DOI: 10.1111/tgis.12829

RESEARCH ARTICLE

Transactions in GIS WILEY

Geomorphometric analysis of the natural and anthropogenic seascape of Naples (Italy): A high-resolution morpho-bathymetric survey

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Funding information
PON 03PE_00164"Rete Intelligente dei Parchi Archeologici (RIPA - PAUN)

Abstract

This research aims to reconstruct the submerged morphologies of the high-coast sectors of Naples discriminating between landforms and anthropogenic structures, by analysing the high-resolution data of a multibeam survey in a GIS environment. In the case of natural landforms, a signal analysis was performed to characterize the seabed and discern between sandy and rocky bottom, together with a slope analysis pointing to the detection and mapping of different orders of palaeo-shore platforms at different bathymetric ranges and interpreted as erosional traces of the Holocene sea cliff retreat affecting the study area, mainly caused by a subsiding trend that exacerbated the glacio-hydro-isostatic sea-level rise. Then, the detected palaeo-shore platforms were further analysed to quantify their roughness degree and, consequently, the differential erosion affecting the rocky platforms. On the other hand, regarding the submerged anthropogenic structures, the multibeam survey allowed several underwater archaeological remains of Roman Age to be mapped, demonstrating the high cultural relevance of the study area.

1 | INTRODUCTION

Geomorphometric studies (i.e., quantitative analysis of the Earth's surface; MacMillan & Shary, 2009) of particular marine areas, realized through the use of cutting-edge high-precision indirect approaches, are increasingly widespread due to the ability of these new technologies to target the slightest morphological change of the seabed and to realize extensive mapping of the study areas, essential for both their historical and geomorphological characterization, and otherwise impossible to achieve (Anderson, Holliday, Kloser, Reid, & Simard, 2008; Caporizzo et al., in press; Lecours, Dolan, Micallef, & Lucieer, 2016; Lecours, Lucieer, Dolan, & Micallef, 2015; Mattei, Rizzo, Anfuso, Aucelli, & Gracia, 2020; Mattei, Troisi, et al., 2019; Micallef, Berndt, Masson, & Stow, 2007; Passaro et al., 2016).

The coastal sector of the city of Naples is an interesting example of an area of high natural and cultural interest that was subjected to a continuous geomorphological evolution over time, and particularly during the Holocene.

In particular, the considerable geomorphological interest is related to its morphological characteristics and a peculiar coastal conformation set on volcanic tufaceous deposits with high erosion rates testified by the presence of numerous relict submerged platforms, related to the joint effect of local subsiding trends and glacio-hydro-isostatic sea-level rise on rocky coast (Amato et al., 2018; Aucelli, Cinque, Mattei, Pappone, & Rizzo, 2019; Aucelli, Cinque, Mattei, Pappone, & Stefanile, 2018a; Mattei, Aucelli, Caporizzo, Peluso, et al., 2020; Mattei et al., 2018; Pappone et al., 2019).

Indeed, rocky coasts can be defined as dynamic complex coastal systems characterized by morphological modification induced by the combined action of endogenous and exogenous forcing (Trenhaile, 1997, 2011; Woodroffe, 2002).

High-coast sectors are the result of prevailing landward retreat which leads to the formation of erosional geomorphological features as shore platforms or tidal notches that can be used to detect past relative sea level (RSL) variations (Bilbao et al., 2020; Duguet et al., 2021; Rovere et al., 2016). In particular, shore platforms are sub-planar surfaces dipping seaward and limited landward by the sea-cliffs (Bilbao et al., 2020). The inner margins of palaeo-shore platforms are directly related to the ancient RSL and their formation is favoured by the wave action, often exacerbated by bio-erosion and weathering (Bird, 2000; Pappalardo et al., 2016; Sunamura, 1992; Trenhaile, 1987, 2011). Their extension depends on the hardness of the sea-cliff lithology and the duration of the related sea-level stability (Bird, 2000; Kanyaya & Trenhaile, 2005; Swirad et al., 2020; Trenhaile, 2005).

In the case of a high coastal sector located within an active volcanic area, under conditions of general sea-level stability or slow sea-level rise, a morpho-evolutive cycle with variable duration will produce the formation of a first-order shore platform that can be abruptly interrupted by local vertical ground movements (VGMs) and volcanic activity, responsible for the end of this first geomorphological cycle and the beginning of a new one (Aucelli et al., 2019, 2020; Cinque et al., 2011).

The high erosion rates characterizing rocky cliffs and the presence of numerous relict submerged platforms are an issue of considerable importance in the framework of coastal vulnerability studies of densely populated areas regarding the determination of risk and safety assessment (Mattei, Aucelli, Caporizzo, Rizzo, & Pappone, 2020; Mattei, Troisi, et al., 2019; Rizzo, Aucelli, Gracia, & Anfuso, 2018; Rizzo, Vandelli, Buhagiar, Micallef, & Soldati, 2020).

On the other hand, the study area is a typical example of volcanic rocky coast in which relicts of emerged and submerged platforms were studied in order to reconstruct the Holocene VGMs of volcanic origin that affected Naples and its surrounding area (Aucelli et al., 2018a; Cinque et al., 2011; Mattei, Aucelli, Caporizzo, Peluso, et al., 2020).

It is worthy to note that this coastal area has also high cultural value intensified by the presence of several archaeological remains of ancient settlements scattered along the abovementioned submerged platforms (Ascione et al., 2020; Aucelli, Cinque, Giordano, & Mattei, 2016; Aucelli, Cinque, Mattei, & Pappone, 2017; Aucelli et al., 2018a, 2018b; Mattei, Aucelli, Caporizzo, Peluso, et al., 2020; Mattei, Aucelli, Caporizzo, Rizzo, et al., 2020; Mattei, Rizzo, Anfuso, Aucelli, & Gracia, 2019; Pappone et al., 2019). Indeed, this coastal sector was inhabited from the first Greek colonization, with the establishment of the old city of Parthenope in the seventh century BC near Pizzofalcone Hill, and throughout the entire Roman Age, with the foundation of ancient Neapolis in the sixth to fifth centuries BC in the neighbourhood of the current Piazza Municipio (Vacchi et al., 2019, and references therein). Consequently, the archaeological ruins, nowadays mainly submerged and witness to the glorious past of this area, represent a huge part of the local historical heritage that, first of all, need to be mapped, catalogued, and protected as a wealth resource of the city.

For this purpose, high-precision morpho-acoustic surveys, and indirect surveys in general, represent one of the most effective instruments for the detection and mapping of the ancient natural and anthropic traces that constitute an irreplaceable source of data for the characterization and reconstruction of the morpho-evolution of the area over time, testifying to the effects of the ongoing climate change on the ancient settlements as well as on the coastal modifications (Aucelli, Cinque, Mattei, & Pappone, 2016; Aucelli et al., 2018a, 2019, 2020; Mattei, Aucelli, Caporizzo, Peluso, et al., 2020; Mattei et al., 2018; Pappone et al., 2019).

In this article we focus on the geomorphometric characterization of the Neapolitan high-coast sectors derived from the application of a multibeam survey, one of the most accurate and detailed technologies in terms of seabed morphology data (Lecours et al., 2015; Schimel, Healy, Johnson, & Immenga, 2010), demonstrating the great utility of morpho-acoustic and remote sensing investigation techniques in the characterization of the seabed and its morpho-evolution over time.

2 | GEOLOGICAL AND GEOMORPHOLOGICAL SETTING

The coast of the city of Naples covers a length of about 24 km ranging from Pietrarsa, located on its eastern border, to La Pietra, representing its western limit (Figure 1). Generally, the Neapolitan coastal area is characterized by an alternation of small pocket beaches, rocky cliffs, and wide coastal plains (Vacchi et al., 2019) strongly urbanized since the first Greek colonization. The landscape morphology is the result of the intense interaction between morpho-genetic processes of volcano-tectonic origin and the exogenous modelling action related to the wave action and the superficial freshwater outflow (Cinque et al., 2011).

The high coast sectors, in particular, are mainly characterized by the presence of the Neapolitan Yellow Tuff (NYT, 15 ka BP; Isaia et al., 2019) and the other volcanic deposits related to the minor following eruption which characterized the volcanic history of the Campi Flegrei district (Aucelli et al., 2019; Deino, Orsi, Piochi, & de Vita, 2004). They are represented by the headland of Pizzofalcone and the opposite Castel dell'Ovo islet, located in the central area, and by the Posillipo Hill, constituting the western portion of the coastline (Figure 1).

The Pizzofalcone promontory (Figure 1), which hosted the first Greek settlement established along the Gulf of Naples, the so-called city of Parthenope, is characterized by a height of 60 m mean sea level (MSL) and a steepness of about 80% (Pappone et al., 2019). The headland is bordered on its west side by the Chiaia coastal plain, which extends for about 600 m at the base of a palaeo-sea cliff 174 m high, and on the eastern margin by the Municipio plain, located at the foot of the Pendino Terrace and nowadays strongly modified by the construction of the port of Naples (Pappone et al., 2019). The dominant bedrock of the area is represented by the NYT, found almost everywhere in the whole area of Naples, and its underwater sector is mainly constituted by submerged beach deposits (Isaia, Iannuzzi, Sbrana, & Marianelli, 2016).

The Castel dell'Ovo islet, formerly called Megaris, stands right in front of the headland of Pizzofalcone (Figure 1), bordered by two different orders of submerged tufaceous palaeo-shore platforms located at about –5 and –3 m MSL, respectively (Mattei, Aucelli, Caporizzo, Peluso, et al., 2020). Both the promontory and the islet are made of Castel dell'Ovo Tuff (OVO, 78 ka BP; Isaia et al., 2016), while the SW sector of the OVO formation is mantled by NYT through an erosional unconformity (Isaia et al., 2016; Pappone et al., 2019).

The formation of the sea-stack of Castel dell'Ovo is attributed to the continuous wave action also responsible for the retreating of the sea-cliff whose footslope traces are still visible along Via Chiatamone (Mattei, Aucelli, Caporizzo, Peluso, et al., 2020).

