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Spatio-temporal evolution of sediment waves developed on the Gulf of Valencia margin (NW Mediterranean) during the Plio-Quaternary

Marta Ribó [a,*], Pere Puig [a], Roger Urgeles [a], David Van Rooij [b], Araceli Muñoz [c]

[a] Institut de Ciències del Mar (ICM-CSIC), Pg. Marítim de la Barceloneta, 37-49, E-08003, Barcelona, Spain
[b] Ghent University, Dpt. Geology & Soil Science, Krijglaan 281 s-8, B-9000 Ghent, Belgium
[c] TRAGSATEC — Secretaria General de Pesca, Madrid, Spain

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ABSTRACT

Several fields of large-scale sediment waves have been observed along the Gulf of Valencia continental margin (NW Mediterranean). The largest sediment waves develop on the continental slope, extending from 250 to 850 m water depth, with wavelengths ranging between 500 m and 1000 m and wave heights from ~2 m to ~50 m. On the lower part of the slope, sediment waves are quasi-stationary "vertically accreting", becoming up-slope migrating towards the mid- and upper part of the slope. A second group of sediment waves have developed over the outer continental shelf, with wavelengths of 400 to 800 m and heights of 2 to 4 m, also displaying an up-slope migrating pattern. Multi-channel seismic lines crossing the continental margin show that the sediment waves over the continental slope region have been continuously developed on the foreset region of the prograding margin clinoform. Several units of sediment waves have been identified in the sedimentary record, evolving in accordance with the margin progradation. Detailed analysis of single-channel (sparker) seismic profiles revealed the presence of several sediment depositional subunits over the outer continental shelf, some of them with successive development of sediment waves being truncated by erosive surfaces, likely related to Quaternary eustatic sea-level oscillations. These erosional surfaces can be followed downslope into paraconformable strata of the sediment waves on the continental slope, where constant bedform growth is observed, without being affected by sea level changes. Based on geophysical data, the thickness of the sediment waves mapped units show that the largest sediment waves (in wave ratio, length and height) develop where sediment deposition rates are the highest, coinciding with the upper part of the continental slope (foreset clinoforms), confined by the presence of structural highs. The development of these sediment waves has been previously explained by the interaction of internal waves over the continental slope. Because sediment waves are preserved in the sedimentary record since the Lower/Pliocene, internal waves activity could have been present in this part of the margin shortly after the Zanclean reflooding of the Mediterranean Basin, following the Messinian desiccation event ~5.6 My ago. Deep water hydrodynamic conditions were re-established at that time, modulating sediment transport and deposition over the continental slope and outer continental shelf.

1. Introduction

The interaction of internal waves (i.e. waves propagating in a density-stratified fluid driven by gravitational restoring forces) over continental shelves and slopes creates high turbulence near the seafloor. Therefore, it is an important dissipation and mixing mechanism with implications for biological productivity and sediment transport (Hosegood et al., 2004; van Haren and Gostiaux, 2011; Lamb, 2014). Sediment resuspension and/or transport caused by internal waves, generally through the generation of intermediate and bottom nepheloid layers, has been evidenced by in-situ measurements (McPhee-Shaw and Kunze, 2002; McPhee-Shaw et al., 2004; Ribó et al., 2013). In that sense, internal waves have been suggested to play an important role in shaping the continental slopes (Cacchione et al., 2002; Puig et al., 2004; Klymak et al., 2011). Additionally, large-scale sedimentary bedforms over present-day continental margins worldwide have been inferred to result from internal-wave-generated currents (e.g., Stride and Tucker, 1960; Heathershaw and Codd, 1985; Karl et al., 1986; Lee et al., 2002; Faugères et al., 2002; Ediger et al., 2002; Mosher and Thomson, 2002; Puig et al., 2007; Urgeles et al., 2011a; Reeder et al., 2011; Dunlap et al., 2013; Bøe et al., 2015; Belde et al., 2015).

