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Morphological variability of submarine mass movements in the tectonically-controlled Calabro-Tyrrhenian Continental Margin (Southern Italy).

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ABSTRACT

The acquisition of high resolution morpho-bathymetric data on the Calabro Tyrrhenian continental margin (Southern Italy) enabled us to identify several mass-wasting processes, including shallow gullies, shelf-indenting canyons and landslides. In particular, we focus our attention on submarine landslides occurring from the coast down to -1700 m, with mobilized volumes ranging from some hundreds up to tens of millions of cubic meters. These landslides also show a large variability of geomorphic features in the headwall, translational and toe domain. Based on their morphology and distribution, four main classes of coastal/submarine landslides have been recognized: a) rocky coastal/shallow-water failures characterized by large hummocky deposits offshore; b) large-size and isolated scars with associated landslide deposits, mostly occurring on open slope environment and lower part of tectonically-controlled escarpments; c) a linear array of coalescent and nested landslide scars occurring in the upper part of tectonically-controlled escarpments and canyon flanks; d) a cauliflower array of small and coalescent scars occurring in canyon headwall. The latter two classes of landslides are also characterized by a marked retrogressive evolution and their landslide deposits are generally not recognizable on the morpho-bathymetric data. By integrating the morpho-bathymetric dataset with the results of previous studies, we also discuss the main factors controlling the variability in size and morphology of these submarine landslides to provide insights on their failure and post-failure behavior.

KEYWORDS

landslide scars; canyon; fault escarpments; contourite deposits; digital elevation model; continental slope

1 INTRODUCTION

Landforms associated to submarine mass movements are ubiquitous in all marine settings at very different depths and slope steepness [1-3]. Their study has significantly increased in the last two decades in relation to the technological advances both in seafloor imagery system and seismic techniques as well as to the growing interest for their hazard potential [4-5]. These events can directly impact offshore or coastal infrastructures [6-7] or cause local but destructive tsunami waves, as for instance observed at Nice in 1979 [8] and Stromboli in 2002 [9]. The tsunamigenic potential of mass movements greatly depends on the water depth and size of the slope failure, even if the geometry, initial acceleration and velocity play a significant role [5]. Until now attention is mainly focused on large-scale mass-movements (volumes in the order tens or thousands of cubic kilometers) capable to produce regional tsunamis with wave heights of tens of meters. Smaller landslides in shallow-water areas have been often overlooked, even if they could be also more hazardous than the larger ones, because they typically occur more frequently than the larger events, and they can generate local but destructive tsunamis [7]. This kind of landslides is very common in geologically-active margins, where mass-wasting processes can affect percentage of seafloor areas higher than 50% (and up to 90% in some cases; [10 and reference therein]). This is, for instance, the case of the tectonically-active Calabro-Tyrrhenian margin encompassed between Cape Vaticano to the north and the Messina Strait to the south (Fig. 1). This margin formed during the opening of the back-arc Tyrrhenian Basin, in turn controlled by the NW-oriented subduction of the Ionian crust beneath the Calabrian Arc [11]. The Calabrian Arc and offshore areas have been largely affected by

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extensional faults since the Miocene [12-13], able to produce large and frequent earthquakes, such as the 1783 seismic sequence, the Capo Vaticano 1905 or the Messina 1908 events [14].

