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Geohazard Features of the Ionian Calabrian Margin

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ABSTRACT
Here we present a detailed description of different geomorphic features to complement the Maps of Geohazard Features of the Ionian Calabrian Margin produced by the Magic project (Marine Geohazard along Italian Coasts). Some of the most striking features we imaged are sources of widespread and recurrent geohazards. These include multiple coastal landslides, failure scars along open slopes, shelf-indenting retrogressive canyon headwalls and active fluid venting structures, that we investigated by integrating regional high-resolution multibeam sonar and sub-bottom profiling data. The main triggers and predisposing factors for the marine geohazards that we identify in our study area include frequent seismic activity, the rapid uplift of the margin since 1 Ma and the presence of Messinian evaporites at depth. Large-scale gravity-driven movements and the incipient retrogressive canyon headwalls are of particular concern, as they are located just a few hundred meters from the coast, where critical infrastructures and densely populated urban centers are situated, and also where high-resolution geophysical data are often lacking. Overall, our study provides a key reference for more detailed follow-up studies to foster a better understanding of marine geohazard occurrences. The insights provided are critical for planning monitoring programs and for the protection of coastal settlements and marine infrastructures along the Calabrian Ionian margin.

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KEYWORDS
Marine geohazards; seafloor mapping; Ionian Calabrian Margin

1. Introduction

This article introduces the Maps of Geohazard features of the Ionian Calabrian Margin (ICM) produced by the MaGIC project (Marine Geohazard along Italian Coasts), a large joint initiative that involved the whole marine geological research community in Italy through 2007–2013. The features were identified in multibeam data and, therefore, rely on the morphological expressions of seafloor and shallow subsurface processes and events.

The cartographic results are illustrated within a general map of the physiographic domains of the Sea (1:250,000 scale) and five maps (1:100,000 scale) subdivided as follows: Capo Spartivento (Sheet 35), Siderno (Sheet 36), Punta Stilo (Sheet 37), Catanzaro (Sheet 38) and Crotone (Sheet 39) (for location see Figure 1). The maps were produced using the same interpretative and cartographic standards, described by Ridente and Chiocci (this volume). This article describes the main morphological features indicative of geohazards along the ICM, and is subdivided into five distinct subchapters (4.1–4.5) addressing each Sheet.

2. Study area: Ionian Calabrian Margin

The ICM is a tectonically active convergent margin developed above an NW-dipping subduction zone involving the Ionian oceanic slab, and marking the plate boundary between Africa and Europe (Figure 1). The onshore to offshore morphology of the ICM reflects two main geodynamic processes: (1) accretionary tectonics during SE-ward migration of the ICM since the Middle Miocene—this process led to the formation of a complex accretionary prism composed of a submerged accretionary wedge and an exposed nappe

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Supplemental map for this article can be accessed online at https://doi.org/10.1080/17445647.2024.2349785.

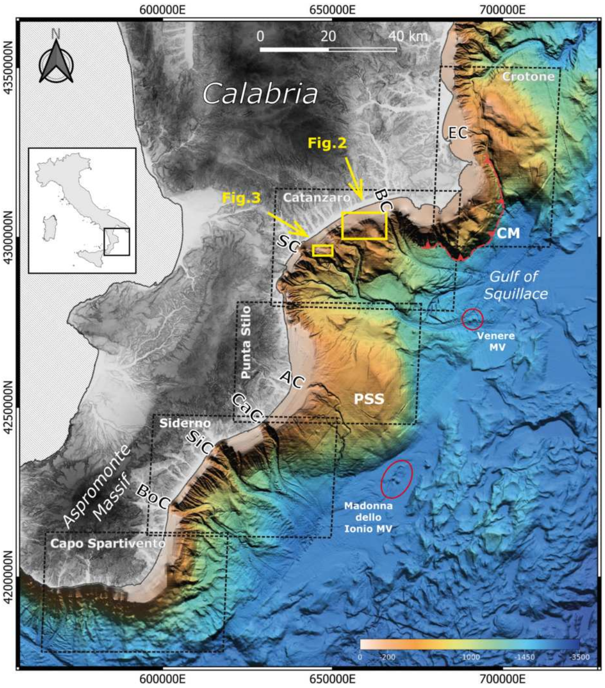

Figure 1. Shaded relief map across Calabria and the ICM, relative to the main morpho-sedimentary features identified from seabed and sub-bottom datasets. Offshore bathymetry is based on DTMs of variable resolution (5–20 m grids). BoC—Bovalino Canyon, SiC—Siderno Canyon, CaC—Caulonia Canyon, AC—Assi Canyon, PSS—Punta Stilo Swell, SC—Squillace Canyon, BC—Botricello Canyon, EC—Esaro Canyon, CM—Crotone megaslide (outlined in red). Red circles indicate the location of the Venere and Madonna dello Ionio mud volcanoes.

