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Original article

The geological record of a mid-Holocene marine storm in southwestern Spain

L'enregistrement géologique d'une tempête marine holocène du Sud-Ouest de l'Espagne

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Abstract

Integrated analysis of a 50-m long sedimentary core collected in the central part of the Odiel estuary (SW Atlantic coast of Spain) allows delineation of the main paleoenvironmental changes that occurred in this area during the Holocene. Eight sedimentary facies were deposited in the last *ca*. 9000 years BP, confirming a transgressive–regressive cycle that involves the transition from fluvial to salt marsh deposits with intermediate marine tidal deposits. A storm event is detected at *ca*. 5705 ^{14}C years BP (mean calibrated age) with distinct lithostratigraphical, textural, geochemical, and palaeontological features.
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Résumé

L'analyse géologique d'un forage obtenu dans la partie centrale de l'estuaire du fleuve Odiel (Sud-Ouest de l'Espagne) a permis la définition des principaux événements paléoenvironnementaux holocène dans ce secteur. Huit facies sédimentaires ont été différenciés sur un substrat néogène. Ils constituent un cycle transgressif–régressif incluant des dépôts marins entre graviers fluviatiles à la base et des sédiments fins de marais. Un événement de haute énergie (tempête) a été enregistré vers *ca*. 5705 ^{14}C years BP au sommet, dont les caractéristiques lithostratigraphiques, géochimiques et paléontologiques sont distinctives.
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Keywords: Estuarine facies; Storm; Holocene; SW Spain

Mots clés : Facies ; Estuaires ; Tempête ; Holocène ; SO Espagne

1. Introduction

In the last decade, numerous investigations have focused on the geological deposits derived from the action of past storms, tsunamis, and other high-energy events. Most of these studies are based on textural analyses of sediments through vertical sections and sometimes include geochemical data (Chague-Goff et al., 2002) and microfaunal studies based on ostracods (Hindson and Andrade, 1999), planktonic and benthic foraminifera (McMurty et al., 2004; Abrantes et al., 2005; Williams et al., 2006), dinoflagellates (Allen, 2003), or pollen (Kontopoulos and Avraimidis, 2003). Generally, a single event was detected (Dawson and Smith, 2000; Banerjee et al., 2001;

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Altunel et al., 2004), although as many as six tsunamis have been recorded in a few cores (i.e., Kontopoulos and Avraimidis, 2003; Nomade et al., 2005). Storm or tsunami periodicity has been tracked in very recent time series (from 1950 or later), with the application of both spectral and Monte Carlo analysis (Levin and Sasorova, 2002; Watts, 2004).

In coastal environments, sedimentary deposits associated with tsunamis are characterized by: (a) large boulders, boulder ridges, pebbles, and shells high above the modern storm level (Scheffers and Kelletat, 2005); (b) washover fans (Luque et al., 2002); (c) sandy, sometimes bioclastic sheets with evidences of bidirectional flows (Nanayama et al., 2000); (d) sandy layers intercalated in muddy deposits (Fujiwara et al., 2000); or (e) shell-bearing deposits sandwiched by fossil soils (McMurty et al., 2004). Usually, they have an erosional base and consist of coarser sediments relative to the overlying and underlying layers (Takashimizu and Masuda, 2000). In contrast, important erosion may be detected in the adjacent shallow-marine environments (Abrantes et al., 2005). Sedimentological and geomorphological imprints of these high-energy deposits are reviewed in Dawson and Shi (2000) and Scheffers and Kelletat (2003).

In these areas, the geological record of storm events is constituted by: (a) sandy layers with basal erosional surfaces interlayered in muddy sediments (Myrow and Southard, 1996; Budillon et al., 2005); (b) new beach ridges added periodically to sandy spits (Rodríguez-Ramírez et al., 2003); or (c) lumachellic layers of mollusc shells interbedded within massive, bioturbated levels (González Delgado et al., 1995). Differences between the geological record of storm or tsunamis are reviewed in Davies and Haslett (2000). Tsunami deposits are generally thinner than those of storms, they can extend hundreds of meters inland, create a new macrotopography and usually comprise a single bed that is normally graded overall (Goff, 2006).

