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Abstract

Sediment starved passive margins, particularly those of insular slopes, display significant mass transport activity despite the absence of environmental stresses from high sedimentation rates. The "Menorca Channel" represents the up to 120 m deep shelf sector connecting the Menorca and Mallorca Islands (Balearic Islands – Western Mediterranean). South of the Menorca Channel submarine gravitational processes have been mapped and interpreted from swath-bathymetry, TOPAS parametric echosounder and deep-towed videos. The shelf-break is located at an average depth of 140 m, and sediment instability is a widespread phenomenon. The slope region south the Menorca Channel shows a number of submarine canyons disrupting the outer shelf. The north-easternmost canyon is the more active feature, with an incised axis and scars shaping the flanks up to their edges. Headwall scarps, between 140 and 700 m depth, are up to 20 m high. The shallower scarps producing slab-type failures have carved the outer edges of planar sedimentary bodies interpreted as formed in shallow environments during previous glacial stages. Results show that a variety of sediment instability processes extensively shape the southern upper slope of the Menorca Channel. Submarine canyons develop on the Emile Bodout Escarpment (EBE), a passive tectonic feature which bounds the slope region of the study area. A number of knickpoints within the canyons suggest backward erosion control on mass wasting and, at the same time, that slope failure is one of the main drivers for canyon upslope migration. Steep gradients of the upper slope, the presence of weak layers

and the action of major storms during lowstand stages are additional factors likely to influence the distribution and frequency of mass wasting processes in this area.

Chapter 29
Submarine Mass Movements Along a Sediment Starved Margin: The Menorca Channel (Balearic Islands – Western Mediterranean)

Claudio Lo Iacono, Roger Urgeles, S. Polizzi, J. Grinyó, M. Druet, M. Agate, J.M. Gili, and J. Acosta

Abstract Sediment starved passive margins, particularly those of insular slopes, display significant mass transport activity despite the absence of environmental stresses from high sedimentation rates. The "Menorca Channel" represents the up to 120 m deep shelf sector connecting the Menorca and Mallorca Islands (Balearic Islands – Western Mediterranean). South of the Menorca Channel submarine gravitational processes have been mapped and interpreted from swath-bathymetry, TOPAS parametric echosounder and deep-towed videos. The shelf-break is located at an average depth of 140 m, and sediment instability is a widespread phenomenon. The slope region south the Menorca Channel shows a number of submarine canyons disrupting the outer shelf. The north-easternmost canyon is the more active feature, with an incised axis and scars shaping the flanks up to their edges. Headwall scarps, between 140 and 700 m depth, are up to 20 m high. The shallower scarps producing slab-type failures have carved the outer edges of planar sedimentary bodies interpreted as formed in shallow environments during previous glacial stages. Results show that a variety of sediment instability processes extensively shape the southern upper slope of the Menorca Channel. Submarine canyons develop on the Emile Bodout Escarpment (EBE), a passive tectonic feature which bounds the slope region of the study area. A number of knickpoints within the canyons suggest

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backward erosion control on mass wasting and, at the same time, that slope failure is one of the main drivers for canyon upslope migration. Steep gradients of the upper slope, the presence of weak layers and the action of major storms during lowstand stages are additional factors likely to influence the distribution and frequency of mass wasting processes in this area.

29.1 Introduction

Submarine landslides are present across the full range of continental margins, tectonic settings (Hampton et al. 1996) and oceans (Weaver et al. 2000; Huhnerbach et al. 2004; Chaytor et al. 2009). Seafloor instability is triggered when the driving stresses acting on the slope exceed the resisting forces (Hampton et al. 1996). The factors that may induce submarine slope failure are divided between those that increase the driving stress (e.g. earthquakes) and those that reduce the shear resistance (e.g. high sedimentation rates, non-equilibrium consolidation and pore pressure build-up). Earthquakes typically occur on tectonically active margins, while high sedimentation rates are characteristic of continental margins fed by large river systems. Passive margins of insular slopes are devoid of large earthquakes and onshore watersheds are relatively small, implying that large river systems cannot be formed and therefore sediment delivery to the adjacent continental margins is rather limited. Despite the overall lack of these typical trigger mechanism and pre-conditioning factors for slope instability, submarine landslides are ubiquitous on some sediment-starved insular slopes such as those of the study area. In this study we present a morphological characterization of the mass wasting processes observed along the southern margin of the Balearic Promontory, between Menorca and Mallorca Islands (Balearic Islands – Western Mediterranean) (Fig. 29.1a). The main aims are to explore the factors that induce submarine slope failure in this environment and to better highlight the controls on the long-term evolution of sediment undersupplied insular slopes.

