Journal of Geography and Cartography (2023) Volume 6 Issue 1
doi:10.24294/jgc.v6i1.1855

REVIEW ARTICLE

A review of the CARG Project of the Campania Region (marine counterpart; southern Tyrrhenian Sea): New perspectives in marine geology and cartography

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ABSTRACT

A review of the CARG Project of the Campania Region (marine counterpart) up to water depths of 200 m is herein proposed referring to the Gulf of Naples (southern Tyrrhenian Sea) aimed at focusing on the main scientific results obtained in the frame of this important project of marine geological cartography. The Gulf of Naples includes several geological sheets, namely n. 464 "Island of Ischia" both at the 1:25,000 and 1:10,000 scale, n. 465 "Island of Procida" at the 1:50,000 scale, n. 466–485 "Sorrento–Termini" at the 1:50,000 scale, n. 446–447 Naples at the 1:50,000 scale, and n. 484 "Island of Capri" at the 1:25,000 scale. The detailed revision of both the marine geological and geophysical data and of the literature data has allowed us to outline new perspectives in marine geology and cartography of Campania Region, including monitoring of coastal zone and individuation of coastal and volcano-tectonic and marine hazards.

Keywords: CARG Project; Marine Geology and Cartography; Gulf of Naples; Campania Region; Southern Tyrrhenian Sea

ARTICLE INFO

Received: 24 December 2022
Accepted: 15 May 2023
Available online: 2 June 2023

1. Introduction

In this paper, a review of the CARG Project of the Campania Region has been carried out aimed at outlining new perspectives in marine geology and cartography. This is one of the most important projects in the field of marine geology carried out in Italy, allowing for the acquisition, processing, and geological interpretation of a large amount of geological and geophysical data. These data have been published in the geological maps and in the explanatory notes to the geological sheets, but they have been also interpreted in many scientific publications and papers.

The history of the CARG Project of the Campania Region is described, necessary for the comprehension of the project and its review. In April 1997, the "Geomare Sud" CNR Research Institute (now CNR ISMAR of Naples, Italy) was entrusted with the experimental creation of marine geological maps at a scale of 1:50,000 relating to the sheets "Salerno" (n. 467), "Sorrento" (n. 466) and "Procida" (n. 465) within the framework of the program agreement between the Presidency of the Council of Ministers-National Geological Service (now ISPRA, Rome, Italy) and the National Research Council (CNR, Rome, Italy). This project foresees that the survey of the marine geological cartography is carried out at a scale of 1:25,000 and returned and computerized at a scale of 1:50,000. Furthermore, at the same scale and with agreements between the Geomare Institute and the National Geological Service (which did not provide for further funding), the coverage of the coastal areas that fall within the "Termini" (n. 485) and "Capri" (no. 484) geological sheets.

In the second half of 1999, and on various occasions, the Geotechnical, Geothermal, and Soil Defense Sector (Campania Region, Naples, Italy), which coordinates the CARG activities within the Campania Region, requested the Geomare Sud Institute for a project and economic evaluation for the completion of the geological sheets to the scale 1:50,000 measured at scale 1:10,000 and up to water depths of 200 m for the sheets "Sapri" (n. 520), "Capo Palinuro" (n. 519), "Agropoli" (n. 502), "Foce Sele" (n. 486), "Island of Ischia" (n. 464), "Napoli" (n. 446–447), "Termini" (n. 485), "Island of Capri" (n. 484), "Mondragone" (n. 429) and "Sessa Aurunca" (n. 416) with detection up to and including the physiographic unit of the Promontory of Gaeta.

In the first half of 2001, the Campania Region provided for the financing of marine geological maps with CARG modality in collaboration with the Research Institute of the National Research Council, for the completion of the geological sheets at the scale 1:50,000 detected up to the scale 1:10,000 and up to water depths of 200 m for the sheets "Sapri" (n. 520), "Capo Palinuro" (n. 519), "Agropoli" (n. 502), "Foce Sele" (n. 486), "Island of Ischia" (n. 464), and "Naples" (n. 446–447).

In the second half of 2001, in support of the "Extract Plan for Coastal Erosion" financed by the Sarno, North-West, and Liri-Garigliano-Volturno Regional Basin Authorities, the Geotechnical Geothermal and Soil Defense Sector of the Campania Region requested the CNR ISMAR of Naples a project and economic evaluation for the completion of the geological sheets at the 1:50,000 scale in the CARG area, this time at the 1:5,000 and 1:10,000 scale in coastal areas with particular regard to the areas between the shoreline up to water depths of 20 m.

In November 2001, the Geotechnical Geothermal and Soil Defense Sector of the Campania Region produced an overall document, submitted for the relative financing to the Sarno North-Western and Liri-Garigliano-Volturno Regional Basin Authorities in which the general lines, the modalities and the economic cost estimate proposed by various groups (Underwater Geology, Marine Geology, Coastal Morphology), which, coordinated by the competent sector of the Campania Region, should have supervised the realization of the entire project.

It is clear, from history up to this reconstruction, that the marine geological cartography project has progressively moved from an initial experimental phase with characters of Regional Geology to a completely different phase which, for the needs of regional planning and land management, provides for detailed surveys on a scale of 1:10,000.

This progressive shift of the research center of gravity from the initial general scales to the detailed ones of the latest proposals (which imply different acquisition specifications) poses significant problems for the homogeneity of the data collected over the years, not only for the change in scale that the new projects require, but also for the technological gap of the equipment used for data collection.

It should be remembered that the CARG National project for the realization of the marine geological cartography of the sheets "Salerno" (n. 467), "Sorrento" (n. 466), and "Procida" with a 1:25,000 scale survey can be considered contiguous to the CARG project financed by the Campania Region for the realization of marine geological cartography on a scale of 1:10,000 within water depths of 200 m, but not able to respond, unless a technical-scientific (and consequently also economic) adaptation, to the new specifications required by the CARG project financed by the Campania Region.

The location of the geological maps of the Campania Region is shown in **Figure 1**.

The Gulf of Naples includes several geological sheets, namely n. 464 "Island of Ischia" both at the 1:25,000 and 1:10,000 scale, n. 465 "Island of Procida" at the 1:50,000 scale, n. 466–485 "Sorrento–Termini" at the 1:50,000 scale, n. 446–447, "Napoli" at the 1:50,000 scale, and n. 484 "Island of Capri" at the 1:25,000 scale. The geological maps are completed by significant explanatory notes (**Table 1**), which have described the geological setting of the maps both onshore and offshore.

This review aims at individuating new perspectives in the marine geology and cartography of the Campania Region, including the monitoring of the coastal zone and the individuation of coastal and volcano-tectonic and marine hazards. Coastal areas are highly sensitive geological zones, whose modification is a function of several geological processes. The Campania region hosts both low coasts

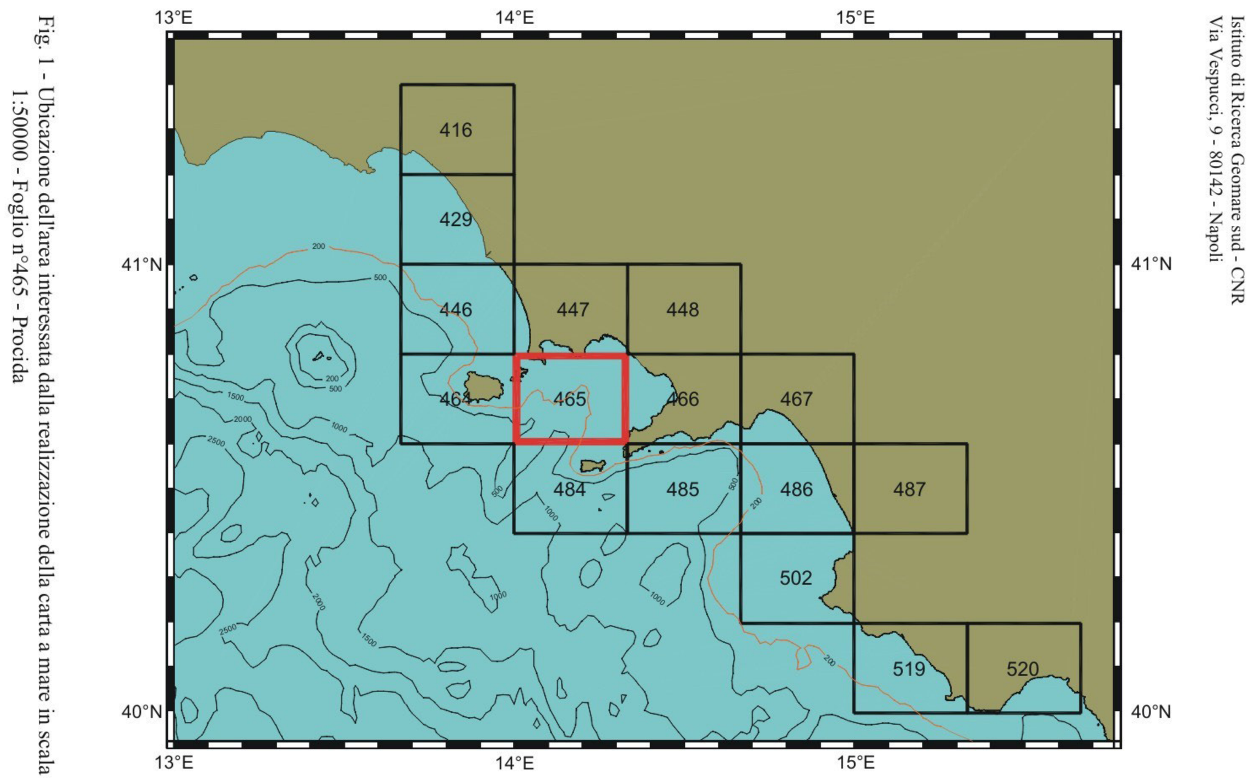

Figure 1. Location map of the geological sheets of the CARG Project (Campania Region). As an example, the geological map n. 465 "Island of Procida" is underlined with bold red line.

Table 1. Geological maps and explanatory notes of the CARG Project of the Campania Region

Location	Geological map	Scale	Explanatory notes
Gulf of Naples	n. 464 "Island of Ischia"	1:25,000; 1:10,000	[1]
Gulf of Naples	n. 465 "Island of Procida"	1:50,000	[2]
Gulf of Naples	466–485 "Sorrento–Termini"	1:50,000	[3]
Gulf of Naples	446–447 "Napoli"	1:50,000	[4]
Gulf of Naples	484 "Island of Capri"	1:25,000	[5]
Gulf of Salerno–Cilento	486 "Foce del Sele"	1:50,000	[6]
Gulf of Salerno–Cilento	502 "Agropoli"	1:50,000	[7]
Gulf of Salerno–Cilento	519 "Capo Palinuro"	1:50,000	[8]
Gulf of Salerno–Cilento	520 "Sapri"	1:50,000	[9]

and high coasts, whose geomorphologic setting and geologic evolution are quite different.

The Ischia coast, for instance, displays two main zones: the northern sector discloses hills, while the southern one reveals coastal cliffs, promontories and embayments (**Figure 2**). Low coasts have undergone a strong erosional retreat, as in the case of the Maronti beach, where significant beach nourishment has been realized. The tracts of the rocky coasts of Ischia can be correlated with erosional surfaces, produced during the Quaternary for interacting volcano-tectonic processes, eustatic sea-level variations, and climate forcing. A significant control factor in modeling the morphology of the rocky coasts is represented by the coastal landslides, genetically related to the sea action, together with the wave erosion at the toe of coastal cliffs, i.e., the scouring, triggering the rock falls[10].

Marine hazards in the Gulf of Naples have been recently discussed based on geomorphologic interpretation[11]. A slope gradient map and a high slope map have been constructed to individuate the areas potentially prone to sliding. The cluster of the slope gradient distribution and the consequent re-classification process has allowed us to define six slope classes, resulting in a thematic map of the seabed morphological structures and, in further detail, a map of the structure classes of the Naples canyons. Three domains have been distinguished from high gradients on the slope map, suggesting a high geologic hazard of submarine features (southern Ischia slope, Naples canyons, southern Capri–Sorrento slope). Detailed geomorphological maps of these domains have been constructed based on the geological interpretation and the structure classes defined by the Bathymetric Position Index. These maps could provide a useful tool for planning and management of coastal zones in the submarine portions of Naples Bay.

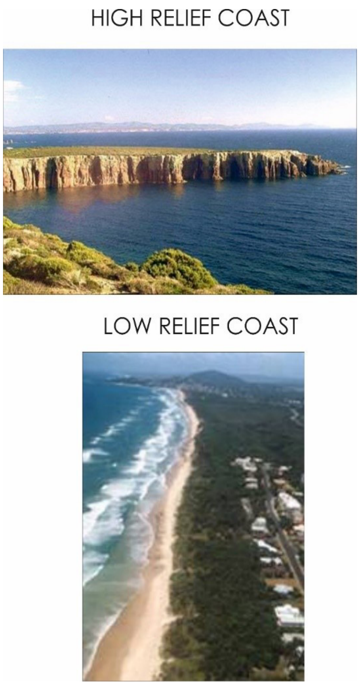

Figure 2. High-relief coasts and low-relief coasts of Ischia.