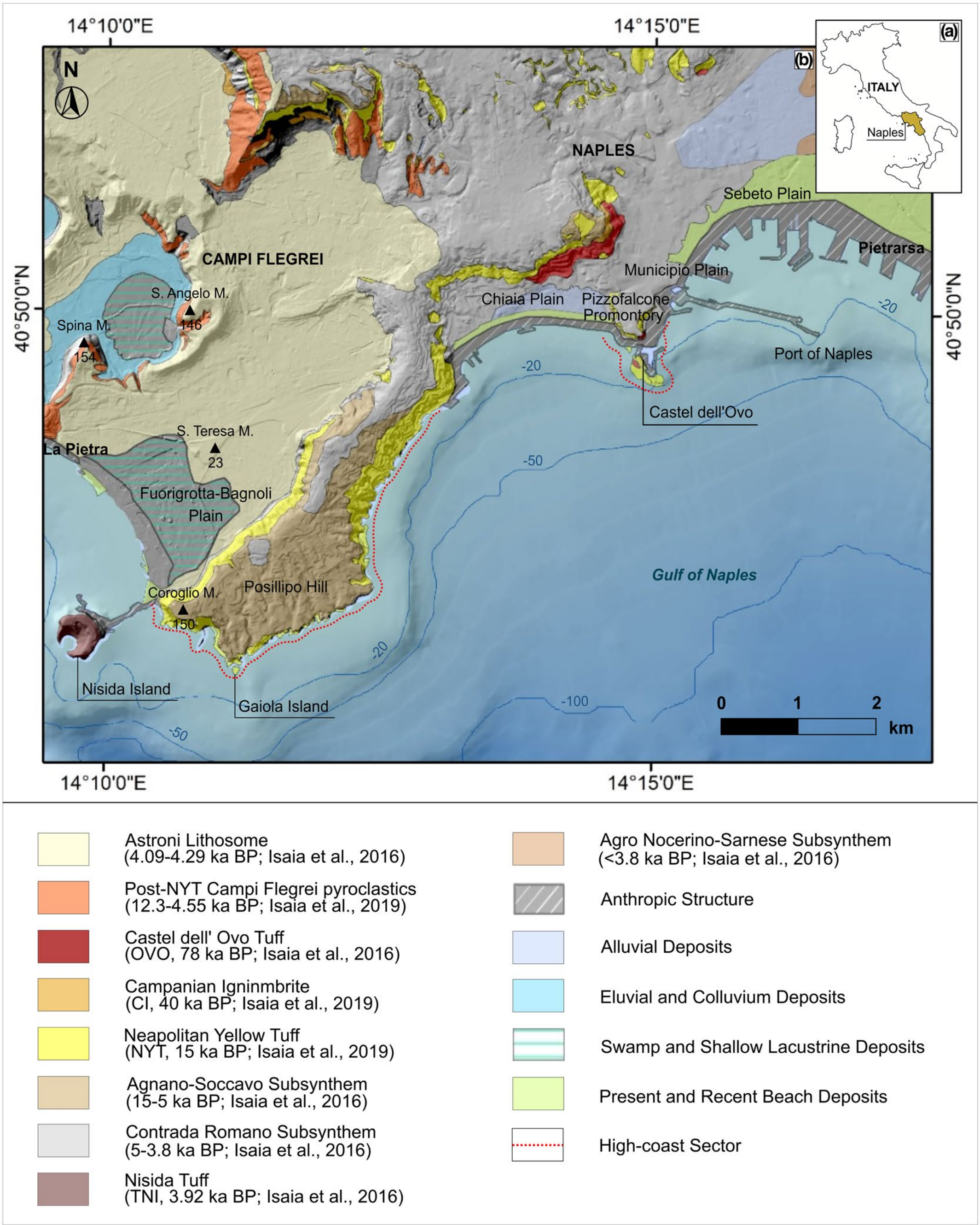

FIGURE 1 (a) Location map of the study area. (b) Geological map of the city of Naples (after Isaia et al., 2016)

Posillipo Hill is an asymmetrical and homoclinal structure mainly made of NYT, characterized by an increasing height towards the south. This high coastal sector with a length of about 5 km is interrupted by the presence of several small embayments hosting pocket beach systems, and it owes its actual morphology to the Holocene interplay between anthropic activity and endogenous/exogenous natural factors (Aucelli et al., 2018a, 2019; Mattei, Aucelli, Caporizzo, Rizzo, et al., 2020).

In particular, during the Holocene the area was affected by a prevailing cliff retreat mainly caused by a subsiding trend, which exacerbated the general sea-level rise (Aucelli et al., 2019; Mattei et al., 2018). The acceleration of the subsiding trend between the first century BC and the first century AD led to the formation of two orders of shore platforms archaeologically dated and located between −1/−3 m and −4/−6 m MSL (Aucelli et al., 2018a).

The SW sector of the Posillipo Hill is characterized by the presence of two small islands of volcanic origin, Gaiola and Nisida, and, in their midst, a sea-cliff reaching the maximum height of 150 m MSL at Coroglio Mount (Figure 1). Gaiola, famous for hosting the luxury Pausilypon Roman villa, is mainly made of NYT and is constituted by two minor promontories, connected by a bridge, with a maximum length and height of about 90 and 11 m MSL, respectively. The tuff cone of Nisida, made entirely of Nisida Tuff (TNI, 3.92 ka BP; Isaia et al., 2016), is characterized by a circular shape with a diameter of about 550 m and a maximum height of about 100 m MSL.

3 | METHODOLOGY

3.1 | Morpho-acoustic survey

Selected sectors within the study area were investigated by means of a multibeam echo sounder (MBES), pole-mounted on a small vessel equipped for hydrographic services. The survey was carried out on 4–6 December 2019 between 9.30 a.m. and 2.30 p.m.

Bathymetric data were logged along 90 acquisition routes for a total length of 43.5 km, investigating a total area of about 2 km^2 in the bathymetric range −40 m to −1 m MSL. A survey speed of about 3 knots was kept in order to ensure vessel control in very shallow water and to achieve full acoustic coverage. The data quality benefited from favourable marine environment conditions that ensured very limited vessel movement (heave ±0.15 m, pitch/roll ±3°), already corrected by the motion sensor.

On 4 December, the equipment was installed and calibrated (see Section 3.2). Moreover, sector 1 was investigated, covering an area of about 0.77 km^2 in the bathymetric range −40 to −1 m MSL. On 5 December, sector 2 was surveyed, covering an area of 0.75 km^2 in the bathymetric range −30 to −1.25 m MSL. Finally, on 6 December, sector 3 (area 0.6 km^2) was mapped at a depth between 1 and 18 m. A total amount of 193 million bathymetric points were stored in 294 data files.

3.2 | Multibeam system and post-processing

Bathymetric data were collected by means of a Teledyne Reson SeaBat7125 MBES (operational frequency 400 kHz), pole-mounted on a small vessel equipped for hydrographic services. The sonar SeaBat7125 provides a 140° across track swath on the seafloor, characterized by 1° of beamwidth along track. The receive array forms 512 individual 0.5° wide beams; phase values of central beams and amplitude values of external beams provide bottom detection to a maximum depth of 150 m. An SBG inertial system ensured time synchronization (pulse per second signal) for positioning data from a Trimble BX982 Global Navigation Satellite System (GNSS) dual antenna receiver and for vessel movement data (heave, pitch, roll) from an Ekinox-U motion sensor (see Table 1 for detailed equipment technical specification). The inertial system transmitted synchronized position, ship heading and motion data to the SeaBat7125 control unit and the Teledyne PDS acquisition software (Figure 2).

The equipment set-up included the measurement of the physical offsets and the calibration procedure. The offsets of each sensor to a fixed point were stored in the acquisition software in order to refer all sensor data to a common point, usually the vessel's centre of rotation. The calibration procedure computed the residual mounting angles between the multibeam transducers and the motion sensor. A series of specific track-lines were travelled on identifiable targets and processed by means of the Teledyne PDS calibration module. The software computed

TABLE 1 Equipment technical specifications

Multibeam SeaBat7125	
Frequency	400 kHz
Max ping rate	50 Hz (±1 Hz)
Along-track transmit beamwidth	1°
Across-track receive beamwidth	0.5°
Pulse length	30–300 μs continuous wave
300 μs–20 ms frequency modulated (X-range)	
Number of beams	512
Max swath angle	140°
Typical depth	0.5—150 m
Depth resolution	6 mm
Ekinox-U motion sensor	
Pitch accuracy	0.05°
Roll accuracy	0.05°
Heading accuracy	0.1°
Heave accuracy	5 cm or 5%
Trimble BX982 GNSS	
Accuracy	Sub-metric

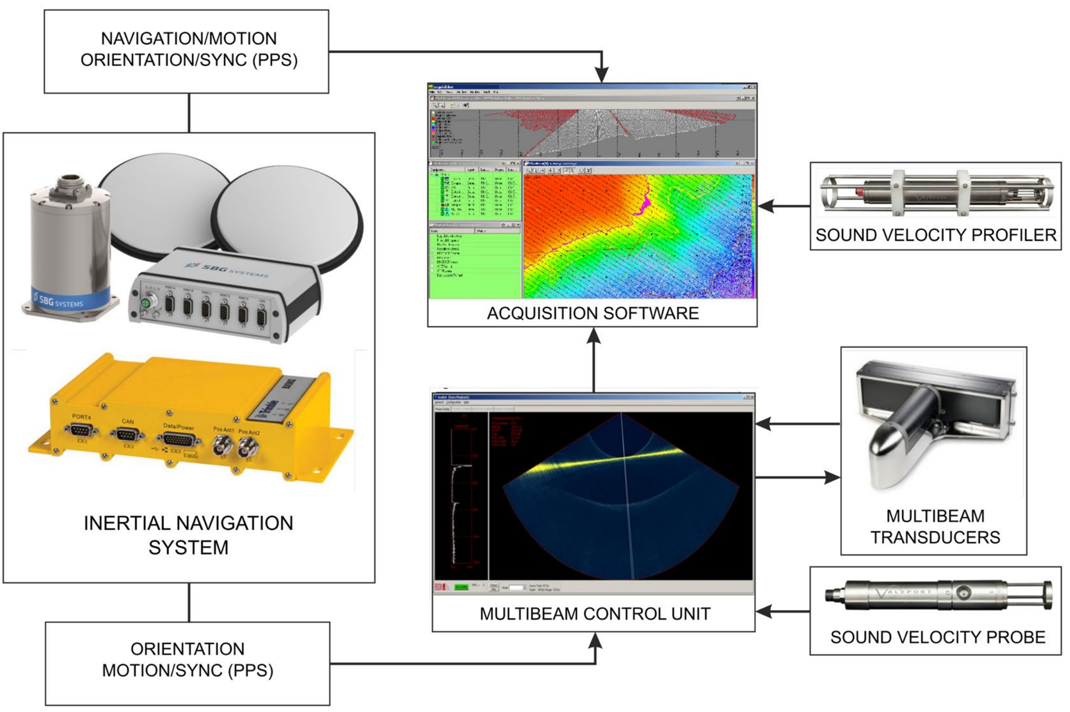

FIGURE 2 Diagram of connections between equipment and sensors

the minimum difference between the produced surfaces and the corresponding residual angles through a series of iterations (Figure 3). The resulting values +0.33°, −1.80° and −0.01°, for roll, pitch and yaw angles respectively, were and used during acquisition to achieve corrected bathymetric data.

