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Science

Geohazard features of the Tyrrhenian Calabria

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ABSTRACT
This paper accompanies the Maps of Geohazard features of the Cilento and the Calabro-Tyrrhenian continental margin in the southern Tyrrhenian Sea (Italy). The main geohazard-related features were derived from extensive seafloor mapping through the collection of high-resolution multibeam data acquired during several oceanographic cruises. They encompass many fluids seepage features, fault scarps, landslides scars, gullies, channels, and canyons. Hazards related to coastal landslides and shelf-indenting canyons are very high in these sectors (especially in southern Calabria) due to active seismicity coupled with rapid uplift, high sedimentation rates and narrow or totally absent continental shelf, thus promoting a direct connection between steep slopes and coastal areas. In this setting, mass-wasting features can directly impact coastal or submarine infrastructures or indirectly create local tsunami waves, as observed in historical times. Moreover, this physiographic setting of the margin facilitates the transfer of marine litter toward deep-sea areas.

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Magic Project; geohazard; seafloor mapping; landslides; canyon; fluid seepage

1. Introduction

The article illustrates the Maps of Geohazard features of the Cilento and the Calabro-Tyrrhenian continental margins (Main Map), produced by the MaGIC project (MArine Geohazard along Italian Coasts), a large coordinate initiative that involved the whole marine geological research community in Italy in 2007–2013. The features were derived from multibeam surveys and therefore mainly rely on all morphological expressions of seafloor and shallow subsurface processes and events.

Two levels of interpretation are presented: the map of the Physiographic Domain at scale 1:250,000 and the map of the Morphological Units and Morpho-bathymetric Elements (areas and vectors respectively) at 1:100,000 scale.

2. Study area: Cilento and Calabro-Tyrrhenian continental margin

The study area mainly encompasses the Cilento and the Calabro-Tyrrhenian continental margins that developed in the forearc/backarc region of the Tyrrhenian-Ionian subduction system (Milia et al., 2009; Iannace et al., 2018; Corradino et al., 2020, 2021; Figure 1). The orogenic structure of the Cilento–Maratea mainland consists of a tectonic multilayer which piled up in the Lower Miocene (Bonardi et al., 2009; Ciarcia et al., 2009). A further tectonic inversion phase occurred in the Upper Miocene–Lower Pliocene and led the marginal formations of the Apennine platform to overthrust the internal units toward the North (Bulgheria Mount, Figure 1). The structural highs bordering the subsiding Policastro basin, filled with more than 2000 m of sediments, have undergone vertical displacements mostly between the Early Pleistocene and Late Pleistocene, as testified by the altitude of marine terraces recognizable between 7 and 400 m a.s.l. (Ascione & Romano, 1999). The southern Apennine orogen is decoupled from the Calabro-Peloritan arc by an E-W subduction-transform edge propagators (STEP) fault at the northern margin of the retreating slab (Rosenbaum et al., 2008). The location of the surface projection of

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Supplemental map for this article can be accessed online at https://doi.org/10.1080/17445647.2024.2347897.

