: B-88018
Q7: R-2263
Q8: B-88020
Q9: B-88019
LV: R-2278
LV: GX-21825
LV: GX-21826
LV: GX-21823
LV: GX-21824
LV: B-154082
LV: B-154079
LV: B-145202
VAT: DAMS-006385
AA: DAMS-008483
AR: DAMS-008481
PB: DAMS-006383
BT: CNA269
BT: B-145203
EWE
washover fans A
crevasse splay A
La Marismilla
Vetalengua
Doñana spit
La Algaida spit
Las Nuevas

Figure 3

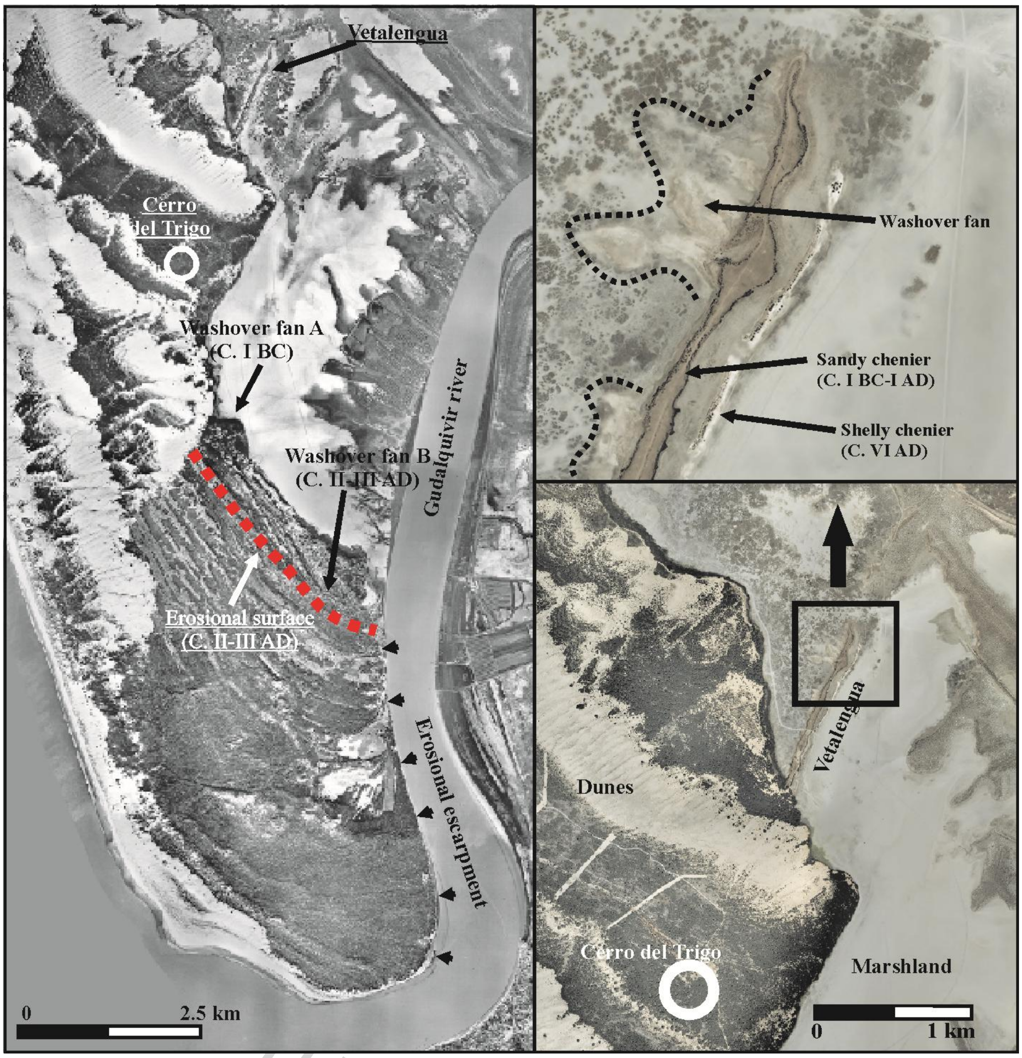

Vetalengua
Cerro
del Trigo
Washover fan A
(C. I BC)
Washover fan B
(C. II-III AD)
Gudalquivir river
Erosional surface
(C. II-III AD)
Erosional escarpment
0
2.5 km
Washover fan
Sandy chenier
(C. I BC-I AD)
Shelly chenier
(C. VI AD)
Dunes
Vetalengua
Cerro del Trigo
Marshland
0
1 km

