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SCIENCE

High-resolution morpho-bathymetry of the Gulf of Naples, Eastern Tyrrhenian Sea

Salvatore Passaro[a], Stella Tamburrino[a,b], Mattia Vallefuoco[a], Serena Gherardi[a], Marco Sacchi[a] and Guido Ventura[a,c]

[a]Istituto per l'Ambiente Marino Costiero, Consiglio Nazionale delle Ricerche, Naples, Italy; [b]Istituto per l'Ambiente Marino Costiero, Consiglio Nazionale delle Ricerche, U.O.S. Capo Granitola, Trapani, Italy; [c]Istituto Nazionale di Geofisica e Vulcanologia, Rome, Italy

ABSTRACT
We present a high-resolution bathymetric map of the Gulf of Naples (Italy), which is surrounded by the two main volcanic complexes of Mt. Somma-Vesuvius and Phlegrean Fields. The morphology is obtained from swath bathymetric in a Digital Terrain Model with a 5 m grid cell size. Bathymetric data display the main seafloor morphologies with a resolution never obtained before. These morphologies include the Ammontatura and Dohrn Canyons, the Penta Palummo, Nisida, Miseno and Banco della Montagna banks, and the bathymetric features of the submerged sector of the Somma-Vesuvius volcano. Overall, a prevailing volcanic nature characterizes the seafloor morphologies located in the northern sector, while the southern one is dominated by sedimentary features. The Final Map could be useful for the evaluation of the volcano-related hazards in the area.

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1. Introduction

High-resolution bathymetry maps developed with upgraded multibeam swath technologies allow us to better characterize the morphological expression of the seafloor, with a particular focus on risk assessment in continental shelf areas (Passaro, de Alteriis, & Sacchi, 2016; Somma et al., 2016). The Gulf of Naples (Eastern Tyrrhenian Sea, Figure 1) is subjected to high intensity human uses linked to coastal zone pressures and to a variety of natural hazards, such as seismicity, volcanism, gravity slides and potential tsunamis (e.g. Tinti, Pagnoni, & Piatanesi, 2003). It is an approximately rectangular marginal basin (NW oriented) with an area of about 900 km^2 on which stands part of the Campanian Volcanic Province (CVP). CVP is one of the areas of the world exposed to a significant volcanic hazard (over 1 million people lives in this area). The hazards include both marine and inland seismicity, deformations and landslides. The volcanic hazard is strictly related to a re-activation of the magmatic systems of the Phlegrean Fields, Mt. Vesuvius and Ischia Island. Ground deformation is particularly marked at the Phlegrean Fields and Ischia Island, where differential rates of movement are probably related to the presence of volcano-tectonic faults and hydrothermal systems (Acocella & Funiciello, 1999; Passaro et al., 2013). Seismic and bradyseism crises characterize the Phlegrean Fields, where an uplift of 1.8 m from 1982 to 1984 caused the evacuation of about 30,000 people from the town of Pozzuoli. Ischia has been subjected, in historical time, to natural seismic activity and lateral collapses (Aiello, Passaro, & Marsella, 2012; de Alteriis et al., 2010).

Here we show a high-resolution (5 m grid) bathymetric map of Naples Bay. Despite the growing attention to the monitoring of the CVP activity on land, little is known of the submerged portion of these volcanoes. Specific information exists on the coastal area of Vesuvius and the Phlegrean Fields, but these mainly come from seismic profiles, magnetic and gravimetric data or sediments samples (Aiello et al., 2005; 2009; D'Argenio et al., 2004; De Vivo, Scandone, & Trigila, 1993; Fusi, Mirabile, Camerlenghi, & Ranieri, 1991; Iorio et al., 2014; Iuliano, Mauriello, & Patella, 2002; Mirabile, De Marinis, & Frattini, 2000; Passaro et al., 2013, 2014; Pennetta, Pescatore, & Vecchione, 1984; Pescatore, Diplomatico, Senatore, Tramutoli, & Mirabile, 1984; Sacchi et al., 2005, 2014; Secomandi et al., 2003; Somma et al., 2016) but there is a lack of detailed knowledge of the bathymetry. Previous morpho bathymetric data available for this area were characterized by a lower resolution (20 m grid) and a higher noise-to-signal ratio (Aiello et al., 2001).