During the survey, filter settings and control displays were used to check the multibeam data quality. The data logging progress was shown in real time using a colour-coded digital terrain model (DTM). A probe and profiler collected sound velocity values near the multibeam transducers and along the water column, required for refraction coefficient correction and proper depth computation; sound velocity profiles were collected before surveying in the selected study areas (Figure 4).

The survey lines were planned and travelled in order to have 25–50% overlap between adjacent swaths to achieve a very high-resolution seafloor coverage.

Bathymetric data were processed using the Teledyne PDS editing module. Tide data, collected by the national tidegauge network (https://www.mareografico.it), were applied to the data set, to set up the real depth (Figure 5).

The Editing module combines 3D swath editing, DTM editing and positioning control, for data cleaning: supervised data de-spiking and real-time DTM updating were used to preserve data accuracy and resolution.

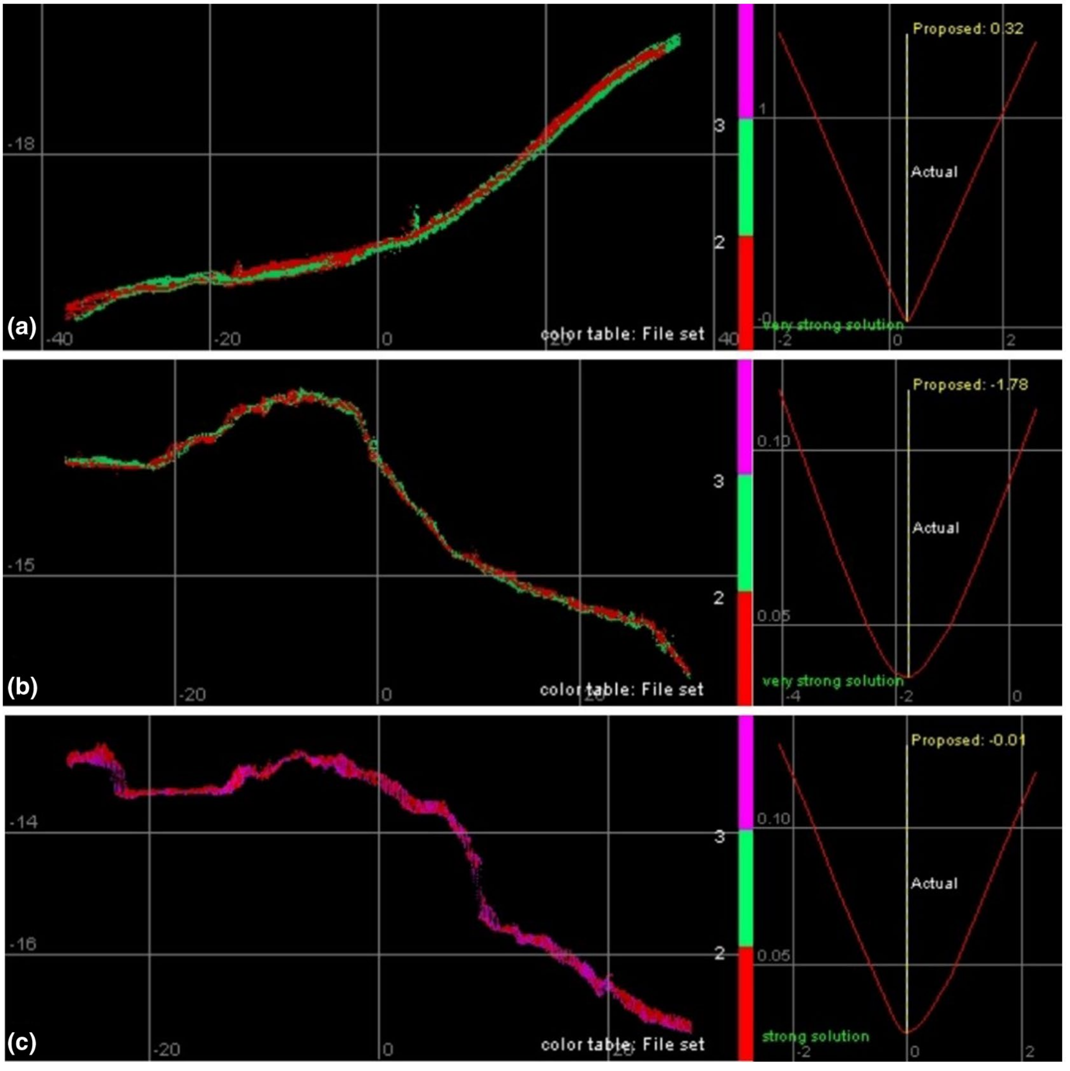

FIGURE 3 Multibeam calibration summary with surface difference (sin) and proposed angle values (dx) for: (a) roll; (b) pitch; and (c) yaw

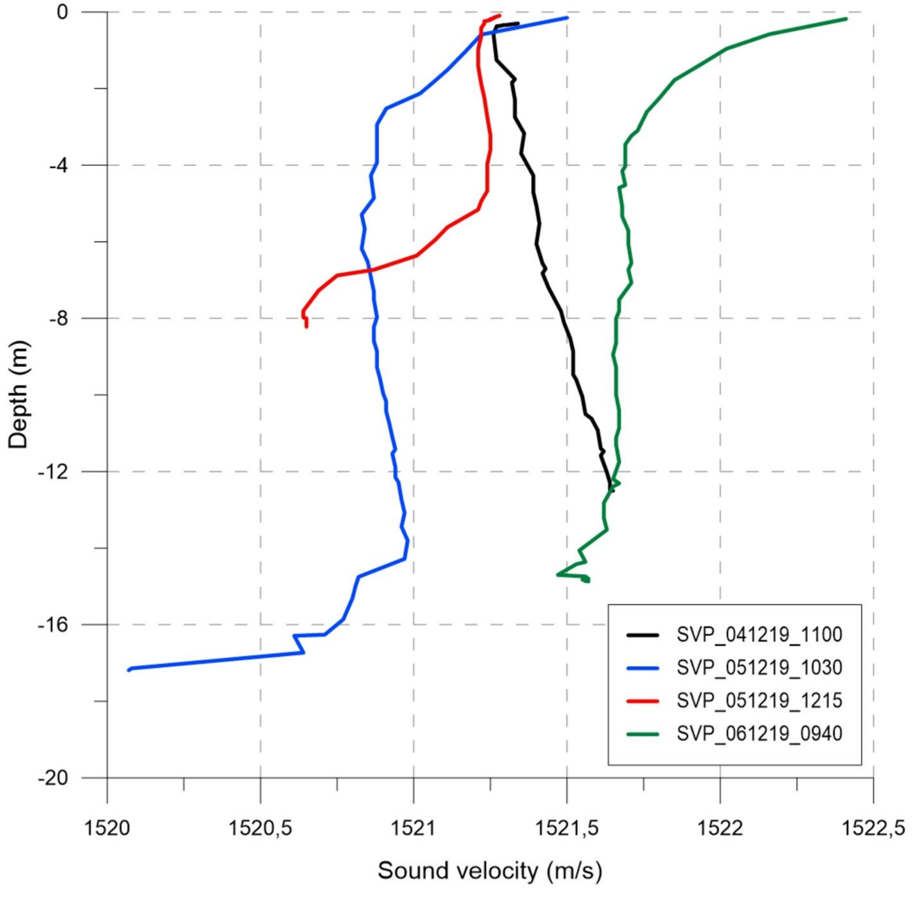

FIGURE 4 Sound velocity profile collected for multibeam survey

The processed data were finally exported to create a high-resolution image of the seafloor. The final 0.25 × 0.25 m grid cell DTM covers about 2 km^2 in a water depth range of −40 to −1 m MSL.

3.3 | GIS and morphometric analysis

The high-precision DTM derived from the multibeam surveys was morphometrically analysed in a GIS environment in order to detect the main submerged morphologies and differentiate between those of natural and anthropogenic origin. In the case of natural landforms, a signal analysis was performed to characterize the seabed and discern between sandy and rocky bottom, by overlaying our morpho-acoustic data with the geological data from the official map (Isaia et al., 2016). In addition, a slope analysis was carried out in order to detect and map different orders of platforms.

In particular, the slope analysis was carried out considering four slope classes: gentle (0–5°); moderate (5.1–8.4°); strong (8.5–24°); and extreme slopes (24.1–87.4°). The surfaces characterized by gentle slope were interpreted as palaeo-platforms, including the areas classified as moderate slope probably related to a slight differential erosion and/or to the sea-level dynamics present during their formation. The areas characterized by strong and extreme slope values were interpreted and classified as scarps.

