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Relict sand waves in the continental shelf of the Gulf of Valencia (Western Mediterranean)

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ABSTRACT

The presence of fossil or relict bedforms is common in the Quaternary fill of modern continental shelf due to sea level oscillations, tectonic subsidence and migration of associated sedimentary facies. The continental margin of the Gulf of Valencia has been strongly influenced by glacio-eustasy and neotectonics. High-resolution multibeam bathymetry data, seismic reflection profiles and box core samples were collected across the continental shelf of the Gulf of Valencia during the DERIVA cruises carried out in 2010 and 2011. The integrated analysis of this data set and high-resolution mapping of the relict bedforms on the Valencian continental shelf, ranging between 50 and 90 m allowed the study of previously identified system of sand waves located in front of the present-day Albufera de Valencia lagoon. The system is composed of 27 ridges with a NNE–SSW orientation, i.e. oblique to the present shoreline, in which the lateral horns point backwards. These sand waves can reach 10 m in height and 3 km in length resulting in a maximum slope of 6°. According to seismic stratigraphic and relative sea level curve reconstructions, these sand waves were formed during the Younger Dryas (~12–10 ky BP). Consequently, they have been classified as Holocene sand waves associated with coastal sedimentary evolution.

1. Introduction

The middle-shelf along the margin of the Gulf of Valencia is covered with a system of large linear ridges, oriented oblique to the predominant bottom current. The shelf processes generating such bedforms are influenced by steady baroclinic currents, such as intruding oceanic currents and tidal currents, and also by meteorological forcing. The seabed features of the study area vary widely in size and morphology, due to a number of different factors, such as: grain size, grain density, sediment distribution, sediment supply, and the bottom shear stress field (Amos, 1990).

Modern sedimentary processes may provide the key to understanding the conditions for the genesis of relict bedforms. The inner-shelf environment is complex as it is influenced by the interplay of the sea level stability or fluctuation and sediment transportation on not only the shelf but also the littoral. Large sand bodies preserved on the shelf can provide the main sources and deposits of sand, and can control the sand dynamics and these include barrier islands, delta lobes, large ebb-tidal deltas, shoals, ridges and other features associated with low stand river valleys.

Sand waves and large bedforms are found on continental shelves worldwide, with examples being the eastern US continental margin (Edwards et al., 2003; Fenster et al., 1990; Figueiredo et al., 1981; Goff et al., 1999; Harrison et al., 2003; McBride and Moslow, 1991; Swift et al., 1978; Twichell et al., 2003; Whitmeyer and FitzGerald, 2008), the Canadian margins (Amos and King, 1984; Amos et al., 2003; Barrie et al., 2009; Hoogendoorn and Dalrymple, 1986; Li and Amos, 1999; Piper, 1991), the Brazilian and Argentinian continental margins (Figueiredo, 1980; Parker et al., 1982), the European continental margin, in the North Sea (De Maeyer et al., 1985; Dyer and Huntley, 1999; Houboldt, 1968; Houthuys et al., 1994; Trentesaux et al., 1994, 1999; Van de Meene et al., 1996, Van de Meene and Van Rijn, 2000; Walgreen et al., 2002), those of Germany (Antia, 1994), Denmark (Anthony and Leth, 2002; Kuijpers et al., 1993) and France (Berné et al., 1998, 2007; Bassetti et al., 2006), the continental margins of India (Wagle and Veerayya, 1996), Japan (Ikehara and Kinoshita, 1994), China (Bartek and Wellner, 1995; Berné et al., 2002; Wang et al., 2012; Yang, 1989; Yoo et al., 2002), Korea (Park et al., 2003), Australia (Harris, 1988), and the margins of North and South Africa (Flemming, 1978, 1980; Green and Smith, 2012; Ramsay et al., 1996).

Sand waves are thought to have three distinct origins: (1) sand waves that are fossil or relict features, such as barrier islands and spits which formed prior to the Holocene transgression and have only slightly been modified after their formation (e.g. Hyne and Goodell, 1967; McClennen and McMaster, 1971; xMcBride and Moslow, 1991). (2) Sand waves that are still actively being formed, changing and evolving.

