Sediment characteristics and internal architecture of offshore sand ridges on a tideless continental shelf (western Mediterranean)

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Abstract:	<p>An integrated approach, combining swath bathymetry, an extensive dataset of vibrocores and high-resolution seismic reflection data was used to assess the origin and evolution of offshore sand ridges in a tideless continental shelf (Gulf of Valencia, western Mediterranean). The sand ridges are located in the mid-outer shelf at 55-85 m water depth, obliquely oriented to the shoreline. They are 1.5 to 7 m high, with a wavelength between 600 and 1,100 m, and a mean height-wavelength ratio of 0.004. The sand ridges are composed of well-sorted medium sand and are partially covered by a mud layer, evidencing a moribund stage. They overlie an erosion surface that locally crops out at the seafloor and is interpreted as the Holocene wave ravinement surface. In the sediment cores, this surface corresponds to an erosional lag composed of coarse sand and gravel with pebbles. Small topographic irregularities on this surface are interpreted as shoreline-associated features that may act as the precursor for ridge development. Their preservation within the sand ridges could be related to the hardness of these features. Internally, the sand ridges display high-angle dipping reflections, indicating ridge migration towards the southeast in the direction of the present-day sediment transport direction. The presence of interbedded mud layers, associated with these reflections, indicates intermittent episodes of mud deposition when active. The internal architecture of some small ridges also provides new insights into their transition from active to moribund state, as evidenced by a change in the geometry of the internal units from progradational to aggradational that are finally overlain by onlapping finer deposits over the flanks and in the troughs. The Gulf of Valencia sand ridge field constitutes a valuable potential sand resource of 22·million m³ of well-sorted medium and</p>

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ABSTRACT

An integrated approach, combining swath bathymetry, an extensive dataset of vibrocores and high-resolution seismic reflection data was used to assess the origin and evolution of offshore sand ridges in a tideless continental shelf (Gulf of Valencia, western Mediterranean). The sand ridges are located in the mid-outer shelf at 55-85 m water depth, obliquely oriented to the shoreline. They are 1.5 to 7 m high, with a wavelength between 600 and 1,100 m, and a mean height-wavelength ratio of 0.004. The sand ridges are composed of well-sorted medium sand and are partially covered by a mud layer, evidencing a moribund stage. They overlie an erosion surface that locally crops out at the seafloor and is interpreted as the Holocene wave ravinement surface. In the sediment cores, this surface corresponds to an erosional lag composed of coarse sand and gravel with pebbles. Small topographic irregularities on this surface are interpreted as shoreline-associated features that may act as the precursor for ridge development. Their preservation within the sand ridges could be related to the hardness of these features. Internally,

the sand ridges display high-angle dipping reflections, indicating ridge migration towards the southeast in the direction of the present-day sediment transport direction. The presence of interbedded mud layers, associated with these reflections, indicates intermittent episodes of mud deposition when active. The internal architecture of some small ridges also provides new insights into their transition from active to moribund state, as evidenced by a change in the geometry of the internal units from progradational to aggradational that are finally overlain by onlapping finer deposits over the flanks and in the troughs. The Gulf of Valencia sand ridge field constitutes a valuable potential sand resource of 22·million m³ of well-sorted medium and coarse sand with limited mud content, that must be preserved as strategic sand reservoir.

Keywords: Bedforms, storm-dominated sand ridges, sedimentary structures, palaeotopography, preservation, sand sources, coastal protection, and sustainability.

1 INTRODUCTION

Offshore sand ridges, also named shoreface-detached ridges or drowned ridges, are large-scale bedforms observed on middle and outer continental shelves in both tidal-dominated (Berné et al., 2002; Liu et al., 2007) and storm-dominated environments (e.g. Swift et al., 1972; Bassetti et al., 2006; Simarro et al., 2015). In tidal-dominated settings, offshore sand ridges show elevations of 25 to 30 m with orientations that are 5°-30° rotated with respect to the peak tidal flow direction, generally in an anticlockwise sense in the northern hemisphere (Dyer and Huntley, 1999; Liu et al., 2007). Offshore sand ridges on storm-dominated continental shelves are smaller (up to 12 m high), and show an orientation oblique to the shoreline (e.g. 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. They are mostly composed of fine to coarse sand (e.g. Swift and Field, 1981; Dalrymple and Hoogendoorn, 1997; Snedden and Dalrymple, 1999), and are characterised by a predominant asymmetric transverse profile with steeper down-current flanks (Bassetti et al., 2006; Li and King, 2007) and internal oblique reflections (Goff et al., 2005; Durán et al., 2018).

The genesis of sand ridges can be explained by the stability model of Huthnance (1982), initially developed for linear sandbanks in tide-dominated settings and subsequently accepted for the formation of sand ridges on storm-dominated shelves (Dalrymple and Hoogendoorn, 1997; Snedden and Dalrymple, 1999). Based on this model, the requirements for sand ridge development include 1) availability of sufficient sand, 2) presence of currents capable of transporting sand-sized sediment; and 3) a pre-existing irregularity in the seafloor topography that initiates the flow-bed interaction. Sand source for ridge formation is commonly provided by marine reworking of ebb-tidal delta deposits (Swift et al., 1972; Figueiredo et al., 1982; McBride and Moslow, 1991), barrier-island and fluvial delta deposits (Swift et al., 1972; Bassetti et al., 2006), and periglacial deposits (Hoogendoorn and Dalrymple, 1986; Li and King, 2007), while sand transport is mainly attributed to near-bottom currents induced by storms, wind waves and/or tide-induced flows at the foot of the shoreface (Trowbridge, 1995; Goff et al., 1999; Snedden and Dalrymple, 1999). Regarding the initial topographic irregularity, the most common precursors for sand ridge formation are shoreline-associated features such as ebb-tidal deltas (e.g. McBride and Moslow, 1991; Snedden et al., 1994; Snedden and Dalrymple, 1999; Robinson and McBride, 2006), nearshore bars, large dunes (Snedden and Dalrymple, 1999) or random topographic irregularities on the ravinement surface (Snedden and Dalrymple, 1999; Durán et al., 2018). It has been suggested that this precursor irregularity may later be removed or greatly reduced in size through subsequent erosion during sand ridge migration (McBride and Moslow, 1991; Snedden et al., 1999).

Following the work of Huthnance (1982), several studies were conducted on the physical mechanisms responsible for the generation of sand ridges on continental shelves. For tidal sand banks, such models have been developed and analysed by Hulscher et al. (1993) and de Swart and Hulscher (1995). The formation of sand banks appears to be due to the combined effect of residual circulations, which develop owing to tide-topography interactions (Zimmerman, 1981). For shoreface-connected ridges on storm-dominated shelves, several theories have been proposed for their formation and evolution. The first model was presented by Trowbridge

(1995) who explained the formation of these ridges as morphodynamic self-organization related to frequent storm-driven currents. In this model, the physical mechanism for the development of the sand ridges is the offshore deflection of the storm-driven alongshore flow at the ridge crests and sediment convergence in the offshore direction due to the slope. Successive improvements of this model included bedload, suspended load sediment transport and a depth-dependent stirring of sediment by waves (Calvete et al., 2001). During sea level rise, the shoreface-connected 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 drops below the critical velocity for entrainment and transport of sediment (Nnafie et al., 2014), forming a field of isolated bedforms in deeper waters. At present, sand ridges on the middle and outer shelf are defined as active when they can develop or migrate, relict when there is no interaction with present-day processes, and moribund if sedimentary processes tend to degrade their morphology or modify their original characteristics (Yang, 1989; Dyer and Huntley, 1999). In a slightly different way, De Swart and Yuan (2018) suggest that moribund sand ridges occur when sand transport is absent in the entire ridge area (equivalent to relict sand ridges), whereas “quasi-active” sand ridges (Liu et al., 2007) are characterized by intermittent dynamics caused by the highest-energy events.