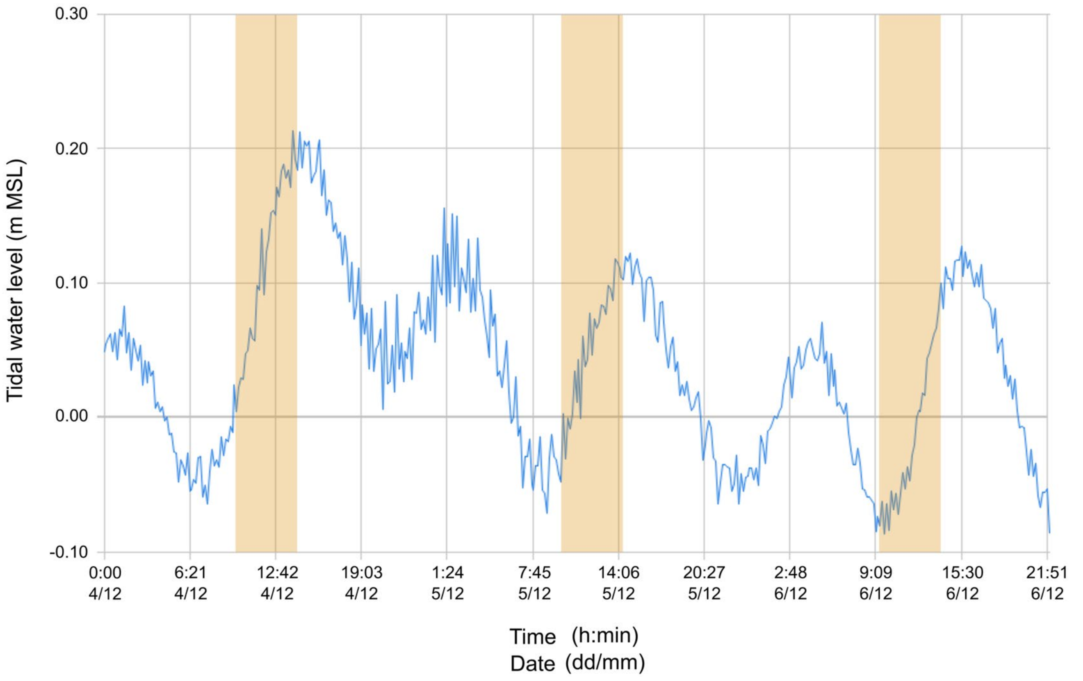

FIGURE 5 Variation of the tidal water level in the Gulf of Naples, 4–6 December 2019 (data from the ISPRA—Rete Mareografica Nazionale) and the levels during the surveys (areas highlighted in orange)

Moreover, to quantify the differential erosion affecting the rocky platforms, the roughness degree (R_D) of every surface was calculated. For each platform, the calculation was made by comparing the percentage of gentle-to-moderate slope sectors with the percentage of strong-to-extreme slope sections allowing the detection of low-, medium-, and high-roughness areas.

4 | RESULTS FROM THE MORPHOMETRIC ANALYSIS OF MULTIBEAM DATA

4.1 | Pizzofalcone promontory

The Pizzofalcone promontory is a remnant of a tufaceous headland anthropogenized since the first colonization stages in the Gulf of Naples. Several erosion traces along the emerged and submerged sectors testify to the complex Holocene morpho-evolution of this sector. The first significant submerged landform is the small bank (85 × 50 m) detected between 11 and 16 m depth in the proximity of the modern pier (Figure 6b).

This structure nowadays appears covered by soft sediments and probably during the fifth century was used as hard basement for the construction of a lighthouse, as shown in a 1,479 painting by Francesco Rosselli (Figure 7).

In the eastern submerged sector of the Pizzofalcone promontory, a 120-m wide sub-horizontal surface was mapped between San Vincenzo pier and Santa Lucia harbour (Figure 6c). It appears covered by sediments, with a NE–SW extension of 240 m and a max slope of 3°. The surface ends with an outer margin at −10 m MSL, and a scarp sloping 23° seaward (Figure 8).

The same 10-m deep outer margin is visible at the Santa Lucia port entrance with a NE–SW extension of 50 m (Figures 6d and 8). In this area, the platform was almost totally buried by modern construction, such as

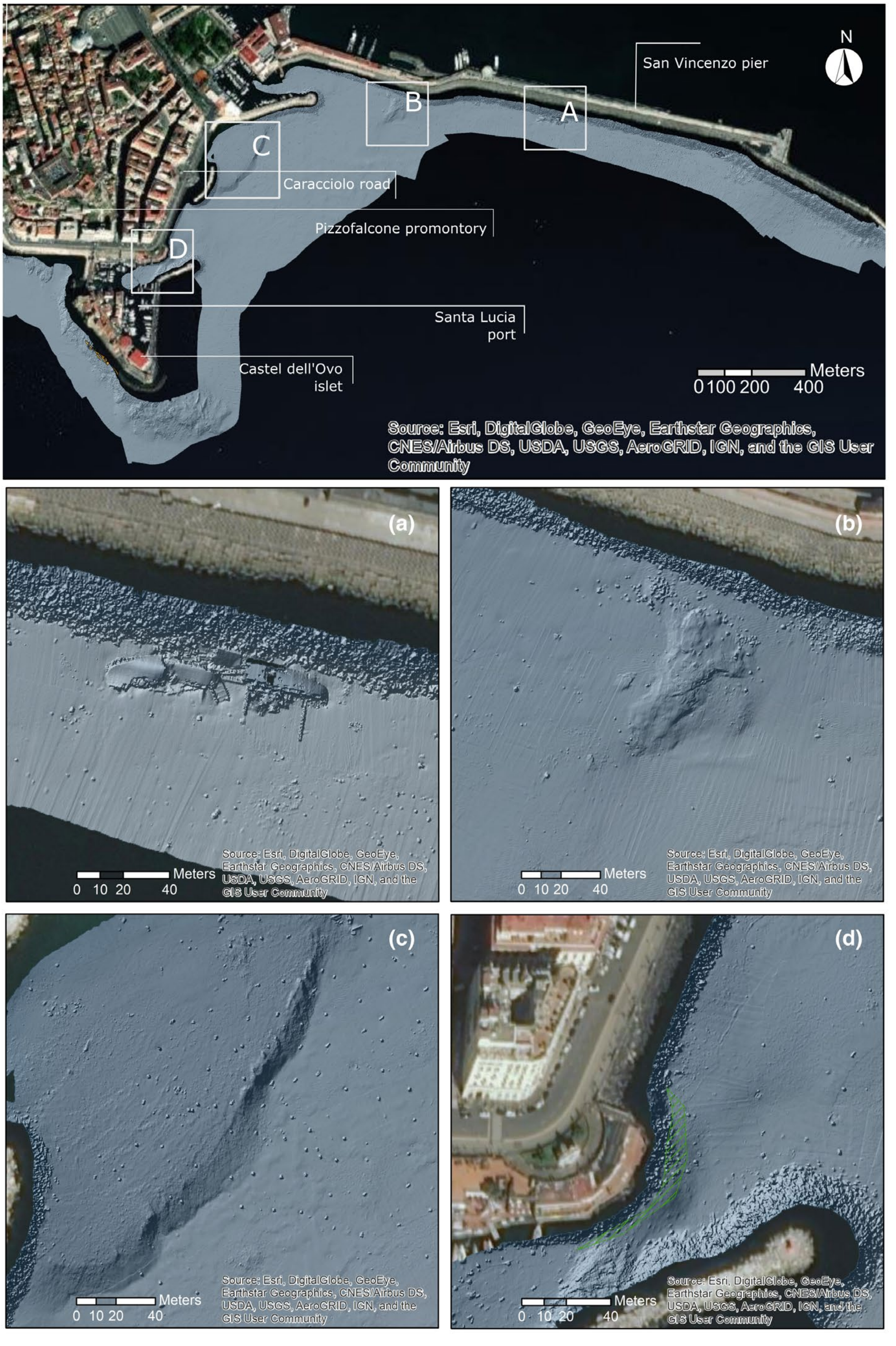

FIGURE 6 The area around the Pizzofalcone promontory and the main submerged features detected. (a) Detail of the shipwreck detected from the year 1962. (b) Detail of the small submerged landforms located near the modern pier, probably hosting a lighthouse in the fifth century AD. (c) Detail of the sub-horizontal surface detected between San Vincenzo pier and Santa Lucia harbour. (d) Detail of the outer-margin continuation of (c) at the entrance of Santa Lucia port

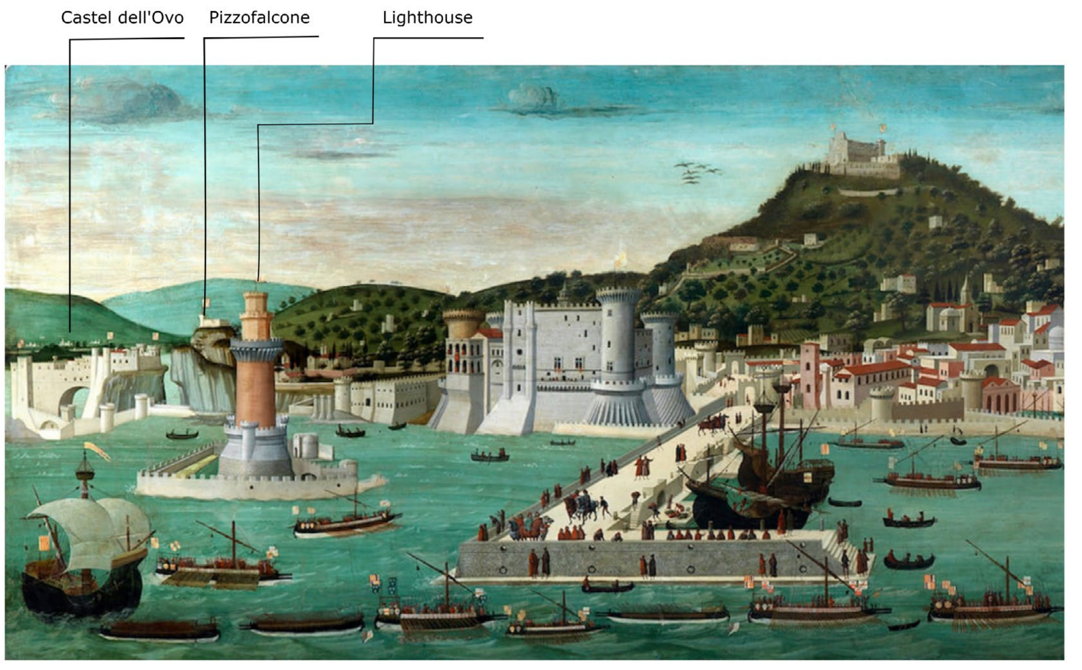

FIGURE 7 Detail of the famous painting *Tavola Strozzi* by Francesco Rosselli (1472–1473) in which the Pizzofalcone promontory, the historical lighthouse, and Castel dell' Ovo are visible

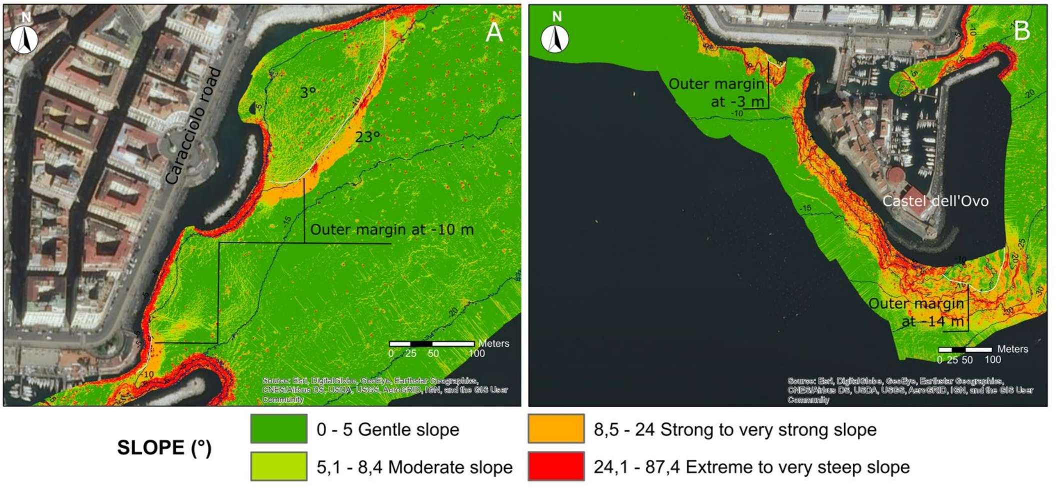

FIGURE 8 Detail of the wide sub-horizontal surface detected between San Vincenzo pier and Santa Lucia harbour (b) and its outer margin at −10 m MSL extending across the whole perimeter of Castel dell' Ovo Islet (a)

the Caracciolo coastal road and sailing club buildings. Both these landforms lead to a retreating sea-cliff trend affecting the Pizzofalcone promontory in the last millennia that induced the formation of wide shore platforms, nowadays totally submerged and used as hard basement for the construction of coastal anthropic structures. The acoustic signature of these platforms suggests that a sediment coverage filled all traces of differential erosion typical of this kind of tufaceous landforms.