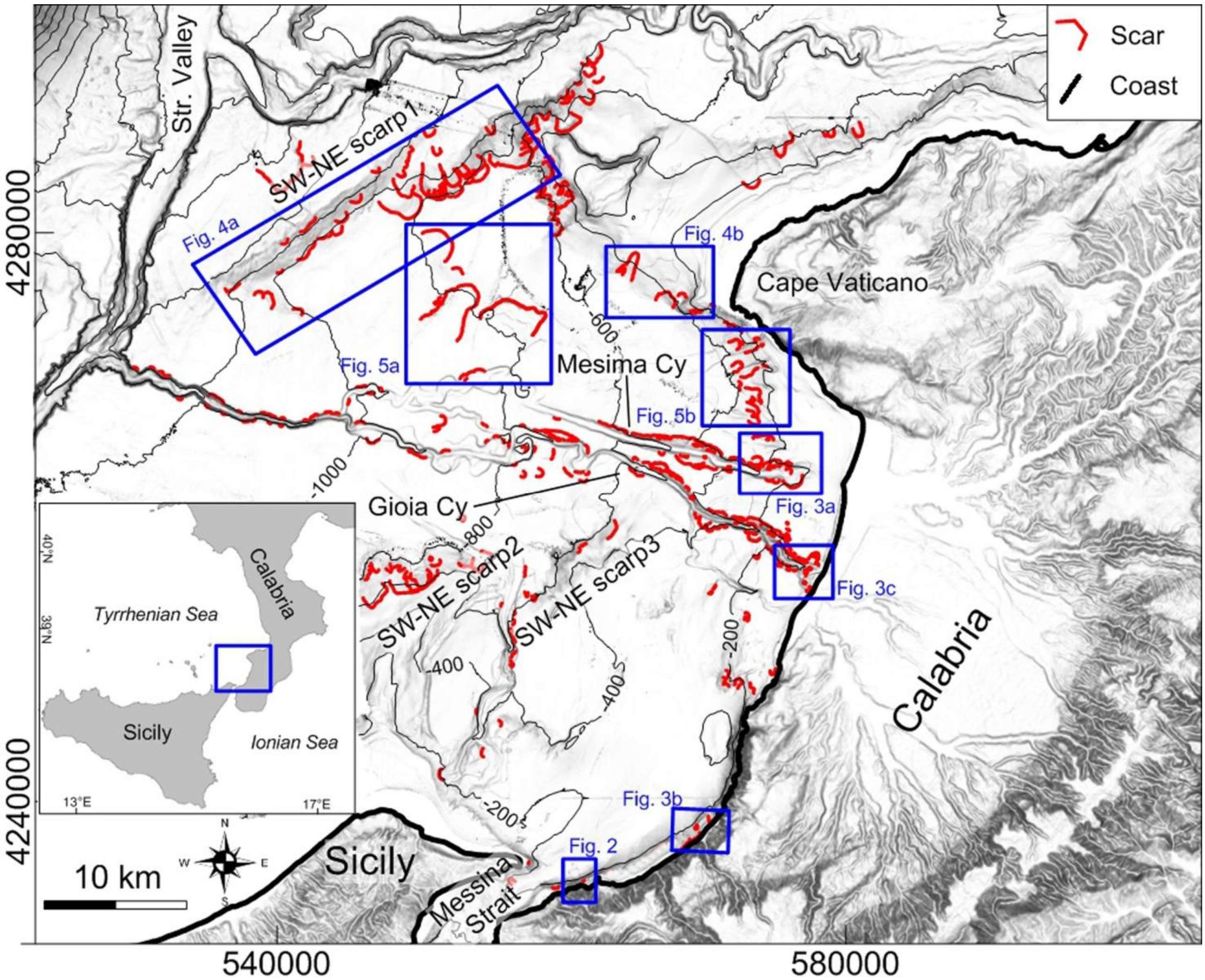

Fig. 1 Shaded relief map of the Calabro-Tyrrhenian continental margin encompassed between Cape Vaticano and the Messina Strait (location in the inset), with the indication of the recognized landslide scars (red lines from [15]) and the location of the following figures (blue boxes)

The coastal area is also affected by relevant uplift rates (rates up to 2 mm per year) since the Middle Pleistocene [16]. Because of this tectonic uplift, the shelf is commonly narrow and steep, and it receives a large amount of sediment by subaerial erosion of the coastal range. This latter is, in fact, carved by a network of steep and short river courses, locally named Fiumara [17], characterized by a torrential regime, during which flash-flood sedimentary gravity flows are often generated [18-20].

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Due to the concomitant occurrence of all these preconditioning and triggering factors, this continental margin is largely affected by widespread mass-wasting processes ranging at different spatial scales during time. A basin-scale mass-transport deposit (Nicotera Slump, [21]) covering an area of 636 km^2 and with an estimated volume of about 30 km^3 is recognizable in the slope stratigraphy. Over 400 landslide scars are recognizable on the morpho-bathymetric data, affecting an area of >85 km^2 and mobilizing approximately 1.4 km^3 of sediment (Fig. 1; [15]).

In this paper, we deal with the landslides recognizable on multibeam bathymetry to evidence the variability of geomorphic features related to these submarine mass movements along the Calabro-Tyrrhenian Margin through a review of selected case studies. This dataset is also used to discuss what are the main factors in controlling the failure and post-failure behavior of the recognized landslides.

2 DATA AND METHODS

The data presented in this study are morpho-bathymetric data collected during several oceanographic cruises performed onboard Urania and Minerva1 vessels (National Research Council) and small boats for shallow-water surveys. Data were acquired between the coast and 2000 m water depth using multibeam systems (Kongsberg and Teledyne Reson) working at frequency of 50-455 kHz in order to gain the best resolution for each bathymetric interval. Data were processed with Caris Hips and Sips and gridded at variable cell-size, ranging from 1 m in shallow-waters to 25 m in deep-waters.

3 LANDFORMS ASSOCIATED TO SUBMARINE MASS MOVEMENTS

Geomorphic features related to mass-wasting processes are widespread in the study area, and include landslide scars and associated deposits, shallow gullies, well-cut channels and canyons

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variably incising the shelf and slope. In this work, we focus on features related to submarine mass movements, i.e. landslide scars and associated deposits. The distribution of these landforms is not random but concentrates in some areas, reflecting the larger scale geomorphic and tectonic setting of the continental margin, characterized by submarine canyons (3.1), tectonically-controlled escarpments (3.2) and open slopes (3.3).

Besides these submarine landslides, blocky deposits associated to coastal rocky failures are also recognizable in the study area. The most striking example occurs off the Scilla village, where a cluster of hummocky reliefs, with a diameter of 20–180 m and height of 2–30 m with respect to the surrounding seafloor is recognizable at the base of the continental slope between -270 and -305 m (Fig. 2). These deposits were related to the Mt. Pacì 1783 tsunamigenic landslide, triggered during the second main shock of the 1783 earthquake sequence [22]. Nevertheless, the presence of a submarine scar coaxial with the subaerial one could suggest a multiple event and raise questions on the timing/triggering relationships between the two failures [23]. It is also noteworthy that similar blocky deposits associated to rocky coastal landslides have been found northward, close to Palmi village [23].