Several studies have focussed on the description of the internal-wave deposits and the main facies association in the sedimentary record of ancient marine environments (Gao and Eriksson, 1991; Gao et al., 1998; He and Gao, 1999, He et al., 2008; Bádenas et al., 2012). However, there are not many documented examples of internal-wave/tide deposits in modern marine settings. One example are the reservoir

* Corresponding author.
E-mail address: mribo@icm.csic.es (M. Ribó).

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sands in the Kutein Basin, which were initially interpreted as deep-water turbidites (Saller et al., 2006). These reservoir sands were later reinterpreted as tidalites formed by deep-marine tidal currents (Shanmugam, 2008), since internal waves and internal tides were measured at this site (Hatayama, 2004; Ray et al., 2005; Pujiana et al., 2009). Shanmugam (2013) provides a compilation of occurrence of internal waves in 51 regions of the world oceans, and give some examples of deposition of baroclinic sands in deep-marine environment (e.g. Kirshna-Godavari Basin, Bay of Bengal, in Shanmugam et al., 2009). Recently, Belde et al. (2015) observed sediment waves on the Browse Basin, Australian North West Shelf, which were also preserved on the sedimentary record. These authors suggested that the modern and the palaeo-sediment waves could have been generated by the same formation process, interaction of internal waves with the seafloor.

In the Mediterranean Sea, the interaction of internal waves over the continental slope has been recently studied in the Gulf of Valencia (GoV) margin, northwestern Mediterranean Sea (van Haren et al., 2013; Ribó et al., 2013; Ribó et al., 2015). At this same area, a recent study analyzing the multibeam bathymetry, high-resolution sub-bottom profiles and sediment cores has determined the presence of large-scale fine-grained sediment waves, classified as mud waves. These sediment waves are distributed in three main fields, with those most developed being present in the northern and central parts of the GoV (Ribó et al., 2016). The sediment accumulation rates computed from the sediment core data collected over the upper continental slope, showed higher rates on the sediment wave crests than on the downslope flanks. This pattern indicates that the sediment waves are up-slope migrating and are still growing in present-day conditions (i.e., at a 100 year timescale). The genetic mechanism for these sediment waves has been inferred to be near-inertial internal wave activity interacting with the seafloor, conditioning the sediment transport and deposition over the continental slope (Ribó et al., 2016). In the GoV, the sediment waves that develop over the continental slope are accompanied by smaller (in wavelength and height) sediment waves over the outer continental shelf. The present study focuses on the seismic stratigraphic analysis of the sediment waves observed over the GoV outer continental shelf and their link with the sediment waves over the continental slope. In addition, with the analysis of the Plio-Quaternary sedimentary record, this study aims to trace the origin of the sediment waves on the continental slope back in time, and to determine their influence on the architectural pattern of the sedimentary prograding clinoform in the GoV continental margin.

2. Regional setting

The structure and stratigraphy of the Ebro and Valencia margins (Fig. 1), extending from the Early Miocene to the Quaternary, have been extensively described (Soler et al., 1983; Medialdea et al., 1986; Alonso et al., 1990; Farrán and Maldonado, 1990; Bartrina et al., 1992; Mauffret et al., 1992; Maillard et al., 1992, 2006; Maillard and Mauffret, 1999, 2013; Martínez del Olmo, 2011). However, only few studies have focused in the southwestern end of the Valencia Trough, where the GoV is located (Fig. 1). These studies were mainly focused to the tectonics and sedimentation on the continental shelf (Díaz del Río et al., 1986; Maldonado et al., 1983; Rey and Fumanal, 1996).

