Journal of Maps

ISSN: (Print) (Online) Journal homepage: www.tandfonline.com/journals/tjom20

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To cite this article: Francesca Budillon, Eleonora Martorelli, Alessandro Conforti, Giovanni De Falco, Alessandro Bosman, Gabriella Di Martino, Marco Firetto Carlino, Martina Misuraca, Sara Innangi, Martina Pierdomenico, Andrea Sposato, Renato Tonielli, Daniele Casalbore, Roberto Capperucci, Aida Maria Conte, Francesco G. Falese, Michela Ingrassia, Ennio Marsella, Cristian Montanaro, Eleonora Morelli, Roberto Sisinni & Francesco L. Chiocci (2024) Geohazard features of the Gulf of Naples and Pontine Islands (Eastern Tyrrhenian Sea), Journal of Maps, 20:1, 2378935, DOI: 10.1080/17445647.2024.2378935

To link to this article: https://doi.org/10.1080/17445647.2024.2378935

JOURNAL OF MAPS
2024, VOL. 20, NO. 1, 2378935
https://doi.org/10.1080/17445647.2024.2378935

Geohazard features of the Gulf of Naples and Pontine Islands (Eastern Tyrrhenian Sea)

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ABSTRACT
In this paper, we describe the geohazard-related elements of the Eastern Tyrrhenian Sea continental margin, situated between the 40° and 41° North latitude. These features were recognised principally through morphological analysis. The investigation utilized medium – and high-resolution digital models of the submarine landscape, produced within the framework of the Magic project (Marine Geohazard along Italian Coasts), and primarily focusing on the bathymetric range of 50–700 meters. The surveyed area encompasses a recently formed continental margin, which connects the internal segments of the Apennine fold-and-thrust belt, verging NE, to the Tyrrhenian Sea bathyal plain, a 3000-m-deep back-arc basin that has developed since the Middle-Late Miocene. Several classes of hazard-related elements have been identified offshore, primarily associated with high-gradient slopes and a large number of volcanic edifices and banks. These include canyon systems, erosive scarps, landslide complexes, fault – and volcanic-related features, such as the products of the volcanic edifices instability, which claim to varying degrees of geo-hazard. Additionally, bedforms, fluid seepages and creeping phenomena in the prodelta slopes suggest high morpho-tectonic and environmental dynamics.

Highlights

- This article reports on the thematic maps developed along the Lazio – Campania offshore (Central-eastern Tyrrhenian Sea, Italy) within the framework of the Magic Project, based on geomorphological analysis of the HR Digital Elevation Model of the seafloor.
- Several classes of hazard-related elements have been identified offshore, mainly associated with high-gradient slopes, volcanic activity and intense morphodynamic processes.
- The entire suite of maps created in the context of the Magic Project serves as a valuable base of knowledge, extending to the national scale and benchmarks for future monitoring of critical sites and geo-hazard-related features, as well as for maritime spatial planning actions.

ARTICLE HISTORY
Received 16 November 2023
Revised 26 June 2024
Accepted 4 July 2024

KEYWORDS
Magic project; submarine geo-hazard; seafloor mapping; morphological analysis; digital elevation models (DEMs); Tyrrhenian Sea

1. Introduction

The article illustrates the maps of geohazard-related features offshore of the Pontine Islands, Gulf of Naples and Gulf of Salerno. These maps were produced between 2007 and 2013 within the framework of the Magic project (Marine Geohazard along Italian Coasts), a nationally coordinated venture that led to examining approximately 100,000 km^2 of seafloor deeper than − 50 m around the Italian Peninsula (Chiocci et al., 2021). The features were derived from the analysis of submarine Digital Elevation Models (DEMs) and primarily rely on the morphological expression of the seafloor and shallow sub-bottom geo-morphological processes and events, regardless of their timing.

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Over the last decades, relevant advances in marine geohazard knowledge have been achieved primarily through large-scale, high-resolution multibeam bathymetry and geo-referenced mapping of hazard-related features. Pioneering studies on submarine landslides (Huhnerbach and Masson, 2004; Urgeles & Camerlenghi, 2013 and references therein), paved the way for research on marine geohazard based on Multibeam echosounders (MBES) surveys. These surveys have proven indispensable for coastal management and risk assessment (Chiocci et al., 2011) and strategic planning for marine infrastructure upgrading (pipelines, cables, harbor breakwaters etc.). Conducting such surveys in a repeated mode over time (4D) (Kelner et al., 2016 among many others), would be particularly appropriated in areas where seabed monitoring actions are advisable, e.g. areas with ongoing volcanic and seismic activity (De Natale et al., 2017), recurrent gravitational instability, erosional processes (de Alteriis et al., 2010; Ferrando et al., 2021), and multiple threats from natural and anthropogenic stressors (Budillon et al., 2022a, 2022b; Sprovieri et al., 2022).

The Main Maps present two levels of interpretation: (i) the Physiographic Domains and (ii) the Morphological Units and Morpho-bathymetric Elements (Sheets 1–5), at approximately 1:325,000 and 1:85,000 scales, respectively.

