Evolution of offshore sand ridges in tideless continental shelves (Western Mediterranean)

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ABSTRACT: An extensive dataset of vibrocores and high-resolution seismic data were analysed to characterise offshore sand ridges on the Gulf of Valencia and the Murcia continental shelves, in the western Mediterranean Sea, with the aim of improving knowledge about the formation and evolution of these bedforms. Sediment coring revealed a layer of coarse sand and gravel with pebbles corresponding with the basal reflector of the sand ridges and interpreted as the Holocene ravinement surface. The architecture of the sand ridges reveals the presence of small, mound-like features interpreted as coastal deposits that could have served as a precursor for the sand ridges genesis. The different degree of preservation of the precursor within the sand ridges observed in the western Mediterranean reveals a gradation from partially to fully evolved sand ridges with increasing water depth. The offshore sand ridges represent valuable potential sand resources that must be preserved as strategic sand reservoirs.

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. Shoreface-connected sand ridges are observed on the shoreface and inner shelf in water depths shallower than 20 m (McBride and Moslow, 1991, Guerrero et al., 2018). Offshore sand ridges, or shoreface-detached ridges, are located on the middle and outer shelf (e.g. Goff et al., 1999; Simarro et al., 2015). They are interpreted as formed in shallow waters and detached from the shoreface during the transgression (McBride and Moslow, 1991).

A depositional model for the evolution of shoreface-connected sand ridges into detached sand ridges was developed by McBride and Moslow (1991) and subsequently expanded by Snedden et al. (1999). The model includes three stages of development, based on the extent to which a ridge retains evidence of its initial irregularity: a) juvenile, where the initial irregularity forms; b) partially evolved, where ridges migrate enough to erode the precursor; and c) evolved, with limited to no trace of the initial stage of development.

In this work, we present the detailed characterization of offshore sand ridges located on the Gulf of Valencia (GoV) and the Murcia continental shelves in the western Mediterranean Sea based on the analysis of an extensive vibrocore dataset and high resolution seismic data. The aim of this study is to provide additional information about the formation and evolution of these bedforms in tideless continental shelves.

2. STUDY AREA

The GoV and Murcia continental shelves are storm-dominated, microtidal (< 0.2 m) environments with a low sediment input by rivers. The main river discharging into the GoV is the Turia River (Fig. 1), with a small mean discharge of 14 m^3/s. Only small, ephemeral streams flow into the Murcia continental shelf (Fig. 1).

The GoV continental shelf has a variable width up to 30 km, with the shelf edge located at ~150 m water depth (Fig. 1). The Murcia continental shelf is narrower; it has an average width of 4 km, locally up to 10 km with the shelf edge located at 80-120 m water depth (Acosta et al., 2013). Surficial sediments in both shelves are characterized by a mud blanket that extends along the middle and outer shelf, with the exception of two isolate areas of sandy sediments, where the sand ridges were observed.

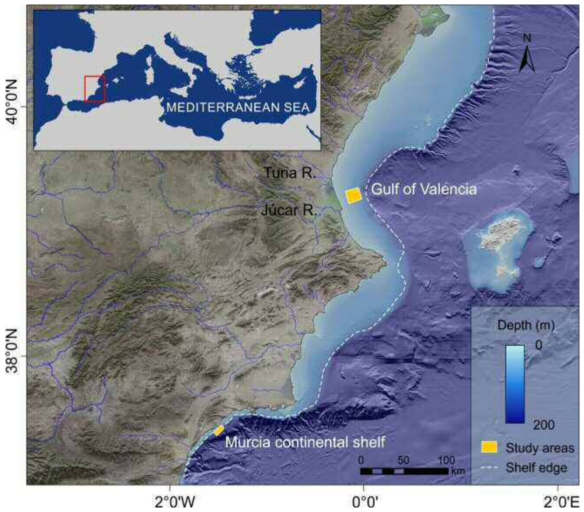

Figure 1. Shaded-relief colour map of the Mediterranean margin of the Iberian Peninsula showing the location of the study areas. Topographic data provided by the Spanish National Geographic Institute (www.ign.es). Bathymetric data downloaded from the EMODnet portal (http://portal.emodnet-bathymetry.eu/).