2. Geological background

CVP is bounded by the Southern Apennine Chain (to the west) and the Tyrrhenian Sea (to the East), and includes the active volcanoes of Ischia, the Phlegrean Fields and Somma-Vesuvius, along with Procida Island and some submarine volcanoes. The volcanism has a

CONTACT Salvatore Passaro salvatore.passaro@cnr.it
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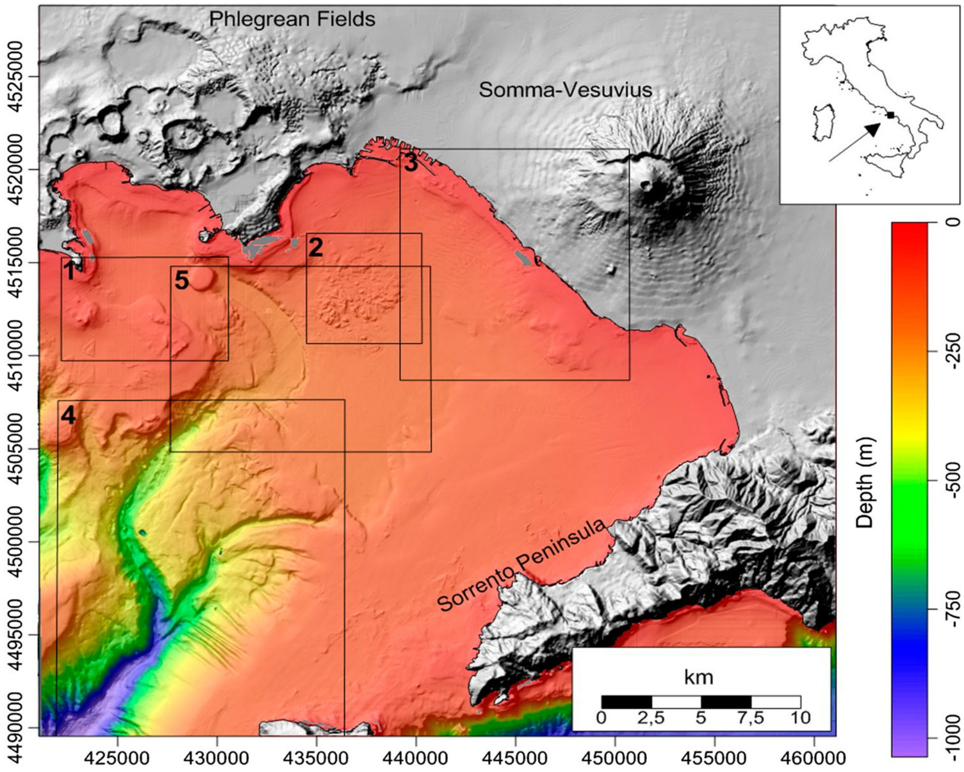

Figure 1. Location map and morphology of Naples Bay. Numbered rectangles indicate the successive figures.

potassic affinity and developed over the last 300–360 ky (age of the oldest rocks found in deep wells (e.g. Orsi, Di Vito, & Isaia, 2004 and references therein), with the emission of lava flows, domes, and pyroclastics related to strombolian, lava fountain, plinian and caldera-forming eruptions. The last eruptions occurred at Ischia Island in 1302 AD (Vezzoli et al., 1988), Phlegrean Fields in 1538 AD (Di Vito, Lirer, Mastrolorenzo, & Rolandi, 1987) and Mt. Somma-Vesuvius in 1944 AD (Santacroce et al., 2008). Overall, these three active volcanoes are aligned along a WNW–ESE strike suggesting a magma ascent along an E–W lithospheric discontinuity separating the central Tyrrhenian Sea from the southern one (e.g. Acocella & Funiciello, 2006; Berrino, Corrado, & Riccardi, 2008). The volcanic deposits are affected by NW–SE and NE–SW striking normal faults related to the still active northeastern migration of the Apennines. The CVP faults and eruptive fissures of the recent (<15 ka) activity of the Phlegrean Fields follow a prevailing NW–SE strike. Volcanic features of the CVP include a number of submarine vents (e.g. Penta Palummo, Miseno, Nisida banks) that develop offshore the Phlegrean Fields, within and around in Pozzuoli Bay (De Pippo et al., 1984; Ferraro & Molisso, 2000). These are typically represented by monogenic volcanic centers that mostly formed in shallow marine environments and were active at different stages during the last 200 ky (Milia, 2010; Sacchi et al., 2014). Mt. Somma-Vesuvius volcanic features include slides, debris avalanches and eruptive morphologies (Milia, Torrente, & Bellucci, 2012). Between distal products of the Phlegrean Fields and Mt. Somma-Vesuvius is located the Banco della Montagna seafllor high, a hummocky-like convex morphology made up of rising sediments dragged up by gas overpressure (mainly volcanic CO2; Passaro, Tamburrino et al., 2016). Finally, the Ammontatura and Dohrn channels are the main sedimentary features of the area (D'Argenio et al., 2004).