stack of metamorphic and sedimentary units, the well-known Calabria–Peloritani terrane (Bonardi et al., 2001; Gutscher et al., 2015; Minelli & Faccenna, 2010; Polonia et al., 2011; Rossi & Sartori, 1981; Sartori, 2003); (2) km-scale regional uplift (up to 1 mm yr^{-1}) of the onshore and shallow shelf areas since the Mid-Pleistocene, resulting in the exhumation of the inner areas of the margin (Faccenna et al., 2012; Westaway, 1993). On the seabed, the interaction of these processes resulted in an irregular morphology expressed along the Crotone-Spartivento Basin (Ceramicola et al., 2009, 2014a, 2014b, 2014c; Mangano et al., 2021; Morelli et al., 2011; Praeg et al., 2009), a Miocene to recent depocenter that is part of the ICM and lies uncomformably on the Calabrian–Peloritani terrane. The latter terrane is an independent arcuate block that connects the NW-trending southern Apennine chain in the north, to the E-trending Sicilian–Maghrebian chain in the southwest (Zecchin et al., and references herein).

Morphologically, the ICM is characterised by a narrow (in places absent) continental shelf that extends to a water depth of 70–120 m. This shelf gives way to an irregular continental slope extended to a water depth of about 2000 m (Figure 1). To the northeast, the slope is broader and dominated by structural highs that separate intraslope basins (e.g. the Amendolara Ridge and the Corigliano Basin). To the South, the shelf is narrower and the slope steeper (up to 15°), above the deep-water Crotone–Spartivento forearc basin. The entire ICM is dissected by spectacular submarine canyons, which form the largest morpho-sedimentary erosional features of the area, inferred to be relatively young (Ceramicola et al., 2014a, 2014b, 2014c, 2015; Coste, 2014) (Figures 1 and 2). The northern area includes two main canyon systems (Corigliano and Neto) that feed into the large Taranto Valley. The southern area includes eight main canyon systems feeding the forearc basin (Ceramicola et al., 2024) (Figure 1).

The headwalls of many canyons lie near or at the coastline, with their retrogressive character and associated failures (e.g. Cirò, Punta Alice, Neto, Squillace, Catanzaro, Siderno canyons) having been identified as the main marine geohazards of the ICM coastal area (Figure 1 and 2) (Amblas et al., 2022; Ceramicola et al., 2014a, 2015; Morelli et al., 2011). Other possible hazards are due to the presence of slumps, slides, mud volcanoes and cold seeps, some of which lie relatively near to the coastline (Ceramicola et al., 2014a, 2014b, 2014c; Foucher et al., 2009; Loher et al., 2018; Mascle et al., 2014; Mangano et al., 2020; 2021; 2023; Praeg et al., 2014; Zecchin et al., 2018) or on the canyon headwalls (Ceramicola et al., 2014a; Morelli et al., 2011). These features favor the retrogressive trend of submarine canyons toward the coast. In addition, seabed structural elements such as faults, folds and thrusts have been mapped and their seismogenic potential is being assessed.

3. Methods and software

As the maps were produced using the same interpretative and cartographic standards, the procedure is described in detail in Ridente and Chiocci (this volume). The legend of the Physiographic Domain map is present on the map while the legend of the Morphological Units and Morpho-bathymetric Elements map is present as a separate sheet. The high-resolution multibeam bathymetry data were acquired by the research vessel R/V OGS Explora using echosounders Reson SeaBat 8111 (up to 500 m water-depth) and the Reson SeaBat 7150 (for deep water surveys) in the frame of the MaGIC, the MESC (Morphology and Evolution of the submarine canyon in the Ionian margin of Calabria), and the WGDT (Morphology and Architecture of the Western Portions of the Gulf of Taranto) projects using PDS2000 software. The data were processed in OGS using Caris software and a DTM at variable resolution (5–20 m) was generated. The seafloor mapping was carried out using a dedicated version of the Global Mapper® software ('MaGIC project' release). The sub-bottom profiles were carried out using a Benthos Chirp II hull mounted with 16 transducers. The data