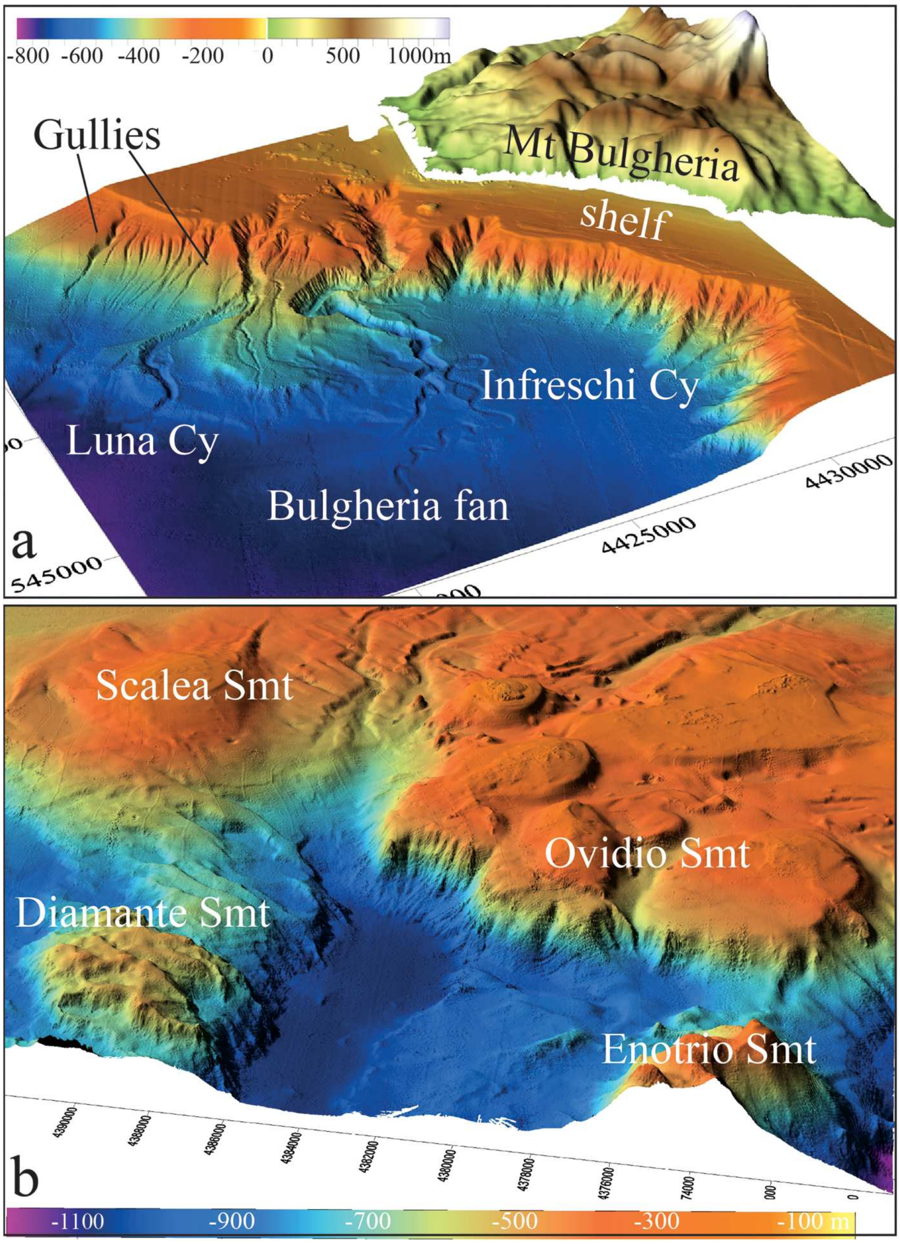

Figure 1. (a) 3-D image of the Mt Bulgheria and offshore area (for location refer to sheet 11 Maratea), where the continental shelf is indented by a network of gullies and two canyons (i.e. Infreschi and Luna canyons) forming the small Bulgheria fan. (b) 3-D image of the flat-topped seamounts recently identified offshore Scalea (for location refer to sheet 12 Diamante) and interpreted as volcanic edifice by De Ritis et al. (2019) by integrating bathymetric, seismic and magnetic data.

this STEP fault corresponds with the Sangineto Line (Totaro et al., 2014) and possibly extends toward the Southern Tyrrhenian Sea along the Palinuro volcanic range (Cocchi et al., 2017; De Ritis et al., 2019). Both are sites of active seismicity and large fluxes of rising fluids. Presently, an extensional stress regime compatible with the post-orogenic NE–SW extension has been detected in the entire study area (Presti et al., 2013). Specifically, the isostatic rebound of the Calabro-Peloritan block and asthenosphere upwelling in response to the south-eastward rollback of the subducting plate is responsible for the tectonic uplift that markedly characterizes the evolution of this area in the last 0.7 Ma (Gvirtzman & Nur, 1999). This tectonic uplift is witnessed by the present-day elevation of raised marine terraces along the Calabro-Tyrrhenian coasts, allow average rates to be estimated, which are up to 1 mm/year since the Middle Pleistocene and 2 mm/year if averaged to the Holocene (Antonioli et al., 2006). Part of this uplift has been accommodated by normal faults that run along the inner side of the Calabrian arc, extending through the Strait of Messina along the Ionian coast of Sicily (Monaco & Tortorici, 2000). This active tectonic belt is about 370 km long, representing one of the most seismically active sectors of the Italian peninsula, where several historical and pre-instrumental (ca. magnitude ≥6) earthquakes have occurred (CPTI, 2004). This tectonic setting also formed a coastal mountain range, pervasively carved by steep and short subaerial river courses characterized by torrential regimes (locally known as fiumara stream; Sabato & Tropeano, 2004). Flash-floods periodically occur within these short-rivers, often evolving into hyperpycnal flows when they enter the sea and being thus able to transport a large amount of debris into the sea (e.g. Casalbore et al., 2011). Largely due to its tectonic evolution, the Calabro-Tyrrhenian continental margin is characterized by a narrower to nearly absent continental shelf if compared to that off Cilento and passes abruptly to a steep continental slope (Fabbri et al., 1980). The continental slope is commonly interrupted by intra-slope basins delimited seaward by intra-slope ridges, E-W striking off the Cilento promontory and from NNE-SSW to NNW-SSE oriented off the Calabrian arc, before reaching the continental rise and the Tyrrhenian abyssal plain. Quaternary sedimentary dynamics on this continental margin are characterized by the interplay between tectonic, physiography, sea-level changes, and sedimentary input (Gamberi & Marani, 2006). The continental slope is largely dominated by mass-wasting features (slide scars, gullies, canyons) that cover up to 52% of the entire continental margin (Chiocci & Casalbore, 2017).