2. Study area: the geology of Ventotene and Palmarola basins, Gaeta, Naples, and Salerno gulfs

The continental margin off the Lazio-Campania regions is located in the central-eastern Tyrrhenian Sea and exhibits typical characteristics of an extensional domain associated with the geodynamic evolution of a back-arc basin: (i) widespread normal faulting (Figure 1), (ii) high heat flow rates, (iii) large volumes of ignimbrite formations (Malinverno & Ryan, 1986; Della Vedova et al., 2001; Bellucci et al., 2006) and (iv) high subsidence rates in the basinal domains (Milia & Torrente, 2007). During Neogene times, the Tyrrhenian side of the Southern Apennines experienced the effects of the eastward migration of the W-dipping subduction zone (Patacca, & Scandone, 2007). Since the Upper Miocene, the migration of the accretionary prism led to the extension in the back-arc area, resulting in the onset of the Tyrrhenian Basin (Doglioni, 1991) and, since Pliocene, volcanic activity. Initially, an E-W-oriented rifting episode created major Apennine normal faults and structures, which are now poorly traceable due to subsequent tectonic events overprinting (Caiazzo et al., 2006), in the Gaeta Gulf and Campania Plain (Milia et al., 2013). Since Upper Pliocene - Early Pleistocene, the tectonic regime present in this sector of the chain is of the extensional type towards ESE, approximately. It is expressed through the development of WNW-ESE faults with left transtensive kinematics, linked to the opening phases of the Tyrrhenian Sea and the contemporary migration of the Calabrian Arc towards the ESE (Casciello et al., 2006; Conti et al., 2017; Milia et al., 2013). The combined displacement of these structures shaped the physiography of the central-eastern Tyrrhenian margin, characterized by strongly subsiding half-grabens and uplifting interposed ridges. This geological context gave rise to several intraslope basins (Palmarola and Ventotene basins, Gaeta, Naples and Salerno Gulfs), bounded by steep escarpments (Pontine escarpment, Amalfi escarpment) and minor seamounts (Figure 1) (Cuffaro et al., 2016; Marani & Gamberi, 2004; Milia & Torrente, 1999; Misuraca et al., 2018; Torrente & Milia, 2013; Zitellini et al., 1984). Epi – and volcani-clastic deposits, locally reaching 3000 ms (two-way travel time, TWTT) in thickness, are accommodated in the morpho-structural depressions, (Mariani & Prato, 1988). The strike-slip kinematics along WNW-ESE oriented lineaments has been ascribed to the disjunction between Southern Apennines and the Calabrian arc (Knott & Turco, 1991; Doglioni et al., 1996) or, in the view of a broader geodynamic context, to the development of a Subduction-Transform-Edge-Propagator fault along the northern margin of the Ionian slab (Milia et al., 2017). Starting from Middle-Upper Pleistocene, a NW-SW oriented extentional regime is established, still acting, with the development of NW-SE striking normal faults, dipping toward the Tyrrhenian Sea (Caiazzo et al., 2006; Casciello et al., 2006).

Overall, the area is characterized by widespread intense and long-lasting magmatic and volcanic activity, as recorded by the products of the Pontine Archipelago, Campi Flegrei volcanic field, Phlegrean Islands, Mt. Somma-Vesuvius and Mt. Roccamonfina. Additionally, buried or submerged Plio-Pleistocene volcanic edifices occur on the continental margin (Torrente & Milia, 2013; Cuffaro et al., 2016; Misuraca et al., 2018; Conte et al., 2020a). The western group of the Pontine Islands records the oldest volcanic activity (4.2 Ma) in the study area, characterized by orogenic calc-alkaline rhyolites (Peccerillo, 2005; Conte et al., 2016), whereas the Phlegrean Islands and Mt. Somma-Vesuvius resulted from the most recent volcanic activity. In the Gulf of Naples, the Campanian Grey Tuff (CGT) and Neapolitan Yellow Tuff (NYT), aged 39 kyr (De Vivo et al., 2001) and 15 kyr (Deino et al., 2004), respectively.

3. Methods

All 71 maps produced within the scope of the Magic Project were drafted using consistent interpretative

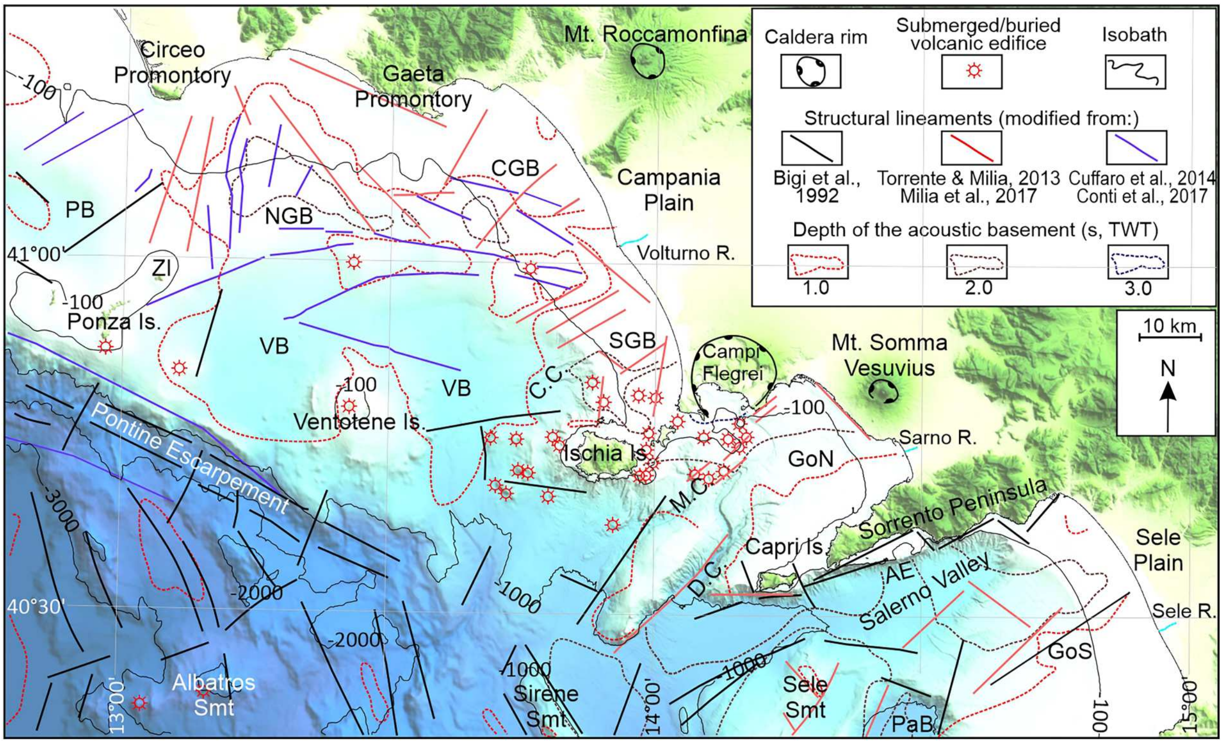

Figure 1. Bathymetry (from IAMC-CNR, now ISMAR CNR, and Emodnet dataset; isobath in metres), main structural lineaments and volcanic edifices of the Lazio-Campania continental margin. The isochrons (s, TWT) of the acoustic basement and structural lineaments have been compiled according to Bigi et al. (1992), Cuffaro et al. (2016), Conti et al. (2017) and Milia et al. (2013, 2017). NBG, Northern Gaeta Basin; CGB, Central Gaeta Basin; SGB, Southern Gaeta Basin; GoN, Gulf of Naples; GoS, Gulf of Salerno; ZI, Zannone Island; VB, Ventotene Basin; PB, Palmarola Basin; PaB: Paestum Basin; AE, Amalfi Escarpment; CC, Cuma Canyon; MC, Magnaghi Canyon; DC, Dohrn Canyon.