Figure 4

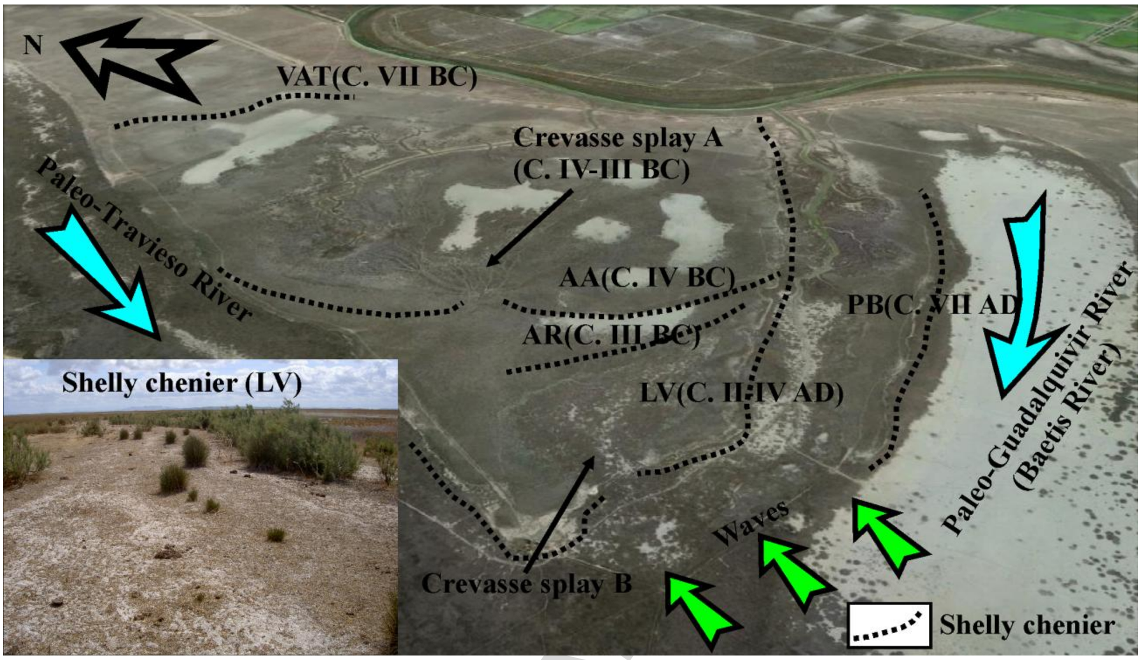

N
VAT(C. VII BC)
Crevasse splay A
(C. IV-III BC)
Paleo-Travieso River
AA(C. IV BC)
AR(C. III BC)
PB(C. VII AD)
Paleo-Guadalquivir River
(Baetis River)
Shelly chenier (LV)
LV(C. II-IV AD)
Waves
Crevasse splay B
Shelly chenier