Offshore sand ridges have been widely described on modern continental shelves, and also have been identified in the sedimentary record. However, despite the abundance of evidence of modern sand ridges, unequivocal transgressive sandstone bodies as analogues of shelf ridges are scarce (Suter, 2006). The limited occurrence of ancient sand ridges is mostly due to ambiguous interpretations of these sand bodies. Several marine sandstone bodies, initially interpreted as shelf sandstone deposits (Tillmand and Martinsen, 1984; Krause and Nelson, 1991), were subsequently reinterpreted as incised-valley deposits (Sullivan et al., 1997) or lowstand shoreline deposits (Walker and Bergman, 1993). Driven by the need to improve the interpretation of ancient sand ridges in the sedimentary record, new emphasis has been put on the definition of key criteria for the identification of ancient shelf-ridge deposits based on new

data from both modern (Suter, 2006; Snedden et al., 2011) and ancient shelf ridges (Posamentier, 2002; Schwarz, 2012; Leva López et al., 2016). Therefore, further investigation is needed to fully understand how active sand ridges gradually become moribund and how these features are preserved in the geological record.

There is a high interest in understanding the formation and evolution of sand ridges on the mid-outer shelf because they may dissipate surface wave energy and thereby protect sedimentary coasts, and represent potential locations for offshore windfarm installations. Furthermore, offshore sand ridges constitute strategic resources and may be an important source of sediment to maintain beach stability (e.g. beach nourishments). During the last decade, the increasing shortage of sand around the world has forced governments to go farther offshore to obtain new sand supplies. Shoals, sand ridges and other sediment bodies developed on the mid and outer shelf (e.g. Schwab et al., 2013; Durán et al., 2015; Ribó et al., in press) are expected to serve as long-term sand resources for beach nourishment and coastal restoration projects.

In this work, we present a detailed analysis of the sediment characteristics and internal architecture of offshore sand ridges developed on a storm-dominated continental shelf, the Gulf of Valencia (GoV) continental shelf in the western Mediterranean (Fig. 1). Tidal action in the western Mediterranean Sea is very small, with tidal amplitudes of approximately 0.2 m, so it is frequently considered as tideless (King and Williams, 1949). Tidal currents are very weak (few cm/s) and only detectable in absence of waves and winds (Guillén et al., 2002), with a negligible impact on morphodynamic processes. This hydrodynamic setting differs from other shoreface-connected sand ridges develop on storm-dominated continental shelves, such as the North Sea off Belgian and Dutch microtidal coasts, where tidal amplitude is higher than 1 m, and tidal currents and storms are both important sediment stirring agents (Van de Meene, 1994).

The present study is based on an integrated approach combining swath bathymetry, an extensive dataset of vibrocores and high-resolution seismic reflection data. The cross-ridge seismic profile originally presented by Simarro et al. (2015) is herein re-examined by incorporating collocated

(or nearly so) sediment cores in order to compare the fine-scale internal structure of the sand ridges with the textural information provided by vibrocores. The aim of this work is to provide a better understanding of: (1) the formation and long-term migration of offshore sand ridges on tideless continental shelves; (2) the transition from active to moribund sand ridges and their potential for preservation; and (3) the potential use of these bedforms as sand reservoirs for shoreline protection.

2 STUDY AREA

The continental shelf of the Gulf of Valencia (GoV) extends from the southern Ebro shelf (south of the Columbretes Island) to the promontory of Cap La Nao, in the western Mediterranean Sea (Fig. 1). It has a variable width with the shelf edge at ~150 m water depth. The shelf is wider south of the Columbretes Islands (exceeding 47 km), but it severely narrows towards the south (~35 km wide) reaching its minimum width at the southern end off Cap La Nao, where it is only 15 km wide (Rey and Díaz del Río, 1983).

The GoV continental shelf is a storm-dominated environment with a source of sediment from riverine inputs and a marked seasonal wave climate (Maldonado et al., 1983; Young et al., 1983), with October–April being the most energetic period. The tidal amplitude in the study area is usually below 0.2 m. The main river discharging in the area is the Turia River (Fig. 1), which shows a typical Mediterranean regime with most of the discharge concentrated in high magnitude and low frequency flood events (Martín-Vide, 1985; Martín-Vide et al., 2008). The mean discharge recorded by gauging stations in this river is around 14 m³/s with strong peaks higher than 400 m³/s (with extremes up to 3000 m³/s during the 1957 flood; Cánovas, 1958). In addition, short ephemeral streams flowing into the GoV. These streams carry very coarse material and experience very strong floods in Spring and Autumn when water discharge may be up to 590 m³/s (Sanjaume et al., 1996). Sediment inputs of the Turia River contribute towards the development of sand barrier beaches and those from the ephemeral streams develop pebble barrier beaches (Sanjaume et al., 1996). At present, the GoV continental shelf is characterised

by relative sand starvation.

The water circulation in the GoV and over the Ebro continental shelf is strongly controlled by the wind pattern (Espino et al., 1998; Font, 1990), and local mesoscale events forced by wind bursts and by the Ebro River discharges (Salat, 1995; Salat et al., 2002). The along-shelf sediment flux towards SSW is dominant over the mean seaward cross-shelf flux, with maximum near-bottom sediment fluxes associated with storms (Young et al., 1983; Puig et al., 2001; Palanques et al., 2002). A hydrodynamic study focussing on the sand ridges area reveals that near-bottom shear stress, as generated during storm conditions, is able to resuspend and transport sandy and muddy sediments in the middle shelf (Simarro et al., 2015).

The stratigraphic record of the GoV continental shelf comprises a thick series of Plio-Quaternary deposits composed of several barrier-lagoon systems, whose formation has been related to Late Quaternary stillstand periods (Rey and Diaz del Rio, 1983; Albarracín et al., 2013; Lobo et al., 2015), and their preservation is favoured by high subsidence rates (Albarracín et al., 2013). During the Holocene, rising sea levels resulted in the erosion of these deposits through wave ravinement, forming an erosive surface mantled by gravel and coarse sand that determines the baseline level of the present-day sedimentation on the GoV shelf (Rey et al., 1999). At present, sand and gravels, composed of mixed amounts of clastic and carbonate, cover the inner shelf (Fig. 1b), whereas a muddy blanket extends along the middle and outer shelf (Giró and Maldonado, 1983), with accumulation rates of about 1.3–1.9 mm/y (Maldonado et al., 1983; Young et al., 1983). Only in the central part of the continental shelf, an isolated area of sandy sediments occupies the middle shelf (Giró and Maldonado, 1983; Rey et al., 1999).