and cartographic standards (Chiocci et al., 2021), including those presented in this study (Main Maps). These standards encompassed mapping criteria, legend, partitioning of mapped elements into homogeneous layers and the software employed (Casalbore et al., 2024; De Falco et al., 2024; Morelli et al., 2024). The geomorphic elements were primarily derived from the analysis of high-resolution digital terrain models (DTMs), with grid cell sizes ranging from 10×10 m in the shallowest to 50×50 m in the deepest sectors and were obtained from the MBES dataset acquired in 1997–2007-time span (Chiocci et al., 2021). Additionally, seismic line interpretations were used to support the analysis at targeted sites.

The legend for the Physiographic Domain layer is included in the overview map, whereas the legend of the Morphological Units and Morpho-bathymetric Elements map is presented separately (Supplemental maps).

4. Maps of morphological units and morpho-bathymetric elements

4.1. Western Pontine Islands (MaGIC sheet 5)

The Sheet 5 ‘Western Pontine Islands’ is located on the southern sector of the Lazio continental margin (central Tyrrhenian Sea), off the Circeo Promontory, and includes the western islands of the Pontine Archipelago (Ponza, Palmarola and Zannone) and minor submerged volcanic edifices (Main Maps, Sheet n. 5). The three islands are located at the summit of a morpho-structural high, mainly elongated in the NE-SW (the Ponza-Zannone high) and NW-SE direction (the Ponza-Palmarola high). The Ponza-Zannone high separates the Palmarola and Ventotene intra-slope basins, which have undergone high-rate subsidence during the Plio-Pleistocene (Zitellini et al., 1984). The western islands of the Pontine Archipelago are mostly composed of volcanic units, rhyolites and trachytes, emplaced during the Plio-Pleistocene (Conte et al., 2020a and references therein). The volcanic activity ceased approximately 0.9 Ma ago with the emplacement of trachytic products in the southern sector of Ponza Island (Conte & Dolfi, 2002).

The three islands are surrounded by a narrow shelf with varying widths (minimum width of 1.5 km south to Ponza Island, maximum width up to 8 km between Ponza and Palmarola), mainly controlled by the offshoots of the volcanic bedrock in the subsurface, and bounded by a well-defined shelf break, located between – 95 and – 160 m. On the shelf, the seafloor morphology is highly irregular due to the presence of several rock outcrops are close to the coasts and are composed of Plio-Pleistocene volcanic units (Chiocci & Martorelli, 2018). The limited accommodation above the volcanic bedrock hampered sizable sedimentation in the inner shelf. Conversely, a moderate-thick sediment prism formed close to the shelf break (i.e. the western Pontine submarine depositional terrace; Chiocci & Orlando, 2004; Casalbore et al., 2017); it represents an infralittoral prograding wedge formed during the LGM period (Chiocci & Martorelli, 2018).

The outer shelf/shelf-break sector is locally characterized by slope instability with two main submarine slides located south of Ponza Island, close to Punta La Guardia, and several gullies and canyons mostly located along the shelf break of the southern sector. Moreover, offshore Zannone Island five peculiar giant depressions (max. 0.5 km^2), with complex shapes, are bounded by 1–20 m-high steep escarpments (Figure 2). These giant depressions represent the morphological expression of hydrothermal emissions, associated with a recently discovered shallow-water hydrothermal field (Martorelli et al., 2016), in which the major depression is the Zannone Giant Pockmark, characterized by several active vents (Ingrassia et al., 2015) and by mineralization and alteration products (Conte et al., 2020b).

The continental slope can be subdivided into two main sectors:

- the slopes facing the Palmarola and Ventotene basins are generally characterized by a regular morphology and gentle slope gradients; here, medium-size landslides scars and deposits along the flanks of the Palmarola intraslope ridges have been recently

