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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 BCE to 476 CE). The largest event occurred in the 2nd–3rd century CE. 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 CE 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 Radiocarbon dating, geomorphological analysis, and historical references fail to warrant the so-called '218–209 BCE' Atlantic tsunami, as hypothesized in the received scientific literature.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.

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 neotectonic 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

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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., 2013). 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 BCE and 1900 CE (Campos, 1991), four of which dating to the years 218–216 BCE, 210–209 BCE, 60 BCE, and 382 CE, 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 São 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 CE (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 BCE to the 4th century CE (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, semidiurnal.

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