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Formation, evolution and present-day activity of offshore sand ridges on a narrow, tideless continental shelf with limited sediment supply

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ABSTRACT

An integrated approach combining swath bathymetry, high-resolution seismic reflection and seabed sediment sampling was performed to characterize a field of sand ridges on the Murcia continental shelf in the western Mediterranean Sea. The aim of this work was to improve knowledge about the formation, evolution and present-day dynamics of these bedforms on a narrow, tideless continental shelf receiving little sediment input. Sand ridges are observed on the middle shelf at water depths ranging between 58 and 78 m. The sand ridges are 1.5 to 3 m high and show a predominant E-W orientation oblique to the present-day shoreline. Smaller-scale subaqueous dunes (0.3–1.3 m high) appear superimposed on the sand ridges and beyond the ridge field. The subaqueous dunes show a NW-SE orientation and asymmetric profiles, with the lee side facing southwest. The comparison of two bathymetric surveys 10 years apart revealed that the subaqueous dunes are migrating towards the southwest at very low rates ($\sim 3\ \mathrm{m\ yr^{-1}}$). Internally, both sand ridges and dunes display southwestward dipping oblique reflections, indicating long-term migration in that direction.

The morphology, architecture and distribution of the Murcia sand ridges suggest that they were formed in a shallow-water environment during the Holocene transgression and were later detached from the coast due to the subsequent sea level rise. The shallow architecture of the sand ridges reveals the presence of small, mound-like features within the sand ridges, most probably associated with coastal deposits, which could have served as a precursor for the development of the sand ridges. The preservation of these deposits within the sand ridges evidences limited offshore ridge migration. At present, active subaqueous dunes superimposed on the sand ridges suggest that they may play a significant role in the ridge evolution. At a regional scale, the comparison of the Murcia sand ridges with those described in the western Mediterranean allows us to propose a gradation from partially evolved to fully evolved sand ridges with increasing water depth.

1. Introduction

Sand ridges are widespread bedforms found on many continental shelves at a wide range of water depths from the nearshore to the shelf edge (McBride and Moslow, 1991; Guillén et al., 2017). Shoreface-connected sand ridges develop on the shoreface and inner shelf at water depths shallower than 20 m, where sediment supply is abundant and currents are intensive enough to move the sediment (Swift et al., 1978; McBride and Moslow, 1991). They show linear, elongated shapes with an oblique orientation with respect to the shoreline. The typical elevation of these ridges is between 1 and 12 m high, and their spacing ranges from 1 to 20 km.

Sand ridges are also observed on the middle and outer shelf in both tidal-dominated (Berné et al., 2002; Liu et al., 2007) and non–tidal-dominated environments (e.g. Swift et al., 1972; Goff et al., 1999; Bassetti et al., 2006; Simarro et al., 2015), and are known as offshore sand ridges or shoreface-detached ridges. In tidal-dominated settings, offshore sand ridges show elevations of 25 to 30 m with orientations that are primarily determined by the peak tidal direction (Dyer and Huntley, 1999; Liu et al., 2007). Offshore sand ridges in non-tidal continental shelves are smaller (up to 12 m high) and show an orientation oblique to the shoreline (Snedden et al., 2011; Simarro et al., 2015), caused by a steady alongshore current over a shelf with a transverse slope with respect to the coastline. These ridges are

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characterized by a predominant asymmetric transverse profile, with steeper down-current flanks (Bassetti et al., 2006; Li and King, 2007) and internal oblique reflectors (Goff et al., 2005; Durán et al., 2015). Offshore sand ridges located on the middle to outer shelf are interpreted as shoreface-connected sand ridges formed during the Holocene transgression (Figueiredo et al., 1981; Swift and Field, 1981). During the ensuing sea level rise, these ridges became progressively detached from the shoreface, slowing their growth and decreasing their migration rate until they eventually drowned when the near-bed orbital velocity dropped below the critical velocity for erosion of sediment (Nnafie et al., 2014). At present, sand ridges on the middle and outer shelf are defined as active, relict or moribund (Yang, 1989; Dyer and Huntley, 1999).

Offshore sand ridges are well-described on storm-dominated shelves such as the North Atlantic shelf, the Gulf of Mexico and the North Sea, although they have been studied less in the Mediterranean Sea. Most of the studied ridges developed on wide (70–150 km wide) continental shelves where the sand source for ridge formation is provided during, or immediately before, the transgression by marine reworking of ebb-tidal deltas (Swift et al., 1972; Figueiredo et al., 1981; McBride and Moslow, 1991), barrier-islands and fluvial deltas (Duane et al., 1972; Swift et al., 1972; Bassetti et al., 2006; Simarro et al., 2015), and periglacial deposits (Hoogendoorn and Dalrymple, 1986; Li and King, 2007). However, sand ridges on narrow shelves or shelves with limited sediment availability have received less attention. Examples of sand ridges in sediment-starved environments can be found in West Central Florida (Edwards et al., 2003; Harrison et al., 2003). These ridges are smaller than their counterparts situated along the Atlantic margin and are separated by exposed rock surfaces (Harrison et al., 2003).

There is an interesting debate about the present-day dynamics of sand ridges on middle to outer shelves and the influence of secondary bedforms on their maintenance and migration (Goff et al., 2005; Bassetti et al., 2006; Li and King, 2007). Goff et al. (2005) concluded that sand ridges shallower than 50 m display active sand dunes on their flanks, which are responsible for sand ridge migration, whereas deeper sand ridges display no evidence of secondary bedforms (Goff et al., 1999). However, observations in other areas revealed the presence of secondary bedforms over deeper sand ridges, as in the Gulf of Lions in the northwestern Mediterranean (Bassetti et al., 2006) and Sable Island in Canada (Li and King, 2007).