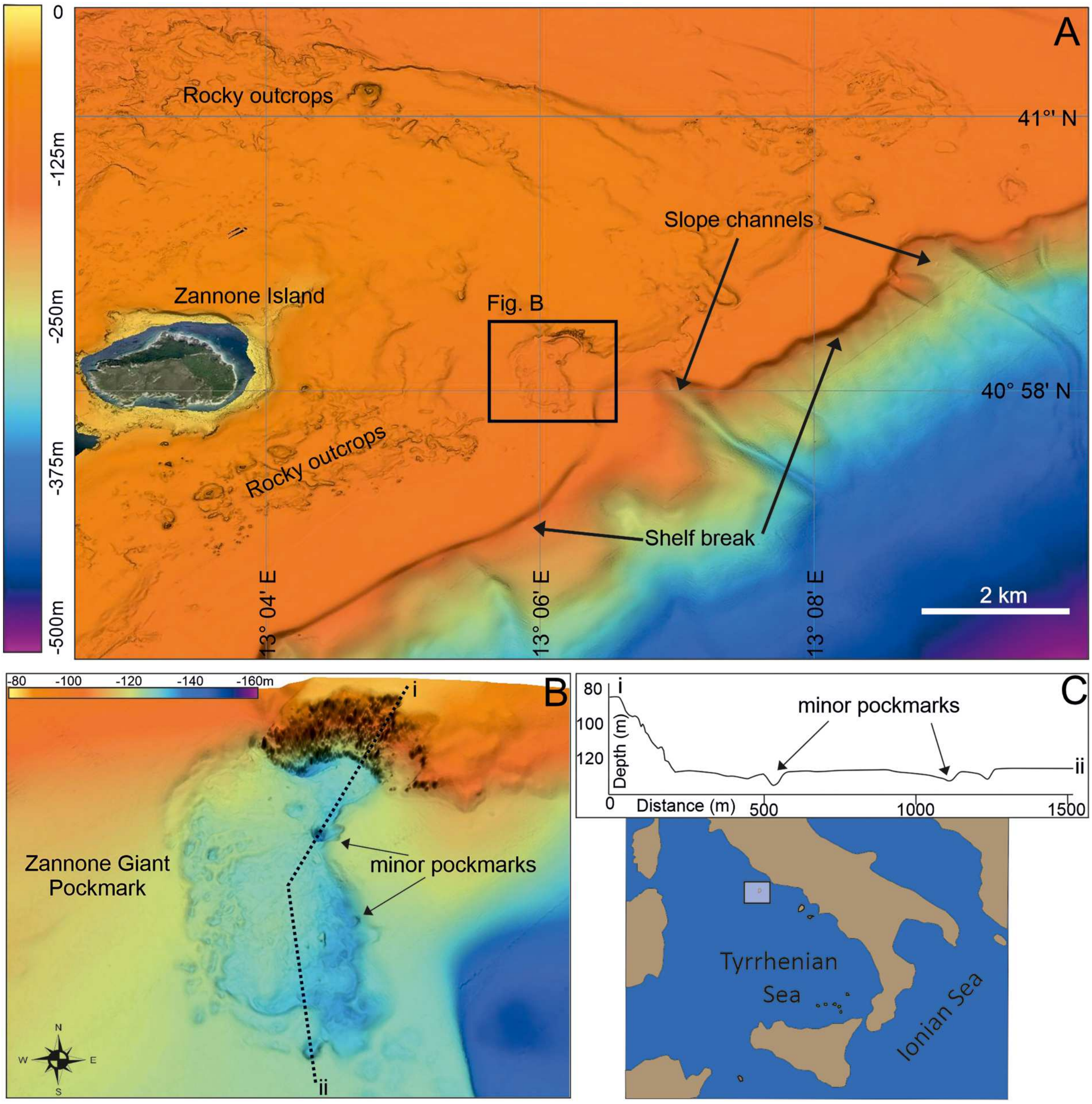

Figure 2. (a) Shaded relief map of the shelf and upper slope off the Zannone island, where rocky outcrops, slope channels and pockmarks are present; (b) 3-d image of Zannone Giant Pockmark (location in Figure 2a; vertical exaggeration 5x), a large seafloor depression characterized by an irregular seafloor (Ingrassia et al., 2015), where minor pockmarks are also present; (c) bathymetric profile (location in Figure 2b, dashed black line; vertical exaggeration 5x) across the Zannone Giant Pockmark.

described, likely controlled by slope gradients and tectonic structures (Casalbore et al., 2016a).

- the slope facing the Vavilov Basin that is pervasively affected by erosive-instability processes, in response to high slope gradients (locally exceeding 30°; Chiocci et al., 2003) associated with NW-SE extensional faults (Conti et al., 2017). Here, widespread slide scars, erosional channels, canyons and gullies are recognizable.

4.2. Ventotene (MaGIC sheet 6)

The Sheet 6 ‘Ventotene’ includes the seafloor surrounding the Ventotene and Santo Stefano islands, which belong to the eastern Pontine Archipelago (Main Maps, Sheet n. 6). These islands, located about 50 km off the coasts of the Gulf of Gaeta, represent the emergent part of a large volcanic edifice (the Ventotene Volcano), currently inactive. The Ventotene Volcano is a truncated-cone-shaped strato-volcano emplaced during the Pleistocene (0.8–0.13 Ma, Peccerillo, 2005). Its base has a diameter of 20-25 km and lies at about 700 m water depth. The volcanic activity includes several explosive eruptions with the youngest and most prominent event – the Parata Grande Tuff, dated around 0.15 and 0.3 Ma, (Perrotta et al., 1996) – ensued in a caldera collapse. Such event is also testified by the presence of a sub-circular depression located west of Ventotene Island evidenced by multibeam bathymetric data (Casalbore et al., 2016b). A well-developed insular shelf surrounds the volcano, which is characterized by widespread rock outcrops, often covered by biogenic build-up and Posidonia oceanica meadows. The shelf margin displays several slope breaks related to the presence of a set of submarine depositional terraces (SDT, Chiocci & Orlando, 2004; Casalbore et al., 2017; Budillon et al., 2022a).

Volcanic-related (i.e. cones and secondary eruptive centres, dikes and/or eruptive fissures) and erosive and mass-wasting features characterize the flanks of the edifice. Erosional morphologies, such as landslide scars and channel heads, incise the edge of the SDT, causing its retreat through retrogressive erosion along the whole margin of the volcanic edifice (Casalbore et al., 2016b). Conversely, in the south-eastern sector, the insular shelf displays the largest width. The Ventotene Volcano is located at the center of a subsiding area, the Ventotene intra-slope basin, whose evolution is related to the extensional tectonics associated with the opening of the Tyrrhenian Sea during Lower Pliocene (Zitellini et al., 1984; Conti et al., 2017). The basin is E-W oriented and has a sub-circular geometry. It is bordered by the Ponza-Zannone morpho-structural high to the NW, by a submarine ridge adjacent to La Botte Islet to the SW, by the continental slope of the central Tyrrhenian margin to the N and NE, and by the volcanic edifice of Ischia to the E. The southern sector gently merges with the lower continental slope. The basin reaches a maximum depth of about 950 m in the eastern part and is filled with Plio-Quaternary sediments that can be up to 1000 m thick. The morphology of the basin seafloor is quite smooth, apart from some bedform fields and low relief fault scarps. The main features of the basin are represented by isolated morphological highs, located in the N, NW and S sectors. At a more detailed spatial scale, several small-scale depressions, interpreted as pockmarks are widespread on the seabed (Ingrassia et al., 2015).