The present-day morphology of the continental shelf displays a complicated topography determined by the presence of modern and relict features, which are the result of the glacioeustatic oscillations from the Upper Pleistocene to the Holocene. Modern prodeltas and infralittoral prograding wedges, and carbonate-cemented relict coastal barrier islands (i.e., beachrocks) dominate the inner shelf (Giró and Maldonado, 1983; Rey and Díaz del Río, 1983;

Alcántara-Carrió et al., 2013), whereas large sediment bodies, interpreted as sand ridges, are found on the middle shelf (Maldonado et al., 1983; Albarracín et al., 2014; Simarro et al., 2015). The sand ridges occur between 55 and 85 m water depth showing a predominant NE-SW orientation, oblique ($\sim 50^\circ$) to the isobaths (Maldonado et al., 1983; Rey and Díaz del Río, 1983; Albarracín et al., 2014) (Fig. 2a). The ridge heights (H) range from 1.5 to 7 m, the wavelength (L) from 600 to 1,100 m, the crestline length from 1,100 to 3,100 m (Simarro et al., 2015), with a mean relation H/L of 0.004. These ridges are asymmetric with the steeper lee face on the southeast side of the crest, consistent with the present-day net sediment transport direction.

3 DATA AND METHODS

The analysis of the GoV sand ridges is based on the interpretation of swath bathymetry, very high-resolution seismic reflection data and sediment cores (Fig. 2). Swath-bathymetry was acquired in 2010 using the Elac Seabeam 1050D 180 kHz multibeam echosounder mounted on the R/V García del Cid. Sound velocity data were obtained from multiple conductivity, temperature and depth (CTD) casts collected during the cruise. Post-processing of multibeam data (including correction for heading, depth, pitch, heave and roll) was conducted using the CARIS HIPS and SIPS Hydrographic Data Processing System. Tidal and sound velocity corrections were applied and the sounding data were cleaned to remove erroneous soundings. Filtered soundings were gridded into 4 m resolution bathymetric surface with 100% coverage. The gridded multibeam data sets were projected to Universal Transverse Mercator (UTM) 30N zone projection in the World Geodesic System (WGS) 1984 geographic coordinated system. Crests and troughs of the sand ridges were defined using the bathymetric position index (BPI), as modified from the topographic position index as defined by Weiss (2001).

Information from a total of 279 vibrocores was provided by the Spanish Ministry of Agriculture, Food and Environment (Sub-Directorate General for Coastal Protection) (Fig. 2b). Vibrocores were collected in 2007 onboard the R/V Investigador. Positioning was determined with a differential GPS. Vibrocores were 4-5.5 m long with a diameter of 90 mm. Each sediment core

was sub-sampled every 0.5 m for grain size analysis, resulting in 2754 samples. Grain-size distributions were computed via sieving with the following diameters: 4.5, 2, 1, 0.71, 0.5, 0.42, 0.25, 0.16, 0.125, 0.074 and 0.063 mm. Mean values and sorting were calculated geometrically (in metric units) using the graphical method of Folk and Ward (1957), included in the GRADISTAT software (Blott and Pye, 2001). The following classes were used to describe the sediment samples: gravel (sediment size fractions >2 mm), coarse sand (2-0.5 mm), medium sand (0.5-0.25 mm), fine sand (0.25-0.063 mm) and mud (<0.063 mm). The analysis of sand grain composition was based on binocular microscope examination of grains. No direct access to the vibrocore samples was possible, preventing further detailed analyses. Bathymetric and sediment data were integrated using Esri's ArcGIS 10.5 software. A surficial sediment texture distribution map was based on the Folk classification (1954).

A high-resolution seismic reflection profile across the sand ridges was obtained in 2011, using a Kongsberg TOPAS PS 018 Parametric sub-bottom profiler installed onboard the R/V Vizconde de Eza by the Spanish Secretariat for the Sea and the Spanish Oceanography Institute. The TOPAS transmitted each 1–2 s, with a beam angle of approximately 5° , and a modulated frequency sweep ranging between 16 and 20 kHz, resulting in a vertical resolution of about 15 cm. Standard processing was applied to the seismic data, including time variable gain (TVG) amplifying during acquisition and band-pass filtering. High-resolution seismic reflection data were imported as SEG-Y files into the KINGDOM SUITE™ software for interpretation. Seismic reflection data were complemented with a previous dataset collected in 1983, using a 3.5 kHz sub-bottom profiler installed onboard the R/V García del Cid, available from the database of the Marine Science Institute, CSIC (Figs. 1 and 2b). Sound velocities used for time-to-depth conversion were 1550 m s^{-1} in water and 1650 m s^{-1} in sediment. Seismic reflection lines are represented in two-way travel time (milliseconds TWTT), and gradient values are given in degrees. Individual sand ridges located along the seismic profile acquired in 2011 are named as ridges I to XI to assist in identification in the following discussion (Fig. 2).

4 RESULTS

4.1 The basal surface of the sand ridges

The high-resolution seismic reflection profile displays a strong reflector at the base of the sand ridges, named hereafter as basal reflector, which corresponds to a major erosion surface that can be traced along the whole continental shelf (Fig. 3). This surface exhibits a rough topography with high-reflectivity mounded morphologies and high-relief areas from beachrocks that locally crop out at the seafloor (Fig. 3). The gradient of this surface is 0.2° in the middle shelf and increases to 0.5° in the outer shelf. In the area of the sand ridges, the basal reflector underlies the sand ridges and intersects, or comes very close to, the seafloor in the deeper parts of the troughs, as observed from the sand ridges VI to IX (Fig. 4). Across the sand ridge field (Fig. 4), the basal surface dips gently (0.04°) towards the southeast from ~ 92 ms (~ 72 m) in the northern sector to ~ 104 ms (~ 81 m) in the southern one, and shows an irregular topography.

Sediment cores penetrating the basal reflector evidence a layer of gravel with pebbles at depths between 1.5 and 5.5 m below the seafloor (mbsf) in the sand ridges (e.g. cores 107, 113, 114, 116 and 190; Figs. 4 and 5) and at 0.5–2.5 mbsf (e.g. cores 100 and 108; Fig. 4) or locally exhumed at the seafloor (e.g. core 193; Fig. 4) in the troughs between ridges. An example of this coarse lag at the base of the sand ridges can be observed in sand ridge IX, where the sediment cores penetrate almost 3 m into the seafloor through the basal reflector (Fig. 5). At the core location, this reflector lies ~ 2 ms (~ 1.6 m) below the seafloor. The grain size analysis reveals a surficial layer of mud and sand (fining upwards) over a layer of gravel that extends from 1.7 to 2.7 mbsf. Sediment samples from the coarse lag are composed of gravel (60% on average, up to 98%) and coarse sand (21% on average, up to 68%) with a low mud content ($< 4\%$) and median grain sizes up to 4.75 mm (Fig. 6g). Core photographs show abundant mixtures of cobbles (64–256 mm) and boulders (> 256 mm) (Fig. 7). This coarse sediment layer provides the only likely candidate for generating the impedance contrast necessary to produce this strong reflector. A similar correlation was observed in most vibrocores collected along the seismic line

(e.g. cores 27, 30 and 116; Fig. 4) with the exception of some sediment cores where the basal reflector is associated with a change from fine sediment above to poorly sorted sand below (e.g. cores 62 and 108; Fig. 4). The lack of evidence of the coarse lag in these cores could be due to the reduced thickness of this deposit and the sampling method. The coarse lag is commonly thicker than 0.5 m, which corresponds to the sampling frequency.