3. Data and methods

Multibeam echosounders (MBES) are standard equipment used to simultaneously collect several depth measurements called 'beams'. Thanks to an acoustic ping, usually emitted in the 20–500 kHz, MBES insonifies a seafloor portion allowing the collecition of a scattered 'numb' of depth. The bathymetric survey of Naples Bay was carried out by IAMC-CNR in August of 2014, as part of the SAFE_2014 oceanographic survey, on board the Urania research vessel using a Simrad EM 710 multibeam echosounder (Kongsberg©inc.).

This echosounder is characterized by a 70–100 kHz acoustic source frequency, 400 soundings per swath and 140° pulse width, and allow data acquisition upto 1200 m depth (2000 m in cold water with low salinity). The MBES system receives real-time geo-referencing positioning using a differential global positioning system receiver (that ensures a sub-metre accuracy), and values for inertial corrections of the boat for roll, pitch, yaw and heave corrections. Sound velocity profiles (SVP) were measured each 6–8 h or more frequently, if required by rapidly changing oceanographic/metereological conditions. SVP values were

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normally applied in real-time during surveys or in a later processing phase. A tidal correction derived from the national tide gauge network was also applied to increase vertical resolution. In addition, a hull-mounted SVP sensor was used for continuous, real-time measurements of the sound velocity and temperature in the surficial seawater strata.

MBES data processing was carried out with PDS2000 software following International Hydrographic Organization (IHO) standards (2008). Processing was chiefly aimed at the removal of navigational errors, noise reduction (i.e. de-spiking), removal of poor quality beams, and tidal and sound velocity corrections (e.g. de Alteriis, Passaro, & Tonielli, 2003). At the processing stage, depth measurements are spatially re-organized into a regular matrix termed a 'grid', or a Digital Terrain Model (DTM). The average resolution of a DTM derived from MBES depends on several parameters, including: (a) water-depth range of the survey area, (b) number of beams, (c) SVP accuracy, (d) instrumental frequency and positioning system used. Vertical resolution mostly depends on the instrument frequency while the horizontal resolution depends mainly on the 'footprint' (i.e. on the number of beams per square unit as a function of water-depth). The final processed data allowed a 5 m cell size. Terrestrial data are derived from the official topographic grid of the Military Institute for Geography (IGM; 20 m grid cell), acquired between 1985 and 1990 by using aerial photogrammetry (Amadio, 1992).

4. Results and discussion

The final DTM derived from the MBES depths (0 to −1023 m b.s.l., Figure 1) covers an area of 900 km^2. The final map (Figure 1 and Main Map) shows an overall articulated seafloor morphology, due to the presence of volcanic, structural and sedimentary features. Volcanic features are located in the northern sector of Naples Bay. In this area, volcanic morphologies represent the marine counterpart of the inland volcanic complexes. On the northeastern side of the Bay, seafloor morphologies mirror the distal deposits of the Mt. Somma-Vesuvius volcanic complex, while on the northwestern side, several seamounts are located on the southern boundary of the Phlegrean Fields caldera complex. In addition, a complex seafloor morphology locally called Banco della Montagna occurs between these domains. The southern sector of Naples Bay is dominated by sedimentary morphologies.

4.1. Phlegrean Fields offshore morphologies

The Phlegrean Fields activity led to the emplacement of the Phlegrean caldera that stretches out in the Pozzuoli Bay (e.g. Somma et al., 2016). Three main volcanic banks, poorly covered by sediments (Ferraro & Molisso, 2000), lie in proximity to Pozzuoli Bay (Figure 2(a)), that is, Miseno (Figure 2(a) and 2(b)), Penta Palummo (Figure 2(a) and 2(c)) and Nisida (Figure 2(a) and 2(d)). In particular, Miseno Bank is characterized by a nearly square, 1500 m extended shape, that reaches −35 m b.s.l. (Figure 2(b)). Its top is asymmetric, with a deeper southwestern slope and a N40°E striking feature. Penta Palummo Bank is a quasi-rectangular edifice measuring 3.6 × 2 km with a N130°E preferential elongation. On its summit area two main bodies, presumably volcanic, are present. The first volcanic body lies on the northeastern side and strikes N 130°E for about 1.4 km up to −50 m b.s.l. (Figure 2(d)). The second body is located in the southwestern sector of Penta Palummo Bank. It has an irregular shape with pronounced margins and its top is slightly concave (Figure 2(d)). This shape could be formed during past explosive activity on a preexisting volcanic edifice. Its central area is occupied by a small cone, probably resulting from a rejuvenation of the activity. Nisida Bank is near the coast, and is located in the southeastern sector of Pozzuoli Bay (Figure 2(c)). It shows a sub-circular shape (about 1.3 km diameter) with a flat top at −75 m bsl. This shape is quite similar to those characterizing pyroclastic volcanoes (e.g. Banco d'Ischia; Passaro, Matano et al., 2016). Penta Palummo and Miseno Banks are among the oldest offshore vents (120–18 ky), as they underlie a forced regression and lowstand deposits associated with the eustatic sea level fall that occurred between the Marine Isotpoic Stage (MIS) 5e (ca. 120 ky B.P.) and the Last Glacial Maximum (LGM) (ca. 18 ky B.P.). The Miseno bank is the relic of a younger volcanic cone that formed between 18 and 8 ky B.P. during the early stage of sea-level rise following the LGM.