The GoV is one of the Cenozoic basins that formed on the northwestern Mediterranean during the Early-Middle Miocene (>20 Ma) active extensional phase (Díaz del Río et al., 1986). In this period, several extensional sub-basins developed, within a system of NE–SW oriented horsts and grabens (Maillard et al., 1992; Maillard and Mauffret, 1999). The GoV continental shelf is defined as part of the stable passive continental margin, extending southwards from the Ebro shelf. With respect to the Ebro margin the GoV shelf has a highly reduced sedimentary cover (Stanley, 1977; Mauffret, 1979; Serra et al., 1979; Rey and Díaz del Río, 1983) and narrows rapidly to a width of 20 km in the south (Fig. 1). The shaping of the GoV shelf is mainly dominated by the deep-seated graben system characterized by N–S trending extensional faults, sub-parallel to the present-day coastline (Fig. 1) (Díaz del Río et al., 1986). The extension of the GoV was attenuated during the Burdigalian–Langhian (~16 Ma), when the compression in the Betic cordillera started affecting the Balearic Promontory (Geel, 1995). The post-rift stage was followed by the deposition of two major prograding megasequences: 1) a Miocene one, the Castellon Group, dominated by a progradational terrigenous shelf-slope complex, recording a major regression that reflects the significant infilling of accommodation space created during post-rift subsidence (Dañobeitia et al., 1990; Bartrina et al., 1992); and 2) a Plio-Quaternary one. The Plio-Quaternary prograding megasequence, known as the Ebro Group, overlies the Messinian unconformity (Lanaja, 1987; Maillard et al., 2006), which defines the Miocene/Pliocene boundary. This unconformity corresponds to the drastic sea-level drawdown during the Messinian Salinity Crisis (MSC) (Lofi et al., 2003; García et al., 2011; Urgeles et al., 2011b). The MSC (~5.96–5.33 Ma) (Hsü et al., 1973; Krijgsman et al., 1999; Garcia-Castellanos et al., 2009) induced major erosion of the continental margins and development of large canyon systems, while evaporites and anhydritic sequences were deposited in the basin center. The stratigraphic record of most Mediterranean margins is strongly marked by the occurrence of the MSC (Hsü et al., 1973). Preservation of this MSC sedimentary record (Urgeles et al., 2011b) is strongly influenced by the exceptionally rapid restoration of deep marine conditions (Garcia-Castellanos et al., 2009).

The study of the Plio-Quaternary sequence in the Mediterranean basin, has mainly focussed on determining links between sea-level fluctuations and the deposition of sedimentary facies and shelf-edge sand bodies (Bassetti et al., 2006, 2008; Rabineau et al., 2006; Liquete et al., 2008; Gámez et al., 2009; Sierro et al., 2009). During the Plio-Pleistocene the southern region of the GoV experienced subsidence at a rate of ~0.45 m ky^{-1}, suggesting a structural control in the sediment depositional behavior and in the coastal morphology (Rey and Fumanal, 1996). The sedimentation over the continental shelf is predominantly fluvial and involves large amounts of sands, whereas the middle and outer shelf are dominated by the silt and clay fractions (Rey et al., 1999). Overall, the series of Plio-Quaternary deposits in the GoV, progressively becomes thinner towards the south, near the Ibiza Channel (Fig. 1), in the direction of the Betic system (Rey and Díaz del Río, 1983).

During the Last Glacial Maximum (LGM) sea-level fell up to 110 m below present mean sea-level. Rising sea-levels during the post-glacial marine transgressions (PMT) resulted in the erosion of bedforms formed during the LGM and marks the basal sequence of the deposition of shelf deposits (Rey et al., 1999). Over the GoV inner shelf the recentmost sedimentary cover is characterized by the occurrence of several barrier-lagoon systems, whose formation has been related to Late Quaternary stillstand periods, and their preservation implies very high subsidence rates (Albarracín et al., 2013; Alcántara-Carrió et al., 2013). Recent studies have identified sand ridges offshore the Valencia shelf, developed in coastal settings during the recentmost PMT (Simarro et al., 2015). It has been hypothesized that sediment dynamics of the inner shelf favors the maintenance of the morphology of such sand ridges. Similarly, sediment dynamics on the outer shelf also contributes in the development of the sediment waves observed in this study. Evolution of these sediment waves is also probably influenced by eustatic sea-level fluctuations.

The circulation of ocean currents on the GoV continental shelf has been described to be highly affected by the wind pattern and currents are intensified by these winds as the shelf width narrows to the south (Han et al., 1983), from Valencia to near the southern boundary of the GoV, at Cap La Nao promontory (Fig. 1). Over the continental slope, circulation has been described as seasonally dominated by the Northern Current, entering the GoV as an unstable meandering jet (Font et al., 1988; García et al., 1994; Pinot et al., 1994, 1995 and Pinot et al.,