



Geomorphological characterization and marine geohazard assessment of mass transport deposits in the Graham Bank (Sicily Channel, Central Mediterranean)

Abstract Subaqueous gravity-driven mass movements and their resulting mass transport deposits (MTDs) are primary agents in shaping continental margins and volcanic edifices. This study provides a high-resolution geomorphological and geophysical characterization of MTDs in the Graham Bank, a complex setting in the Sicily Channel (Central Mediterranean) where active rifting, anorogenic volcanism, and vigorous oceanographic circulation converge. High-resolution multibeam bathymetry (5 m grid) integrated with sub-bottom CHIRP seismic profiles documents a complex seafloor shaped by the interaction of tectonics, volcanism, and oceanographic processes at water depths between ~10 and 350 m. We mapped and classified a diverse spectrum of deposits into three thematic categories: (i) large-scale volcanoclastic debris avalanches (up to 2.2 km² and thicknesses exceeding 20–30 m) characterized by blocky topography and amphitheater scars; (ii) tectonically-controlled rockfalls at the foot of steep escarpments; and (iii) soft-sediment deformation structures (slumps and channelized-fills) showing mounded hummocky facies and basal erosional unconformities. These features are variably distributed across three main physiographic domains: the volcanic sector, a fault-bounded erosive channel, and an adjacent flat outer-shelf area. Our findings suggest a conceptual "cascading" morphogenetic framework where tectonic rifting with NW–SE-oriented normal faulting and high regional heat flow (75–100 mW/m²) pre-condition the slopes, while regional seismicity ($M_L \geq 5$) and bottom-current erosion (Atlantic Ionian Stream) act as possible transient destabilizing mechanisms. Volcanic-driven instabilities may be related to volcanic activity; the 1831 eruption illustrates the system's capacity for rapid morphodynamic change, though direct temporal links to individual MTDs cannot be established without sediment dating. The Graham Bank thus represents a high-instability environment where MTDs record the combined effects of internal geodynamic forcing and external oceanographic modulation, providing a key natural laboratory for assessing gravity-driven processes. The proximity of these features to submarine cables and pipelines, coupled with the recent volcanic history of the area (e.g., the 1831 eruption), underscores a preliminary geohazard concern warranting further investigation in this sector of the Mediterranean.

Keywords Sicily channel · Mass transport deposits (MTDs) · Submarine volcanism · Geohazard · Physical oceanography · Seismic reflection

Introduction

The transfer of sediment from continental shelves to the deep sea is a fundamental geological process that shapes continental margins worldwide (Posamentier and Kolla 2003). Central to this transfer are subaqueous gravity-driven mass movements, which result in the formation of Mass Transport Deposits (MTDs), referred to as Mass Transport Complexes (MTCs) when comprising multiple events (Caradonna et al. 2025). These deposits are a primary component of the stratigraphic record in deep sea settings (Shipp et al. 2011) and have been extensively documented across diverse geological environments (Canals et al. 2004; Moscardelli and Wood 2008; Clare et al. 2018).

Ranging in scale from localized slumps to basin-wide features covering thousands of km², MTDs encompass a broad spectrum of depositional products, including slides, slumps, and debris flows (Festa et al. 2014). Characterizing these features requires an integrated, multi-scale approach. On a basin scale, 3D seismic reflection data serves as the primary tool for identification, where MTDs typically show chaotic, low-continuity, and low-amplitude seismic facies, often bounded by high-amplitude erosional basal surfaces (Posamentier and Martinsen 2011; Ford 2021). Furthermore, external morphologies such as hummocky top surfaces and compressional frontal structures provide predictive indicators for understanding their emplacement dynamics and tectonic settings (Posamentier et al. 2015).

Recent advances in seismic attribute analysis have enhanced the delineation of the complex internal and external architecture of these bodies (Caradonna et al. 2025; Lenz and Sawyer 2021). Internally, MTDs reveal significant structural complexity, including relatively undeformed megaclasts rafted within a deformed matrix, intricate fold-and-thrust systems, and pervasive shear fabrics (Alsop and Marco 2011; Sobiesiak et al. 2017). The basal shear zone is particularly critical, often characterized by intense deformation and liquefaction, which can significantly influence mobility and underscore their potential as marine geohazards (Ogata et al. 2014; Sun and Alves 2020).

Generally, the initiation of MTDs results from a complex interplay of sedimentary and tectonic factors. Rapid burial of cohesive sediments can generate overpressure, leading to gravitational instability (Moretti et al. 2001; Odonne et al. 2010), particularly in areas characterized by high sediment supply (Lee et al. 2007; Gamboa et al. 2010). Furthermore, external forcing such as tectonic strain, seismic activity, and sea-level fluctuations significantly reduces the shear strength of sedimentary strata (McAdoo et al. 2000; Owen

et al. 2011), while the presence of interstitial gas can further compromise stratigraphic stability (Molina et al. 1998).

In volcanic settings, such as insular flanks and seamounts, mass movements frequently attain volumes that far exceed those of terrestrial landslides. These environments are characterized by specific triggers, including the rapid accumulation of unstable volcanic products and magmatic/eruptive processes that mobilize vast quantities of material. The resulting morphologies such as lava fields, blocky topography, and hummocky terrains reflect a synergy of internal and external forcing, including magmatic overpressure, dyke intrusions, and regional seismicity. While large-scale failures are catastrophic, the frequency of smaller-scale MTDs is critical for the continuous morpho-structural remodeling of volcanic edifices (Clare et al. 2018). Global analogues from Hawaii (Moore et al. 1994), the Canary Islands (Masson et al. 2002), and the Aeolian archipelago (Casalbore et al. 2014) illustrate how hydrothermal alteration and pore-fluid pressurization act as key pre-conditioning factors, facilitating the transition from stable slopes to catastrophic collapses.

Beyond their geomorphological impact, MTDs are of paramount scientific and economic significance. Their emplacement can jeopardize seafloor infrastructure, such as pipelines and telecommunication cables, and possesses the potential to trigger tsunamis (Festa et al. 2014; Sun et al. 2017). Conversely, their chaotic internal structure and fine-grained matrix allow them to function as effective regional seals for hydrocarbon systems. Therefore, understanding their distribution and triggering mechanisms ranging from seismic shaking to gas hydrate dissociation is essential for comprehensive marine geohazard assessment.

Despite the global understanding of mass-transport deposit dynamics, high-resolution investigations into areas where tectonics, volcanism, and oceanography converge remain sparse. This study provides a geomorphological characterization of submarine mass transport deposits in the Graham Bank, Sicily Channel, where these forces interact. Through integrated bathymetric and seismic analysis, we document the morphological diversity and spatial distribution of MTDs. While our findings suggest potential links to structural, volcanic, and oceanographic controls, these interpretations remain preliminary and require future chronological and geotechnical validation. The results establish a foundational baseline for understanding mass-movement processes in this tectonically and volcanically active setting.

Geological setting and physiography

The Sicily Channel, located in the central Mediterranean Sea, is a physiographic element situated between the southern coast of Sicily, the northern coast of Africa, and the Malta Escarpment (Fig. 1). It represents a portion of the foreland belonging to the Africa-Europe convergent margin (Catalano et al. 1996; Granath and Casero 2004; Finetti et al. 2005). The Sicilian Fold and Thrust Belt (FTB) resulted from the tectonic stacking of units derived from the deformation of Mesozoic paleogeographic domains, which developed along the African rifted continental margin (Catalano et al. 1996; Finetti et al. 2005; Basilone et al. 2016a).

The FTB progrades over a northwest-dipping regional monocline composed of Mesozoic carbonate platform deposits from the

Hyblean foreland, which overlies the stretched African continental crust (Catalano et al. 2000). The foreland area, exposed in south-eastern Sicily (Hyblean-Maltese Plateau) and submerged within the Sicily Channel (Pelagian Block), is the product of the interaction between the Sicilian-Maghrebian collision and the Sicily Channel rifting (Fig. 1; Argnani 1990; Torelli et al. 1991; Catalano et al. 1993; Sulli 2000; Cavallaro and Coltelli 2019; Agius et al. 2022).

The contemporary structural framework of the 'Sicily Channel Rift Zone' is defined by NW-SE oriented, sub-vertical Neogene-Quaternary normal faults that govern a horst-and-graben configuration (e.g., the Pantelleria, Malta, and Linosa grabens). Since the Early Pliocene, rifting processes have thinned the continental crust to 15–18 km (Argnani 1993; Civile et al. 2008; Agius et al. 2022), leading to the formation of the aforementioned grabens and triggering widespread subaerial and submarine volcanic activity (e.g., Pantelleria and Linosa islands, Graham and Nameless banks). This volcanism is characterized by anorogenic magmatism with alkaline to peralkaline affinity (Corti et al. 2006; Rotolo et al. 2006). Heat flow values show relatively high isothermal contours located between the Graham, Nerita, and Terribile Banks, where a flow of 75 to 100 mW/m² is recorded (geothopica.igg.cnr.it). Seismic activity generally involves hypocenters up to 20 km deep with magnitudes $M_L < 3.5$ (Chiarabba et al. 2005; Galea 2007). However, most earthquakes occur along a N-S trending belt between the Sciacca offshore and Lampedusa Island, reaching depths of 60 km and magnitudes $M_L \geq 5$ (Calò and Parisi 2014).

Morphology and oceanography

The Sicily Channel (Fig. 1) comprises a shallow marine sector characterized by an 80 km wide continental shelf, primarily represented by the Adventure Bank. This bank, with a seafloor depth ranging from 75 to 205 m, is separated from the southern coast of Sicily by the 'Mazara Channel' and is connected to the 1300 m deep 'Pantelleria graben' via a continental slope that descends from −150 to −1000 m with gradients up to 14°. Graham Bank, the south-eastward extension of the Adventure Bank, is characterized by a complex geomorphological setting (Fig. 2). This includes a volcanic region with at least 7 main cones and several small positive morphologies (Carapezza et al. 1979; Beccaluva et al. 1981; Calanchi et al. 1989; Peccerillo 2005; Lodolo et al. 2012; Coltelli et al. 2016) and a flat continental platform dominated by fluid escape phenomena strictly related to recent tectonics (Spatola et al. 2018). Graham Bank has been affected by numerous volcanic eruptions even in historical times, such as in 1831 and in 1837, when the Ferdinandea volcanic island emerged and rapidly disappeared (Colantoni 1975; Spatola et al. 2023).

Modified Atlantic Water enters the Sicily Channel through the Sicily Strait and flows eastwards, splitting into two sub-currents: the Atlantic Ionian Stream (AIS) and the Atlantic Tunisian Current (ATC, Fig. 1; Sorgente et al. 2011). The ATC flows along the African coast, while the AIS flows south of the Adventure Bank and proceeds south-eastward. Immediately south of the study area, the AIS interacts with the Levantine Intermediate Water, which is saltier and deeper (between −200 and −400 m) and flows in the opposite direction (Millet 1999; Lafuente et al. 2002; Bonanno et al. 2014). Several loop currents such as the Adventure Bank Vortex (ABV), Pantelleria Vortex