On the contrary, the geologic hazard of the Gulf of Salerno and of the Cilento Promontory is still relatively unknown, except for the general lines. Aiello and Marsella[12] have outlined the geologic evolution of the Cilento Promontory The geological evolution of coastal and marine environments offshore the Cilento Promontory (submerged beach, inner shelf, outer shelf, lowstand system tract, Pleistocene relict marine units, and rocky units of the substratum) has been discussed through the identification of corresponding deposits and their cartographic representation. The seismic stratigraphy of the Agropoli continental shelf (southern Campania) has been highlighted through the geological interpretation of a densely spaced grid of Chirp seismic profiles.

Budetta[13] has revealed that almost 56% of the coastal area of the Cilento Promontory displays high landslide hazard, 27% is characterized by medium landslide hazard, whereas only 17% is characterized by low landslide hazard. Data regarding failure mechanisms, landslide mobility as well as run-out distances of about 228 landslides directly or indirectly triggered by the wave motion were collected. Using these data and the IFFI Catalog ("Inventario Fenomeni Franosi Italiani"), a Coastal Landslide Density Map has been constructed[13].

Guida and Valente[14] have shown the terrestrial and marine landforms along the Cilento Promontory as a framework for the assessment of the landslide hazard and environmental conservation. Despite the high capability of erosion of the rocks emerging from the sea and the effects of human activities, a wide variety of landforms are preserved in this area. The Licosa Cape and the promontory of Ripe Rosse located in northern Cilento have been used as reference areas. Methods were used that enabled us to obtain detailed digital cartography of each area and consequently apply physical-based coastal evolution models. The proposed approach has provided better management of coastal risk mitigation in the Campania region.

Aiello and Caccavale[15] have described the depositional environments of the Cilento offshore based on marine geological data. The toe-of-coastal cliff deposits and submerged beach deposits, the inner shelf deposits and bioclastic deposits, the outer shelf deposits and bioclastic deposits, the lowstand system tract, and the Pleistocene relict marine units have been identified. The littoral, inner shelf, and outer shelf environments have been interpreted as the highstand system tract of the Late Quaternary depositional sequence. The palimpsest deposits of emerged to the submerged beach have been recognized on sub-bottom profiles and calibrated with gravity core data collected in previous papers.

2. Materials and methods

The rapid evolution of research in the field of Earth Sciences and the importance of geological cartography in land management have made a new geological survey necessary for the creation of updated cartography with greater information content. The data acquired in the context of this topic also allow us to define the dynamics of the current and recent sedimentation; this knowledge is necessary for sustainable use and for the protection of coastal zones and shelf areas. In this regard, the CNR ISMAR of Naples, Italy, carried out a series of oceanographic campaigns, which contributed to the collection of a considerable amount of data.

Multibeam data have been mostly collected on the R/V Urania (CNR), while other vessels (Thetis, Luigi Sanzo; CNR) have been used at water depths lower than 50 m for coastal surveys. There is a complexity related to the scale of execution of the bathymetric surveys of the CARG Project. In the theoretical range of 0–20 data were acquired with sufficient detail for a return at the scale of 1:5,000. In the 20/200 bathymetric range, data were acquired with sufficient detail to be returned to the scale of 1:10,000. The whole data acquisition plan (seismic, bathymetric, acoustic, and sampling) was suitably established on the basis of the bathymetric bands, the morphology of the seabed, and the course of the coastline, with the aim of achieving the expected objectives. The construction of a topographical base of the coastline and bathymetric bases with predetermined scales was an integral part of the implementation of the project in question, and in particular for the area of sheet n. 465. For this purpose, the CNR-ISMAR of Naples carried out the digitization of the coastline of the Campania Region on aerial photos provided by the Campania Region in 2004, in order to provide a reliable working base for cartographic restitution.

The operational indications for the acquisition of geophysical data within the internal platform extended between the mean sea level 0 m and –30 m are included in an area that coincides with the limit of direct surveys carried out by the underwater geologist immersed in safe conditions and therefore the limit of the possibility of carrying out "truth at sea". These indications are partly extended to the remaining area of the continental shelf, adapting them to the geomorphological conditions of the seabed, with the aim of drawing up geological maps of the seabed, both at a scale of 1:25,000 and at a scale of 1:10,000.

The geophysical surveys carried out for the CARG Project include single beam bathymetric surveys of submerged beaches in the bathymetric belt from 0 m to 5 m; Multibeam bathymetric surveys with total coverage of the range between –5/–200 m for low coasts and theoretical 0.0/–200 for high coasts; high definition Side Scan Sonar mapping and total coverage of the range between –2 and –50 m for low coasts and 0 (theoretical)/–50 m and adequate coverage according to the characteristics of the seabed in the –50/–200 m (performed with conventional Side Scan Sonar or using the Side Option of coastal Multibeam systems); high-resolution seismic surveys according to significant routes for the stratigraphic definition of the substrate.

The data acquisition campaigns carried out as part of the CARG Project are positioned in differential DGPS. The use of differential positioning allows the acquisition of marine geophysics data and high-precision sampling. The most used navigation programs are NAVPRO, (Communication Technology, Italy), HYDRO, (New Zealand), and PDS 2000 (Thales Geosolutions, The Netherlands), used mainly for Multibeam surveys. The Datum used for the acquisition of the ship points (fix) during the acquisition of the profiles is WGS 84. The most commonly used projection is the UTM (Universal Transverse Mercator) but other datum has been used or can be used (ED 50, Rome 40) and projections (Gauss-Boaga).

In particular, the Multibeam bathymetric survey carried out for the CARG Project (survey carried out with Multibeam ELACMK2) was performed using the GPS system in differential mode for positioning the data[16] (**Figure 3**). The connection between the differential stations on the ground and the onboard station for the transmission of the differential corrections was provided by radio links in the VHF band (146.875 MHz). In order to ensure its accuracy and reliability, 4 reference points were used, strategically located so that each point of the work area could be covered simultaneously by two stations. The detection routes, parallel to the coast, were appropriately spaced in order to obtain total coverage; the speed is such to guarantee high sampling frequencies of the digital data, while always guaranteeing digital safety, the maneuverability of the boat (usually acquisition speeds between 4 and 7 knots are used). The detection routes, parallel to the coast, were appropriately spaced in order to obtain total coverage; the speed is s as to guarantee high sampling frequencies of the digital data, while always guaranteeing digital safety, the maneuverability of the boat (usually acquisition speeds between 4 and 7 knots are used).

A profiler for the values of pressure, temperature and conductivity (multi-parametric probe CTD) was used for the calibration of the Multibeam in order to adopt a correct value of the speed of

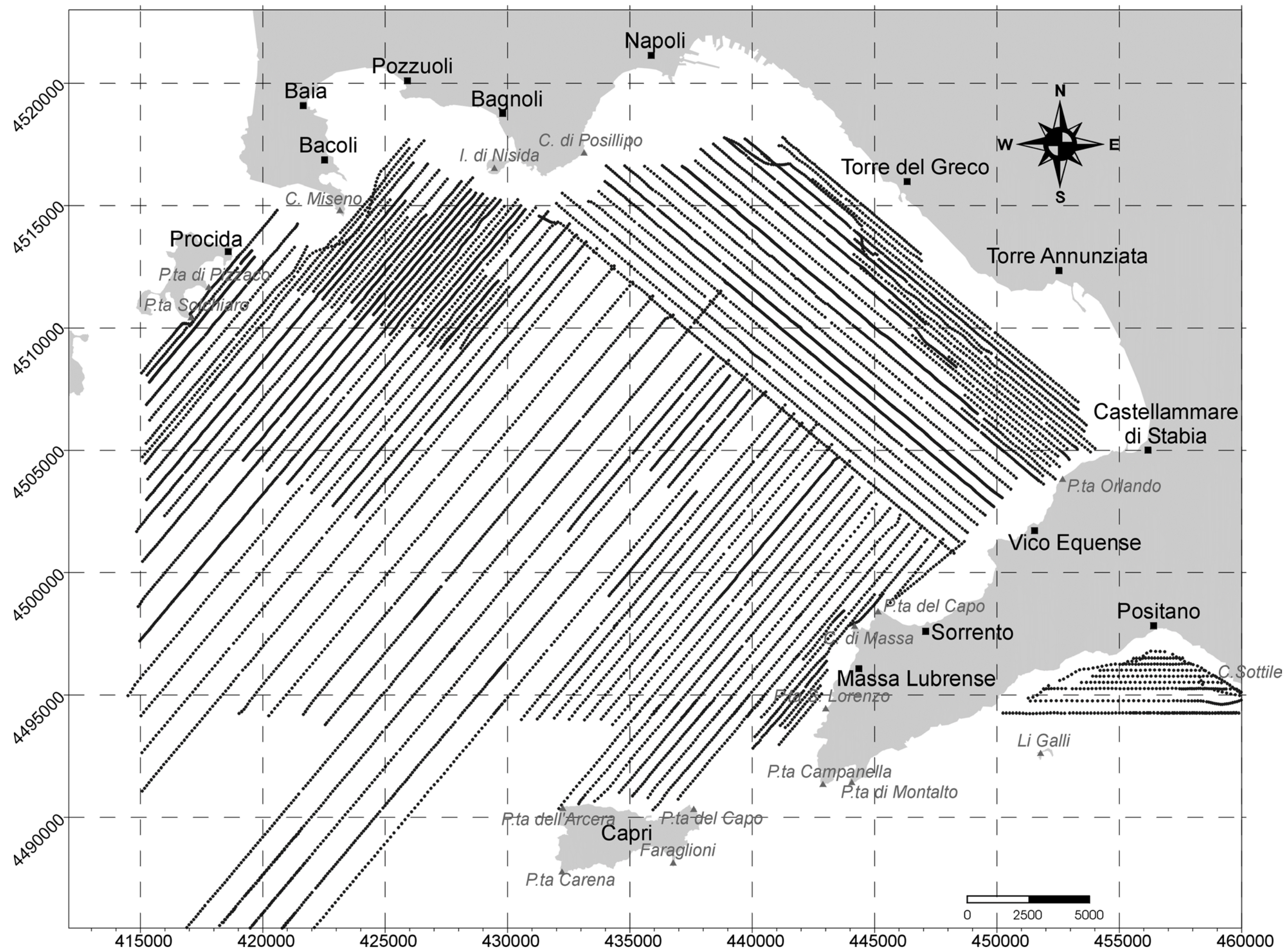

Figure 3. Multibeam bathymetry navigation lines (ELAC BottomChart MK2) and Subbottom Chirp profiles acquired during the GMS97-01 cruise (1997)[16].

sound in the water. Speed profiles were performed via CTD at regular intervals every 6 h. In addition, the Chirp Sub-bottom profiler system supplied to N/O Urania was used during the acquisition of the Multibeam survey. This allowed the acquisition of a densely-spaced grid of Sub-bottom profiles on the same navigation strips of the Multibeam, allowing a detailed calibration of the morphological structures recognizable at the seabed from the bathymetry.

Multichannel seismic data have also been recorded. The multichannel seismic acquisition system with pneumatic sources supplied to the CNR ISMAR of Naples consists of a multichannel seismic recorder Stratavisor (Geometrics Inc.) and a 24-channel cable or streamer (also prepared for 48 channels), distributed in three active sections, of 50 m each, provided for each channel of 8 piezoelectric hydrophones, with 6.25 m or 12 m inter-track; a seismic source Watergun S15, from 10 c.i. of capacity; a 210 c.i. Airgun source for greater penetration; a trigger to command the firing of the guns; an analog filtering bench, built at the South Geomare, consisting of 12 active band-pass filters with 60–600 Hz cut-off frequencies. The pneumatic sources are connected with airlines (umbelicals) to 1 or 2 Bauer compressors capable of delivering volumes of air at a pressure of 140–180 bar suitable for a burst frequency of even 1 sec. (for the Watergun) or 3–4 sec. (for the Airgun).

As part of the CARG Project, a grid of multichannel reflection seismic profiles was acquired in the Gulf of Naples using the Airgun seismic sources supplied to the CNR-IAMC in Naples. The geological interpretation of these profiles made it possible to carry out a reconstruction of the stratigraphic and structural arrangement of the Gulf of Naples[16,17]. During the GMS00-05 oceanographic cruise (October–November 2000), a grid of seismic profiles was acquired in the Gulf of Naples, using the Watergun acquisition system[18]. A grid of Sub-bottom Chirp profiles and magnetic profiles[19] were acquired on the same navigation lines as the seismic sections. The multichannel seismic data were stored on cassettes and CDs, which depend on the acquisition system. The recording was made using a 200 m long seismic cable (active section = 150 m and passive section = 50 m). The shots were carried out at a constant interval of 6.5 m (or 8 sec). The reception range was 6 m, the minimum offset of 130 m and coverage of 1,200%. The sampling interval was selected at 1 msec (sampling rate = 1,000 Hz).

A densely spaced grid of single-channel seismic profiles has been interpreted in the frame of the CARG Project during the mapping of the marine areas of the geological sheet n. 464 ‘‘Island of Ischia’’ at the scale 1:25,000[1,20]. The seismic grid was recorded using a Sparker Multitip seismic source. The seismic lines have been plotted on the marine Digital Elevation Model (DEM), allowing a detailed geological interpretation of the main morphological structures occurring at the seabed. The seismic grid consists of 13 dip seismic lines in the southern offshore, running perpendicularly to the shoreline, and 2 tie lines, parallel to the shoreline.

Seabed and subsurface samples have been collected. One of the most critical phases is the taking of samples, especially in a marine environment. In coastal and marine areas, seabed sediments show great spatial and temporal variability. Bottom and subsurface sediments are typically collected with bucket-type samplers, box-corers, and core barrels. Sedimentary, metamorphic, or magmatic rocky outcrops are instead sampled by dredging. The sedimentological characterization of the seabed is ensured by analyzing the samples taken using a box corer and bucket, while the stratigraphy of the first substrate is studied using gravity and/or piston core barrels. The lithology and age of rock outcrops are defined by dredging samples.