29.2 Geological Framework

The Balearic Promontory is a structural elevation including four major islands (from west to east: Ibiza, Formentera, Mallorca and Menorca) resulting from successive pre-Oligocene subduction of Africa beneath Eurasia, Oligocene rifting and oceanic accretion during the Miocene (Acosta et al. 2001). The Promontory separates the Balearic–Provençal Basin to the north from the Algero-Balearic Basin to the south (Acosta et al. 2002). The study area lies on the southern flank of the Menorca Channel between the islands of Mallorca and Menorca (Fig. 29.1a). A NE–SW steep scarp, the Emile Baudot Escarpment (EBE) bounds the southern margin of the Promontory, including the Menorca Channel (Fig. 29.1a). The EBE has been

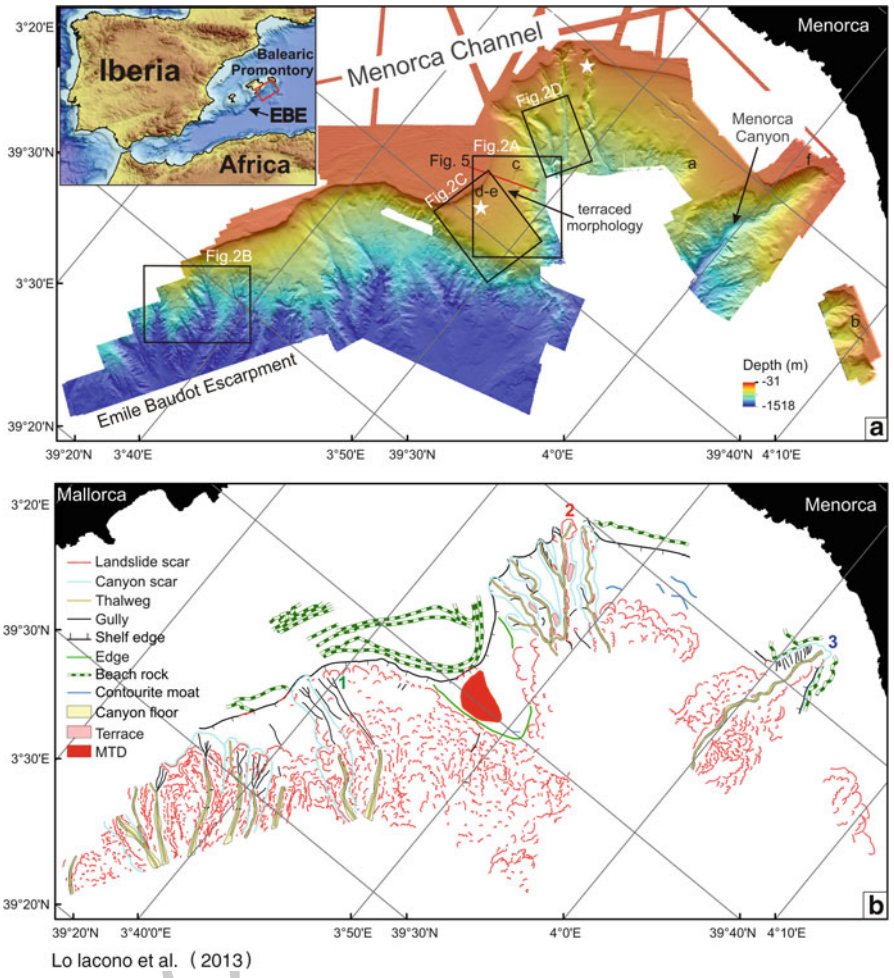

Fig. 29.1 (**a**) Bathymetry of the study area south of the Menorca Channel. *Black boxes* mark locations of detailed maps shown in Fig. 29.2. *Lower case letters* indicate the position of the images in Fig. 29.4. *Red line* shows location of parametric profile in Fig. 29.5. *White stars* show dredging locations. *Inset* shows location of the study area. (**b**) Interpretation of bathymetric data. *Colored numbers* indicate thalweg long profiles in Fig. 29.3