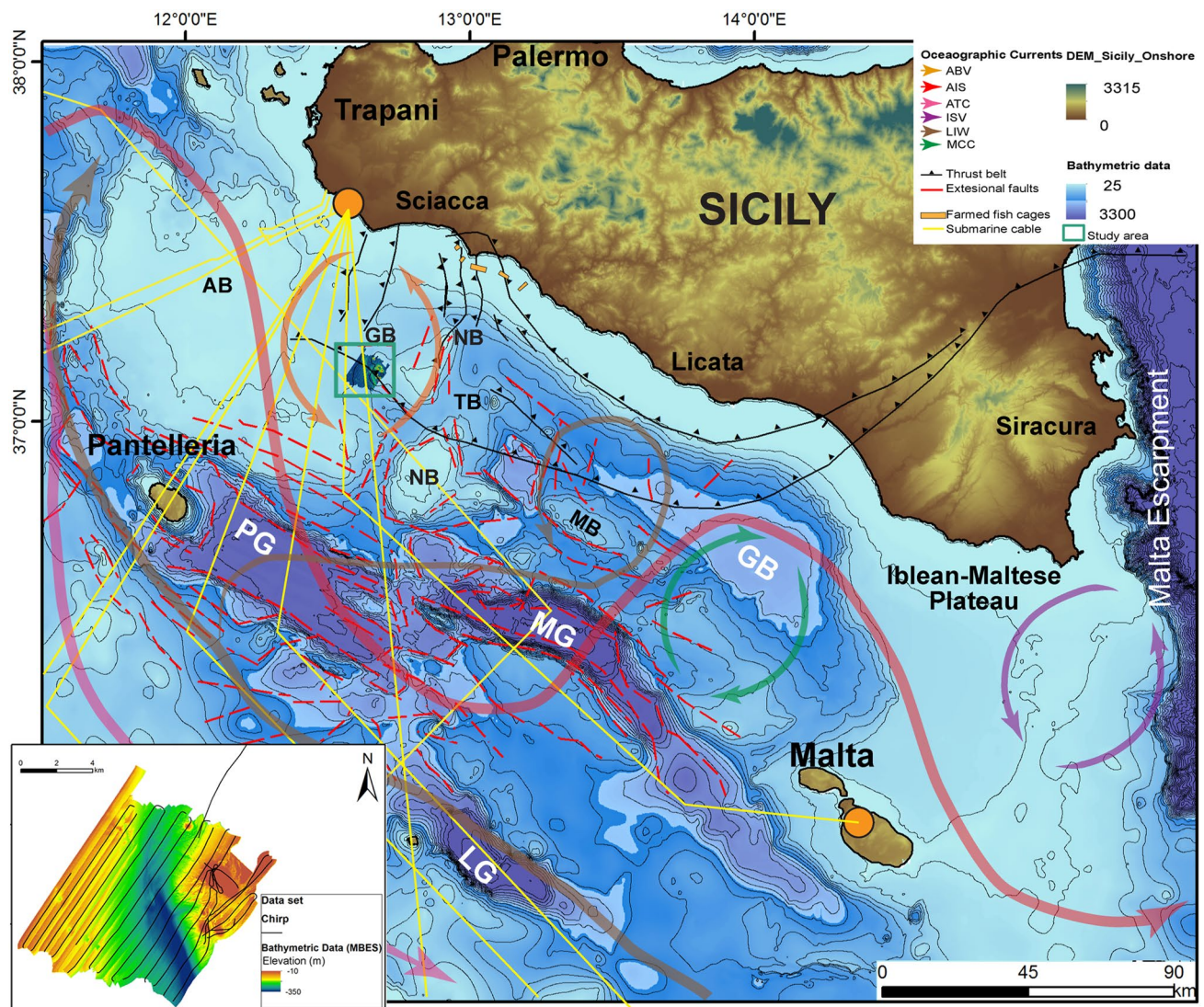


Fig. 1 Bathymetric map of the Sicily Channel (Central Mediterranean) displaying main physiographic elements, Plio-Pleistocene graben systems (PG: Pantelleria Graben, MG: Malta Graben, LG: Linosa Graben), and locations of submarine cables. Background bathymetry from EMOD-net (<http://www.emodnet-bathymetry.eu>). Inset shows spatial coverage of high-resolution multibeam bathymetry and sub-bottom CHIRP seismic profiles (black lines). Water mass pathways (Levantine Intermediate Water—LIW; Modified Atlantic Water—MAW; Adventure Bank Vortex—ABV; Atlantic Tunisian Current—ATC; Atlantic Ionian Stream—AIS; Maltese Channel Crest—MCC) are shown based on circulation models

(PV), and the Maltese Channel Crest (MCC) dominate the oceanic dynamics around the Adventure Bank, Pantelleria, and the Malta Islands (Fig. 1; Lermursiax and Robinson 2001; Gabersek et al. 2007).

Materials and methods

Marine geophysical data

The study area was investigated using a multi-scale, high-resolution geophysical approach during the ACUSCAL cruise (2015), conducted aboard the R/V *Minerva* as part of the RITMARE Project (CNR IAMC, Sez. Capo Granitola, Mazara del Vallo). This integrated dataset (inset in Fig. 1) allows for the detailed

documentation and classification of mass transport deposits (MTDs) and their associated geomorphological characteristics.

Swath bathymetry and morphological analysis

Seafloor topographic data covering an area of 100 km² were acquired using a Reson SeaBat 7160 multibeam echosounder (MBES), operating at a nominal frequency of 44 kHz with 512 beams.

- **Data Positioning:** Precise spatial coordinates were maintained using differential Global Positioning Systems (dGPS).

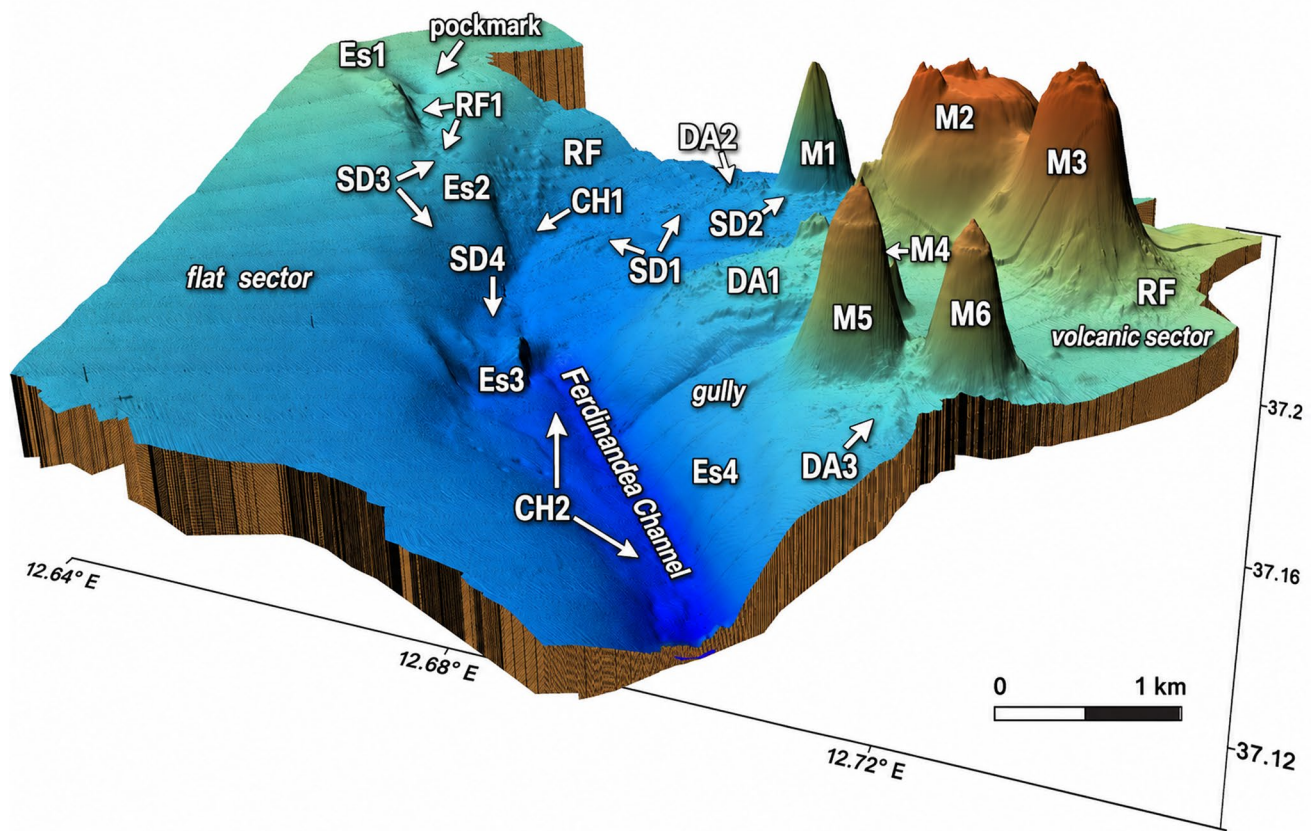


Fig. 2 Three-dimensional perspective view (vertical exaggeration 8×) of the study area showing observed morpho-structures: aligned mounds (M1–M7), aligned mounds (Am1–Am3), fault escarpments (Es1–Es4), and pockmarks (D1–D2 aligned; D3 clustered; D4 isolated). These features are separated by the NW–SE Ferdinandea Channel characterized. Labels indicate mapped features; interpretations of their origin (volcanic, tectonic, fluid flow-related) are discussed in the Results section

- **Processing Workflow:** Raw multibeam data were processed via PDS-2000 software, involving noise filtering, erroneous beam removal, and sound velocity corrections.
- **Visualization:** A Digital Terrain Model (DTM) was generated with a 5 m grid size. Further analysis, including 3D modeling and shaded relief generation, was performed using Global Mapper and Golden Software Surfer 9 to interpret the morpho-bathymetric features of the area.
- **Volumes were estimated** using the Cut and Fill tool in ArcMap 10.8. This tool computes the volume of material removed or added by comparing the elevation values of a surface with those of a reference plane or another surface. It integrates the elevation differences over the entire area, distinguishing between positive (fill) and negative (cut) values to quantify the total amount of removed and accumulated material (<https://desktop.arcgis.com/en/arcmap/latest/tools/spatial-analyst-toolbox/cut-fill.htm>).

Deposit boundaries were delineated using bathymetric data whenever available, as the relatively articulated seafloor topography allowed for clear morphological recognition of deposit limits. This approach provides more reliable boundary definition than alternative methods, as the bathymetric surface directly reflects the

depositional geometry. The reference surface for the Cut & Fill analysis was derived from seismic reflection data, which was selected to represent the pre-depositional (or basal) topography, allowing the volume calculation to quantify material accumulation above this datum. Following standard practice for MBES-derived volume estimates, we conservatively estimate a qualitative uncertainty of approximately $\pm 20\%$. This estimate reflects the good (though not optimal) spatial coverage of our seismic data, which introduces moderate uncertainty in reference surface interpolation across areas with sparse seismic control. These methodological choices ensure that the volume estimates cited in the geohazard assessment section are supported by robust data and appropriately qualified with respect to their limitations.

High-resolution seismic reflection profiles

To characterize the internal architecture and sub-surface expression of MTDs, approximately 200 km of seismic reflection profiles were collected with a line spacing of 800 m.

- **Instrumentation:** Data were acquired using a hull-mounted Teledyne/Benthos CHIRP III profiler. The system operated within a frequency range of 2–7 kHz, utilizing a pulse length of 10 ms and a ping rate between 250 and 750 ms.

- **Acquisition and Processing:** Data storage was managed through SWANPRO software, while subsequent processing and interpretation were conducted using IHS Markit suite and GeoSuite Work packages. Processing steps included Automatic Gain Control (AGC), Time Variant Gain, Swell Filtering, and Muting.
- **Time-Depth Conversion:** Conversions were based on lithostratigraphic and sonic log data from the Sicily offshore. A seismic P-wave velocity of 1600 m/s was adopted for Holocene sediments, while a velocity of 1500 m/s was used for the seawater column.

Results

Geomorphological and seismostratigraphic outline

The study area encompasses a portion of the outer continental shelf and upper slope, with depths ranging from 10 to 350 m. The irregular seafloor morphology reveals a pronounced physiographic dichotomy with two main sectors separated by an asymmetric channel (named Ferdinanda channel).

- The eastern sector corresponds to the Graham Bank volcanic edifice. It shows a jagged morphology defined by aligned mounds, ridges, and a cluster of active volcanic cones. Seven morphological highs that comprise a cluster of small seamounts have been identified and mapped. Most of these features display flat summits (i.e., guyots, labeled M1–M7 in Fig. 2). Small gullies are observed incising the seafloor, with shallow depths and limited lateral extent, connecting the main volcanic cones to the Ferdinanda Channel, and are often spatially associated with the mapped scars (Figs. 2 and 3). This region is characterized by acoustically opaque to transparent seismic facies, resulting from poor penetration of the seismic signal (Unit B in Figs. 4, 5, 6, 7, 8, and 9) representing the magmatic substrate of the Graham Bank volcanic region.
- The western sector is characterized by a flatter morphology with an average slope gradient of 1.2–1.5° (increasing westward). The seafloor is punctuated by aligned, fault-controlled normal pockmarks, and steep, NW–SE oriented elongated escarpments (Es1–3 in Fig. 2). This region consists of two seismic units: Unit A is interpreted as the Middle Pleistocene substrate (Figs. 7 and 8). It shows a discontinuous seismic pattern with reflectors offset by normal faults dipping toward the NNE and SSW. The latter locally displace the seabed, forming steep fault escarpments (Es1–3 in Figs. 2 and 3). Unit C consists of a multi-layered Upper Pleistocene–Holocene sequence in unconformity on Unit A (Figs. 7 and 8). This unit is characterized by alternating groups of high-amplitude, progradational-to-aggradational reflectors with good lateral continuity and low-amplitude reflectors. It is affected by NNE-dipping normal faults; the most prominent of these features is a fault escarpment 36 ms TWT (29 m) high (Es2 in Figs. 2 and 3). Within seismic Unit C, main chaotic seismic facies were identified on the basis of their external geometry and internal seismic character. These bodies occur discontinuously above the older seismic units and display mounded morphologies. They are characterized by chaotic to discontinuous internal reflections, truncational stratal discordances, hummocky geometries, and folded beds. This combination of seismic attributes indicates internally deformed and laterally

confined deposits, which are consistent with mass-transport deposits (MTDs).