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 table. Global mapper and IHS Kingdom suite are used for bathymetric and seismic data visualization and interpretation. Consider that the maps are realized after a discussion between guest editors along with the editorial board of the *Journal of Map*.

4. Maps of morphological units and morpho-bathymetric elements

4.1. Acciaroli (MaGIC sheet 10)

The Sheet 10 ‘Acciaroli’ includes the continental margin off the Cilento Promontory in southern Campania region, between Punta Licosa and Capo Palinuro. A wide continental shelf area develops down to 140–180 m depth and is separated into two sectors by a structurally controlled, N-S-oriented rocky ridge. The eastern side is dominated by the fluvial yields from the Alento River and more eastwards by patches of bedrock outcroppings. The western sector, chiefly sediment-starved, is shaped by wave-cut terraced surfaces at different depths in the inner shelf (Savini et al., 2021), bedform fields and relict sand bodies relative to the last stages of late Pleistocene forced regression and early stage of post-glacial transgression in the outer shelf (Ferraro et al., 1997; Iorio et al., 2014; Sammartini et al., 2019). A large part of the map is occupied by the continental slope that develops from 140/180 m depth down to 1380 m depth and includes part of the Palinuro intra-slope basin and of the surrounding reliefs, attaining a topographic drop of up to 1000 m in less than 13 km. Indeed, the extensional tectonic phases occurred on a regional scale since the Lower Pleistocene and more local transpressive/transtensive events (Milia et al., 2017), have caused large vertical displacements of the substrata and the stack of structural-controlled reliefs. Therefore, slope gradients may locally exceed 20°, favoring sediment failures in the proximity of the structural lineaments. The occurrence of rocky substratum in the subsurface of the Cilento margin and the low dip of the shelf, wide up to 20 km (Ferraro et al., 1997), steered the confinement of the geohazard-related features along the slope, where structural-controlled erosive scarps, slide scars (Bellonia et al., 2008; Trincardi et al., 2003) and pockmark fields occur (Sammartini et al., 2019). The morphological features of the landslide scars, the slide-slip surfaces and the stratigraphic framework depicted by the VHR seismic profiles concur to define most of the sediment failures as being translational slides above weak stratigraphic surfaces, the latter broadly traceable along the Cilento margin (Budillon et al., 2014; Iorio et al., 2014). The Licosa landslide, affecting an area of almost 30 km^2, is a single failure event aged in a time lapse between 14 and 11 ky BP. The Acciaroli landslide, affecting an area of almost 58 km^2, features a more complex niche, made by multiple headscarps that document multistage failures. Both the slides achieved limited run-out due to the down dip morphological confinement of the E-W oriented intra-slope reliefs. The cause–effect relation between structural lineaments and slide scars can be supported by the spatial proximity of the features (Sammartini et al., 2019) and by the enduring seismicity of the offshore. Indeed, the tectonic displacement along the Licosa Channel allows speculation that the presence of an active fault might be responsible for the ultimate triggering of slope instability in the area. This prominent fault, recently identified (Iorio et al., 2014; Sammartini et al., 2019), is likely to be the product of the current southern Tyrrhenian tectonic strike-slip extension trending NE–SW (Milia et al., 2017).