This coarse deposit marks a sharp lithological passage with the underlying deposits, which display significant lateral variability (Fig. 4). In the northern sector of the sand ridge field, underlying sediments are composed of moderately to well-sorted fine sands (67% on average, up to 95%) with a variable content of medium (1-51%) and coarse (0-23%) sand (Figs. 4 and 6b). Conversely, in the southern sector of the sand ridge field, sediments beneath the coarse lag are mostly composed of coarse sand (23% on average, up to 58%) and gravel (36% on average, up to 66%) (Figs. 4 and 6c). The change in the sediment characteristics of the lag deposit and the underlying sediments, coarsening towards the south, is also evidenced by the seismic attributes of the basal surface that becomes more irregular and reflective with poor seismic penetration, particularly under the sand ridges (Fig. 4).

4.2 Sediment characteristics of the sand ridges

The seismic unit overlying the basal erosion surface corresponds to the sand ridges unit. The thickness of this unit varies between 0 and 2.4 m in the troughs, but it can be up to 8.2 m in sand ridge crests (Fig. 4). The sand ridges are commonly asymmetric with the steepest slope facing the SE, with the exception of some smaller ridges that show a nearly symmetric profile (e.g. ridges I, III and VII). The dip angle of the steeper slope is 0.7°-3.5° (1.9° on average), whereas the angle of the gentle slope is 0.5°-1.6° (1.0° on average), with a slope ratio of ~1:2. This slope ratio indicates that sand ridges are commonly asymmetric.

The surficial sediment distribution on the sand ridge field reveals the presence of a discontinuous mud domain that is mostly composed of mud (75% on average) and medium sand (15% on average) with a low fine (6% on average) and coarse (4% on average) sand content.

The mud content within this domain increases towards the north up to 98% in the northernmost sector (Fig. 8b). This mud domain preferentially occupies the troughs between ridges, with the exception of the northernmost sand ridges where it extends over the ridges crest (e.g. ridge I and part of ridge IV; Fig. 8a). Surficial sediment on the crests of sand ridges are mostly composed of medium (40% on average) and coarse (8% on average) sand with low gravel content ($< 8\%$).

The thickness of the mud layer varies between 0.5 and 1.5 m (up to 3 m) increasing towards the north (Figs. 4 and 8c). The minimum thickness of this layer occurs on the crest of the sand ridges, as well as in the troughs between ridges VI to IX, where a coarse-grained deposit (up to 40% of gravel) is emergent at the seafloor (Fig. 4). In addition to this north-south textural pattern, important crest/trough surficial textural variations were also observed. Mud content is high in the troughs between ridges (mud content of 60-90%) decreasing towards the crests, which are characterised by sandy sediments with a mud content of 10-30%. Along the crest of individual ridges, the mud content also increases from the centre to the outside edges (Figs. 8b,c).

Four types of sediment cores have been distinguished based on their main sedimentological characteristics, showing a gradual transition among the different categories. Types 1 and 2 are dominated by coarse-grained sediment and are preferentially located on the crest and flanks of the sand ridges, whereas types 3 and 4 are dominated by fine-grained sediments and are located in the troughs.

Type 1 cores, located on the crest of the sand ridges (Fig. 9a), are characterised by a sand layer with a low mud content ($< 20\%$) that extends along the entire length of the core (e.g. VC10 and VC28; Fig. 9b) and hits the coarse lag when the sediment core penetrates the base of the sand ridges (e.g. VC114 and VC121; Fig. 9b). The sand layer consists of well-sorted medium (56% on average, up to 83%) and coarse (29% on average, up to 87 %) sands with up to 20% of mud and 10% of gravel (Fig. 6d). Binocular microscope observations indicated that these sediments are composed of subangular and subrounded quartz grains ($>94\%$) with a low content of

bioclasts (2-5%) and rock fragments (1-2%). The biogenic fraction is composed of fragmented gastropods, foraminifera, bivalves and echinoderm spicules.

Type 2 cores are located on the crest and flanks of the sand ridges (Fig. 9c). In these sediment cores, the layer of well-sorted medium and coarse sand appears covered by a surficial layer of mixed sediment, consisting of sand (33% on average, up to 68%) and mud (69% on average, up to 98% in the northernmost sand ridges) (Figs. 9d and 6c). The thickness of this surficial layer of mud and sand is commonly 0.3-1 m thick, but it can be up to 2.5 m at the edge of some ridges (e.g. sediment core 275; Fig. 9d).

Locally, the sandy facies of Types 1 and 2 cores display interbedded mud layers at different depths (e.g. cores 10 and 105 in Fig. 9). The interbedded mud layers exhibit similar textural characteristics of the surficial mud layer; they are mostly composed of mud with a variable content of fine and medium sand (Fig. 6b).

Type 3 cores appear preferentially in the troughs between the sand ridges (Fig. 10a). They are characterised by the presence of a surficial mud layer (0.5-1 m thick) with 55-85% of mud (Figs. 6a and 10b). Mud content within this layer decreases from the troughs towards the flanks of the sand ridges. As noted above, considerable lateral variability exists among these cores. In the northern sector of the sand ridge field, Type 3 sediment cores are characterised by a surficial mud layer overlying the coarse lag. A thick (up to 4 m) layer of moderately to well-sorted fine sand dominates the sediment cores below the coarse lag (e.g. cores 25 and 264; Figs. 4, 6f and 10b). A similar pattern can be also found in some Type 2 sediment cores, such as VC 275 (Fig. 9), where they are located on the lower region of the sand ridge flank, near the trough, evidencing the gradual change in the grain-size trends between the sand ridges and the troughs between ridges. Conversely, Type 3 sediment cores in the southern sector are more heterogeneous in grain size with a higher content of coarse sand and gravel (e.g. cores 193 and 211; Figs. 4, 6e and 10b). Locally, the coarse lag is located at less than 1 m below the seafloor with absence of an overlying layer (e.g. cores 100, 193; Figs. 4 and 9b).

Lastly, Type 4 cores are located in the troughs between ridges in the northernmost sector of the sand ridge field (Fig. 10c). They are characterised by a thick (1-3.5 m) surficial mud layer with a mud content between 85% and 98% (Fig. 10d). Similar to Type 3 cores, thin, intercalated coarse beds are also observed at different depths in Type 4 cores.

