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New Geomorphological and Historical Elements on Morpho-Evolutive Trends and Relative Sea-Level Changes of Naples Coast in the Last 6000 Years

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Abstract: This research aims to present new data regarding the relative sea-level variations and related morpho-evolutive trends of Naples coast since the mid-Holocene, by interpreting several geomorphological and historical elements. The geomorphological analysis, which was applied to the emerged and submerged sector between Chiaia plain and Pizzofalcone promontory, took into account a dataset that is mainly composed of: measurements from direct surveys; bibliographic data from geological studies; historical sources; ancient pictures and maps; high-resolution digital terrain model (DTM) from Lidar; and, geo-acoustic and optical data from marine surveys off Castel dell' Ovo carried out by using an USV (Unmanned Surface Vehicle). The GIS analysis of those data combined with iconographic researches allowed for reconstructing the high-resolution geomorphological map and three new palaeoenvironmental scenarios of the study area during the Holocene, deriving from the evaluation of the relative sea-level changes and vertical ground movements of volcano-tectonic origin affecting the coastal sector in the same period. In particular, three different relative sea-level stands were identified, dated around 6.5, 4.5, and 2.0 ky BP, respectively at +7, −5, and −3 m MSL, due to the precise mapping of several paleo-shore platforms that were ordered based on the altimetry and dated thanks to archaeological and geological interpretations.

Keywords: coastal landscape evolution; geomorphological analysis; palaeo-shore platform; relative sea-level changes; sea-level proxy; vertical ground movements; campi flegrei volcanic area

1. Introduction

The susceptibility of coastal towns and metropolis to the negative effects of the ongoing sea-level rise [1–5] depends on a series of factors, among which the behaviour of the land in terms of vertical ground movements (VGMs). In this regard, remote sensing methods can resolve ongoing vertical motions at sub-mm/year precision, which provides very precise and useful data [6–9].

However, in tectonically active areas, the chronological observation window has to be enlarged, by also considering the local vertical ground movements that occurred in the last centuries or millennia. Said movements can be identified and measured by dating a variety of possible proxies [10–16] indicating past positions of the relative sea levels (RSL). The obtained data are then corrected by subtracting the component due to eustatic and glacio-hydro-isostatic processes [10,12,17–21].

Among the proxies traditionally used to determine past RSL positions are those of geomorphological nature, such as coastal notches [22], marine terrace and shore platforms [23–25], or sedimentary facies [26–32]. Shore platforms, in particular, are initially created by wave quarrying and abrasion activities, but they can also be modelled by bio-erosion and weathering, particularly where tidal exposure is significant. The dimensions of shore platforms, under stable sea-level conditions, depend on the duration of the sea-level stand and they are intimately related to the intensity of wave processes, hardness, and structure of the rocks forming the platform, and the height of the sea cliff to be worn back [25,33,34]. Relict shore platforms also have a relevant role in the present study, since Naples, the second most populated conurbation of Italy, has a hilly topography and its coast alternates promontories and narrow coastal plains.

On the other hand, on a Mediterranean scale, the geomorphological analysis of these coastal landforms along with the interdisciplinary interpretation of the main sea-level indicators carried out in several recent studies [5,10,11] allowed for reconstructing the glacio- and hydro-isostatic influence on the Holocene sea-level changes. In particular, in Mediterranean regions that were affected by minimal tectonic influence, the glacio-isostatic adjustment (GIA) was the major driver of the decametric RSL rise in the last 8000 years. On the contrary, in geologically complex sectors, as the case of the mid-eastern Tyrrhenian coast in which the study area falls, complex volcano-tectonic behaviours that are primarily influenced the RSLs variations and related coastal changes during the Holocene [35]. Nevertheless, coastal vertical movements can be also fundamental for calibrating earth rheology models and ice sheet reconstructions in seismic active sectors, as in the case of North-Eastern Aegean Sea, which is mainly influenced by the activity of the North Anatolian Fault [20].

In the last ten years, the knowledge about the ancient vertical ground movements and related RSLs variation along the Naples coasts was deeply improved thanks to several geoarchaeological studies carried out during the excavation of a new coastal line of the subways systems. These studies analyzed complex stratigraphic records of former littoral deposits, well-dated by the presence of pottery fragments and the remains of ancient coastal structures [36–41].

In particular, during the Late-Holocene, the Neapolitan coastal sector has been affected by a subsiding trend, both along the high rocky coast of Posillipo and in the adjacent low coast of Chiaia and Municipio up to the limits of the Sebeto Plain [36,37,42–46]. In the case of Posillipo promontory (western periphery of Naples), the relative sea-level rise that was caused by this subsidence resulted in a retreating trend of the coastline. On the contrary, despite the subsidence, the coastal plains of Naples experienced a progradation of hundreds of meters thanks to the strong sediment supply that is ensured by both the longshore drift and torrential discharge from the hilly hinterland, probably favoured by anthropic impact [37–40].

A sector for which no specific study has been carried out till now is the Pizzofacone promontory. It was the starting point of our investigation, which was later extended to the nearby coastal plain of Chiaia and the seafloor between the said promontory and the islet of Castel dell'Ovo, formerly called Megaride. (see Figure 1 for location).

In this paper, new data are presented regarding the relic landforms that charcterize the western part of Naples coasts. In particular, we present the results of a geomorphological interpretation of high-resolution topographic models of the onshore and nearshore stripes, obtained from both direct and indirect measurements. For landforms that were masked by modern constructions, it was also essential for the study of documental data from historical sources. The aim was to gather elements for reconstructing the late Holocene evolution of the coastal landscape and gain new additional data about the local history of vertical ground movements during the Holocene.

2. Geological and Geomorphological Background

The city of Naples is located along the Tyrrhenian coasts, in the western sector of Campi Flegrei volcanic area [41]. This 60 ky old active volcano is known worldwide for the VGMs that have affected its territory in the last millennia and they have strongly influenced the Holocene evolution of its coasts [47–54].

The Campi Flegrei volcanic area is a poly-calderic system made of structural depressions that cover an area of about 230 km^2 and it is mainly shaped by three super-eruptions. The older one was the Campanian Ignimbrite (CI) eruption that occurred 40 ky BP [55,56]. After this complex event, the northern part of the just-formed caldera was invaded by the sea. The second eruption, which led to the formation of the Masseria del Monte Tuff, occurred 29.3 ky BP [57]. It preceded the Neapolitan Yellow Tuff (NYT Deino et al. [58]) eruption occurred 15 ky BP that contributed to the formation of the younger caldera [59,60].

After 15 ky BP, the volcanic activity of Campi Flegrei was characterized by three eruptive epochs, E1 between 15 and 10.6 ky BP, E2 between 9.6 and 9.1 ky BP, and E3 between 5.5 and 3.5 ky BP [61]. During each epoch, alternating magma/hydrothermal fluid inflation and deflation processes controlled the morphological evolution of this volcanic area.

Further, vertical ground movements (VGM) of meter-scale occurred in the periods preceding and following each eruption, which produced rapid relative sea-level variations along the whole coastal sector (Isaia et al. [62] and reference therein).

During the periods of volcanic quiescence dividing each eruptive epoch, the Campi Flegrei coasts were modelled by the wave action, recording erosional and depositional traces of these relative sea-level stands. The better-preserved evidence of this alternation (between VGMs and quiescence) is recorded in the sedimentary succession of La Starza hanging marine terrace that shows a sequence of depositional events that outline the interplay between inflation and deflation episodes (62 and reference therein). In this sequence, the three eruptive epochs (E1,15–10.6 ky, E2,9.6–9.1 ky, and E3, 5.5–3.8 ky, [61]) appear to be coupled with prevalent uplift and possible minor deflating episodes. The major uplift, greater than 100 m, occurred before the beginning of the E3 epoch activity. On the contrary, prevailing subsidence occurred during quiescent periods, from 8.59 to 5.86 ky, and generally after 3.8 ky BP and before the Monte Nuovo eruption (1538 AD), the last volcanic event that deeply modified the morphology of the area. This eruption, which led to the formation of Monte Nuovo tuff cone [63–66], represents the only example showing important ground uplift (up to 15 m), coupled with an eruptive activity (1538CE; [67,68]).