4.2. Maratea (MaGIC sheet 11)

The Sheet 11 ‘Maratea’ includes the continental margin off the southern Campania region, between Capo Palinuro to the West and Torre Talao to the South-East. Off Capo Palinuro, a large continental shelf with an edge at 140 m depth and a gentle slope cut by several subparallel intra-slope gullies (Dalla Valle et al., 2013) occurs; off Sapri, the shelf edge occurs between 90 and 200 m depth, and the slope is deeply cut by herringbone-shaped furrows that locally indent the shelf retrogressively. At the base of the upper slope, a concave-shaped depocentre occurs, the Sapri Basin (Bartole et al., 1984; Gamberi & Marani, 2004), limited southwards by two intra-slope reliefs. The margin is dominated by the occurrence of a spectacular small-scale canyon-fan system seemingly fed by long-shore currents interesting the Cilento coast. Two lobes, fed by Luna and Infreschi canyons, compose the fan and are aggregated in the Sarpi basin between 500 and 700 m depth (Figure 1(a)). Levee breaches due to overspill turbidite deposition, overbanks deposits and abandoned meanders also typify the fan. East of the canyon system, an erosive escarpment is present, characterized by deep furrows and narrow ridges produced by linear erosive processes; evidence of linear scours at the base of this escarpment, down to about 800 m depth document the erosive passage of sediment fluxes as distant as 15 km off the shelf edge (Budillon et al., 2011). In the Policastro Gulf, close to the coast, at about 40 m of depth, active groundwater seeps have generated a large field of deep pockmarks, some of them exceeding 30 m deep with respect to the rim at the seabed (Buongiorno Nardelli et al., 2017). In the Lucania area, the tectonic interbedding of a clayey succession among carbonatic thrusts identified on land, caused phenomena of deep gravitative deformation in the Maratea Valley (Guerricchio & Melidoro, 1996) and in the nearby marine setting, in correspondence with the maximum retreat of the shelf (Colantoni et al., 1997). In this area, at the base of the slope, several lobes of turbidite deposits have been identified, denoting an ongoing morphological shaping of the submerged landscape (Pennetta, 1996). Two relict features related to past lower stands of sea level are preserved at 90 m depth (5 km-long littoral sand ridge) and 110 m depth (low stand marine terrace).

4.3. Diamante (MaGIC sheet 12)

The Sheet 12 ‘Diamante’ encompasses the Tyrrhenian continental margin of northern Calabria between the villages of Guardia Piemontese and Granata (Santa Maria del Cedro). The area is characterized by a rather narrow (4–8 km) and steep (1–2.5°) continental shelf, with the shelf break located at a maximum depth of 150 m. The continental shelf has a general smooth morphology, except for the occurrence of morphological highs, rising for 10–30 m from the surrounding seafloor. These features are commonly found between 30 and 110 m water depth, and they can be interpreted as bioherms and/or substrate outcrops. On the continental shelf, two large fields of seafloor bedforms, with the crests oriented obliquely to the contours, are recognizable. These bedforms are characterized by wavelength of several tens of meters and sub-metric height, and they are likely formed by bottom currents. In the continental shelf sectors facing the mouth of ‘fiumare’, bedforms with the crest oriented parallel to the isobaths along with narrow and rectilinear gullies, are also recognizable. Gullies can be interpreted as the erosive trace associated with the passage of hyperpycnal flows on the seafloor generated by flash-floods of fiumara streams, similar to what was observed in other tectonically controlled settings (Casalbore et al., 2017; Chiocci & Casalbore, 2011). The genesis of the bedforms is more complex, as largely discussed in the literature and can be referred to as sediment deformation (i.e. creep), or erosive-depositional processes due to the flowing of density currents (Urgeles et al., 2011 and references therein). In the deeper sectors, a striking feature is represented by a series of flat-topped morphological highs with a sub-conical or slightly elongated morphology (Ovidio, Scalea, Diamante, Enotrio seamounts, Figure 1(b)), rising for about 200–700 m from the surrounding seafloor. Based on their morphology and relation with the nearby chain of volcanic seamounts (including Enotrio, Glabro and Palinuro Seamounts), these features have been recently interpreted as volcanic edifices (De Ritis et al., 2019). Their flat-topped summit developed between 120 and 400 m depth can be related to the wave erosion during the Quaternary sea-level fluctuations accompanied by subsidence processes, similar to what was observed in other submarine volcanic settings (Chiocci et al., 2013; Romagnoli et al., 2018).