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This category typically describes Atlantic margin ridges, which are post-transgressive features and have been formed by sediment transport driven by the interaction between storm-flow and nearshore topography (Huthnance, 1982a,b; Rine et al., 1991; Snedden et al., 1994; Swift and Field, 1981; Trowbridge, 1995). (3) Sand waves that correspond to moribund sand ridges (Liu et al., 2007).

The mechanisms responsible for the formation, mobility and stability of sand waves have been described by Boczar-Karakiewicz et al. (1990) and Trowbridge (1995). Storms and resulting infragravity wave patterns are the main agents for generating shoreface connected ridges. There are many factors to consider in the genesis and evolution of sand waves on continental shelves: (1) sea-level, before or after the Holocene transgression, which will define the ravinement surface (Bassetti et al., 2006; Berné et al., 1998); (2) dominant oceanographic processes such as tidal currents (Berné et al., 1994; Collins et al., 1995; Kenyon et al., 1981; Trentesaux et al., 1999), littoral currents (Lane and Restrepo, 2007, Whitmeyer and FitzGerald, 2008), waves (e.g. Allen, 1980; Calvette et al., 1999), dominant extreme waves in storm episodes (Berné et al., 1998; Hoogendoorn and Dalrymple, 1986; Dalrymple and Hoogendoorn, 1997; Parker et al., 1982; Snedden et al., 1994; Snedden and Dalrymple, 1999; Stubblefield and Swift, 1981; Van de Meene et al., 1996), or sediment transport due to a combination of storms and shore currents (Figueiredo et al., 1981; Swift and Field, 1981; Swift et al., 1978; Trowbridge, 1995); (3) finally, the current stage of activity of these features (active, relict or quasi-moribund) implying that the sand waves correspond either to reworked transgressive deposits (Edwards et al., 2003; McBride and Moslow, 1991; Snedden and Dalrymple, 1999; Snedden and Dalrymple, 1999), or to post-transgressive active sand waves, which were formed via sediment transport driven by the interaction between storm-flow and nearshore topography. Several hydrodynamic mechanisms have been advanced to account for ridge formation during a period of erosional shoreface retreat. They fall into two classes: coastal boundary flow models and stability models. The two are not mutually exclusive (Figueiredo, 1980). Dyer and Huntley (1999) proposed a classification of sand ridges and banks according to their degree of evolution. Overviews of modern shelf sand ridges can be found in Snedden and Dalrymple (1999) and Snedden et al. (2011).

The environmental implications of the formation of near-shore sand waves frequently close to a lagoon and barrier, and in general oblique to them, include the presence of an inlet and mouth that contribute sediment to the system (McBride and Moslow, 1991). The recognition of such structures in the stratigraphic record may enable the reconstruction of ancient depositional environments and processes (Goff et al., 2005).

A sand wave is a composite, flow oblique (or parallel) linear accumulation of composite sand, usually of measureable relief (Amos and King, 1984). These are usually large bedforms (1–4 km wide; 2–10 km long; 2–6 m high) oriented obliquely to the regional contours (typically at 30°). Sand waves are formed in nearshore environments (e.g., Swift and Field, 1981) and, according to some authors, can continue to be modified or even entirely reformed in depths of up to 40 m (Goff et al., 1999; Rine et al., 1991; Snedden and Dalrymple, 1999; Snedden et al., 1994). However, other studies suggest that ridges become inactive in depths of over 20 m (Stubblefield and Swift, 1981; Swift et al., 1984; Stubblefield et al., 1984). At water depths such as the ones occurring in this study area, the sand waves are likely to be moribund and are most probably relict features of a shallower hydrodynamic regime (Goff et al., 1999; Swift et al., 1984).