interpreted as evidence of the right-lateral strike–slip fault system that bounds the south Algero- Balearic basin (Mauffret et al. 2004). It is worthy to note the absence of earthquakes along the fault in the last 80 years (IGN, USGS), indicating the aseismic character of this feature. In the study area, the Menorca submarine canyon and other minor incisions converge towards a narrow channel (the South Mallorca Trough) that feed the Menorca Fan, a wide fan-shaped area along the base of the EBE (Camerlenghi et al. 2009). The Menorca channel has reduced or

null river sediment inputs. Sediments composing the seafloor mainly originate from local coastal erosion processes and by a variable carbonate production of bioherms (Barberà et al. 2012).

29.3 Methods

The data presented in this study was primarily collected for the INDEMARES-LIFE Project (www.indemares.es) of the Instituto Español de Oceanografia (IEO) and the Institut de Ciències del Mar (ICM-CSIC). Multi beam data were acquired during five cruises between 2010 and 2012 with a Simrad EM302 on the RV Miguel Oliver. Processing and visualization of bathymetric data were performed with CARIS HIPS system and ARC-GIS respectively. TOPAS PS18 high-resolution seismic records and rock dredges were collected in 2012 by IEO on the RV Miguel Oliver. Video surveys were conducted using the manned submersible JAGO (GEOMAR) in depths of 120–400 m. Video analysis was performed with the Final Cut software.

29.4 Results

The continental margin south off the Menorca and Mallorca Islands presents a width of ∼10–20 km and is mainly characterized by several lineations. These features display a curved morphology generally parallel to the bathymetric contours (Fig. 29.1). At least 8 bars, likely representing beachrock deposits, are recognized for a 90–110 m depth range (Fig. 29.1b). The shelf break, 120 m deep, is relatively sharp and indented by few canyons, particularly off Mallorca (Fig. 29.1). Off the shelf break, the upper slope is relatively smooth and has a terraced morphology (Figs. 29.1a and 29.2a). These terraces display also a smooth morphology that is only disturbed by Mass Transport Deposits (MTD) with hummocky morphology (Figs. 29.1b and 29.2c). The upper reaches of the slope display few canyons in the whole survey area. The only major canyon is the Menorca Canyon which evolves from the southern Menorca slope; it is well incised on the continental shelf and has well developed side valleys (Fig. 29.1). In between Menorca and Mallorca, off the Menorca Channel, the erosional features are rather shallow and do not incise significantly on the shelf (Fig. 29.1). These features resemble channels rather than canyons. Off south Mallorca, no major canyons develop, despite the middle slope showing pervasive gullying (Figs. 29.1 and 29.2). From north to south, the long profile of the canyons-channels-gullies shows increasing evidence of non-equilibrium conditions, with several knickpoints present within the gullies off Mallorca (Fig. 29.3), some of them related to failure scars (Figs. 29.1 and 29.3). Some knickpoints show elevations that exceed 200 m, with long-profile slopes that are remarkably different upslope and downslope from the knickpoint (Fig. 29.3).