4.4. Paola (MaGIC sheet 13)

The Sheet 13 ‘Paola’ faces the Calabro-Tyrrhenian coast between Amantea and Cetraro towns. Morpho-bathymetric data show a complex physiographic setting of the margin, characterized by a narrow continental shelf and by intra-slope basins and reliefs that separate the continental slope into an upper and a lower sector. The continental shelf is narrow (2–6 km) and steep (1–2.5°) and characterized by an uneven morphology, produced by numerous rocky outcrops and bioherms, that rise up to 40 m from the surrounding seafloor. At the mouth of the gravel-bed fiumara streams, large bedform fields and gullies occur on the shelf, suggesting erosive-depositional processes related to hyperpycnal flows generated during or just after flash-flood events. Beyond the shelf break, located at 140–150 m depth, the continental slope is deeply incised by several small canyons that cause the retreat of the shelf break through small-size landslide scars at their heads. Submarine canyons are typically characterized by straight courses and develop subparallel to each other along the narrow (7–13 km) and steep (2–4.5°) upper slope, vanishing down to the slope base. Some landslide scars were identified on the upper slope. The Sheet 13 also includes the northern sector of Paola Basin, one of the largest peri-Tyrrhenian basins (Fabbri et al., 1981) that continues outside the sheet area for about 30 km covering an area of some 210 km^2. The Paola Basin is bordered offshore by several intra-slope ridges, elongated in the NNW-SSE direction, rising up to 300 m from the surrounding seafloor. The origin of these ridges is ascribed to a compressive tectonic phase that affected the whole Calabrian margin during the Middle Pleistocene (Argnani & Trincardi, 1988, 1993; Corradino et al., 2020). The physiographic setting of the margin and the Quaternary tectonic deformation that still affects the Calabrian Arc is responsible for high sedimentation rates on the continental margin (1 mmy^{-1}) that determined the accumulation of thick Plio-Pleistocene deposits (>5000-m-thick) within the Paola Basin (Canu & Trincardi, 1989).

4.5. Santa Eufemia Gulf (MaGIC sheet 14)

The Sheet 14 ‘Golfo di S. Eufemia’ encompasses the southern part of the Paola intra-slope basin and the Santa Eufemia Gulf, between 40 and 700 m depth. The complex physiography of the continental margin includes a narrow continental shelf and the Paola intra-slope basin, which separates the continental slope into upper and lower slope sectors. The continental shelf is up to 10-km-wide on the S. Eufemia Gulf, between Cetraro and Pizzo Calabro towns, whereas it is very narrow to completely absent near Capo Vaticano Promontory, in the southern sector of the sheet. The shelf break is located between 110 and 170 m depth (Gallignani, 1982). Between 70 and 100 m depth, the continental shelf is characterized by several features of small relief interpreted as bioherms and/or substrate outcrops (Chiocci & Orlando, 1995). In front of the mouth of fiumara rivers, bedform fields were observed, sometimes incised by small channels (gullies) that merge at greater depths into the head of small submarine canyons. On the shelf, the post-glacial depositional sequence is thick (>60 m) in front of main fiumara mouths (Chiocci et al., 1989). In the northern part of the Sheet 14, the continental slope is narrow (3–5 km) and steep (<6°). It is characterized by several short submarine canyons and strongly affected by gravitational instability processes. At about 600 m depth, the slope gently merges with the Paola intra-slope basin (Gallignani, 1982). Conversely, in the southern part of the Sheet 14, the continental slope is less steep (1–2°) but deeply incised by the Angitola Canyon, one of the main eastern tributaries of the Stromboli Canyon. The Angitola Canyon head is formed by two branches located at 114 and 190 m depth; its course changes from a straight to a meandering course, possibly in relation to a change in slope gradients (Soh & Tokuyama, 2002). The course of the Angitola Canyon has evidence of strong tectonic control (Corradino et al., 2021) A large ridge (Maida Ridge) is present nearby the Angitola Canyon, representing the superficial expression of NNE-SSW to NE-SW trending anticlines related to an Early Pliocene right-lateral transpressional tectonic (Corradino et al., 2021). Moreover, a large set of shallow (<1.5 km) NNE-SSW oriented faults scarps, successively formed in a left-lateral transtensional regime since the Early Pleistocene, characterize the seafloor in the same area.