- The intervening channel, which has a length of 10 km and a depth range of 250 to 350 m, varies in width from 0.8 to 1.5 km. It is bounded on its SW and NE margins by sub-vertical fault-escarpments (Es2–4 in Fig. 2). This channel crosses the entire study area, following a predominant N–S and NW–SE orientation (Ferdinanda Channel in Figs. 2 and 3; see Spatola et al. 2023 for further details).

Characterization of mass transport deposits (MTDs)

High-resolution bathymetric data and CHIRP profiles allowed the identification and mapping of numerous MTDs that are distributed throughout the previously described sectors. These features display a wide range of morphologies and dimensions (Figs. 2 and 3; Tables 1 and 2). To better highlight the broader patterns and potential triggering mechanisms, these features have been grouped into three thematic categories based on their geomorphological, seismic and sedimentary characteristics.

Volcanic rock avalanches (volcaniclastic-derived MTDs)

This category includes large-scale failures associated with the instability of volcanic flanks. These features are characterized by jagged seafloors and blocky topography. The blocky topography facies is a transparent to chaotic seismic facies characterized by discontinuous, very low-amplitude reflectors and by an overall low internal seismic coherence. It is overlain by high-amplitude, laterally continuous reflectors corresponding to large chaotic bodies that are widespread within the volcanic region, particularly at the base of the volcanic cones, where the seafloor has a pronounced hummocky topography (DA1–4 in Fig. 9).

The following features were mapped in detail as follows:

- DA1: A large, fan-shaped body (~2.2 km² wide, Table 2) characterized by an extremely jagged seafloor with chaotic, blocky topography. It is located at the base of the western flank of M2, approximately 65 m below its flat summit. This deposit is associated with an amphitheater scar steep up to 21° that affects the flank of the volcanic cone (Figs. 3, 4, and 5). Rotated blocks are observed at the base of the mapped scar. Block size decreases toward the distal sector, and minor escarpments dipping toward the channel are visible in the lower part of the deposit (Fig. 3a).
- DA2: A small fan-shaped body (~0.28 km² wide, Table 2) with blocky seabed topography, located at the base of the western flank of M1 (Figs. 2, 3a, and 4). It is linked to a well-defined amphitheater scar up to 26° steep, featuring rotated blocks at its base (Fig. 3a).
- DA3: A small, elongated, lobe-shaped body (~0.28 km² wide, Table 2) characterized by blocky topography occurs at the base of volcanic cone M6, where an arcuate amphitheater scar cuts the southwestern flank of M6 (Figs. 2 and 3a; Table 1).
- DA4: A mound-shaped body (~0.15 km² wide, Table 2) situated at the base of the northern side of the largest volcanic cone M2 at the depth of about 150–170 m (Fig. 3b). It is likely linked to the prominent amphitheater scar carving the northwestern flank and the flat top of the volcano. The material from the

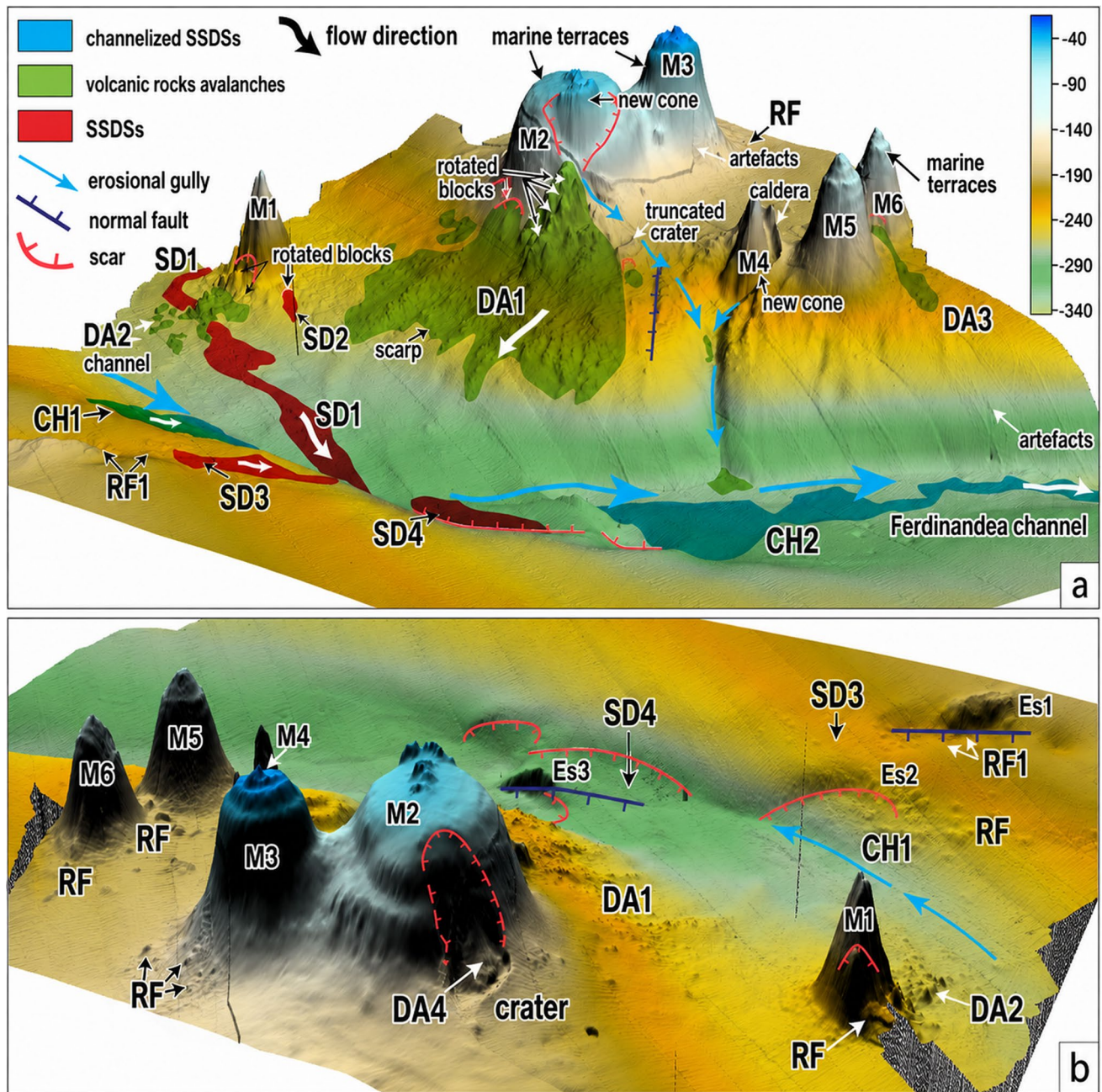


Fig. 3 Three-dimensional perspective view (vertical exaggeration 5×) of the study area from south (a) and north (b) viewpoints, displaying observed seafloor morphology including mounds, scars, and channel features. Overlaid labels indicate interpreted deposits (DA, RF, SD, CH) and tectonic features (Es1–Es4 fault escarpments); fault lineaments and channel geometry represent observational data, while mass-transport classifications are interpretations based on seismic facies and morphological characteristics

scar appears to be accumulated within a subcircular depression ~ 500 m long, ~ 250 m wide and ~ 15 m deep (Fig. 3b).

Rockfalls

This group consists of smaller, isolated deposits typically found at the base of steep, tectonically-active or volcanic slopes:

- RFs: Small, isolated dome-shaped bodies, locally associated with arcuate small scars (e.g., the 26° gradient scar on the

northern side of M1, Fig. 3b), mapped at the foot of various volcanic cones (Fig. 3a, b).

- RF1: A cluster of heterometric blocks (0.136 km² wide) creating a jagged seabed at the foot of a steep fault escarpment (Es1) in the northwestern corner of the region (Figs. 2, 3b, and 6; Tables 1 and 2). These are bordered to the northwest by a large pockmark where the seabed has a concave-upward morphology.

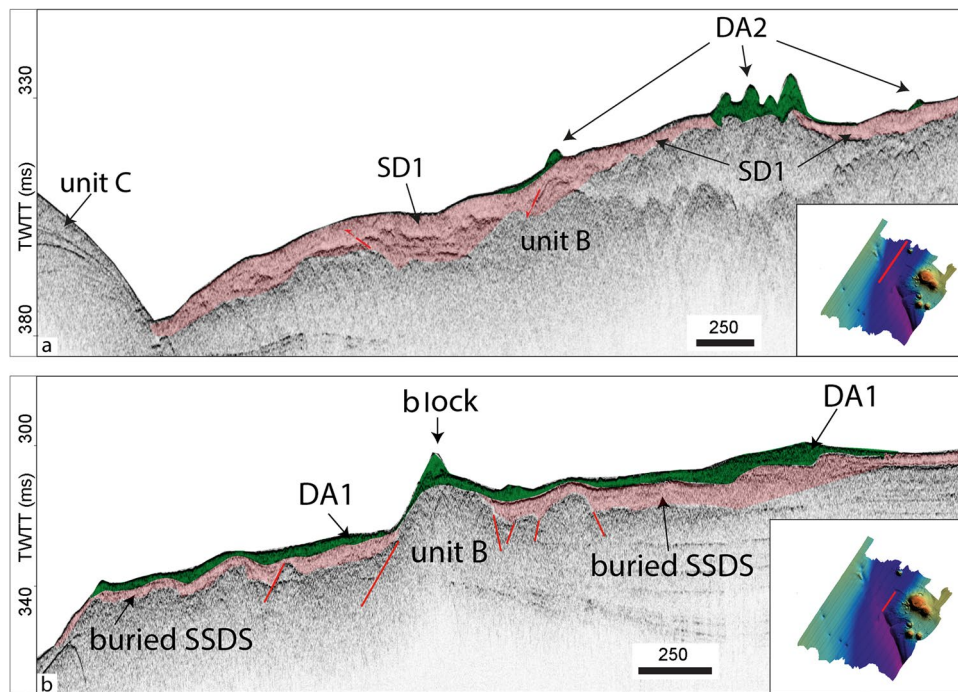


Fig. 4 Sub-bottom CHIRP seismic profiles illustrating: **a** chaotic acoustic units (labeled SD1, DA2) within the Ferdinanda Channel and western region; **b** chaotic bodies (DA1) and buried soft-sediment deformation structures (SSDSs) in the eastern region

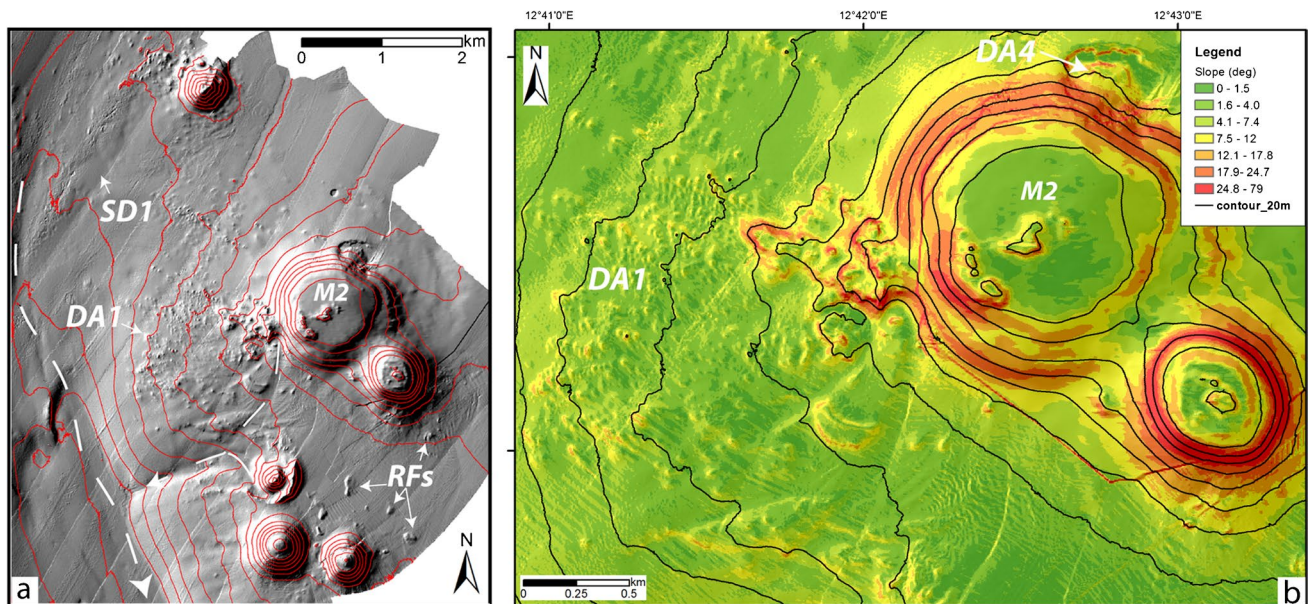


Fig. 5 **a** Hillshade representation of the seafloor around volcanic cones M2; **b** corresponding slope gradient map showing steep flanks (up to 21°) on volcanic edifices