Several effects of the CF volcano-tectonic activity were recorded in Naples city that is located in the peripheral sector of this volcano. Indeed, its present landscape is the result of the mantling of preexisting volcanic edifices [36] by the NYT, and pyroclastic units that are related to the three eruptive epochs. Important evidence of this intense volcano-tectonic activity is also represented by several fault scarps, mainly SW-NE and NW-SE oriented (e.g., [36,37,69]).

The morphology of Naples coastal sector (Figure 1) is characterized by landforms due to endogenous dynamics [37,70], superimposed torrential dissections, and erosive traces of wave action [36].

The resulting coastal landscape is made of alternating small bays hosting both narrow coastal plains and cliffed promontories, such as that of Pizzofalcone (Figure 1).

Depositional sequences of pyroclastic deposits, reworked by alluvial and/or colluvial processes, are recorded in the main coastal plains of Chiaia and Municipio and they were deeply studied in the last years, thanks to the underground excavations [37–40]. The present elevation of well-dated shoreface deposits demonstrates that an overall subsidence affected these areas in the last 4000 years [37], even if a prograding/aggrading trend mostly prevailed because of sedimentary inputs coming from the hillslopes, probably favoured by anthropic forcing.

The present morphology of the cliffed promontories led to suppose that complex morphogenesis, which are related to the interplay between volcano-tectonic activity and marine processes, modelled these landforms since the Holocene transgression.

In the case of Pendino terrace, Cinque et al. [36] supposed that it formed during the early Holocene, because the depositional volcanic sequence presents at the top the fallout of “Soccavo 4” eruption (belonging to E1 eruptive epoch), and it also includes the fallout deposits of the Agnano-Monte Spina eruption (belonging to E3 eruptive epoch). Furthermore, other minor hanging terraces can be detected along the slope of Pizzofalcone promontory and in Chiaia plain. Regardless, presently, not enough chronological and morphogenetic data have been acquired about these landforms, even if they can be considered to be crucial to understanding the coastal evolution of this sector, when considering that they represent clear evidence of ancient sea-level stands.

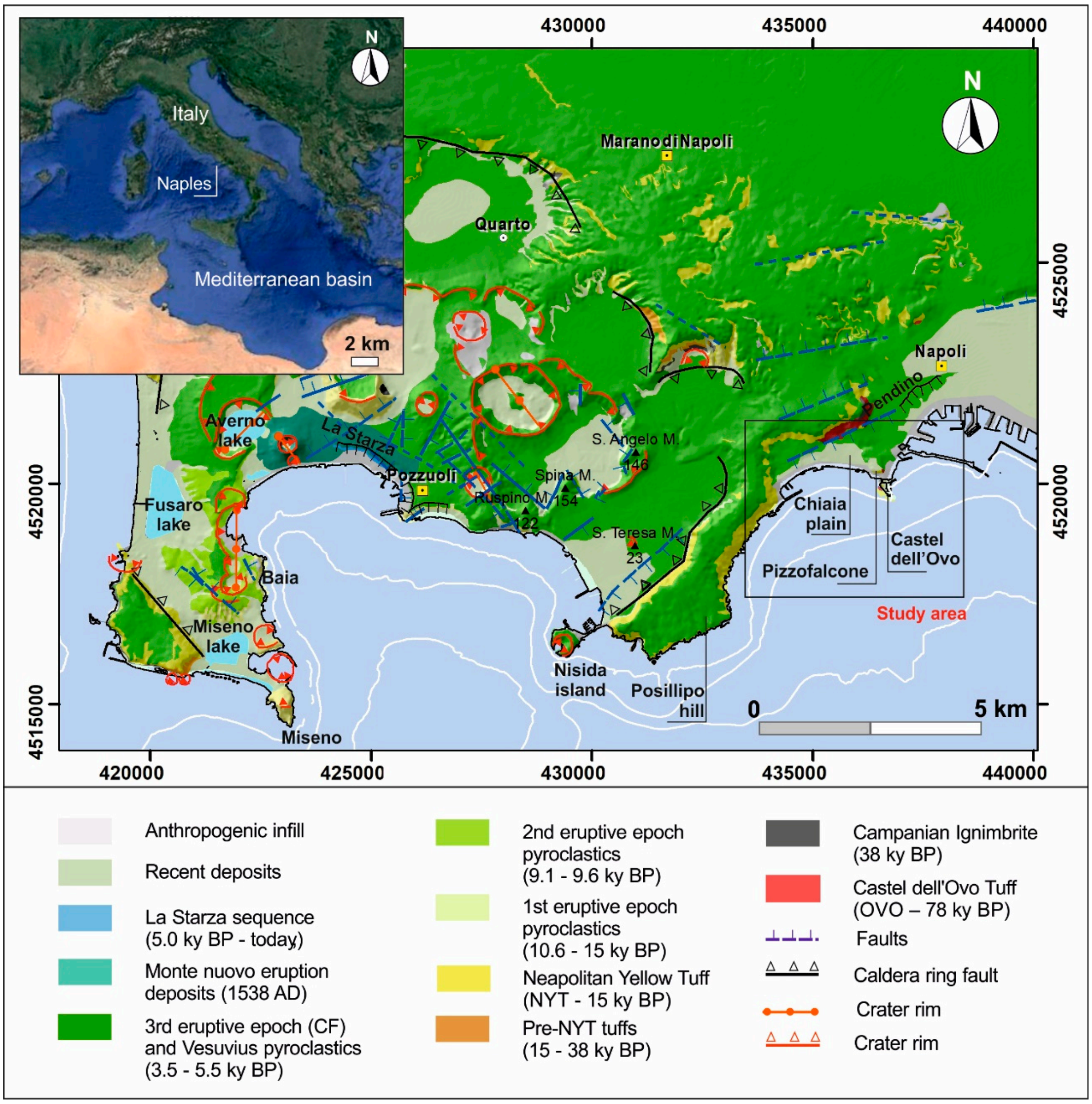


Figure 1. Geological sketch of Naples and Campi Flegrei (after Isaia et al. [71]; DiVito et al. [68]).

3. Materials and Methods

In this study, several direct and indirect surveys were carried out in the emerged and submerged sectors to obtain a detailed geomorphological characterization of the whole study area (black square in Figure 1). In particular, several direct surveys were carried out in the emerged coastal sector between Chiaia coastal plain and Castel dell'Ovo. Instead, the underwater sector off Castel dell'Ovo was surveyed using a USV (Unmanned Surface Vehicle) that was equipped with morpho-acoustic and optical sensors [72–75].

By overlaying these new data with historical sources, ancient pictures and maps, bibliographic, geological, and coring data, High-resolution digital terrain model (DTM) from Lidar and bathymetric data, the knowledge on the Holocene morpho-evolutive trend of Naples coasts were improved (Figure 2). On the other hand, the analysis of iconographic sources is a visualizing approach to geomorphological interpretations that can be considered to be highly efficient in urban contexts where the original landforms were masked by anthropogenic interventions [76,77].