4.3 Internal structure of the sand ridges

The internal architecture of the sand ridges is well established in the smaller sand ridges, such as the sand ridges IV, IX and XI (Figs. 5 and 11). In the largest ridges, the seismic profile displays a thick pattern of parallel reflections that mimic the seafloor, corresponding to an artefact of the acoustic signal that masks the internal structure of the sand ridges (Fig. 4). Small sand ridges, like sand ridge IV, are characterised by steep clinoforms and a convex, upper boundary surface (Fig. 11). The clinoforms have a thickness up to 10 ms (~8.25 m) and dip toward the SE. Locally, small mound-like features with low relief (up to 1 m high) and limited extend (less than 350 m wide) are identified within the sand ridges (Figs. 4 and 11). In some small ridges, such as ridge IV, different internal subunits can be identified (Fig. 11): an aggradational lower unit, named Unit 1, that comprises internal convex reflectors; a progradational seismic unit (Unit 2), characterised by relatively high-angle clinoforms with 1-1.5° dipping foresets; a thin (~0.3 m thick) ridge-conform unit (Unit 3) characterised by slightly divergent internal reflections with gentle dipping angle (around 0.7°) that onlap onto high-angle clinoforms, and an upper unit (Unit 4). These units, identified in the seismic profiles, are consistent with the textural variation observed in the sediment cores across the sand ridges (Fig. 11). The high-angle clinoforms (Unit 2) consist of medium and coarse sand with a low content of mud, corresponding to the lower unit identified in the Type 2 cores (VC 116), located on the flanks of the sand ridges. The upper aggradational unit (Unit 3) and the low-angle divergent seismic facies (Unit 4) can be correlated to the surficial unit of mixed sediment (mud and sand) observed in the Type 2 cores. This surficial layer becomes thicker with increasing distance from the crest ridges, with maximum

values in the trough, corresponding to the surficial layer described in the Type 3 cores (e.g. VC 113). A coarse lag deposit corresponding to the basal reflector of the sand ridges is observed in both sediment cores.

Seismic facies between the sand ridges are characterised by subparallel, aggradational reflections with a very low dipping angle towards the south corresponding to fine-grained sediment in the sediment cores (Figs. 4 and 11), indicative of low-energy sediment fill. Below the basal reflector, the seismic facies exhibit a semi-transparent pattern due to the thickness of the sand ridges. Laterally continuous low-angle to flat seismic reflections can be identified below the basal reflector only under the northern sand ridges (e.g. sand ridges IV and IX; Fig. 4). Locally, buried mound-like features can be identified in these strong reflectors. These facies evolve southwards to opaque facies due to the poor penetration of the seismic waves below the coarse sediments of the erosional surface (Fig. 4). Detailed seismic analysis of small sand ridges also revealed the presence of high-angle clinoforms under the sand ridges (Fig. 11).

5 DISCUSSION

5.1 Interplay between the palaeo-topography and sand ridge formation and migration

The analysis of high-resolution seismic reflection data document a basal reflector beneath the sand ridges that corresponds to a regionally recognized erosion surface, previously interpreted as the Holocene ravinement surface (Albarracín et al., 2014; Simarro et al., 2015). Sediment cores penetrating this surface intersect a thin (commonly less than 0.5 m thick, Fig. 4), coarse-grained deposit composed of siliciclastic coarse sand and gravel with pebbles and cobbles associated to this surface, which supports this interpretation. This coarse-grained deposit corresponds to a transgressive lag formed by shoreface erosion of the underlying strata during transgression. In the southern sector of the sand ridge field, this lag marks a sharp lithological change from poorly-sorted coarse sand and gravels in the underlying deposits to well-sorted medium sand reworked in the sand ridges, suggesting a transition from coastal plain to marine conditions (drowning phase). The underlying sediments are found to be coarser towards the

southeast and these coarse-grained deposits also thicken towards the southeast (Fig. 4), most likely due to the proximity of coastal streams supplying coarser material. The ravinement surface locally crops out at the seafloor in some troughs between the ridges, evidencing relative sand starvation. At present, the source of the sandy sediment should be limited to the winnowing of coarse deposits associated with the erosion of this surface. The highly reflective mounded morphologies, as identified in the ravinement surface, are similar to those described on other continental shelves, such as US Atlantic shelf (Goff et al., 2005; McHugh et al., 2010), in the English Channel (Mellet et al., 2012; Mellet and Plater, 2018), on the South African shelf (Petrorius et al., 2016), in the Gulf of Cádiz (Lobo et al., 2018) and in the North Sea (Emery et al., 2019). On the US Atlantic shelf, irregular highs with chaotic reflections have been related to coarse-grained, armoured shallow-water deposits (Goff et al., 2005) or coastal headlands (Schwab et al. 2014). On the South African shelf, offshore Durban, acoustically opaque and isolated ridges with local high-relief pinnacles were interpreted as cemented coastal deposits such as beachrocks and/or aeolianites within palaeo-barrier complexes (Green et al. 2013; Salzmänn et al. 2013; Pretorius et al. 2016). On the Dogger Bank (North Sea), elongated, mounded morphologies bounded by a continuous high-amplitude top reflector were also interpreted as remnants of early phases of barrier building (Emery et al., 2019). Very similar facies and morphologies have been reported on the Mediterranean continental shelves of western Sardinia (De Falco et al., 2015), Gulf of Lion (Tesson et al., 2015) and Murcia (Durán et al., 2018), also interpreted as preserved coarse-grained, commonly lithified coastal deposits. A similar interpretation can be inferred for the irregular mounds in the GoV based on their seismic characteristics. The high degree of acoustic impedance suggests their development in a nearshore environment as cemented beach deposits or armoured shallow-water deposits associated to palaeo-barrier complexes. The presence of buried mound-like features, and high-angle clinoforms below the ravinement, are also evidence of drowned barriers within the stratigraphic record. This agrees with the identification of carbonate-cemented relict coastal barrier islands and associated coastal lagoons of the inner shelf (Rey and Diaz del Rio, 1983; Alcántara-Carrió et al., 2013; Albarracín et al., 2013).

These shoreline-associated features, preserved over the ravinement surface, may act as the precursor for sand ridge development, producing an initial bathymetric irregularity large enough to disturb linear water flows under suitable conditions of available sand and active storm-induced bottom-currents at the foot of the shoreface. Morphodynamic models demonstrated that sand ridges may develop spontaneously as free instabilities of the coupled water-bottom system (e.g. morphodynamic self-organization) (Huthnance, 1982; Trowbridge, 1995; Calvete et al., 2001). However, their evolution is much faster when they develop from a suitable previous topography (Nnafie et al., 2014).

As ridges migrate, sediment is eroded from the up-current (stoss) flank relative to the net transport direction and deposited on the down-current (lee) side. The analysis of high-resolution seismic reflection data has revealed the presence of internal oblique reflections dipping towards the southeast in the GoV sand ridges, providing insights into their migration (Figs. 5 and 11). As ridges migrate, sediment is eroded from the up-current (stoss) flank relative to the net transport direction and deposited on the down-current (lee) side, forming high-angle foresets. The presence of dipping reflections within ridges has been described also in other storm-dominated ridges in the Mediterranean (Bassetti et al., 2006; Lo Iacono et al., 2010; Durán et al., 2018) and on North American Atlantic continental shelves (Goff et al., 1999; Li and King, 2007, Snedden et al., 2011; Goff and Duncan, 2012). In the New Jersey sand ridges, burrowed, low-density mud beds within the high-energy upper ridge unit were interpreted as accretionary surfaces associated with cessation of migration followed by reactivation of ridge movement (Snedden et al., 2011). In the GoV sand ridges, the presence of thin mud beds interbedded in Type 1 and 2 cores (on crests and flanks) suggests intermittent episodes of mud deposition, in an otherwise sandy storm-dominated setting, during the active phase of the sand ridges. Mud drapes would be associated with high riverine fine sediment discharges directly deposited on the shelf or transported offshore during storms and settled from suspension in the waning stage of storms. Subsequent increased wind-driven currents during storms would most likely increase the migration rate. The alternative explanation of intercalated mud drapes on lee slopes of sand

ridges by migration of small superimposed bedforms (Reesink and Bridge, 2007) is unlikely here, since no superimposed bedforms were observed.