On the southwestern Spanish coast, 18 tsunamis have been documented since 218 BC (Campos, 1992), with the generation of washover fans (Luque et al., 2001, 2002) or bioclastic sandy sheets (Lario, 1996; Ruiz et al., 2004). Other tsunamigenic layers have been found at *ca*. 5300 ^{14}C years BP, *ca*. 4182–4152 ^{14}C years BP and 3862–3763 ^{14}C years BP (Ruiz et al., 2005). In this area, the tectonic source of earthquakes and the associated tsunamis are located along the Azores fault, generated by the dynamics of the Iberia–Africa plate margin (Zitellini et al., 1999, 2004). In addition, this zone is exposed to frequent winter storms, with a remarkable periodicity (3–6 years in most cases; Rodríguez-Ramírez et al., 2003).

The aim of this paper is the geological characterization of the different sedimentary bodies that constitute the infilling of the Odiel River estuary (SW Spain). Lithological, geochemical, and palaeontological data are the basis for the recognition of Holocene palaeoenvironmental changes, with special attention to the identification of high-energy events like storm or tsunamigenic deposits.

2. The Odiel estuary

The Odiel River estuary is a bar-built system (cf. Fairbridge, 1980) located on the southwestern Spanish coast. This coastal environment is well-known for high levels of heavy metals (Ruiz, 2001; Borrego et al., 2002, 2004) derived from: (1) the large amounts of suspended and dissolved trace elements coming from the acid drainage of the Iberian Pyrite Belt, the biggest sulphide ore in Europe and (2) the presence of two industrial complexes in the estuarine central basin, including chemical factories, petroleum refineries, and a paper mill.

The inner part of this coastal environment is composed of wide tidal flats and salt marshes separated by ebb-tide channels. The mouth is composed of three geographical elements (Fig. 1), separated by three channels: (1) the Punta Umbria spit, to the west, (2) the Saltes Island, which comprises a complex system of sandy ridges, subparallel to the coastline, and (3) the Torre Arenillas spit, developed on the eastern margin and directly linked with a Plio-Pleistocene cliff.

The Iberian Pyrite Belt constitutes the main geological substratum of the Odiel River drainage network. Near the mouth, the Holocene estuarine sediments were deposited on Miocene–Pliocene siliciclastic sediments deposited in marine/continental environments (Civis et al., 1987). This Tertiary succession is composed of basal grey-blue clays and marls (Gibraleon Clays Formation) and upper fine sands and grey-yellow marls (Huelva Formation). These formations constitute a large system of cliffs distributed along the coastline that surrounds the estuary.

3. Materials and methods

A continuous core (50 m long) was obtained from Bacuta Island, located near the main channel of the Odiel River (Fig. 1). Initial analysis delineated the main lithostratigraphic units using particle size analysis of 35 subsamples (20 g) and the estimation of the clay-silt contents in a ZM model COULTER particle counter. Geochemical analyses of additional subsamples were performed on the bulk samples by X-ray Assay Laboratories, Toronto (Canada). Metal concentrations were determined by X-ray Fluorescence (SiO_2, Al_2O_3, CaO, MgO, Na_2O, K_2O, Fe_2O_3, MnO, TiO_2, P_2O_5) and ICP Spectrometry (Be, Sc, V, Cr, Mn, Co, Ni, Cu, Zn, As, Sr, Y, Zr, Mo, Ag, Ba, La, Pb, Bi). Calibration is based on over 40 international standard reference materials.

The palaeontological record was obtained from 50 g subsamples washed through a 63 μm sieve to remove the mud fraction and then dried. Bivalves and gastropods were identified to the species level, whereas the total ostracod fauna was picked and 300 foraminifers were counted (if possible), with a subsequent extrapolation to the whole sample.

Two dates were produced at the Geochron Laboratories by radiocarbon analysis of mollusc shells. Data were calibrated using CALIB version 4.2 (Stuiver and Reimer, 1993) and the Stuiver et al. (1998) calibration dataset. The final results correspond to calibrated ages (*ca.*) using 2σ intervals with a reservoir correction (-440 ± 85 years) as suggested by Lario (1996) and Dabrio et al. (1998, 2000) for this area. Ages discussed below are expressed as the highest probable age of the 2σ calibrated range (e.g., van der Kaars et al., 2001).

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