4.2. Banco della Montagna

The Banco della Montagna morphologic high (Figure 3(a) and 3(b), and Main Map) is a volcanic feature made up of a quasi-circular, NE–SW structurally controlled hummocky-like morphology (D'Argenio et al., 2004; Passaro et al., 2014). It is a younger than 12 ky B.P feature emplaced through a complex set of dome-like structures rising from the pyroclastic and marine layers that crop out from the post LGM sediments (Passaro, Tamburrino et al., 2016). This doming effect is probably driven by overpressure generated by fluid vents entrapped in gas saturated layers (Ventura, Passaro, Tamburrino, Vallefuoco, & Sacchi, 2016). It extends for about 4 km between −100 and −180 m b.s.l., and is characterized by a convex, southward tilted shape (Figure 3(b) and profile P1). The rising volcanic deposits have the same chemical affinity as

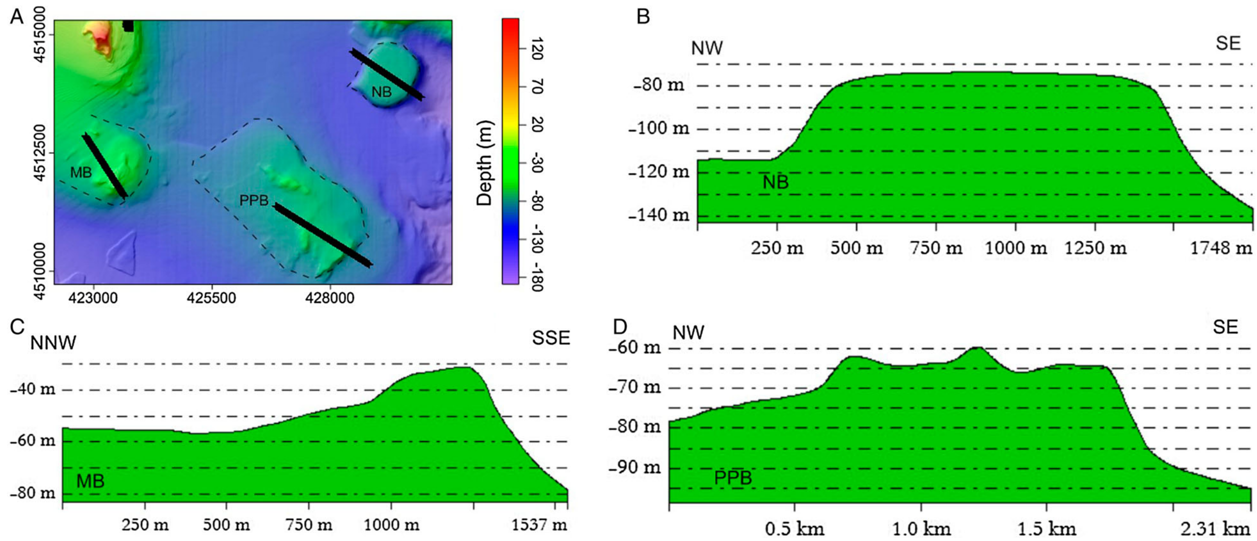

Figure 2. Morphology of volcanic banks on the southern sector of the Phlegrean Fields Caldera (location is the frame 1 in Figure 1). (a) DTM and location of MB (b), NB (c) and PPB (d) profiles. MB = Miseno Bank, PPB = Penta Palummo Bank, NB = Nisida Bank.

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the Phlegrean Fields products (D'Argenio et al., 2004; Insinga, 2003).