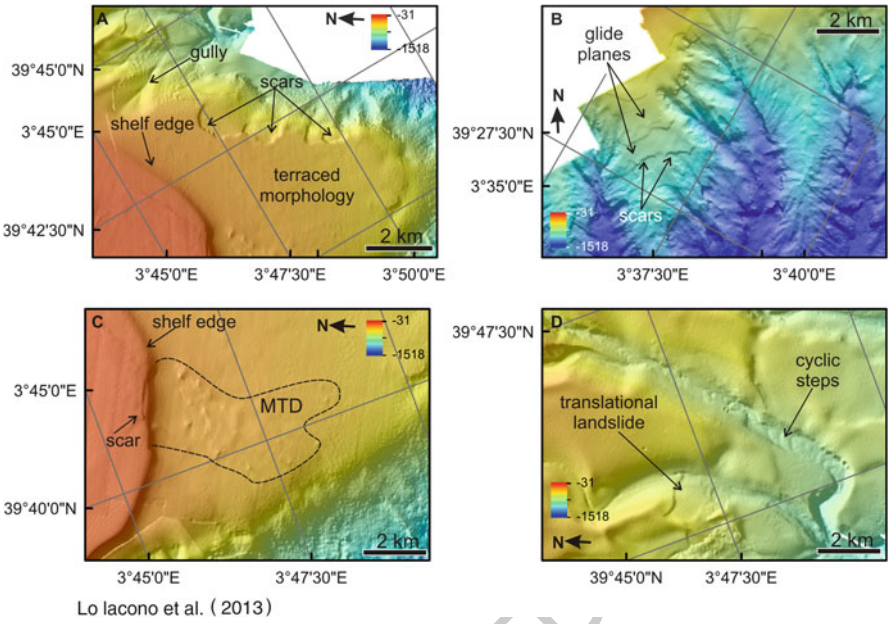

Fig. 29.2 Details of multi beam bathymetry showing (**a**) slab slides at the side flank of a submarine canyon (**b**) slab like stepped landslide scars at the head and interfluve of submarine canyons (**c**) hummocky MTD originating from littoral terrace/depositional body with beach rocks and (**d**) cyclic steps within submarine channel/canyon (see Fig. 29.1a for location)

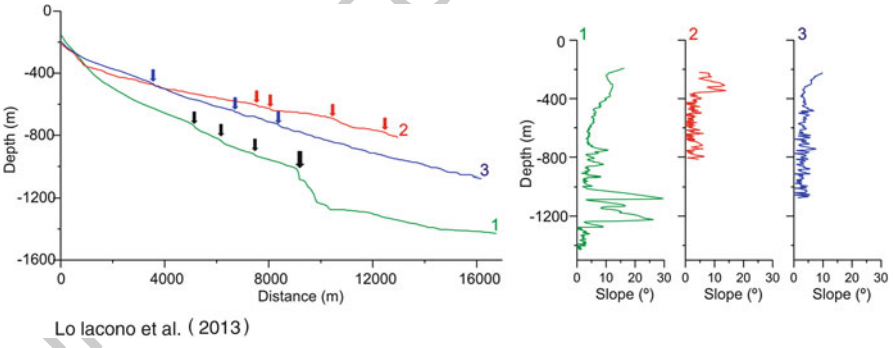

Fig. 29.3 Canyon long profiles (*left*) of selected canyons along the southern margin of the Menorca southern slope showing prominent and some more conspicuous knickpoints (*arrows*). Slope gradients with depth for the same canyons are shown to the *right*. For location of long-profiles see *colored numbers* in Fig. 29.1b

Analysis of video records (Fig. 29.4) shows that rocky outcrops generally coincide with the headscarps of landslides and show strata heads (Fig. 29.4a) and sub-vertical walls (Fig. 29.4b). Sediments along the shelf margin and the upper slope are mainly composed of bioclastic medium to coarse sands and gravels,

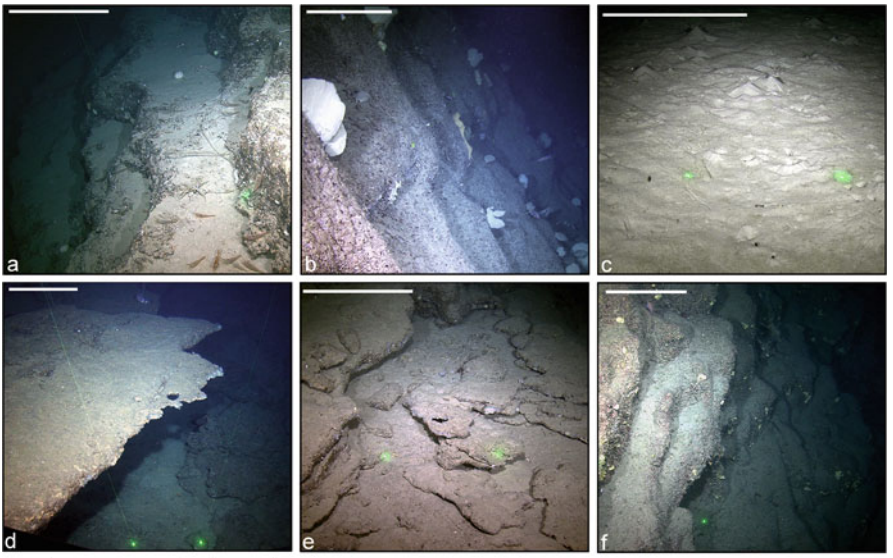

Fig. 29.4 Images extracted from the Jago video records on the Menorca upper slope, (**a**) strata head outcrops along a landslide scar, (**b**) tens of meters deep sub-vertical scar entirely encrusted by red algae, (**c**) bioclastic sands, (**d–f**) landslide composed of carbonate bioclastic deposits (beachrocks?), (**g–i**) vertical walls and boulders in the Menorca Canyon head. Location of the images is indicated with the letters on Fig. 29.1a. *White bar* corresponds to the length of 50 cm