4.6. Gioia Tauro (MaGIC sheet 15)

The Sheet 15 ‘Gioia Tauro’ encompasses the Calabro-Tyrrhenian continental margin comprised between Capo Vaticano and the Messina Strait. The continental shelf is narrow (max width 2–3 km) or totally absent and has an average slope of 1°; the shelf break is located at about 130 m depth. The continental slope is interrupted, at about 800 m depth, by the Gioia intra-slope basin, a subsiding area about 70-km-wide (Gamberi & Marani, 2008). This margin is shaped by a large suite of mass-wasting features, with more than 400 slide scars identified in this area, mobilizing approximately 1.4 km^3 of sediments (Casas et al., 2016). A large slide complex covers an area of about 18 km^2 off Capo Vaticano and affects contourite deposits (Martorelli et al., 2016) as well as two large (2- and 4-km wide, respectively) landslide scars at about 800 m depth nearby the Capo Vaticano ridge (Casalbore, Martorelli, et al., 2018). Besides the submarine landslides, the main erosive-depositional feature is the 60 km-long shelf-indenting Gioia-Mesima canyon-channel system (hereafter GMS, Figure 2; Gamberi & Marani, 2008). The GMS can be morphologically divided into three reaches, mainly in relation to changes in regional slope gradients, with higher values (on average 5°) for the lower and upper reaches, where the trace of recent sedimentary dynamics is present (Casalbore, Falcini, et al., 2018; Morelli et al., 2022; Pierdomenico et al., 2016). Specifically, the upper reach of Gioia Canyon, which hosts vulnerable marine ecosystems but also large litter accumulations (Pierdomenico et al., 2018, 2020), is formed by two branches that surround the main entrance of the Gioia Tauro Harbor (Figure 2). Here, a landslide-generated tsunami occurred at the head of the Gioia Canyon in 1977 (Colantoni et al., 1992). This slide evolved into a turbidity current flowing into the GMS and was responsible for a