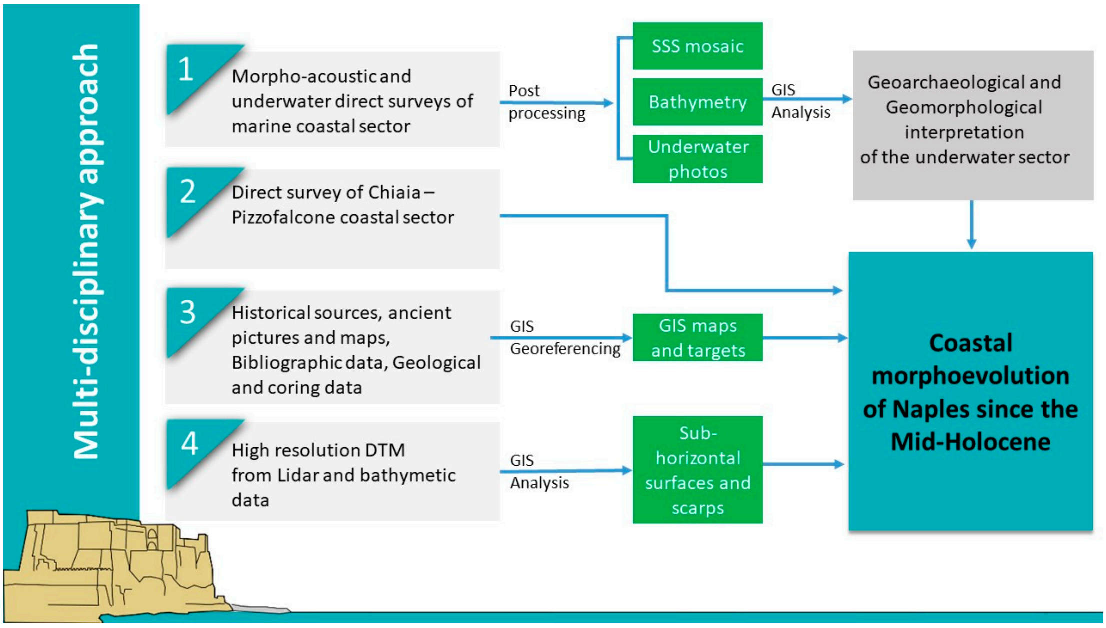


Figure 2. Flowchart describing the methodological approach used in this research.

3.1. Data and Sources

As described in the following sections, the new data from morpho-acoustic surveys (SSS ad Bathymetry) were GIS-processed together with data from direct underwater surveys to interpret the underwater landforms (point 1 in Figure 2), i.e., submerged paleo-shore platforms sculptured in tuff and precisely mapped in the following geomorphological map of the study area.

The geological units presented in the map were GIS-reconstructed by integrating data from [71] with those that were obtained by reinterpreting several stratigraphic records (see Figure 4 for location) contained in the 1967 Geological Report of Naples Municipality, and measurements taken during direct inspections carried out in the whole coastal sector (point 2 in Figure 2, Table 1).

Table 1. List of data and sources used in this research.

Type	Source	Date	Resolution (m)
Recent photos	New data		-
SSS mosaic	New data	2019	0.5 × 0.5
Bathymetric data	New data	2019	0.1 × 0.1
DTM from LIDAR	Ministry of Environment	2013	
Isobaths	CARG project	2013	1 line/meter
Geological units	[68,71]	2016	-
Coring n. 66	Naples Municipality Report	1967	-
Painting by Consalvo Carelli	Jpg—free source	1836	-
n. 2 1800′ photos	Jpg—free source	1800	-
Painting by William Marlow	Jpg—free source	1790	
The painting by Lancelot-Théodore Turpin de Crissé	Jpg—free source	1819	
Painting by Anton Pitlo	Jpg—free source	1820	
1800′ painting of Chiaia	Jpg—free source	1800	
Map of Naples by Lafrery	Jpg—free source	1566	

Besides, the GIS project was populated with several bibliographic data from previous studies, georeferenced historical maps, data interpreted from ancient pictures, and high-resolution DTM from Lidar (Table 1, Figure 2). The result was the reconstruction of the original shape of some ancient emerged shore-platforms, used here as sea-level markers (points 2,3,4 in Figure 2) and deeply described in the Results section.

3.2. Morpho-Acoustic and Underwater Survey

The underwater sector was surveyed with direct and indirect methods.

The indirect survey mainly consisted of an integrated marine survey (Figure 3) that was carried out using a prototype of unmanned surface vessel (USV). MicroVeGA is a technological project of USV pursued by the GEAC (Geologia degli Ambienti Costieri) research group of Parthenope University, intending to carry out high-resolution surveys of the submerged landscape, particularly in the presence of archaeological structures that can be intended as witnesses of this ancient coastal landscape [54,72–75].

Figure 3. MicroVeGA survey in the marine area off Castel dell' Ovo (photos taken by the authors during the surveys).

All of the data are broadcast in real-time both to a base station and to all operators involved in the research (geophysicist, archaeologist, geomorphologist, etc.).

The main task is the acquisition of data that are related to the morphology of the seabed, in order to reconstruct the underwater three-dimensional landscape, using geophysical (Single Beam Echo Sounder and Side Scan Sonar) and optical (underwater cameras for photogrammetry) instruments [78–85].

The onboard instrumentation mainly consists of a 200 KHz digital echosounder; a 450 KHz digital side-scan sonar; and, a high definition underwater photographic system.

The Single-Beam Echo Sounders (SBES) is an Ohmex with 200 KHz acquisition frequency and 60 m as maximum measured depth, which is therefore optimized for coastal bathymetric measurements.

The Side Scan Sonar (SSS) Tritech StarFish 450 C is optimized for coastal waters (450 KHz CHIRP transmission) and engineered for installation on drones. Under optimal conditions, the instrument has a resolution of 0.02 m. During the survey, the slant range of the instrument was 50 m with a 50% overlap between lines, in order to obtain a total coverage and reconstruct the morphology of both the target and the seabed [70].

The photographic system that was installed on-board of MicroVeGA consists of two Xiaomi YI Action cameras and a GoPro Hero 3 [74].

The main underwater targets that were detected during the indirect survey were surveyed by a team of specialized scuba divers (two geomorphologists and an archaeologist), assisted by two surveyors on a support boat with GIS-GPS cartographic station, which were useful for detecting the georeferenced targets. For each target, a direct measurement of its submersion was performed using a graduated level staff, in order to better constrain the archaeological interpretations and evaluate the present submersion of both natural landforms and main archaeological structural elements.

3.3. Geomorphological and GIS Analysis

The geomorphological analysis that was applied to the emerged and submerged sectors of the study area allowed for discriminating between natural/anthropic landform shapes. Among the main morphological elements interpreted as evidence of ancient landscapes, several terraced surfaces were detected by overlaying photo-interpretation, onsite surveys, analysis of high-resolution DTMs, and the interpretation of historical paintings and/or maps.

These landforms were interpreted according to the following criteria:

1. morpho-structural analysis of the coastal sector by in situ surveys;
2. morphometric analysis of extension, slope, and borders by spatial-analyzing the high-resolution DTMs;
3. altimetric ordering and connectability between terrace relicts;
4. analysis of historical sources, painting, and maps describing the landforms before the anthropic modifications; and,
5. definition of the primary process forming the surface (erosion, deposition, etc.).

A specific procedure was applied to the collected data in order to obtain the above-mentioned interpretations. In the first instance, an onshore-offshore DTM was built by interpolating the LIDAR (from the Ministry of Environment, 0–200 m MSL) and bathymetric data (from the CARG project, 0–20 m MSL) with a Topo to Raster interpolator (1 × 1 m grid).

Secondly, the slope map, which was obtained from the abovementioned DTM, was reclassified in three classes based on the slope value: sub-horizontal surfaces between 0 and 5%; gently sloping surface between 5 and 15%; steep slopes greater than 15%.

The sub-horizontal surfaces thus identified were interpreted as terraced surfaces, if sculptured in rock and matching with criteria at points 1 and 2. In the case of emerged terraced surfaces, the geological characterization was obtained from direct surveys and the analysis of both coring data and historical painting. Instead, in the case of the submerged ones, the classification of their geological and geomorphological characters was obtained from the analysis of the SSS signal and direct underwater surveys [45].

Finally, the terraced surfaces were interpreted as paleo-shore platforms, according to [25], and then classified in three orders, depending on their altimetry and dating, as described in the Results section.

3.4. Shore Platforms as Sea-Level Indicators

The paleo-shore platforms that were detected in this study were interpreted as sea-level index points (SLIPs), by detecting the inner margin of each landform [2]. The inner margin forms at the same level of the mean higher high water (MHHW), i.e., the average of the higher high water height of each tidal day observed over a Tidal Datum Epoch (National Oceanic and Atmospheric Administration-NOAA). Consequently, the RSL that is associated with this indicator is:

$$\mathrm{SLIP}_i = \mathrm{E}_i - \mathrm{MHHW}$$

where E_i is the present elevation of the inner margin of paleo-shore platform i.

