

Research Article

Recent mass transport deposits in the Gulf of Cagliari

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ABSTRACT

Sedimentary deposits due to slope failures and submarine landslides are common on continental margins. The availability of five new high resolution 2D multi-channel seismic profiles, integrated by Multibeam data, provides unprecedented insight into the shallow submarine geomorphology of the Gulf of Cagliari. The study area, located in the southern Sardinia offshore, exhibits several Mass Transport Deposits (MTDs) during the Upper Quaternary. They move from the continental slope and the north-east flank of the Banghittu High.

We identified the recent 26 km long MTD-CG1, of which we interpreted the translational domain, characterized by weak deformation, and the toe domain, with a predominantly compressional and erosional regime. This erosion is produced locally by the basal shear zone (bsz) which represents the detachment surface of the slide. Both MTD domains are crossed by vertical conduits and fluid migration that produce buried pockmarks. In the translational domain an underlying carbonate buildup offered greater strength to sliding, resulting in an undisturbed sector. The MTD-CG1 is composed of Middle-Upper Pleistocene sediments which, during the Holocene, assumed an initial direction towards SE, to become towards the SW in the Carbonara Valley. After the gliding, the MTD was cut by the last incision phase of the canyon system which markedly characterizes the physiography of the gulf.

The MTD-CG1 is primarily predisposed to instability by its steep slope gradient and fluid presence, while possible triggers include eustatic sea level changes and seismic activity.

1. Introduction

The Mediterranean Sea is highly vulnerable to offshore geological hazards, including seismic activity, sedimentary slope instabilities, and fluid flow processes (Urgeles and Camerlenghi, 2013; Ercilla et al., 2021). Submarine landslides represent one of the most significant geohazards in the region, resulting from a combination of preconditioning factors and triggering mechanisms, which vary depending on the specific geological and environmental contexts.

One of the most frequent triggers is a sudden increase in pore pressure, which weakens sediment layers and reduces their shear strength (Bromhead and Cooper, 1992; Sultan et al., 2004). While this typically leads to small to localized failures, it can also induce larger regional events when combined with other factors. Seismic disturbances, rapid sediment deposition, and sea level fluctuations also play significant roles, depending on local conditions (Sultan et al., 2004; Canals et al., 2004). In tectonically active regions, for instance, earthquakes can

weaken sediments, increasing the likelihood of slope failure (Locat et al., 2002; Masson et al., 2006). Sea level fluctuations, particularly during glacial-interglacial cycles, modify hydrostatic pressure and sedimentation rates, contributing to long-term slope instability (Urgeles and Camerlenghi, 2013; Brooks and Adams, 2020). These processes interact with preconditioning factors, such as steep gradients and weak sediment layers, determining the susceptibility to landslides. While steep slopes increase gravitational stress, failure occurs only when other factors, such as overpressured sediments or tectonic weaknesses, are present (Hampton et al., 1996; Locat et al., 2002). The combined effect of these factors contributes to slope instability on both small and large scales settings.

Submarine landslides are widely recognized as a key components of continental margin evolution, recorded both in modern (Moore, 1978; Hampton et al., 1996; Masson et al., 2006; Shanmugam, 2010) and in ancient sedimentary sequences (Urgeles and Camerlenghi, 2013; Ogata et al., 2019). Their identification and classification are based on

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advanced geophysical techniques, such as seismic reflection and multi-beam bathymetry, enabling a detailed reconstruction of past slope failure events (Weimer, 1989).

In the southern Sardinian margin, particularly in the Gulf of Cagliari, during the Plio-Quaternary, the continental slope was affected by submarine canyon headwall retreat and unchanneled turbiditic flows, with sediment redistribution observed on the lower slope (Paliaga, 2015). These processes likely operate on both localized and regional scales, contributing to slope instability. In the Sant'Elia-Foxy Canyon system, surface sediments are affected by flow waves, indicating ongoing gravitational instability (Deiana et al., 2017).

Although the Gulf of Cagliari is not exposed to significant geological hazards, such as major earthquakes or tsunamis, gravitational instability remains a key process shaping the continental slope. Understanding these processes is crucial for reconstructing the long-term evolution of the margin and assessing potential implications for sedimentary dynamics and slope stability.

This study aims to investigate the geomorphological and geological processes driving gravitational instabilities within the Plio-Quaternary sequence of the Sardinian margin, focusing on the youngest Mass Transport Deposit (MTD) located on the continental slope of the Gulf of Cagliari. By analysing the internal architecture and external morphology of the shallowest MTD in the region, called MTD-CG1, the study explores how pre-existing morphological features have influenced its evolution. A key research question is the relationship between the development of

MTD-CG1 and the incision of the submarine canyon system in the Gulf of Cagliari.

Specifically, this research examines the spatial distribution, relative age, and geological impact of MTD-CG1, investigating its interaction with the Sarroch, Sant'Elia-Foxy, and Carbonara canyon systems that cross the gulf. A fundamental question arises: does MTD-CG1 predate or postdate the formation of these canyons? Answering this requires determining whether the canyons incised an already deposited MTD-CG1 or, conversely, whether the mass transport deposit moved within pre-existing canyons.

Understanding the influence of the canyon system on the deposition and movement of the MTD provides critical insights into the interplay between sedimentary transport, gravitational failure, and seafloor morphology. This research contributes to a deeper understanding of submarine slope instability and mass transport processes, offering valuable perspectives on the recent geological evolution of the region.

2. Geomorphological setting

Sardinia is a geologically complex island with very low seismicity, as only a few low-energy seismic events have been historically recorded, the most notable occurring in 1616 and 1771 (Meletti et al., 2020). The southern continental margin of the island is strongly influenced by tectonic structures, particularly by a major lineament running from N-NW to S-SE, aligned with the Capo S. Elia promontory (Fig. 1). This

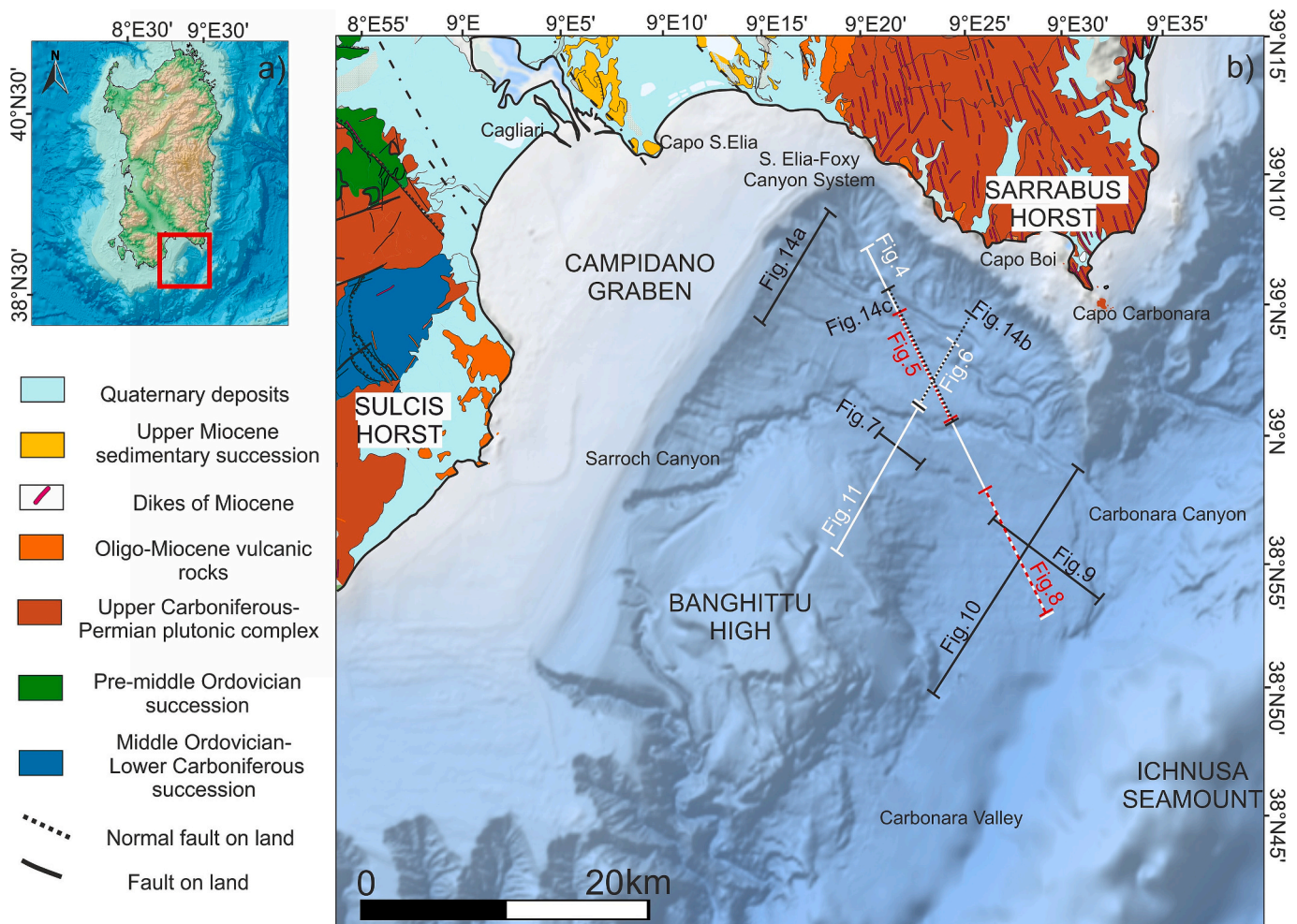


Fig. 1. a) Location of the study area on the southern Sardinia offshore; b) Zoom of the study area: bathymetry from “EMODnet bathymetry”, Land geology from Carmignani et al., 2016. The white, red and black lines indicate the location of the figures. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

structure, associated with the Plio-Pleistocene extensional dynamics, delineates the boundary between the Cagliari and Sarrabus shelves and has contributed significantly to the geological evolution of the region (Ulzega et al., 1986).

The Gulf of Cagliari, located on the southern continental margin of Sardinia, shows contrasting physiographic and tectonic domains. Structural highs, such as the Banghittu High and Ichnusa Seamount, further shape the submarine topography of the gulf, segmenting its sedimentary systems (Fanucci et al., 1976; Lecca et al., 1998; Meleddu et al., 2016). These features reflect the influence of extensional tectonics during the Plio-Pleistocene, which led to the formation of intrashelf and intraslope basins that serve as key sites of sediment accumulation (Lecca et al., 1988).