Slumps and glides

These deposits involve the failure of stratified, water-saturated sediments, often showing evidence of interaction with bottom currents. They appear with different seismic facies: The rotational facies is chaotic seismic facies internally characterized by discontinuous,

very low-amplitude reflectors with a transition into reflection-free zones or discontinuous high-amplitude reflectors with an arcuate geometry (Fig. 7b). The unit is capped by a very high-amplitude reflector, while its basal surface is defined by a generally continuous, high-amplitude reflector with a concave to strongly irregular

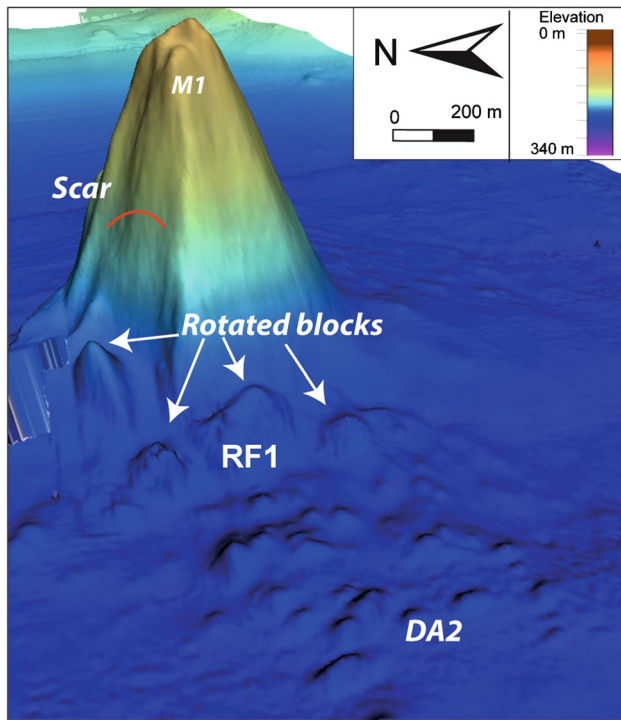


Fig. 6 Three-dimensional perspective view (vertical exaggeration 8×) of volcanic cone M1 with scattered polygonal blocks at its base. The blocky, fragmented material visible on the seafloor is interpreted as rockfall accumulation derived from slope failure of the steep volcanic flank

shape (Fig. 7b). This facies characterizes the small bodies occurring within the volcanic region (e.g., SD2 in Fig. 8c, SD3 in Fig. 7b, and SD4 in Fig. 8a). The Tabular facies internally appears transparent and locally chaotic, displaying very low-amplitude, discontinuous

reflectors. It is bounded at the top by a continuous, high-amplitude planar reflector (Fig. 8). The basal surface consists of a continuous, high-amplitude, slightly irregular reflector that rests unconformably on Unit B (Fig. 8). This facies corresponds to the chaotic body SD1, which internally is characterized by offset seismic reflectors (Fig. 8). The mapped bodies are:

- SD1: An elongated body ($\sim 0.897 \text{ km}^2$ wide, Table 2) forming a hummocky topography seabed immediately south of M1 (Figs. 2, 3a, and 5; Table 1). In the northwestern sector, it is cross-cut by DA2, indicating that DA2 represents a more recent instability event.
- SD2: A smaller, sub-circular dome-shaped body ($\sim 0.025 \text{ km}^2$ wide, Table 2) at the base of the southern flank of M1, associated with a small, concave scar (Figs. 2, 3a, and 6; Table 1).
- SD3: A southeastward-pointing, arcuate, elongated body (0.75 km^2 , Table 2) with rough seafloor morphology. It sits at the foot of the 30 m high fault escarpment (Es1) and extends into the Ferdinanda channel (Figs. 2, 3, and 7; Table 1).
- SD4: A fan-shaped, partially buried body ($\sim 0.53 \text{ km}^2$ wide, Table 2) in the central sector of the channel (Figs. 2, 3, and 8; Table 1). It is associated with a 1.2 km long, arcuate, concave NW–SE oriented scar (Figs. 3b, and 8).

Channelized fills

These deposits involve the failure of stratified, water-saturated sediments and are often found in association with channelized seafloor features or structural depressions (CH1-2 in Figs. 2 and 3). In seismic sections, these bodies are characterized by a mounded hummocky facies, consisting of chaotic seismic signals with high-amplitude reflectors alternating with low-amplitude ones, defining bodies with a convex geometry, and clear pinch-outs (Fig. 7b). These bodies are variable in thickness and often are characterized by a clear basal erosional unconformity (Fig. 9).

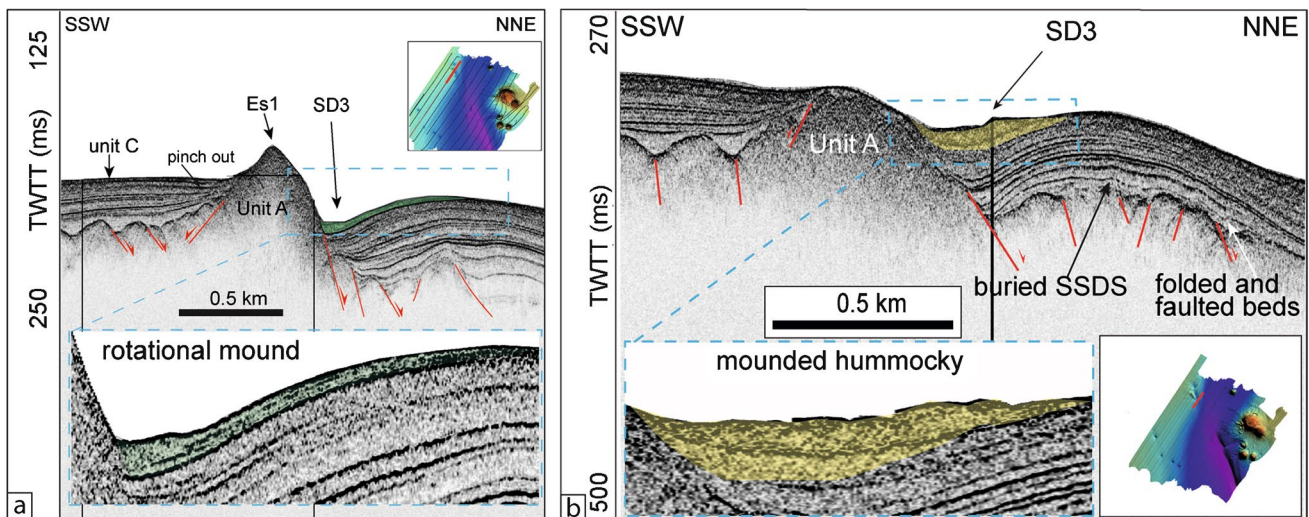


Fig. 7 Detail of CHIRP sub-bottom seismic profile showing the occurrence of chaotic acoustic reflectors with discontinuous, low-amplitude seismic facies (SD3) within the shallow subsurface. Lower panels show enlarged views of the same feature

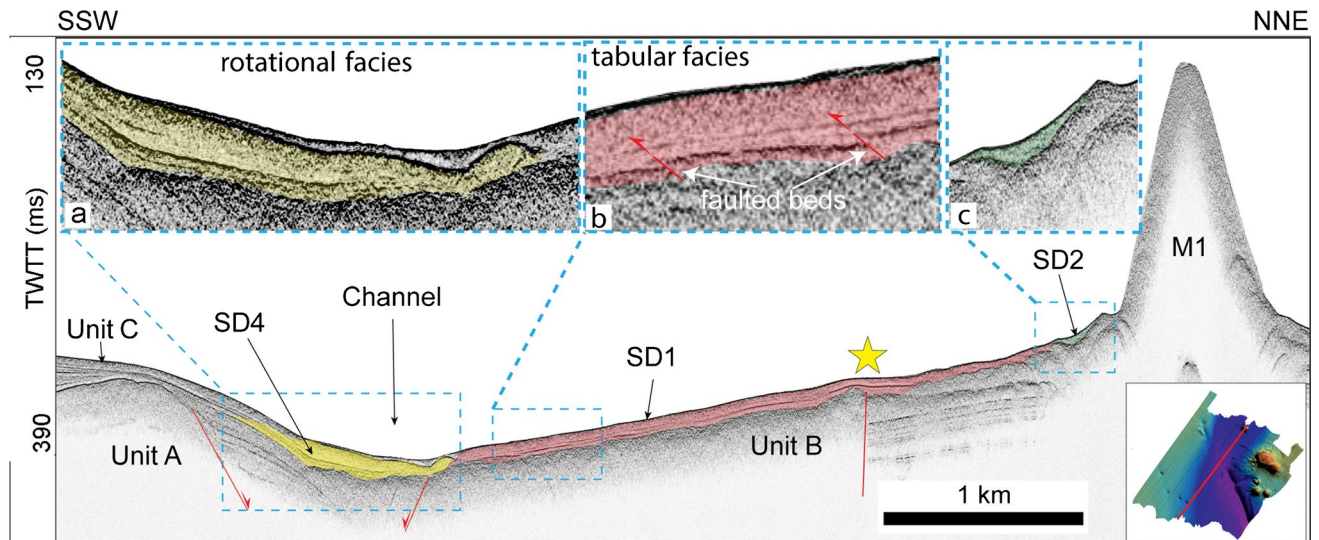


Fig. 8 Sub-bottom CHIRP seismic profile displaying chaotic acoustic units (SD1, SD4, SD2) within the western and eastern regions and the Ferdinanda Channel. The seismic character chaotic reflectors with diffuse basal surfaces indicates internal deformation. Yellow star indicates the epicenter of the 22-08-2003 earthquake (magnitude ML 2.6) (modified from Spatola et al. 2018)

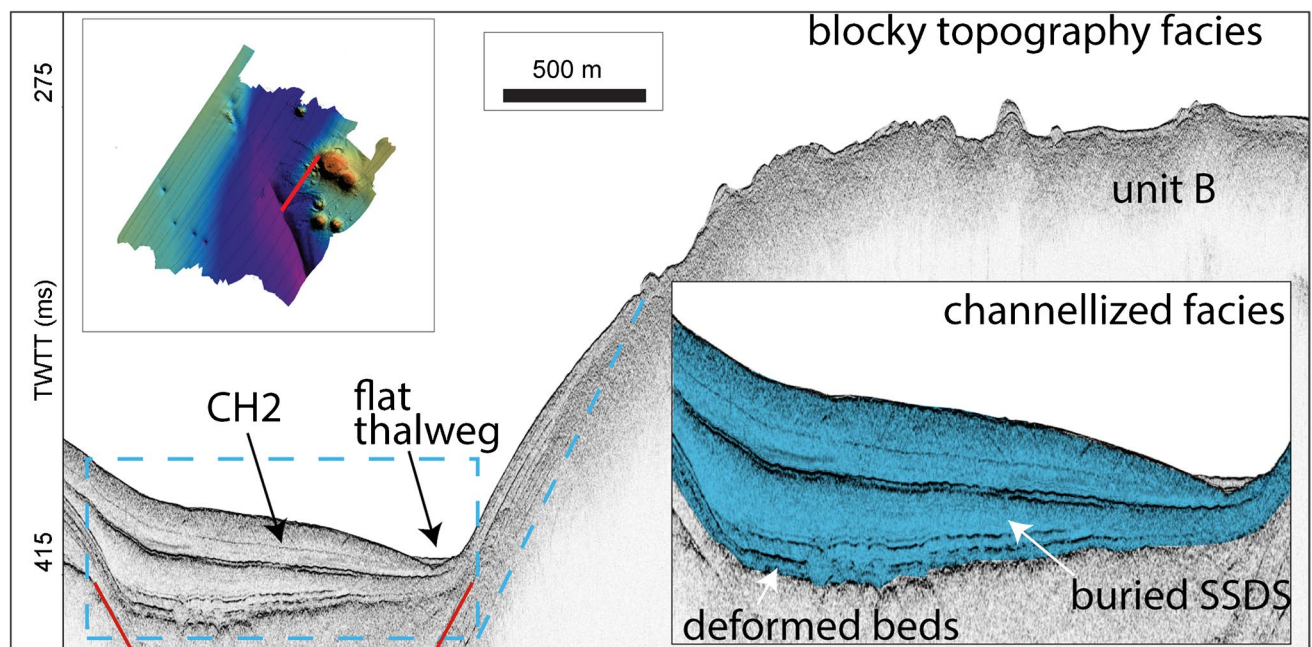


Fig. 9 Sub-bottom CHIRP seismic profile across the Ferdinanda Channel showing a buried soft-sediment deformation structure (SSDS) overlying clear, deformed bedding

- CH1: Is an elongated body ($\sim 0.96 \text{ km}^2$, Table 2) with hummocky seafloor topography in the northernmost sector of the channel, originating from the base of escarpment Es2 (Figs. 2 and 3; Table 1). Here, the channel features an incised U-shaped thalweg (moderately concave), transitioning to a V-shape with asymmetric flanks between the depth of 310 m and 325 m, with a downslope gradient of about $1\text{--}2^\circ$.
- CH2: A larger irregular, elongated body ($\sim 2.46 \text{ km}^2$ wide, Table 2) occurs in the southernmost portion of the Ferdinanda channel. It is separated from CH1 by a concave escarpment approximately 20 m high (Es3 in Fig. 3b). In this sector, the channel thalweg is flat (gradient $< 1^\circ$), while the channel walls display slopes between 4° and 7° , forming elongated escarpments up to 100 m high (Figs. 2 and 9).