Other relevant features of the sheet are: (1) the Cuma Canyon, a 70 km-long turbidite system, whose head is composed of three main branches extending for about 18 km across the continental slope and locally affected by debris avalanches and sedimentary gravity flows originated from Ischia Island (see also Supplemental maps, Sheet n.7), and (2) a series of erosive channels, which originate from the shelf break offshore of the Volturno river mouth, carving the upper slope, down to about 500 m water depth. These features were probably related to hyperpycnal flows following the large volcaniclastic input generated by the nearby Campi Flegrei volcanic field, during the early stages of post-glacial transgression (Chiocci & Casalbore, 2011).

4.3. Ischia (MaGIC sheet 7)

The Sheet 7 ‘Ischia’ is located on the Campania continental margin and includes the Phlegraean Islands (Ischia, Procida and Vivara), the Bay of Pozzuoli, the ‘Banco di Fuori’ intra-slope relief and the distal sectors of Magnaghi and Dohrn canyons (Main Maps, Sheet n. 7). A deep-buried main structural lineament, located along the inner section of the Dohrn Canyon, bounds the northwest sector of the Gulf of Naples, where the submarine topography is significantly influenced by volcanic processes and morphologies (Bruno et al., 2003). Notable features include erosive scarps, volcanic banks, canyon heads, hummocky topographies, substrata outcrops which jointly configure an uneven seabed.

The volcanic activity of Campi Flegrei, Ischia and Procida islands, documented by the outcropping products, spans the last 0.15 Ma and has been characterized by low-intensity eruptions, which generated small monogenic eruptive centres, and by major events primarily correlated with thick ignimbritic flows and pyroclastic fall out (Rosi & Sbrana, 1987; Rosi et al., 1988; Scarpati et al., 1993; Sbrana et al., 2018). Large eruptions have been accompanied by caldera formations and subsequent resurgences, as testified by the Mt. Epomeo resurgent block on Ischia Island (Orsi et al., 1991; Acocella & Funiciello, 1999; Vezzoli et al., 2009), La Starza terrace at Campi Flegrei and uplifted marine terraces in the Bay of Pozzuoli (Sacchi et al., 2014; Steinmann et al., 2018; Natale et al., 2022). Ischia Island is made of alkali-trachytic products and is part of a much wider volcanic complex that extends further west of the island in the submerged sectors (Figures 1 and 3) (Bruno et al., 2002).

The Ischia Island and Campi Flegrei are active volcanic areas, as proved by intense hydrothermal activity (Chiodini et al., 2004), localized seismicity (Giudicepietro et al., 2021; Selva et al., 2021), historical and current ground deformation (Buchner et al., 1996; Vilardo et al., 2009). The Campi Flegrei sector has been under geophysical and geochemical monitoring since the 1980s, for it is regarded as one of the most hazardous volcanic calderas worldwide, due to the combination of volcanism and shallow seismicity unrest in a densely populated coastal area (Orsi et al., 1996; De Natale et al., 2017). Recent studies, conducted after the conclusion of the Magic Project, have unveiled new significant findings at the seafloor: the uplifted seafloor areas, the fractures associated with apical doming deformation and multiple fluid venting sites connected to post-caldera activity (Sacchi et al., 2014; Di Napoli et al., 2016; Somma et al., 2016; Steinmann et al., 2016, 2018).

Despite 20 y-long geodetic measurements showing constant subsidence in the western sector of Ischia Island (Beccaro et al., 2021), a wide range of geological and geophysical data indicate that the island has been uplifting since 33 ky BP. The uplift has significantly controlled the morphological evolution of the island (Gillot et al., 1982; de Vita et al., 2006), particularly the collapses affecting the lateral flanks (Tibaldi & Vezzoli, 2004; Della Seta et al., 2012), that have left a marked footprint on the present-day seabed (Chiocci et al., 1988; Chiocci & de Alteriis, 2006; de Alteriis & Violante, 2009; de Alteriis et al., 2010; Passaro et al., 2016a). Indeed, the continental shelf north and west of Ischia Island accommodates the offshoots of huge mass movements – sudden collapses or slow deformations – resulting from the volcano-tectonic uplift of the island. Several debris avalanches radiating out from Mt. Epomeo entered the sea (Budillon et al., 2003; Violante et al., 2003; Milia et al., 2021) in prehistoric times and currently lie on the shelf as blocky deposits (Figure 3). The most distal elements rest in the heads of the Cuma Canyon's lateral branches, and still others lie further downslope in the canyon path; this condition raises the question whether the branches originated or were further carved precisely because of the impressive landslides' runout.

Seismic lines acquired for the geological mapping project of the marine areas (Servizio Geologico d'Italia, 2019), though not calibrated by coring data, and therefore interpreted solely in seismic-stratigraphic relative terms, highlight the geometric relationships between mass transport/avalanchig deposit, characterized by chaotic seismic facies and hummocky morphologies, sedimentary units made of mixed marine / fine-grained epiclastic material and 'deaf' units of volcanic origin. In the western area at least four mass transport deposits, interbedded within well-stratified units, can be identified (Figure 3).

The sector south of Ischia Island exhibits broad erosional scarps that come within a few hundred meters of the shoreline, canyon heads that lap rocky headlands (Alberico et al., 2018), canyon talwegs embedded between steep sidewalls and deep-seated slump lobes and debris avalanches linked to mass wasting phenomena. All these features point to an intense morphological evolution of the continental slope, up to very recent times. Among these features, the most distinctive one is certainly the IDA (Ischia debris avalanche), which originated from the south slope of Ischia. Blocks from this avalanche are observed up to 50 km downslope (Chiocci & de Alteriis, 2006; de Alteriis et al., 2010) and seemingly overprint the outer fan of the Magnaghi Canyon. This observation, based solely on morphological analysis, establishes an important chronological relationship between depositional and erosive processes in the area.