During the Plio-Quaternary, the depositional systems of the gulf are organized into three main domains: i) the carbonate platform environment, mainly represented by the Banghittu High, consists of residual submarine structures composed predominantly of carbonate-bioclastic deposits (Lecca et al., 1998); ii) slope environments, flanking structural highs such as the Ichnusa Seamount, characterized by hemipelagic deposits and fine-grained turbidites that evidence gravity-driven sediment transport (sensu Bouma et al., 1985); iii) the deep-marine basin in the depocenter, where high-energy turbidites and low-energy hemipelagic deposits alternate (Lecca et al., 1998).

The Holocene evolution of the Cagliari shelf reveals a typical three-part zonation: siliciclastic coastal sands dominate the inner shelf, bioclastic sands produced by *Posidonia oceanica* characterize the mid-shelf, and sandy muds are prevalent on the outer shelf (Lecca et al., 1998). This zonation reflects active sediment transport linking the shelf to the Sardinian Valley through canyons and slope basins (Tamburrino et al., 2019). At the distal margin of the gulf, a progradational wedge on the upper slope, composed of silts and clays, represents reduced tractive energy and Holocene sedimentation processes related to the last glacial regression (Orrù et al., 2011; Sechi et al., 2023). Holocene and Late Pleistocene deposits overlay earlier Pleistocene regression cycles and Neogene sediments, incorporating evidence of sea-level fluctuations such as beach rocks and erosional features (De Muro and Orrù, 1998; Deiana et al., 2021).

The western Cagliari platform, which extends about 40 km in width and has a gradient of approximately 3–4° in the inner platform (Meleddu et al., 2016), transitions into a slope that descends to depths of about 1260 m, where it is incised by several submarine canyons. In contrast, the eastern Sarrabus platform is narrower, only a few kilometers wide, and descends rapidly to depths of about 1000 m (Fig. 2). These canyons, shaped by retrogressive erosion and gravitational instabilities, play a significant role in the region's sedimentary and morphological dynamics (Paliaga, 2015). Among them, the Sarroch Canyon and the S. Elia Foxy Canyon System cut through the shelf break and merge in the lower slope to form the Carbonara Canyon, near the Sarrabus slope, influencing the overall geomorphology of the area (Ulzega et al., 1986) (Fig. 2).

The outer Cagliari shelf and upper continental slope show retrogressive erosion processes which impact the heads of the canyons. Intrachannel landslides have been documented in these areas (Ulzega et al., 1986; Meleddu et al., 2016), and gravity currents occasionally lead to the deposition of large blocks. Pockmark fields, commonly linked to fluid emissions from creep zones created by landslides, are often observed in similar geological settings (Riboulot et al., 2013; Deville et al., 2020; Riera et al., 2022). In addition, crescent-shaped bedforms, known as cyclic steps, have been identified within the head scarp of the Foxy Canyon (Deiana et al., 2017). These features, created by recurrent erosion and deposition driven by gravity, have wavelengths ranging from tens to a hundred meters and heights of several meters (Meleddu et al., 2016). In terms of sediment accumulation, high-energy events such as large-scale turbidity currents or slope subsidence are ruled out in the region. Instead, sedimentation is primarily attributed to low-intensity turbidity currents or hyperpycnal flows, which are considered the main contributors to sediment transport and deposition in the

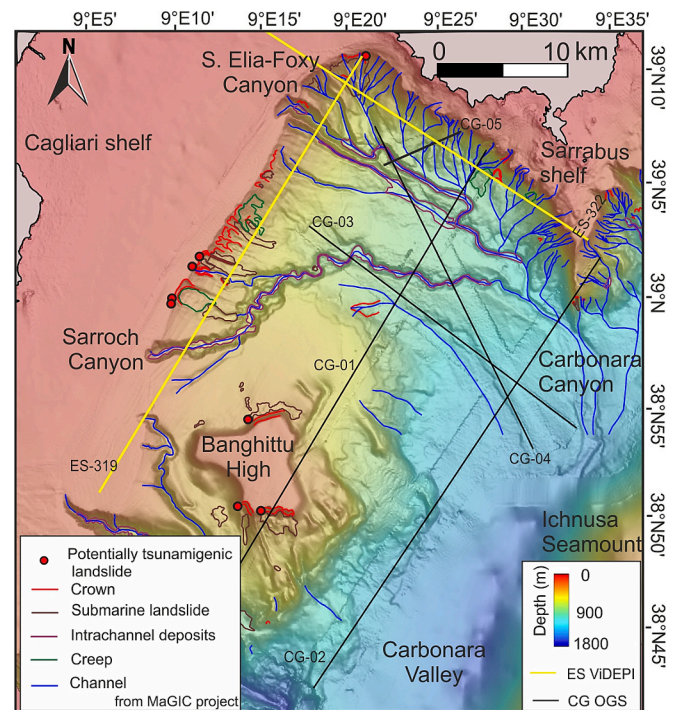


Fig. 2. Study area in the Gulf of Cagliari.

basin (Paliaga, 2015).

3. Material and methods

The main data used in this work were collected in the Gulf of Cagliari as part of the Western Sardinia project in a collaboration between the Istituto Nazionale di Oceanografia e di Geofisica Sperimentale (OGS) and the Universities of Trieste and Cagliari. More specifically, five multichannel seismic reflection profiles (CG lines) and a multibeam echosounder bathymetry (MB) were acquired by the vessel N/R OGS Explora in September 2010 (Zgur et al., 2010). In this work, the CG profiles were integrated with the lower-resolution ES profiles from the ViDEPI project (2009) to provisionally cover the upper slope. The seismic profiles and bathymetric data were imported into a project using Petrel™ seismic interpretation software (Schlumberger Ltd).

3.1. Multichannel seismic reflection profiles

The acquisition of the CG profiles was optimised to investigate the Quaternary sedimentary package. The seismic streamer was a 1500-m-long cable, with 120-channels and a geophone spacing of 12.5 m. The seismic source consisted of two GI-GUNs with a total volume of 710 cubic inches (11.2 l) with an 8-s recording, for an average shot spacing of 25 m and a 30-fold coverage for each common midpoint. Based on the recording parameters used, the maximum available theoretical frequency cannot exceed 150 Hz. Based on the criterion that defines the resolution of a seismic source as $\lambda/4$ (where λ is the wavelength), it can be deduced that at an average velocity of 2000 m/s, the minimum thickness that can be recorded with this source is about 3 to 4 m. The raw data was processed with the industrial software package Echos™. The gain (compensation for transmission losses, absorption and spherical divergence) was calculated and applied by inverting the amplitude decay curve. The seismic data was then processed to obtain time-migrated sections with the stacking velocity field.

3.2. Bathymetric data

The bathymetric data were acquired using the multibeam echosounder Reson Seabat 8111 (100 KHz) hull mounted on R/V OGS Explora (Zgur et al., 2010), which defines a resolution of 50 m along the seismic profiles. They were integrated by the open-access European Marine Observation and Data Network (EMODnet), characterized by 115 m resolution multibeam bathymetry (www.emodnet-bathymetry.eu, 2020) and by the 100 m resolution of the MaGIC (Marine Geohazards along the Italian Coasts) data (<https://github.com/pcm-dpc/MaGIC>). MaGIC is a project supported by the Italian Civil Protection Department that aims to investigate geohazards along the Italian continental margins (Chiocci and Ridente, 2011).

Data and positions of morpho-bathymetric features of the Gulf of Cagliari, from the MaGIC project, were incorporated into the study (Fig. 2). This allowed the mapping of potentially tsunamigenic landslides, landslide crowns and creep zones. The identified seismic features were then correlated with the mapped sedimentary processes, facilitating a better understanding of the relationships between sedimentary orientations and their source deposits.

3.3. MTD characterization

The Quaternary strata were analyzed using seismic stratigraphic interpretation, with a focus on seismic facies and on geometry of sedimentary features, following the methodologies developed by Mitchum et al. (1977), Mulder and Cochonat (1996), Frey Martinez et al. (2005), Moscardelli et al. (2006), and Moscardelli and Wood (2008). The initial 2D analysis was further refined through the integration of geomorphological elements. Seismic geomorphology techniques (Posamentier and Morris, 2000; Posamentier, 2004; Posamentier et al., 2007) were applied to identify key geological patterns at the map scale, which were subsequently examined in greater detail using the available seismic lines.

The characterization of the MTDs was based on a detailed seismic facies analysis, which revealed lithofacies variations within the Upper Quaternary sedimentary unit. These deposits, often associated with gravity-driven downslope processes, were identified by their characteristic opaque, chaotic, and discontinuous seismic facies. MTDs, commonly referred to as submarine landslides, occur on submarine slopes and typically involve the downslope movement of materials, sometimes over considerable distances and volumes, into low-gradient areas (Hampton et al., 1996; Owen et al., 2007). Due to their high mobility, MTDs exhibit significant variability in seismic signatures (Mohrig et al., 1998; Gee et al., 1999).

To characterize the MTDs, we first analyzed the geomorphological features and internal architecture, following the framework established by Moscardelli and Wood (2008). Seismic reflection data were interpreted to identify variations in the continuity, amplitude, and configuration of the internal reflections. These parameters allowed us the recognition of gravitational deposits and their stratigraphic relationships within the depositional succession. MTDs were classified as chaotic or transparent, based on their internal seismic reflection configuration, which varies according to the nature of the starting materials and the distance over which the material has traveled (Masson et al., 2006; Rovere et al., 2014).

The basal shear zone (bsz) or basal continuous surface, a key structural feature in MTDs, was identified and analyzed. This surface represents a deformation zone between the mass transport material and the underlying substrate (Frey Martinez et al., 2005; Alves and Lourenço, 2010; Richardson et al., 2011). The bsz is crucial for understanding the dynamics of material flow and the associated kinematic behavior (Alves, 2010; Fossen and Cavalcante, 2017; Cardona et al., 2020; Sobiesiak et al., 2018).

The study of the bsz focused on evaluating the factors influencing the transformation of mass flow styles, including material viscosity, water

absorption, frictional stress, flow acceleration, and interactions with underlying lithologies (Mohrig et al., 1998, 1999; Elverhøi et al., 2000; Lucente and Pini, 2003; Posamentier and Kolla, 2003; Ilstad et al., 2004; De Blasio et al., 2005; Moscardelli et al., 2006; Posamentier and Walker, 2006; Moscardelli and Wood, 2008; Alves, 2010; De Blasio, 2011; Dey et al., 2016; Otsubo et al., 2018). We applied the model of Lewis (1971) to examine the distribution of deformation along the bsz, categorizing it into three domains: head, translational and toe domains.

Although the available seismic lines include both CG and ES profiles, only the CG profiles cross the translational and toe domains. These profiles do not cover the headwall and the upper slope regions. In contrast, the ES profiles, available on the VIDEPI website, have lower resolution, limiting their ability to identify the MTD analyzed in this study. Only the ES-319 profile has been useful for this study. Therefore, our analysis concentrated on the translational and toe domains, where the CG profiles provided sufficient detail to observe the key features and structures.