When considering that a micro-tidal range characterizes the study area [86], the present elevation of their inner margin was corrected for the value of MHHW that, in the Gulf of Naples, is 0.45 m (data from Rete Ondametrica Nazionale). About the local wave climate, the Gulf is characterized by frequent marine stormy events during winter and autumn with wave height values up to 4.8 m, mainly approaching from 180° to 210°. In the same way, seasonal data demonstrated that the study area is also strongly exposed to prevailing waves whose approaching directions range from S to SW [87–94].

If the inner margin of a shore platform is not precisely detectable, the medium-altitude of these landforms can be considered a marine limiting point (*sensu* Vacchi et al. [10]).

4. Results

The geology of the study area is characterized by a bedrock made of NYT, only outcropping along the steepest hillslopes, and a cover of Holocene pyroclastic and volcanoclastic units occurring with a variable thickness on terraces, footslopes, and coastal plains.

In the plains and, in particular, in Chiaia coastal plain, the bedrock is covered by alluvial deposits related to the climatic instability that occurred during the transition from humid to arid conditions in the late Holocene [37]. Indeed, in the near high rocky coast sector, the NYT crops out along the paleo-sea cliffs still visible at Pizzofalcone promontory and Castel dell' Ovo islet.

The trans-disciplinary analysis of documental data from historical sources and high-resolution topographic data from direct and indirect measurements of the onshore-offshore sector of Naples produced several relevant results concerning the Holocene evolution of this coastal sector.

Firstly, the relicts of three orders of paleo-shore platforms were detected along the coastal sector and intended as evidence of ancient sea level stations. Precisely, these forms represented the starting point for the geomorphological interpretations that were carried out in this study, which produced three main results: the high-resolution geomorphological map of the Naples coastal sector (Figure 4); the morpho-evolution model since the mid-Holocene (see Figure 14); and, the relative sea-level variations and related vertical grounds movements occurred in the area in the same period (see Figure 15).

The first result, i.e the geomorphological map of the study in Figure 4, was obtained by overlaying the bibliographic data with those derived from our geological and geomorphological analysis, as described in the Methods section.

In the map, the three orders of the paleo-shore platforms and the Greek–Roman littoral deposits were mapped and they represented the key strength of the Holocene evolutive model proposed in this study for the Naples coastal sector. In addition, the emerged scarps were differenced in natural, when preserved their original shape; anthropically modified, when the primary morphogenetic factor was of natural origin, but the shape was modified by anthropogenic activities; anthropogenic scarps, when the primary morphogenetic factor was the human intervention.

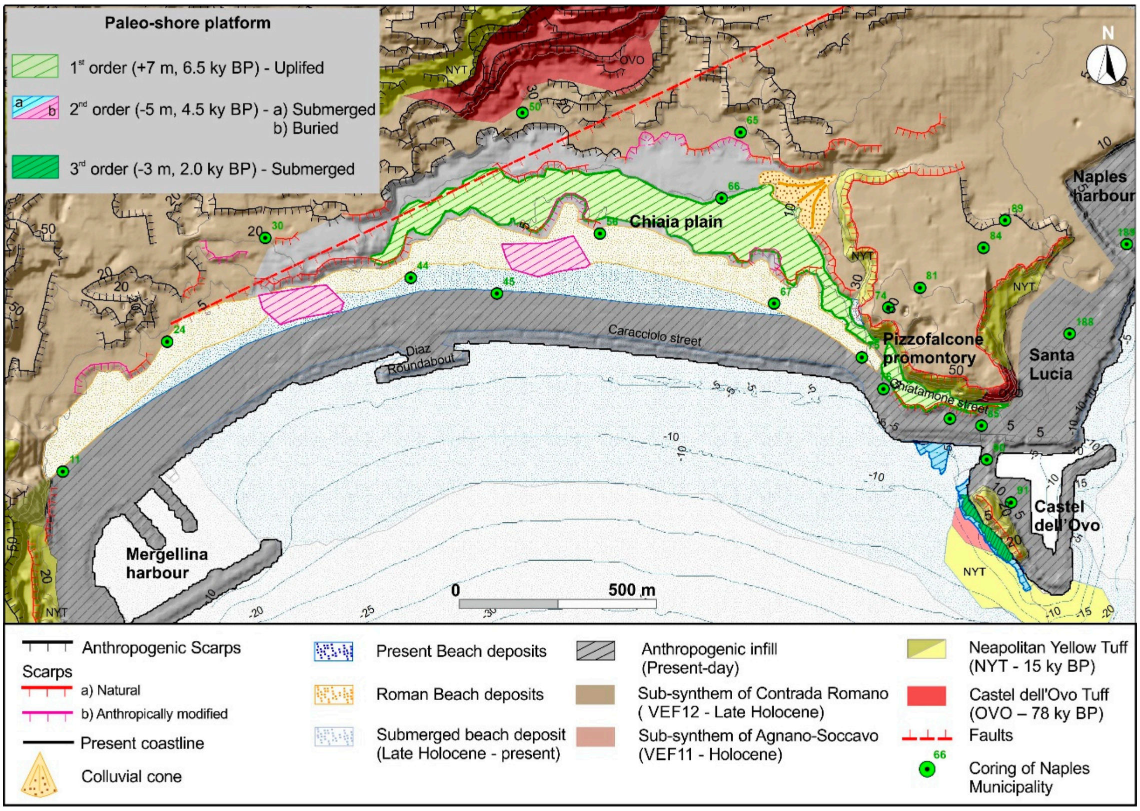


Figure 4. Geomorphological map of the study area: geological units were reconstructed by integrating data from [71] with those obtained by reinterpreting several stratigraphic records contained in the 1967 Geological Report of Naples Municipality (numbered in green in the map), and measurements taken during direct inspections carried out in the whole coastal sector.

4.1. First-Order Paleo-Shore Platforms

The first order (i.e., highest) of platforms is an emerged landform that extends from near the point of Pizzofalcone promontory to the Chiaia plain. This terrace has never been reported previously, probably because the strong urbanization affecting the area since the late 19th century made it difficult to perceive all of the topographic details of the area and—more relevant—to discriminate the natural component from the anthropic one.

Fortunately, this coastal sector appears depicted in several ancient painting and this helped us to understand the local geomorphological situation before the complete urbanization.

By overlaying the results from field surveys, high-resolution DTM analysis (Figure 5), and the study of ancient maps and photos, it became evident the old age of the 4°-inclined terrace that occurs a few meters above sea level, below the cliff that borders the Pizzofalcone hill. Nowadays, its inner margin runs at about 9 ± 1 m MSL.