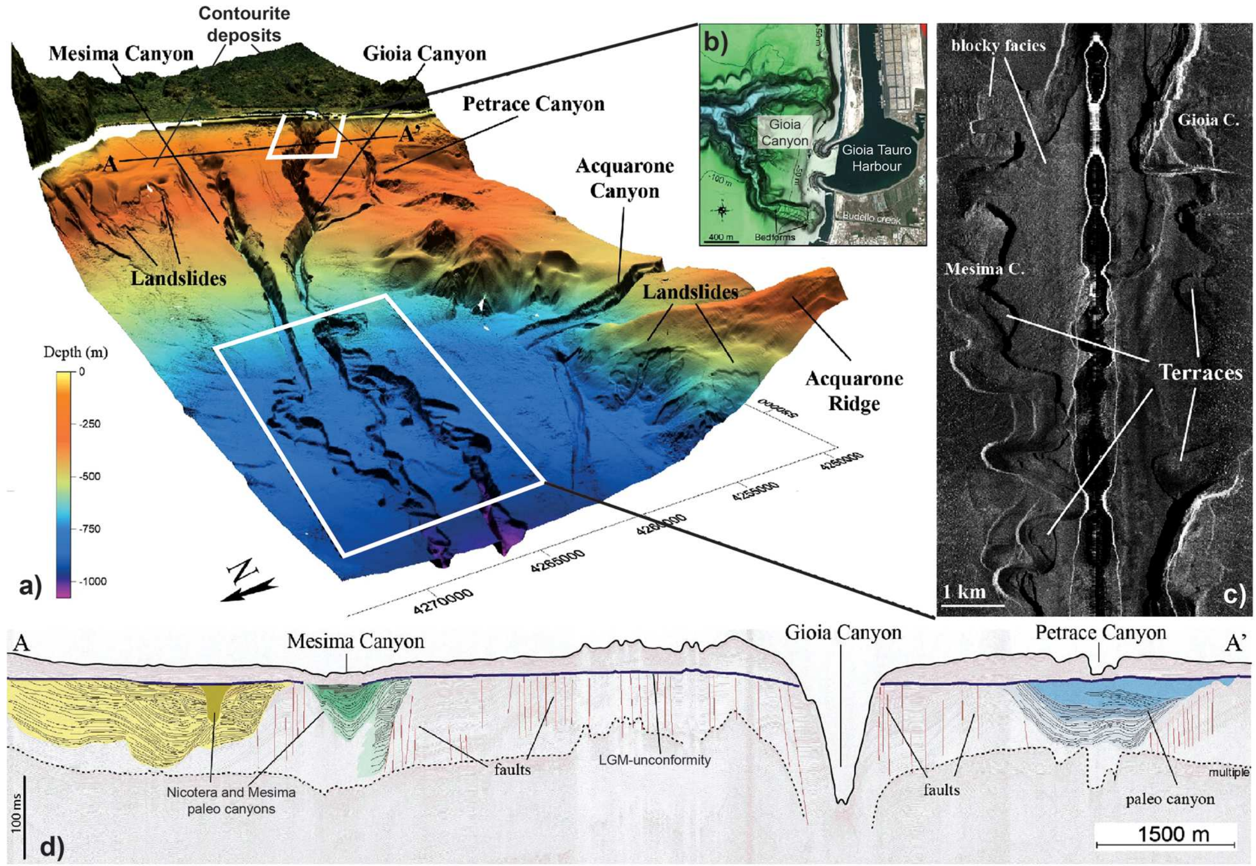

Figure 2. (a) 3-D image of the upper and median reaches of the Gioia-Mesima canyon-channel system (GMS) and surrounding areas (for location refer to sheet 15 Gioia Tauro), where landslides and contourite features are present. (b) Zoom of the Gioia canyon head located in a very shallow-water sector, few tens of meters far from the Gioia Tauro Harbor, one of the main terminals for the Mediterranean transhipment. (c) TOBI side scan sonar image (high backscatter in light-grey tones) showing the meandering pattern of the median reach of the GMS, with the presence of multiple terraces. (d) Line drawing of a Sparker seismic profile crossing the different canyon and paleo-canyon head present in the area (for more detailed information refer to Morelli et al., 2022).

cable break at about 600 m depth, about 15 km far from the source area. Another catastrophic landslide-generated tsunami occurred in 1783 at Scilla Village, where a seismically induced subaerial rock-slide entered the sea. Its deposits are recognizable in the Scilla Valley and are made up of several megablocks, whereas the matrix of the deposits was reworked by the strong currents flowing from the Messina Strait (Casalbore et al., 2016 and reference therein). These currents also explain the presence of large coarse-grained sediment wave fields and a contourite channel attributed to the long-term action of LIW outflow debouching from the Messina Strait (the Scilla Channel; Martorelli et al., 2022). The bedforms can be attributed to intense tidal currents coming from the Messina Strait (Longhitano, 2013) and in some cases to internal wave interaction with the seafloor (e.g. Droghei et al., 2016).

5. Conclusions

In the study area, the continental shelf is narrow or even absent, except for the area north of the Policastro Gulf, where the shelf rapidly enlarges to several km. The continental shelf typically has an overall smooth morphology, except for the presence of small morphological highs associated with bioherms and/or substrate outcrops, and areas characterized by erosive-depositional landforms (gullies and bedforms) linked to fluvial input. Beyond the shelf break (at 120–150 m depth), the continental slope is generally steep and incised by several landslide scars, channels and canyons (e.g. the Infreschi, Luna, Angitola and Gioia-Mesima canyons). Canyon heads are commonly located at the shelf break, except for some of them that deeply indent the shelf up to the coast, such as the Gioia Canyon, thus representing a major geohazard for coastal and submarine infrastructures. In addition, recently active tectonic features were identified, especially in southern Calabria. These deserve detailed studies to assess the seismo-tectonic hazard. The continental slope is commonly interrupted by intra-slope basins that represent subsiding areas where very thick Plio-Pleistocene deposits accumulate. These basins are bounded seaward by intra-slope ridges that can be associated both to the folding of sedimentary units or to volcanic edifices, as for instance observed off the northern part of the Calabrian margin.

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Data availability statement

Data are available upon reasonable request by contacting the first authors at the mail address daniele.casalbore@uniroma1.it.

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