The toe domain was characterized by compressive structures and thrust systems, with movements occurring perpendicular to the strike of thrust faults (Prior et al., 1984; Frey Martinez et al., 2005; Bull et al., 2009). The overall morphology of the toe domain often shows a convex descending profile, indicating the downslope termination of the MTD.

Given the absence of calibrations and sediment core data in the continental slope, the age of the MTD-CG1 was estimated using a proportional depth-age method, which was the only possible approach for dating the deposition. The depths of the MTD-CG1 base and top below the sea bed were compared with the established ages of 0 million years (Ma) for the sea bed and 2.58 Ma for the Quaternary base reflector (International Commission of Stratigraphy, 2023). This method provided an approximation of the MTD-CG1 deposition age, assuming a constant sedimentation rate throughout the Quaternary. Although sediment decompaction was considered, its influence was found to be negligible. In the absence of sediment cores and calibration data, the applied method offers valuable insights into the temporal framework of the MTD-CG1 deposition.

3.4. Seismic attributes

To characterize seismic facies and assess their lateral variations, a selection of seismic attributes was applied to reflection seismic data. These attributes facilitated the detection of fluid presence and the identification of structural features within mass transport deposits (MTDs). Given the variety of seismic attributes that can be derived from raw reflection data, it is essential to choose those that best highlight relevant geological features. As noted by Coléou et al. (2003), “there is no rule for selecting which attribute will best illustrate changes in rock properties.” Consequently, we employed several attributes, each selected for its ability to reveal key sedimentary characteristics.

- 1) Regular reflection amplitude: this basic attribute is derived from the raw seismic data and serves as a foundation for others. Strong amplitude variations indicate significant impedance contrasts, reflecting differences in velocity and density within the subsurface. These contrasts are particularly sensitive to fluid variations, as different fluids influence seismic wave propagation.
- 2) Envelope (also known as instantaneous amplitude): representing the amplitude of the oscillatory function, this attribute highlights structural discontinuities, lithological boundaries, faults and depositional changes, providing insights into the lateral variation of sedimentary facies.
- 3) Local structural dip: serving as an edge-detection method, this attribute identifies rapid changes in local dip, such as at channel edges or faults. Using two-way travel time (TWT) profiles, it offers qualitative insights into structural features, aiding in the identification of key geological features influencing sedimentary processes.

These attributes allow a more comprehensive analysis of lateral variations in mass flow, improving the understanding of the subsurface geology.

4. Results

Gravitational seabed instabilities within the Upper Quaternary sedimentary sequence of the slope in the Gulf of Cagliari have been analyzed and mapped, with particular attention to the MTD-CG1 and the Banghittu Landslide (BLs). These features were identified, described, and mapped to reveal their spatial distribution and associated geological characteristics (Fig. 3b, 4). The MTD-CG1 extends approximately 26 km in a NW-SE direction (Fig. 3). The translational domain has an average length of 16 km and an average width of 9 km, with bathymetric slopes ranging between 1.5° and 3° (Fig. 3a). The toe domain borders to the SE with the Carbonara Canyon and to the north of the Ichnusa High, extends further towards SW, for about 8 km as seen from the bathymetric step. The toe domain, instead, is characterized by gentler bathymetric slopes, ranging between 0.5° and 2° (Fig. 3a). The rise of fluids within the MTD is observed in both domains (Fig. 3b). In contrast, the Banghittu Landslide (BLs) sliding phenomenon is located on the NE slope of the Banghittu High (Fig. 3), where the bathymetric gradient varies between 5° and 9° (Fig. 3a).

4.1. The MTD-CG1

The MTD-CG1 is located at depths of 600 to 1000 m below the seabed and is bounded at its base by a slightly inclined seismic marker with negative polarity, corresponding to the bsz. This boundary separates the displaced mass from the underlying material. The thickness of MTD-CG1 varies across its domains and is covered by a thin sedimentary layer whose thickness sometimes approaches the limits of seismic resolution (Fig. 4).

The seismic facies of MTD-CG1 predominantly exhibit low-amplitude acoustic reflections, with distinct characters in each morpho-structural domain.

4.1.1. Translational domain

In the translational domain the MTD-CG1 is characterized by alternating undisturbed and deformed sectors. In the so-called undisturbed sector, parallel reflectors are observed, with a thickness averaging 38 ms TWT (Figs. 5, 6). It is located in the middle slope area, between the Sarroch and S. Elia-Foxy canyons below the MTD, and is marked by an opaque seismic facies and topped by inclined reflector (Figs. 5, 6). This structure, at a depth of about 100 ms TWT below the seabed, exhibits a mound-shaped reflection configuration, lateral seismic facies changes and draping effects of the overlying layers. This undisturbed sector consists of unaffected, undeformed sediments, while the MTD flowed around it without disrupting its internal structure.

Thrusts and back-thrusts are located at the flanks of the undisturbed sector, where attribute analysis shows the highest dip values (Fig. 5e). These structures converge on the bsz, with the floor detachment acting as a forethrust, marking the main kinematic features of the deposit.

The MTD-CG1 is characterized by numerous pockmarks indicating fluid migration, sometimes buried several tens of milliseconds TWT below the seabed. They are concentrated within the MTD (Figs. 5, 6, 7), particularly in the intra and lower slope regions, between the Sarroch and Banghittu highs. Fluids migrate through vertical or oblique conduits, intruding into cohesive portions of the mass and generating widespread pockmarks in the Upper Quaternary sedimentary unit (Figs. 5, 6, 7). Envelope attribute analysis (Figs. 5c, 7c) highlights a high contrast in acoustic impedance. The bsz appears as a discontinuous basal surface, affected by the presence of fluids (Figs. 5, 6).

The translational domain of MTD-CG1, located between the north-eastern flank of Banghittu to the west and the Sarroch canyon to the northeast, is marked by the presence of pockmarks and fluid migration within the deposit, as well as thrusts and back-thrusts (Fig. 7). The discontinuous thickness of the MTD-CG1 visible in Fig. 7, particularly evident towards the southeast, produces its decreasing to around 20 ms.

A chaotic facies deposit, designated as MTD-CG3, is identified below MTD-CG1 at approximately 1050 ms (Fig. 7b). This deposit is also affected by fluid presence, as indicated by the envelope attribute (Fig. 7c).

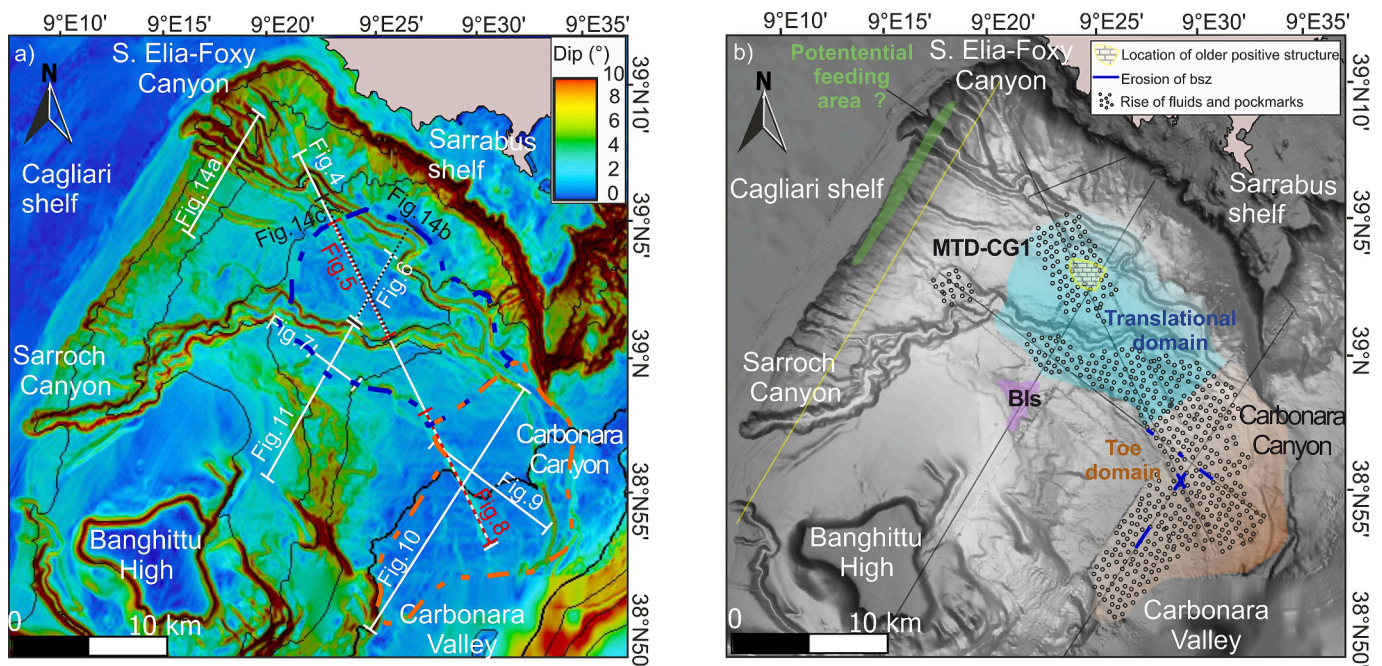


Fig. 3. a) Bathymetric slope map; b) Distribution of translational (blue area) and toe (brown area) domains of the MTD-CG1. A buried older positive structure (yellow small area) affects the movement of the MTD, which is also cut by several pockmarks (small circles). The sliding phenomenon called Banghittu Landslide (BLs, pink area) seems currently active on the NE-flank of the Banghittu High. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

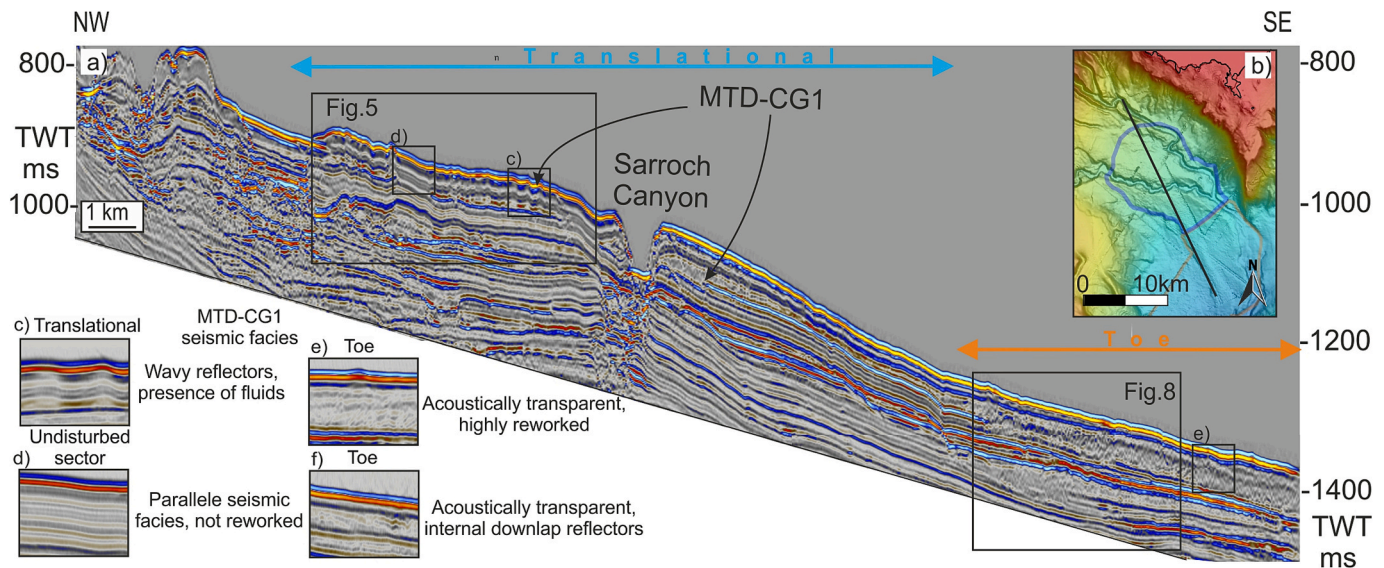


Fig. 4. a) Seismic profile crossing the MTD-CG1. The top of MTD is very close to the seafloor. The small boxes on the left represent the different seismic facies. b) Location map. MTD-CG1 seismic facies: c) translational; d) undisturbed sector; e-f) toe, f) from Fig. 9.