Sand ridges in the GoV continental shelf are located between 55 and 85 m water depth, covering an area of 35 km^2. The sand ridges show a predominant NE-SW orientation, obliquely to the isobaths (Maldonado et al., 1983) (Fig. 2). The ridge height (H) ranges from 1.5 to 7 m, with a spacing (L) between 600 and 1,100 m (Simarro et al., 2015). The sand ridges are asymmetric with the lee face on the south side of the crest.

Sand ridges in the Murcia continental shelf are observed between 58 and 78 m water depth, covering an area of 13 km^2 (Durán et al., 2018) (Fig. 3). They are 1.5 to 3 m high and show E-W orientation oblique to the shoreline. Smaller-scale subaqueous dunes (0.3-1.3 m high) appear superimposed on the sand ridges (Fig. 3). The dunes are asymmetric with the lee side facing south-west. The comparison of two bathymetric surveys 10 years apart revealed that the dunes are migrating towards the southwest at very low rates (~3 m yr^{-1}).

3. DATA AND METHODS

The analysis of the sand ridges is based on the interpretation of very-high resolution seismic reflection data, surficial sediment samples and sediment cores (Figs. 2 and 3).

Seismic data were acquired in 2011 onboard the R/V Vizconde de Eza and in 2013 onboard the R/V Angeles Alvariño in the GoV and Murcia continental shelves, respectively, using a Kongsberg TOPAS PS018 parametric sub-bottom profiler.

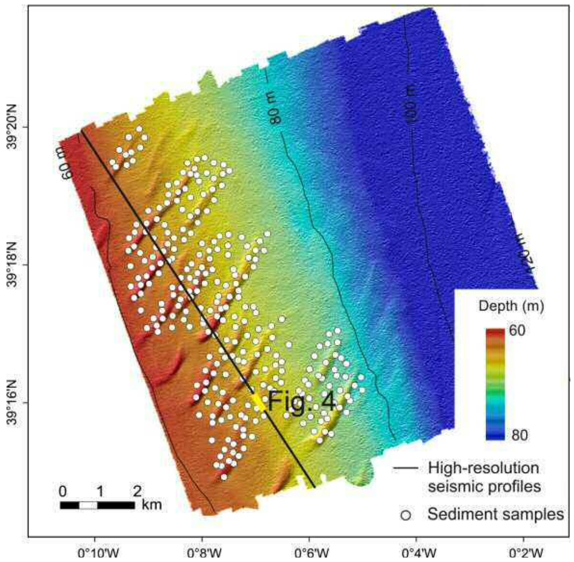

Figure 2. Shaded-relief colour bathymetry of the GoV sand ridges including the location of the high-resolution seismic profile and the sediment cores. Modified from Durán et al., 2015.

A total of 279 vibrocores were retrieved in the GoV continental shelf in 2007 by the Spanish Ministry of Agriculture, Food and Environment (Sub-Directorate General for Coastal Protection) (Fig. 2). Vibrocores, usually 4-5.5 m long, were sub-sampled every 0.5 m. for grain size analysis. In addition, 20 surficial sediment samples were collected on the Murcia continental shelf.

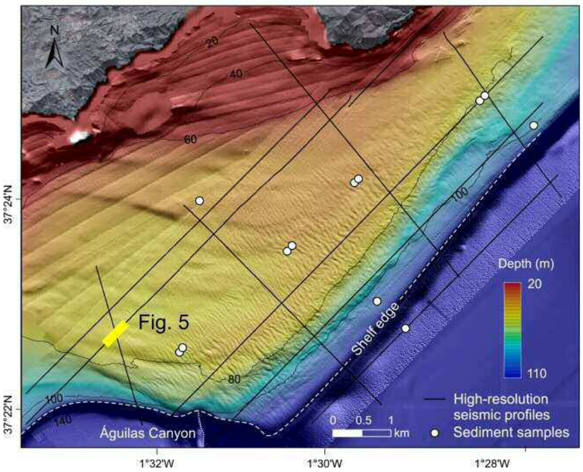

Figure 3. Shaded-relief colour bathymetry of the Murcia continental shelf including the location of the high-resolution seismic profiles and the surficial sediment samples. Modified from Durán et al., 2018.