Figure 5

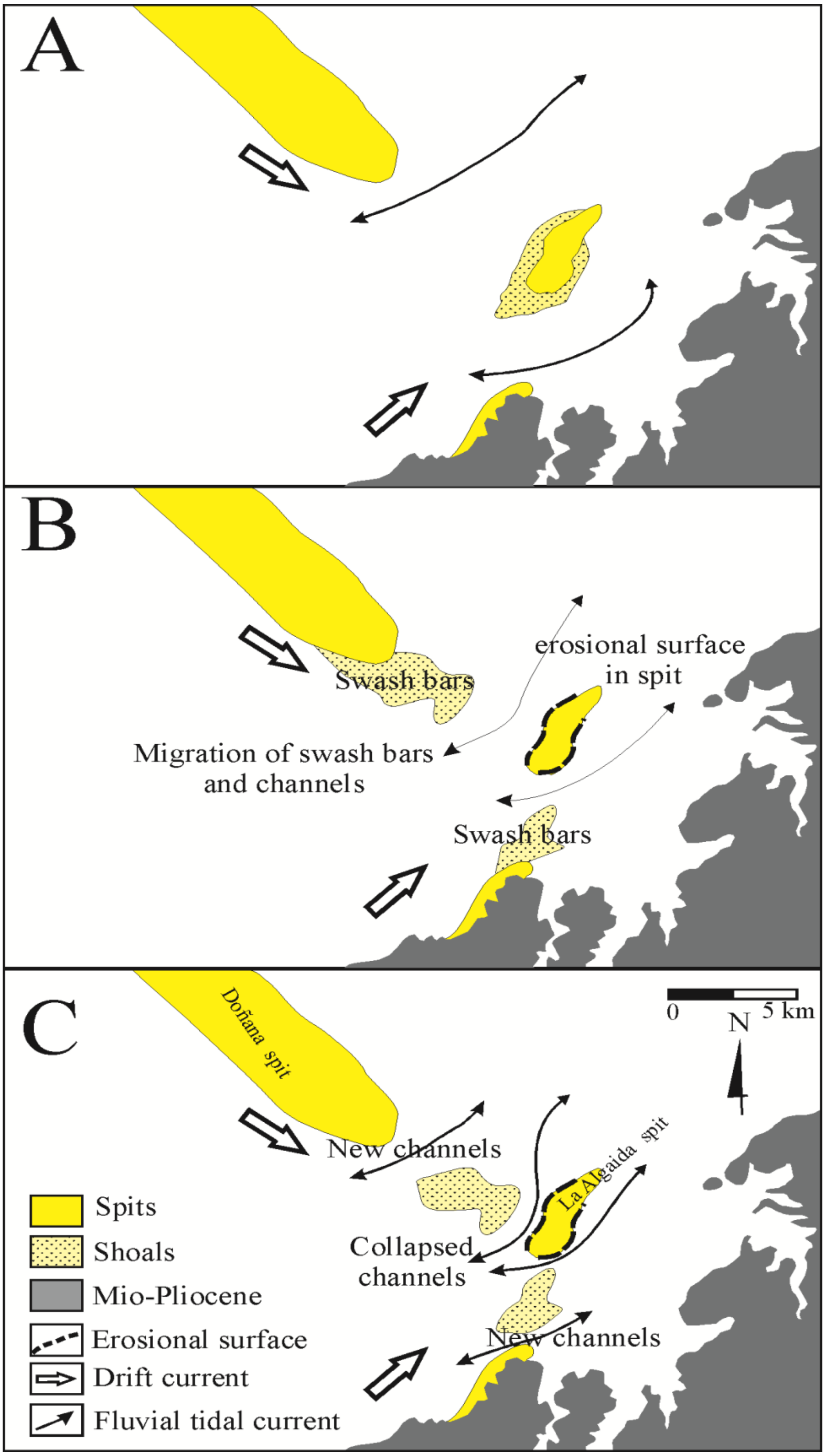