The Magnaghi and Dohrn canyons run almost in parallel and are separated by the Banco di Fuori ridge, a meso-cenozoic carbonate monocline, bounded to the southeast by a major structural lineament (Milia & Torrente, 1999). The Magnaghi canyon spans about 20 km in length and originates from the continental shelf south of Procida, between the Ischia and Gaia volcanic banks (Milia & Torrente, 2003), over an area of 20 km^2. The canyon's thalweg is deeply incised along its middle section, with side walls having slopes of up to 40°. Several channels and gullies from Ischia Island and Banco d'Ischia converge from the right side, whereas a great number of niches affect the left canyon wall. The tributary channels are often suspended at the confluence with the canyon's axis, indicating a subsequent re-incision of the main thalweg. The Canyon Dohrn develops for about 50 km, from the Gulf of Pozzuoli to about 1100 m deep south of the Banco di Fuori along the NE-SW-oriented structural lineament that bounds the ridge. Here, too, several gullies and tributary channels are disconnected from the main canyon base level. Particularly, the side branch from the southern shelf features an elevation drop of about 100 m.

4.4. Napoli (MaGIC sheet 8)

The Sheet 8 'Naples' encompasses the eastern sector of the Gulf of Naples off the Mt. Somma-Vesuvius shore, the surrounding marine sectors of Capri Island and Sorrento Peninsula, as well as the western portion of the Gulf of Salerno, and the Salerno Valley, an ENE-

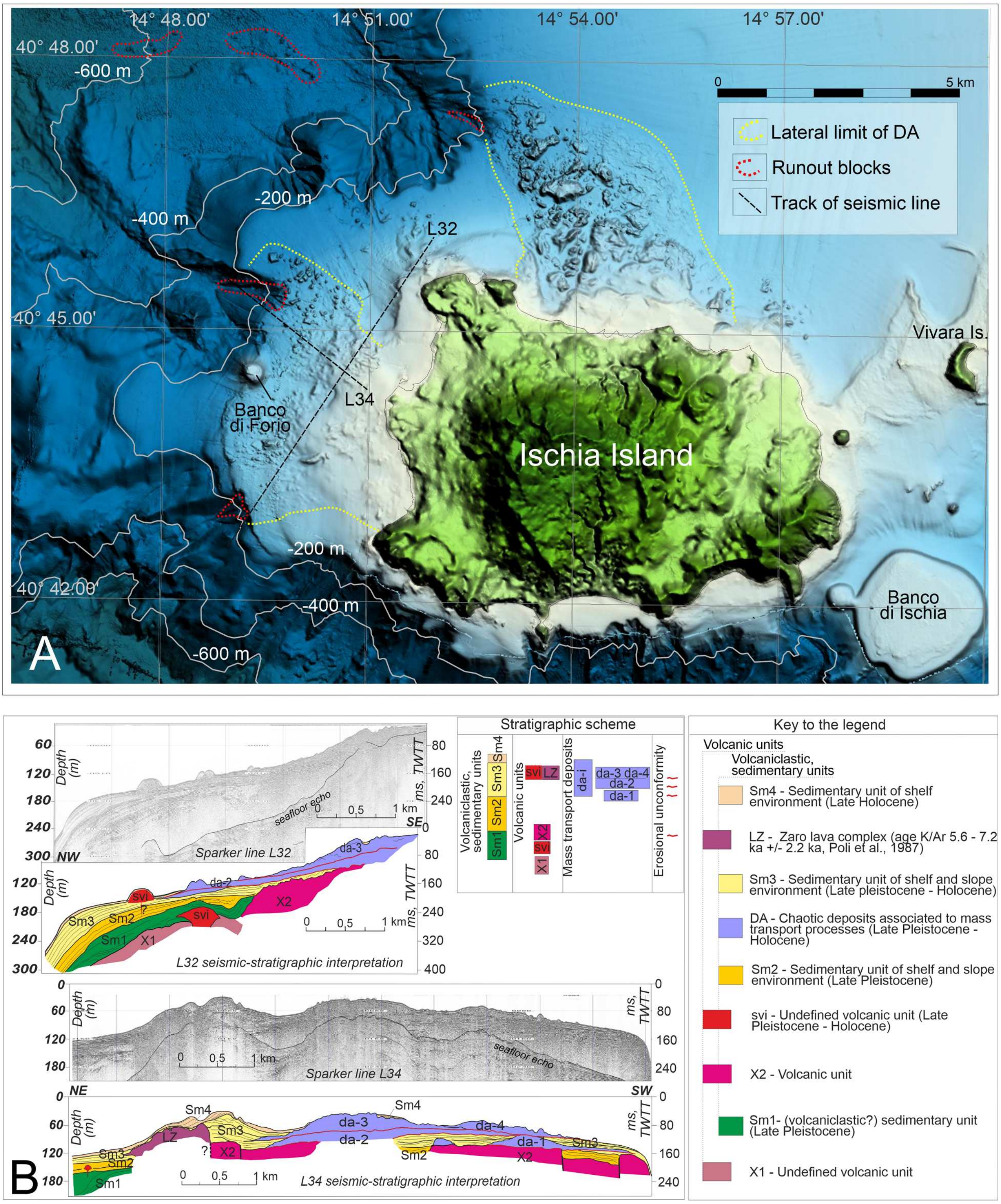

Figure 3. (a) Shaded relief map of the continental shelf and upper slope around Ischia Island, where large mass transport deposits lie (yellow dashed line), related to the gravitational instability episodes of the island's flanks; (b) interpretation of seismic lines (Sparker 1 kJ), acquired within the framework of a cartographic project, shows the stratigraphic relations among chaotic deposits, marine units and deaf seismic units (modified from Servizio Geologico d'Italia, 2019) in the western sector of Ischia Island: at least four events of mass transport depositions are evident.

WSW elongated structural depression, exceeding 1000 m in depth (Main Maps, Sheet n. 8).