4.1.2. Toe domain

The toe domain of the MTD-CG1, located on the lower slope of the gulf, exhibits chaotic seismic facies, thrust systems, and a southward-inclined bsz (Figs. 8, 9, 10).

The thickness of the MTD-CG1 reaches a maximum value of approximately 50 ms TWT (Fig. 8), decreasing towards the south-east sector to around 26 ms TWT (Fig. 9). In this outer sector, some continuous internal reflectors with negative polarity display downlapping terminations, indicative of a prograding sedimentary body.

Thrust systems are generally rooted in the bsz, but also occur as isolated features (Figs. 8, 9). These structures exhibit both low and high-angle orientations, with the highest dip values identified in the structural attribute analysis (Fig. 8c).

The toe domain, extending from the southeastern sector near the Banghittu High to the Carbonara Canyon, exhibits erosive interactions of the bsz with the underlying substrate (Fig. 10d). A distinct bathymetric step (Fig. 10e) defines the southwestern limit of the MTD-CG1, resulting in localized thickening (approximately from 25 to 60 ms TWT) (Fig. 10b). At the foot of the Banghittu High, the MTD-CG1 terminates, with internal SW-verging thrust originating from local compression. To the northeast, the deposit is truncated by the Carbonara Canyon (Fig. 10a).

Fluid migration up through the sedimentary sequence is also observed, as emphasized by the envelope attribute (Fig. 10c). Even in this domain, fluid migration occurs through vertical or oblique conduits, facilitating the formation of pockmarks.

Beneath the toe domain of the MTD-CG1, an older buried MTD, referred to as MTD-CG4, is found within the sedimentary sequence. This unit is characterized by a transparent and chaotic seismic facies (Fig. 8).

4.2. Other recent mass movement systems

On the northeast flank of Banghittu High, the here called Banghittu Landslide (BLs) has been identified (Fig. 11). To the southwest, the headwall is characterized by small tilted blocks sliding towards the deeper sector. The upper layers exhibit a wavy sliding pattern, also affecting the seabed (Fig. 11). Towards the northeast, the BLs becomes discontinuous and thins as it progresses deeper, eventually reaching the toe domain, where material accumulates. A basal detachment surface defines the sliding interface.

Beneath the BLs, the older mass transport deposit MTD-CG2 is

observed. In its headwall domain, parallel and continuous seismic layers are interrupted by a fault rooted in the bsz (Fig. 11b), which induces the chaotic rearrangement of the sediments. On the steeper sections (Fig. 11b), the body slides down, contributing to the accumulation at the slope base. Seismic imaging shows a deformation of the seabed concordant with the top of the chaotic layers of the MTD.

It should also be noted the buried MTD recognized in the profile of Fig. 8 at a depth of about 1400 ms TWT. It reached a thickness of about 70 ms TWT, corresponding to 50–60 m. The MTD-CG1 has been intercepted by the profile on both sides of the Sarroch Canyon. Within the opaque wedge, an undeformed stratified block indicates less deformed sectors.

4.3. MTD-CG1 and recent canyons: A relative age assessment

The Sarroch Canyon originates near the northern Banghittu High, initially following an east-west orientation. As it progresses downslope, its course shifts to a NW-SE direction before merging with the S. Elia-Foxy Canyon, ultimately forming the Carbonara Canyon. Seismic profiles (Figs. 4, 11, 12, 14) clearly show that the MTD-CG1 has been incised by canyon formation, with remnants preserved along both canyon flanks, particularly within the translational domain. In the Sarroch Canyon, an earlier phase of incision (C2 in Fig. 12a) was subsequently infilled and overlain by sub-horizontal sediments, which include reworked deposits of the MTD-CG1. The incision phase C1 represents the most recent erosional event, distinctly postdating the MTD-CG1. This phase is also observed in the S. Elia-Foxy and Carbonara Canyons (Fig. 12b, c), confirming the relative age assessment.

The seismic section located near the Sarroch Canyon (red outline in Fig. 11a) shows continuous sediment deposition throughout the Quaternary, providing a suitable reference for estimating the age of the MTD-CG1. Interval velocities obtained from velocity analysis (Fig. 13a) were used to depth-convert the seismic profile (Fig. 13b), allowing the calculation of deposition ages. By applying a proportional depth-age method, we determined that the base of the MTD-CG1 is located at 53 m, while its top is at 13 m below the sea bed (Fig. 13b). These depths correspond to estimated ages of approximately 250 ky (yellow arrow in Fig. 13c) and 60 ky (blue arrow in Fig. 13c).

The MTD-CG1 consists of Middle Pleistocene sediments, which have been deformed by gravity sliding from the Holocene to the Present.

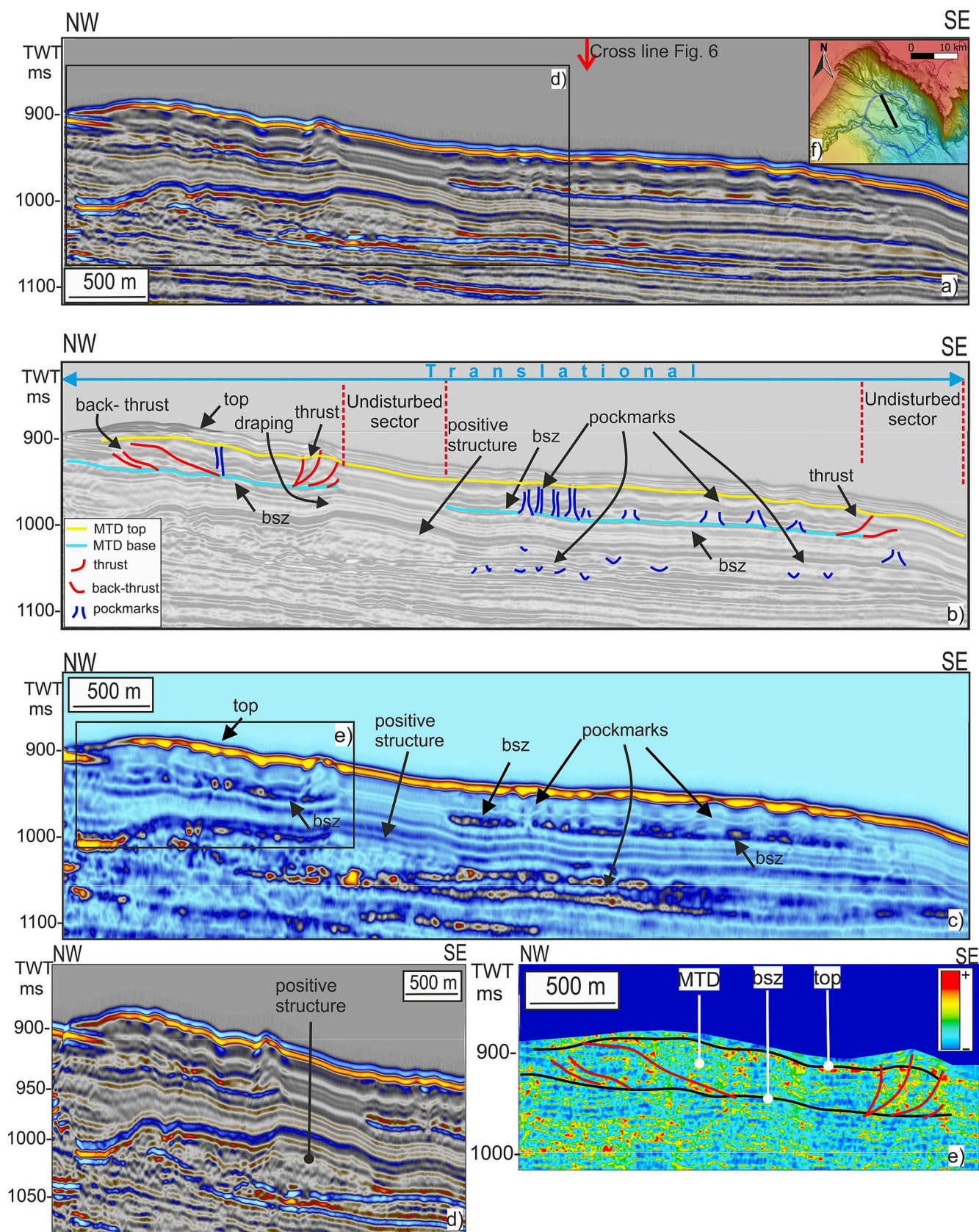


Fig. 5. a) Uninterpreted and b) interpreted profile across the translational domain of the MTD-CG1; c) Envelope attribute. Fluids below the bsz are highlighted by a high acoustic impedance contrast and by pockmarks related to accumulation of gas; d) Zoom of a positive structure; e) Structural dip attribute of a parts of the seismic section; f) Location map.

