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Headland-associated banner banks generated during the last deglaciation near the Strait of Gibraltar (Gulf of Cadiz, SW Spain)

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ABSTRACT

The inception and evolution of large-scale bedforms on the Barbate Platform (Gulf of Cadiz, SW Iberian Peninsula) are investigated based on a detailed study of multibeam bathymetric data, high-resolution seismic profiles and tidal current simulations. Elongated rocky outcrops and several large-scale bedforms classified as sand banks were identified on the platform: Barbate, Zahara, El Palmar, El Varadero and Caños de Meca banks. The Barbate and Zahara banks exhibit the most complex internal stratigraphic architecture, which comprises five seismic units. The basal unit (U_1) is interpreted as incised valley infill and is overlain by nearshore bars (U_2). Two high-energy growth phases (U_3 and U_4) that combine progradation and accretion form the present-day external bank shape. Superimposed bedforms covered these banks under the modern hydrodynamic regime (U_5). The multiphase accretion and progradation of U_3 and U_4 in the Zahara and Barbate banks were closely linked to the presence of a palaeo-headland — termed here as palaeo-Cape Trafalgar — and strong tidal current eddies that resulted from the progressive flooding of the Barbate Platform during the last deglaciation. This configuration was relatively stable while the rocky outcrops were exposed to sub-aerial conditions, forming a palaeo-coast with coastal bluffs. We suggest that during this period of coastal stabilization, U_3 and U_4 grew as banner banks on either side of the palaeo-Cape Trafalgar. The present study proposes that the configuration of palaeo-headland associated with palaeo-banner banks (Zahara and Barbate banks) along each side of the palaeo-Cape Trafalgar represents a transgressive analogue model of headland-associated tidal bank systems developed in funnel-shaped coastal systems terminating in narrow straits.

1. Introduction

Subaqueous large-scale bedforms comprise elongate bodies — roughly 10 s km long, several kilometres wide and 10 s m high (Snedden and Dalrymple, 1999). Subaqueous large-scale bedforms generally occur as fields of regularly spaced, parallel or en echelon sediment bodies (Off, 1963; Caston, 1972) that may cover extensive seafloor areas of up to 10,000 s km^2. These bodies are among the largest and most distinctive morpho-sedimentary features found in ancient shallow-marine settings and modern continental shelves (Ashley, 1990; Dyer and Huntley, 1999; Reynaud and Dalrymple, 2012). Their occurrence depends on two limiting factors: sediment availability and the existence of tidal or other currents capable of moving the sand (Dyer and Huntley, 1999). Modern large-scale bedforms usually occur in shallow-water depths, between 20 and 50 m, although in some settings such as the Celtic Sea they have been reported at water depths between 100 and 150 m (Marsset et al., 1999; Reynaud et al., 1999). They may produce significant depocentres and thus are potential candidates for land reclamation (Wang et al., 2012). In addition, they may be considered modern analogues of ancient hydrocarbon-bearing sand deposits (Tillman and Martinsen, 1987; Bergman and Walker, 1999; Snedden et al., 2011; Zhuo et al., 2014).

A basic distinction can be made between storm and tide-built large-scale bedforms (Swift, 1985). On many modern continental shelves, tides are generally the main dynamic process responsible for sediment transport and migration of large-scale bedforms. Large-scale tidal bedforms have been described in the southern North Sea (e.g., Berné et al., 1994; Trentesaux et al., 1999) and the Yellow Sea (e.g., Lee et al., 2009; Wang et al., 2012; Yoo et al., 2016). Tidal large-scale bedforms, known as banner banks, are also found in the lee sides of areas resistant to erosion such as headlands or islands where the coast changes in direction at severe angles (Dyer and Huntley, 1999; Snedden and Dalrymple, 1999), as described in the Bay of Fundy (Shaw et al., 2012;

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Li et al., 2014; Todd et al., 2014) or Portland Bill in the English Channel (Bastos et al., 2002, 2003, 2004). The formation and maintenance of banner banks would most likely be related to the development of transient tidal eddies at each side of a cape and the associated variations in shear stress and sediment flux over the course of a tidal cycle (Signell and Harris, 2000). Wind-driven currents also play an important role as bedform generators, for example in areas close to straits (Nelson et al., 1999). Large-scale storm-built bedforms such as those formed in nearshore environments of the north-eastern US Atlantic shelf (Swift and Field, 1981; Goff et al., 1999; Snedden et al., 2011) or the Valencia continental shelf, western Mediterranean Sea (Albarracín et al., 2014; Simarro et al., 2015), are smaller than their tidal-built counterparts.

In the long term, the internal configuration and morphology of large-scale bedforms are controlled by a number of factors, such as tectonics and/or climate-driven sea-level variations (Reynaud and Dalrymple, 2012). In particular, rising sea-level is believed to exert a major control on the evolution of large-scale bedforms (Dyer and Huntley, 1999; Park et al., 2006; Reynaud and Dalrymple, 2012), as the genetic processes may be modified over time and may be different from the ones maintaining them under present-day oceanographic conditions. Prevailing genetic models therefore argue for the existence of a continuum between juvenile coastal deposits and constructional, fully-developed large-scale shelf bedforms as flow patterns evolve in response to the sea-level rise and the subsequent landward coastline displacement (Snedden and Dalrymple, 1999). Some recent works suggest that the long-term development of major bedforms is also conditioned by the basement morphology (Bastos et al., 2003; Franzetti et al., 2015).