The surface samplings are located for perpendicular transects to the coast, taking into consideration the main bathymetric bands. The cores are positioned based on the interpretation of the seismic profiles to evaluate the thicknesses and grain size variations of the more superficial stratigraphic intervals and to identify the depositional sequences.

This *in situ* sampling phase is followed by a laboratory analysis phase, which consists of sedimentological analyses and paleontological analyses. The sedimentological analyses have been carried out following several procedures, including the descriptive analysis of the samples (photographs and visual description based on the ODP protocol); the particle size analysis using a Laser Diffraction Particle Size Analyzer model Sympatec Helos/KF and a vibrating sieve model IG3/WET, which will analyze the fraction below and above 1,000 μ respectively; the data processing and grain-size characterization of the sample according to the most commonly used classification systems, histograms and semilogarithmic cumulative curves and calculation of the main statistical parameters; the production of maps at the required scale representative of the areal distribution of sediments. Ternary diagrams of the sedimentological data have also been produced[15].

3. Geologic setting

A new geologic map of the Campania Region, including the Naples and Salerno Bays, has been recently constructed[21] (**Figure 4**). This map results from the re-interpretation of the available geologic cartography at the 1:100,000 scale (Italian Geological Survey). This map shows that the Southern Apennines is composed of different thrust sheets, related to Meso-Cenozoic deep basin to shallow water successions, crossed by Quaternary coastal plains on the Tyrrhenian sector (Campania Plain, Sele Plain).

The orogenic structure consists of three main tectonic complexes, including the Ligurian Accretionary Complex, the Apennine platform units and the Lagonegro-Molise Basin units[21]. These complexes are unconformably overlain by Miocenic to Pliocenic wedge-top basin deposits and by Quaternary marine and volcanic deposits (**Figure 4**). The kinematic complexes are reported in **Figure 4**[21]. In particular, the Ligurian Accretionary Complex consists of the Nord-Calabrese Unit and of the Parasicilide unit. The Nord Calabrese Unit is made up of three formations, including the Crete Nere Formation, the Saraceno Formation, and the Sovereto Formation[22]. The Parasicilide unit consists of four formations, including the Argille Scagliose Formation, the Monte S. Arcangelo Formation, the Argille Varicolori Formation, and the Arenarie di Albanella Formation[23]. In the southern sector, the Apenninic platform is composed of the M.te Bulgheria and Roccagloriosa units, the Alburno-Cervati-Soprano units, and of the Maddalena-Foraporta unit (**Figure 4**). In the central sector, the Apenninic platform is composed of the Capri Island unit, the Lattari-Picentini-Marzano-Sarno-Avella and Caserta units,

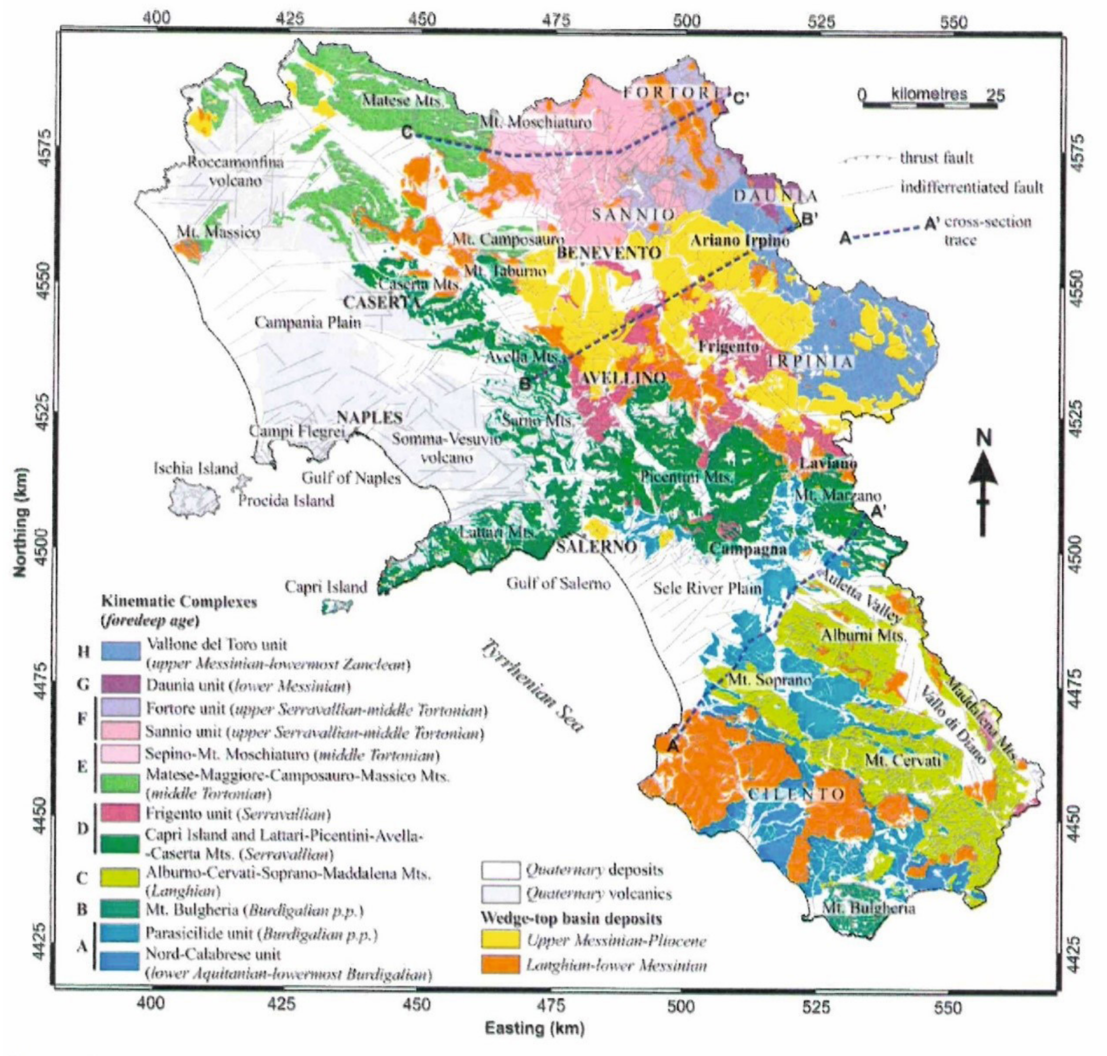

Figure 4. Geologic map of the Campania Region (modified after Vitale and Ciarcia[21]).

and the Laviano-M.te Croce unit (**Figure 4**). In the northern sector, the Apenninic platform is composed of the Camposauro, Matese, Maggiore and Massico Mts unit. The Lagonegro-Molise Basin unit consists of the Frigento unit, the Sepino-M.te Moschiaturo unit, the Sannio unit, the Fortore unit, the Daunia unit, and the Vallone del Toro unit[24] (**Figure 4**). The wedge-top basin deposits include five main cycles, i.e., the Cilento Group, the Castelvetere Group, the Altavilla Group, the Baronia Formation and the Sferracavallo Formation. The Cilento Group includes the Pollica and S. Mauro Formations[8]. The Castelvetere Group, overlying the Cilento Group, includes numerous formations[21]. Finally, the Pleistocene-recent deposits filling the Quaternary coastal plains of Latium-Campania (Campania, Garigliano, and Volturno river plains) consist of marine, lacustrine, fluvial, and volcanic sediments[25–28].

The Gulf of Naples represents an excellent natural laboratory, where the sedimentary filling has recorded the interactions between tectonic, volcanic, and depositional/erosional processes, which acted together with the tectonic uplift and deformation of the underlying areas that emerged during the Pleistocene.

The peculiarity of the Gulf of Naples with respect to the adjacent peri-tyrrhenian basins (i.e., the basins of Terracina and Gaeta to the north and the Policastro basin to the south) is due both to the presence of a structural high carbonate basement (Sorrento Peninsula-Capri Island high), which played a fundamental role in the identification and recent tectonic evolution of the basin itself, and to the strong volcanic activity during the upper Pleistocene (volcanic centers of Campi Flegrei, Somma-Vesuvius and the islands of Ischia and Procida), which has created a considerable complexity in the distribution of sedimentary and volcanic seismic units[16,17]. The western sector of the Gulf of Naples is characterized by the prevalence of seismic units of a volcanic nature, frequently associated with positive magnetic anomalies, while the eastern one is characterized by the presence of sedimentary units.

After an initial impulse of scientific research on the Gulfs of Naples and Pozzuoli between the 70 s and 80 s resulting from the need for new investigations following the bradyseismic crises[29–34], there has been a recent scientific production on the stratigraphy of the seismic units of the Gulf of Naples based on models of sequence stratigraphy[20,26–28].

A notable boost to volcanological research on the Gulf of Naples has been given in the last twenty years by the Vesuvius Observatory, currently merged into the National Institute of Geophysics and Volcanology, which boasts publications of a high scientific level on various methodological aspects and above all on seismic and environmental risk linked to the Somma-Vesuvius, including tomography of the volcano[35,36].

Over the past twenty years, the Gulf of Naples has been the subject of numerous reflection seismic surveys, especially single-channel seismic surveys recorded with a Sparker source by the Institute of Oceanology of the Naval University Institute of Naples[30,31,34,37], but also of multichannel seismic recorded by Experimental Geophysical Observatory of Trieste[32], recently reprocessed and reinterpreted[38].

The offshore between the Sorrento Peninsula and the Cilento Promontory, which houses the structural depression of the Gulf of Salerno, is characterized by a relatively large and extensive continental shelf (up to 25 km) west of the Cilento coast, with a thin sedimentary (from a few tens of meters to a few hundred meters thick). South of the Sorrento Peninsula, there is a tiny continental shelf (maximum 11 km) and there are very steep continental slopes, which delimit the structural depression of the Salerno Basin. The identification and the tectonic arrangement of the Salerno Basin were mainly controlled by the main Capri-Sorrento Peninsula fault, which has a WSW-ENE trend (with an average throw of about 1,500 m; **Figure 5**, intermediate inset), which delimits the structural high to the south of the Sorrento Peninsula, where Mesozoic carbonate platform deposits emerge extensively. Previous studies in the Salerno and Cilento offshore mainly concerned the stratigraphy and sedimentology of the Quaternary deposits[39–41]; less attention has been paid to the structural setting of the area, which at the same time has been intensively explored by the Italian oil companies[42,43].

The Salerno Basin (or Salerno Valley) is a half-graben of the Pleistocene age, whose identification and tectonic structure were controlled by the direct fault (with probable strike-slip component) Capri-Sorrento Peninsula[41]. This fault also controlled the origin of the Salerno canyon, which shows active erosional processes and syn-sedimentary tectonics. The acoustic basement is composed of Mesozoic carbonate platform units (Mina 1, Milena 1 and Margherita Mare 1 lithostratigraphic wells; https://www.videpi.com/) and the overlying Miocene siliciclastic units related to the "Liguride Units" and associated Miocene foredeep deposits ("Cilento Units"), outcropping on land in the Cilento Promontory[8,21,22].

The Salerno Valley shows an example of a complex Quaternary filling of a tectonically controlled sedimentary basin, recording the interactions between the effects of eustatic sea level changes and the effects of tectonic activity in the source region and tectonic strain in the depositional area, which reaches up to recent times. The high sedimentary inputs, combined with a limited dispersion of sediments, have produced the deposition of a thick succession of Quaternary age, which locally exceeds 3,000 m in thickness. The filling of the basin is composed of marls and marly clays with interbedded sands and conglomerates and then of marly clays with interbedded fine sands (Pleistocene). Based on offshore well data, the average thickness of the Pleistocene filling of the Gulf of Salerno ranges between 1,500 m and 2,000 m. In the Cilento offshore (Milena 1 and Margherita Mare 1 wells; https://www.videpi.com/), a regional unconformity, probably of Messinian age, associated with a non-depositional and/or erosional hiatus (the Pliocene is completely missing) characterizes the base of the Pleistocene sequences.

The Cilento Promontory constitutes a morpho-structural high, which is interposed between the coastal depressions of the Sele Plain—Gulf of Salerno and the Gulf of Policastro, whose reliefs also reach 1,700 m in height. These reliefs are made up of powerful successions of siliciclastic and carbonate turbiditic sequences ("Flysch del Cilento" Auct.), which dip towards the ground in the main carbonate reliefs of the southern Apennines ("Alburno-Cervati Unit" Auct.). Normal faults of

Quaternary age define the edges of the structure of the Cilento Promontory. Apart from the carbonate structures of Capo Palinuro and Monte Bulgheria and a few other isolated outcrops, the mountains and hills that characterize the Cilento Promontory are formed by terrigenous rocks that have accumulated inside deep basins in a time interval between Upper Mesozoic and Upper Miocene. The oldest of these formations belongs to the Northern Calabrian Unit[21,22].

4. Results

A merged DEM of the Gulf of Naples and of the Gulf of Salerno has been constructed (**Figure 5**) joining the Multibeam bathymetric data recorded in the Naples Bay (http://www.isprambiente.gov.it/Media/carg/campania.html) and the Multibeam data recorded in the SISTER II oceanographic cruise in the Gulf of Salerno[41]. The main morpho-structural lineaments have also been reported. This map represents a useful base for reviewing and discussing the results obtained in single geological sheets, as reported in the following sub-headings.