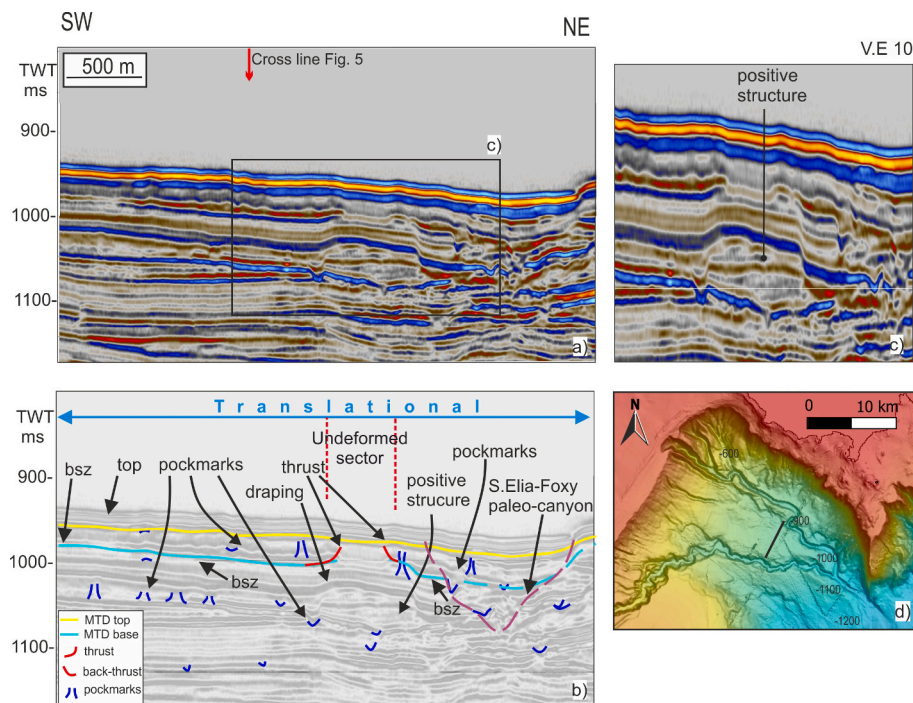


Fig. 6. a) Uninterpreted and b) interpreted seismic profile across the translational domain; c) Zoom of the positive structure; d) Location map.

5. Discussion

5.1. Evidence of fluids

Presence of diffuse fluids and fluid escape structures have been evidenced within the Upper Quaternary succession in the Gulf of Cagliari (Fig. 3). The phenomenon is particularly concentrated in the intra- and lower slope regions, between the Sarrabus shelf and Banghittu High. Fluid upwelling affects the MTD-CG1, highlighted by widespread pockmarks (Figs. 5, 6, 7, 10). These fluid escapes occur through vertical or oblique conduits into the mass transport deposit and, in some cases, they form mushroom diapiric-like structures (Figs. 5c, 7c, 10c) likely due to forced expulsion of overpressured material linked to a liquefaction process, analog to what analyzed by Ogata et al. (2012) in south-central Pyrenees region.

According to Allen (1982), liquefaction occurs when fine sediments produced by the erosion process are fluidized by excess pore pressure triggered by mass transport events. We hypothesize that in the Gulf of Cagliari the erosion by mass transport processes removed sedimentary material mixed with fluids, contributing to the liquefaction, facilitating fluid migration and leading to the formation of fluid escape structures (Figs. 5, 7, 9, 10).

In areas affected by mass transport erosion, the bsz acts as an irregular surface capping the underlying undeformed substrate. These observations are supported by studies in other regions, such as in the Gulf of Mexico, where Hampton et al. (1996) linked pockmarks to gas hydrate destabilization and sediment liquefaction during mass transport events. Similarly, in the North Sea, Hovland et al. (1993) found that fluid migration, driven by overpressure in sedimentary columns, resulted in pockmark formation. In other regions, similar associations have been documented as Lastras et al. (2004) highlighted in the western Mediterranean, where fluid expulsion occurred due to sediment destabilization.

5.2. The buried isolated carbonate platform

The seismic profiles have allowed us to identify an unaffected “undisturbed sector” which is located above a positive structure (Figs. 5, 6,

14). We ascribe this structure to a carbonate buildup following the criteria discussed by Bubb and Hatlelid (1977), Veeken (2013), and Słonka and Krzywiec (2019), based on seismic evidence: (i) mound-shaped reflection configurations; (ii) lateral changes in seismic facies between the accumulations and the surrounding layers; and (iii) draping effects of overlying layers on these accumulations (Figs. 5, 6). This interpretation is further supported by regional studies on carbonate production (Lecca et al., 1998; Lecca et al., 2005) demonstrating carbonate activity on the Cagliari Shelf since the Middle to Upper Pleistocene. Additionally, modern carbonate productivity remains significant in the Capo Carbonara Canyon area, where coral colonies have been identified at depths of 80 to 115 m (Orrù and Panizza, 2009; Cau et al., 2015) (Fig. 14d). Furthermore, Hovland (1990) correlated the presence of carbonate reefs to the migration of methane fluids, as also recognized by Del Ben et al. (2011) in the central Mediterranean Sea.

We hypothesize that this small structural high would have offered greater strength to the movement of the upper layer, slowing its advance. Conversely, it produced an accentuated lateral gravitational flow and compression along the flanks of the rigid structure, resulting in some little thrusts (Figs. 5, 6). In this setting, the undisturbed sector above the structural high likely represents in situ preserved sediments rather than a true component of the MTD. The MTD-CG1 appears to have flowed around this obstacle, from the slope towards the basin, moving on the path of least resistance and leaving this sector largely undeformed.

5.3. Instabilities of the area

The Gulf of Cagliari hosts multiple mass transport deposits (MTDs), landslides, debris flows and retrogressive erosion processes along the continental slope. In addition, multibeam data and seismic surveys from the MaGIC project have identified large-scale gravitational instability at the summit of Sant’Elia-Foxy Canyon (Deiana et al., 2017).

The Banghittu Landslide (BLs), on the eastern flank of the Banghittu High, causes significant seafloor deformation, disrupting the buried sedimentary layers and producing an irregular seabed morphology (Figs. 3, 11), indicating ongoing landslide activity. This feature aligns with the findings from Orrù et al. (2024), who detected evolved block

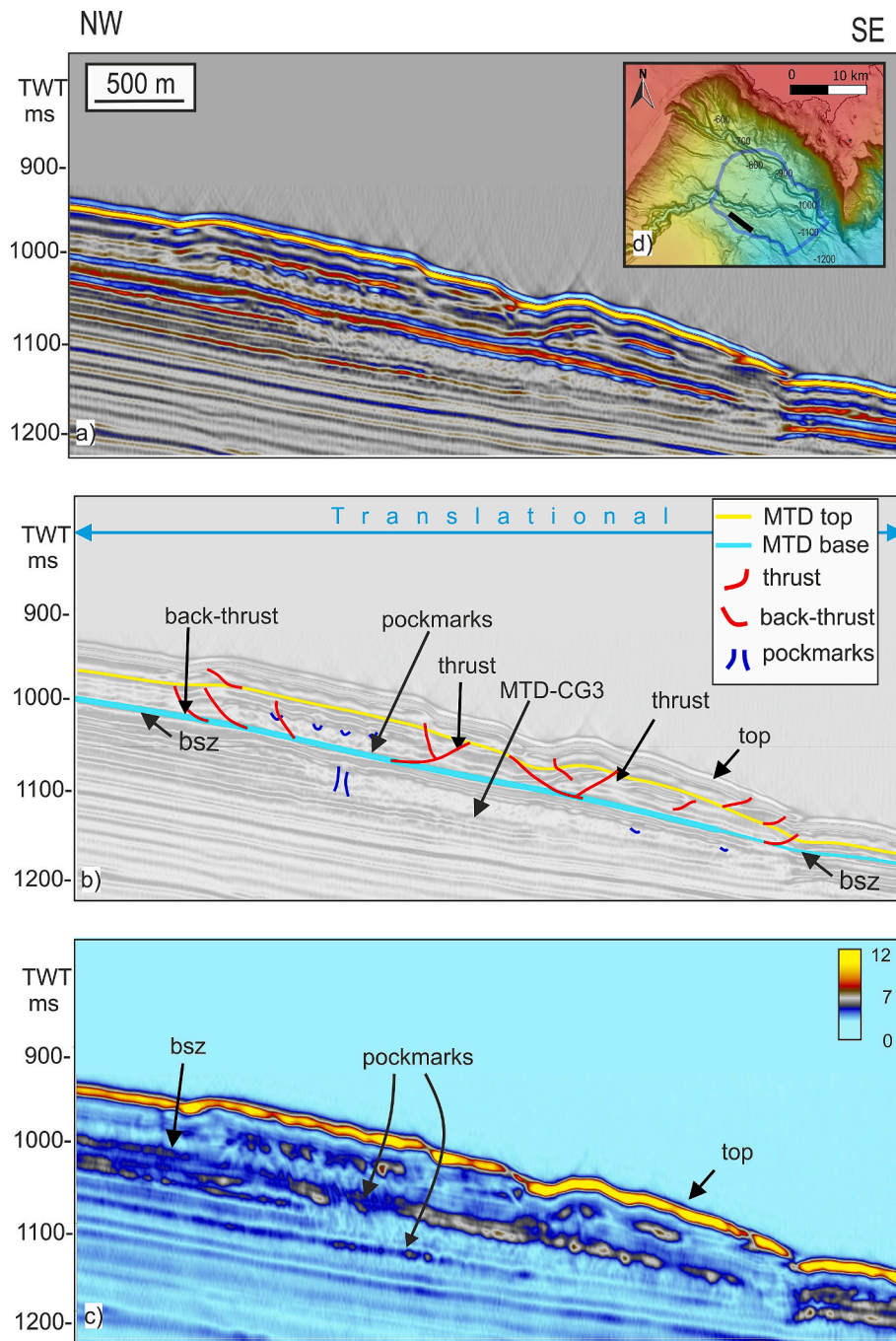


Fig. 7. a) Uninterpreted and b) interpreted seismic profile crossing the translational domain: the sea bottom steps are consistent with the deformation of internal layers of the MTD-CG1. c) The Envelope attribute suggests presence of fluids through the bsz and rising up to the seabed. d) Location map.

slides producing debris-avalanche deposits and highlighting the geomorphological complexity of this sector.

The MTD-CG2 is characterized by defined headwall and toe. The seabed concordant with the top of the chaotic layers suggests that its sliding is active and it passively transports overlying sediments (Fig. 11).

Further down, below the translational domain of the MTD-CG1 (Fig. 7), another older episode of slope instability has been identified as MTD-CG3. Additionally, below the toe domain of the MTD-CG1, the MTD-CG4 highlights the recurrent nature of mass transport events in the gulf (Fig. 8).

The recurrence of several submarine landslides at different depths, has also been documented in the southern Sardinian slope by Yeakley et al. (2017).

The multiple MTD systems are caused by sediment loading, tectonic activity and fluid migration.