4. RESULTS

4.1 Sediment characteristics

The analysis of the sediment cores provides information about the sedimentary structure of the sand ridges. The sand ridges are composed of well-sorted medium and coarse sand (85% on average) with a low content of mud (<20%) and gravel (<10%). A coarse layer composed of coarse sand and gravel (up to 98%) with presence of pebbles and cobbles is observed at the base of the sand ridges (Fig. 4). Locally, the sandy facies display interbedded mud layers at different depths.

In the flank of the sand ridges, the sand layer appears covered by a surficial layer of fine-grained sediments (0.3-1 m thick) composed of sand (33% on average) and mud (69% on average) (Fig. 4). The mud content of this layer increases up to 98% in the troughs between ridges, where it can be up to 3.5 m thick.

In the Murcia continental shelf, surficial sediment samples are mostly composed of medium to coarse sand (33%-60%) with a mud content lower than 40%. Only in some locations, the sediment is composed of coarse sand and gravel (about 64%).

4.2 Seismic data

The high-resolution seismic profiles display a strong reflector that truncates the underlying seismic units and locally emerges at the seafloor in the deeper parts of the troughs between ridges (Figs. 4 and 5). It corresponds to a major erosional surface that can be trace along the whole study areas. It shows an irregular topography with local relieves up to 3 ms, or ~2.5 m.

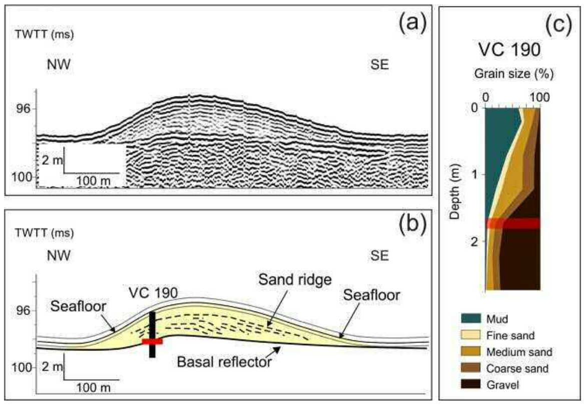

Figure 4. (a) Uninterpreted and (b) interpreted high-resolution seismic profile of a small sand ridge. (c) Sediment corer description. Red line indicates the location of the basal reflector identified in the seismic profile. A sound velocity of 1550 m/s was used. Solid grey lines indicate parallel reflectors mimicking the seafloor surface. See figure 2 for location.

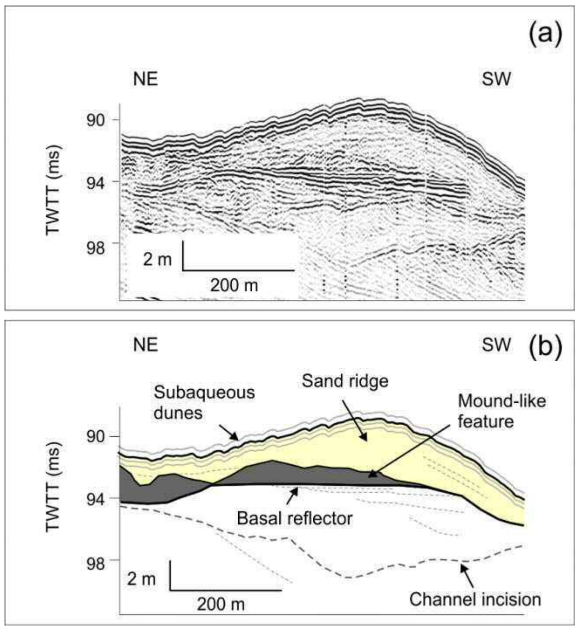

Figure 5. (a) Uninterpreted and (b) interpreted high-resolution seismic profile of sand ridges. Note that the basal reflector locally outcrops at the seafloor. Location is shown in Fig. 3.

In the GoV, this reflector corresponds to the coarse lag identified in the sediment cores at the base of the sand ridges (Fig. 4). In the Murcia continental shelf, the coarse nature of this surface is evidenced by the presence of coarse sand and gravel in the areas where the erosional surface is exposed.