Observations on the Atlantic Margin off New Jersey and Sable Island revealed that in the absence of mud-burying morphologies, sand ridges at water depths shallower than 50 m display active sand dunes on their flanks, which are responsible for sand ridge migration (Goff et al., 1999). In deeper waters (>50 m), however, sand ridges appear to cease evolving via dune dynamics (Goff et al., 2005), although continued modification is accomplished through winnowing and erosive sculpting (Goff et al., 1999; Goff and Duncan, 2012). At present, sand ridges in the GoV show no evidence of migration, as indicated by the presence of a continuous mud blanket, associated to riverine fine sediment discharges, that covers part of the sand ridge field, particularly in the northern sector (Fig. 8).

The degree to which a ridge has migrated has important stratigraphic implications for the internal structure of the ridge. Bedform migration and growth (passing and deepening of the troughs) can excavate deeply into the substrate below the sand ridges, progressively destroying evidence of its precursor irregularity (Snedden and Dalrymple, 1999) and providing an addition to wave erosion in the formation of the ravinement surface (Goff, 2014). The nature of the initial irregularity and the degree of subsequent migration can explain the diversity of sand ridge characteristics. Based on the extent to which a ridge retains evidence of its precursor irregularity, MacBride and Moslow (1991) and Snedden and Dalrymple (1999) differentiate between partially evolved ridges close to, or attached to, the shoreline (Snedden et al., 1994; Robinson and McBride, 2006) and fully evolved ridges in the middle shelf (Snedden et al., 1994; Dalrymple and Hoogendoorn, 1997; Bassetti et al., 2006). The internal architecture of the GoV sand ridges reveals recognizable evidence of their precursor irregularity. The preservation of the initial irregularity within these sand ridges could be related to the apparent hardness of these basal features. Common precursors for sand ridge development described in other continental shelves include ebb-tidal deltas and sand bars (e.g. McBride and Moslow, 1991; Snedden et al., 1994; Snedden and Dalrymple, 1999; Robinson and McBride, 2006) that are

more easily eroded. However, the coarse nature of the precursor for the GoV ridges (coarse-grained or cemented) makes them highly resistant to erosion, thus favouring their preservation. Limited migration of the sand ridges, as evidenced by the predominance of aggradational over progradational facies in seismic data, may also have contributed to reduce erosion of underlying sediments and to maintain the characteristics of the initial paleotopography.

5.2 Evolution from active to moribund sand ridges: potential of preservation

The current morphology, sediment characteristics and internal structures of the GoV sand ridges indicate that they can be found at two different stages of evolution. The northern sand ridges (sand ridges I to IV) show gentle morphology and are buried by a thick mud layer, suggesting that these bedforms would be at the last stage of their geological evolution. This is supported by the internal architecture of these ridges that changes from progradational to aggradational and, ultimately, onlapping finer deposits over flanks and in troughs, providing evidence of the transition from active to moribund state (Fig. 11). The mud layer that covers the sand ridges is part of a large mud belt that extends along the middle shelf, with the exception of a small area within the sand ridge field, dominated by sandy sediments (Giró and Maldonado, 1983; Rey et al., 1999; Fig. 1). The burial of these sand ridges by the mud blanket should favour the preservation of these ridges on the middle shelf.

The internal architecture of these ridges also provides useful information for the identification of analogous ancient isolated marine sand bodies in outcrop and the subsurface. The GoV sand ridges have some common key characteristics that are used as diagnostic criteria for shelf ridges (Snedden et al., 2011; Schwarz, 2012; Leva Lopez et al., 2016). These diagnostic criteria include: sand ridge detachment from coeval shoreline deposits; an orientation oblique to the shoreline; a sharp basal unconformity with low topographic relief; presence of dipping, mud-draped internal surfaces; uniform grain-size with no significant grain gradation within the sand ridge unit; and a non-erosional upper-boundary surface with a convex up geometry and transitions into marine muds. In addition, new recognition characteristics can be derived from

the analysis of the GoV sand ridges. The different changes in geometry of the internal units (aggradation, migration, ridge-conform aggradation (no migration) and onlapping of finer deposits over flanks and in troughs) provide evidence of the growth and final stage of evolution of sand ridges that gradually become moribund until being covered by mud.

Whereas the internal structures of the northern sand ridges provide evidence of their degradation, the morphology and sediment characteristics of the sand ridges in the southern sector of the sand ridge area (ridges V to XI) differs from moribund ridges. Sand ridges V to XI are mainly composed of medium sand with a thin mud layer that pinches out towards the crest of the sand ridge and increases their thickness towards the troughs (Figs. 4 and 8), evidencing preferential accumulation of fine sediment between ridge crests. Resuspension processes observed on the ridges suggest that sediment dynamics (preferentially at the crest) still occur at present (Simarro et al, 2015). The mud drape may therefore be removed from the ridge crest, but it is preserved in the troughs due to a slight reduction in current velocity.

Active sand ridges are commonly characterised by an asymmetrical cross-section with maximum slope of the lee-side up to 7° and stoss-side slopes of $\sim 1^\circ$ (Stride, 1982). The higher slope gradients ($\sim 1.5^\circ$ on average) are found in active shoreface-connected sand ridges, whereas active offshore sand ridges are gentler (Swift and Field, 1981) (Fig. 12). Conversely, the transverse profile of moribund ridges is gentler, with a mean steep slope of 1° (up to 2.3°) and a mean gentle slope of 0.5° (Stride, 1982; Durán et al., 2018). The sand ridges in the GoV sand ridges field show gentle flanks ranging from 0.5° to 1.6° (1° on average), and steep flanks between 0.7° and 3.5° (1.9° on average) (Fig. 12), being the southern ones the steepest (mean gentle flanks of 1.13° and mean steepest flank of 2.21°). These values are higher than those reported for other moribund sand ridges (Stride, 1982; Swift and Field, 1981; Durán et al., 2018). Indeed, the GoV sand ridges are steeper than other active offshore sand ridges described on the Atlantic continental shelf (Li and King, 2007; Snedden et al., 2011). For instance, active offshore sand ridges near Sable Island show gentle slopes of 0.49° and steep slopes of 0.58° on average (Li and King, 2007). On the New Jersey middle shelf, active sand ridges show average

gradients between 0.4° and 1.0° (Snedden et al., 2011).

At a regional scale, it could be predicted that the steepness and asymmetry of the sand ridges would change with increasing water depth. Observations in Sable Island and the New Jersey continental shelves revealed that sand ridges become gentler and more asymmetrical with depth (Swift and Field, 1981; Goff et al., 1999; Li and King, 2007) (Fig. 12). In the Western Mediterranean, sand ridge asymmetry increases from $\sim 2:3$ in the Ebro Delta shoreface ridges (Guerrero et al., 2018) to $\sim 1:2$ in the Murcia and GoV offshore ridges (Durán et al., 2018; this work), showing a similar pattern to the NW Atlantic sand ridges. Moribund offshore sand ridges on the Murcia middle shelf are also gentler than active sand ridges on the Ebro Delta, in agreement with the transition from active nearshore to moribund offshore ridges. However, this tendency is not observed in the GoV southern sand ridges, which are even steeper than the Ebro Delta ridges (Fig. 12), suggesting that these ridges are not completely inactive and could be considered as “quasi-active” sand ridges as defined in other areas (Liu et al., 2007).