5.4. Basal interaction of the MTD-CG1

Based on the interaction of the bsz with the underlying substrate, and using the terminology proposed by Sobiesiak et al. (2018), we have interpreted “free-slip flows” in the translational domain, where the mass movement can travel over the underlying substrate with minimal interaction, leaving no significant trace of its passage on the shear surface, absence of large-scale erosion or deformation and only minor mobilization between the flow and the underlying deposits (Sobiesiak et al., 2016; Sobiesiak et al., 2018; Kumar and Sain, 2020). This also

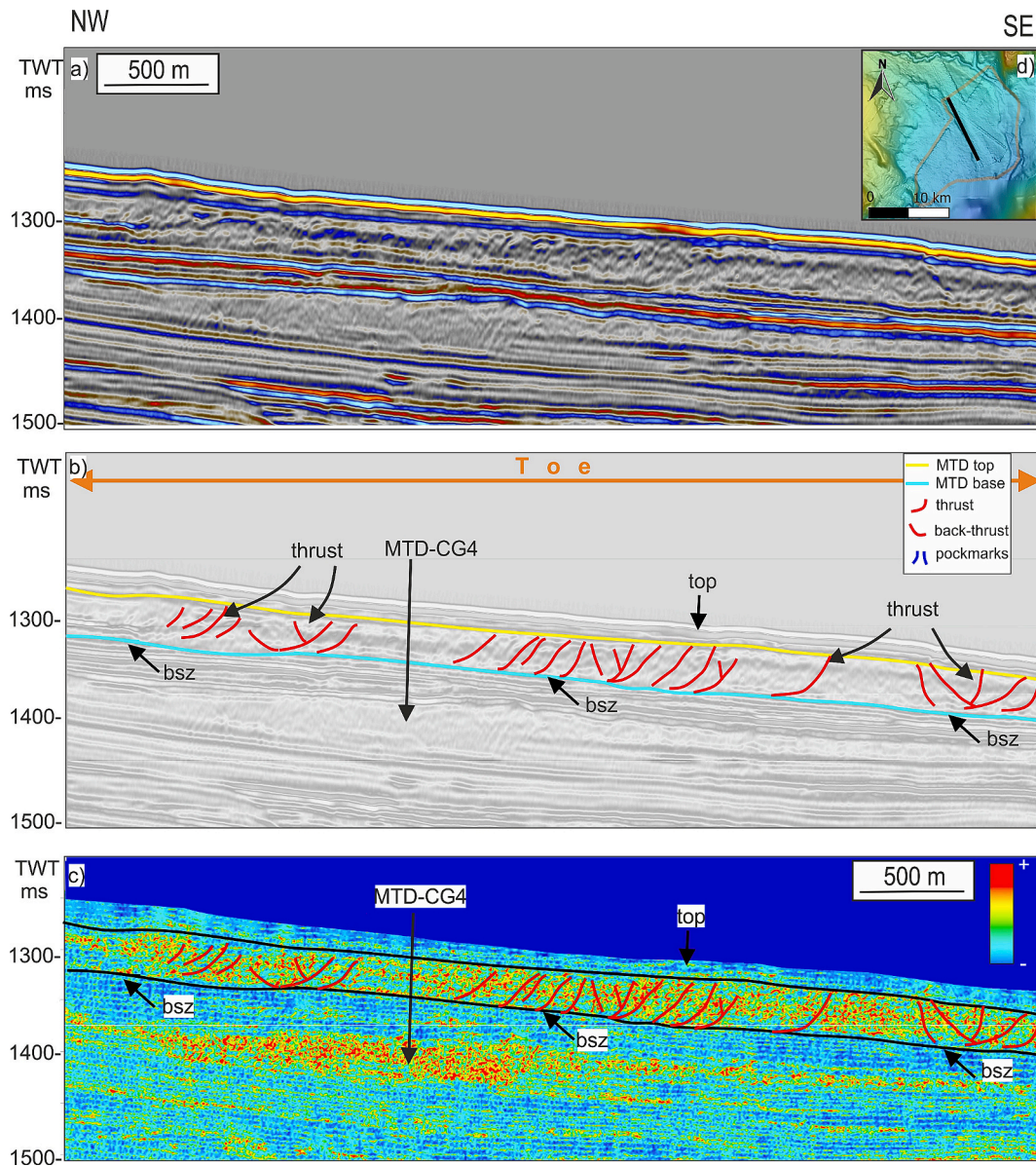


Fig. 8. a) Uninterpreted and b) interpreted seismic profile crossing the toe domain of the MTD-CG1. c) Local dip attribute applied to the seismic line where the buried older MTD-CG4 is better highlighted. d) Location map.

indicates a high shear strength of the underlying material, which resists major flow-substrate coupling. The key drivers behind free-slip flows include: (i) basal erosion in the headwall domain, where substrate material is detached and incorporated into the flow (Alves, 2015; Dunlap et al., 2010; Festa et al., 2016; Macdonald et al., 1993); (ii) internal deformation of the substrate, leading to plastic deformation, as observed by Sobiesiak et al. (2018); (iii) a combination of these causes. Seismic data reveal the presence of fluids throughout the sedimentary sequence, which can form a lubricating layer at the base of the MTD, reducing shear strength and facilitating movement (Mohrig et al., 1999).

In contrast, in the toe domain, basal interactions are characterized by “no-slip flows”, leading to considerable erosion of the underlying substrate (Fig. 3) which extends deep beneath the displaced mass (Figs. 8, 9, 10). The no-slip condition suggests that the bsz is not sufficiently lubricated, resulting in deep erosion of material beneath the MTD.

The interaction in the toe domain of the MTD-CG1 results in significant substrate erosion and incorporation of displaced material into the flow. The erosion and embedding of the underlying layers are indicative of a no-slip flow regime, where the MTD movement exerts considerable

forces on the substrate, preventing the mass flow from sliding freely over the surface. These interactions result in deepening of the bsz over time, as the flow becomes more turbulent and erosive (Cattaneo et al., 2020) (Fig. 4). Probably, the presence of fluids and overpressure in the substrate, reducing the shear strength at the bsz, facilitated this process.

This spatial variability results from a combination of several factors during mass flow, including water incorporation, increases in material velocity, changes in pore fluid pressure, frictional stresses, viscosity, interactions with underlying lithologies or degrees of lithification, bathymetric obstacles, and flow channelization, among others (Mohrig et al., 1998; Elverhøi et al., 2000; Posamentier and Kolla, 2003; Moscardelli et al., 2006; Alves, 2010).

In the toe domain the thrust faults originate from the bsz (Figs. 8, 9, 10) (Lewis, 1971) indicating a compressional regime further evidenced by the local dip attribute (Fig. 8c). Compression is predominantly active near the Banghittu High and at the foot of the Sarrabus shelf (Fig. 10).

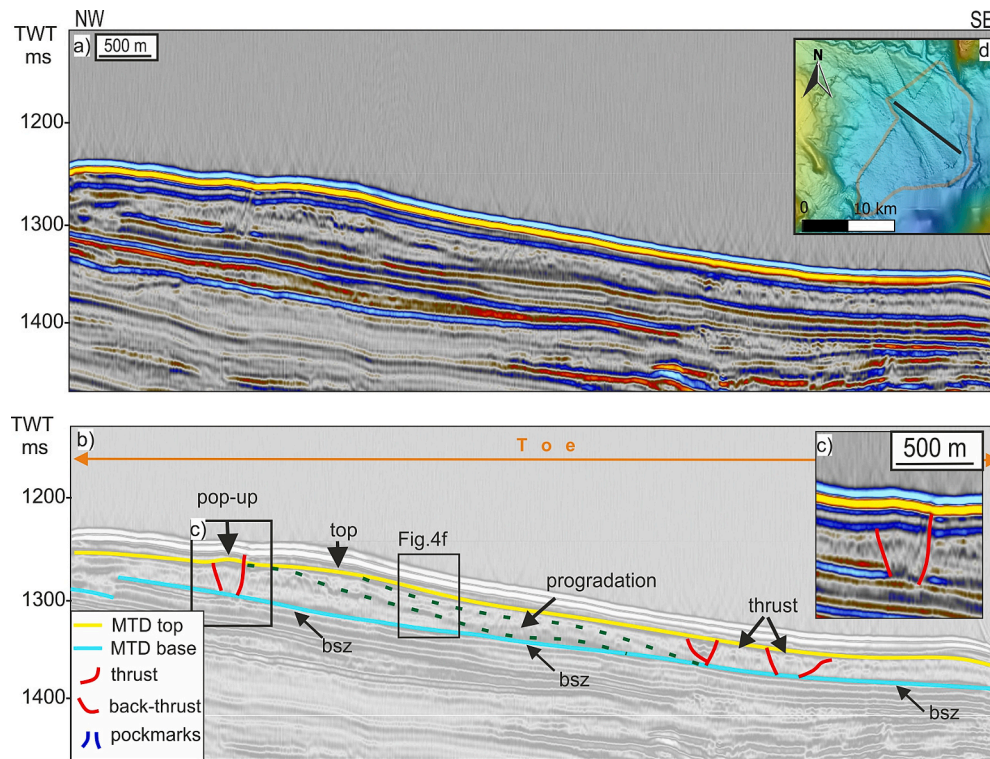


Fig. 9. a) Uninterpreted and b) interpreted seismic profile crossing the toe domain: the MTD-CG1 also involves a prograding body (green lines); c) Pop-up zoom; d) Location map. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

5.5. Potential factors controlling instability

Based on the available data, the instability that led to the formation of MTD-CG1 is driven by a combination of predisposing factors such as slope gradient and presence of fluids, and plausible triggers, such as sea level changes and earthquakes.

i) Slope Gradient. The bathymetric slope map (Fig. 3a) highlights significant variations along the margin. In the upper slope, where several submarine landslide are present (mapped by the MAGIC project, Fig. 2), the gradients range between 5° and 10° , which appears to favor gravitational instability (Fig. 3a). In the middle slope, characterized by translational domain, the gradients range from 1.5° to 3° , while in the lower slope, dominated by compressional deformation, the values range from 0.5° to 2° (Fig. 3a). Although steep slopes are typically linked to more possible failure (Canals et al., 2004), large landslides can also occur on more moderate gradients, even up to $2\text{--}5^\circ$. This is favoured under conditions of increased pore pressure or seismic activity (Sultan et al., 2004; Kvalstad et al., 2005; Hornbach et al., 2007; Masson et al., 2006; Urgeles and Camerlenghi, 2013). We suppose that the potential feeding area of the MTD-CG1 was at the boundary of the continental shelf and upper slope, close to the current shelf break (Fig. 3b).

ii) Presence of Fluids. Fluid migration in the Upper Quaternary sedimentary layers is evidenced by pockmarks and vertical conduits, significantly contributing to the destabilization of the MTD-CG1. Furthermore, the chaotic architecture within the produced MTD likely enhances fluid migration. The migration of overpressured fluids through these layers is a direct trigger for slope instability. In particular, the presence of fluid escape structures such as pockmarks is indicative of fluid migration. These fluids interact with sedimentary materials by increasing pore pressure which, in turn, induces frictional resistance between sediment particles and a reduction in shear strength, thus promoting the initiation of landslides (Hovland et al., 1993; Hampton et al., 1996; Lastras et al., 2004). This phenomenon has been already recognized in the Mediterranean submarine landslides, where fluid presence often correlates with landslides (Hovland et al., 2002;