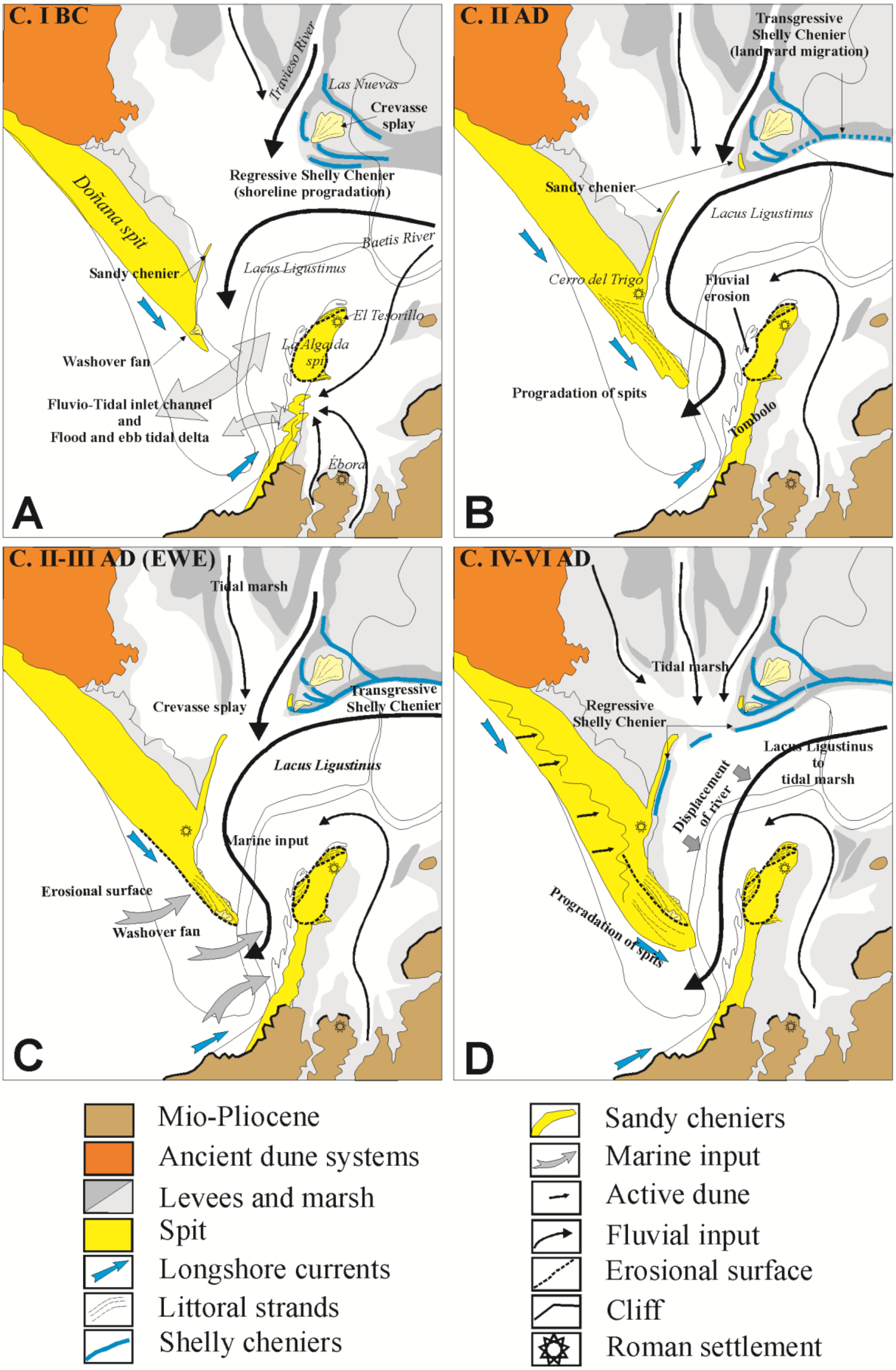

