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Atlantic extreme wave events during the last four millennia in the Guadalquivir estuary, SW Spain

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ABSTRACT

A multidisciplinary study from a number of drilled cores in the Guadalquivir estuary has made possible to identify as many as three extreme wave events and their facies in the 4th millennium BP (A: ~4000 cal yr BP, B: ~3550 cal yr BP, and C: ~3150 cal yr BP). These events, which caused strong erosion in the Guadalquivir sandy barrier and in the neighboring aeolian systems of El Abalario, brought about significant paleogeographical changes that may have affected human settlements established in the area during the Neolithic and Copper Age periods and during the Middle Bronze Age. The three events can be spatially correlated and their facies differentiated from more proximal to more distal from the coastline. The most proximal facies is characterized by a massive accumulation of shells, a sandy or sandy–muddy matrix, an erosive base, a highly diverse mixture of species (marine and estuarine), and lithoclasts. The most distal facies presents a muddy–sandy matrix, dominance of estuarine fauna, shell accumulation, presence of terrestrial species, mudpebbles, pebbles in a clayey matrix, and bioturbation. The evidence presented will further advance scientific knowledge about the impact of extreme wave events on coastal areas in SW Iberia and NW Africa.

Introduction

The impact of extreme wave events can create a complex sedimentary record that has significant morphological effects and drastic ecological impacts in low-energy coastal environments (Bondevik et al., 1997; Dawson and Smith, 2000; Sawai, 2002). Tsunamis and coastal storms are two of the most dangerous and yet most common extreme wave events that affect coastal locations (Morton et al., 2011). These high-energy events cause the deposition of sedimentary beds that have certain specific sedimentological and paleontological characteristics (Fujiwara et al., 2000; Goff et al., 2012).

It is difficult to distinguish tsunamis from severe storms in coastal sedimentary records insofar as both tsunamis and severe storms are high-energy marine events that generate very similar deposits. Many studies have tried to identify diagnostic criteria to differentiate between the two types of events (Fujiwara et al., 2000; Nanayama et al., 2000; Goff et al., 2004; Morton et al., 2007; Goff et al., 2012; Ramírez-Herrera et al., 2012). Because both tsunamis and severe storms impinge violently on the coast and result in the inundation of extensive areas by seawater, both have been referred to as "Extreme Wave Events" or EWEs (Kortekaas and Dawson, 2007; Bridge, 2008; Switzer, 2008; Switzer and Jones, 2008; Lario et al., 2010). Yet it is essential to distinguish between tsunami and storm deposits in sedimentary records, if only because paleo-event analyses are used to predict event recurrence and to conduct hazard vulnerability assessments. Establishing such a distinction is not an easy task, however; numerous multiproxy data, to be found widely distributed in a study area, are needed for such purpose.

Geomorphological and sedimentological features generated by EWEs are well known along the coasts of SW Iberia. Such events have been attributed to tsunamis and/or storm surges (Lario et al., 2010). At present, strong storms occur in the Gulf of Cadiz with a cyclicity regulated by the North Atlantic Oscillation (NAO; periodicity of ~6 yr) as well as by solar irradiation (sunspot cycles) (periodicity of ~11 yr) (Rodríguez-Ramírez et al., 2003). Tsunamis affecting the Gulf of Cadiz have drawn increasing interest since the recent devastating tsunamis in Indonesia, Thailand, and Japan. The received literature registers as

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many as sixteen tsunamis hitting the coasts of the Gulf of Cadiz between 218 BC and AD 1900 (Galbis Rodríguez, 1932–1940; Campos, 1992; Bermúdez and Peinado, 2005). Traces of some of these events in the sedimentary record have been sought over the past few decades (Andrade, 1992; Andrade et al., 1994; Lario et al., 1995; Dawson et al., 1996; Dabrio et al., 1999; Luque et al., 2002; Whelan and Kelletat, 2003; Alonso et al., 2004; Gracia et al., 2006; Morales et al., 2008; Baptista and Miranda, 2009; Gutiérrez-Mas et al., 2009; Morales et al., 2011). The epicenters of the corresponding earthquakes have traditionally been placed some 200 km southwest of Cape São Vicente, near the Gorringe Bank (Martínez Solares et al., 1979), yet current analyses point to movements along the Azores-Gibraltar Fault or along associated minor faults such as the Marques de Pombal Fault (Baptista et al., 1998; Terrinha et al., 2003). Historically, the most recent one occurred on November 1, 1755: the notorious "Lisbon earthquake." The tsunami impacted on coastal areas of the Iberian Peninsula and Morocco (Levret, 1991; Scheffers and Kelletat, 2005; Whelan and Kelletat, 2005; Gracia et al., 2006), its effects reaching as far as the south coast of England (Foster et al., 1991).

The interested reader will find in today's geological literature a reference to at least eight EWEs impacting on the SW Iberian Peninsula over the past seven thousand years: ~7000–6800 cal yr BP, ~5700–5300 cal yr BP, ~4500–4100 cal yr BP, ~3900–3700 cal yr BP, ~2700–2200 cal yr BP, ~2200–2000 cal yr BP, ~1500 cal yr BP, and AD 1755 (Lario et al., 2010, 2011; Morales et al., 2011). Comparing the onshore with the offshore records of earthquake-related turbidite deposits (Gràcia et al., 2010) has reduced this number to five tsunamis in the same time span (Lario et al., 2011), within calibrated ages of ~7000–6800 cal yr BP, ~5500–5000 cal yr BP, ~3900–3600 cal yr BP, ~2200–2000 cal yr BP, and AD 1755.