The Gulf of Naples and the Gulf of Salerno lie in the southwestern part of two morpho-structural depressions that include the Campania Plain and the Sele Plain on the mainland and are separated by the Sorrento Peninsula structural high (Figure 1). Both depressions developed as half-grabens and were structurally lowered by NW-SE striking normal faults and NE-SW-striking listric faults (Casciello et al., 2006). The sedimentary infill consists of some thousands of meters of sediments resulting from the dismantling of the Apennine chain, volcanic products and epiclasts (Milia & Torrente, 1999; Milia et al., 2017).

The continental shelf in the inner Gulf of Naples exhibits an almost smooth topography. More articulated seafloors are observed offshore of Mt. Somma – Vesuvius, particularly at the Banco della Montagna mound and near the inner sections of the canyon heads. In these sectors, wavy bedforms marking the entry of pyroclastic flows into the sea, volcanic domes, lava flows, debris avalanches, crater-like sinkholes (Milia et al., 2008 and references therein; Passaro et al., 2016b) and active fluid vents (Passaro et al., 2014, 2018; Paoletti et al., 2016) can be observed at the seafloor. Offshore of the Sarno river mouth, wavy bedforms indicate creep deformation in the prodelta section of the pumice deposits from the 79 AD eruption (Sacchi et al., 2005). Recently, evidence of seabed doming and widespread fluid emissions have also been identified at the Banco della Montagna mounds and off the Somma-Vesuvius coast (Passaro et al., 2016b).

In the Gulf of Salerno, a tectonically controlled ENE-WSW trending steep slope (locally exceeding 20°) connects the narrow shelf to the deep part of the Salerno Valley via a large base-of-slope apron. The entire slope is affected by extensive erosional processes, resulting in a deeply carved erosive scarp, characterized by furrows and gullies arranged in a herringbone pattern, alternating with highly unstable crests. The heads of deep channels run close to the coast and serve as the primary pathways for transferring coastal sediment downslope.

The southern slope of the Salerno Valley experienced recurrent mass failure processes. In this area, a complex landslide system known as the Poseidonia landslide covers an area of 200 km^2. It is formed by a depletion front 12 km – long at about 300 m of depth and by a set of transverse ridges and an apron belt at the foot of the slope. The landslide area is situated within a continental margin sector that has been deformed and weakened by older, deep-seated gravitational deformations (referred to as the 'father landslide'). This feature is marked by a deep trench in the depletion area at the slide crown, as well as SW-NE trending compressional ridges – the longest of which exceeds 17 km in length – folding the marine succession in the toe region (Budillon et al., 2014). The junction of the deep trench and the fault-controlled slope of the Paestum Basin may have possibly favored the uprising of fluids and the formation of major pockmarks with uncommon dimensions and deepness (Figure 4 a – d).

The broad vertical displacements (up to 1.500 m), resulting from extensional tectonics and accompanying seismic activity, are seen as the primary agents responsible for gravity-driven mass wasting processes recorded in the stratigraphic succession of the Salerno Valley and the adjacent intraslope basins (Aiello et al., 2009; Budillon et al., 2014; Sammartini et al., 2019).

4.5. Salerno (MaGIC sheet 9)

The Sheet 9 'Salerno' encompasses part of the continental margin off the Sorrento Peninsula, the Sele Plain and the Cilento Promontory. It mainly comprises the continental shelf, the upper continental slope and the proximal sector of the Salerno Valley, which lies within the Salerno half-graben (Main Maps, Sheet n. 9).

The overall thickness of the Pleistocene basin infills within the Salerno half-graben, based on offshore wells and seismic data, ranges between 1500 and 2000m, locally reaching up to 3000 ms (Bartole et al., 1984; Sacchi et al., 1994). These sediment successions consist of marine clastic, epicontinental and volcaniclastic deposits, organized in a complex stratigraphic architecture. They document interactions between glacio-eustatic sea-level fluctuations, volcano-tectonic activity in the source region and tectonic deformation in the sinks.

The asymmetric morphology of the margin reflects the structure of the half-graben: the continental shelf is very narrow to the north, corresponding to the emergence of the regional faults (Milia & Torrente, 1999), whereas it is much broader to the south, due to the presence of bedrock in the subsurface. Consequently, the most significant hazard-related morphological features cluster in the northern sectors of the bay and include landslide scars, gullies and canyon heads associated with the erosive scarp that bounds the Salerno Valley. Additional distinctive morphological elements are observed in the relict and current Sele River prodelta system: in the first case, a set of coalescing channels behind the shelf break fed a deep-sea fan in the Salerno Valley during the Late Pleistocene lowstand of sea level and the early stage of postglacial transgression, when the alluvial plain extended nearly to the present-day shelf break (Aucelli et al., 2012). In the second case, undulated sediment features in the present-day prodelta slope, likely related to density flows of riverine origin (Urgeles et al., 2011) cover an 8 km^2 area. Finally, two extensive fields of wavy bedforms occur in the southern sector of the map on the outer shelf, deeper than 150 m, with crests perpendicular to the isobaths. These features are possibly associated with the ongoing action of geostrophic currents at the shelf margin.

5. Conclusions

The submarine landscape in this sector of the Tyrrhenian margin presents a unique scenario due to the complexity and variety of geomorphic elements potentially associated with varying degrees of hazard. The morpho-bathymetric data reveals a highly articulated submarine landscape, primarily resulting from the recent structuring of the continental margin and