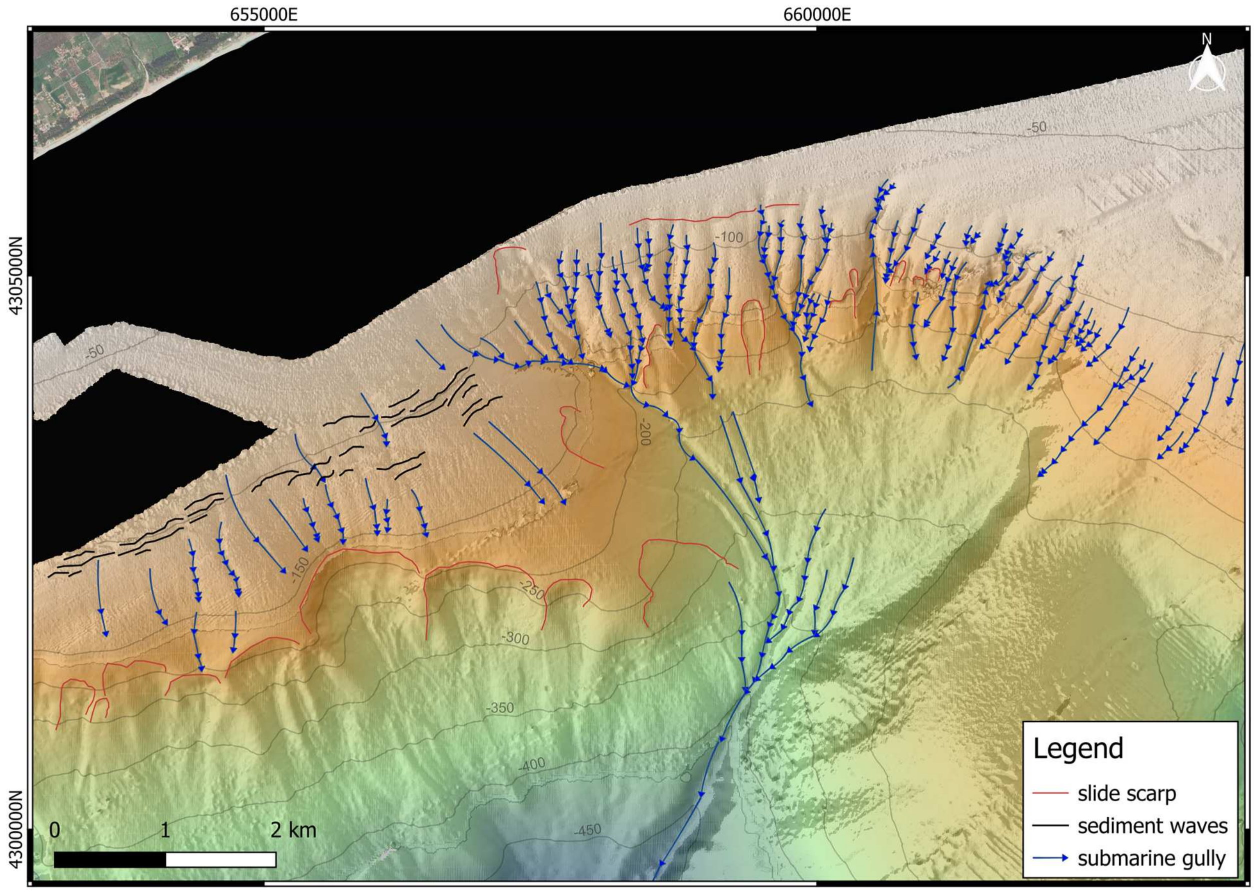

Figure 2. Shaded relief of the headwalls of the canyon cutting into the Gulf of Squillace. The steep arcuate headwalls are shown in red and the numerous gullies in blue. The location of this area is shown in Figure 1.

were output in XTF format and converted to SEGY format. The interpretation of the geomorphic features was obtained by integrating seabed morphologies with information from subsurface data, specifically the acoustic character of the reflections and their continuity in the subsurface.

4. Maps of morphological units and morpho-bathymetric elements

4.1. Capo Spartivento (MaGIC Sheet 35)

Sheet 35 'Capo Spartivento' encloses the sector of the ICM between Melito di Porto Salvo and Capo Bruzzano (Figure 1; Ceramicola et al., 2021). This portion of the ICM is characterised by recent tectonic activity i.e. Pliocene subsidence, followed by regional uplift since the Middle Pleistocene (Faccenna et al., 2012; Ferranti et al., 2007). Onshore, several streams characterised by their seasonal, torrential regime (i.e. the 'Fiumare') flow down from the Aspromonte Massif, reaching the coastal zone near the towns of Brancaleone, Bova Marina and Melito di Porto Salvo. Between the western boundary of sheet 35 and Capo Spartivento, the E–W elongated coastal line shows marked indentations, with pronounced bays and promontories (Figure 1). On the contrary, in the eastern portion of the sheet, the N–S elongated coastal line has a more regular and rectilinear pattern, only interrupted by the Capo Bruzzano promontory (e.g. Colizza, et al., 2021). These two different coastal sectors correspond to offshore areas with distinct physiographic settings.