D'Angelo et al., 2020). The fine-grained sediments present in the slope environment of the Gulf of Cagliari (Lecca et al., 1998) are more susceptible to fluidization and failure, due to the weakening effect of fluids, particularly under overpressure conditions (Ogata et al., 2012). This process contribute to the significant weakening of the sediment sequence (Grozic, 2003; Liu et al., 2022).

iii) Eustatic Sea-Level Changes. During the Quaternary ice age and the subsequent Holocene sea-level rise after the Last Glacial Maximum (Lambeck and Chappell, 2001), sea level fluctuations likely played a significant role in triggering the destabilization of the MTD-CG1 in the Gulf of Cagliari, particularly due to their impact on sediment compaction and pore pressure in the Upper Quaternary layers. In particular, the rising sea levels, by increasing the hydrostatic pressure in the sediments, can reduce effective stress and promote destabilization, particularly in areas with pre-existing weak structures (Gargani, 2024). Also the fall in sea level causes changes in sediment compaction and triggers the reactivation of pre-existing weaknesses, leading to failure (Sultan et al., 2004; Masson et al., 2006; Hermanrud et al., 2013; Vanneste et al., 2014). In the potential feeding area of the MTD-CG1 (Fig. 3b), these fluctuations, coupled with enhanced fluid migration, further mobilized the sediment and triggered mass transport processes.

iv) Seismic Activity. Seismic events represent a significant external trigger for mass transport deposits because earthquakes can induce liquefaction, increasing pore pressure and reducing the cohesion of fine-grained sediments, making them more prone to movement (Lee and Edwards, 1986; Sultan et al., 2004). Recent seismic events in southern Sardinia, such as those documented by Meletti et al. (2020), highlight the seismic activity of the region. For instance, the 13 November 1948 earthquake (Mw 5.1) and the seismic activity recorded in 2000 and 2006, in southern Sardinia, could have contributed to sediment destabilization. No specific earthquake has been directly linked to the MTD-CG1, anyway the seismic events occurred in the gulf testify potential triggers for mass transport processes.

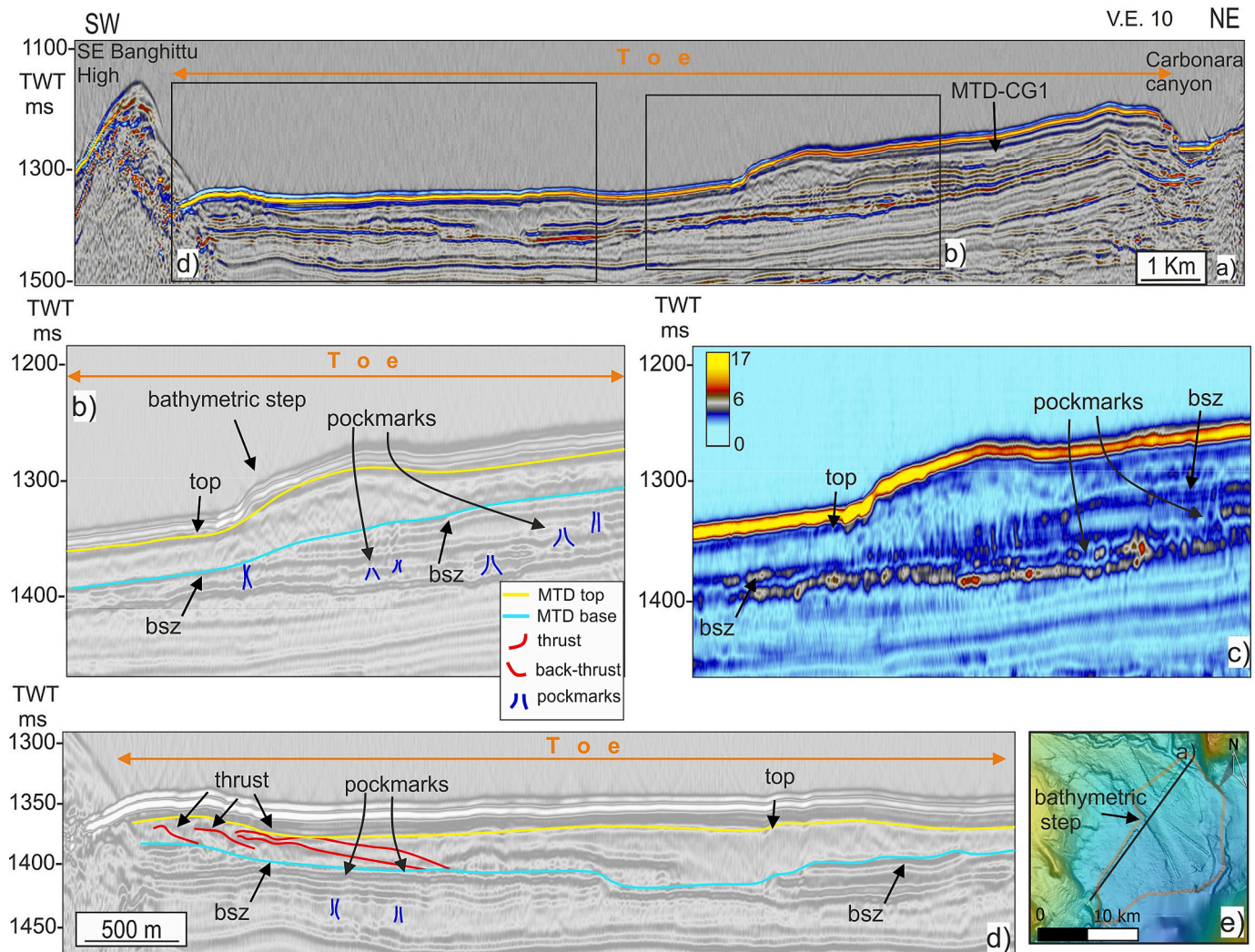


Fig. 10. a) Seismic profile crossing the toe domain from the deep SE - Banghittu High to the Carbonara Canyon. b) Interpreted detail showing the bathymetric step evident in a). c) Envelope attribute highlights the uncontinuous bsz and several pockmarks. d) interpreted seismic detail of the outermost MTD-CG1 ending at the foot of the Banghittu High. Some internal thrust originate from local compression and the base of the MTD involves levels at different depths. e) Map location.

6. Conclusions

The seismic dataset with unprecedented resolution in the study area provided essential insights into the geomorphological evolution of the seabed during the Upper Quaternary. This dataset allowed for the identification of buried gravity glidings (MTD-CG1÷4), with MTD-CG1 representing the youngest event in the region.

The MTD-CG1, which is primarily composed of a sedimentary unit deposited during the Middle-Upper Pleistocene, was significantly deformed by gravity gliding during the Holocene time and subsequently affected by the last incision of the canyon system.

This youngest MTD extends approximately 26 km in a NW-SE direction along the continental slope, with a clear movement towards the basin. The deposit exhibits a complex internal structure, with flow variations: from a “free-slip” regime in the translational domain, weakly deformed and crossed by fluid migration and pockmarks, to the “no-slip” flow in the toe domain where a compressional regime prevails. The basal shear zone provides insights into flow transformation of mass flows from “non-erosional” regime in the translational domain to “erosional” regime in the compressional domain. A buried carbonate buildup provided greater strength to the sliding, determining an undisturbed sector composed by in situ preserved sediments bordered by little thrusts of the translational domain.

Beyond MTD-CG1, on the northeast flank of the Banghittu High, seismic profiles evidence that the Banghittu Landslide (BLs) interacts with older deposits of the MTD-CG2 and both appear to be active. These findings point to a long-term process of gravitational sliding, with different MTDs and BLs shaping the geological landscape over time.

Geomorphological features observed in the study area, such as vertical conduits and pockmarks, provide clear evidence of fluid migration within the sediments. This fluid presence, in combination with the steep slope gradient, is highly conducive to gravitational sliding. Role of eustatic sea level changes and seismic activity in triggering mass transport events remain uncertain. Although this, the overall geological context of the area, characterized by Plio-Quaternary extensional tectonics and rare earthquakes, suggest their potential contribution to slope destabilization. Further research is needed to refine our understanding of the timing, triggers, and mechanisms behind these mass transport events.

CRediT authorship contribution statement

Maria Cristina Caradonna: Writing – original draft, Visualization, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Anna Del Ben:** Writing – review & editing, Visualization, Supervision, Resources, Methodology, Conceptualization. **Gian Andrea**