4.1 Geological sheet n. 464 "Island of Ischia"

Ischia is one the most interesting sheets of the CARG Project, characterized by a complex

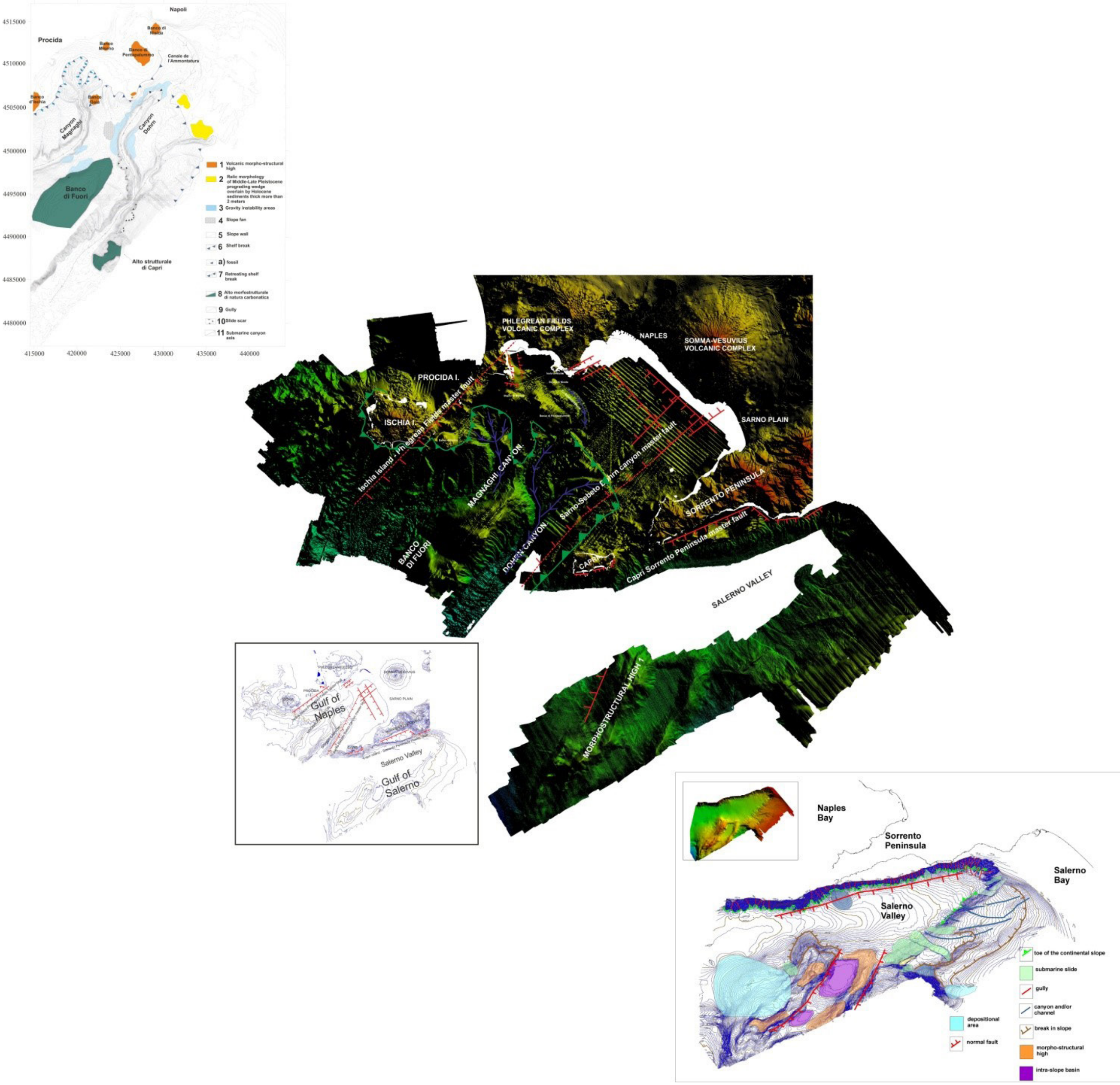

Figure 5. Merged DEM of the Gulfs of Naples and Salerno. The main morpho-structural lineaments have also been reported. The green line with filled triangles corresponds to the shelf break. The upper inset shows a detailed geomorphologic map of the Naples canyons. The medium inset shows the main fault systems of the two gulfs. The lower inset shows a detailed morpho-structural map of the Salerno Valley.

and beautiful geology, both onshore and offshore. Reviewing this geological map implies deepening some research lines, respectively the tephrostratigraphy and volcanic markers both onshore and offshore, the debris avalanche deposits, both onshore and offshore, the seismo-stratigraphic setting and the volcanic and sedimentary seismic units and the marine terraces, the tectonic uplift and the caldera resurgence.

4.1.1 Tephrostratigraphy and volcanic markers

Marine sediments represent a natural archive capable of preserving levels of tephra produced by volcanic eruptions, thanks to their almost continuous rate of sedimentation. The geochemical characterization of tephra in marine sediments contributes to the improvement of knowledge about the magmatic evolution of the volcanic provinces that insist in the Mediterranean area over a wide time range. Due to the presence of numerous active volcanoes, the Mediterranean Sea represents an ideal site for tephrostratigraphic and tephrochronological interpretations. There are currently works in the literature that provide for this area, consistent and reliable tephrostratigraphic patterns useful for large-scale correlations[44–46].

Zanchetta *et al*.[44] have highlighted that the occurrence of tephra beds in Quaternary Mediterranean successions represents a useful tool for dating and correlating different sedimentary archives. These tephras can resolve the long-standing issues in palaeo-climatology and can correlate the terrestrial and marine paleoclimate archives. Regional tephras derive from central and southern Italy, the Hellenic Arc, and Anatolia. Several layers occurred at the time of the S1 sapropel formation between c. 8.4 and 9.0 ka BP (Mercato, Gabellotto-Fiumebianco/E1, Cappadocia) and other important tephras (Avellino, Agnano Monte Spina, "Khabur" and Santorini/Thera) occurred during the second and third millennia BC, marking an important and complex phase of environmental changes during the mid-to late-Holocene climatic transition[44]. Monaco *et al*.[45] have shown a high-resolution distal tephra record preserved in the lacustrine sedimentary succession of the Fucino Basin, central Italy. The investigated record spans the 430–365 ka time interval, covering the Marine Isotope Stage 11 (MIS 11), and provides important insights into peri-Tyrrhenian potassic explosive volcanism from sources located in central Italy against a backdrop of Mediterranean paleoclimate records. Tephra analysis is undertaken for the first time on a sediment core (I-08) from Lake Ioannina, northwest Greece, for the interval spanning 46–4 ka BP[46]. Detailed visible and "crypto-" tephra analysis identifies deposits associated with explosive volcanism at Italian volcanic sources, including Campi Flegrei, Pantelleria, and the Aeolian Islands. Two visible tephra layers, the Campanian Ignimbrite (CI/Y-5; ca. 39.8 ka BP) and Pantelleria Green Tuff (PGT/Y-6; ca. 45.7 ky) have been identified.

The tephrostratigraphy and the volcanic markers of Ischia have been deeply studied both onshore[47–49] and offshore[50–52]. **Figure 6** shows the main tephra of Ischia individuated by Brown *et al*.[47] based on a detailed geological survey of the southern sector of Ischia. The main tephra individuated at Ischia is the S. Angelo Tephra, the Mago Tephra, the Olummo Tephra, the Tisichiello Tephra, the Porticello Tephra, the Capo Grosso Tephra, the La Roia Tephra, the Chiummano Tephra and the Schiappone Tephra. The S. Angelo Tephra and the Mago, Olummo, Tisichiello, and Porticello Tephras pertain to the Pre-Monte Epomeo Green Tuff volcanism[47] (**Figure 6**). The Sant'Angelo Tephra consists of two units, the first one composed of pumice fall deposits and dark-brown ignimbrites, and the second one composed of two monomict breccias separated by a 1 m thick pumice fall deposit[47].

The Mago, Olummo, Tisichiello and Porticello Tephras are equivalent to the Pignatiello Formation of Vezzoli[53]. The Mago Tephra crops out at Grotta del Mago (**Figure 7**) and is composed of phonolitic pumice lapilli associated with a paleosol, overlying a coarse-grained scoriaceous breccia. The Grotta del Mago, located on the south-eastern coast of the island between Punta Lume and Punta Parata, has changed its name several times since it was discovered following its particular coloring; here the fishermen took refuge looking for a place to shelter during the violent storms and on those occasions, a man with a long white beard and flowing hair always appeared, sitting on the rocks of the cave with a good-natured air.

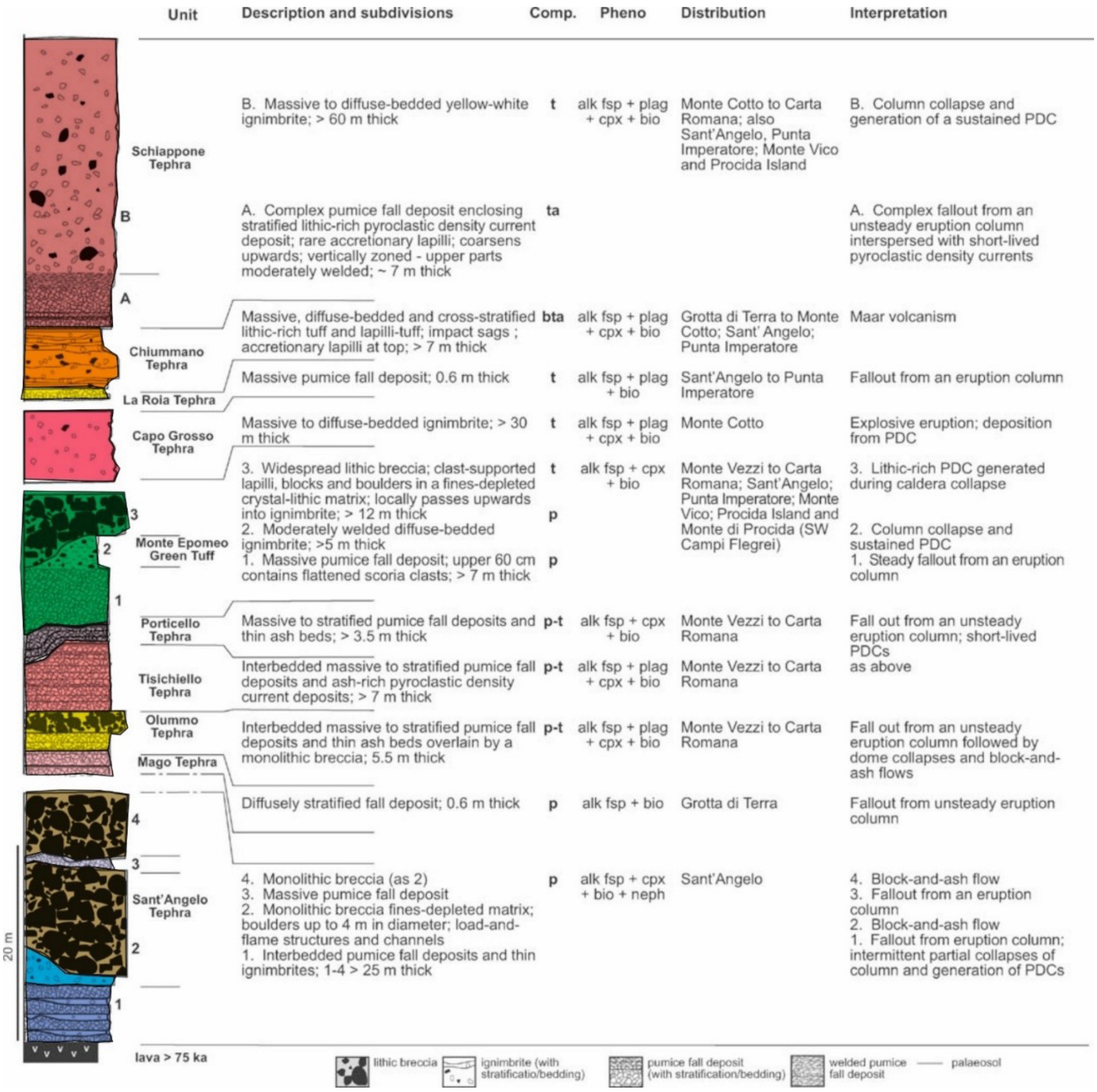

Figure 6. Tephrostratigraphy of Ischia (modified after Brown *et al.*[47]).

Figure 7. Grotta del Mago, Ischia (https://www.isoladischia.net/la-grotta-del-mago-ad-ischia).

The Olummo Tephra crops out around the Grotta del Mago and is composed of phonolite pumice lapilli and interstratified ash layers and breccias (**Figure 6**), unconformably overlying a palesol developed at the top of the Mago Tephra. The Tisichiello Tephra crops out eastwards of Monte di Vezzi and is genetically related to a brown paleosol, located in its upper part. It is bounded upwards by an angular unconformity, which locally cuts down to the Mago Tephra, locally punctuated by box canyons filled by marine and volcaniclastic sediments. The Porticello Tephra crops out at Procida and is equivalent to the "Pomici pliniane C"[54]. This tephra is composed of clast-supported pumice and lithic lapilli. It overlies the Tisichiello Tephra through an unconformity and a paleosol.

