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Geomorphology of the NE Sicily continental shelf controlled by tidal currents, canyon head incision and river-derived sediments

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The NE Sicily continental shelf, imaged by multibeam bathymetry data and CHIRP/sparker seismic profiles, is less than 5 km-wide, and is located in a tectonically active margin characterized by strong regional uplift rates. In this paper, we show how variations of geomorphic elements in the study area are tied to spatial and temporal changes in the driving forces that control the seafloor processes. This study demonstrates that the geomorphology of continental shelves can vary over very short spatial scales depending on the uneven distribution of sediment supply from rivers and sediment transfer both across and along the shelf by oceanographic currents. In the northeastern part, three sandwave fields were mapped in the highstand sediment wedge that, due to the small size of rivers, is restricted to the inner shelf. The sandwave fields are found in proximity of the Messina Straits, a shallow water sill with strong tidal currents between the Tyrrhenian and the Ionian Seas. The bedform fields have sandwaves of variable shape, wavelength and orientation, reflecting along-shelf variations of tidal current strength and sediment grain size distribution. In the southwestern shelf, rivers are larger and form deltas that shape a considerable part of the shelf, often having their distal, still channelized delta front at the shelf edge. In some cases, deltas are built close to the heads of canyons and a large volume of the river-borne sediments is directly fed to the deep sea through delta front terminal distributary channels. Where rivers are small, the outer shelf lacks recent river borne sediment and presents a relict morphology consisting of submerged coastal systems formed during previous sea-level lowstands. The tectonics of the study area mainly consist of structures that have a NNE–SSW trend similar to the extensional faults responsible for the Siculo-Calabrian Rift Zone in the nearby emerged areas. Our study extends the area affected by the regional deformation belt into the NE Sicily offshore.

1. Introduction

Continental shelves are the submarine areas closest to land and, as a consequence, fluvial sediment transport to the offshore, albeit in combination with oceanographic processes, is the main control for the development of geomorphic elements on the shelf. Waves, storms, currents and gravity-driven flows are the main oceanographic processes that are active in the shelf and can redistribute river-borne sediment across and along the shelf, creating sediment transport gradients and contributing to the creation of geomorphic elements on the shelf (Wright, 1995; Fagherazzi and Overeem, 2007). In addition, climate and tectonics operate at different spatial and temporal scales in controlling the way and the site of sediment accumulation (Wright, 1995; Fagherazzi and Overeem, 2007; Sommerfield et al., 2007). For example, temporal migration of different environments on the shelf occurs due to the advancement and retreat of the coastline in response to sea-level variations.

The location of the rivers and the size of the discharge from their drainage basins remain the main controls on the site of sediment input to the coastal area and on shelf depocenters (Swift and Thorne, 1991; Wright, 1995; Olariu and Steel, 2009). Along continental margins, modern deltas started to develop, following the decelerated eustatic sea-level rise, in late Holocene (Stanley and Warne, 1994; Sommerfield et al., 2007). Depending on the amount and type of river-borne sediments, shelf morphology and oceanographic conditions, deltas of different sizes and nature were formed and their progradation can now be seen to have reached different locations across the shelf (Burgess and Hovius, 1998; Porebski and Steel, 2006). Although modern deltas are mainly restricted to the inner shelf, in some cases their distal portions can also reach the outer shelf and the shelf edge (Porebski and Steel, 2006).

Continental shelves are also the areas where sea-level oscillations have the widest effects, resulting in phases of emergence and submergence that alternate over several thousands of years during cycles of sea-level variations. As a consequence, the geomorphology of the continental shelf not only records the present-day morphogenetic agents but it can also document past landscape shaping processes. The latter is the case where original landforms created during past sea-level stages have

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not been overprinted by subsequent sedimentation or erased by successive erosional processes and are found outcropping on the seafloor of relict shelf portions (Shepard, 1932; Emery, 1968; Swift et al., 1971; Mallett et al., 2013).

Particularly in active margins, tectonic structures, both active and quiescent, play an important direct role in the resulting morphology of the continental shelf and can have a significant impact on the development of other processes, such as current pathways and intensities, sediment entry points, the creation and destruction of accommodation space. Offshore tectonic structures are sometimes more revealing than their terrestrial counterparts, which are often largely obscured by the weathering of the subaerial environment. Furthermore, the structural style of the shelf allows for the extension of the interpretation of regional tectonic structures into the offshore and to refine the pattern of potential seismogenic sources in seismically active areas.

On continental shelves, large-scale tidal bedforms, such as megaripples and sandwaves are important geomorphological elements for their impact on human activities (energy, communication and shipping industries) and their relevance in marine spatial planning (sand extraction). Sandwaves are large flow-transverse bedforms formed by a reversing flow such as a tidal current (Allen, 1980). The use of the descriptive term “sub-aqueous dunes” was recommended by Ashley (1990) for all large-scale flow-transverse bedforms. These bedforms show height classes of 0.25–0.4 m (small), 0.44–2.8 (large) and >2.8 m (very large) (heights calculated after Berné et al., 1993) and corresponding spacings of 5, 10 and 100 m.

Sometimes the term dune is used when the sediment grain size is unknown (*e.g.* Gómez et al., 2010), but the term “sandwave” is also used irrespective of the grain size (Barnard et al., 2006). Van Landeghem et al. (2009) used the term “sediment wave” rather than “sub-aqueous dune” in the Irish Sea to indicate those bedforms where the sediment composition could not be identified, leaving the term “sandwave” for those where the grain size was available. On the other hand, in the literature, sediment waves are often regarded as those bedforms created by either downslope-flowing turbidity currents or along-slope-flowing bottom currents in deep-water settings (Wynn and Stow, 2002). These sediment waves display wave heights of 1–70 m and wavelengths of 0.1–6 km (Wynn et al., 2000).