3.1 Submarine mass movements on submarine canyons

In the study area, a main canyon-channel system is present, being formed by the Gioia and Mesima shelf-indenting canyons (Fig. 1; [13,24]). Minor channels are also recognizable, such as the Bagnara Channels in the southern part. Landslide scars are recognizable both at the headwall and flanks of the Gioia-Mesima canyons system, commonly showing a semicircular and regular shape (Fig. 3). On the contrary, the morphological evidence of clear deposits associated to landslide deposits is often lacking on the multibeam bathymetry. Landslide scars occurring along the canyon flank generally have a larger size (diameters ranging from some hundreds of meters up to few kilometers; Figs. 3a and c) with respect to the canyon headwall (Figs. 3b and c). These scars are

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often coalescent and nested each other, forming a linear to sinuous array of instability features following the main path of the canyon.

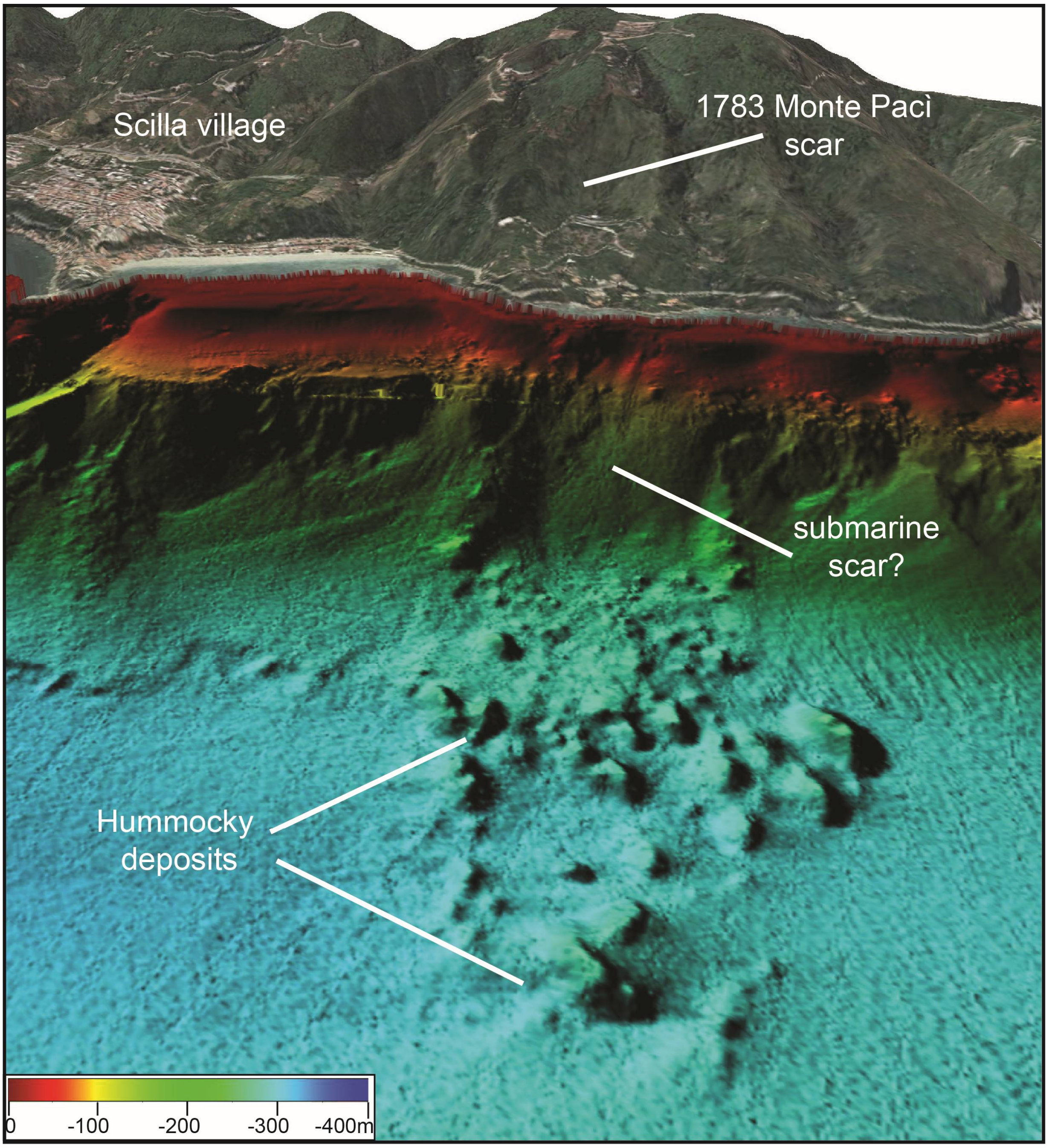

Fig. 2 3-D view of the hummocky deposits related to the 1783 Monte Pacì rocky and tsunamigenic landslide occurring off Scilla village, for location see Fig. 1.