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coming from the degradation of the wide benthic assemblages present in the area (Fig. 29.4c). Most of the rocks observed along the shelf margin and in the head of the Menorca Canyon are likely composed of bioclastic deposits (Fig. 29.4d, e). The substrate along the deep sub-vertical walls (Fig. 29.4f) is probably composed of the Tertiary carbonate rocks outcropping on-land in Menorca. Dredge rock samples collected on the 230 m deep landslide deposit (Fig. 29.2c) and in the Menorca Canyon head (−120 m) present the same lithological typology. Samples correspond to graded bioclastic and lithoclastic cemented coarse sands to gravels with a minor fine sediment component (Fig. 29.4d, e). Grains are sustained by secondary carbonate cements and several entire or partially fragmented shells are observed.

Parametric TOPAS sub-bottom profiles display typical downlap and toplap geometries for the sedimentary body that defines the shelf break (Fig. 29.5). Below the shelf break the seismic facies is initially well stratified and sub-parallel in areas where the seafloor shows relatively smooth relief. The stratified facies are often truncated at scarps 10–20 m high that root at distinct stratigraphic levels (Fig. 29.5). In deeper water with a more gullied relief some stratification is visible, although this is masked by the presence of hyperbolae induced by canyon roughness.

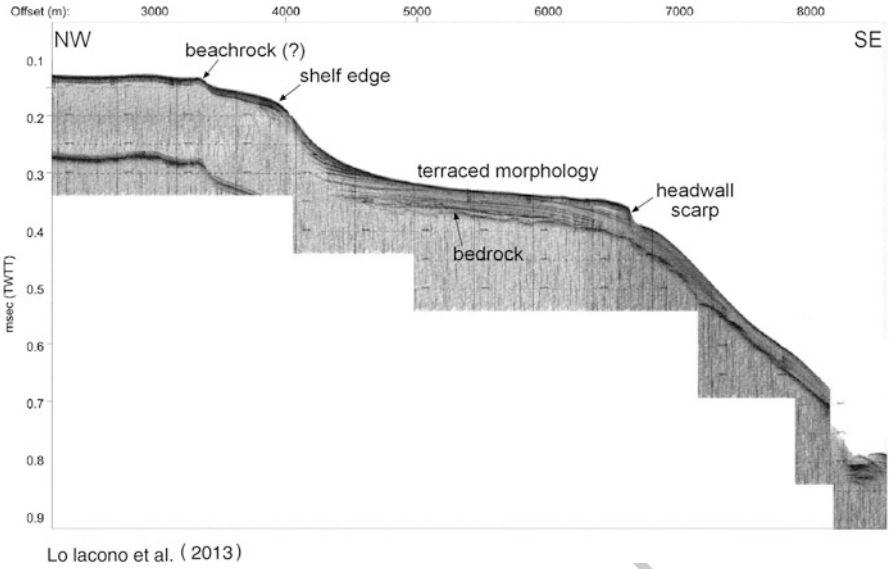

Fig. 29.5 TOPAS high-resolution parametric profile displaying slab slides on the upper slope of the southern Balearic Margin. See Fig. 29.1a for the location of the profile

The canyon's thalweg often displays opaque acoustic facies, but in some instances transparent deposits are observed within the canyons or at their foot.

29.5 Discussion

29.5.1 Factors Pre-conditioning Failure in Sediment Starved South Balearic Margin

The South Balearic margin is devoid of significant seismic activity and sedimentation rates are low (from 0.2 to 0.9 m kyr^{-1}) (Betzler et al. 2011), without major rivers delivering sediment in the adjacent coastal zone. Nevertheless, the large amount of scars and slab-like features surprisingly indicate a dominance of mass-wasting processes (Fig. 29.1b). Most of these landslides, however; appear to be associated to canyon heads and flanks. The bathymetric data, particularly the southern half, shows that there is a clear distinction in slope smoothness between the upper and lower continental slope and that most of the incisions do not indent the shelf edge (Fig. 29.1). Also the prominent knickpoints observed within some of the canyons and gullies (Fig. 29.3) highlight backward erosion processes along those canyons. The ultimate process responsible for such backward erosion is not clear from the data set presented in this study, but it is tentatively ascribed to nowadays inactive