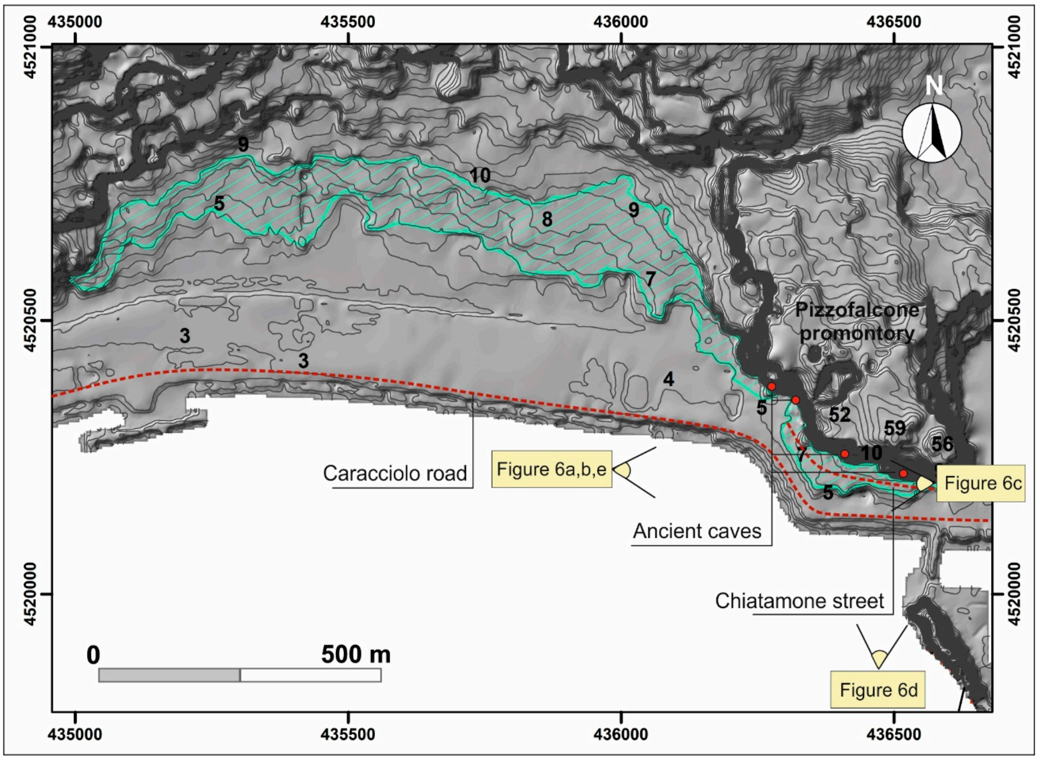


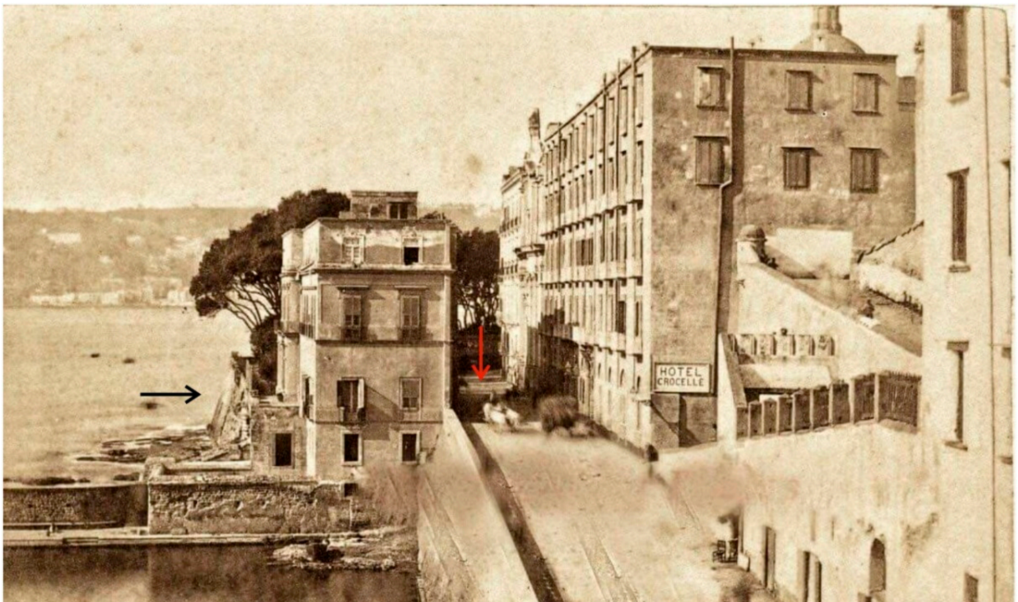
Figure 5. High-resolution DTM of the study area (1 × 1 m) with the first order paleo-shore platform highlighted with inclined green lines, contour lines in grey, elevation spots in black, and the roads described in the main text in dashed red.

Nowadays, the outer edge of the terrace is poorly visible as it is partially buried. The active sea cliff in NYT, which appears in ancient depictions (Figure 6), was buried by landfills in 1869 when a new coastal road (Via Caracciolo) was also constructed.

(**a**)

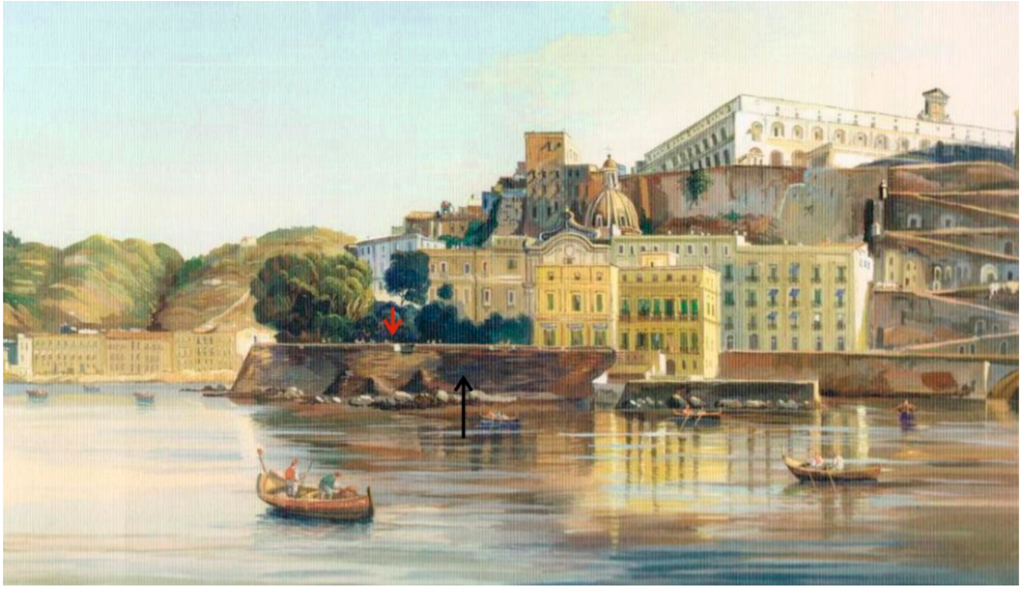
Figure 6. *Cont.*

(**b**)



(**c**)

Figure 6. *Cont.*



(**d**)

(**e**)

Figure 6. Five images showing ancient views from the south of Pizzofalcone promontory, see Figure 5 for point of view. The black arrows indicate the active sea cliff in NYT, detected downslope of the first order platform (red arrows). (**a**) Painting by Consalvo Carelli 1836, view from SW; (**b**) 1800′ photo, view from SW; (**c**) 1800′ photo, view from SE; (**d**) painting by Anton Sminck Pitloo 1820, view from S; and, (**e**) painting by William Marlow 1790, view from SW.

Measurements that were taken on more paintings of the 18th and 19th centuries allowed for estimating in 6–7 m the height of the ancient sea cliff (Figure 6).

The fact that the platform at issue is cut in the same cemented tuff forming the whole promontory (the NYT; see Section 2) was also ascertained by some direct inspections in the basements of modern buildings that are dug into the platform itself.

It was impossible to base the interpretation of the terrace on sedimentological and/or palaeo-ecological characters of associate deposits because of the urbanization of the area and the consequent lack of outcrops. However, it was interpreted as an ancient abrasion platform by excluding other possible interpretations in virtue of the morphological properties of the terrace itself and the scarp above it (Figure 7).