North of Capo Spartivento, the continental shelf is on average 7 kilometers wide, an exceptional extension when compared to the other sectors of the ICM. It is characterized by a flat morphology, locally interspersed by small topographic highs that are more common along the shelf edge. Common fluid escape vents are revealed by reflections blanking on seismic lines and seabed pockmark features (e.g. Colizza, et al., 2021). Such fluid circulation can potentially control sediment compaction, particularly in upper Quaternary deposits (i.e. precipitation of authigenic carbonates; Lo Iacono et al., 2011). In the adjacent slope area, erosional channels of smaller dimensions and lateral continuity are frequent with respect to the western sector of sheet 35 and, more generally, to other slope areas of the ICM (Colizza et al., 2008; Cuppari et al., 2004). Along this slope sector seabed erosion is chiefly controlled by the active mass movement, which often interrupts the continuity of the narrow submarine channels carved along the continental shelf edge.

The occurrence of large, well-defined slide scars (maximum width 5.2 km, maximum length 1.5 km) testifies to how mass wasting processes chiefly control the evolution of the upper slope morphology. These features are also present at the base of the slope but are less pronounced and widespread.

Westward of Capo Spartivento, the extension of the continental shelf is sharply reduced from 5 km up to (locally) a few tens of meters (e.g. in front of the towns of Bova Marina and Condofuri Marina). In this sector, the erosion is focused on the canyon headwalls and can locally result in the complete, retrogressive disruption of the shelf with direct interaction (e.g. induced gravitative phenomena) with the coastal areas. This complex and extended system of canyon headwalls is linked to an N–S oriented, deeply carved system of canyons further downslope (Figure 1).

At the base of the slope (i.e. to the SE of Capo Spartivento) there is a prominent and laterally continuous scarp, which reaches a maximum height of 250 meters and a length of 20 km. The rectilinear trend and continuous, lateral extension of this scarp suggest its origin can be ascribed to recent tectonic activity along a NE–SW trending regional fault system.

The complex morpho-bathymetry of the continental margin revealed in sheet 35 ‘Capo Spartivento‘ highlights the key role played by high-energy erosional processes (e.g. focused erosion at canyons headwalls and high-energy, channelised fluid flows) as triggers of slope instability and large-scale mass wasting. The most relevant geohazard features are developed in the western sector of the sheet, where an extended system of canyons with active retrogressive erosion affects the entire continental shelf close to the littoral areas (locally with canyon heads carved 50 meters from the coastline).

Along the eastern slope sector, the importance of mass wasting features testify to their predominance over channel erosional processes, the latter being usually dominant in other areas of the ICM (Ceramicola et al., 2009, 2014a, 2014b; Corradino et al., 2023; Morelli et al., 2009; 2011).

Furthermore, the occurrence of fluid escape vents (pockmarks and authigenic carbonates) and the prominent NW–SE seabed fault scarps at the base of the continental slope suggest an important interaction amongst recent tectonic activity, fluid escape processes and mass wasting as verified in other areas offshore Italy (e.g. Ligurian Sea; Morelli et al., 2022, 2024). Hence, further investigations aimed at assessing the potential geohazard of these critical areas, which are located only a few kms away from a densely urbanized coastal area are envisaged

4.2 Siderno area (MaGIC Sheet 36)

The Sheet 36 ‘Siderno‘ is located along the ICM, between the Bovalino and Caulonia marina (Figure 1). Here, the western portion of the margin is characterised by a straight coastline and a very narrow, at times completely absent, continental shelf repeatedly incised by the multiple headwalls of the Marina di Gioiosa Ionica, Marina di Caulonia, Bovalino and San Nicola canyon systems. In this portion of the seabed, headwalls form a complex system of rectilinear subparallel gullies indenting the margin slope along over 20 km, reaching at times a short distance from inhabited areas, coastal infrastructure and major communication routes (i.e. railway network). On the eastern portion of the margin, we observe the continental shelf widening and the shelf-break giving away to the more gentle slopes of the Punta Stilo Swell. Here, the multiple scarps of the Assi failures identified on the high-resolution bathymetric data combined with stacked and buried debris flow observed in sub-bottom data, revealed repeated mass wasting events in recent times (Ceramicola et al., 2014a, 2014b, 2021). In terms of geohazards, Sheet 36 ‘Siderno‘ shows several features that deserve attention and further studies and monitoring activities are recommended in the area.