Other tephra pertains to the post-Monte Epomeo Green Tuff volcanism (**Figure 6**)[47]. In particular, the La Roia Tephra, poorly exposed with respect to other tephras, crops out between Monte S. Angelo and Punta Imperatore and is constituted by normally-graded pumice lapilli, overlying a paleosol developed in breccias of Monte Epomeo Green Tuff (MEGT). The Capo Grosso Tephra crops out at Monte Cotto (Barano d'Ischia) and is composed of a trachyandesite ignimbrite, unconformably overlying the Lower Scarrupata di Barano Formation[53]. The Chiummano Tephra is an important volcanic marker, cropping out at Scarrupata di Barano and in scattered outcrops of southern Ischia. It is composed of ignimbrite, rich in lithics, and includes distinctive sedimentary structures, such as cross-stratification and dune bedding[47]. Finally, the Schiappone Tephra (**Figure 6**), outcropping at several sites of Ischia (Monte Cotto, Punta della Pisciazza, Monte Vico, Punta Imperatore) and at Procida, is represented by a thick volcanic sequence composed of two members (A, B)[47]. Member A is composed of pumice fall and pyroclastic density current deposits, from trachyandesitic to trachytic, overlain by a thick sequence of white ignimbrites (member B). Based on previous volcanological interpretation the Schiappone Tephra has been interpreted as an extra-caldera ignimbrite of the MEGT[53,54].

The tephrostratigraphy in the Ischia offshore has been discussed by de Alteriis *et al.*[50]. These authors have established a core tephrostratigraphy of southern Ischia offshore based on core analyses at water depths ranging between 895 m and 1,093 m in southern Ischia, taking as reference the Ischia Debris Avalanche[55]. The studied cores have drilled a Late Pleistocene-Holocene sequence composed of lower slope hemipelagic clays and muds. In this hemipelagic sedimentation, several lithofacies occur, respectively represented by debris flow deposits, air-fall tephra layers, and volcaniclastic turbidites. All cores have shown the systematic occurrence of an upper debris flow unit (DF1), taken as a stratigraphic marker. The tephra and other deposits have been described taking the DF1 deposits as a volcanic stratigraphic marker as post-avalanche, syn-avalanche and pre-avalanche sequences[50] (**Figure 8**).

The post-avalanche sequences are characterized by three tephra layers, namely IT1, IT2 and IT3 (**Figure 8**). The IT layers are composed of medium-to-fine-grained volcanic ashes; while IT2 and IT3 have a broad distribution in the whole studied area, IT1 occurs only at proximal sites.

The syn-avalanche sequences are represented by debris flow and debris avalanche deposits, including the DF1 deposit. The most representative lithofacies is the debris flow deposit DF1, detected at 10 cores at the same stratigraphic level, consisting of coarse-grained, poorly-sorted deposits, with volcanic clasts (lavas, tuffs, tuffites), under a few decimetres thick hemipelagic drape. At a few cores, the DF1 deposit evolves to a grain flow deposit or to a debris avalanche matrix facies sensu Ui *et al.*[56] (for the description of the debris avalanche deposits of Ischia see also Aiello[57]). The source area of these deposits seems to be represented by the Monte Epomeo Green Tuffs (MEGT; 55 ky BP).

The pre-avalanche sequences are represented by two ash layers (IT4 and IT5), respectively represented by light pumices and by glass shards (**Figure 8**)[50].

The tephra chemistry has shown that the tephra IT1-IT4 have a composition ranging between trachyte and trachyphonolite, while IT5 shows a potassic trachybasalt to latite composition. Low alkali content has indicated Ischia as the main source area for tephras IT4 to IT4, while tephra IT5 has a chemical affinity with the Solchiaro volcanic products (Procida). Tephra has been correlated with inferred sources/dated events on land.

Starting from the oldest ones, the IT5 tephra has been correlated with the Solchiaro eruption of Procida, representing a discrete volcanic marker in the Tyrrhenian Sea and in the Monticchio Lake succession[58] (19 ky BP). The tephra IT4 has been correlated with the S. Angelo eruption of Ischia (17.8 ky BP), which occurred in the southwestern sector

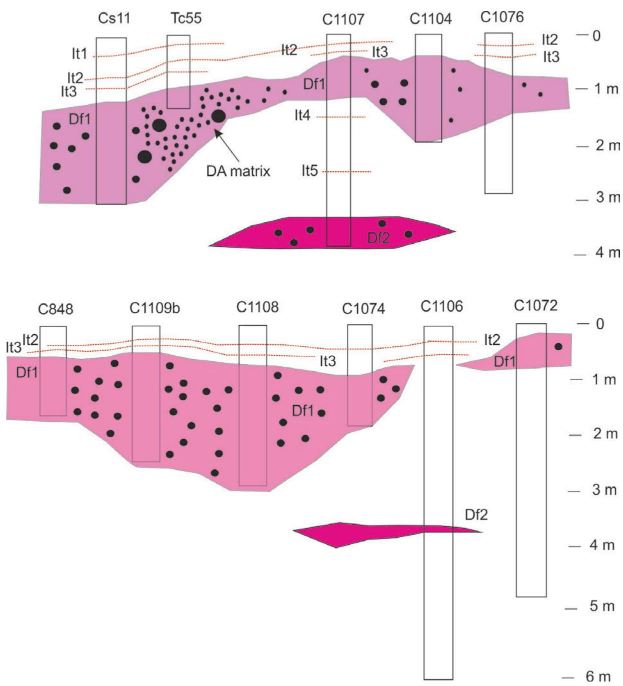

Figure 8. Sketch stratigraphic correlation between main tephra and debris avalanche/debris flow deposits in the Ischia offshore (modified after De Alteriis *et al.*[50]).

of Ischia.

The tephra IT3 follows the DF1 event and can be correlated with the Ischia volcanic activity predating the Cretaio event (Cava Bianca Tephra; IV Century BC).

The tephra IT2 has been correlated with the Ischia/Cretaio event (60 AD), being the most widespread volcanic marker in this area.

The tephra IT1 has been correlated with the recent eruption of Arso (Ischia; 1302 AD).

4.1.2 Debris avalanche deposits

The debris avalanche deposits of Ischia have been deeply studied both onshore[1,59,60] and offshore[20,50,55,57]. In the geological map of Ischia Sbrana *et al*.[1] have highlighted several stratigraphic units corresponding with debris avalanche deposits (Bocca di Serra Unit, Punta del Soccorso Unit, Lacco Ameno Unit).

The Bocca di Serra unit is composed of coarse-grained massive deposits composed of blocks and megablocks sourced by the Synthem of Rifugio di S. Nicola immersed in a coarse-grained matrix composed of lapilli and blocks. It has been interpreted as debris avalanche deposits formed on the southern slope of the resurgent block of the Epomeo Mt.[1].

The Punta del Soccorso unit is constituted by coarse-grained deposits, formed by blocks and megablocks, mainly derived by the Synthem of Rifugio di S. Nicola, immersed in a coarse-grained matrix, derived from the disgregation of the same tuffs. Hummocky structures have been identified in the outcrops of the Forio town. The Punta del Soccorso unit overlies quite entirely the western sector of the island, between the shoreline and the toe-of-slope of the Epomeo Mt. resurgent block. These deposits have been correlated with the corresponding units in the adjacent offshore[20].

Figure 9. The Lacco Ameno mushroom, a relict morphology composed of the debris avalanche deposits of the Lacco Ameno unit (modified after https://www.tripadvisor.it/Attraction_Review-g580213-d7146844-Reviews-Fungo_Di_Lacco_Ameno-Lacco_Ameno_Isola_d_Ischia_Province_of_Naples_Campania.html).

The Lacco Ameno unit is well exposed in the famous Lacco Ameno mushroom (**Figure 9**) (https://www.tripadvisor.it/Attraction_Review-g580213-d7146844-Reviews-Fungo_Di_ Lacco_Ameno-Lacco_Ameno_Isola_d_Ischia_Province_of_Naples_Campania.html). This unit is composed of tuff megablocks and blocks of the Synthem of Rifugio di S. Nicola, immersed in a coarse-grained matrix, composed of clasts and pebbles. The debris avalanche deposits of the Lacco Ameno unit were formed due to the collapse of the northern sector of the Epomeo Mt. resurgent block[1].

De Vita *et al*.[60] have shown that the gravitational deposits of Ischia have been deposited during four main phases, dated between 5.5 and 2.9 ky BP, around 2.9 ky BP, between 2.6 and 2.3 ky BP and between 2.3 and 1.9 ky BP. The gravitational deposits were both older and younger than the emplacement of the volcanic rocks, testifying that the slope instability has been controlled by vertical movements, which have activated and re-activated faults and fractures representing preferential ways for rising fluids. A cyclical slope instability has been suggested, genetically related to the tectonic uplift, caldera resurgence, and volcanic phases.

The deposits of seven debris avalanches, both superimposed and laterally distributed, have been recognized to the north and to the west of the resurgent block of the Epomeo Mt, overlying all the lowlands between Casamicciola, Forio, and Succhivo[59]. Some of them have been interpreted as the subaerial correlative units of the offshore deposits.

Six large debris flows (lahars) and some smaller movements (rock falls, slumps, debris and rock slides, debris flows) have also been recognized. In particular, the source areas of the detachments do not show the horseshoe shape, typical of the debris avalanches, but are defined by the intersections of faults, NE-SW, N-S, and NW-SE trending, generat-

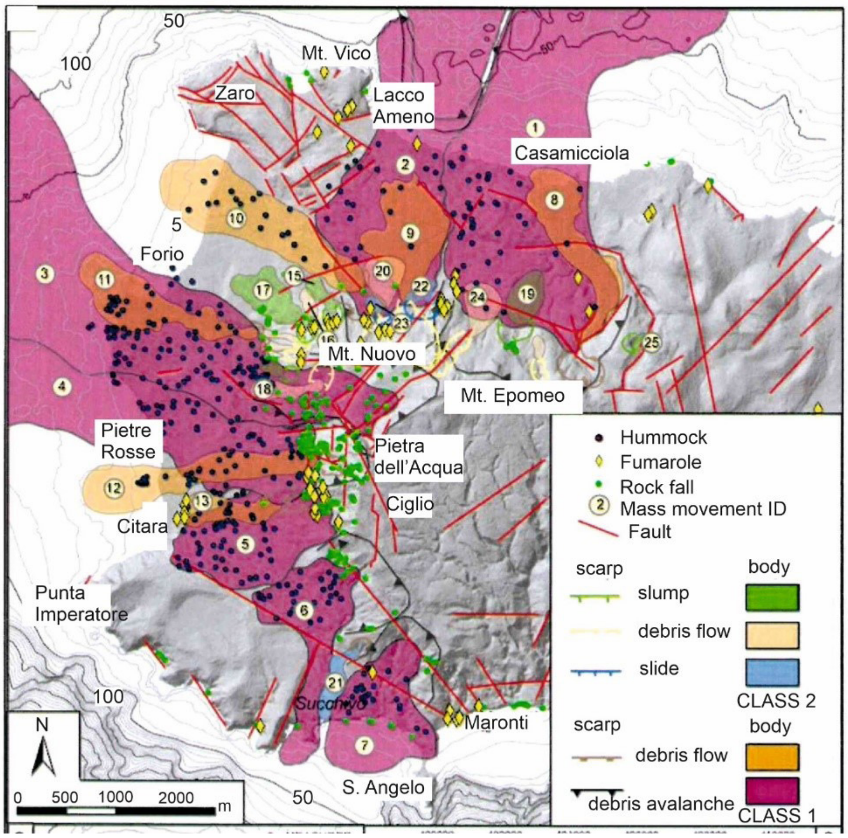

Figure 10. Sketch map showing the main gravitational landforms of Ischia (modified after Della Seta *et al*.[59]). Circled numbers refer to the main mass movements: 1: Debris Avalanche of Casamicciola; 2: Debris Avalanche of Lacco Ameno; 3: Debris Avalanche of Falanga; 4: Debris Avalanche of Pietre Rosse; 5: Debris Avalanche of Citrunia; 6: Debris Avalanche of Ciglio; 7: Debris Avalanche of Succhivo; 8: Lahar of Casamicciola; 9: Lahar 07.1228; 10: Lahar of S. Francesco; 11: Lahar of Forio; 12: Lahar of Citara; 13: Lahar of Cuotto; 14: DSGSD of Monte Nuovo; 15: MN-A; 16: MN-B; 17: MN-C; 18: MN-D; 19: 03-04-1881; 20: 02.02.1828; 21: Chiarito debris rock and slide; 22: debris slide; 23: debris slide; 24: slump; 25: slump.

ed during the resurgence[59]. A sketch map has been constructed in order to show the main gravitational landforms (**Figure 10**).

In particular, the Debris Avalanche of Lacco Ameno, Holocene in age, is a wide body with hummocky surface, matrix-supported, with blocks of lavas and tuffs. Large blocks forming hummocks are composed of Monte Epomeo Green Tuffs and boulders of laminated pyroclastic sequences.

The Debris Avalanche of Pietre Rosse, Holocene in age, is a wide body with an erosional surface at its base, with hummocks composed of Monte Epomeo Green Tuffs and lava boulders.

The Chiarito debris and rock slide and the Debris Avalanche of Ciglio have been dated back to the eighth-seventh century BC through archeological constraints and are correlated to the eruption of the Chiarito tephra.