Table 1 Classification scheme for submarine mass-movement deposits showing: (1) interpreted deposit types, (2) observational criteria (morphology and seismic facies), (3) possible triggering processes, and (4) confidence levels. This structure separates observational evidence from interpretations to enhance methodological transparency

Interpreted deposit type	Observational criteria (Morphology & Seismic Facies)	Possible triggering process	Confidence level
Debris Avalanches (DAs)	Blocky topography with extensive lateral run-outs; high-amplitude chaotic seismic response	Catastrophic volcanic flank collapse; high-energy granular flow	High
Rockfalls (RFs)	Dome-shaped bodies; chaotic seismic response; fragmented material at slope base	Abrupt gravitational failure from steep slopes due to seismicity or tectonic tilting	High
Slumps (SSDs—Rotational)	Chaotic stratification; internal folding; disrupted reflectors within channelized bodies	Rotational displacement along curved failure surfaces; slope instability or sediment overloading	Moderate
Glides (SSDs—Translational)	Subtle deformation of aggrading-prograding reflectors; extensional features at head; compressive structures at toe	Lateral sliding along basal detachment sub-parallel to bedding; coseismic fault displacement	Moderate
Channelized Fills (SSDs – CHs)	Hummocky seafloor topography; syn-sedimentary folding; intra-formational truncations	Bottom-current reworking and undercutting of pre-existing deposits	Moderate

Abbreviations: *DAs* Debris Avalanches; *RFs* Rockfalls; *SSDs* Soft-Sediment Deformation Structures; *CHs* Channelized Fills. Slumps/glides (SDs) and channelized fills (CHs) are both subtypes of the SSDs category

Discussion

Interpretation and classification of mass transport deposits (MTDs)

The numerous chaotic bodies mapped at the Graham Bank and in the surrounding area are interpreted as submarine MTDs, involving the downslope displacement of heterogeneous sediment masses under the influence of gravity. MTDs encompass a wide spectrum of deposits, including slides, slumps, debris flows, and turbidites (Moscardelli and Wood 2008; Posamentier and Martinsen 2011; Clare et al. 2018). In this study, different MTD types were distinguished based on their diagnostic morphological expression and seismic facies, which reflect different deformational styles and emplacement processes. On the basis of seafloor morphology, internal geometry, seismic character, and inferred rheological behavior, the identified MTDs were classified into: (i) debris avalanches (DAs); (ii) rockfalls (RFs); and (iii) soft-sediment deformation structures (SSDs), which comprise slumps and glides (rotational and translational deformation, respectively; SDs) and channelized fills (CHs) (Table 1).

Soft-sediment deformation structures

Soft-sediment deformation structures (SSDs) develop when originally stratified sediments are deformed under gravitational loading and related stress conditions while still unlithified or semi-consolidated (Lowe 1979). Such deformation typically occurs during syn-sedimentary to early post-sedimentary stages, prior to complete lithification (Leeder 1987; Owen 1987). In the Graham Bank area, SSDs are identified by chaotic to disrupted stratification, folded and faulted beds, discontinuous reflectors, hummocky geometries,

and intra-formational truncation surfaces. These features occur within elongated and channelized bodies (CH1–2) and along steep slopes (SD1–4) (Figs. 2 and 3), indicating deformation of originally layered deposits.

CHs and SD2–4 are interpreted as slump-related accumulations formed by rotational sliding of sediment masses from channel flanks. In contrast, more subtle deformation affecting the aggrading-prograding reflectors of the Upper Pleistocene–Holocene semi-consolidated deposits (Unit C) draping the northeastern channel slope (e.g., SD1) is consistent with the process of gliding. The presence of extensional structures at the head and compressional features at the toe of SD1 further supports its classification as an SSDS (Alsop and Marco 2011; Moretti and Van Loon 2014; Basilone et al. 2014, 2016b). In terms of size, geometry, and seismic facies, the SSDs described here are comparable to mass-transport deposits recently documented in several sectors of the Mediterranean Sea. This correspondence suggests that similar pre-conditioning factors and triggering mechanisms may have controlled their emplacement, pointing to a regional-scale consistency in the processes governing soft-sediment deformation in Mediterranean submarine environments (e.g., Gamberi et al. 2015; Urlaub et al. 2022; Talling et al. 2022).

Rockfalls

Rockfalls result from the abrupt gravitational failure of fragmented bedrock or over-consolidated sediments from steep slopes. These processes produce talus and scree deposits characterized by a high degree of fragmentation (Varnes 1978; Nardin et al. 1979). Dome-shaped bodies mapped along the flanks of volcanic cones (RFs in Figs. 2, 3, and 4a) and steep fault escarpments (RF1 in Figs. 2

Table 2 Morphometric parameters of the mass transport deposits (MTDs) identified in the study area, including geographic coordinates, planimetric dimensions (length, width, perimeter), deposit area (2D and 3D), volume, slope gradient, and thickness

ID	Latitude	Longitude	Length (m)	Width (m)	Perimeter (km)	Deposit area 2D (km ²)	Deposit area 3D (km ²)	Volume (km ³)	Slope (deg)	Thickness (m)
DA1	37° 10' 22.1443" N	12° 41' 34.6393" E	2100	2000	6.6	2.15	2.2	0.15	21	—
DA2	37° 12' 11.2353" N	12° 41' 11.6538" E	740	540	2.6	0.278	0.283	0.028	23.5	5.2
DA3	37° 08' 40.7177" N	12° 42' 26.4908" E	1200	200	2.7	0.279	0.282	0.027	5.8	6
RF1	37° 11' 51.4507" N	12° 39' 12.2662" E	700	165	1.8	0.136	0.137	0.0011	11	6.4
SD1	37° 11' 53.6259" N	12° 40' 40.1697" E	3600	280	7.9	0.897	0.9	0.022	2	6.3
SD2	37° 11' 52.1719" N	12° 41' 18.8561" E	310	100	0.75	0.0247	0.0248	0.000193	4.8	5.7
SD3	37° 11' 12.2173" N	12° 39' 55.7357" E	2600	280	5.8	0.75	0.76	0.018	2	3.5
SD4	37° 10' 5.2958" N	12° 40' 4.1897" E	1340	617	3.25	0.528	0.529	0.00483	2	9.6
CH1	37° 11' 44.9497" N	12° 39' 50.1878" E	2800	850	6.8	0.961	0.965	0.038	1.5	6.7
CH2	37° 08' 46.2300" N	12° 41' 1.2812" E	4600	500	9.4	2.458	2.46	0.04	2.3	9
DA4	37° 10' 59.2168" N	12° 42' 53.1678" E	545	300	1.65	0.149	0.152	0.000138	12	—

DA Debris avalanche; RF Rockfall; SD Slump/glide (a subtype of the soft-sediment deformation structures, SSDSs); CH: channelized fill (a subtype of the SSDSs). Dashes indicate parameters that could not be reliably estimated

and 3) are interpreted as polygonal blocks as evidence of rockfall accumulations.

Although direct grain-size data are unavailable, the high-amplitude and chaotic seismic response may reflect a strong internal acoustic heterogeneity, commonly associated with coarse-grained and poorly sorted mass-transport deposits. Similar seismic characteristics have been widely documented in deposits related to volcanic flank instability, where mixtures of blocks, breccias, and finer volcanic material produce disrupted and high-contrast seismic facies. This interpretation is consistent with established conceptual and observational models of submarine volcanic slope failures (e.g., Moore et al. 1989; Masson et al. 2002; Micallef et al. 2007; Gamberi et al. 2011; Clare et al. 2018).

Debris avalanches

The bodies identified as DA1-4, associated with volcanic cones in the western region (Figs. 2 and 3), are interpreted as small debris avalanche deposits. These typically originate from deep-seated failures on steep volcanic flanks, resulting in a widespread blocky topography (e.g., Mulder and Alexander 2001; Masson et al. 2002). Discriminating between rockfalls and debris avalanches in submarine volcanic settings is a challenge and requires the integration of deposit scale, seafloor morphology, internal seismic character, and depositional context. In the study area, rockfalls are typically characterized by small-volume, highly localized accumulations derived from the gravitational detachment of individual blocks or small block clusters from steep scarps. These deposits commonly form thin sheets and display simple geometries with limited lateral continuity. In contrast, debris avalanches appear to result from the collapse of larger portions of volcanic flanks and generate laterally extensive, thick, and internally heterogeneous deposits. They are commonly associated with hummocky seafloor morphology, irregular mounded surfaces, and chaotic, high-amplitude seismic facies with poor internal continuity. Such deposits often extend well beyond the immediate base of the source scarp and partially infill the Ferdinanda channel. The presence of deeply incised gullies and arcuate slide-scars on the largest cones (e.g., M2 and M3) support our interpretation. Another strong argument supporting our interpretation is that, in seismic profiles, rockfalls are typically expressed as isolated high-amplitude reflections or small chaotic bodies with sharp basal contacts, whereas debris avalanches are characterized by broader chaotic units, diffuse basal surfaces, and complex internal acoustic heterogeneity, locally affected by small-scale faulting as highlighted by offset seismic reflectors. Therefore, the occurrence of large, laterally continuous chaotic bodies associated with hummocky seafloor morphology and developed within a volcanic physiographic setting supports their interpretation as debris avalanche type deposits rather than simple rockfall accumulations. Finally, this interpretation is consistent with documented volcanic island collapses, as described for the Canary Islands (Urgeles et al. 1997; Masson et al. 2002, 2008), Réunion Island (Indian Ocean; Ollier et al. 1998), the Aeolian Arc (Romagnoli et al. 2009), and the Vanuatu Arc (southern Pacific; Clare et al. 2018). However, the deposits described in this study are not directly comparable in terms of scale, as they are significantly smaller than those associated with major volcanic island collapses. Instead, the similarities primarily concern the physiographic and geological context, including steep volcanic slopes, local structural control,

and gravitational instability affecting volcanoclastic and sedimentary sequences.

Driving forces and trigger mechanisms

The Graham Bank area represents a complex geodynamic cross-roads where tectonic rifting, anorogenic magmatism, and vigorous bottom currents converge. Our results suggest that the MTDs identified are not the product of a single trigger, but the result of a synergistic "multi-hazard" framework.

Tectonic and magmatic pre-conditioning

The study area is characterized by high heat flow (75 to 100 mW/m²) and alkaline to peralkaline magmatism, indicating deep-seated geodynamic activity. This thermal state, combined with the presence of sub-vertical fault systems, is interpreted as a potential pre-conditioning factor for slope instability. As seen in Stromboli (Aeolian Arc), magmatic overpressure and dyke intrusions can significantly deform the edifice flanks before failure (Casalbore et al. 2011). At Graham Bank, the spatial correlation between MTDs and syn-sedimentary faults suggests that tectonic tilting and volcanic inflation create the necessary bathymetric gradients for instability.

The Soft-Sediment Deformation Structures (SSDs), including slump deposits (SDs) and channelized fills (CHs) identified at Graham Bank (Figs. 2, 3, 6, 7, 8, and 9), likely developed within unconsolidated to semi-consolidated sediments through a significant reduction in shear resistance. As suggested by the architectural analysis, this deformation was driven by the complex interaction between gravitational loading and specific weakening mechanisms (Owen et al. 2011).

A key observation is the positive spatial correlation between SSDs and sub-vertical syn-sedimentary fault systems. These faults, which affect both the sedimentary succession and the underlying volcanic substrate are sealed by the overlying SSDs (Figs. 6, 7, 8, and 9) and appear to have acted as possible pre-conditioning factors. Tectonic activity contributes to slope instability not only through immediate triggers but also through long-term slope modification, such as fault-controlled oversteepening and tectonic tilting. In this context, the Graham Bank reflects a geodynamic setting where tectonic strain and volcanic-related deformation (e.g., magmatic overpressure or sill intrusions) act in synergy to enhance gravitational driving forces.