4.3. Somma-Vesuvius marine features

The northeastern sector of Naples Bay is characterized by a relatively shallow water area occupied by a series of partly superimposed morphologies related to the evolution of the Mt. Somma-Vesuvius volcanic complex (Figure 4(a)). Here the distal sector of the SW slope of the volcano displays evidence of repeated changes in the seafloor morphology due to accretion and/or erosion, likely due to the concomitant action of erosion associated with eustatic sea-level

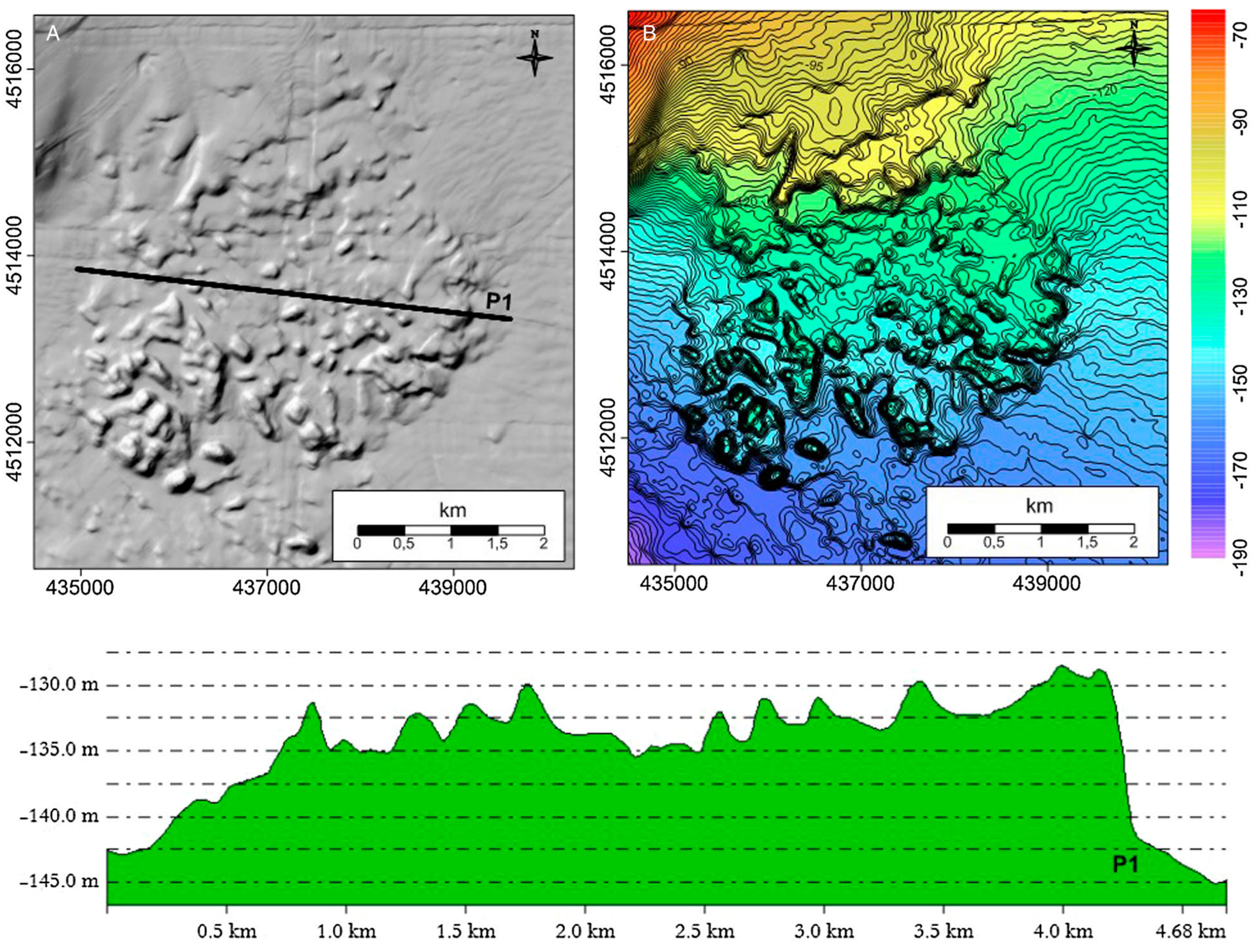

Figure 3. Morphology of Banco della Montagna (location is frame 2 in Figure 1). (a) Shaded relief, (b) contour map (isobaths at 1 m interval) and (c) bathymetric profile showing the apical hummocky-like morphology that characterizes the bank.