Internally, the sand ridges are characterized by high-amplitude, high-angle internal reflectors dipping towards the south (Figs. 4 and 5). Locally, small mound-like features with low relief (up to 1 m high) are identified at the base of the sand ridges, showing a high degree of acoustic impedance. They are commonly observed in the Murcia sand ridges (Fig. 5) but also in some ridges in the GoV.

5. DISCUSSION

5.1 Sand ridge formation on tideless continental shelves with limited sediment supply

The sand ridges identified in the GoV and Murcia continental shelves rest on a regionally recognized erosional surface. In the Murcia shelf sector, this surface caps channel fill deposits, suggesting a transition from fluvial to marine conditions. In the GoV, it corresponds to a coarse sand or pebble lag that is overlain by a thick layer of sandy-sediments in the sand ridges and fine-grained sediments in the troughs. This basal surface in interpreted as the ravinement surface associated with the Holocene sea level rise. Accordingly, the sand ridges might have formed during the Younger Dryas at about 10,000 years BP, favoured by the deceleration of sea-level rise.

The architecture of the sand ridges also reveals the presence of small, mound-like features. Based on their acoustic signature, these features are interpreted as coast-associated features such as cemented beach deposits or armoured shallow-water deposits that may act as the nucleus for sand ridge genesis through the interaction between flow and seabed roughness. Their preservation within the sand ridges indicates that these ridges have not migrated enough to erode the precursor.

The formation of sand ridges on the GoV and Murcia continental shelves suggests that despite the low fluvial sedimentary contribution, enough sand was locally available for ridge development, most likely derived from marine reworking of coastal deposits during transgression. However, the limited sediment availability determines the reduced areal extent of the sand ridge fields in comparison with other storm-dominated sand ridges developed in areas with higher sediment availability, such as the Atlantic shelves of North America (Goff et al., 1999; Li and King, 2007), where sand ridges spread over tens of kilometres along the continental shelf.

5.2 Sand ridge evolution

Internally, the sand ridges display SE dipping oblique reflectors indicating long-term migration towards the south. These reflections appear associated with mud layers interbedded in sand sediment suggesting episodic ridge migration, with intervals of reactivation after relatively calm periods dominated by mud deposition.

The comparison of the sand ridges observed in the GoL and Murcia continental shelves with those described in the Gulf of Lions (GoL), north of the study areas, reveals some differences in their architecture (Fig. 6). On the Murcia continental shelf, most sand ridges contain evidence of their precursor (Fig. 6b), whereas in the GoV only some ridges display evidence of their initial irregularity (Durán et al., 2015) (Fig. 6c). In fact, where the precursor is preserved, it is smaller than that those observed in the Murcia sand ridges. Sand ridges in the GoL show no traces of the initial stages of development (Bassetti et al., 2006) (Fig. 6d).

Based on the differences in the sand ridge location and the preservation of the precursor, we can establish a gradation from partially evolved sand ridges on the Murcia continental shelf to more evolved ones in the GoV and the fully evolved ones in the GoL. These observations agree with the sand ridge evolution described on the New Jersey continental shelf (McBride and Moslow, 1991;

Snedden et al., 1999), where sand ridges are found today in three stages of development, the deeper sand ridges being older and more evolved than the shallower ones.