Differently, the canyon headwall is often characterized by a cauliflower shape, formed by small (100–200 m wide) and coalescent scars, which affect the littoral wedge at depths < 15 m, thus suggesting a recent erosion (Figs. 3b and c). The comparison between geo-referenced aerial photos

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and time-lapse multibeam bathymetries collected in the last decade at the headwall of the Gioia Canyon and Bagnara channels evidenced the occurrence of repeated retrogressive landslide scars [23,25]

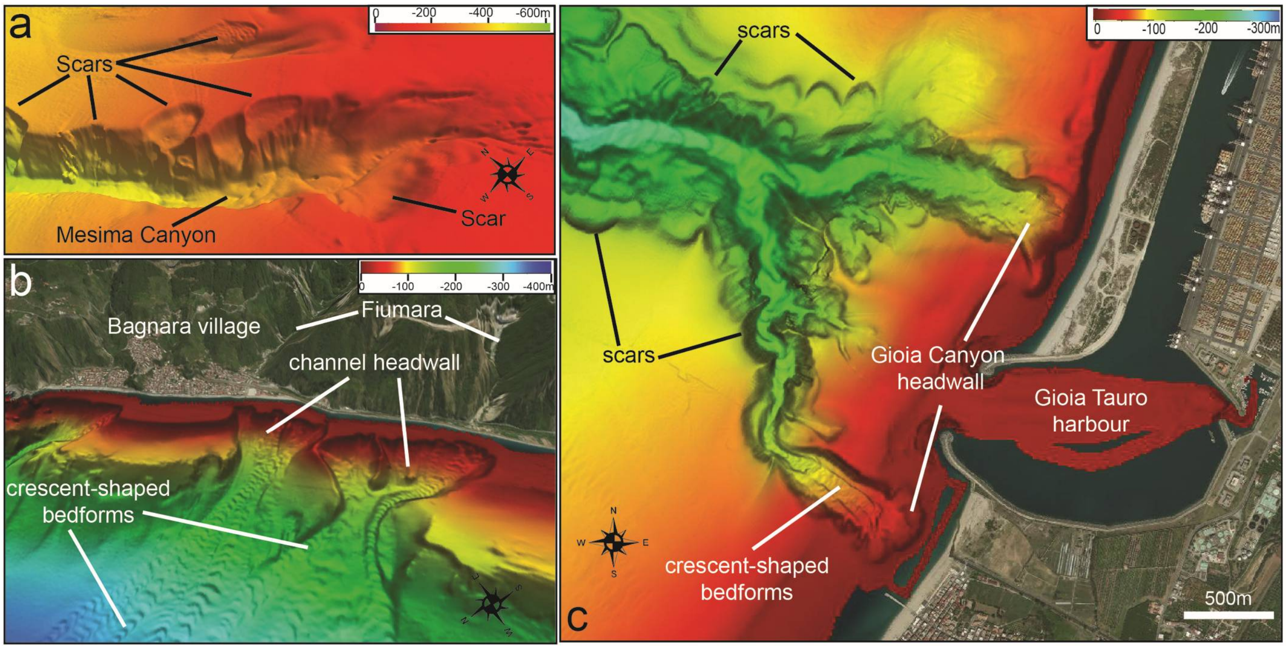

Fig. 3 a) 3-D view of the coalescent landslide scars affecting the outer flanks of the Mesima Canyon b) 3-d view of the Bagnara Channels (b), where a cauliflower headwall formed by small landslide scars present is recognizable along with coaxial trains of crescent-shaped bedforms. c) Shaded relief of the upper reach of Gioia Canyon head, formed by two branches that isolate the entrance of the Gioia Tauro harbor. Note the cauliflowers shape of the southern headwall of the Gioia Canyon as well as coalescent and nested landslides scars present along the flanks of the Gioia Canyon. Location of the figures 3a, b and c is provided in Fig. 1.

These slides can mobilize volumes comprised between 5.000 and 50.000 m^3 and are able to produce a coastal retreat of the littoral wedge in the order of tens of meters for each event. Moreover, channelized features located downslope of these scars are characterized by occurrence of coaxial trains of arcuate or crescent-shaped bedforms, with wavelength of tens to hundreds of meters and amplitude of a few meters (Figs. 3b and c).

3.2 Submarine mass movements on tectonically-controlled escarpments

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Several tectonically-controlled scarps are present in the area. One of the most prominent morpho-structural features of the area is the Capo Vaticano ridge extending down to 1000 m water depth (Figs 1 and 4). Particularly, the SW and NE flanks of this ridge are formed by linear, steep (7°-20°) and up to 300 m high escarpments, suggesting a tectonic control on their development. Downslope, the Cape Vaticano ridge is cut by a 20 km long and few hundred meters high fault scarp between -1000 and -1400m, oriented along a SW-NE direction (scarp1 in Figs 1). Minor SW-NE escarpments are also present between -800 and -600 m, even if they are markedly less steep and high with respect to the previous one (scarps 2 and 3 in Fig. 1).