In the same area, the wreck of a cargo ship sunk in 1962 was mapped at a depth of −23 m MSL (Figure 6a).

4.2 | Castel dell'Ovo sector

Castel dell'Ovo islet is another erosional remnant of the Pizzofalcone promontory retreat (Figure 9). According to Mattei, Aucelli, Caporizzo, Peluso, et al. (2020), this sea-stack formed during the maximum marine inundation in the area between 7.5 and 6.0 ka BP. Its submerged part has a complex morphology characterized by evidence of differential erosion with alternating strong-slope and steep-slope areas.

In this area, three orders of platforms sculptured in NYT were mapped at different bathymetric ranges and interpreted as palaeo-shore platforms presently submerged.

A first narrow strip of platform was detected between −14 and −9 m (7,350 m^2), in the southern cape of the islet. The landform is characterized by a 50-m wide sector with a slope less than 5° and some eroded rough sectors with higher slope values. The outer margin is the maximum original extension of the Pizzofalcone headland (Figure 8b) and is bordered by very strong slopes (reaching depths of −25 to −30 m MSL).

Other minor findings of this order platform were detected on the western sector of the islet with moderate slopes. In this sector, two additional order of platforms were mapped at −4 to −6 m and −3 m MSL, respectively (Mattei, Aucelli, Caporizzo, Peluso, et al., 2020; Pappone et al., 2019).

In the whole sector, the outer scarp of these landforms reaches −10 to −14 m MSL and is buried downslope by a soft sediment coverage, as demonstrated by the analysis of the acoustic signature overlaid with previous geoacoustic surveys (Isaia at al., 2016; Figure 9).

The platform at −3 m (third order), for a total area of 1,460 m^2, was mapped at the base of the vertical archaeological structure of Roman Age and interpreted as a fish tank by Pappone et al. (2019), also used to date the platform. Remnants of the same order platform are visible in the underwater sector north of the islet, at the footslope of the Pizzofalcone promontory (Figure 8b), where the platform reaches a width of 30 m.

The Roman shore platform is separated from the older one (second order, dated between 4.5 and 2.2 ka BP; Mattei, Aucelli, Caporizzo, Peluso, et al., 2020) by a narrow steep-slope scarp located between −3 and −4.5 m MSL. The second-order platforms at −4 to −6 m MSL reach a maximum extension seaward of 12 m.

The second- and third-order platforms show strong traces of erosion; in fact, their R_D is 90 and 69%, respectively (Table 2, Figure 9). The first platform appears with wide smooth areas (3,947 m^2) occupying more than 50% of the total surface.

These landforms were interpreted as evidence of a poly-phase subsidence affecting the area in the last 4.5 ka (Mattei, Aucelli, Caporizzo, Peluso, et al., 2020).

4.3 | Posillipo sector

The underwater sector of Posillipo sea-cliff is mainly modelled in shore platforms with different dimensions and located at a depth between −3 and −11 m MSL. These landforms were already identified in previous studies (Aucelli et al., 2018) and classified in three orders despite their lower precision (1×1 m grid) compared to the dataset analysed in this study.

In this study, the slope analysis of the high-resolution DTM (0.25 × 0.25 m grid) derived from the new multibeam survey highlights gentle- to moderate-sloping sectors at three different depth ranges scattered in the underwater area, with complex morphologies. The third-order platforms are positioned at −3 m MSL, the second between −4.5 and −6 m MSL, and the first between −7 and −11 m MSL, with a total extension of 7,255, 22,070, and 61,260 m^2, respectively. Narrow very-steep slopes separate these three orders of platforms (Figure 10).

The first-order platform, detected between −7 and −11 m MSL, is the most extensive in the southern area between Capo Posillipo and Marechiaro (Figures 10b and 11c–e) where a medium erosion degree was measured (56% of rough areas in Table 3, R_D) and a maximum width of 40 m. The first-order platform is totally covered by

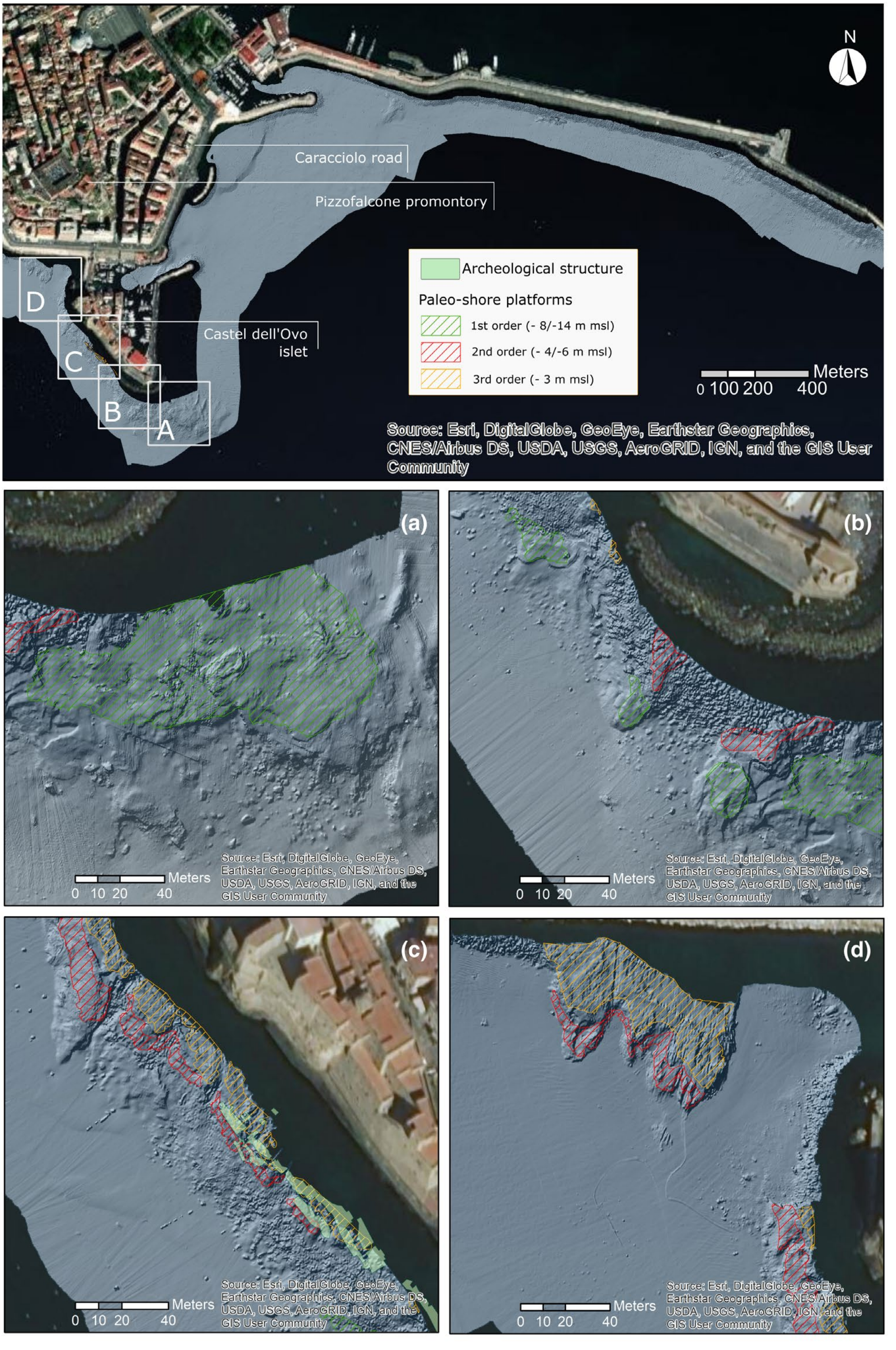

FIGURE 9 The area around Castel dell' Ovo islet and the main submerged features detected. (a) Detail of the southernmost sector and the first and second order of palaeo-shore platforms. (b), (c) Details of the central sectors and the three orders of palaeo-shore platforms and archaeological structures. (d) Detail of the northernmost sector and the second and third order of palaeo-shore platforms

TABLE 2 Morphometric characterization of the three orders of submerged platform detected along the Castel dell'Ovo coastal sector with: slope classification (column 1); slope class area (m^2, column 2); slope class percentage (column 3); and roughness degree obtained from the sum of the last two slope classes (R_D, column 4)

Slope	Area (m^2)	%	% R_D
Third order			
1–5°	492	15	
5–8.5°	564	16	
8.5–24°	1,769	52	
>24°	594	17	
Total surface	3,419	100	69
Second order			
1–5°	96	4	
5–8.5°	168	6	
8.5–24°	1,409	53	
>24°	977	37	
Total surface	2,650	100	90
First order			
1–5°	2,093	27	
5–8.5°	1,854	25	
8.5–24°	3,011	40	
>24°	599	8	
Total surface	7,557	100	48

sediments along the northern part of the promontory. Here the underwater sector with depth greater than −6 m MSL has a slope less than 3° and an extension ranging between 300 and 480 m. This flat area ends with an outer margin at −10 m MSL in the northern half of the area and at −20 m MSL in the southern half (Figure 10a). The strongly sloping scarp reaches a depth of −30 m MSL.