The RF1 deposit is interpreted as the result of rockfalls originating from the steep fault escarpment (e.g., Es1 in Fig. 2), affecting the middle Pleistocene lithified deposits (Unit A). The close stratigraphic and spatial relationship between the MTDs and the fresh fault scarps, where the deposits drape or are directly associated with the escarpment, suggests that rockfall emplacement occurred shortly after fault displacement (Figs. 2 and 3), thereby constraining the relative timing of deposition with respect to tectonic activity.

In a volcanic setting such as the study area, volcanic processes exert a primary control on the genesis and evolution of mass-transport deposits (MTDs). The RFs and DA1-4 (rockfalls and debris avalanches), mapped in the Eastern Volcanic region, consist of volcanoclastic material removed from the flanks of the edifices, indicating that slope stability is strongly influenced by volcanically driven morphological changes (Casalbore et al. 2011). This interpretation is supported by the presence of large scars truncating the volcanic cones (Figs. 3 and 5). Notably, these scars also affect

terrace-like surfaces developed near the summits of the edifices. Unlike the marine terraces described by Casalbore et al. (2016) at Salina Island (Southern Tyrrhenian Sea), which are primarily related to eustatic sea-level fluctuations, the terraces observed in the Graham Bank area are not considered directly comparable. Instead, they are interpreted as geomorphic surfaces associated with volcanic uplift phases, likely driven by magma-related inflation, thermal expansion, and consequent bulging of the volcanic edifice. In this context, historical bathymetric comparisons (Colan-toni 1975) provide an independent line of evidence, suggesting that the most recent morpho-structural adjustments may be temporally related to the 1831 volcanic eruption, illustrating the system's capacity for rapid morpho-structural change; however, this historical event cannot be used to date individual MTDs without sediment cores or stratigraphic correlation. Unlike the massive debris avalanches of Hawaii or the Canaries, the MTDs at Graham Bank (e.g., DA1–DA4) involve smaller volumes but show remarkably similar morphological signatures, such as amphitheater scars and blocky topography. This suggests that regardless of the total volume of mobilized material, the "morphogenetic fingerprint" of instability in rifted volcanic margins is governed by a universal set of geodynamic drivers: tectonic oversteepening, magmatic pulse, and seismic loading (Moore et al. 1994; Masson et al. 2002).

Seismic triggering and global analogues

While individual seismic events (like the 2003 ML 2.6 earthquake) are difficult to link directly to specific deposits, the regional seismic background (with hypocenters up to 20 km deep and magnitudes exceeding ML 5 in the N-S trending belt, Chiarabba et al. 2005; Galea 2007; Calò and Parisi 2014) a plausible regional destabilizing factor; however, its role as a primary trigger for specific deposits cannot be confirmed without slope stability calculations, ground-motion estimates, or evidence of synchronous failures. Shallow seismic activity, even at moderate magnitudes, is a globally recognized potential driver for liquefaction and excess pore-pressure development in under-consolidated marine sediments. Shallow seismic activity, even at moderate magnitudes, is a globally recognized driver for liquefaction and excess pore-pressure development in under-consolidated marine sediments (Seilacher 1969; Allen 1986; Obermeier 1996; Montenat et al. 2007). The Graham Bank findings are consistent with mass-transport records documented in other active rift and volcanic settings as the Gela Basin and the Adventure Bank (Central Mediterranean), where seismically-induced slope failures have been documented (Gardiner et al. 1993; Minisini et al. 2007; Micallef et al. 2013), suggesting that the Sicily Channel acts as a regional-scale laboratory for earthquake-induced slope failures.

The complex interplay between tectonic faulting, magmatic activity, and volcanoclastic instability documented at Graham Bank mirrors documented processes in major volcanic archipelagos worldwide. These comparisons provide a robust framework for interpreting the triggering mechanisms in the Sicily Channel. In the Hawaii Islands, the 1975 movement of the Hilina Slump represents a seminal example of synergistic triggering, where a large-scale mass movement was accompanied by both a major earthquake and a simultaneous small volcanic eruption. Moore et al. (1989; 1994) interpreted these events as mutually reinforcing, where tectonic displacement and magmatic activity combined to destabilize the

volcanic flank. A similar interplay has been documented in the Canary Islands and Cape Verde, where Masson et al. (2002) in the Canary archipelagos highlighted how deep-seated tectonic rifting and high-energy environmental conditions act as long-term pre-conditioning factors for catastrophic failures. Their interpretations suggest that where structural strain intersects volcanic edifices, the resulting stratigraphic weakening facilitates large-volume mass transport events. Comparable processes have been also described across the Aeolian Arc: Studies across the Aeolian Islands (e.g., Stromboli) and Ischia demonstrate that magmatic inflation, hydro-thermal alteration, and pore-fluid pressurization significantly reduce the shear strength of submerged volcanic flanks. As noted by various authors, in these settings, regional seismic "shaking" often acts as the final trigger for slopes already destabilized by magmatic overpressure or tectonic rifting (Chiocci and De Alteris 2006; Romagnoli et al. 2009; Casalbore et al. 2011).

Similar to these global analogues, the instability at Graham Bank appears driven by a synergy of internal and external forcing. The spatial correlation between identified SSDSs and sub-vertical fault systems is consistent with tectonic strain as a possible preconditioning factor, while magmatic processes such as sill intrusions or magmatic overpressure, may have further enhanced gravitational driving forces. Analogous to the conceptual "cascading" frameworks proposed for the Aeolian Arc, the Graham Bank seafloor is consistent with a high-instability environment where seismic activity may provide transient stress sufficient to trigger failure in already weakened strata, though this hypothesis requires further testing through numerical slope stability analysis.

Oceanographic forcing: the role of bottom currents and hydrodynamic interaction

The geomorphological evolution of Graham Bank is heavily influenced by vigorous oceanographic forcing, particularly within the epipelagic zone (0–200 m). High-resolution hydrodynamic models for this depth range provide robust data, capturing the seasonal thermocline and the interaction of key Mediterranean water masses. The interplay between these currents and the seafloor topography acts as a primary driver for instability, especially in the channelized sectors. The study area is a dynamic crossroads for the eastward flow of Modified Atlantic Water (MAW) and the deeper outflow of Levantine Intermediate Water (LIW) (Fig. 1). The Atlantic Ionian Stream (AIS), the main branch of the MAW, generates superficial velocities exceeding 0.25 m/s (Fig. 10). This high-energy flow triggers continuous basal undercutting of the channelized fills (CH1, CH2) and the flanks of the Ferdinandea channel. By preventing the natural stabilization of the sediment pile, these currents maintain steep topographic gradients that facilitate localized slumping.

The well-resolved model for the 0–200 m range confirms that the mounded hummocky facies observed in seismic profiles are not relict features but are actively shaped by current-driven scouring. Mesoscale features, such as the Adventure Bank Vortex (ABV, (Lermusiaux and Robinson 2001) further enhance turbulence, promoting the mobilization of unconsolidated volcanoclastic material, and small contouritic deposits (Spatola et al. 2018). Just as observed in the Atlantic margins (Canary Islands) where contour currents undercut debris avalanche deposits (Masson et al. 2002), act as long-term pre-conditioning factors for catastrophic

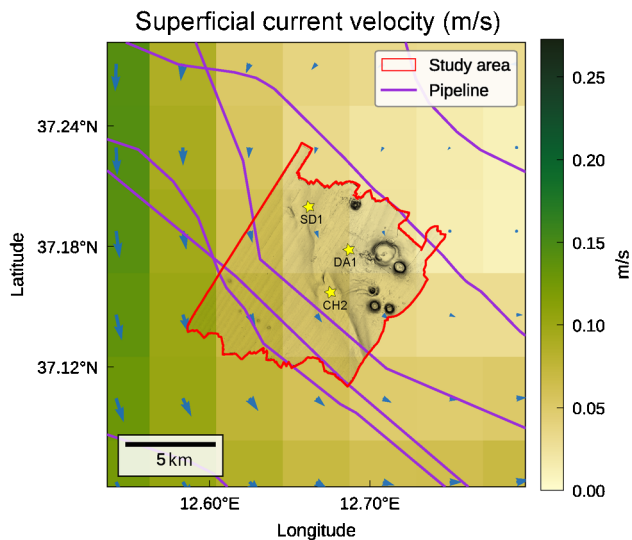


Fig. 10 Annual mean surface current velocity field ($\text{m}\cdot\text{s}^{-1}$) derived from CMEMS Mediterranean Sea Physics Reanalysis (MEDSEA_MULTIYEAR_PHY_006_004) at ~ 4.2 km horizontal resolution. Arrows indicate current direction and magnitude. Bathymetric hillshade underlies the velocity field. Red polygon marks study area boundary; purple lines indicate submarine pipeline routes. Stars denote locations of main identified MTD features. Current velocities exceeding $0.25 \text{ m}\cdot\text{s}^{-1}$ observed in the Atlantic Ionian Stream are interpreted as capable of promoting basal erosion and sediment reworking in the channelized sectors

collapses, the AIS at Graham Bank can actively erode the base of channelized fills (CH1, CH2). This continuous undercutting (basal erosion) maintains steep gradients and prevents the stabilization of the sediment pile. The spatial correlation between peak current velocities and the submarine cable network (Fig. 10) underscores a potential concern for infrastructure. The intense hydrodynamic activity at these depths may promote scouring and free-spanning, potentially exposing infrastructure to mechanical fatigue. In summary, the oceanographic regime at Graham Bank represents a plausible modulating factor for ongoing instability; current velocities exceeding $0.25 \text{ m}\cdot\text{s}^{-1}$ documented from reanalysis data are consistent with the capacity for bed erosion and sediment reworking, though direct near-bed measurements and bed shear stress calculations are needed to confirm their role as active destabilizing agents.

Preliminary geohazard implications

The high-resolution mapping of MTDs around the Graham Bank provides critical data for assessing marine geohazards in the Sicily Channel. The study area is characterized by a high density of submarine landslides showing significant variability in runout distance and failure volume, with the largest debris avalanche (DA1) covering an area of $\sim 2.2 \text{ km}^2$. The proximity of these features to critical submarine infrastructure, including telecommunication cables and energy pipelines that pass within 0.5 km of the identified scars or directly intersect the depositional lobes represents a potential geohazard source for seafloor infrastructure that warrants monitoring and further quantitative assessment (Fig. 10). Specifically: (i)

Direct Impact and Scouring: Large-scale events like DA1 and DA2, characterized by blocky topography and rotated megaclasts, could cause severe mechanical damage or severance of pipelines through direct impact or sudden sediment loading. (ii) Basal Instability: The identified Mounded hummocky facies in channelized sectors (CH1, CH2) suggest active sedimentary transport and basal erosional unconformities. The continuous undercutting by the Atlantic Ionian Stream (AIS) may lead to the exhumation or "free-spanning" of buried cables, significantly increasing their vulnerability to fatigue and current-induced vibrations. This study could serve as a critical model for understanding how internal geodynamic forces and external oceanographic currents converge to drive gravity instabilities. Future hazard mitigation strategies must integrate these geomorphological findings with real-time monitoring and numerical runout modeling to quantify the specific impact scenarios for the anthropogenic assets crossing this high-instability environment.

Post-1831 morphodynamic evolution and future stability scenarios

The Graham Bank is a highly dynamic environment where the morphogenetic evolution of MTDs is closely linked to recent volcanic activity, most notably the 1831 eruption that led to the ephemeral formation of Ferdinandea Island. This historical event, occurring less than two centuries ago, highlights a rapid buildup of volcaniclastic material and the creation of inherently unstable, steep-sided slopes. Although the last eruptive phase likely contributed to morpho-structural reorganization, the MTDs identified (particularly DA1–DA4) cannot be directly dated to the 1831 eruption without sediment cores or stratigraphic correlation. Their occurrence in a volcanically active setting is consistent with instability processes associated with eruptive cycles, but this remains a working hypothesis.

Looking forward, the evolution of landslides in this sector presents a dual threat to anthropogenic assets: (i) Episodic Reactivation: Future magmatic or eruptive pulses driven by the area's high heat flow ($75\text{--}100 \text{ mW}/\text{m}^2$) and anorogenic magmatism—could trigger new, large-volume debris avalanches. Such events would pose an immediate risk of mechanical rupture to pipelines and cables through direct impact or burial. (ii) Progressive Degradation: Even in the absence of new eruptions, the synergy between tectonic strain and the undercutting action of the Atlantic Ionian Stream (AIS) promotes the retrogressive migration of existing headwall scars. This long-term "chronic" instability can lead to the slow exposure and eventual suspension (free-spanning) of pipelines, making them susceptible to hydrodynamic failure. Given that the 1831 eruption demonstrates the system's capacity for rapid and violent geomorphological change, the proximity of submarine infrastructure to these active instability centers requires a monitoring approach that accounts for both sudden volcanic triggers and the persistent erosive power of Mediterranean bottom currents.