Most part of these escarpments is largely affected by nested and coaxial landslides scars, having diameters variable from some tens to several hundreds of meters (Fig. 4a). The plan-view shape of these scars is variable from semi-circular to elongated along slope; on the whole, deposits associated to these landslide scars are difficult to recognize on morpho-bathymetric, except for a few isolated landslide scars occurring in the lower part of the escarpment (Figs. 1 and 4b). In detail, two main scars with associated deposits can be recognized on the SW flank of Cape Vaticano ridge: the first scar (S1 in Fig. 4b) shows an elongated shape (1800x600 m), with a steep and 20 m high headwall. Landslide deposits associated to S1 cover an area of 1.5 km^2 and have an average thickness of 10 m, displaying a rough superficial morphology. The second scar (S2 in Fig. 4b) shows instead a semicircular shape, with a diameter of 1.3 km; the head-scarp has height of 15 m and slope gradients of 33°. Landslide deposits associated to S2 cover an area of 1.56 km^2, with an average thickness of 12 m; their morphology is quite rough, with the occurrence of small ridges in the distal part that can be interpreted as pressure ridges. Both scars have an overall smooth surface, with the preservation of small ridges and/or detached slab of sediments within them.

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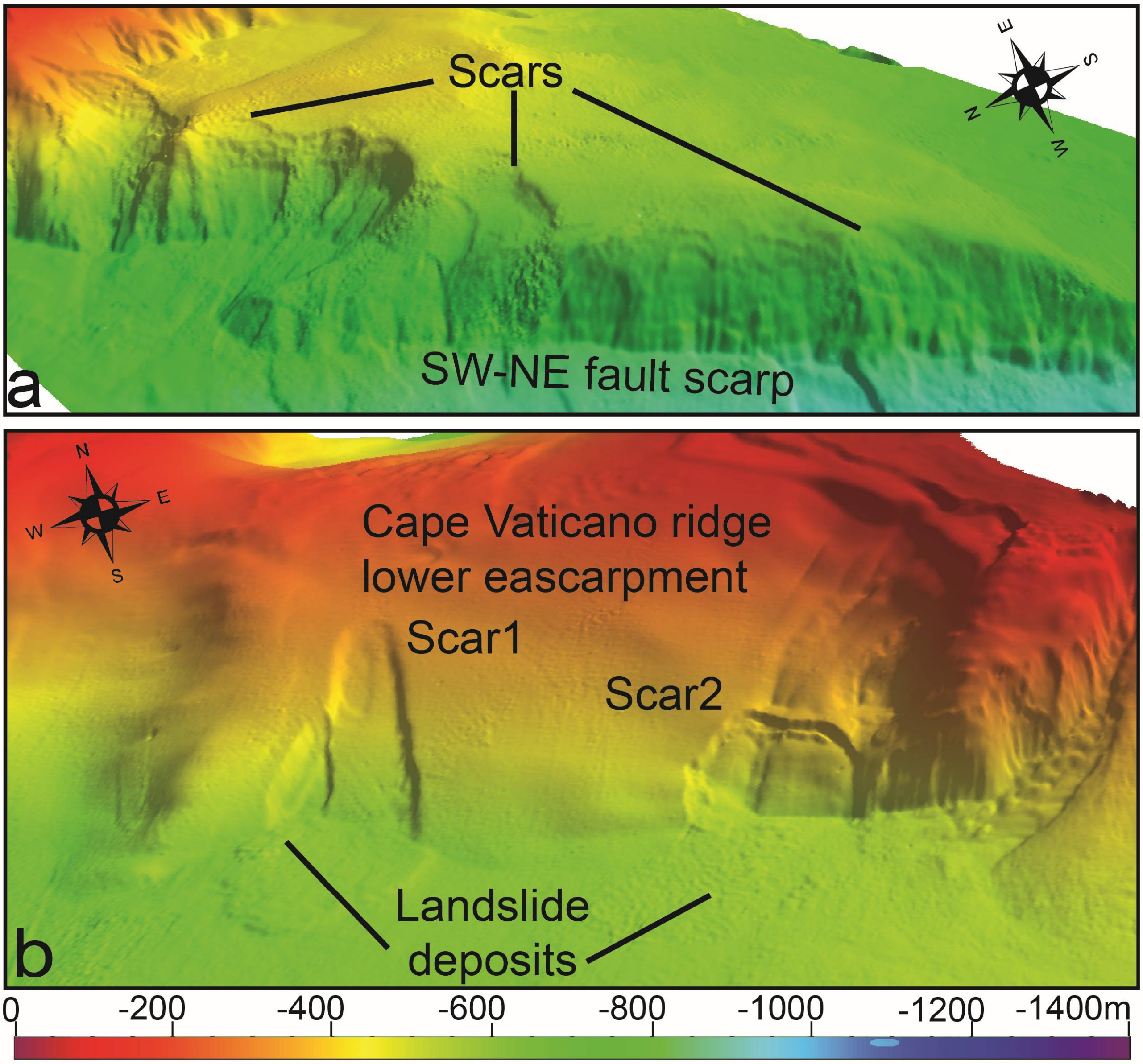

Fig. 4 (a) 3-D view of the SW-NE tectonically-controlled escarpments recognized in the lower continental slope off Capo Vaticano ridge (for location see Fig. 1), largely affected by nested and coalescent disintegrative-like landslides. (b) 3-D view of the tectonically-controlled escarpment forming the SW flank of Cape Vaticano ridge (for location see Fig. 1), where isolated landslide scars with associated deposits are present.