In this paper, we use the term “sandwave”: i. To avoid confusion with the sediment waves that are present in the slope channels of the study area (Gamberi and Rovere, 2011; Gamberi et al., 2013); ii. To be consistent with the literature, where the term “sandwave” is more frequently used instead of dunes, when dealing with modeling and coastal engineering studies (*e.g.* Besio et al., 2004). Compound sandwaves are defined as flow-transverse marine subaqueous dunes with superimposed megaripples (10 m wavelength and 1 m height) and have a typical length of 100 to 800 m and heights of several meters (Rubin and McCulloch, 1980; Ashley, 1990; Besio et al., 2004; van Dijk and Kleinhans, 2005).

In this paper, we describe the geomorphology of the NE Sicily shelf through the interpretation of multibeam bathymetric data and CHIRP seismic profiles. We show how its current morphodynamics are largely controlled by the varying size of the river drainage basins along the margin and how the tectonic structures, mapped in the shelf, mimic the complex tectonic framework that characterizes the deformation belt (Siculo-Calabrian Rift Zone) present across northeast Sicily and southern Calabria.

2. Geological setting

The study area is located along the NE Sicily margin between Capo Milazzo and the area offshore Capo Rasocolmo (Fig. 1a). On land, the Peloritani Mountains are the southern portion of the Calabrian Arc where the tectonic basement nappes of the Kabilo-Calabride units, that tectonically overlie the Apenninic–Maghrebian Chain, outcrop (Lentini et al., 1996, Fig. 1a). The orogenic wedge was affected by the extensional tectonics that led to the opening of the Tyrrhenian back-arc basins at the rear of the Maghrebian thrust belt (Patacca et al., 1987). As a result, NNE–SSW-trending normal faults and NW–SE-trending strike–slip faults give rise to the horst and graben structural setting of NE Sicily (Di Stefano and Lentini, 1995; Lentini et al., 2000). Basement nappes of the Kabilo–Calabride units are exposed on the NE–SW elongated horsts (*i.e.* Castanea Ridge), whereas Miocene to Quaternary sediments fill the grabens (*i.e.* Barcellona Trough; Fig. 1a). Within this complex tectonic setting, the largest tectonic feature of the Calabrian Arc (Fig. 1b) is the Siculo-Calabrian Rift Zone (SCRZ, Fig. 1c), a 370 km long belt that runs continuously along the inner side of the Calabrian Arc, through the Messina Straits and along the Ionian coast of Sicily and extends also westward into the Aeolian Islands Arc (Monaco and Tortorici, 2000).

High regional uplift rates affect the NE Sicily area (Westaway, 1993) and are amplified by local uplift connected with the vertical movements of single fault blocks of probably active structures (Catalano et al., 2003; Scicchitano et al., 2011). Although uplift rates are high and co-seismic slip has been suggested, in the study area no significant seismicity, focal mechanisms (Gasperini et al., 2012) or stress indicators are mapped (Montone et al., 2012).

3. Data set

The Digital Terrain Model (DTM) used for the interpretation of the geomorphology of the study area (Fig. 1a) was compiled from data acquired with different multibeam systems on board several oceanographic vessels. High resolution bathymetric data were acquired during two cruises in the upper slope and shelf area, carried out on board R/V Mariagrazia in 2009 and 2010 using a hull-mounted Kongsberg EM3002D (300 kHz) and a pole-mounted Reson 7111 (100 kHz) multibeam system respectively. In 2011 some sectors of the outer shelf were re-mapped with a hull-mounted Kongsberg EM710 (70–100 kHz) multibeam system on board R/V Urania. All the multibeam data have been merged and post-processed using CARIS HIPS and SIPS software; a 5-m-resolution DTM was produced for the shelf area, while a 20-m-resolution DTM was attained for the slope area.

Together with multibeam data acquisition, high resolution CHIRP seismic profiles were acquired on board R/V Mariagrazia and Urania with a hull-mounted Teledyne BENTHOS III CHIRP system having a frequency modulation between 2 and 20 kHz. The CHIRP profiles shown in this paper were acquired in 2009. They are spaced at about 2 km (Fig. 1a) and have 0.5-m-vertical resolution. Two seismic profiles were acquired in August 2103 with a 1 kJ sparker source and recorded by an EdgeTech 265 hydrophone cable towed behind the vessel (Fig. 1a).

4. Data description and interpretation

4.1. Shelf sector n. 1

The shelf sector n. 1 is comprised between the northeastern limit of our data and the Sindaro canyon head (Figs. 1a, 2). Here, the inner continental shelf down to a depth between 80 and 70 m has an average dip of 1.85°, with slope ranges of 0.8° and 2.7°. Three fields of sandwaves with different characteristics are present (Fig. 2). The southern sandwave field has bedforms with NW–SE directed crests (Fig. 2). They consist of relatively smaller and more discontinuous bedforms with wavelengths of 250 m and heights of 1 m superimposed on larger bedforms with a spacing of 500 m and heights of 2 m (Fig. 3a). The central sandwave field has bedforms with crests oriented in an E–W direction and variable sizes (Fig. 2). They consist of very large (*sensu* Berné et al., 1993) bedforms with wavelengths of 500 m and heights of 5 m and superimposed large sandwaves with spacing of 250 m and heights of 2.5 m (Figs. 3b, 4a, b). Due to the close range of sizes, these cannot be described as compound sandwaves. Simple sandwaves are