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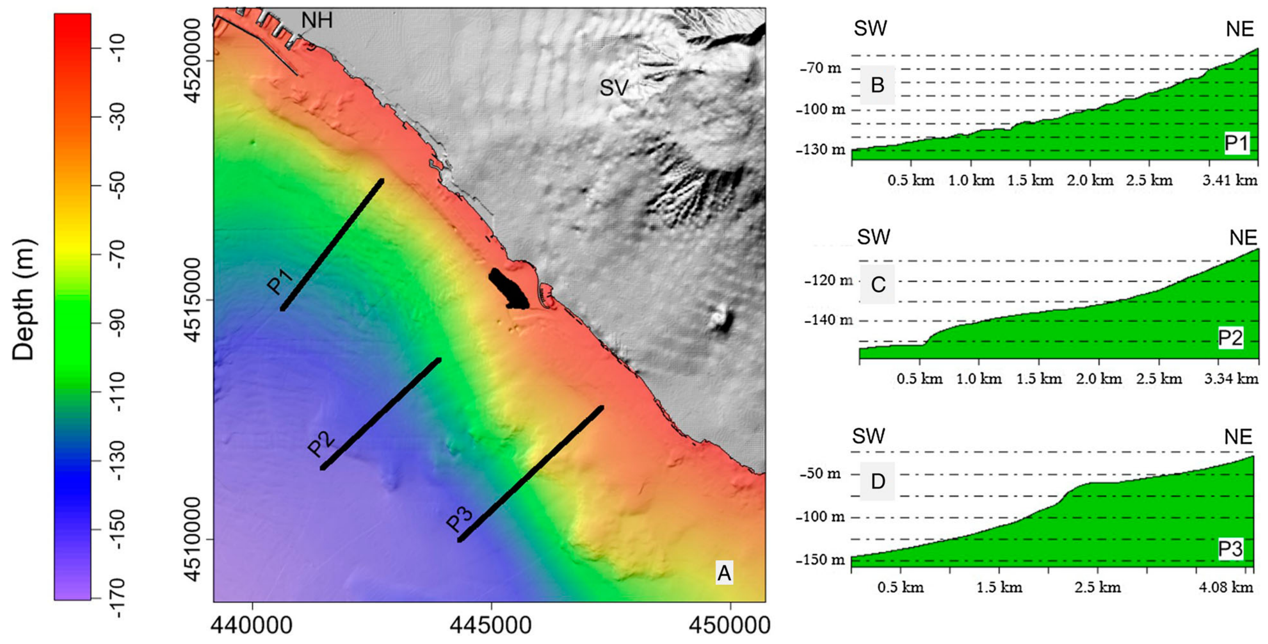

Figure 4. Distal sector of Mt. Somma-Vesuvius volcanic complex (location is frame 3 in Figure 1). (a) DTM and location of P1 (b), P2 (c) and P3 (d) profiles.