The Debris Avalanche of Casamicciola is a wide body with hummocky surface and has been dated back to the Holocene (< eighth century BC, with the lower age limit which is given by the underlying volcanic deposits of the Punta La Scrofa tephra). It has been controlled by a volcano-tectonic trigger inferred by the analogy with other historical debris avalanches of Ischia.

The Debris Avalanche of Falanga, Holocene in age, is a wide body with a hummocky surface, whose submerged part corresponds with the Western Ischia Debris Avalanche.

The Debris Avalanche of Citrunia is a wide body with a hummocky surface, massive and ungraded, triggered by volcano-tectonics. The Debris Avalanche of Succhivo has been dated back to the second-third century AD and is a wide body with hummocky surface, composed of massive and ungraded deposits.

Chiocci and de Alteriis[55] have reported or the first time the Ischia Debris Avalanche (IDA), a catastrophic collapse of Ischia during prehistorical times, triggered by the volcano-tectonic uplift of the Mt. Epomeo resurgent block. The failure caused a subaerial to underwater horseshoe slide scar on the meridional side of the isle and achieved a debris avalanche discharged as far as 50 km from the isle. All along the spot, part of the debris avalanche evolved into a debris flow covering an area of 250–300 km^2. The leading failure was pursued, and predated, by repeating, terrestrial and underwater failures. Two submarine hummocky deposits are found north and west of the island and are connected to the southern collapse. Such volcanic attitude, previously unknown for Ischia Volcano, has likely generated tsunami waves over the Bay of Naples highlighting their impact on prehistorical/historical communities.

Aiello *et al*.[20] have described the debris avalanche deposits offshore northern Ischia based on seismo-stratigraphic data. These deposits have wedge-shaped external geometry and chaotic facies, are arranged into two distinct, superimposed bodies (H1 and H2). The debris avalanche deposits were emplaced during two main, distinct volcano-tectonic events occurring on the continental shelf off Casamicciola. The two bodies, H1 and H2, are characterized by facies hetheropy with the upper seismic unit of the basin filling[20].

Aiello[57] has described the debris avalanche deposits of the Ischia offshore based on sedimentological and geological results. Heterometric blocks and blocks of tuffs and lavas, wide from tens to hundreds of meters, immersed in a coarse-to-fine-grained detritus matrix compose these deposits. Their basic judgment has been completed based on their coastal labeling and, as they serve as the offshore correlative units, the flag of the coastal units has been retained[1]. They encompass four main lithologic associations, i.e., the Casamicciola-Ischia harbor unit (GSN/GST), the Lacco Ameno unit (LMO/LCA), the Punta del Soccorso unit (PUS/PSC), and the Bocca Serra unit (BSR/BCS). The submarine outcrops are in the northern Ischia offshore between Lacco Ameno and Casamicciola and in the western Ischia offshore between Punta del Soccorso and Punta Imperatore.

4.1.3 Volcanic and sedimentary seismic units

The volcanic and sedimentary seismic units of Ischia have been strongly debated[1,20,61–63].

Sbrana *et al*.[1] have recognized ten seismo-stratigraphic units have been proposed (US1-US10), as follows:

US1) seismo-stratigraphic unit with chaotic reflections at the base and parallel at the top (lava deposits, probably erupted by the Ruommoli volcano;

US2) seismo-stratigraphic unit with parallel reflectors, having a good lateral continuity and a limited amplitude (tuffs and ashes probably erupted by the Formiche di Vivara volcano;

US3) seismo-stratigraphic unit, from acoustically transparent to semi-acoustically transparent, having a high frequency (ignimbrite deposits; "Sintema del Rifugio di S. Nicola");

US4) seismo-stratigraphic unit with alternating stratified and highly stratified reflectors (Citara tuffs);

US5) seismo-stratigraphic unit with parallel reflectors having a good lateral continuity (volcanic deposits associated with the submarine volcanic field of the Forio offshore);

US6) seismo-stratigraphic unit, reflection-free, with variable amplitude (Campanian Ignimbrite);

US7) seismo-stratigraphic unit with regular and continuous seismic reflectors (marine deposits);

US8) seismo-stratigraphic unit with reflectors from stratified to semi-chaotic (Solchiaro tuff);

US9) seismo-stratigraphic unit with hummocky geometries, discontinuous, irregular seismic reflectors (debris avalanche deposits);

US10) seismo-stratigraphic unit with stratified reflectors, having a good lateral continuity and high amplitude.

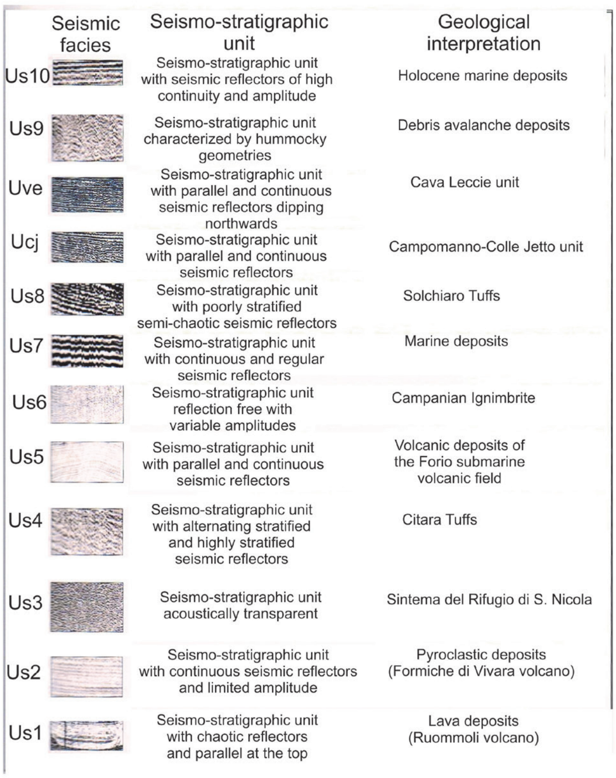

Figure 11. Seismo-stratigraphic units of the Ischia offshore (modified after Sbrana *et al*.[1]).

Aiello *et al*.[20] have shown the stratigraphic and structural setting of the Ischia volcanic complex based on submarine seismic reflection data. The stratigraphic architecture of the northern Ischia offshore has been discussed based on the geological interpretation of the seismic profile L27, located on the Casamicciola offshore (**Figure 12**).

The main seismo-stratigraphic units are represented in (**Figure 12**):

1) An undetermined volcanic off Casamicciola corresponding to the acoustic substratum, in facies hetheropy with the youngest units of the basin filling and eroded at its top by a subaerial unconformity;
2) The volcanic domes of Casamicciola, representing the magmatic uprising along faults, interlayered in both the lower and the intermediate seismic units of the basin filling (**Figure 12**);
3) The upper seismic unit of the basin filling

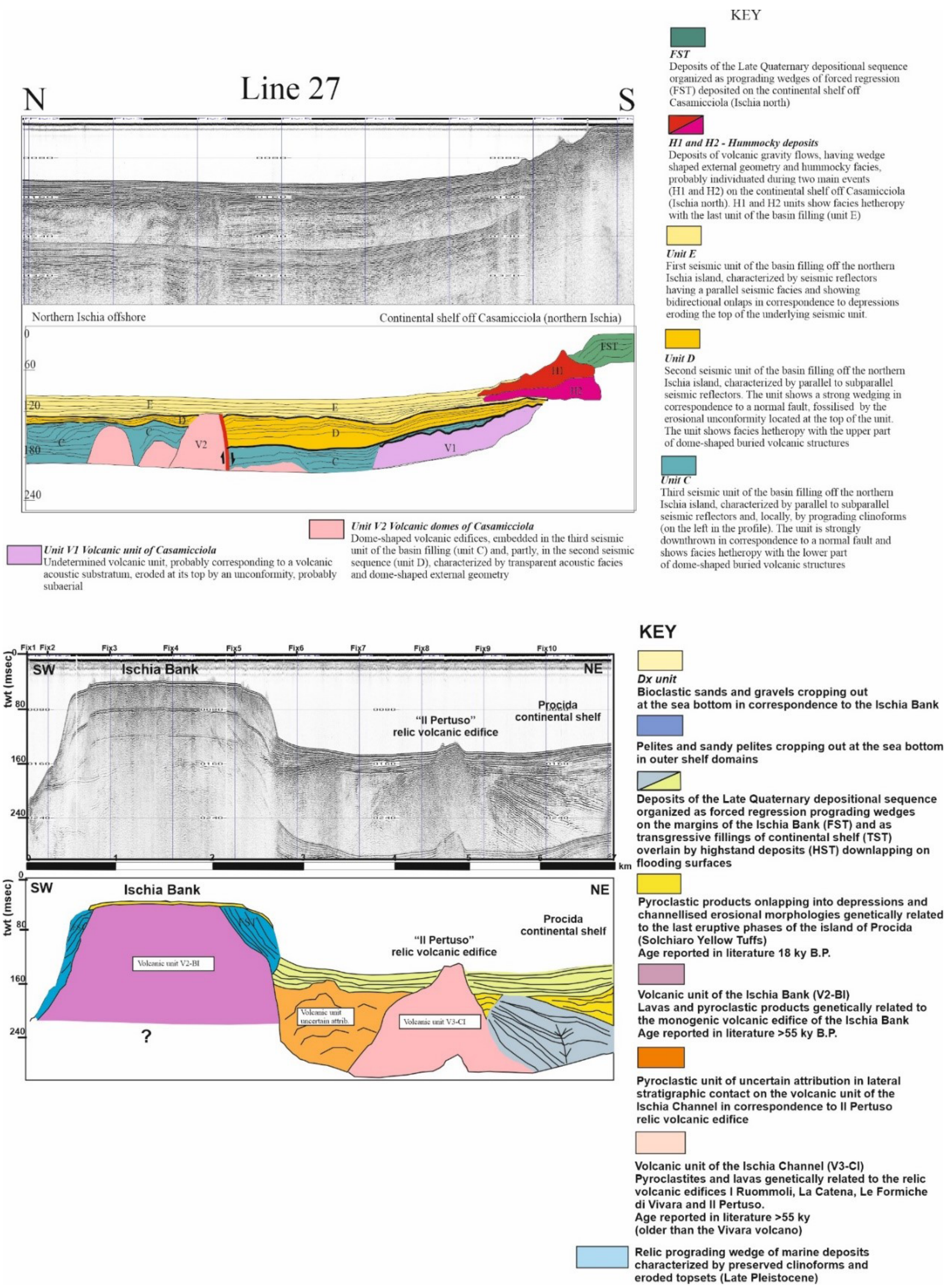

Figure 12. Seismic profiles L27 and L57 (and corresponding geological interpretation) (modified after Aiello *et al*.[20]).

(unit E, **Figure 12**), characterized by parallel to-subparallel seismic reflectors and, locally, by prograding clinoforms;

4) The intermediate seismic unit of the basin filling (unit D, **Figure 12**), characterized by parallel-to-sub parallel seismic reflectors. strongly wedging in correspondence to a normal fault;
5) The lower seismic unit of the basin filling (unit C, **Figure 12**), characterized by reflectors having parallel seismic facies and showing bidirectional onlaps;
6) The debris avalanche deposits (H1 and H2), with chaotic seismic facies;
7) The forced regression prograding wedges of the Late Quaternary depositional sequence.

The stratigraphic architecture of the south-eastern Ischia offshore has been depicted through the geological interpretation of the seismic profile L57.

The main seismo-stratigraphic units, both volcanic and sedimentary, are represented by:

1) A volcanic acoustic basement (unit V2-B1, **Figure 12**), characterized by acoustically-transparent seismic facies, composed of lavas and pyroclastites genetically related to the main morpho structure of the Ischia Bank;
2) The unit of Ischia Channel (unit V3-CI, **Figure 12**), made of pyroclastites and lavas genetically related to relict hydromagmatic volcanic edifices of eastern Ischia;
3) A pyroclastic unit, underlying the marine deposits of the Ischia Channel filling depressions and channels;
4) A Pleistocene relict prograding wedge, characterized by prograding clinoforms.

Aiello[62] has reconstructed the seismo-stratigraphic architecture of the Late Quaternary to Holocene volcanic and sedimentary seismic units in the Ischia offshore and correlated them with the coastal units of the adjacent mainland.

Four sectors have been selected to perform such a correlation, in particular:

- The Succhivo coastal cliff (southern Ischia)-L39 seismic line;
- The northern Ischia offshore from the Ischia harbor to the "Spiaggia degli Inglesi" beach-L26 seismic line;
- The Cava dell'Isola beach (western Ischia)-L33 seismic line;
- The Punta dello Schiavo tuff coastal cliff (south-western Ischia)-L37 seismic line.

In particular, the Succhivo tuff coastal cliff is characterized by the S. Angelo Tuffs, the toe of coastal cliff deposits, and the submerged beach deposits. The S. Angelo Tuffs are composed of hydromagmatic tuffs erupted from a tuff cone located in the Punta del Chiarito offshore. In the basal part of the coastal cliff tuff breccia occurs, overlain by stratified dune-bedded gray-yellow tuffs, and closed by plane parallel-bedded, gray, coarse-grained, and fine-grained ash tuffs. The toe-of-coastal cliff deposits are formed by heterometric lava and tuff blocks, with a gravelly-sandy matrix, Late Holocene to recent in age. The submerged beach deposits are composed of gravels, sandy gravels and coarse-grained sands with pyroclastic and lava pebbles, ranging in age from the Late Holocene and the current. The offshore transect has shown five seismo-stratigraphic units, both volcanic and sedimentary in origin.