4.3. Punta Stilo (MaGIC Sheet 37)

The area of Sheet 37 ‘Punta Stilo‘, on the ICM, extends from the southernmost part of the Gulf of Squillace across the broad bathymetric elevation to the south referred to as the Punta Stilo Swell (Figure 1). In this area, the continental shelf is wide (4.5–6 km) compared to adjacent areas, and the shelf-break lies at a water depth of 100–110 m. The continental slope is broad, up to 30 km wide, and shows a concave profile, with gradients increasing (up to 2 m/km̊) in water depths of about 500 m. To the North, the slope results from tectonic activity in the Soverato-Lamezia Shear Zone (Mangano et al., 2022) and is incised by several canyon branches that drain into the large Squillace Canyon system (see Sheet 38). To the North, the isolated Assi Canyon is found. The Punta Stilo Swell is marked by numerous arcuate and irregular scarps that are tall up to 50 m and record repeated slope failure events, the lobate deposits of which can be seen in places, both at the seafloor and in multiple levels within the underlying sedimentary succession (Ceramicola et al., 2014b).

Remarkable features observed on the southern flank of the Punta Stilo Swell are the Assi multiple failure events lying between the Siderno Canyon system to the west and the smaller Assi Canyon to the east. Morpho-bathymetric data show that the slope is characterised by arcuate seafloor scarps indicative of downslope sediment failures, including several scarps located on the upper slope in water depths between 150 and 500 m (first phase of activity). The larger landslide (hereafter simply referred to as the Assi landslide) is visible below a headwall scarp up to 50 m high as an elongated slide scar up to 6 km wide and at least

18 km long, extending across water depths between 500 and 1400 m. It has a minimum width of 3.1 km in water depths of 730 m; above this depth, it shows an NW–SE orientation, whereas below it shows an N–S orientation, (both segments are perpendicular to the regional slope). Bathymetric profiles along and across the landslide show that its upper part has a concave-up profile, whereas the lower part shows a convex-up profile. The lowermost parts of the landslide intersect the Assi canyon, but the gravitational phenomenon has no apparent expression on the adjacent floor of the Spartivento basin. Sub-bottom profiles across the Assi landslide show it contains both stratified and unstratified deposits above a low-angle basal unconformity (c). The upper part of the landslide mainly consists of stratified deposits and rocky blocks with seabed expression, while the lower part contains more mixed acoustic facies. The slide is observed to truncate unstratified deposits, interpreted as older debris flow deposits, including near-seabed layers seen to be linked to the seabed scarps, observed upslope. The main body of the Assi landslide extends over a total area of c. 90 km^2, and we estimate that it mobilized in total ca. 2 km^3 of sediment during two phases: the N–S-oriented lower slide and the NW–SE-oriented upper slide (Ceramicola et al., 2014a, 2014b).

The material mobilized during the Assi landslide was used for tsunami modeling on the assumption that the material failed in a single step (as a volume of 1.85 km^3) and remained a coherent mass. This represents a ‘worst-case‘ scenario, chosen in order to assess the strongest possible consequences a landslide with such parameters may have generated (Ceramicola et al., 2014a,b). The study presents the first attempt to evaluate the potential tsunamigenic hazard associated with submarine mass movements along the ICM of the Mediterranean Sea. The combined results of seabed mapping and numerical modeling allow the risk of tsunamis to the Ionian coastal areas of Calabria to be assessed. Results indicate that the waves generated by such landslides are not catastrophic but can still cause damage, particularly in small harbors along the coast. Here, wave reverberation on bathymetric and coastal features may amplify the wave effects. This highlights that in the Ionian Sea, where coastal areas are closely situated, and continental slopes are not extensive, tsunamis would reach the coast rapidly, within minutes, making it challenging to establish an effective alert system. Therefore, it is recommended that seabed affected by severe geohazards, such as the Assi multiple failure events, should be closely monitored for potential future occurrences. The unpredictability of the sliding phenomena, due to their proximity to the coast and the corresponding shortness of the lead time (in this case about 7 minutes), and the large number of possible tsunami sources recorded by past episodes of failure along the margin, suggests that tsunamis represent a recurrent hazard for Ionian coastal areas and thus need accurate monitoring and further study.