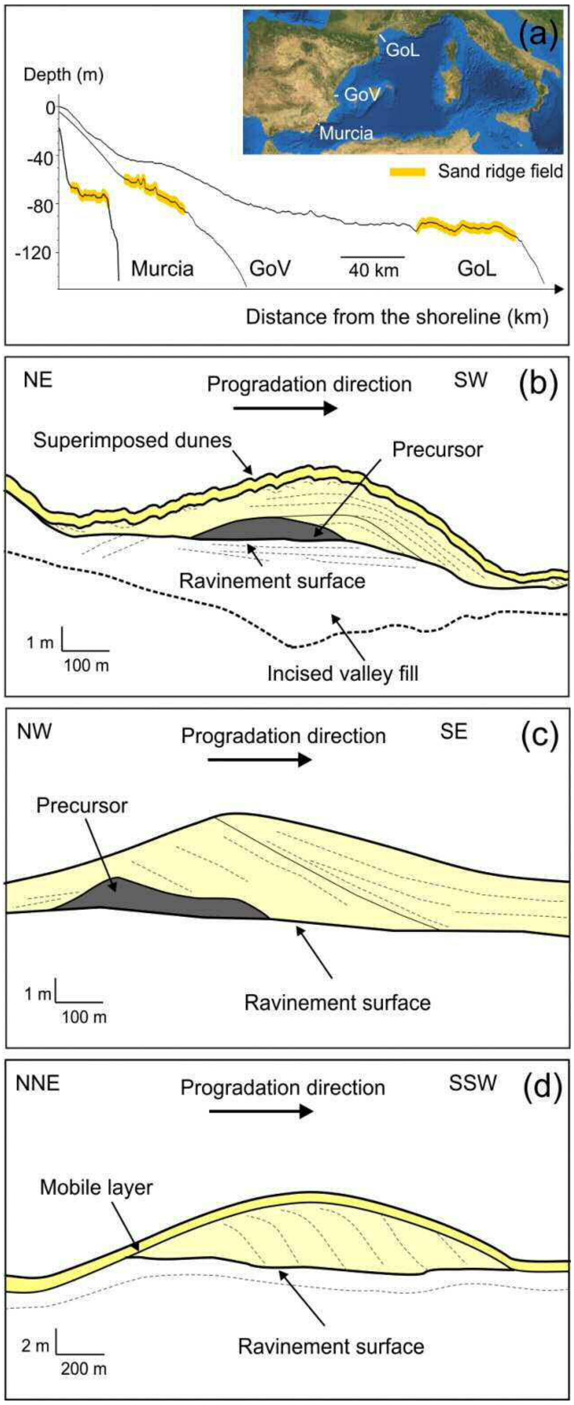

Figure 6. (a) Bathymetric profiles across the Murcia, GoV and GoL continental shelves indicating the location of sand ridges. (b to d) Schematic diagrams illustrating sand ridge architecture observed on the: (b) Murcia, (c) GoV and (d) GoL shelves. Modified from Durán et al., 2018.

5.3 Sand ridges as potential borrow areas

Understanding the formation and evolution of these bedforms is of high interest because of their potential as sources of sediment for beach nourishment and coastal restoration. During the last years, the increasing shortage of sand around the world has let the governments to go further out into the sea to obtain new sand supplies. Shoals, sand ridges and other sediment bodies developed on the middle shelf represent valuable strategic sand resources.

In Europe, around 50 million m^3 of sand and gravel are extracted each year from the inner continental shelf (Sutton and Boyd, 2009). Along the Spanish Mediterranean coast, only between 1997 and 2002, a total fill volume of about 110 millions of m^3 were used for coastal protection (Hamm et al., 2002). In the Valencia sand ridge field, it was defined a potential sand borrow area of 22·million m^3 (Durán et al., 2015). It constitutes a valuable potential sand resource because of the high quality of sediment. However given the level of demand of the region, about 3 million m^3/year since 1950s (Yepes and Medina, 2005), the stored volume of sand only would cover the huge nourishment requirements for recreational purposes for about 7 years.

On that basis, even though offshore sand ridges developed in these continental shelves represent strategic potential sand borrow areas, their use for such an unsustainable goal as artificial beach nourishment is discouraged because of the limited volume of sand.

6. CONCLUSIONS

The architecture of the GoV and Murcia sand ridges provides a better understanding of the formation and evolution of sand ridges in tideless environments.

The sand ridges developed over an erosional surface composed of coarse sand with pebbles that is interpreted as the Holocene ravinement surface.

Coast-associated features can act as a precursor of sand ridge genesis. Their preservation within the sand ridges indicates that these ridges have not migrated enough to erode the precursor.

The formation of sand ridges on the GoV and Murcia continental shelf demonstrates that sand ridges can develop on tideless shelves with a reduced sediment supply when local conditions favour the accumulation of sediment.

The sand ridges observed in the western Mediterranean are found in three stages of development from partially evolved to fully evolved sand ridges with increasing water depth.

Despite the offshore sand ridges constitute valuable potential sand borrow areas, it is recommended to preserve them as strategic sand reservoirs.

7. ACKNOWLEDGEMENT

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