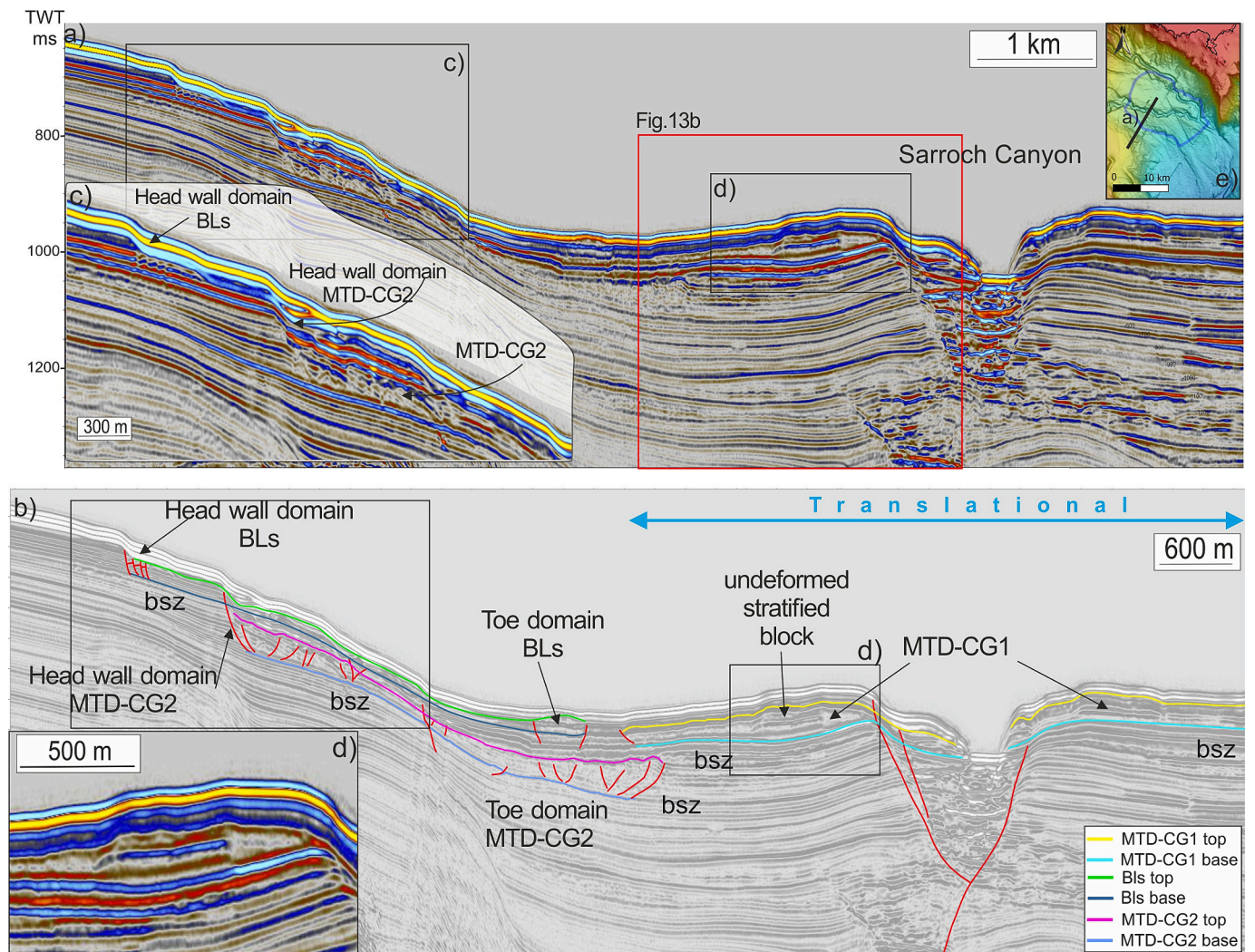


Fig. 11. a) The Banghittu Landslide (BLs) developed on the north-eastern flank of the Banghittu High; b) interpreted profile; c) Zoom of the head wall domain of MTD-CG2 and BLs; d) Zoom of the undeformed stratified block inside the MTD-CG1; e) Map location.

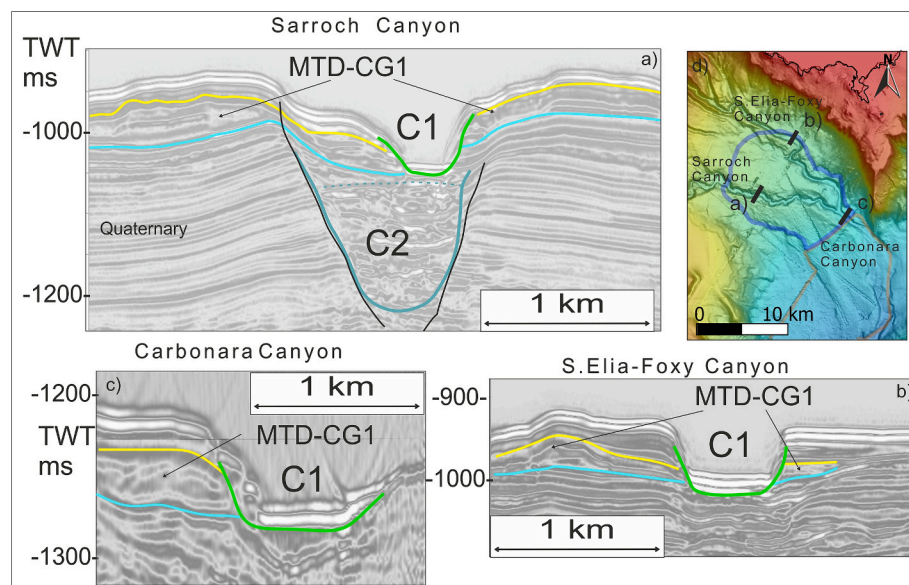


Fig. 12. Cross-cutting relationship between the MTD-CG1 and a) the Sarroch Canyon, b) the S.Elia-Foxy Canyon; c) the Carbonara Canyon; d) location map.

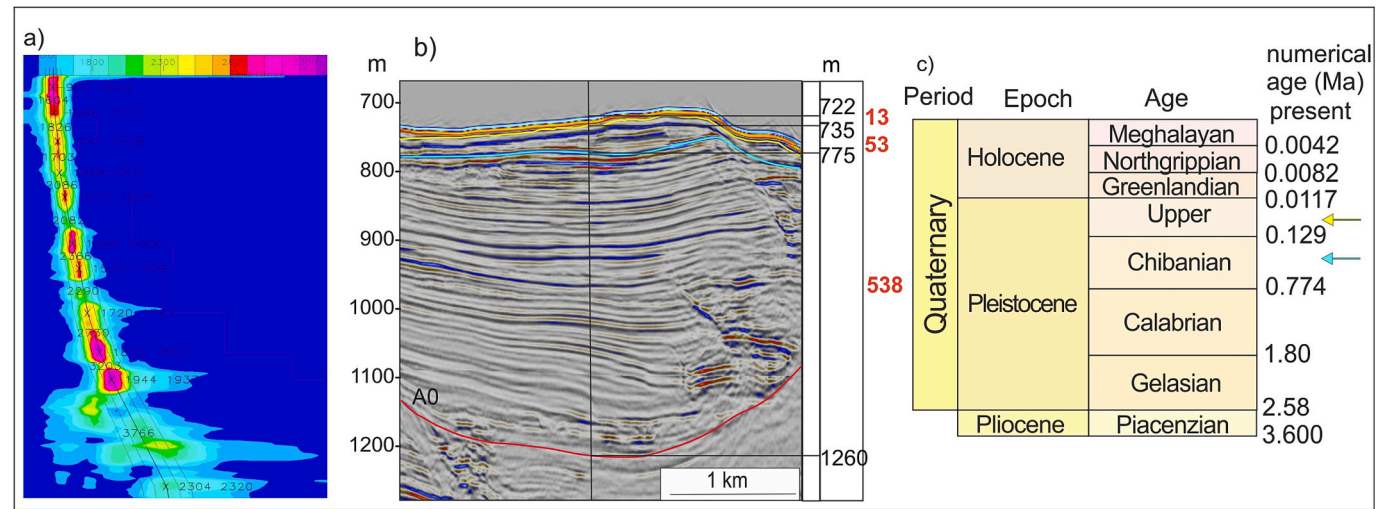


Fig. 13. a) Velocity analysis was performed on the vertical profile (black line in b); b) part of the seismic section, shown in Fig. 11, has been converted to depth; c) chronostratigraphic Quaternary Age.

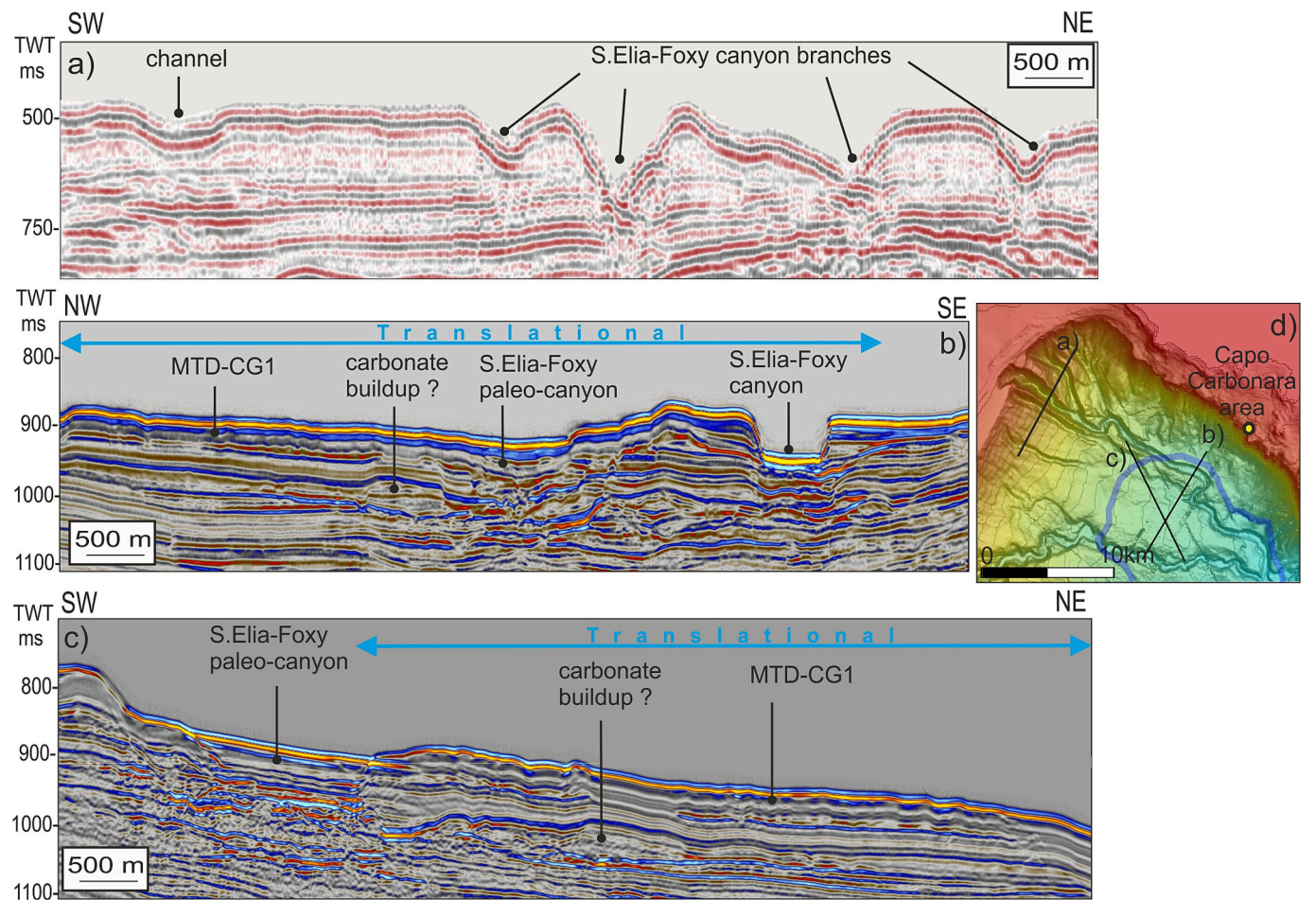


Fig. 14. Distribution of translational domain of the MTD-CG1. The yellow dot in the map indicates the position of red corals dredged and analyzed in the Capo Carbonara Canyon by Cau et al. (2015). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Pini: Writing – review & editing, Visualization. **Riccardo Geletti:** Writing – review & editing, Visualization, Data curation. **Veronica Frisicchio:** Visualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data Availability

The seismic data are available at the Seismic data Network Access Point (SNAP). URL: <https://snap.ogs.trieste.it/>

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