4.4. Catanzaro area (Magic Sheet 3)

The area of Sheet 38 ‘Catanzaro‘ includes almost the entire Gulf of Squillace, a marked embayment of the Ionian coast of Calabria. The gulf is bounded to the North by the Capo Rizzuto promontory and to the South by an E–W-oriented transtensive fault system located along the northern flank of the Punta Stilo Swell (Mangano et al., 2022; Merlini et al., 2000) (Figure 1). Most of the area is part of the Crotone Basin, a Neogene fore-arc depression within the inner Calabrian accretionary prism (Zecchin et al., 2020 and references herein). The Crotone Basin is filled by deposits dating back to the Middle Miocene that record marine deposition interrupted by episodes of uplift and transpression in the Messinian, Pliocene and Pleistocene times (Roda, 1964; Van Dijk, 1992; Zecchin et al., 2012, 2015, 2020). Since the Middle Pleistocene, the Calabrian Arc has experienced rapid uplift up to 1 mm/yr (Westaway, 1993), leading to exposure conditions along the inner part of the basin, while sediments continued to accumulate in the distal areas (Zecchin et al., 2020).

Seismic reflection profiles across the offshore basin show thrust faults that are overlain by a Neogene sedimentary succession up to 2-km-(2 sec) thick (Minelli & Faccenna, 2010). The succession includes diapiric structures that stem from Messinian salt (Rossi & Sartori, 1981) and shale mobilization (Capozzi et al., 2012). The overlying Plio-Pleistocene siliciclastic succession contains unconformities and thrust faults that record post-Messinian tectonics within the inner accretionary prism, in places above Messinian evaporites (Minelli & Faccenna, 2010). Shear zones that episodically switch from trans-tensional to transpressional tectonics, and vice versa, bound the basin to the NE and to the SW (Massari et al., 2010; Van Dijk, 1990).

In this part of the seabed, the continental shelf is only a few kilometers wide (7 km maximum) and in places, where the Squillace Canyon headwalls are active, the shelf is reduced to only a few hundred meters. When not eroded by the canyon headwalls, the shelf-break is visible at about 120 m water depth (Figure 2).

The Squillace Canyon is one of the most impressive features observed in this area. It is about 100 km long and up to 3 km wide in its middle part, with walls 150 m high; the canyon headwall has a dendritic shape that extends over a perimeter of 50 km, with headwalls up to 300 m high (Figure 1). One particularity of the Squillace Canyon is that the headwall incises the shelf very close to the coastline; in some places, only 1 km offshore (Figure 2). Shelf gullies seem to connect the

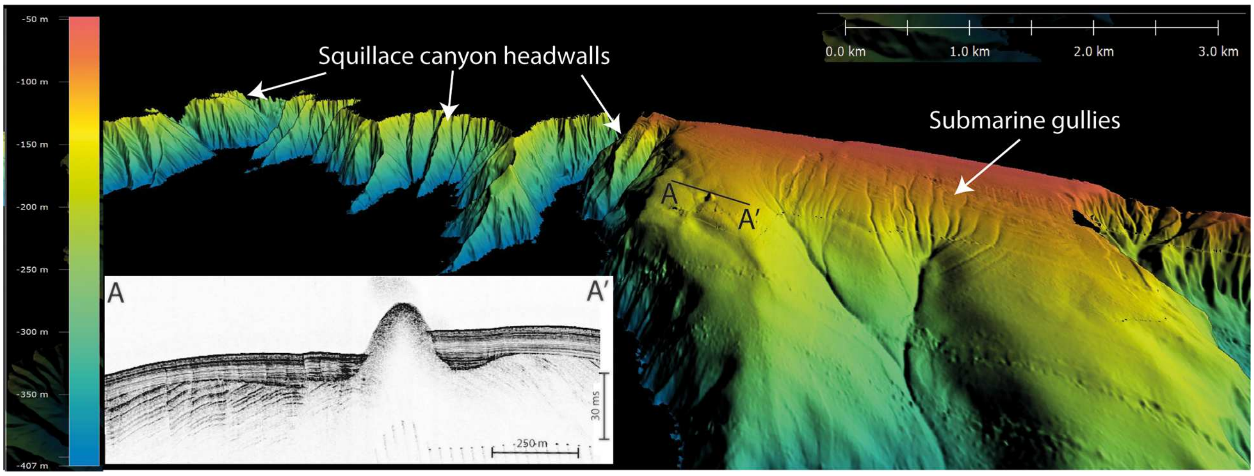

Figure 3. 3D view of the Squillace continental margin (red to blue). Squillace canyon headwalls and submarine gullies are shown with white arrows. Inset shows a seismic profile (AA′) across the Venere mud volcano.