Study limitations

The interpretations presented in this study are based exclusively on bathymetric and CHIRP seismic observations and should be considered as working hypotheses subject to the following data

limitations. (i) Absence of sediment cores and age control: without sediment dating, no chronological constraints can be placed on individual MTDs, and temporal links to specific eruptive or tectonic events (including the 1831 eruption) remain speculative. (ii) Absence of geotechnical data: sediment shear strength, consolidation state, and pore pressure are unknown, precluding slope stability calculations and quantitative assessment of failure probability. (iii) Absence of direct current measurements: near-bed current velocities and bed shear stress have not been measured in the study area; the role of the Atlantic Ionian Stream as an active destabilizing agent is inferred from regional reanalysis data and seismic facies but requires confirmation through in situ hydrodynamic measurements. (iv) Absence of numerical runout modeling: without mobility analysis, the spatial extent of potential future failures and their impact on submarine infrastructure cannot be quantified. These limitations should be addressed in future investigations to transition from the preliminary geohazard screening presented here to a rigorous probabilistic hazard assessment.

Conclusion

The integrated analysis of the Graham Bank seafloor reveals a high-instability environment governed by the synergy of internal geodynamic forces and external oceanographic dynamics. The classification of MTDs into debris avalanches, rockfalls, and soft-sediment deformations allowed us to establish a morphogenetic framework that links seafloor morphology to specific volcanic and tectonic processes.

- **Tectonic-Volcanic Synergy:** Sub-vertical syn-sedimentary faults and magmatic overpressure are interpreted as possible pre-conditioning factors for slope failure, consistent with geomorphological observations but requiring geotechnical validation.
- **Seismic and Hydrodynamic Forcing:** Regional seismicity and bottom-current scouring by the Atlantic Ionian Stream (AIS) are identified as possible destabilizing mechanisms, consistent with basal erosional unconformities in channelized sectors; however, their roles as active triggers require confirmation through stability modeling and direct current measurements.
- **Geohazard Implications:** The identified MTDs represent a potential geohazard source for critical submarine infrastructure (cables and pipelines); quantitative runout modeling and distance-to-infrastructure assessment are needed to define impact scenarios. The 1831 eruption illustrates the system's capacity for rapid geomorphological change, suggesting that the area may retain geomorphological activity, though recurrence and probability cannot be estimated without age control.

This study demonstrates that in complex volcanic-rifted margins, MTDs are not isolated events but part of a continuous morphostructural remodeling process. These findings highlight the Graham Bank as a geomorphological case study of repeated mass-wasting in a tectonically and volcanically active, current-influenced setting, where the interaction between extensional tectonics, episodic volcanism, and oceanographic forcing is consistent with a multi-hazard framework. Further investigation

incorporating sediment cores, age dating, geotechnical measurements, and numerical modeling is required to quantify triggering probabilities and to provide a robust basis for infrastructure risk assessment along active volcanic margins in the Mediterranean and elsewhere.

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Author contribution

Conceptualization, L.B. and D.S.; methodology, L.B., D.S. and A.S.; formal analysis, L.B., D.S. and A.S.; data curation, L.B., D.S.; writing original draft preparation, L.B., and D.S.; writing review and editing, L.B., D.S., A.S. and G.B. All authors have read and agreed to the published version of the manuscript. Luca Basilone and Daniele Spatola contributed equally to this work and share first authorship.

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Data availability

Bathymetric and SBP data can be consulted by contacting the corresponding author: D.S. daniele.spatola@uniroma1.it.

Declarations

Conflicts of interest The authors declare no conflicts of interest.

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References

- Agius MR, Magrini F, Diaferia G, Kästle ED, Cammarano F, Faccenna C, Funicello F, van der Meijde M (2022) Shear-velocity structure and dynamics beneath the Sicily channel and surrounding regions of the central Mediterranean inferred from seismic surface waves. *Geochem Geophys Geosy* 23:e2022GC010394
- Allen JRL (1986) Earthquake magnitude-frequency, epicentral distance, and soft-sediment deformation in sedimentary basins. *Sediment Geol* 46(1–2):67–75. [https://doi.org/10.1016/0037-0738\(86\)90006-0](https://doi.org/10.1016/0037-0738(86)90006-0)
- Alsop GJ, Marco S (2011) Soft-sediment deformation within seismogenic slumps of the Dead Sea Basin. *J Struct Geol* 33:433–457. <https://doi.org/10.1016/j.jsg.2011.02.003>
- Argnani A (1990) The strait of Sicily rift zone: foreland deformation related to the evolution of a back-arc basin. *J Geodyn* 12:311–331
- Argnani A (1993) Neogene tectonics of the Strait of Sicily, in: Max MD, Colantoni P (Eds.) Geological development of the Sicilian-Tunisian Platform. UNESCO Rep Marine Sci 58:55–60
- Basilone L, Lena G, Gasparo MM (2014) Synsedimentary tectonic, soft-sediment deformation and volcanism in the rifted Tethyan margin from the Upper Triassic-Middle Jurassic deep-water carbonates in Central Sicily. *Sed Geol* 308:63–79. <https://doi.org/10.1016/j.sedgeo.2014.05.002>
- Basilone L, Frixo A, Trincianti E, Valenti V (2016a) Permian-Cenozoic deep-water carbonate rocks of the Southern Tethyan Domain. The case of Central Sicily. *Ital J Geosci* 135:171–198. <https://doi.org/10.3301/IJG.2015.07>
- Basilone L, Sulli A, Gasparo Morticelli M (2016b) The relationships between soft-sediment deformation structures and synsedimentary extensional tectonics in upper Triassic deep-water carbonate succession (Southern Tethyan rifted continental margin - Central Sicily). *Sediment Geol*. <https://doi.org/10.1016/j.sedgeo.2016.01.010>
- Beccaluva L, Macciotta G, Di Girolamo P, Savelli C (1981) Upper Miocene submarine volcanism in the Strait of Sicily (Banco Senza Nome). *Bull Volcanol* 44:573–581
- Bonanno A, Placenti F, Basilone G, Mifsud R, Genovese S, Patti B, Di Bitetto M, Aronica S, Barra M, Giacalone G, Ferreri R, Fontana I, Buscaino G, Tranchida G, Quinci E, Mazzola S (2014) Variability of water mass properties in the Strait of Sicily in summer period of 1998–2013. *Ocean Sci* 10:759–770. <https://doi.org/10.5194/os-10-759-2014>
- Calanchi N, Colantoni P, Rossi PL, Saitta M, Serri G (1989) The Strait of Sicily continental rift systems: physiography and petrochemistry of the submarine volcanic centres. *Mar Geol* 87:55–83. [https://doi.org/10.1016/0025-3227\(89\)90145-X](https://doi.org/10.1016/0025-3227(89)90145-X)
- Calò M, Parisi L (2014) Evidences of a lithospheric fault zone in the Sicily Channel (Southern Italy) from instrumental seismicity data. *Geophys J Int* 199:219–225. <https://doi.org/10.1093/gji/ggu249>
- Canals M, Lastras G, Urgeles R, Casamor JL, Mienert J, Cattaneo A, De Batist M, Haffidason H, Imbo Y, Laberg JS (2004) Slope failure dynamics and impacts from seafloor and shallow sub-seafloor geophysical data: case studies from the COSTA project. *Mar Geol* 213(1–4):9–72
- Caradonna MC, Del Ben A, Pini GA, Geletti R, Frisicchio V (2025) Recent mass transport deposits in the Gulf of Cagliari. *Mar Geol* 483:107515
- Carapezza M, Ferla P, Nuccio PM, Valenza M (1979) Caratteri petrologici e geochimici delle vulcaniti dell'Isola "Ferdinandea": Rendiconti della Società Italiana di Mineralogia e Petrologia 35:377–388
- Casalbore D, Romagnoli C, Bosman A, Chiocci FL (2011) Potential tsunamigenic landslides at Stromboli Volcano (Italy): insight from marine DEM analysis. *Geomorphology* 126:42–50. <https://doi.org/10.1016/j.geomorph.2010.10.026>
- Casalbore D, Romagnoli C, Bosman A, Chiocci FL (2014) Large-scale seafloor waveforms on the flanks of insular volcanoes (Aeolian Archipelago, Italy), with inferences about their origin. *Mar Geol* 355:318–329. <https://doi.org/10.1016/j.margeo.2014.06.007>
- Casalbore D, Falese F, Martorelli E, Romagnoli C, Chiocci FL (2016) Submarine depositional terraces in the Tyrrhenian Sea as a proxy for paleo-sea level reconstruction: problems and perspective. *Quaternary Int* 1–11. <https://doi.org/10.1016/j.quaint.2016.07.051>
- Catalano R, Infuso S, Milia A, Sulli A (1993) The submerged Sicilian-Maghrebian chain along the Sardinia Channel-Sicily straits belt, in Max M.D. & Colantoni P. (Eds.). Geological development of the Sicilian-Tunisian Platform. Proceedings of international Scientific Meeting held at the University of Urbino, Italy, 4–6 November, 1992. Unesco Rep Marine Sci 58:43–48
- Catalano R, Di Stefano P, Sulli A, Vitale FP (1996) Paleogeography and structure of the Central Mediterranean: Sicily and its offshore area. *Tectonophysics* 260:291–323
- Catalano R, Franchino A, Merlini S, Sulli A (2000) A crustal section from the Eastern Algerian basin to the Ionian Ocean (Central Mediterranean). *Mem Soc Geol Ital* 55:71–85
- Cavallaro D, Coltelli M (2019) The Graham volcanic field offshore southwestern Sicily (Italy) revealed by high-resolution seafloor mapping and ROV images. *Front Earth Sci* 7:311
- Chiarabba C, Jovane L, Di Stefano R (2005) A new look to the Italian seismicity: seismotectonic inference. *Tectonophysics* 395:251–268
- Chiocci FL, De Alteriis G (2006) The Ischia debris avalanche: first clear submarine evidence in the Mediterranean of a volcanic island pre-historical collapse. *Terra Nova* 18:202–209. <https://doi.org/10.1111/j.1365-3121.2006.00680.x>
- Civile D, Lodolo E, Tortorici L, Lanzafame G, Brancolini G (2008) Relationships between magmatism and tectonics in a continental rift: the Pantelleria Island region (Sicily Channel, Italy). *Mar Geol* 251:32–46
- Clare MA, Le Bas T, Price DM, Hunt JE, Sear D, Cartigny MJ, ... Cronin S (2018) Complex and cascading triggering of submarine landslides and turbidity currents at volcanic islands revealed from integration of high-resolution onshore and offshore surveys. *Front Earth Sci* 6:223
- Colantoni P (1975) Note di Geologia Marina sul Canale di Sicilia. *Giornale di Geologia* (2) 40(1):181–207
- Coltelli M, Cavallaro D, D'Anna G, D'Alessandro A, Grassa F, Mangano G, Patanè D, Gresta S (2016) Exploring the submarine Graham Bank in the Sicily Channel. *Annal Geophys* 59(2):S0208. <https://doi.org/10.4401/ag-6929>
- Corti G, Cuffaro M, Doglioni C, Innocenti F, Manetti P (2006) Coexisting geodynamic processes in the Sicily Channel. *Geol Soc Am Spec Pap* 409:83–96
- Festa A, Dilek Y, Gawlick H-J, Missoni S (2014) Mass-transport deposits, olistostromes and soft-sediment deformation in modern and ancient continental margins, and associated natural hazards. *Mar Geol* 356:1–4
- Finetti I, Lentini F, Carbone S, Del Ben A, Di Stefano A, Forlin E, Guarnieri P, Pipan M, Prizzon A (2005) Geological outline of Sicily and Lithospheric Tectono-Dynamics of its Tyrrhenian Margin from new CROP Seismic Data, in: Finetti I.R. (Ed.), CROP PROJECT: Deep Seismic Exploration of the Central
- Ford J (2021) Geophysical characterisation of the internal structure of mass-transport deposits: challenges in integrating seismic and core data. *Mar Geol* 438:106512
- Gaberšek S, Sorgente R, Natale S, Ribotti A, Olita A, Astraldi M, Borghini M (2007) The Sicily Channel Regional Model forecasting system: initial boundary conditions sensitivity and case study evaluation. *Ocean Sci* 3(1):31–41
- Galea P (2007) Seismic history of the Maltese islands and considerations on seismic risk. *Ann Geophys* 50:725–740
- Gamberi F, Rovere M, Marani M (2011) Mass-transport complex evolution in a tectonically active margin (Gioia Basin, Southeastern Tyrrhenian Sea). *Mar Geol* 279(1–4):98–110
- Gamberi F, Rovere M, Marani MP, Dykstra M (2015) Modern submarine canyon feeder-system and deep-sea fan growth in a tectonically active margin (northern Sicily). *Geosphere* 11(2):307–319
- Gamboa D, Alves T, Cartwright J, Terrinha P (2010) MTD distribution on a 'passive' continental margin: The Espírito Santo Basin (SE Brazil) during the Palaeogene. *Mar Pet Geol* 27:1311–1324. <https://doi.org/10.1016/j.marpetgeo.2010.05.008>
- Gardiner W, Grasso M, Sedgely D (1993) Plio-Pleistocene stratigraphy and recent movements of the Malta platform. In: Max, M.D., Colantoni, P. (Eds.), UNESCO Technical Reports in Marine Science, Urbino, pp. 111–116
- Granath JW, Casero P (2004) Tectonic setting of the petroleum systems of Sicily, in Deformation, Fluid Flow and Reservoir Appraisal in