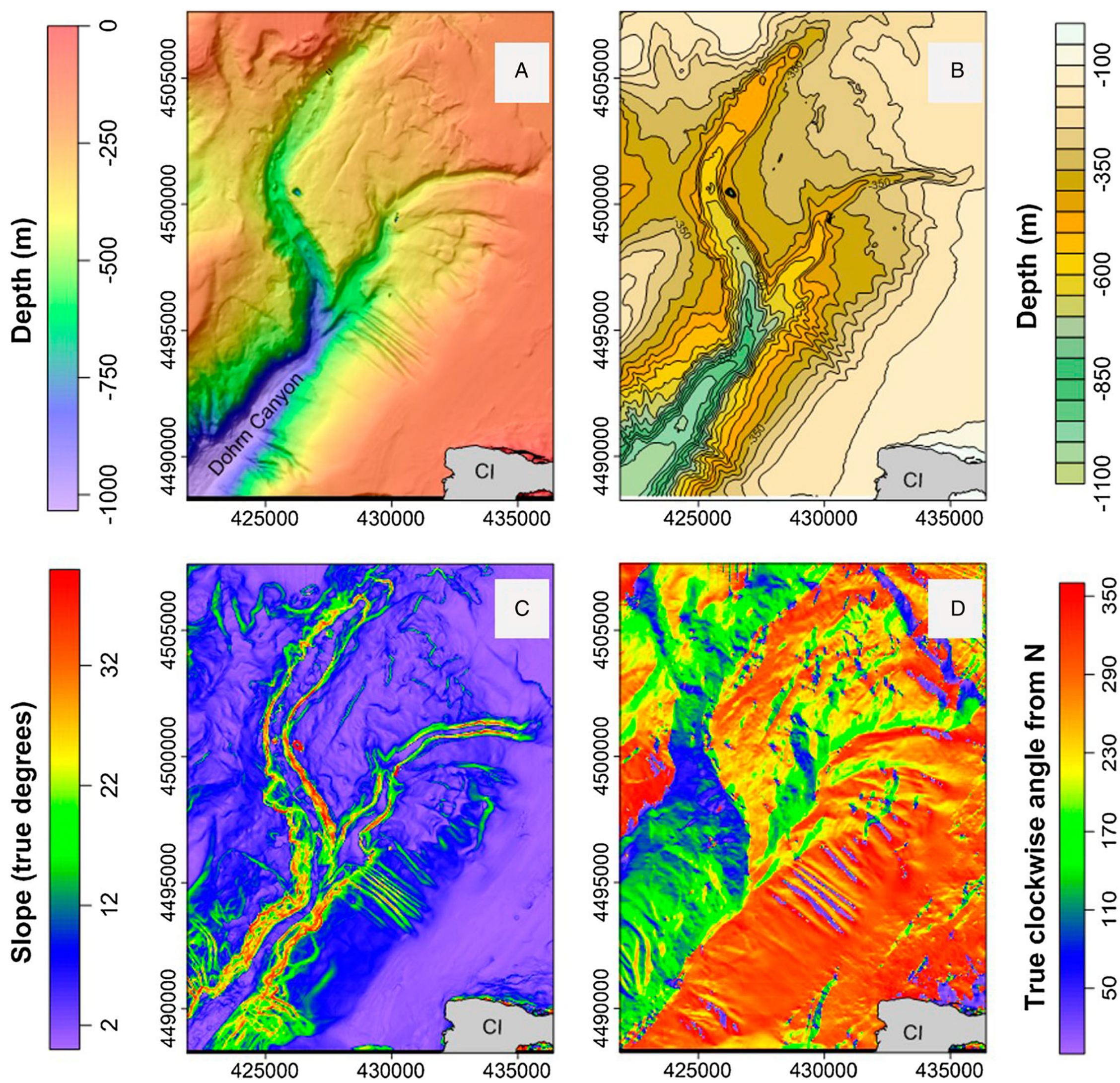

Figure 5. Morphology of Dohrn Canyon (location is frame 4 in Figure 1). (a) Shaded relief map, (b) contour map (contour interval is 50 m), (c) slope map and (d) aspect map.

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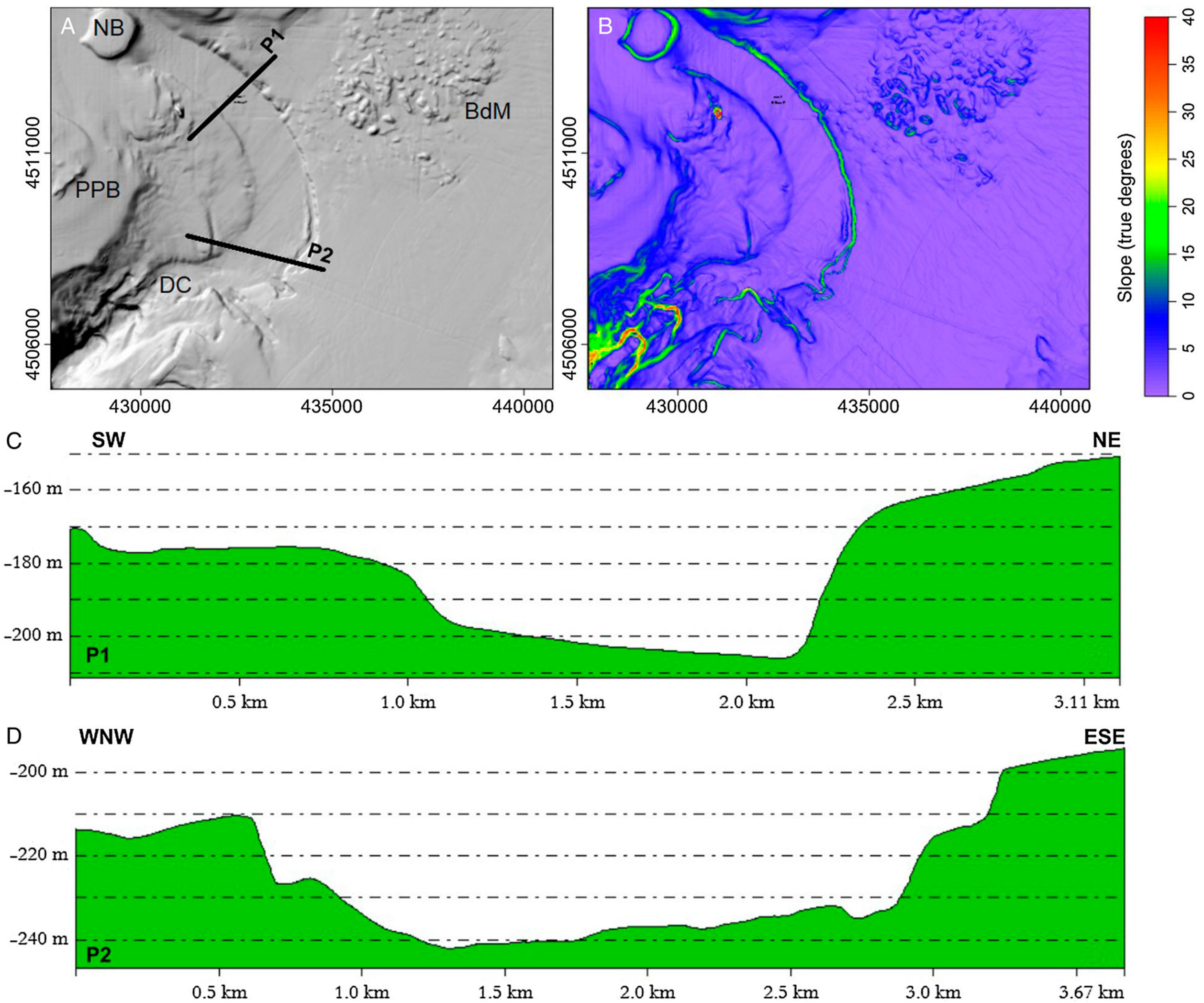