canyon with the terrestrial hydrographic system, which also in this area consists of 'Fiumare' characterised by episodic 'flash floods' (Figure 1). Another particularity is that this large canyon is relatively young, incising the uppermost part of the Quaternary succession deposited in the Spartivento forearc basin. This suggests that the formation of the canyon occurred within the last 1 million years. The canyon crosses several mud volcanoes, such as the Catanzaro MV and the Venere MVs (Ceramicola et al., 2014c; Loher et al., 2018); recent extrusive activity of the Venere MV may have forced the canyon to bifurcate in two branches (Loher et al., 2018) (Figure 1).

The Catanzaro MV is named after the nearby coastal town, as it lies only 5 km offshore, in 150 m of water (Figure 1 and Figure 3). Multibeam data acquired in 2009 reveal a cone up to 25 m high, including an area of high backscatter 140 m wide at the top The water column acoustic anomalies are evident in echosounder and Chirp profiles and prove the MV have recently active (Ceramicola et al., 2014c). Chirp profiles show the mud volcano to correspond in the subsurface to an unstratified body up to 20 m thick and onlapped by stratified sediments, which overlie an angular unconformity that is overstepped by the cone on one side (Figure 3). The Catanzaro MV is inferred to record the eruption of mud breccia during or soon after the formation of the unconformity, which is correlated to the last glacial sea-level low stand (Ceramicola et al., 2014c).

The Venere MVs are located within the channel of the Squillace canyon system, which bifurcates around them, forming a > 70 m deep channel to the south and a < 30 m deep channel to the north (Figure 1). The average slope of the Squillace Canyon is ~0.4° in the southern channel and ~0.1° in the northern channel. Venere is a composite extrusive structure, consisting of an eastern and a western cone 1200 m apart, each up to 100 m high, both in part offset by inward-dipping ring faults that define a ca. 3000 m wide collapse caldera. The northern flanks of both cones have slopes generally <10°, whereas the southern flanks locally exceed 12° in the east and 15° in the west (Loher et al., 2018). Further research in the Squillace Gulf aimed at unraveling mud volcano's relation to deeper geology and the connection of the *Fiumare* with the Squillace canyon headwalls is undergoing at the time of this paper thanks to the EUROFLEETS + Programme that funded the ERODOTO oceanographic cruise on board of the R/V Aegaeo in summer 2023. Identifying the key roles of preconditioning and preparatory factors and quantifying the susceptibility of the geohazard features described in Catanzaro Sheet 38—most of which are only a few hundred meters from densely urbanized areas—is crucial to developing an effective coastal management plan and enhance community resilience.

4.5. Crotone area (MaGIC sheet 39)

The portion of the seabed included in Sheet 39 'Crotone' is part of the Crotone fore-arc basin, which includes sectors both onshore and offshore along the Ionian margin of the Calabrian Arc.

The Crotone basin consists of a sedimentary basin filled with strata ranging from Serravallian to the Pleistocene, deposited in continental to deep-water environments, and organized in major and minor tectonic-sedimentary cycles (Massari et al., 2010; Roda, 1964; Van Dijk, 1990; Zecchin et al., 2012, 2020).

The development of the basin is related to the southeast migration of the Calabrian Arc during the northwest subduction of the Ionian crust, the rollback of which has driven the opening of the Tyrrhenian Sea as a backarc basin, over the last 10 million years (Malinverno & Ryan, 1986; Van Dijk & Scheepers, 1995). The Crotone Basin forms part of a larger Ionian fore-arc basin (Crotone-Spartivento fore-arc), placed landward with respect to the Calabrian Arc accretionary prism (Bonardi et al., 2001).

The depositional history of the Crotone fore-arc basin includes an extensional regime, evidenced by the development of Polio-Pleistocene sub-basins controlled by syn-sedimentary normal faults (Massari et al., 2010; Zecchin et al., 2012). This regime has episodically been interrupted by phases of uplift and deformation during the Messinian, latest early Pliocene and middle Pleistocene, probably linked to the transgressional activation of NW-trending shear zones cross-cutting the Calabrian Arc (Civile et al., 2022; Massari et al., 2010; Roda, 1964; Van Dijk, 1990; Zecchin et al., 2012, 2020). These and other minor compressional events recorded within the succession led to the formation of unconformities within the basin (Roda, 1964; Van Dijk, 1990; Zecchin et al., 2012).