A
B
erosional surface
in spit
Swash bars
Migration of swash bars
and channels
Swash bars
C
Doñana spit
0
5 km
N
New channels
La Algaida spit
Collapsed
channels
New channels
Spits
Shoals
Mio-Pliocene
Erosional surface
Drift current
Fluvial tidal current

Figure 6

Figure 7

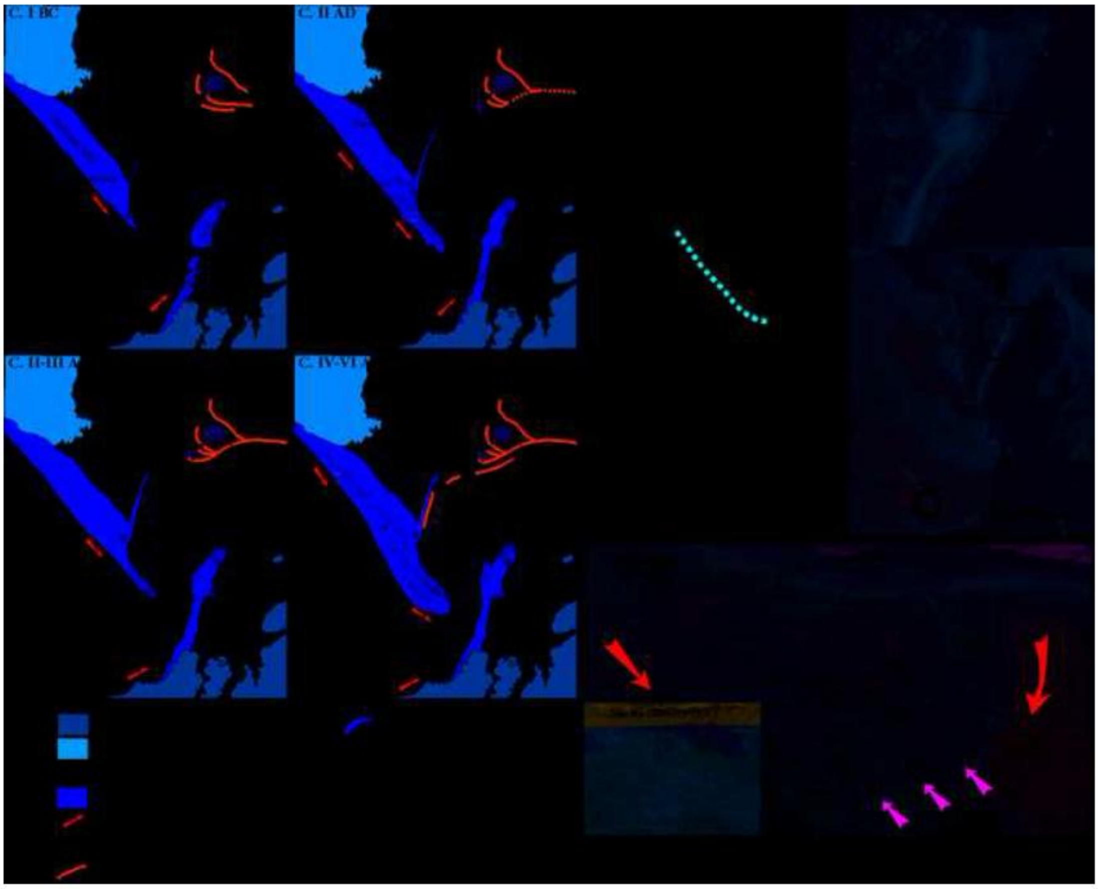


C. I BC
Travieso River
Las Nuevas
Crevasse splay
Regressive Shelly Chenier (shoreline progradation)
Doñana spit
Baetis River
Lacus Ligustinus
Sandy chenier
El Tesorillo
La Algaida spit
Washover fan
Fluvio-Tidal inlet channel and Flood and ebb tidal delta
Ébora
A
C. II AD
Transgressive Shelly Chenier (landward migration)
Sandy chenier
Lacus Ligustinus
Cerro del Trigo
Fluvial erosion
Progradation of spits
Tombolo
B
C. II-III AD (EWE)
Tidal marsh
Crevasse splay
Transgressive Shelly Chenier
Lacus Ligustinus
Marine input
Erosional surface
Washover fan
C
C. IV-VI AD
Tidal marsh
Regressive Shelly Chenier
Lacus Ligustinus to tidal marsh
Displacement of river
Progradation of spits
D
Mio-Pliocene
Ancient dune systems
Levees and marsh
Spit
Longshore currents
Littoral strands
Shelly cheniers
Sandy cheniers
Marine input
Active dune
Fluvial input
Erosional surface
Cliff
Roman settlement