The nearest bedforms to this study area which have been the subject of the study are located on the shelf south of the Ebro delta, near Columbretes, located at a greater depth than the ones considered here (Lo Iacono et al., 2010; Muñoz et al., 2005). Bedforms have also been reported on the continental shelf of Murcia (300 km south of Valencia), located near the coast (Fernández-Salas et al., 2013; ITGE, 1990) and in the Gulf of Lion and in the Gulf of Cádiz (Berné et al., 2007; Lobo et al., 2000).

This study focuses on the interpretation of high resolution bathymetry and on the geomorphological characterization and interpretation of the seabed features of the continental shelf of the Gulf of Valencia, together with a stratigraphic sequence analysis and radiocarbon dating. This has enabled a characterization to be made of the environmental conditions prevailing during the formation of these sand waves and their evolution up to the present day.

2. Regional setting

2.1. Morphotectonic setting

The continental shelf of the Gulf of Valencia (Western Mediterranean) is located from 38.9° to 40° N and from 0.5° W to 0.5° E, with a total length of ca. 111 km (Fig. 1). The continental margin of the Gulf of Valencia is bounded landward by the Eastern Iberian Range and seaward by the Valencia Trough. It extends from Sagunto in the north to La Nao Cape in the south, with structures following a NE–SW trend parallel to the regional Neogene Betic alignment (Acosta et al., 2013; Maillard and Mauffret, 2012).

The continental shelf of the Gulf of Valencia represents the transition between the passive continental Ebro margin in the north, with an intense progradation, and the Betic continental margin in the south, controlled by neotectonic activity. The Valencia Basin represents an aborted rift being linked to the Oligo-Miocene opening of the Northwestern Mediterranean basin in a back-arc context (Maillard and Mauffret, 2012).

The main morphological characteristic of this continental shelf is its very variable width, ranging from 275 km in the north to 68 km in the south. The inner and a part of the outer shelf are characterized by a great variety of sedimentary morphologies and environments, which are greatly influenced by continental factors (Maldonado and Zamarreño, 1983; Rey and Fumanal, 1996; Rey et al., 1999). However, the middle shelf presents the sea bottom subhorizontal with slightly seaward slope and erosive forms which are evidence of a great morphological complexity (Díaz del Río and Fernández-Salas, 2005; Díaz del Río et al., 1986; Maldonado et al., 1983).

Before the Holocene, sand supplied by rivers accumulated on the inner shelf seaward of the present shoreline, but the sedimentary contribution of the rivers in the region has changed since then. In the past, the Júcar and Turia rivers provided larger sediment loads during wet periods. The basal fluvial sediments are composed of Early Holocene or Pleistocene deposits from the Turia River, associated with a very distant coastline (Carmona, 1995). In the present day, the influence of the continental sediment supply from the Ebro River primarily affects the northern sector of the Gulf of Valencia (Alvárez et al., 2010).

Evidence of sea level eustatic oscillation in conjunction with a high rate of local subsidence in the region has been provided by numerous authors (Blázquez et al., 1996; Díaz del Río et al., 1986; Fumanal et al., 1993; Goy and Zazo, 1973; Goy et al., 1996; Rey and Díaz de1 Río, 1983; Rey and Fumanal, 1996; Viñals and Fumanal, 1995; Zazo et al., 1993). Morphological evidence of sea level changes has been identified, such as cemented beach deposits at a depth of 50 m in the southern margin of the Gulf of Valencia (Fumanal et al., 1993; Viñals, 1995; Viñals and Fumanal, 1995), associated to isotopic stage 5e (112,000–119,000 y BP), and, more recently, Pleistocene paleobarriers with associated paleo-lagoon deposits have been located in the sedimentary record of the continental shelf (Albarracin et al., 2013). The most modern of these deposits have been found as outcrops on the inner shelf and are associated with the isotopic stage 5e (Alcántara-Carrió et al., 2013). Moreover, two remarkable paleochannels eroded over the most modern barrier have been associated with isotopic stage 2 (Alcántara-Carrió et al., 2013).

Small fluctuations of the sea level rise in the Mediterranean during the Holocene are reflected in beach and barrier systems, deltas such as that of the Ebro (Somoza et al., 1998), and the Albufera lagoon (the