3.3 Submarine mass movements on open slopes

On multibeam bathymetry, relatively few landslides can be observed on the open slope sectors, even if they often have the largest size among all the recognized landslides. Particularly, three large

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landslides were identified on the continental slope comprised between Cape Vaticano and the Mesima Canyon between -700 and -1000 m (Fig. 5a). This sector is adjacent to the Capo Vaticano ridge but can be considered an open slope sector as minor tectonic control is indicated by seismic profiles [26]. The first scar (S3 in Fig. 5a) is approximately 3.5x4 km and has head-scarp with height of 20-60 m (on average 35 m) and slope gradients of 20°-40°. Small blocks and ridges are present at the base of the main head-scarp, indicating occurrence of material that is not completely evacuated from the scar. Downslope, the detached landslide mass is recognizable on the bathymetry and mostly confined within the landslide scar. Seismic profiles also show that landslide deposits are downslope confined from the northern levee of the Mesima Canyon [26]. The second scar (S4 in Fig. 5a) is approximately 2x4 km and its head-scarp is characterized by an average height of 25 m, with slope gradients of approximately 20°. The scar shows an overall smooth morphology and no clear landslide deposits are recognizable on the bathymetry. The third scar (S5 in Fig. 5a) is 1.7x2.7 km, displaying an overall subdued relief, with a 4-15 m high head-scarp.

Besides these slides, a large landslide complex is recognizable in the upper continental slope off Cape Vaticano (and for this reason named Capo Vaticano Scar Complex, CVSC hereafter, [27]) between -190 m and -500 m. The CVSC covers an area of about 18 km^2, with an estimated mobilized volume of approximately 175x 10^6 m^3. The CVSC is formed by four main landslide scars, having head-scarp with height of 10–25m, and several minor scars with 2–5m high head-scarps. It is noteworthy that the landslide morphology is variable along the CVSC, with the northern part mostly dominated by scars showing a rugged morphology due to material not completely evacuated during the failure, such as detached blocks and ridges parallel to the main head-scarp. On the contrary, the southern part of CVSC is mainly characterized by coaxial and tabular scars having an overall smooth appearance and affecting the steep seaward side of a contourite drift.

At the foot of the CVSC, a rough morphology associated to coalescent and intersecting landslide deposits is present, including pressure ridges, blocks, and erosional remnants (Fig. 5b).

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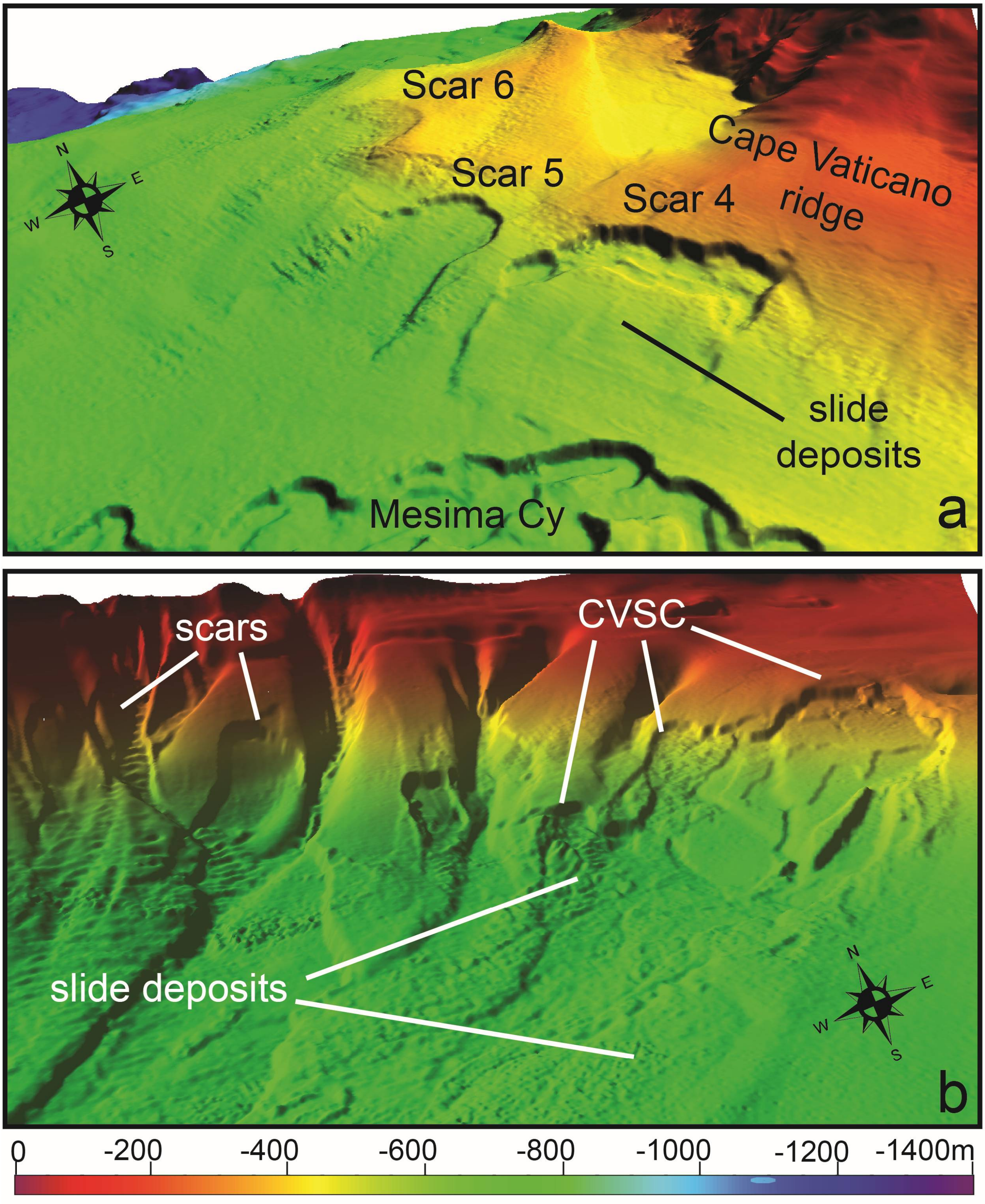