In this study, we present a detailed characterization of offshore sand ridges identified on the Murcia continental shelf (western Mediterranean) in order to provide new evidence about the formation, long-term evolution and present-day activity of such bedforms in tideless environments. This study is based on the analysis of repeated multibeam bathymetry and backscatter data, high-resolution seismic profiles and bottom sediment samples to characterize the morphology and internal structure of the sand ridges and superimposed subaqueous dunes (~1 m high), and to quantify the dune migration. The unique setting of these sand ridges arises from the particular characteristics of the continental shelf: it is a narrow, stepped shelf with a high escarpment at ~80 m water depth, it is affected by fetch-limited waves, and it is characterized by limited sediment availability.

2. Study area

The study area is located on the Murcia continental shelf in the western Mediterranean Sea off Cape Cope (Fig. 1). The Murcia continental shelf is a storm-dominated shelf with a maximum tidal amplitude of about 0.25 m. Wave climate follows a marked seasonal pattern, with the most intense events usually occurring from September to May. Statistical analysis of wave records collected at Cape Palos wave buoy over the period 2006–2016 shows a mean significant wave height (Hs) of 1 m and a maximum Hs of 5.5 m with predominant NE-E and SW directions (Puertos del Estado, www.puertos.es). The highest waves, with maximum wave heights of 7.80 m and an associated peak period of 9.5 s at the peak of the storm, show predominant ENE and SW directions (Fig. 1). The circulation on the shelf is dominated by wind-induced currents and a geostrophic current that carries old Atlantic Waters towards the southwest along the shelf break (Millot, 1999; Ribó et al., 2013). Available data from bottom currents in the study area are restricted to two one-month deployments (August and November 2007) located close to the coastline, at water depths between 33 and 38 m (Fig. 1). The results revealed mean near surface currents of 0.15 to 0.26 m/s (up to 0.88 m/s) and mean bottom currents of 0.11 to 0.15 m/s (up to 0.64 m/s) with maximum bottom currents from the NE and SW (Servicio de Información Oceanográfica de la Región de Murcia).

Medium to small, steep rivers and streams with seasonal flow regimes and a markedly torrential nature flow into the Murcia continental shelf (Fig. 1), but only small, ephemeral streams feed the area of Cape Cope. In addition to a low sediment input by rivers, the submarine canyons deeply incising the continental shelf contribute to the shelf sediment starvation by intercepting the shelf sediment transport (Lobo et al., 2015).

The Murcia continental shelf has an average width of 4 km, extending to 10 km to the north of the study area, off Cape Palos (Fig. 1). It comprises a seaward-dipping platform that finishes in a steep escarpment (7–15°) at about 80–120 m water depth (Acosta et al., 2013; Gómez de la Peña et al., 2016). The shelf break shows an undulating shape along the margin; it is concave north of Cape Cope and convex south of Cape Cope (Fig. 1). It is cut by shelf-indenting submarine canyons, such as the Águilas Canyon, with their heads located at short distances (about 5 km) from the coastline (Acosta et al., 2013). The Águilas submarine canyon is 50 km long, extending from 100 to 2400 m water depth, with an average gradient of 2° and a maximum width of < 3 km, which is reached at the canyon mouth (Gómez de la Peña et al., 2016) (Fig. 1). The Murcia inner shelf is characterized by positive reliefs corresponding to rocky outcrops and small prodeltas that laterally evolve to infralittoral prograding wedges, which represents the geomorphic feature with greatest continuity along the continental shelf (Rey and Díaz del Río, 1983; Catafau et al., 1990; Fernández-Salas et al., 2015). On the middle shelf, an extensive field (7.5 long and 2.8 km wide) of sediment waves (< 1 m high) was observed between Cape Cope and the Águilas submarine canyon head (Acosta et al., 2013) and constitutes the focus of this study. Following the Ashley's (1990) classification, we will hereafter refer to these bedforms as subaqueous dunes based on their morphological characteristics.

The seismic stratigraphy of the continental margin is characterized by a Late Pliocene to Quaternary unit of variable lateral continuity (Gómez de la Peña et al., 2016). Quaternary deposits reach a moderate development due to the narrowness of the shelf, and are locally eroded at the shelf break by submarine canyons (Catafau et al., 1990; Lobo et al., 2015). The Quaternary shelf record is composed of several offlapping wedges separated by erosional surfaces; the wedges are interpreted as shelf-margin deltas linked to different regressive phases (Catafau et al., 1990; Lobo et al., 2015). The Holocene highstand deposits comprise small, coarse-grained inner shelf prodeltaic deposits (Rey and Díaz del Río, 1983; Catafau et al., 1990; Fernández-Salas et al., 2015) and a continuous distal muddy belt that extends along the middle and outer shelf, derived from the transport of suspended fine sediments towards the southwest (Maldonado and Zamarreño, 1983; Maldonado et al., 1983). Only in the area occupied by the sediment waves does sandy sediment dominate across the shelf (Catafau et al., 1990).

3. Data and methods

3.1. Data acquisition

The present study is based on the analysis of high-resolution multibeam data, including bathymetry and backscatter, very high-resolution seismic profiles and surficial sediment samples (Fig. 2). Data were