The maintenance of the ridge morphology in this area of the sand ridge field would be explained by the local hydrodynamics. Boundary-layer hydrodynamic measurements conducted on the sand ridge field showed evidence of active wave and current sediment resuspension and transport episodes during a major storm (Simarro et al., 2015). The influence of the wave field on the resuspension process was established in the initial part of the storm, whereas wave–current shear stress and advective processes dominated in the second half of the storm. The wave–current near-bottom shear stresses generated during storm conditions were able to mobilize the first centimeters of the surface sediment (mud and sand) in this area, producing a net transport towards the SE, oblique (around 20°) to the sand ridge field. Therefore, although the large sand ridges in the GoV do not migrate, sediment dynamics affecting sand ridges during storms likely contribute to the maintenance of their morphology, preventing their burial by fine sediment.

5.3 Sand ridges as potential borrow areas

About 25 billion m³ of sand and gravel are globally mined every year (Steinberg et al., 2010), and the extraction rate is increasing (Krausmann et al., 2009). During the last decade, the total quantity of marine sand and gravel extracted has increased significantly due to more restrictions of the extraction of aggregate from terrestrial sources. Furthermore, the rate of offshore extraction is expected to further increase in the coming years for coastal protection as a measure to counteract sea level rise.

In Europe, most dredging is carried out in northwestern coastal countries where around 50 million m³ of sand and gravel are extracted each year from the inner continental shelf (Sutton and Boyd, 2009). The Netherlands uses around 13 million m³ every year for coastal nourishments. In Spain, there is a strict regulation of aggregate extraction activities, which prohibit the use of marine sand and gravel from the continental shelf for purposes other than beach nourishment. Along the Spanish Mediterranean coast, the beach nourishment programs started in 1983 and continue nowadays. Only between 1997 and 2002, a total fill volume of about 110 millions of m³ was used for coastal protection (Hamm et al., 2002; Hanson et al., 2002). Particularly in the Valencia region, coastal erosion since the 1950s was estimated at 3 million m³/year and is expected to rise over the coming years due to expanding urban development and extensive tourism (Yepes and Medina, 2005). In order to stabilize these coastal sectors and to maintain their environmental and economic value, some 2 million m³ of sand are required each year. The main problem here is that potential marine sand resources are reduced to just one deposit of 20 million m³ of sand located on the inner shelf.

This situation has led to the need to identify new strategic resources with high quality of sand in the middle and outer continental shelf. The quality of a sand reservoir depends on a range of parameters including the sand/mud relation, the content of medium and coarse sand, and the thickness of the surficial mud layer. In the Valencia sand ridge field, it was defined a potential sand deposit based on the following criteria: a surficial mud content lower than 50% or a surficial mud layer thinner than 0.5 m, a sediment layer thicker than 1.5 m and a medium to coarse sand content higher than 60% (Fig. 13). The uppermost limit of this deposit corresponds

to the present seafloor. The lowermost limit is defined by the coarse-grained layer that corresponds to the basal reflector, or the maximum depth of the vibrocores, where they do not penetrate the underlying coarse lag. On this basis, the total surface of the potential borrow areas is about $8 \cdot 10^6 \text{ m}^2$. The potential reservoir has a minimum volume of $35 \cdot 10^6 \text{ m}^3$, of which $22 \cdot 10^6 \text{ m}^3$ corresponds to relatively well-sorted medium and coarse sand, $7.5 \cdot 10^6 \text{ m}^3$ of gravel and $5.5 \cdot 10^6 \text{ m}^3$ of mud.

This sedimentary deposit constitutes a valuable potential sand resource because of the high quality of sediment. However, given the level of demand of the region, the stored volume of sand would only cover the nourishment requirements for recreational and protection purposes of the region for about 7 years. Furthermore, it is expected that accelerate sea level rise caused by global warming in the next decades will increase the demand of sand for beach stabilization purposes. While knowledge of sand ridges is required for the evaluation of the non-renewable strategic mineral resources of the continental shelf, their exploitation must be carefully evaluated following criteria of sustainability and ecological and environmental impact. On that basis, even though the sand ridges on the Valencia outer shelf constitute a finite resource and represent a strategic potential as a sand borrow area, the sand sediment availability in GoV sand ridges is insufficient for a medium-term coastal management strategy based on beach nourishments and it should be discouraged. However, a limited exploitation to avoid the short-term depletion of the sand deposit could be justified as a complementary action in a general coastal adaptation strategy for the next decades.

CONCLUSIONS

The detailed sedimentological characterization of the GoV sand ridges provides valuable information about the formation and long-term evolution of offshore sand ridges on tideless continental shelves.

Sand ridges develop over an irregular erosion surface, mantled with coarse sand with pebbles

and cobbles, that locally crops out at the seafloor in some troughs between the ridges and is interpreted as the Holocene wave ravinement surface. Small topographic irregularities of this surface are related to shoreline-associated features that may act as the precursor for sand ridge development. Their preservation below the sand ridges could be explained by the hardness of these features that makes them highly resistant to erosion.

The internal architecture and sediment characteristics of the GoV sand ridges provide insights into their migration. Internally, sand ridges are composed of well-sorted sand with interbedded mud layers, as interpreted from dipping internal reflections, indicating periods of reactivation after relatively calm periods dominated by mud deposition during the active phase of the sand ridges.

The internal structure of some small sand ridges also provides further insights into their growths and the final stage of evolution of storm-dominated sand ridges that could be used for the identification of ancient isolated marine sand bodies in outcrops and the subsurface. The transition from active to moribund ridges is evidenced by a progressive change from a phase of progradation into a phase of aggradation and finally to the deposition of onlapping finer deposits over flanks and in troughs of the ridges.

Although the northernmost sand ridges appear to be at the last stage of their geological evolution, the morphology and sediment characteristics of other sand ridges show no evidences of degradation. Their maintenance would be explained by local hydrodynamics. Active sediment dynamics during storms (currents and even waves and currents) could be contributing to the maintenance of their morphology, preventing their burial by fine sediments.

Regarding to the use of the Valencia sand ridges as potential borrow area, it was identified as a sand reservoir of $22 \cdot 10^6 \text{ m}^3$ of relatively well-sorted medium and coarse sand with a limited mud content. Because of the high quality of this reservoir, the GoV sand ridge field should be considered as a strategic and finite sand reservoir.

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FIGURE CAPTIONS

Figure 1. (a) Location and shaded relief bathymetric map of the Gulf of Valencia margin. (b) Surficial sediment distribution over the continental shelf. Modified from IGME (2005). Locations of Figures 2, 3 and 4 are also shown.