From the Ischia harbor to the Spiaggia degli Inglesi beach, three geological units occur, including the Ischia Porto spatter, the Sant'Alessandro pyroclastites and lavas (Foce Member), and the Spiaggia degli Inglesi spatter. The Ischia Porto spatter crops out next to the volcanic crater of the Ischia harbor, composed of reddish scoriae, emplaced during historical times.

The Sant'Alessandro pyroclastites and lavas (Foce Member), crop out along the coastal cliff of the Ischia harbor from Parata to Cafiero and are typified by a lava flow, trachytic in composition. The Spiaggia degli Inglesi spatter, cropping out in the coastal cliff surrounding the "Spiaggia degli Inglesi" beach, is distinguished from dark grey lavas and spatters linked to a local small volcanic center. The offshore transect has shown six seismo-stratigraphic units, both volcanic and sedimentary in origin.

The Cava dell'Isola beach (western Ischia) has shown two main volcanic units, including the Citara Tuffs and the Punta delle Pietre Rosse Tuffs, associated with the beach deposits. The Citara tuffs are composed of white to yellow ash tuffs and lapilli-rich ash tuffs, referring to the eruptive activity of tuff cones in the Citara offshore. The Punta delle Pietre Rosse tuffs are brown ash tuffs, supported by matrix, including pumice clasts, and characterized at their top by a thin paleosol. The present-day and recent beach deposits of the Cava dell'Isola beach, grading seawards into the submerged beach deposits, are composed of heterometric medium-coarse-to-fine-grained sands with pebbles, locally enclosing rocks. Their offshore counterpart is represented by nine seismic units, both volcanic and sedimentary in origin.

The Punta dello Schiavo tuff coastal cliff is composed of the Scarrupo di Panza pyroclastic deposits, characterized by trachytic grey tuffs, while the offshore part is characterized by six seismo-stratigraphic units.

4.1.4 Marine terraces, tectonic uplift, and caldera resurgence

The issue of marine terraces of Ischia is strongly related to the tectonic uplift and caldera resurgence of Ischia. Also, if mentioned in several scientific papers[1,62,64–69], it is not still well known and studied in an organized way. In this sub-section, I will try to synthesize the existing knowledge on this intriguing issue.

A marine terrace is a coastal landform mainly controlled by wave action, and by currents, during a relative sea-level still stand. In an uplift process, the marine terraces were formed during the glacial-interglacial passage, when the difference between the sea-level rise and the uplift rates was small. Several terrace orders have been produced on a coastline at the same time as different still-stands of the sea level. An arrangement of marine terraces of several orders with a relationship between the terrace age and its height is direct evidence of tectonic uplift on a coastal area. If this is not the case, only terraces formed during interglacial periods above the present average sea level appear, preserving them from coastal erosion.

A marine terrace is constituted by two erosional geomorphological surfaces, formed during the transgressive-regressive sea-level cycle: an abrasion platform and a cliff. The abrasion or wave-cut platform is a gentle sea dipping surface, whose gradient is controlled by the size and quantity of the sediments produced during its formation. The terrace is bounded landwards by the cliff, a steep seaward dipping surface, whose gradient is controlled by the erosional strength of the outcropping formations.

At Ischia, the vertical ground movements are very significant[64,66,67]. The tectonic uplift of the Epomeo Mt. occurred starting from 55 ky BP up to recent times and was interrupted by several phases of slow subsidence.

The geological processes of uplift and subsidence are suggested by several pieces of evidence, including the occurrence of submarine epiclastic

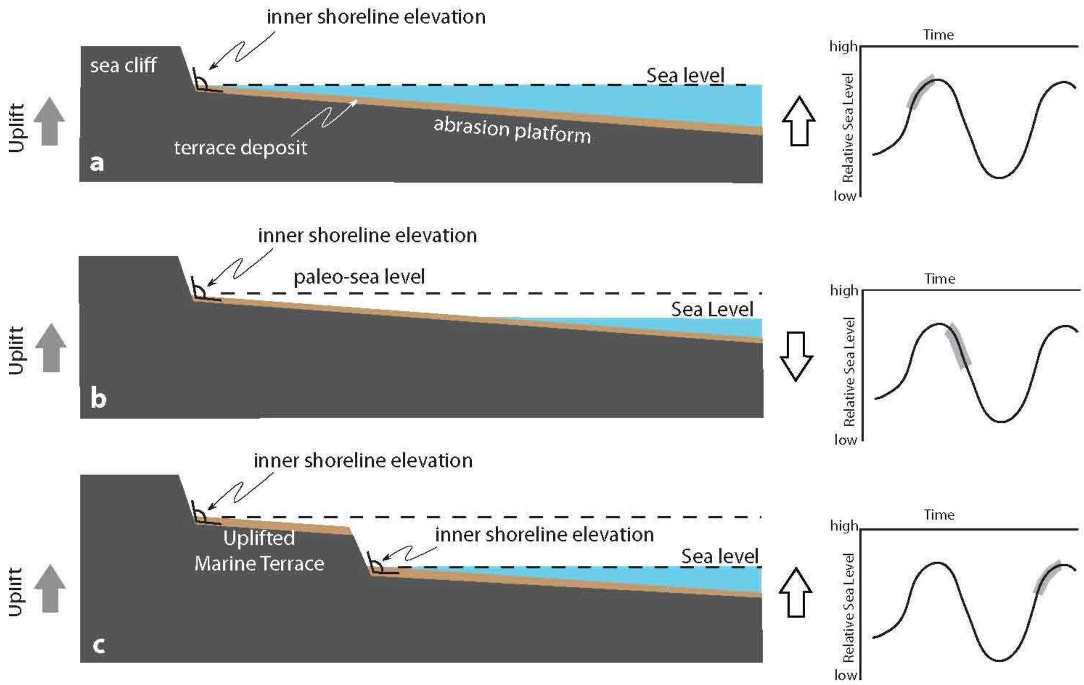

Figure 13. Schematic cartoon illustrating the cutting and abandonment of marine terraces in an actively uplifting landscape in relation to sea level fluctuation. (a) Marine terrace cut during a relative sea level high stand. (b) The sea level drops and the marine terrace is uplifted. (c) During the next relative sea level high stand, a new marine terrace is carved into the landscape below the older terrace (modified after https://serc.carleton.edu/download/images/30773/marine_terrace_formation.jpg).

and marine deposits at the top of Mt. Epomeo (Colle Jetto Formation, Cava Leccie Formation); the presence of marine erosional surfaces and deposits located above the present sea level; the occurrence of yellow tuffs belonging to the S. Costanzo Formation (33–38 ky BP), which outcrop on the western margin of the resurgent block; the faulting, which accompanied the resurgence, of the Citara Formation (44–33 ka BP); the presence of hot springs previously located on the island and located nowadays offshore; the occurrence of little hanging valleys toward the sea and small marine terraces which have been uplifted of about 10–15 m a.s.l.; the presence of roman ruins located few meters b.s.l.[66,67].

During the last 2,000 years, it seems to be a subsidence process, probably interrupted by short uplift phases, with a differential tectonic uplift in the island.

Sbrana *et al*.[68] have suggested that at Ischia, marine terraces and coastal sediments have recorded a tectonic uplift of about 60 m after 5.5 ky BP and have observed structural terraces on the south-eastern marine cliff adjacent to the Maronti beach.

Uplifted ancient shorelines have been recognized in the Forio area along the western side of the island. The subsidence has been considered to be a significant process after the Roman era based on archeological data[66].

The southern shoreface of Ischia Island (Maronti Bay) is characterized by the presence of a depositional terrace (**Figure 14**).

A detailed DEM of the southern Ischia slope has been constructed in order to show the depositional terrace, probably carved in rocks. The average value of the submerged terrace elevation is 9 m. Based on DEM interpretation, the terraced surface appears quite flat.

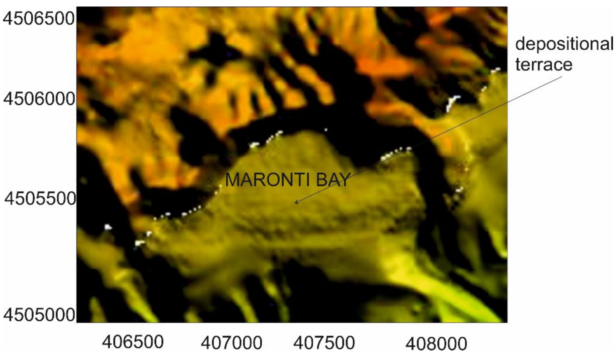

Figure 14. Detailed DEM of the southern Ischia slope showing the Maronti depositional terrace (southern Ischia slope).

4.2 Geological sheet n. 465 "Island of Procida"

Procida is an important sheet of the Gulf of Naples, covering quite the whole Gulf (https://www.isprambiente.gov.it/Media/carg/465_PROCIDA_50/Foglio.html)[2]. Reviewing this geological map implies deepening some research lines, respectively the volcanic banks of the Campi Flegrei offshore, the volcanic and sedimentary seismo-stratigraphic units, the volcanic features of the Somma-Vesuvius offshore, and the physiographic unit of the Procida Island and the corresponding marine deposits.

4.2.1 Volcanic banks of the Campi Flegrei offshore

The volcanic banks of Pentapalummo, Nisida and Miseno are located in the Gulf of Naples (Campi Flegrei offshore) and have been deeply studied[15,28,34,37,70–74]. Pescatore *et al*.[34] have highlighted that in the Gulf of Pozzuoli a coastal platform, a central basin and a belt of submerged volcanic edifices occur (Pentapalummo, Miseno and Nisida Banks; **Figure 15**).

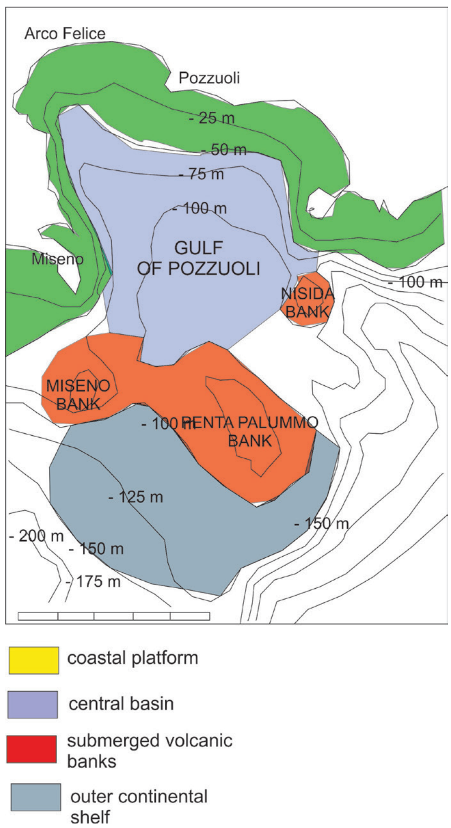

Figure 15. Sketch morphologic map of the Gulf of Pozzuoli, showing the main physiographic units, including the Pentapalummo, Nisida and Miseno Banks (modified after Pescatore *et al*.[34]).

Several seismic profiles have been recorded in the Miseno, Nisida, and Pentapalummo volcanic banks, in order to show the main seismo-stratigraphic units[34]. The stratigraphic architecture next to the Nisida Bank is shown in **Figure 16**. Three seismo-stratigraphic units (A, B, C), separated by regional unconformities (α, β) have been distinguished. The unconformity α, which has been observed only in the inner part of the Gulf of Pozzuoli, has been correlated with a volcano-tectonic event, dated back 5,000–6,000 ky BP, triggering a tectonic uplift shown by the marine deposits of the La Starza marine terrace onshore, on which the Pozzuoli town is located and lying about 30 m above the present-day sea level. The unconformity β has been correlated with the Wurmian regression. The seismo-stratigraphic unit A is the uppermost unit and is bounded below by the unconformity α; it has been interpreted as Holocene marine deposits. The seismo-stratigraphic unit B is associated with volcanic deposits in correspondence with the Nisida Bank (**Figure 16**) and represents a pyroclastic unit. The seismo-stratigraphic unit C is an older marine unit, older than the Wurmian regression (18–14 ky BP).

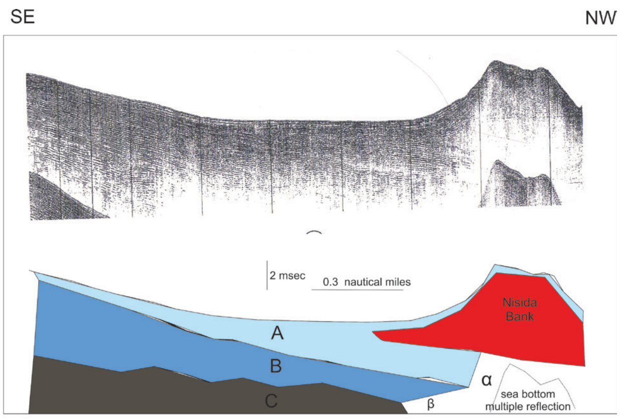

Figure 16. Surfboom seismic profiles showing the stratigraphic architecture next to the Nisida Bank and corresponding geological interpretation (modified after Pescatore *et al.*[34]).

The stratigraphic architecture next to the Pentapalummo bank is shown in **Figure 17**.

These interpretations have been deeply revised by Aiello *et al.*[70] and Steinmann *et al.*[71]. Aiello *et al.*[70] have detailed the results shown in the map of **Figure 15**, by adding many geomorphologic and geologic details (**Figure 18**).