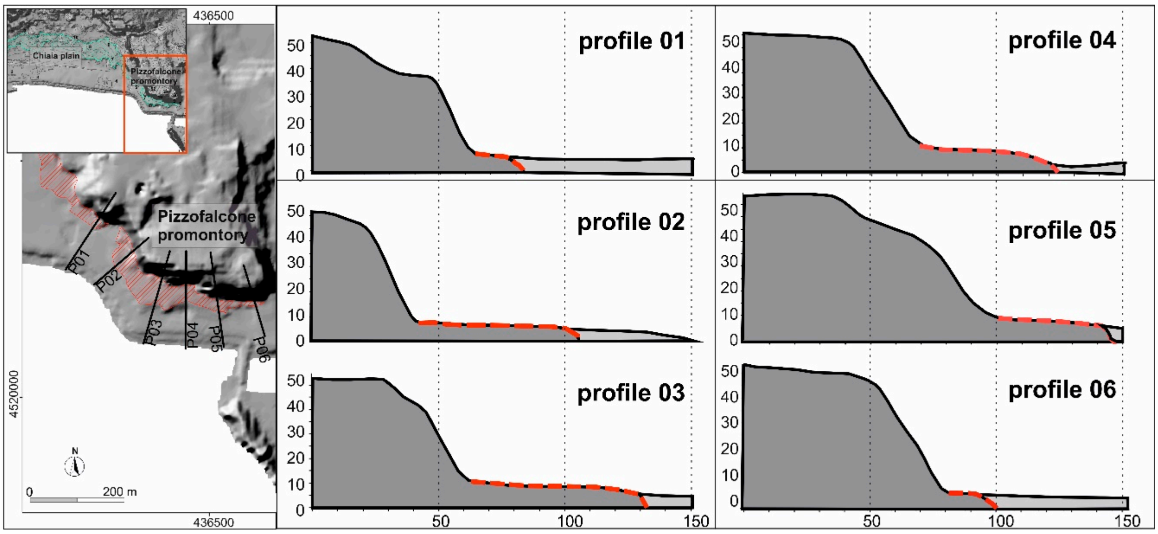


Figure 7. Six topographic profiles across the first-order platform (x and y axis are in metres): the black line is the present profile; the dotted red line is the original profile of the terrace and the light-grey area is the artificial anthropic infill built in the last 150 years. The green area in the inset map defines the perimeter of the 1st order platform and the red box represent the area in which the six profiles were reconstructed.

In particular, the hypothesis of a structural origin was discarded because of the angular unconformity between the terraced surface and the attitude of the bedrock strata. On the other hand, the terrace at issue cannot be ascribed to fault duplication of Pizzofalcone hill flat top, because the course of the scarp above the terrace is too sinuous (Figures 6e and 7) to be interpreted as a fault scarp.

Finally, the alternative interpretation of the terrace as an ancient tuff quarry floor, which is shaped by human activities, implies that the scarp above the terrace should be interpreted as the corresponding quarry front. However, this hypothesis can be excluded when considering the lack of any geometrical regularity—typical of quarry fronts—in the projections and recesses characterising the cliff (Figure 7), whose original shape is visible on paintings that predate the masking by buildings, barbicans, and retaining walls (Figures 6e and 8).

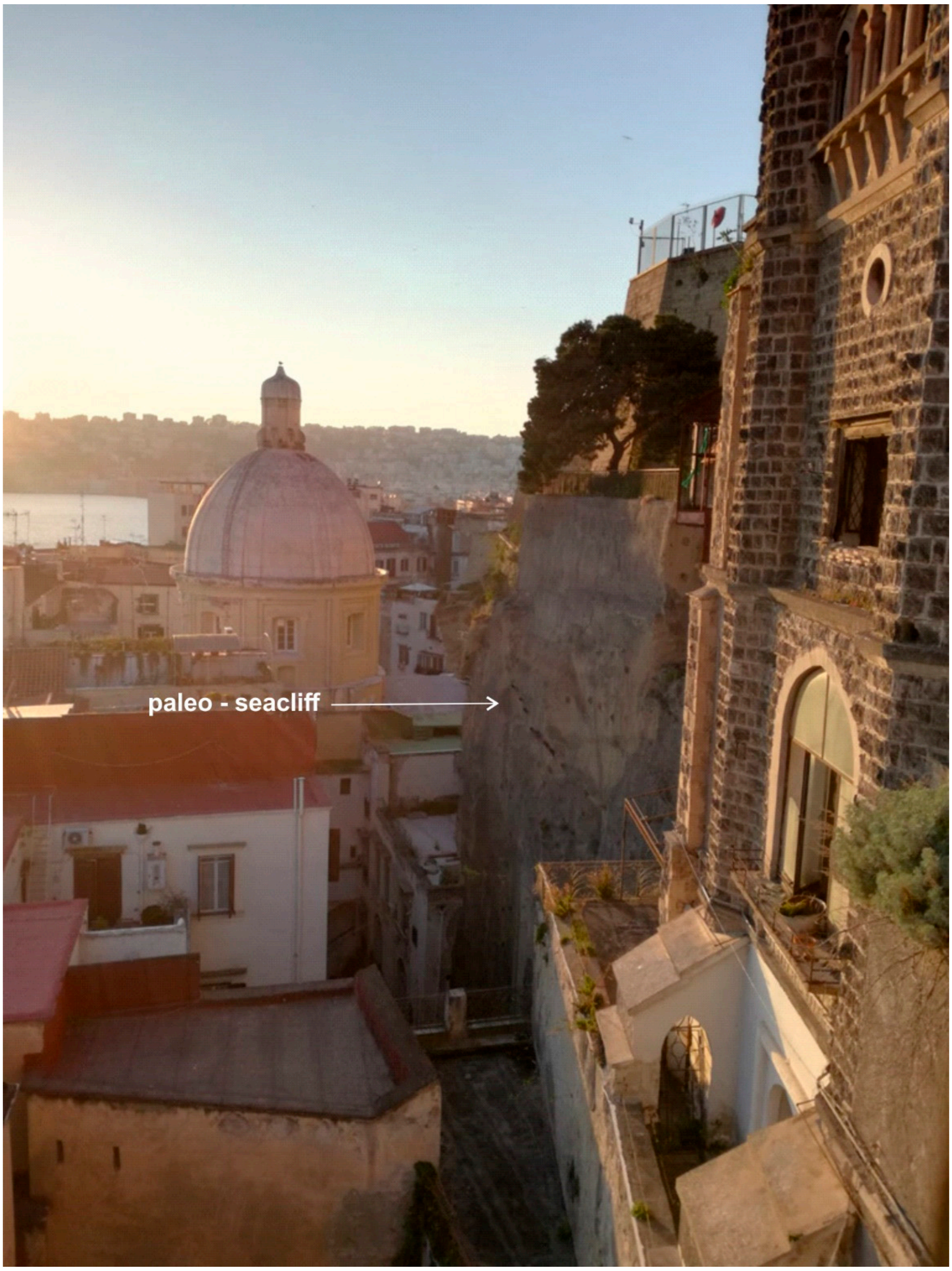


Figure 8. Pizzofalcone promontory. The highest reach of the paleo-sea cliff marking the inner margin of the cliff is cut and disappears under retaining walls and buildings (photo taken by the authors during the surveys).

Against the "quarry hypothesis", there are also (i) the great areal extent of the landform (about 13,000 m^2) and (ii) the excessive height of the hypothetical quarry front (up to 50 m, Figures 7 and 8). Two arguments that acquire particular value by considering that the quarry at issue should be dated to the Greek–Roman antiquity. One of the artificial caves marking the inner edge of the terrace at issue hosted a sanctuary of Serapis during the Greek–Roman period (Figure 9), as demonstrated by both archaeological evidence and narrations by the old authors [95,96].