The second-order platforms between −4.5 and −6 m MSL are uniformly distributed along the whole coastal sector, with a maximum extension of 40 m, always showing the strong effect of a differential erosion, with 55% of rough surfaces (R_D, Table 3). In particular, along the northern area (Mergellina–Capo Posillipo), the outer margin is complexly bordered by a scarp reaching −6 m MSL that is buried downslope by a soft sediment coverage, as described above (Figures 11a,b). This landform was sculptured before Roman times as it hosts several first century BC archaeological remains (Aucelli et al., 2018, 2019), and can be tentatively considered coeval with the second-order platform detected along the Pizzofalcone coast.

The third-order platforms at −3 m MSL are characterized by narrower widths with maximum values of 30 m along the promontory and higher values along the sheltered bays. Their rough surface (52% of total extension) is demonstrated by the alternation of strong-slope and steep-slope areas. The natural sculpting of these landforms started during the first century AD and was likely exacerbated by human action in the same period (Aucelli et al., 2018, 2019).

By comparing the landforms detected in the underwater sector of Posillipo some differences emerge. Firstly, the shore platforms between −7 and −11 m MSL can be mapped only in the southern area (Figure 10b); in the same bathymetric range, the northern sector appears flat but is covered by a sediment layer (Figure 10a). Secondly, the shallower shore platforms (at −3 m and between −4 and −6 m MSL) detected in the southern area are much more extended and complexly shaped than the northern ones.

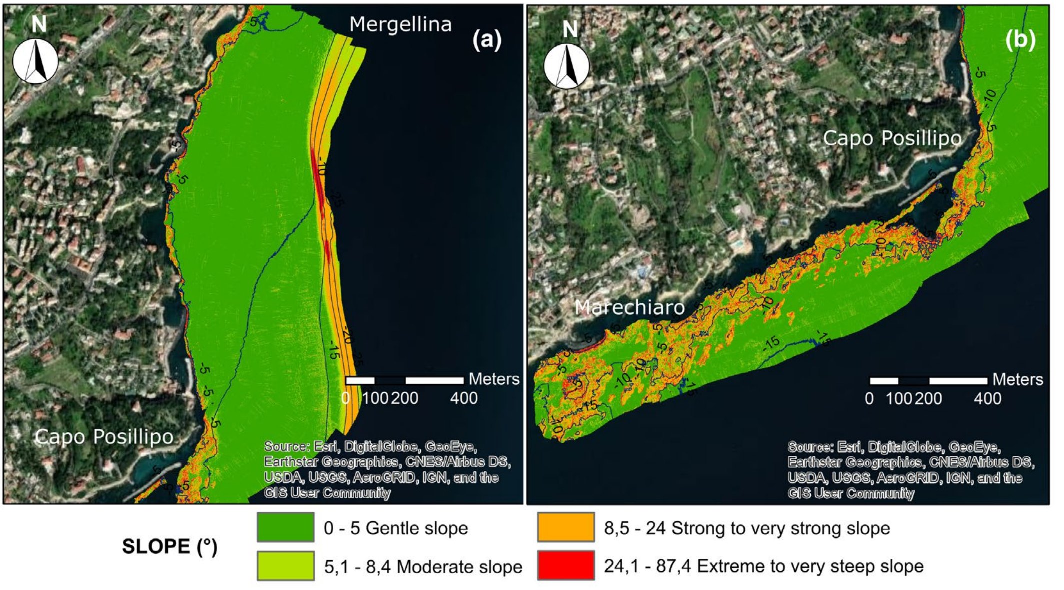

FIGURE 10 Comparison between the submerged landforms detected in the underwater sector between Posillipo and Marechiaro. (a) Detail of the northern sector, characterized by an extensive sedimentary cover. (b) Detail of the southern sector with shore platforms mapped at −7 to −11 m MSL

TABLE 3 Morphometric characterization of the three orders of submerged platform detected along Posillipo coastal sector with: slope classification (column 1); slope class area (m^2, column 2); slope class percentage (column 3); and roughness degree obtained from the sum of the last two slope classes (R_D, column 4)

Slope	Area (m^2)	%	% R_D
Third order			
1–5°	1,338	18	
5–10°	1,921	26	
10–24°	2,991	42	
>24°	1,005	14	
Total surface	7,255	100	56
Second order			
1–5°	4,316	20	–
5–10°	5,632	25	–
10–24°	9,501	43	–
>24°	2,621	12	–
Total surface	22,070	100	55
First order			
1–5°	12,426	20	
5–10°	17,008	28	
10–24°	26,467	43	
>24°	5,359	9	
Total surface	61,260	100	52

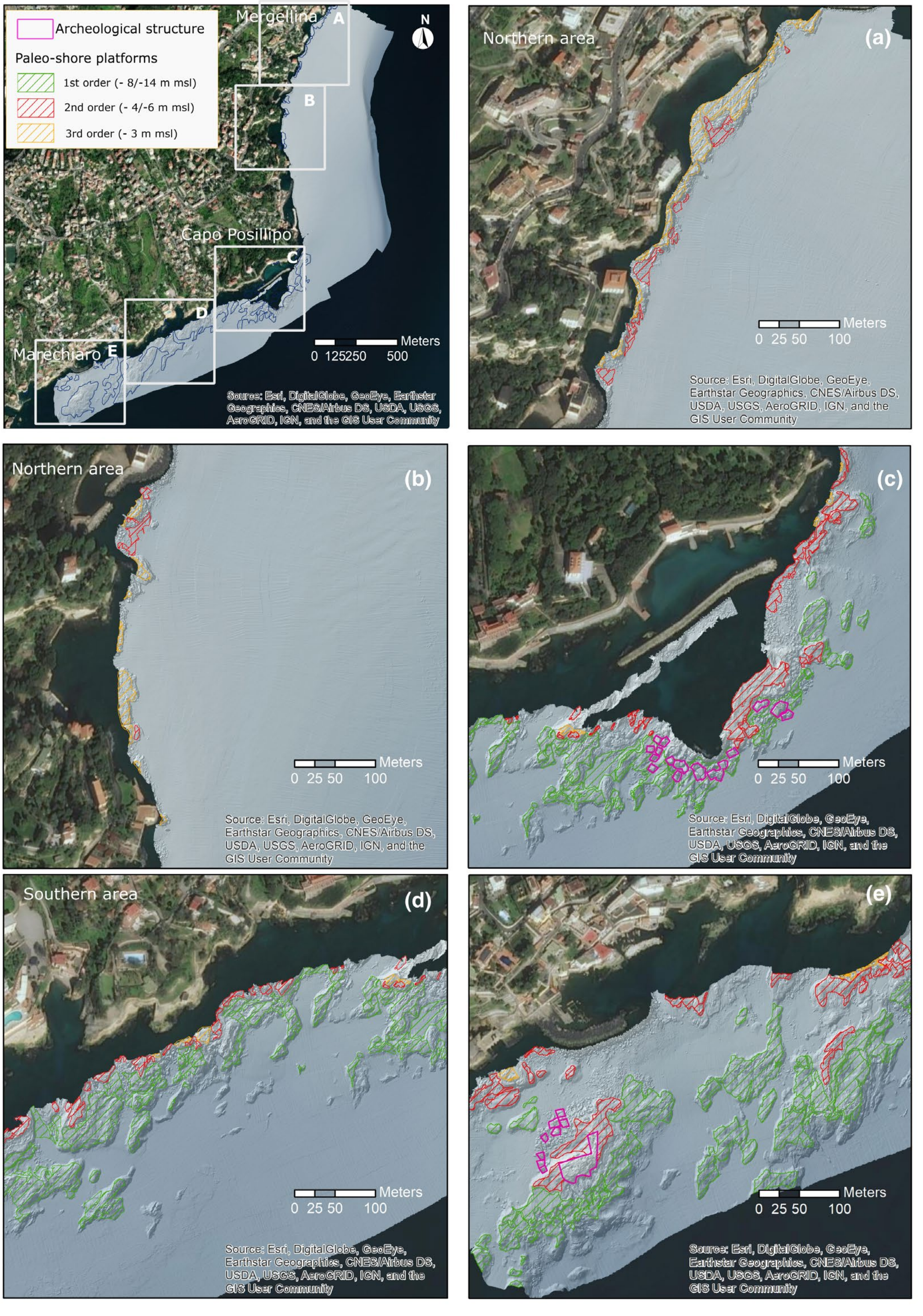

FIGURE 11 The main detected submerged features along the whole Posillipo coast divided into four different consecutive sectors for a better characterization (from (a) to (e) moving southward)

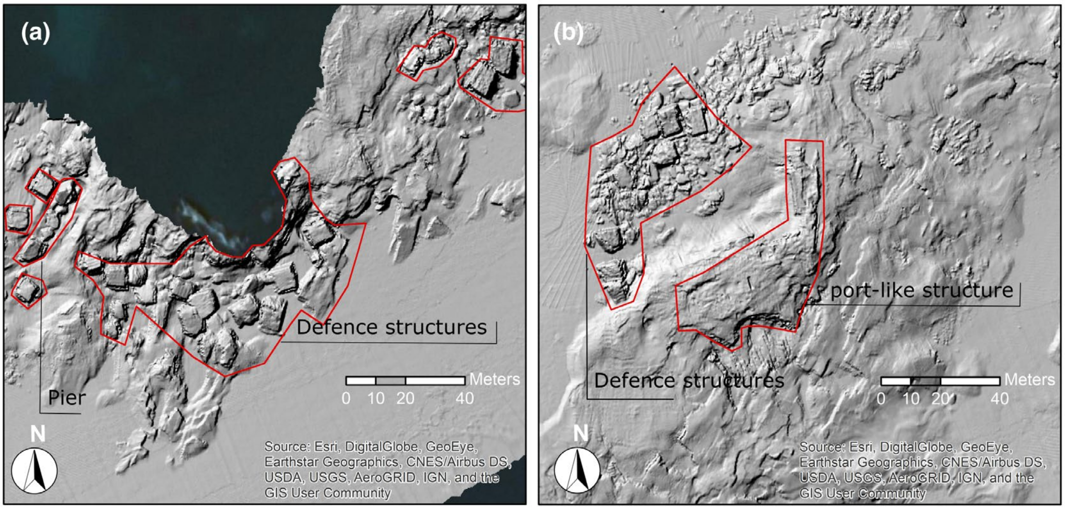

FIGURE 12 The archaeological structures mapped and detected along the Posillipo coastal sector. (a) Detail of the anthropic structures identified along the external sector of the submerged coastal plain of Pietra Salata (after Aucelli et al., 2019). (b) Detail of the anthropic structures identified at Marechiaro and interpreted as port-like structures

These two main differences could be explained by a higher degree of exposure of the southern sector to wave action due to prevailing meteo-marine conditions in the area, as suggested by recent studies (De Ruggiero, Napolitano, Iacono, & Pierini, 2016; De Ruggiero, Napolitano, Iacono, Pierini, & Spezie, 2018; Saviano, Kalampokis, Zambianchi, & Uttieri, 2019). This possible exposure favoured the formation of wider shore platforms during the Holocene.