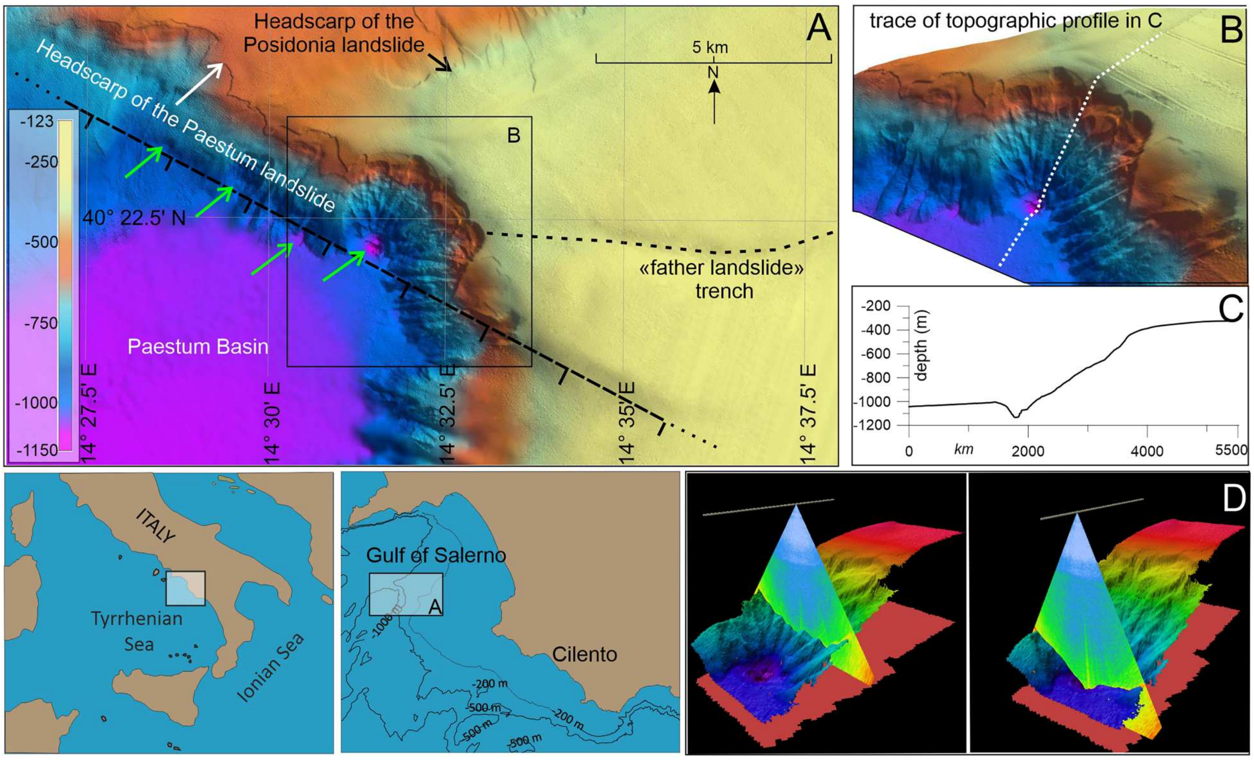

Figure 4. (a) Shaded relief map of the shelf and upper slope approximately 25 km south of the Sorrento Paeninsula, where a set of giant pockmarks (green arrows) occurs along the base of a fault-controlled scarp (dashed-line), bounding the Paestum Basin. The largest pockmark, surrounded by a sub-circular unstable slope, lies at the junction between the fault scarp and the trench of a buried landslide (Budillon et al., 2014); (b) 3D image of the giant-pockmark (vertical exaggeration 2x); (c) topographic profile across the depression (profile track in Figure 4b); (d) echo-soundings in the water column deployed in 2014 did not record any anomalies related to leakages from the seabed.

intense volcano-tectonic activity. Specifically, volcanic processes, differential vertical ground movements, active faulting, glacio-eustasy and rapid dismantling of emerging landscapes, though acting at different time scales, have led to steep slopes, canyoning, deep fans, aprons accretion, gravitational instability and a wide spectrum of volcanic-related features (e.g. channels, gullies, landslides, tuff cones, volcanic structures and banks, fluid venting and wavy bedforms). Key observations made across approximately 10,000 km^2 of seafloor include:

- steep and large escarpments related to regional structural lineaments and significantly impacted by widespread mass-wasting processes. Notable locations include south of the Pontine Islands, west of Ischia Island, south of the Sorrento Peninsula and Capri Island;
- shelf-break retrogression, resulting from the entrenchment of canyon heads. This phenomenon occurs south of Ponza Island, south of the Sorrento Peninsula, south of the Ischia Island and in the Gulf of Gaeta;
- large-scale debris avalanches and debris flows, originating from the lateral slopes of Ischia Island. These mass transport complexes have interacted with lateral branches of the Cuma Canyon and with the Magnaghi Canyon deep-sea fan;
- fluid escape features, both active and inactive, ranging from small to giant dimensions. These features are found off the western Pontine islands, as well as in the Pozzuoli, Naples and Salerno Gulfs;
- extensive bedform fields on the open slope of the shelf margin or within channel/canyon systems in the Gulf of Salerno, south of Ischia Island. These bedform mark recent or ongoing actions of geostrophic and downflowing channelized currents from river mouths.
- a wide spectrum of linear erosive features, including short and localized gullies and channels, up to regionally extending canyons. These features appear to have contributed to the formation of deep – sea fans.

Understanding the submarine morphological features in this geodynamically active and densely populated coastal area, and monitoring those considered most hazardous over time, are crucial practices for geological and environmental risk assessment and implementation of area-based management tools. This study could serve as a benchmark for future monitoring of hazardous features and for spatial planning initiatives, relative to the first decade of the 2000s.

Software

Mapping was implemented using Global Mapper® software, Magic Project release, for bathymetric data visualization and geo-morphological features outlining. Standardization and topological control among maps were carried out using freeware GIS. Figures in this article were compiled with Global Mapper® and Corel Draw® graphical suite.

Acknowledgements

The Magic Project has been funded by the Italian Civil Protection Department. We sincerely thank the crews of R/V Urania, R/V Maria Grazia (CNR), R/V Universitatis (Conisma) and R/V Explora (OGS), who have navigated extensively and contributed to acquiring such large amount of bathymetric data. We are particularly grateful to Massimo Cesarano and Danilo Morelli for their valuable suggestions.

Disclosure statement

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

Data availability statement

Bathymetric data are available at Emodnet website at https://emodnet.ec.europa.eu/en/bathymetry, upon registration. The Atlas of the Magic Project (four levels of map interpretation and accompanying notes to the maps) is available as PDF at https://www.protezionecivile.gov.it/static/114eacd3c18418f93435ef1fc7f1b693/atlante-magic-versione-stampata.pdf Seismic data are available upon request to the corresponding author.

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