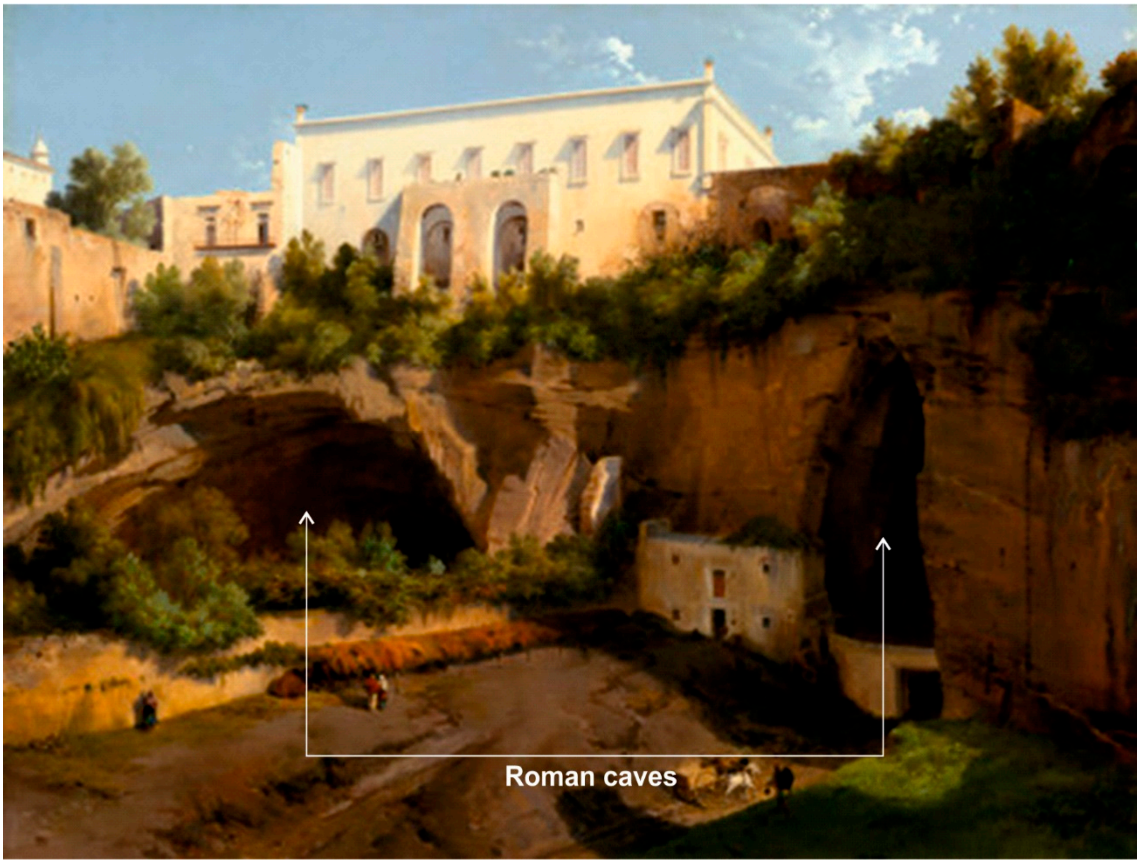


Figure 9. The painting by Lancelot-Théodore Turpin de Crissé "View of a Villa, Pizzofalcone, Naples" (1819), National Gallery of Art, New York.

Moreover, the antiquity of the terrace is also suggested by the traditional toponym Chiatamone, which derives from the Greek word Platamon, meaning—among others—'flat and large stone' (in Homer, 6th century BC) and Flat rock emerging from the sea (in Aratus, 3rd century BC).

Taking into account all of the above-mentioned evidence, the platform at 7–10 m MSL (hereinafter "Chiatamone terrace") is interpreted as a substantially natural landform. More exactly, it is interpreted as an abrasion platform cut in the NYT. Its development occurred side-by-side with the retreat (and height increase) of the sea cliff bordering Pizzofalcone promontory. This platform—whose age will be discussed below—arose above sea level not later than the 2nd century BC, allowing for the extraction of tuff blocks in caves at the base of the former sea cliff. Later on, the caves (Figure 9) were used for religious purposes, as demonstrated by an ancient marble inscription that was dedicated to Serapis [96].

The Chiatamone terrace becomes less and less topographically expressed moving from the point of Pizzofalcone promontory north-eastward (Figures 7 and 8). Nevertheless, the analysis of historical painting led to recovering pieces of evidence destroyed by the strong urbanization. In particular, in the foreground of a painting by Pitloo (1820, Figure 6d), a flattened relict in NYT of this platform is visible.

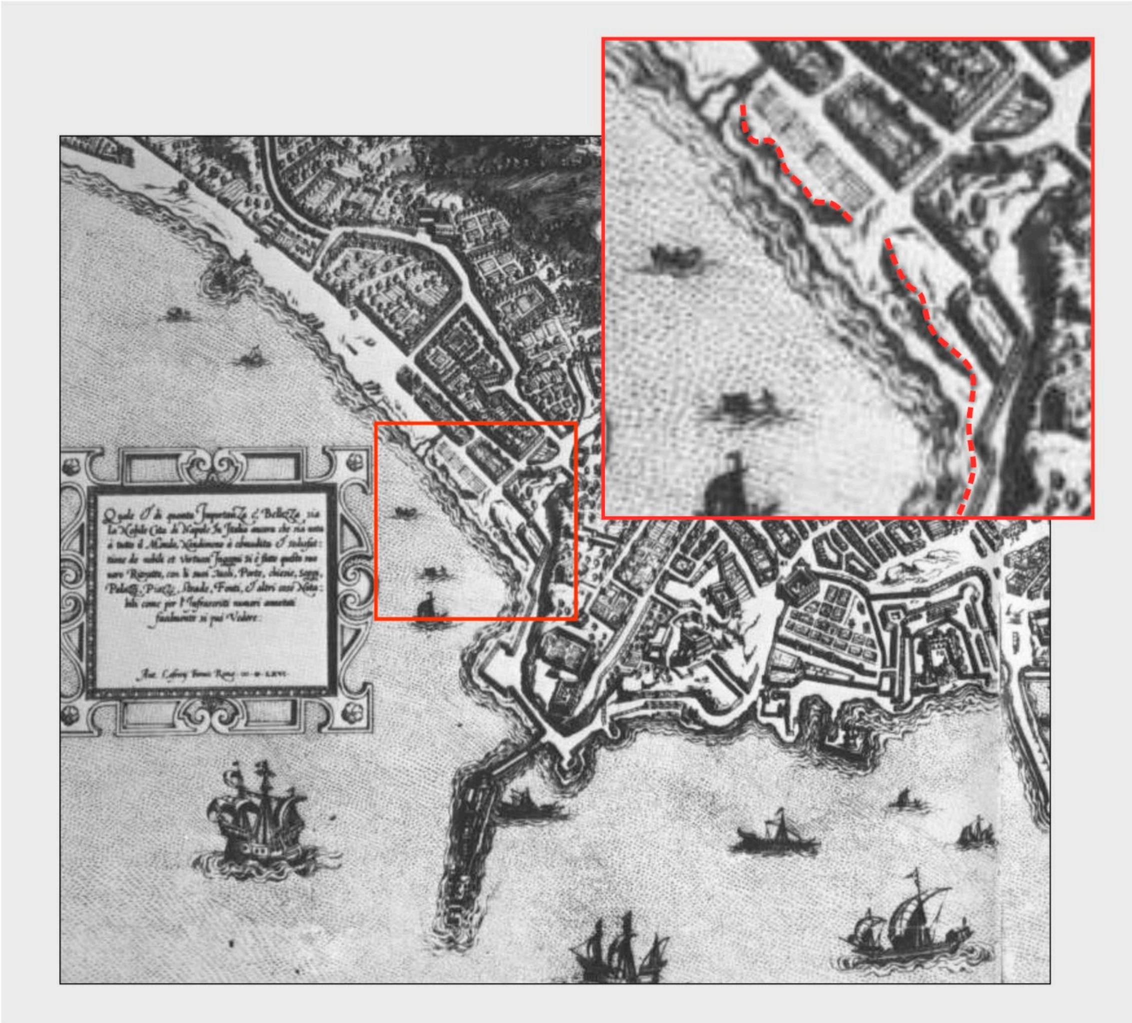
In the adjacent central part of the Chaia plain, the relative sea-level stand that allowed for the sculpturing of the Chiatamone terrace is probably testified by a depositional coastal terrace. Notwithstanding the presence of a late cover of primary and reworked pyroclastics and the complete urbanization of the area, such a terrace may be recognized in the strip of minimum topographic gradient that occurs between 7 and 11 m MSL.

This geomorphological element appears clearly on the DTM of Figure 5 and it is followed downslope by a scarplet a couple of meters high, which is also evident in some paintings of the 19th century, such as the two in Figure 10, where the Lafrery (1566) map, also show this evidence.