The seismo-stratigraphic setting of the Pentapalummo Bank has been detailed, recognizing more

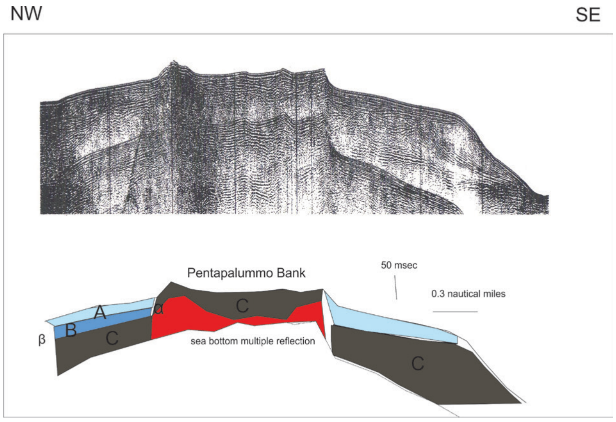

Figure 17. Surfboom seismic profiles showing the stratigraphic architecture next to the Nisida Bank and corresponding geological interpretation (modified after Pescatore *et al.*[34]).

seismic sequences with respect to those previously identified, identifying the volcanic acoustic basement, a pyroclastic unit, and the system tracts of the Late Quaternary depositional sequence (LST, TST, HST1, HST2).

Detailed interpretations of the Punta Pennata and Nisida anticlines have been constructed, coupled with many seismic details related to Nisida, Miseno and Pentapalummo. A new seismo-stratigraphic setting has been then proposed by Steinmann *et al.*[71], reconstructing the general framework of these seismic units.

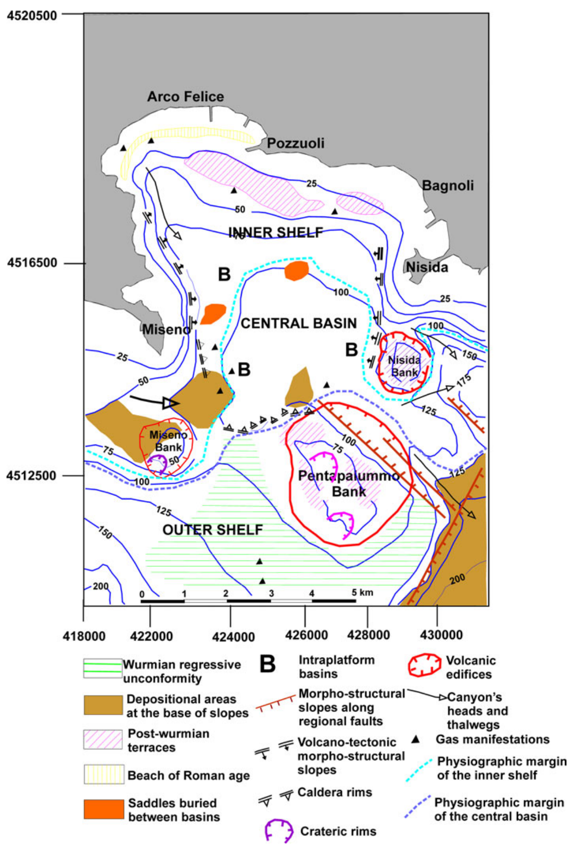

Figure 18. Geomorphologic map of the Pozzuoli Bay (modified after Aiello *et al.*[70]).

4.2.2 Volcanic and sedimentary seismo-stratigraphic units

The volcanic and sedimentary seismic units of the Gulf of Naples, including Procida have been discussed in several key papers[5,17,37,70,72].

Aiello *et al*.[72] have shown a table reporting the main seismo-stratigraphic units identified in the Bay of Naples based on the geological interpretation of Sub-bottom Chirp profiles. They have been reported as follows:

- Unit A: Volcaniclastic and/or pyroclastic deposits (mudflows, lahars, pyroclastic flows), genetically related to the Somma-Vesuvius volcano.
- Unit B: Pyroclastic mounds, composed of alternating coarse-grained volcanogenic sands and pumice levels, genetically related to the Neapolitan Yellow Tuff (19 ky BP).
- Unit C: Holocene marine sediments involved by creeping.
- Unit D: Relict sands deposited during the last sea-level low stand (18–20 ky BP).
- Unit E1: Dome-shaped volcanic unit, genetically related to the Campanian Ignimbrite (37 ky BP).

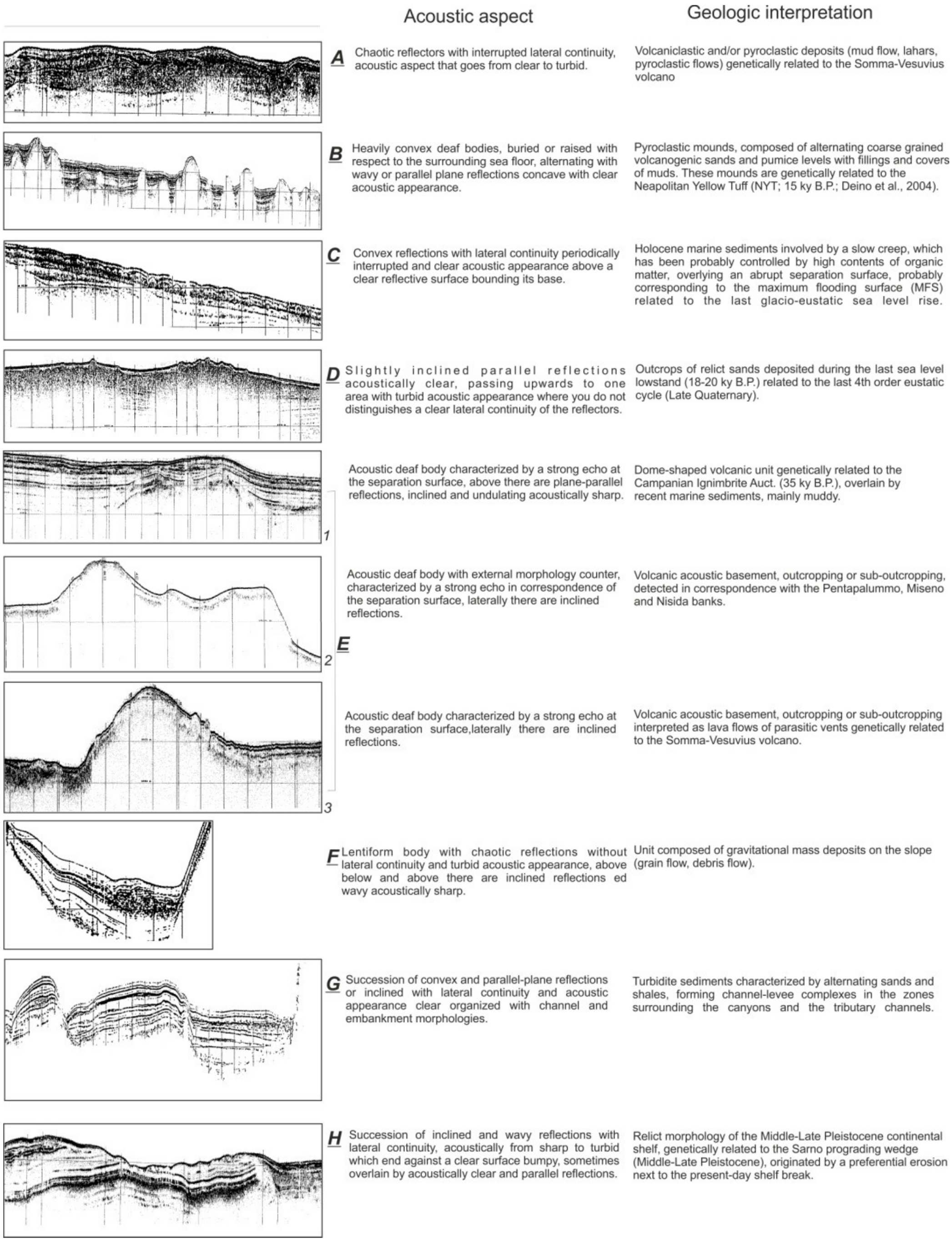

Figure 19. Seismic facies of the Naples Bay based on Sub-bottom Chirp geological interpretation (modified after Aiello *et al*.[72]).

- Unit E2: Volcanic acoustic basement, outcropping or sub-outcropping in correspondence with the Nisida, Miseno and Pentapalummo Banks.
- Unit E3: Lava flows or parasitic vents genetically related to the Somma-Vesuvius volcano.
- Unit F: Gravitational deposits on the continental slope (grain flows, debris flows).

4.2.3 Volcanic features of the Somma-Vesuvius offshore

The volcanic features of the Somma-Vesuvius volcano and corresponding offshore have been investigated in detail[28,38]. A southwestwards lateral collapse of the volcano, probably between 35 and 11 ky BP ago has been suggested based on seismic interpretation[38]. Pyroclastic density current deposits (PDCs) at Vesuvius have been deeply studied[75–78]. Gurioli *et al*.[75] have carried out geological and volcanological studies in the Herculaneum excavations, which are located 7 km westwards of Vesuvius, in order to reconstruct the main features of the pyroclastic density currents and the temporal sequence of the AD 79 eruptive events, which have destroyed Herculaneum. The sedimentary facies of several outcrops (Palestra, Area Sacra, Parete a mare) have been described and interpreted as the result of progressive sedimentation from a single pyroclastic density current, that was subjected to flow transformations as a response to strong irregularities of the substratum[75]. Cioni *et al*.[76] have estimated the temperature of the deposits left by different types of pyroclastic density currents (PDCs) of the AD 79 eruption of Vesuvius, measuring the thermal magnetization (TRM) of lithic clasts carried out by the currents. The sedimentological features, together with the TRM data, have allowed to highlight the main processes which have controlled the variability of the temperatures of the deposits and of the related emplacing currents[76]. Gurioli *et al*.[77] have discussed the influences of the urban fabric on the pyroclastic density currents at Pompei through volcanological and rock magnetic analyses, performed on the deposits of the AD 79 eruption at the Pompei excavations. The magnetic analyses have allowed to quantify the variations in the flow direction and the mechanisms of emplacement of the parental PDCs. These results, integrated with the volcanological data, have shown that all the PDCs that entered the town, were stratified currents, in which the interaction with the urban fabric occurred in the lower part of the current[77]. Shea *et al*.[78] have highlighted the role of the pyroclastic density in the column collapse and the generation of pyroclastic density currents during the AD 79 of Vesuvius. Six pyroclastic density currents (PDCs) were produced during unstable regimes, and have controlled the destruction of the Roman towns around the volcano. New measurements of juvenile clast density and estimations of the ascent parameters have shown that four partial collapses were triggered by the increase in the abundance of dense juvenile clasts within the eruptive column[78]. The study of clasts occurring within six PDC deposits from the AD 79 eruption has revealed that stable to collapsing column transitions coincide with peaks in the abundance of dense juvenile and wall-rock clasts[78]. Aiello[28] has discovered some new seismic units in the eastern Bay of Naples, including 1) a seismic unit, previously interpreted as buried volcanic mounds or cryptodomes and now interpreted as buried tuff rings and compared with other significant tuff rings occurring in the Campi Flegrei volcanic district; 2) a seismic unit, located offshore the Somma-Vesuvius, herein interpreted as the fallout deposits representing the base of the AD 79 eruption of the Vesuvius volcano, and to discuss their relationships with the Somma-Vesuvius and Campi Flegrei volcanic activity.

The updated seismo-stratigraphic framework of the seismo-stratigraphic units recognized in the eastern sector of the Naples Bay includes[28]:

- The A seismic unit, correlated with the Campanian Ignimbrite pyroclastic flow deposits.
- The B seismic unit, correlated with buried tuff rings, similar to tuff rings volcanic edifices of the Neapolitan area.
- The C seismic unit, correlated with the lowstand deposits of the Late Quaternary depositional sequence, found in both the depressions between the buried tuff rings of the B unit and the top of the A unit.
- The D seismic unit, correlated with the Neapolitan Yellow Tuff (NYT).
- The E seismic unit, correlated with a debris flow unit.

- The F seismic unit, correlated with high-stand deposits of the Late Quaternary depositional sequence.
- The G seismic unit, correlated with the PDCs of the pre-AD 79 Plinian eruptions.

5. Discussion and conclusions

The CARG Project has been reviewed, focusing on the Ischia and Procida geological sheets. A merged DEM of the Gulf of Naples and of the Gulf of Salerno has been constructed joining the Multibeam bathymetric data recorded in the Naples Bay (http://www.isprambiente.gov.it/Media/carg/campania.html) and the Multibeam data recorded in the SISTER II oceanographic cruise in the Gulf of Salerno. The main morpho-structural lineaments have also been reported. At Ischia, important research issues have been discussed, including the tephrostratigraphy of Ischia, the debris avalanche deposits, the volcanic and sedimentary seismic units and the marine terraces, tectonic uplift, and caldera resurgence. At Procida, seismic evidence of volcanic banks of the Campi Flegrei offshore has been shown, and the volcanic and sedimentary seismic units have been identified. Volcanic features of the Somma-Vesuvius offshore have been discussed. This review could represent a useful base for monitoring coastal hazards in the Campania region, recently highlighted in the Gulf of Naples based on slope and thematic maps. This review could be enlarged in future papers, focusing on the details of several geological sheets of Campania, excluded by this discussion due to the space motifs.

Conflict of interest

The author declares that she has no conflict of interest.

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