Figure 6. Morphology of the Ammontatura channel (location is frame 5 in Figure 1). (a) Shaded relief with the location of P1 and P2 bathymetric profiles. NB = Nisida Bank, PPB = Penta Palummo Bank, BdM = Banco della Montagna, DC = Dohrn Canyon. (b) Slope map, (c) bathymetric profile P1, (d) bathymetric profile P2.

fluctuations, and deposition of lava flows during effusive activity or pyroclastic flows accompanying explosive events. As a result, slope morphologies in this area result in three main types that can be described as follows: (1) convex, (2) convex to concave and (3) convex with gradients in slope. Typical convex-shaped profiles are due to a smooth transition between the slope and the debris talus at the base of the cliff (Figure 4(b)). Concave-shaped profiles in the apical (shallower) part of the slope passing to convex, toe-shaped morphologies at depth are likely due to the accumulation of lava flows and/or volcaniclastic deposits deriving from the Mt. Somma-Vesuvius (Figure 4(c)). Finally, double concave profiles that exhibit a break-in-slope may be recognized, possibly resulting from the occurrence of a marine abrasion platform.

Toe-shaped fronts also arise from lateral collapses of the Mt. Somma-Vesuvius edifice, that have been dated at 3.5 ka B.P. in the northern part of the area (Figure 4 (a) and 4(b)) and at ky BP in the southern part (Figure 4(d)) (Milia et al., 2012 and reference therein). Positive seafloor morphologies in the distal parts of the area mainly correspond to bedforms associated with pyroclastic flow deposits and lateral collapses of the flanks of the volcanic edifice. These processes occurred over an area extending from the coastline to −150 m b.s.l., and dominate the profile of the continental shelf for ca. 6 km (Milia, Molisso, Raspini, Sacchi, & Torrente, 2008). Other morphological expressions of the shelf are the result of gravity flows (Figure 4(c)) and sediment waves (Figure 4(a)).

4.4. Non-volcanic features

The southwestern sector represents the northern slope of the Sorrento Peninsula, while the sotheastern sector is dominated by the Dohrn Canyon (Main Map). Two branches of the canyon start immediately after the slope-break, located at about −180 m b.s.l. and extend for about 10 km toward the deeper southwestern basin (Figure 5(a) and 5(b)). The transition between the more lifted shelf and the rugged slope surface is evident. Indeed, the slope is dominated by the capture of sediments exerted from the canyon (Figure 5(c)),

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which results in a more rugged morphology. The branches of the canyon join in proximity of Capri Island, where a single segment flows southwestward (Figure 5(d)). The final section of the canyon thalweg (southwestern corner in the Main Map) is about 1400 m wide (Figure 5(a) and 5(b)).

The central-eastern part of Naples Bay is characterized by the presence of the Ammontatura Channel, which is a semicircular canyon with irregular sides (Figure 6(a) and 6(b)). The canyon starts in the Nisida Bank (Figure 6(a)) and terminates at the head of the northernmost branch of the upper sector of the Dohrn Canyon. Its morphology separates the Banco della Montagna area from the Phlegrean Fields volcanic banks. The easternmost levee is steeper (Figure 6(b) and 6(c)) and shows some stepped, presumably structurally emplaced terraces in its deeper segment (at about −200 m depth; Figure 6(b) and 6(d)).

Software

Bathymetric data were processed with Caris Hips and Sips and Fledermaus. The final DTM was obtained by using the PDS2000 grid model editor tool and Surfer. The final map (Main Map) was produced using Golden Software Sufer11.

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Disclosure statement

No potential conflict of interest was reported by the authors.

ORCID details

Salvatore Passaro http://orcid.org/0000-0002-3045-9002

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