- Foreland Fold-and-Thrust Belts, in: Swennen, R., Roure, F. Granath, J. (Eds.) American Association Petroleum Geology Hedberg Series 1, 391–411
- Lafuente JG, García A, Mazzola S, Quintanilla L, Delgado J, Cuttita A, Patti B (2002) Hydrographic phenomena influencing early life stages of the Sicilian Channel anchovy. *Fish Oceanogr* 11:31–44. <https://doi.org/10.1046/j.1365-2419.2002.00186.x>
- Lee HJ, Locat J, Desgagnés P, Parsons JD, Mcadoo BG, Orange DL, Puig P, Wong FL, Dartnell P, Boulanger E (2007) Submarine mass movements on continental margins. *IAS Spec. Publ.* 1–62
- Leeder MR (1987) Sediment deformation structures and the palaeotectonic analysis of sedimentary basins, with a case-study from the Carboniferous of northern England. In: Jones, M.E., Preston, R.M.F. (Eds.), *Deformation of Sediments and Sedimentary Rocks*: Geological Society, London, Special Publication, 29, pp. 137–146.
- Lenz BL, Sawyer DE (2021) Mass transport deposits in reflection seismic data offshore Oregon, USA. *Basin Res* 34:81–98. <https://doi.org/10.1111/bre.12611>
- Lermusiaux PFJ, Robinson AR (2001) Features of dominant mesoscale variability, circulation patterns and dynamics in the Strait of Sicily. *Deep Sea Res Part I Oceanogr Res Pap* 48:1953–1997
- Lodolo E, Civile D, Zanolla C, Geletti R (2012) Magnetic signature of the Sicily Channel volcanism. *Mar Geophys Res* 33:33–44
- Lowe DR (1979) Subaqueous liquefied and fluidized sediment flows and their deposits. *Sedimentology* 23:285–308
- Masson DG, Watts AB, Gee MRJ, Urgeles R, Mitchell NC, Le Bas TP, Canals M (2002) Slope failures on the flanks of the western Canary Islands. *Earth Sci Rev* 57:1–35. [https://doi.org/10.1016/S0012-8252\(01\)00069-1](https://doi.org/10.1016/S0012-8252(01)00069-1)
- Masson DG, Le Bas TP, Grevenmeyer I, Weinrebe W (2008) Flank collapse and large-scale landsliding in the Cape Verde Islands, off West Africa. *Geochem Geophys Geosyst.* <https://doi.org/10.1029/2008GC001983>
- McAdoo BG, Pratson LF, Orange DL (2000) Submarine landslide geomorphology, U.S. Continental slope. *Mar Geol* 169:103–136
- Micallef A, Berndt C, Masson DG, Stow DAV (2007) A technique for the morphological characterization of submarine landscapes as exemplified by debris flows of the Storegga Slide. *J Geophys Res* 112:F02001
- Micallef A, Foglini F, Le Bas T, Angeletti L, Maselli V, Pasuto A, Taviani M (2013) The submerged paleolandscape of the Maltese Islands: morphology, evolution and relation to Quaternary environmental change. *Mar Geol* 335:129–147
- Millot C (1999) Circulation in the Western Mediterranean Sea. *J Mar Syst* 20:423–442
- Minisini D, Trincardi F, Asioli A, Canuz M, Foglini F (2007) Morphologic variability of exposed mass-transport deposits on the eastern slope of Gela Basin (Sicily channel). *Basin Res* 19:217–240
- Molina JM, Alfaro P, Moretti M, Soria JM (1998) Soft-sediment deformation structures induced by cyclic stress of storm waves in tempestites (Miocene, Guadalquivir Basin, Spain). *Terra Nova* 10:145–150
- Montenat C, Barrier P, Ott d'Estevou O, Hibschi C (2007) Seismites: an attempt at critical analysis and classification. *Sedim Geol* 196:5–30
- Moore JG, Clague DA, Holcomb RT, Lipman PW, Normark WR, Torresan ME (1989) Prodigious submarine landslides on the Hawaiian ridge. *J Geophys Res Solid Earth* 94(B12):17465–17484
- Moore JG, Normark WR, Holcomb RT (1994) Giant Hawaiian landslides. *Annu Rev Earth Planet Sci* 22:119–144. <https://doi.org/10.1146/annurev.ev.22.050194.001003>
- Moretti M, Van Loon AJT (2014) Restrictions to the application of “diagnostic” criteria for recognizing ancient seismites. *Journal of Palaeogeography* 3:162–173. <https://doi.org/10.3724/SP.J.1261.2014.00050>
- Moretti M, Soria JM, Alfaro P, Walsh N (2001) Asymmetrical soft-sediment deformation structures triggered by rapid sedimentation in turbiditic deposits. *Facies* 44:283–294
- Mosccardelli L, Wood L (2008) New classification system for mass transport complexes in offshore Trinidad. *Basin Res* 20:73–98. <https://doi.org/10.1111/j.1365-2117.2007.00340.x>
- Mulder T, Alexander J (2001) The physical character of subaqueous sedimentary density flows and their deposits. *Sedimentology* 48:269–299
- Nardin TR, Hein FJ, Gorsline DS, Edwards BD (1979) A review of mass movement processes, sediment, and acoustic characteristics and contrasts in slope and base-of-slope systems versus canyon-fan-basin floor systems. *Spec Publ SEPM* 27:61–73
- Obermeier SF (1996) Using liquefaction-induced features for paleoseismic analysis. In: McCalpin, J.P. (Ed.), *Paleoseismology*. *Int Geophys Ser* 62:331–396
- Odonne F, Callot P, Debroas E-J, Sempere T, Hoareau G, Maillard A (2010) Soft-sediment deformation from submarine sliding: favourable conditions and triggering mechanisms in examples from the Eocene Sobrarbe delta (Ainsa, Spanish Pyrenees) and the mid-Cretaceous Ayabacas Formation (Andes of Peru). *Sediment Geol* 235:249–263
- Ogata K, Mountjoy JJ, Pini GA, Festa A, Tinterri R (2014) Shear zone liquefaction in mass transport deposit emplacement: a multi-scale integration of seismic reflection and outcrop data. *Mar Geol* 356:50–64
- Ollier G, Cochonat P, Lenat JF, Labazuy P (1998) Deep-sea volcanoclastic sedimentary systems: An example from La Fournaise volcano, Réunion Island, Indian Ocean. *Sedimentology* 45:293–330. <https://doi.org/10.1046/j.1365-3091.1998.0152e.x>
- Owen G (1987) Deformation processes in unconsolidated sands. In: *Deformation of Sediments and Sedimentary Rocks* (M.E. Jones and R.M.F. Preston, eds). *Geol Soc Spec Pub* 29:11–24
- Owen G, Moretti M, Alfaro P (2011) Recognising triggers for soft-sediment deformation: current understanding and future directions. *Sediment Geol* 235:133–140
- Peccerillo A (2005) Plio-Quaternary volcanism in Italy. *Petrology, geochemistry, geodynamics*. Springer, Heidelberg
- Posamentier HW, Kolla V (2003) Seismic geomorphology and stratigraphy of depositional elements in deep-water settings. *J Sediment Res* 73:367–388
- Posamentier H, Martinsen OJ (2011) The character and genesis of submarine mass-transport deposits: insights from outcrop and 3D seismic data. In: Shipp, C., Weimer, P., Posamentier, H. (Eds.), *Mass-transport deposits in deepwater settings*. *SEPM Special Publication* 96:7–38
- Posamentier HW, Davies RJ et al (2015) Morphometry of mass-transport deposits as a predictive tool. *Mar Pet Geol* 64:256–270
- Romagnoli C, Kokelaar P, Casalbore D, Chiochi FL (2009) Lateral collapses and active sedimentary processes on the northwestern flank of Stromboli volcano, Italy. *Mar Geol* 265:101–119. <https://doi.org/10.1016/j.margeo.2009.06.013>
- Rotolo SG, Castorina F, Cellura D, Pompilio M (2006) Petrology and geochemistry of submarine volcanism in the Sicily Channel Rift. *J Geol* 114:355–365
- Seilacher A (1969) Fault-graded beds interpreted as seismites. *Sedimentology* 13:155–159
- Shipp RC, Weimer P, Posamentier HW (2011) Mass-transport deposits in deepwater settings: an introduction.
- Sobiesiak MS, Alsop GI, Kneller B, Milana JP (2017) Sub-seismic scale folding and thrusting within an exposed mass transport deposit: a case study from NW Argentina. *J Struct Geol* 96:176–191
- Sorgente R, Olita A, Oddo P, Fazioli L, Ribotti A (2011) Numerical simulation and decomposition of kinetic energy in the Central Mediterranean: insight on mesoscale circulation and energy conversion. *Ocean Sci* 7:503–519. <https://doi.org/10.5194/os-7-503-2011>
- Spatola D, Micallef A, Sulli A, Basilone L, Ferreri R, Basilone G, Bonanno A, Pulizzi M, Mangano S (2018) The Graham Bank (Sicily Channel, central Mediterranean Sea): seafloor signatures of volcanic and tectonic controls. *Geomorphology* 318:375–389
- Spatola D, Sulli A, Basilone L, Casalbore D, Napoli S, Basilone G, Chiochi FL (2023) Morphology of the submerged Ferdinandea Island, the ‘Neverland’ of the Sicily Channel (central Mediterranean Sea). *J Maps* 19(1):2243305
- Sulli A (2000) Structural framework and crustal characteristics of the Sardinia Channel Alpine transect in the central Mediterranean. *Tectonophysics* 324:321–336
- Sun Q, Alves T (2020) Petrophysics of fine-grained mass-transport deposits: a critical review. *J Asian Earth Sci* 192:104291

- Sun Q, Alves T, Xie X, He J, Li W, Ni X (2017) Free gas accumulations in basal shear zones of mass-transport deposits (Pearl River Mouth Basin, South China Sea): an important geohazard on continental slope basins. *Mar Pet Geol* 81:17–32
- Talling PJ, Baker ML, Pope EL, Ruffell SC, Jacinto RS, Heijnen MS, ... Hilton RJ (2022) Longest sediment flows yet measured show how major rivers connect efficiently to deep sea. *Nature Commun* 13(1):4193
- Torelli L, Zitellini N, Argnani A, Brancolini G, De Cillia C, Peis D, Tricart P (1991) Sezione geologica crostale dall'avampaese pelagiano al bacino di retroarco tirrenico (Mediterraneo centrale). *Memorie Società Geologica Italiana* 47:385–399
- Urgeles R, Canals M, Baraza J, Alonso B, Masson DG (1997) The most recent megaslides on the Canary islands: the El Golfo Debris avalanche and the Canary Debris flow. *J Geophys Res* 102:305–323. <https://doi.org/10.1029/97JB00649>
- Urlaub M, Geersen J, Petersen F, Gross F, Bonforte A, Krastel S, Kopp H (2022) The submarine boundaries of Mount Etna's unstable south-eastern flank. *Front Earth Sci* 10:810790
- Varnes DJ (1978) Slope movement types and processes. In: Schuster RL, Krizek RJ (eds) *Landslides, analysis and control*, special report 176. Transportation research board, National Academy of Sciences, Washington, DC., pp 11–33

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Luca Basilone

Oceanographic Institute, São Paulo University,
Praça Do Oceanográfico, São Paulo, Brazil

Daniele Spatola (✉)

Department of Earth Sciences, Sapienza University, Rome, Italy
Email: daniele.spatola@uniroma1.it

Attilio Sulli

Department of Earth and Marine Sciences, University of Palermo,
Palermo, Italy

Gualtiero Basilone

IAS-CNR, UOS Di Capo Granitola, Campobello Di Mazara del Vallo,
Italy