Figure 2. (a) Bathymetry of the sand ridges. Individual sand ridges located along the seismic reflection profile are named as ridges I to XI. (b) Shaded relief map showing the location of the 1983 and 2011 seismic profiles and vibrocores. Locations of Figures 3 and 4 are shown.

Figure 3. High-resolution seismic reflection profile across the GoV continental shelf. High-relief pinnacles in the inner shelf are interpreted as beachrocks (Alcántara-Carrió et al., 2013). See Figures 1 and 2b for location.

Figure 4. (a) Uninterpreted and (b) interpreted parametric sub-bottom seismic profile across the sand ridges. (c) Description of co-located (or nearly so) sediment cores. Projected cores are located at a distance shorter than 150 m from the seismic line. The basal reflector was used as a datum to hang the grain-size trends from the sediment cores. See Figure 2 for location.

Figure 5. Parametric sub-bottom seismic profiles showing reflection amplitudes of two small sand ridges (ridges IX and XI): (a) and (b) uninterpreted profiles showing reflection amplitudes; (c) and (d) interpreted profiles. (e) Description of the sediment core located on sand ridge IX showed in Fig. 5c. See Figure 4 for location.

Figure 6. Grain-size distributions of sediment, composing: (a) the surficial mud layer (VC 48); (b) the interbedded mud layers in the sand ridges (VC 10); (c) the surficial layer of mixed sediment (sand and mud) in the sand ridges (VC 72); (d) the sand ridges sandy layer (VC 114); (e) the poorly sorted sediment facies below the basal surface of the sand ridges (VC 193); (f) the well-sorted fine sand facies below the basal surface of the sand ridges (VC 275); and (g) the coarse lag (VC 18). Locations of samples in the sediment cores are shown in Figures 9 and 10.

Figure 7. Core photograph showing the coarse lag.

Figure 8. (a) Surficial grain-size distribution based on the Folk classification (Folk, 1954, 1974): G, gravel; g, gravelly; (g) slightly gravelly, S, sand; s, sandy; M, mud; m, muddy. (b) Spatial distribution of the mud content in the surficial sediments. (c) Thickness of the surficial mud layer.

Figure 9. (a) Spatial distribution and (b) main characteristics of Type I sediment cores located on sand ridge crests. (c) Spatial distribution and (d) main characteristics of Type II sediment cores located on the flanks of the sand ridges.

Figure 10. (a) Spatial distribution and (b) main characteristics of Type III sediment cores located in troughs between ridges. (c) Spatial distribution and (d) main characteristics of Type IV sediment cores located in the troughs of the northern sand ridges.

Figure 11. (a) Uninterpreted and (b) interpreted parametric sub-bottom seismic profile showing the internal architecture of sand ridge IV. (c) Description of sediment cores. Red lines indicate main discontinuities identified in the seismic profile. Main surfaces identified below the basal reflector are displayed in grey. See Figure 4 for location.

Figure 12. Plot of gentle versus steeper flank slopes for the GoV sand ridges. Mean values of shallower and steeper slopes of the ridges observed in the North Atlantic and Mediterranean shelves are included. Modified and updated from Swift and Field (1981).

Figure 13. Thickness of sediment layers: (a) sand layer overlying the coarse lag. (b) Spatial distribution of the medium and coarse sand content of the sandy deposits overlying the coarse lag.

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Figure 1. (a) Location and shaded relief bathymetric map of the Gulf of Valencia margin. (b) Surficial sediment distribution over the continental shelf. Modified from IGME (2005). Locations of Figures 2, 3 and 4 are also shown.

207x92mm (300 x 300 DPI)

Figure 2. (a) Bathymetry of the sand ridges. Individual sand ridges located along the seismic reflection profile are named as ridges I to XI. (b) Shaded relief map showing the location of the 1983 and 2011 seismic profiles and vibrocores. Locations of Figures 3 and 4 are shown.

185x87mm (300 x 300 DPI)

Figure 3. High-resolution seismic reflection profile across the GoV continental shelf. High- relief pinnacles in the inner shelf are interpreted as beachrocks (Alcántara-Carrió et al., 2013). See Figures 1 and 2b for location.

188x85mm (300 x 300 DPI)

Figure 4. (a) Uninterpreted and (b) interpreted parametric sub-bottom seismic profile across the sand ridges. (c) Description of co-located (or nearly so) sediment cores. Projected cores are located at a distance shorter than 150 m from the seismic line. The basal reflector was used as a datum to hang the grain-size trends from the sediment cores. See Figure 2 for location.

203x170mm (300 x 300 DPI)

Figure 5. Parametric sub-bottom seismic profiles showing reflection amplitudes of two small sand ridges (ridges IX and XI): (a) and (b) uninterpreted profiles showing reflection amplitudes; (c) and (d) interpreted profiles. (e) Description of the sediment core located on sand ridge IX showed in Fig. 5c. See Figure 4 for location.

237x89mm (300 x 300 DPI)

Figure 6. Grain-size distributions of sediment, composing: (a) the surficial mud layer (VC 48); (b) the interbedded mud layers in the sand ridges (VC 10); (c) the surficial layer of mixed sediment (sand and mud) in the sand ridges (VC 72); (d) the sand ridges sandy layer (VC 114); (e) the poorly sorted sediment facies below the basal surface of the sand ridges (VC 193); (f) the well-sorted fine sand facies below the basal surface of the sand ridges (VC 275); and (g) the coarse lag (VC 18). Locations of samples in the sediment cores are shown in Figures 9 and 10.

99x96mm (300 x 300 DPI)

Figure 7. Core photograph showing the coarse lag.

87x64mm (300 x 300 DPI)

Figure 8. (a) Surficial grain size distribution based on the Folk classification (Folk, 1954, 1974): G, gravel; g, gravelly; (g) slightly gravelly, S, sand; s, sandy; M, mud; m, muddy. (b) Spatial distribution of the mud content in the surficial sediments. (c) Thickness of the surficial mud layer.

262x103mm (300 x 300 DPI)

Figure 9. (a) Spatial distribution and (b) main characteristics of Type I sediment cores located on sand ridge crests. (c) Spatial distribution and (d) main characteristics of Type II sediment cores located on the flanks of the sand ridges.

201x159mm (300 x 300 DPI)

Figure 10. (a) Spatial distribution and (b) main characteristics of Type III sediment cores located in troughs between ridges. (c) Spatial distribution and (d) main characteristics of Type IV sediment cores located in the troughs of the northern sand ridges.

201x159mm (300 x 300 DPI)

Figure 11. (a) Uninterpreted and (b) interpreted parametric sub-bottom seismic profile showing the internal architecture of sand ridge IV. (c) Description of sediment cores. Red lines indicate main discontinuities identified in the seismic profile. Main surfaces identified below the basal reflector are displayed in grey. See Figure 4 for location.

190x119mm (300 x 300 DPI)

Figure 12. Plot of gentle versus steeper flank slopes for the GoV sand ridges. Mean values of shallower and steeper slopes of the ridges observed in the North Atlantic and Mediterranean shelves are included. Modified and updated from Swift and Field (1981).

102x88mm (300 x 300 DPI)

Figure 13. Thickness of sediment layers: (a) sand layer overlying the coarse lag. (b) Spatial distribution of the medium and coarse sand content of the sandy deposits overlying the coarse lag.

134x78mm (300 x 300 DPI)