This sector has also high cultural relevance due to the presence of several underwater archaeological remains of the Roman Age (Aucelli et al., 2019), mapped by the multibeam survey.

At Capo Posillipo, 18 *pilae* are laid on a seafloor between −7 and −11 m MSL (Figures 11c and 12a). The aligned *pilae* on the western side of the 3-m deep platform were interpreted as remains of a pier built during the first century BC (Aucelli et al., 2019). The other *pilae* are interpreted as coastal defence structures for the small coastal plain, presently submerged at −3 m MSL but originally emerging during the first century BC (Aucelli et al., 2019). The coastal plain is interpreted as a remnant of a quarry forecourt (Gunther, 1913) used as basement for the construction of three small villas in the same century.

At Marechiaro, a port-like structure coeval with the Pausylipon villa (first century BC) was mapped along with eight *pilae* positioned as defences around it (Figures 11e and 12b). The structure and the *pilae* were laid on the second-order platform.

5 | DISCUSSIONS ON THE ANALYSIS OF MORPHO-ACOUSTIC DATA

The land-surface analysis of the high-resolution underwater DTM calculated along the 8-km long high-coast sectors of Naples allowed a geomorphometric characterization of the surveyed sectors between −2 and −42 m MSL and, consequently, the discrimination between landforms and anthropic structures (Figure 13).

The underwater area of Naples consists of two main morpho-types (Figure 14): a rocky bottom at the footslope of the tufaceous sea-cliffs up to −15 m MSL depth and a sandy bottom from −15 to −42 m MSL. The areal coverage of sandy and rocky bottom resulting from our interpretations is 1.72 and 0.27 km^2, respectively.

Three orders of palaeo-shore platforms were mapped through a GIS analysis of the high-resolution underwater DTM (see Section 4). These platforms are characterized by 50–90% of rough surface (R_D, Tables 2 and 3) and an outer irregular margin as a consequence of wave abrasion that occurred after the formation of the platforms. The outer margins of the mapped palaeo-shore platforms constitute another significant morphological feature since they can be interpreted as the relicts of the upper margins of the ancient sea cliffs, formed during the three evolutionary phases here reconstructed according to previous studies. The total length of these sloping sectors (Table 4), divided into three orders, is 14.6 km.

In particular, along the Pizzofalcone–Castel dell'Ovo sector, the maximum retreat was measured on the southern cape of Castel dell'Ovo islet, where the first-order platform extends seaward up to 210 m.

A more complex morphological context was reconstructed along Posillipo coastal sector. The northern part of this promontory was bordered by narrow shore platforms belonging to the second and third orders, indicating a maximum retreat of 84 m (Figure 15).

Conversely, in the southern area, the three orders of platforms have a complex morphology and a maximum seaward extension of 275 m (Figure 16).

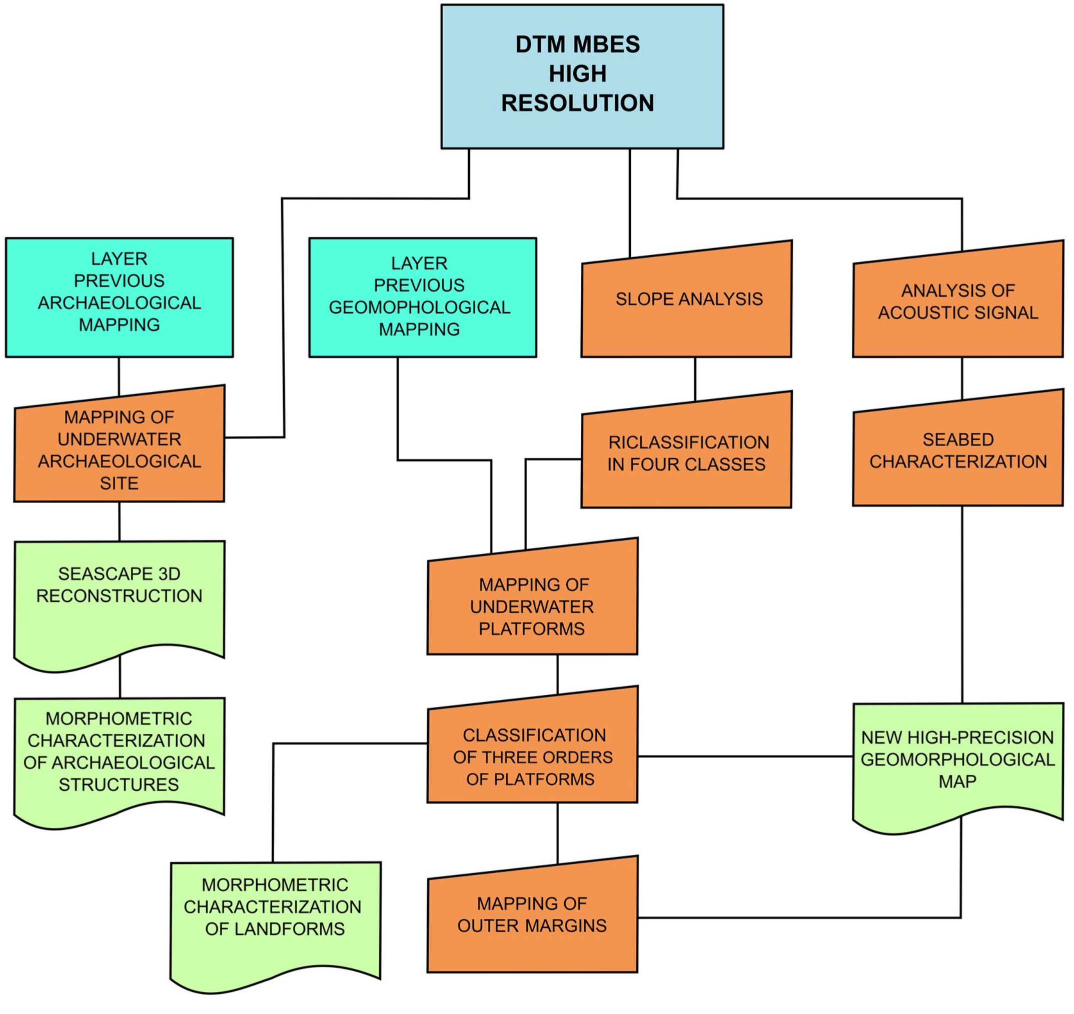

FIGURE 13 Flowchart of the data analysis, including data from previous studies imported into the GIS project (light blue), elaborations and processes (orange), and final products (light green)

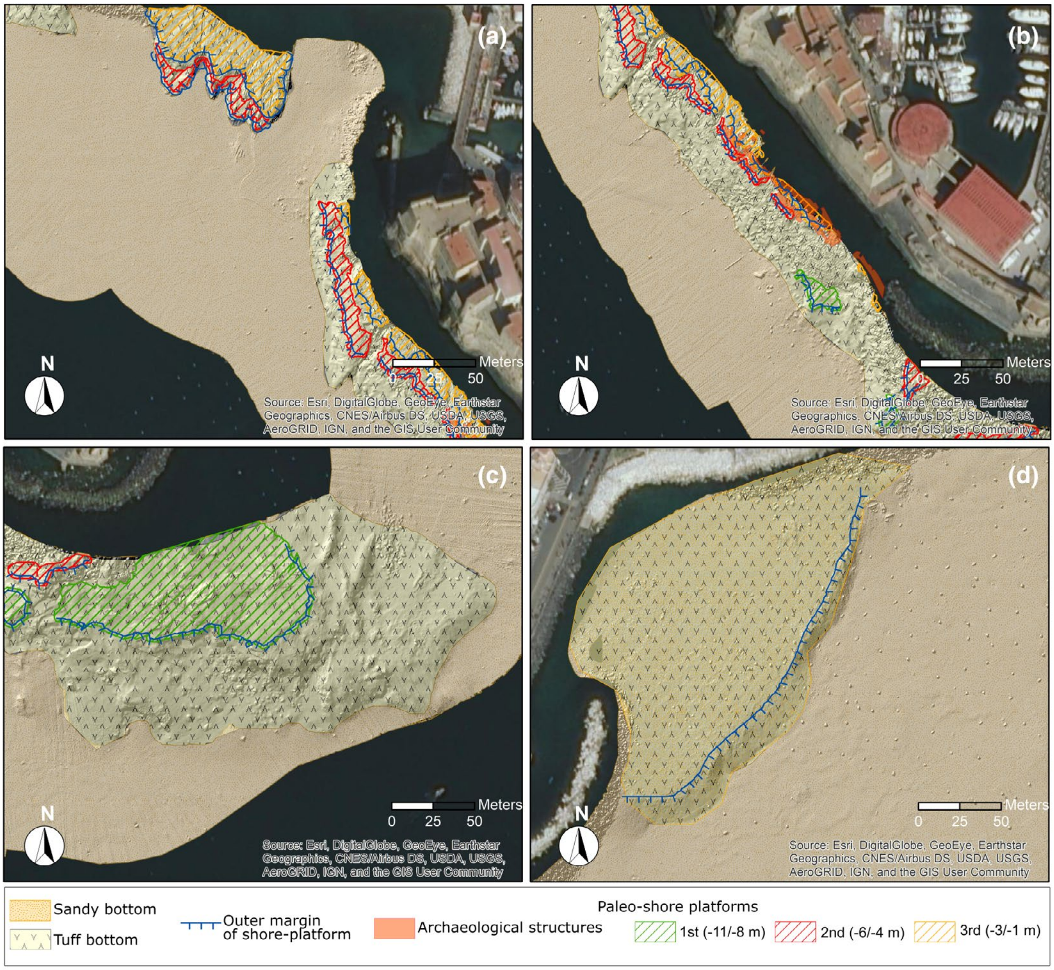

FIGURE 14 Geomorphological mapping of Pizzofalcone–Castel dell'Ovo sector. (a) Northern area of Castel dell'Ovo. (b) Western area of Castel dell'Ovo. (c) Southern area of Castel dell'Ovo. (d) Western side of San Vincenzo pier

The 3D mapping of three underwater archaeological sites allowed a comprehensive visualization of the underwater cultural and natural landscape (Figure 17).