The first, indirect evidence of formations generated by EWEs in the Guadalquivir estuary are chenier deposits and small spits that have formed in the mudflat salt marshes of the estuary (Rodríguez-Ramírez et al., 1996; Ruiz et al., 2005b; Rodríguez-Ramírez and Yáñez, 2008). Additional, more direct evidence comes from sedimentary analysis of sediment cores (Lario et al., 2001; Pozo et al., 2010). Yet a number of factors in the dynamics of the Guadalquivir estuary must be taken into account in attempting to understand its geomorphic evolution, as these factors greatly alter the potential evidence procured from the analysis. In its initial phases before being completely filled, the estuary was a rather large internal lagoon (Rodríguez-Ramírez et al., 1996). Intense tidal and fluvial currents as well as wave movement in the estuary disturbed sediments supplied by EWEs by recycling, mixing, and depositing these sediments in the form of cheniers over fluvial levees (Rodríguez-Ramírez and Yáñez, 2008). These cheniers extend over the surface of the present-day salt marshes and are also buried in the soil. Notwithstanding such complex geomorphic evolution several attempts have been made to establish sequences of tsunamigenic events in the area. Because the nature and dynamics of cheniers were not considered in such attempts, serious mistakes of interpretation have resulted in the scientific literature (Rodríguez-Ramírez, 2009). The only way to secure an analysis of an undisturbed sedimentary record in the lower Guadalquivir marshland is to perform numerous boreholes which will allow having a wide spatial and morphosedimentary view of the sediments along the geography of the old Guadalquivir estuary. Once this is done, the origin of these sediments can be specified.

The main objective of this paper is to document the sedimentary record of EWEs in the lower Guadalquivir marshes over the past 4 millennia and to correlate this record with regional events in the Atlantic Ocean. The evidence presented is the result of a multidisciplinary study of geomorphological, sedimentological, paleontological, chronological, and mineralogical data obtained from fifteen deep and superficial drilled cores which reveal shell-rich and sand facies. Spatially correlated, these drilled cores show the extent and variation of morphosedimentary characteristics of EWEs. This is the first sucessful study on this subject in the Gulf of Cadiz.

Geographical and morphodynamic setting

Located in the central sector of the Gulf of Cadiz, the Guadalquivir estuary is under the influence of the Atlantic Ocean (Fig. 1). It is today enclosed by two spits, Doñana and La Algaida, behind which is a large freshwater marshland of 180,000 ha which includes Doñana National Park, a UNESCOMAB Biosphere Reserve. The estuary comprises the most extensive spit system of the Gulf of Cadiz, which has grown toward the E and SE. At present the spits are partly covered by active dunes. The present freshwater marshes have their origin in the clay contributions of the Guadalquivir and other rivers, which filled the marine estuary in the form of a low-energy finger delta. Growth of the large spits favored this infilling, as they isolated the estuary from the ocean (Rodríguez-Ramírez et al., 1996). There is thus a direct relationship between the littoral and the estuarine formations. With a modest topographic gradient, the freshwater marshes include various muddy and sandy facies which are the byproduct of intense fluvial and marine action.

Hydrodynamic processes in the estuary are controlled by the fluvial regime, the tidal flux, wave action, and drift currents. The largest river draining the Spanish southwest and the main source of fluvial sediments in the entire southwestern coastline, the Guadalquivir has a mean 164 m^3/s annual discharge, even though winter spates can easily exceed 5000 m^3/s (Vanney, 1970). The highest runoff (>1000 $m^3\ s^{-1}$) takes place from January to February, with fluvial current velocities of up to 1 m/s (Vanney, 1970; Menanteau, 1979). The maximum tidal range at the river mouth is 3.86 m (period 1992–2006), with an average of 3.65 m (Spanish Ministry of Public Works). The tidal regime can be described as semidiurnal mesotidal (Borrego et al., 1993).

The wave regime depends directly on the prevailing SW winds, with 22.5% of the days per year in this direction (data of the Instituto Nacional de Meteorología for the city of Huelva: 1960–1990). In the wintertime Atlantic cyclones are common, giving rise to strong SW winds which generate "sea-type" waves more than 6–8 m high (Hsmax; data from Clima Marítimo (OAPE)). These waves cause significant shore erosion, but represent only around 3–5% of the total annual waves. In general, the wave regime in the Gulf of Cadiz is medium-to low-energy, with waves usually smaller than 0.6 m high. Most of the wave fronts approach the coast obliquely and induce littoral currents that transport sand from the Portuguese coast to the Spanish nearshore zone (Cuena, 1991).

Materials and methods

Geomorphology

Aerial photographs from 1956 (1:33,000) and 2010 (1:10,000) were analyzed by photointerpretation to map the detailed geomorphology of coastal sediment bodies. The analysis was complemented by direct observations in the field. The Topographic Map of Andalucia (1:10,000) was used as a base document for geomorphological mapping. All of this information was integrated and analyzed into the gvSIG GIS program.

Lithostratigraphy

It was examined the sedimentary sequence obtained from two boreholes 12 m deep (S7 and S9) and from one borehole 18 m deep (S11). The drilling took place between 2006 and 2009 as part of a multi-institutional research project of regional scope named "The Hinojos Project." The drilling was done by a direct circulation rotary method, with continuous core sampling (Cruse, 1979). Point S9 was placed relatively close to S7 in order to verify the lateral continuity of the sedimentary formations; detailed analyses were only made for S7 and S11 (Fig. 2). Other cores examined were those drilled at points PN and ML, previously studied by Pozo et al. (2010) and Zazo et al. (1999). In addition the present research studied the sediments from a number of shallow drillings (<3 m) in surface formations on both banks of the Guadalquivir River (CV1, CV2, CV3, M1,