Fig. 5 3-D view of the landslide scars affecting the open continental slope encompassed between Cape Vaticano ridge and Mesima Canyon (a) and the Capo Vaticano Scar Complex (CVSC) affecting the upper continental slope characterized by contourite deposits. For location see Fig. 1.

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DISCUSSIONS

5.1 Distribution and variability of submarine mass movements and related controlling factors

The previous section has evidenced the widespread distribution and variability of landforms associated to submarine mass movements in the sector of the Calabro-Tyrrhenian margin comprised between the Cape Vaticano and the Messina Strait, where semi-circular to elongated landslides scar, with variable size and morphology are present. Even if landslides morphology and distribution can be controlled by several factors and processes, varying in space and time (e.g., slope gradients, fall height, lithological characteristics, tectonic activity, sediment supply, pore water overpressure, cyclic load induced by earthquakes or waves, flank undercutting due to turbidity currents), it is noteworthy that most of the observed variability seems to be strictly related to different physiographic/morphological domains where the landslide formed. Based on their morphology and distribution, four main classes of submarine landslides can be recognized: 1) rocky coastal/shallow-water failures associated with cluster of hummocky deposits; 2) large-size and isolated scars with associated landslide deposits, mostly occurring on open slope environment and lower part of tectonically-controlled escarpments; 3) a linear array of coalescent and nested, disintegrative-like landslide scars occurring in the upper part of tectonically-controlled escarpments and canyon flanks; 4) a cauliflower array of small and coalescent disintegrative-like scars occurring in canyon headwalls. In this classification scheme, the CVSC represents a peculiar case of a large complex of coalescent and nested landslide scars developed on the upper continental slope, where a mixed turbidite–contourite system is present [27].

Disintegrative-like slope failures occurring along canyons account for more than half of the total observations (59%), even if they are generally of small- and medium-size, contributing only to the 5.2% of the mobilized sediment volume (Fig. 1; [15]). Another main cluster of small- and medium-size, disintegrative-like landslide scars is observed along the tectonically-controlled scarps affecting the area. In both cases, the landslide scars often representing the head-scarp of underlying

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channelized features, suggesting the occurrence of retrogressive failures for their origin [28]. The overall small size of such failures can be mostly related to the steep slope gradients occurring in canyons flanks and tectonically-controlled escarpments coupled with the frequent seismicity that characterizes the study area. In such setting, sediments cannot accumulate over large areas and for long time spans, giving rise to large-scale failures, as typically observed on the mid and lower continental slopes [29-31]. This finding agrees with submarine landslide inventories in other steep and geologically-active areas, such as in the Gulf of Corinth [32], Gulf of Naples and surrounding areas [33] and offshore Pontine Islands [34-35]. Steep gradients are also likely responsible for the disintegrative-like behaviour characterizing most of these slides [30], i.e. scars having a smooth morphology and associated landslide deposits not recognizable on the bathymetry. This behavior might be related to the fact that slide sediment either lost cohesion during failure or failed as a cohesive mass but disintegrated downslope due to the low mobilized volume and high energy (steep gradients and fall height). In this regard, it should be considered that the total fall height of the slope failures seems also to control the degree of the disintegration of the failed material. In fact, only for those scars located in the lower part of the steep flank of Capo Vaticano ridge, the related mass-transport deposits are still recognizable on bathymetry (Fig. 4b). This evidence is consistent to what was observed along other tectonically-controlled scarps, as for instance on the intraslope Palmarola ridge [36].