The port-like structure at Marechiaro is laid on the second-order shore platform (Figure 17a), while the *pilae* around it and those at Capo Posillipo are positioned on the first-order platform (Figure 17b). This different bathymetric position corroborates the hypothesis that the *pilae* were built as coastal defence structures and, consequently, at that time they emerged less than 1 m (Aucelli et al., 2018, 2019). However, the position of these coastal structures suggests that they have moved from their original, presumably aligned, position. Furthermore, their shape suggests that they have undergone substantial erosion. Both of these aspects suggest that these structures have been severely impacted by wave action in the last millennium and, therefore, require monitoring and legal protection for their preservation.

The fish tank of Castel dell'Ovo (Figure 17c), located on the outer margin of the third-order platform (Mattei, Aucelli, Caporizzo, Peluso, et al., 2020), is exposed to meteo-marine events from the southern sectors. Consequently, monitoring should be applied to conserve the state of the structure.

TABLE 4 Length of the three orders of submerged palaeo-shore platforms detected along the whole high-coast sectors of Naples

Order	Length of outer margin (km)
First	7.9
Second	4.43
Third	2.0

FIGURE 15 Geomorphological mapping of the northern sector of Posillipo promontory divided into four different consecutive sub-sectors for a better characterization (from (a) to (d) moving southward)

6 | CONCLUDING REMARKS

The GIS analysis of multibeam high-resolution data demonstrates the effectiveness of this approach to the geomorphometric study of coastal areas providing information on the underwater landscape. Geomorphological characterization and mapping provided information on the natural processes affecting the Naples high-coast sector, particularly highlighting the exposure to of the southern area of the Posillipo promontory.

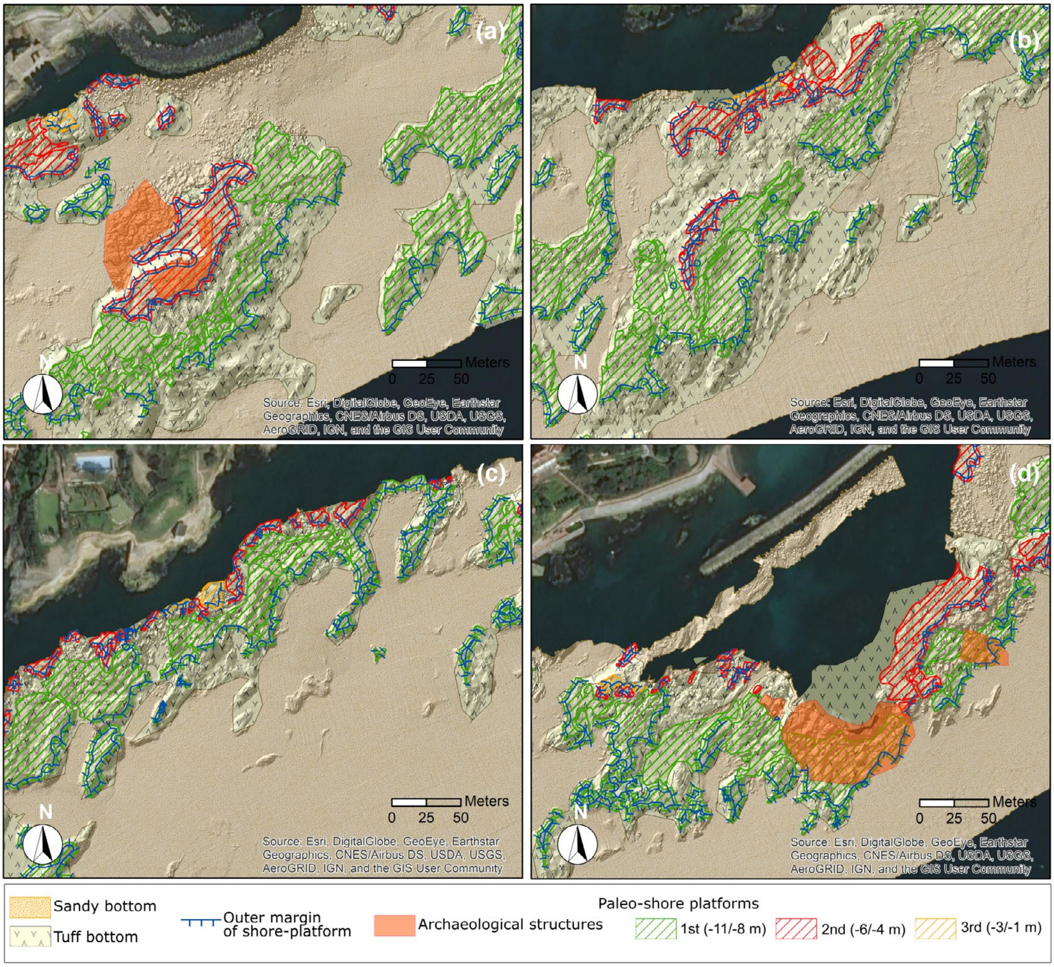

FIGURE 16 Geomorphological mapping of the southern sector of Posillipo promontory divided into four different consecutive sub-sectors for a better characterization (from (a) to (d) moving northward)

The 3D reconstruction of the archaeological structures had a twofold relevance. Firstly, the mapping of the underwater landscape enabled comparison of the present position of the archaeological remains with their original condition, allowing the evaluation of their conservation state. Secondly, a significant documentation of the underwater cultural heritage was obtained with a high spatial precision.

In conclusion, the application of this methodology achieved several goals:

- the geomorphological characterization of the underwater landscape and the consequent deduction of the main ongoing and past morpho-dynamic processing;
- the 3D reconstruction of the underwater seascape in a coastal sector with archaeological value;
- the evaluation of the wave action on the submarine domain by means of a morphometric analysis applied to both landforms and anthropic structures; and
- the detailed 3D documentation of a submerged cultural and natural landscape in a complex urban sector.

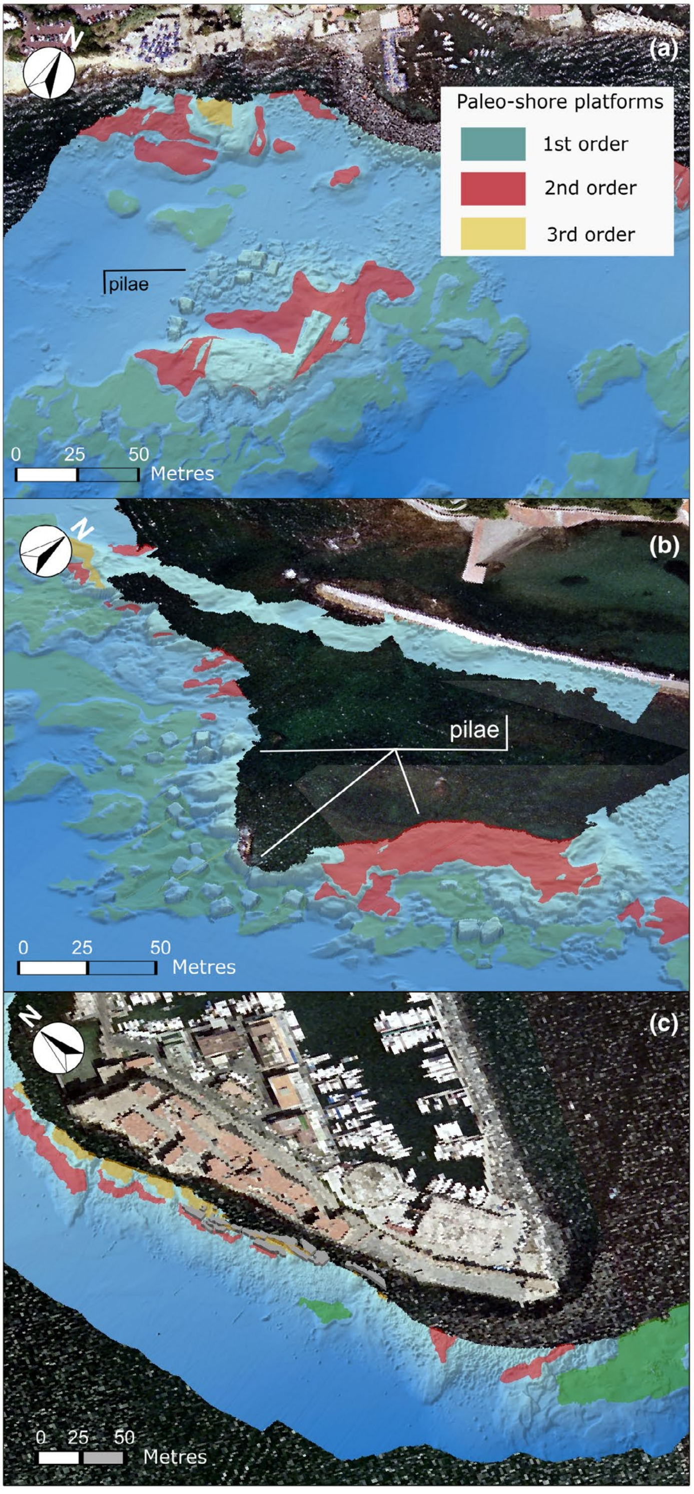

FIGURE 17 Three-dimensional reconstruction of the natural and anthropic seascape in the underwater archaeological sites along the coasts of Naples

ACKNOWLEDGEMENTS

The author sincerely thank Francesco Peluso and Luigi De Luca for their contribution during the marine surveys. This research was funded by Distretto ad alta tecnologia per i beni culturali DATABENC, PON 03PE_00164 "Rete Intelligente dei Parchi Archeologici" (RIPA—PAUN). It also benefited from the discussion at the Neptune meeting (INQUA CMP project 2003P). Open access funding enabled and organized by Universita degli Studi di Napoli Parthenope within the CRUI-CARE Agreement.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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How to cite this article: Caporizzo, C., Aucelli, P. P. C., Di Martino, G., Mattei, G., Tonielli, R., & Pappone, G. (2021). Geomorphometric analysis of the natural and anthropogenic seascape of Naples (Italy): A high-resolution morpho-bathymetric survey. *Transactions in GIS*, 25, 2571–2595. https://doi.org/10.1111/tgis.12829