tectonic features such as the Emile Baudot Escarpment (Acosta et al. 2001). Along the SW Mallorca slope, slope failure appears to be associated with drift deposits (Lüdmann et al. 2012). Contrary to that area, we hypothesize that mass-wasting in the SE Balearic margin is mainly driven by local slope steepening, canyon undercutting and axial incision, with slope gradients of around 5° along the open slope affected by mass wasting processes, 3° along the canyon axis and 30° across the headwall scarps. The gullies, channels and tributaries that drain into the Menorca Canyon (north of the spur with a mass transport deposit sitting on it, MTD in Fig. 29.2c) appear to have a profile that is more in equilibrium, which would explain significantly lower mass-wasting activity compared to those that drain the southern Mallorca slope. It is worth noting, that some of the canyons and gullies also display cyclic steps (Fig. 29.2d): these are believed to be formed by hydraulic jumps in which a flow makes a rapid change from thin, rapid supercritical flow to thick, tranquil sub-critical flow (Fildani et al. 2006). However, repeated lake surveys and analog experiments have shown that cyclic steps and knickpoint migration can also be controlled by submarine landslides (Tourmel et al. 2010).

Translational landslides are common features in the upper slope, with downslope dipping strata inducing the sliding of large slabs, conferring a local stratigraphic control in their generation (Figs. 29.1a and 29.2a, d) and implying that weak layers may be a factor in controlling sediment stability. Nonetheless available data do not allow to highlight the occurrence of weak layers as preferential sliding planes. Evidences of rocky landslides and small avalanches can be found in the cutting of strata heads along the southern Menorca slope and Mallorca shelf, creating sub-vertical to overhanging walls along the shelf edge and canyon heads and flanks (Figs. 29.2 and 29.4). Collected rocks are most probably part of Quaternary sedimentary bodies formed in shallow coastal environments during low sea level conditions. Mechanisms that would explain those landslides involve depositional steepening and loading of the upper slope by cemented planar deposits.

29.5.2 Relevance and Timing of Mass/Wasting Processes in Shaping the South Balearic Insular Margin

Data suggest that mass wasting is a pervasive and widespread sedimentary processes along the southern margin of the Menorca Channel (Fig. 29.1a, b). More than 700 km^2 of the 1,000 km^2 covering the entire study area are carved by landslide scarps, gullies and submarine canyons, corresponding to 82 % of the mapped slope region. This shows the relevance of sediment instability processes in slope shaping sediment-undersupplied insular margins. Absence of fluvial inputs and reduced clastic sedimentation can contribute to the formation of a thin Plio-Quaternary succession over a steep structurally controlled margin, favoring the dominance of erosive processes over depositional regimes (see also Micallef et al. 2013). Given their extension, retrograding mass transport processes have been likely carving the

slope region for a relatively long time. We infer that most landslides probably occurred during the glacial phases, when the outer shelf-upper slope system and the canyon heads suffered stronger hydrodynamic conditions related to storms and sediment transport processes (Hernandez-Molina et al. 2002; Lo Iacono et al. 2011). On top of that, occurrence of biogenic encrustations by benthic communities such as sponges, bryozoans and cold water corals on most of the landslide scars, in some case extensively covering large surfaces (Fig. 29.4b), demonstrate a reduced activity in the present-day, although univocal and reliable data on accretion rates of observed benthic organisms are still not available in scientific literature.

29.6 Conclusions

Multi beam bathymetry and high resolution seismic data reveal widespread presence of mass wasting features in the southern margin of the Menorca Channel, Balearic Islands (Western Mediterranean). Open slope translational landslides, gullies and submarine canyons and channels are the most prominent sediment instability features mapped in the area. Data suggest that dynamics of gravity processes in the area results from the interaction between backward erosion on structurally controlled slopes, stratigraphy and Quaternary sea level oscillations. Mass wasting features cover up to the 80 % of the mapped slope region and suggest a preponderant role in shaping sediment-undersupplied insular margins. Nonetheless, video runs from the study area did not show fresh scars and/or landslide deposits, advocating for a present-day inactivity of mass movement processes, as also confirmed by the extension of encrusting organisms over the observed features.

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