Figure 8

Core location	Lab. Ref.	Depth (m)	Sample (shells)	^{14}C age (BP)	δ^{13}C‰	^{14}C cal yr 2σ (BC-AD)
			Doñana spit			
M1	**CNA273**	**-0.5**	***Glycimeris* sp.**	**2260±45**	**-1.15**	**188 BC - 92 AD**
M2	**CNA268**	**-1**	***Glycimeris* sp.**	**1680±50**	**0.07**	**464 AD - 712 AD**
M3	**CNA270**	**-1.5**	***Glycimeris* sp.**	**1375±45**	**1.79**	**785 AD - 1030 AD**
M4	**CNA275**	**-1**	***Glycimeris* sp.**	**2170±45**	**2.48**	**83 BC - 212 AD**
VL1(a)	R-2283	-0.8	*Cerastoderma* sp	2171±36	--	73 BC - 188 AD
VL1(a)	B-88016	-0.25	*Glycimeris* sp.	2230±60	--	187 BC - 152 AD
VL2(b)	B-154088	-0.40	*Cerastoderma* sp.	1710±50	-0.2	444 AD - 686 AD
			La Algaida spit			
Q1(a)	B-88022	-0.6	*Glycimeris* sp.	2487±70	--	534 BC - 107 BC
Q2(a)	R-2284	-0.5	*Glycimeris* sp.	2233±29	--	142 BC - 96 AD
Q3(a)	R-2272	-0.8	*Glycimeris* sp.	1972±40	--	167 AD - 419 AD
Q4(a)	R-2262	-0.4	*Cerastoderma* sp.	1865±35	--	288 AD - 551 AD
Q5(a)	B-88021	-0.3	*Glycimeris* sp.	1530±70	--	613 AD - 936 AD
Q6(a)	B-88018	-0.3	*Cerastoderma* sp.	1600±60	--	551 AD - 840 AD
Q7(a)	R-2263	-0.25	*Cerastoderma* sp.	1800±40	--	378 AD - 621 AD
Q8(a)	R-88020	-0.4	*Cerastoderma* sp.	1450±70	--	685 AD - 1000 AD
Q9(a)	B-88019	-0.2	*Cerastoderma* sp.	1340±60	--	780 AD - 1091 AD
			Las Nuevas			
VAT	**DAMS-006385**	**-0.5**	***Cerastoderma* sp.**	**2691±30**	**-6.1**	**742 BC - 438 BC**
AA	**DAMS-008483**	**-0.5**	***Cerastoderma* sp.**	**2494±23**	**-2.1**	**413 BC - 196 BC**
AR	**DAMS-008481**	**-0.5**	***Cerastoderma* sp.**	**2404±27**	**0.8**	**351 BC - 113 BC**
PB	**DAMS-006383**	**-0.4**	***Cerastoderma* sp.**	**1612±32**	**-9.5**	**592 AD – 773 AD**
LV(a)	R-2278	-0.4	*Glycimeris* sp.	2284±39	--	200 BC - 69 AD
LV(c)	GX-21825	0	Mollusc sp.	2895±75	0.3	1045 BC - 625 AD
LV(c)	GX-21826	0	Mollusc sp.	2010±110	0.1	15 BC - 533 AD
LV(b)	B-145202	-0.4	*Solen* sp.	2570±70	-1.5	699 BC - 227 BC
LV(c)	GX-21823	0	Mollusc sp.	1960±120	0.2	27 AD - 597 AD
LV(c)	GX-21824	-0.5	Mollusc sp.	1955±80	-1.3	109 AD - 530 AD
LV(d)	B-154082	-0.3	*Cerastoderma* sp.	1940±60	-0.8	146 AD – 492 AD
LV(d)	B-154079	-0.9	*Cerastoderma* sp.	1960±40	-0.9	169 AD - 429 AD
BT(d)	B-145203	-0.9	*Solen sp.*	2140±70	-2.0	105 BC – 292 AD
BT	**CNA269**	**-0.9**	***Cerastoderma* sp.**	**2100±50**	**-1.27**	**9 BC - 300 AD**

Graphical abstract



Highlights

- The Guadalquivir estuary is the end product of a complex geological evolution.
- A wide range of geomorphological and sedimentary developments are EWE-related.
- Geological and archaeological evidence calls for a tsunami around 2nd-3rd c. AD.
- There is no historical evidence for a large tsunami between 218 and 209 BC.
- A multidisciplinary approach is especially apt for archaeologically-rich areas.