In the study area, slope failures occurring in open slopes have the largest dimension and most of them can be interpreted as the result of translational failure in relation to their slope-parallel bedding and fairly constant height of the main head-scarp, similarly to what was observed in others margin [31]. However, despite these slides are close to each other and share similarities in size and failure mechanism, they show significant morphological differences in the headwall, translational and toe domain, suggesting different post-failure evolution mechanisms (e.g. disintegrative-like vs cohesive-like behavior). Such differences can be related to changes in material properties, depth of the failure plane, slope gradients and frontal confinement [37-39]. In the case of Cape Vaticano

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ridge, the cohesive-type S4 slide was confined downslope by the northern levee of the Mesima Canyon with respect to the less confined setting of the disintegrative-like S5 slide. It is also noteworthy that S5 slide is characterized by a lower height and slope gradients of the head-scarp with respect to the S4 slide, suggesting a failure occurring within a weaker or less cohesive material [40]. In the case of CVSC, cohesive-like slides preferentially occur in the northern part of the CVSC, where mixed turbidite–contourite deposits are present, while disintegrative-like slides mainly affected the contourite drifts developed in southern part (Figs. 5b; [27]). This distribution suggests that the different post-failure behavior of the recognized slides can be due to the difference in sediment type (mixed turbidite– contourite deposits vs contourites) mobilized during the failure events along with the occurrence of steep gradients on the seaward side of the contourite drifts.

5.2 Preliminary considerations on the potential geohazard associated to the submarine mass movements in the Calabro-Tyrrhenian continental margin

In this section, we attempt to roughly assess the hazard potential associated to the recognized landslide scars. On the whole, the hazard related to the landslides affecting open slopes can be considered overall low, as these events are relatively few and they commonly occur at depths greater than -120 m. In this depth range, their size is not able to generate significant tsunami waves for surrounding coastal sectors according to a rapid estimation of their potential tsunamigenic based on semi-empirical equations available in the literature [41] and already used in the nearby areas [33, 42]. Similar consideration can be applied also to the small- and medium-size disintegrative-like affecting the tectonically-controlled escarpments and canyons sidewalls present in the area.

On the contrary, the hazard is markedly higher for slope failures occurring at the canyon head of the Gioia Canyon and Bagnara Channels, because of the retrogressive erosion that commonly characterizes the evolution of canyon heads and their proximity to the coast (depths < 10 m and distance of few hundreds of meters). In such areas, retrogressive erosion processes can cause both the failure of coastal areas/infrastructures and small tsunami waves, as recently testified by the 5 x

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10^6 m^3 of material failed at the head of the Gioia Canyon in 1977 during the harbor construction (Fig. 4a; [43]). It is noteworthy a similar tsunamigenic landslide occurred two years later off Nice at the head of Var Canyon during the enlargement of the harbor, causing several damages and casualties [8]. The recent sedimentary activity of Bagnara Channels and Gioia Canyon is witnessed by recognition of crescent-shaped bedforms in their thalweg, commonly recognized in active channel/canyon elsewhere. This activity might be related to the occurrence of small retrogressive failures at the headwall of these channelized features, as evidenced by multi-lapse bathymetric surveys [25]. Another relevant source of hazard in the study area is represented by rocky coastal failures that can affect the coastal range, as witnessed by the tsunamigenic coastal failure occurred in 1783 nearby Scilla village that caused over 1500 casualties. These landslides are favored by the active fault systems affecting the coastal range and can be triggered by the frequent and strong seismicity present in the area.

CONCLUSIONS

This study has focused on the distribution and variability of landforms related to submarine mass movement along the tectonically-active Calabro-Tyrrhenian margin. Results indicate that distribution and morphology of these features are not random, but they are primarily strictly related to the physiographic/morphological domains where slope failures develop. Small disintegrative-type slides mainly occur in the areas with the steeper gradients, such as canyons and tectonically-controlled scarps. Differently larger and isolated landslides occur in open slopes, even if they can be characterized by a large variability of post-failure behavior. Cohesive-like and disentegrative-like slope failures can occur also at short distance in relation to difference in the mechanical properties of the mobilized material, slope gradients and degree of confinement. A peculiar case is represented by the Capo Vaticano Scar complex, whose formation can be related to the presence of a mixed turbidite-contourite systems in the upper continental slope/ outer shelf sector.

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In the study area, the hazard related to submarine mass-movements can be significant, especially for coastal rocky landslides and retrogressive slides at the headwall of shelf-indenting canyons/channels. These events can produce damages to coastal infrastructures and/or casualties as demonstrated by historical tsunamigenic events associated to the 1783 Scilla and 1979 Gioia Tauro slope failures.

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AUTHOR CONTRIBUTIONS

Daniele Casalbore conceived and wrote the manuscript with the help of the other co-authors. Data acquisition was made by Alessandro Bosman, Daniele Casalbore and Eleonora Martorelli; data processing was made by Alessandro Bosman, whereas data analysis was performed by all the authors. Figures were realized by Daniele Casalbore

CONFLICTS OF INTEREST

The authors declare no conflict of interest

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