From the Mid-Pleistocene, the Calabrian Arc underwent differential uplift that led to the emergence of several basins, including the inner part of the Crotone Basin. The Pleistocene uplift is recorded by several orders of marine terraces, which have been investigated by various authors, e.g. Gliozzi (1987), Palmentola et al. (1990), Zecchin et al. (2004, 2011), and Nalin et al. (2007).

Sheet 39 ‘Crotone‘ includes a large area of seabed that extends from the Neto submarine canyon to the Capo Rizzuto high (Figure 1). In this part of the Calabrian margin, the continental shelf is up to 7-km wide. The shelf-break is located at 80–120 m water depth. The slope includes the southern part of the Neto Canyon headwall and the Esaro Canyon and its tributaries. The average gradient of the continental slope on this sheet does not exceed 5° and includes an undulating morphology due to the presence of the Luna and Capo Rizzuto highs. The southern part of the sheet includes the offshore extension of Crotone fore-arc basin.

The area offshore the Capo Rizzuto promontory is characterized by a broad morphological high up to 16 km long and 30 km wide, with an undulating slope profile. The high is bounded by two canyon systems: the Botricello canyon, a short and steep NW–SE oriented system characterized by two subparallel branches that merge downslope, and the Esaro canyon, an overall N–S system that captures several W–E oriented subparallel incisions. The shelf is 5–10 km wide and the shelf-break in 80–120 m depth; the upper continental slope is characterised by a NE–SW elongated intraslope basin (in water depths of ca. 600 m), whereas the lower slope, (750–1350 water depth m) is rather steep (up to 13°). The onshore and offshore parts of the sheet are covered by the Neogene to Quaternary strata of the Crotone fore-arc basin (Figure 1). The most interesting feature observed in this part of the margin is the Crotone Mega-landslide, developed since mid-Pliocene onwards and extending over an area of ca. 1,000 km^2 both offshore and onshore (Minelli & Faccenna, 2010; Mangano et al., 2020; Zecchin et al., 2018) (Figure 1). Following Minelli and Faccenna (2010), most of the Messinian to Plio-Pleistocene succession of the basin is gliding seaward (to the southeast) above a Messinian halite layer. The movement is inferred to involve an onshore up-dip domain, represented by seaward-dipping normal faults found in the northern part of the basin, and a downdip compressional domain located offshore (Minelli & Faccenna, 2010). Zecchin et al. (2015, p. 2018) suggested a lower involvement of the onshore sector in the seaward movement. The offshore compressional domain accounts for the steepness and the lobate plan-view shape of the continental slope off the Crotone area and could be linked to recent minor landslide phenomena observed on the lower steeper slope. The Esaro canyon marks the eastward limit of the mega-landslide offshore Crotone. Regarding the possible triggering mechanism of the mega-landslide, tectonic deformation during the Pliocene time and differential uplift since Mid-Pleistocene are probably the main factors (Zecchin et al., 2018).

5. Conclusions

The portion of the Ionian Calabrian Margin between Capo Spartivento and Capo Rizzuto includes over 150 km of coastline and major gulfs (Siderno and Squillace) and promontories (Capo Spartivento, Rizzuto and Punta Stilo Swell). The most striking geomorphic features in the gulfs are up to 50 km wide canyon systems incising the shelf break that reach water depths over 1000 m. Isolated and multiple failure events of different shapes disrupted the slopes along the morphological highs in the promontories. These failure events are of different sizes and characters, from isolated landslides to large-scale gravity-driven movements, all of which have been recently active. The two gulfs host impressive shelf-incising retrogressive canyon systems, characterized by single or dendritic heads, that in some places advanced up to tens of meters from the coastline. These canyon systems are relatively young (Pleistocene) features, that are still active, and are tectonically controlled by major fault zones. Fluid flow has been observed both in the near bottom sediments along the continental shelves, and in the form of active mud volcanoes located both on the shoulders of canyon heads (Catanzaro mud volcano) and in the basin areas (Venere mud volcanoes). Due to the active geodynamic setting related to the Calabrian arc subduction, these geomorphic features represent a natural laboratory for geohazard assessment and susceptibility. Large-scale gravity-driven movements involving both the onshore and offshore sectors of the Crotone Basin, as well as the incipient retrogressive canyon headwalls, represent potential geohazards and rise concerns about the safety of these coastal areas. Our regional case studies will provide a reference for more detailed future follow-up studies and monitoring of the various geohazard features.

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Disclosure statement

No potential conflict of interest was reported by the author(s).

Data Availability Statement

The authors agree to make data and materials supporting the results and/or analyses presented in this paper available upon reasonable request.

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