Large-scale bedforms similar in internal and external morphology to the aforementioned examples, mapped in the Barbate Platform close to the Strait of Gibraltar in the Gulf of Cadiz, northeast Atlantic Ocean (Lobo et al., 1996, 2000, 2010; Nelson et al., 1999), are the focus of this study. Previous research efforts documented the spatial morphological patterns of major bedforms based solely on the inspection of seismic profiles. Despite the scarcity of fluvial supply to the area, some of these large-scale bedforms show extensive distributions and develop significant thickness (Lobo et al., 2010). This fact is consistent with the prevalence of a high-energy hydrodynamic regime conditioned by the proximity of the strait. Thus, these large-scale bedforms have been linked to the combined activity of two main currents: the North Atlantic Surficial Water, which flows along the Gulf of Cadiz shelf towards the southeast, and the influence of a reversing current, linked to the tidal cycles in the Strait of Gibraltar (Lobo et al., 2014).

We use high-resolution bathymetric data and seismic profiles to interpret the factors driving the generation and development of the large-scale bedforms in the Barbate Platform and ultimately attain the following goals: 1) to map the most significant morphological seafloor features of the study area; 2) to establish a stratigraphic model for the most significant large-scale bedforms identified on the Barbate Platform; 3) to interpret and place both morphological and stratigraphic observations in an evolutive context, by integrating multibeam bathymetry, seismic data and available information on sedimentary dynamics; and 4) to evaluate the role played by the postglacial sea-level rise and the evolving palaeogeographic configuration of this shallow-water margin setting. This work contributes to our understanding of the morphodynamic evolution of coastal systems within the context of rapid sea-level changes.

2. Regional setting

2.1. Location and physiography

The Gulf of Cadiz is located in the northeastern Atlantic Ocean, by the southwestern continental margin of Iberia (Fig. 1). Its northern margin extends from Cape Saint Vincent to the northwest to the Strait of

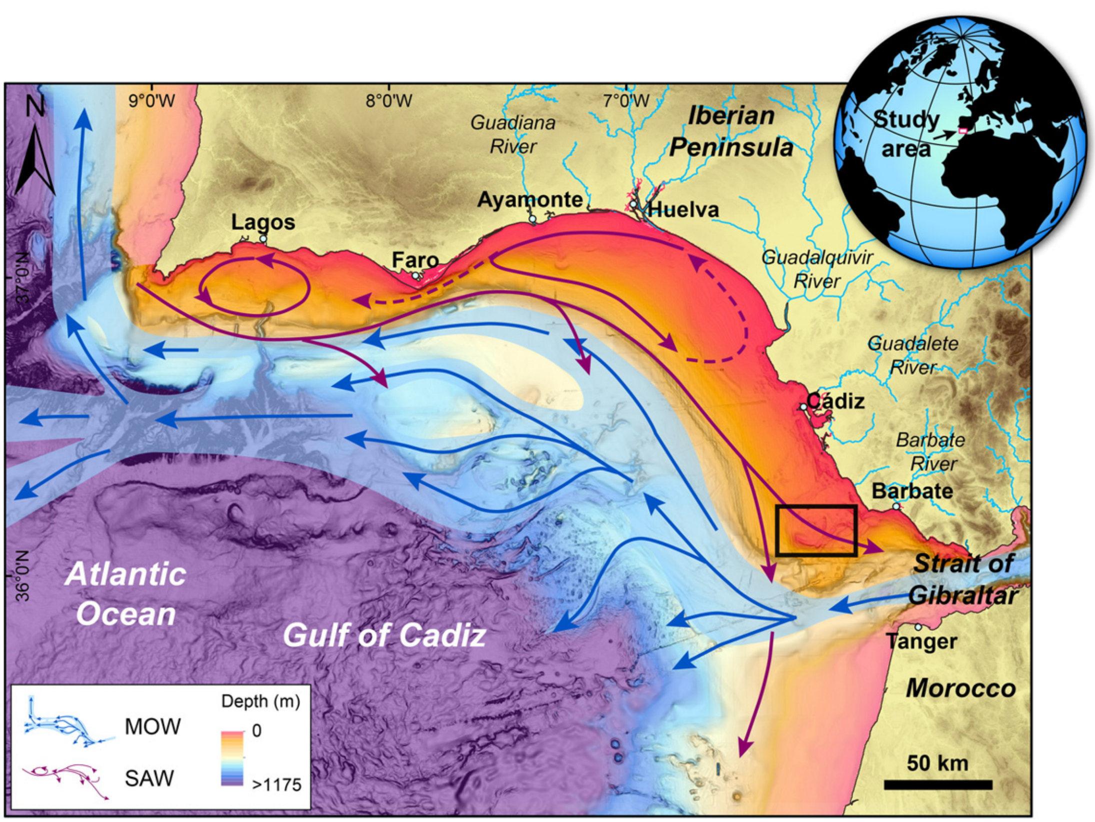

Fig. 1. Geographical location and regional oceanographic setting of the northern Gulf of Cadiz margin. The black box marks the study area (Barbate Platform). Flow paths of the Mediterranean Outflow Water (MOW) after Hernández-Molina et al. (2014); flow paths of the Superficial Atlantic Water (SAW) after García-Lafuente et al. (2006) and Criado-Aldeanueva et al. (2006).