(**a**)

(**b**)

Figure 10. *Cont.*



(**c**)

Figure 10. (**a**) Painting by Anton Sminck Pitlo 1820, view from S; (**b**) 1800′ painting, view from S; and, (**c**) Antony Lafrery (1566), map of Naples with the evidence of the uplifted terrace at Chiaia plain in the central part of the map.

The terrace width ranges from 40 to about 230 m, while its inclination does not exceed 4.2°. Indeed, historical beach deposits [37] buried the footslope of the downslope paleo-sea cliff.

Unfortunately, our scrutiny of pre-existing drilling data did not discover any well-log reporting also palaeo-environmental information for the sediments that form the terrace at issue. However, the log of a well-drilled near the inner margin of the terrace (n. 66, see Figure 4 for location) shows the top of the NYT at −24 m MSL, followed by beds of pyroclastic materials up to −17.5 m MSL and then by alternations of sands and gravelly sands that reach up to 3.5 m MSL. They are tentatively interpreted as shoreface deposits, probably truncated by a phase of subaerial erosion. The said littoral sands are covered by 4.5 m of primary and reworked pyroclastics that could be related to Agnano Monte Spina and Astroni eruptions (4.5 and 4 ky BP; [61], already detected at the footslope of the scarplet [37].

Other stratigraphic indications come from a study that was conducted a few years ago during the excavation of a new subway rail station [37]. It regarded a site located immediately downslope of the scarplet delimiting seaward the terrace at issue. That study allowed for detecting—at elevations ranging from −4.8 to −0.5 m MSL—an abrasion platform that was cut in Agnano Monte Spina and Astroni tephras that were buried by a sequence of littoral sediments testifying palaeo-shorelines migrations between 4.0 ky BP and the 16th century AD [37].

Around the age of this first-order terrace, it postdates the NYT eruption (15 ky BP) and predates the second-order of shore platforms (4.0 ky BP, see Section 3.2).

The data emerging from other studies in the coastal sector east of Pizzofalcone promontory also corroborate this assumption. There, the studies conducted during the excavations for the new subway stations Municipio, Università, Duomo, and Piazza Garibaldi [38–41,97] showed that the tectonic behaviour of the area has been dominated by subsidence with a rate between −2.5 and −1.2 mm/year [40] since at least the Early Bronze Age. As the first order terrace rests at an elevation (7–10 m MSL), demonstrating a subsequent uplift, it must be older than, at least, the 4.0 ky BP.

The residual uncertainty (15 to 4.0 ky BP) can be further reduced by discarding those millennia, during which the rate of post-glacial sea-level rise was too fast to permit the formation of sub-horizontal wave-cut platforms on rocks of appreciable resistance, such as the NYT. Therefore, we believe that the most probable age of our first order terrace does not exceed 6.5 ky (Figure 11).

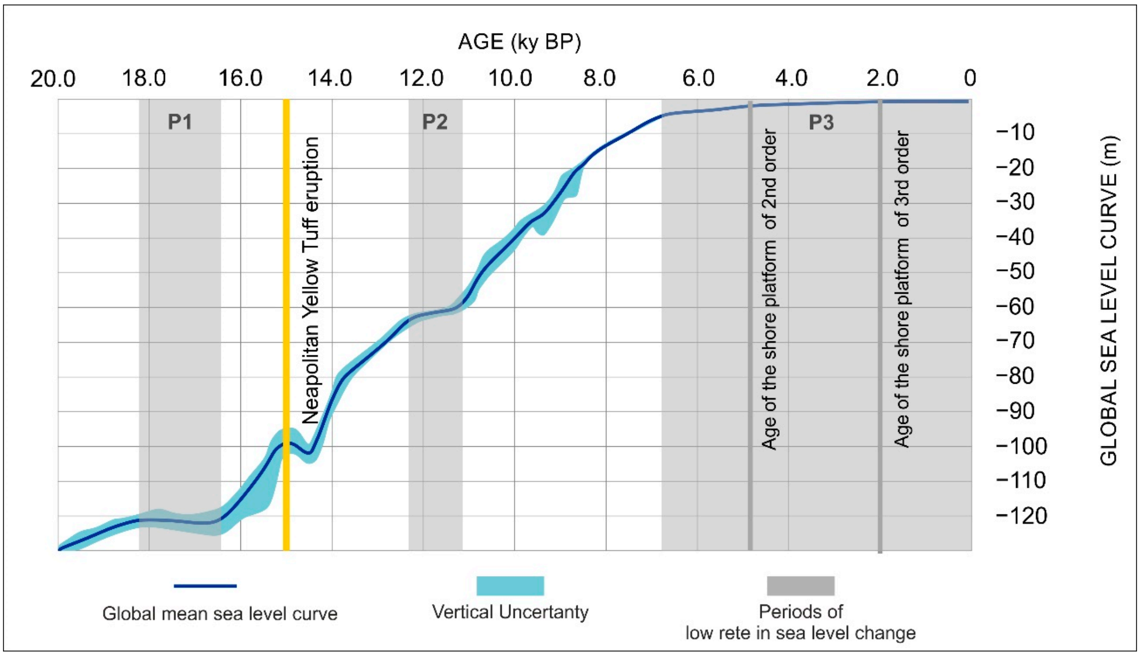


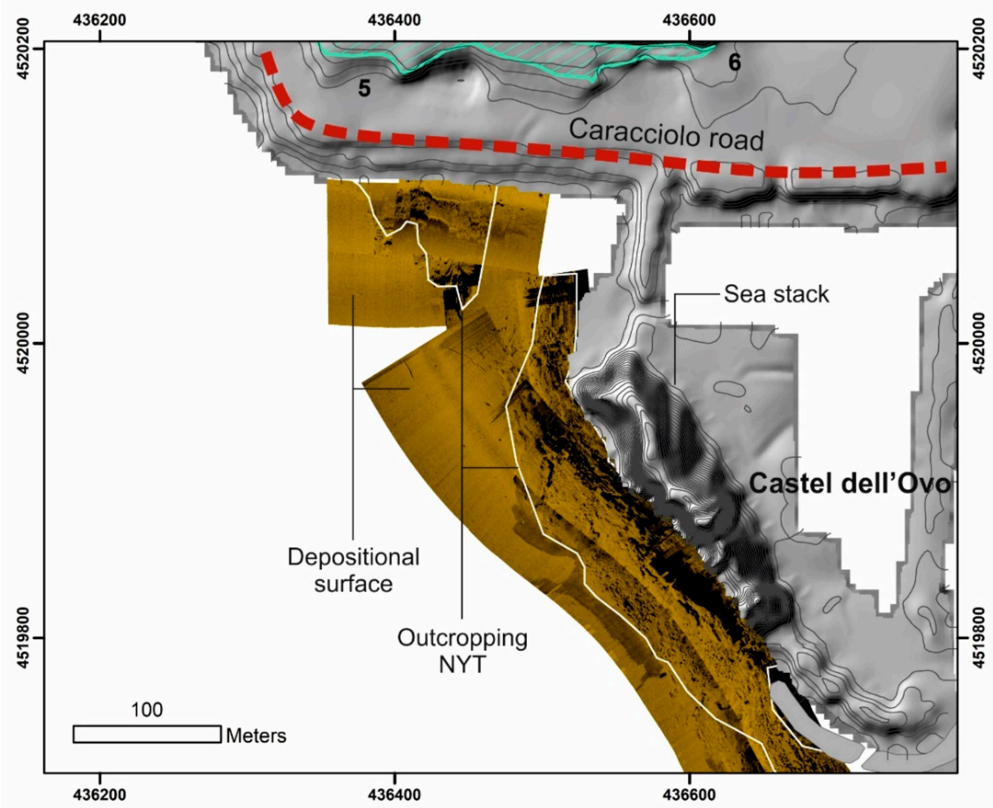
Figure 11. Global eustatic sea-level curve in the last glacial-interglacial circle, after Benjamin et al. [12].

Consequently, an uplift could have been responsible for the lifting of the first order platform some 15 m above the relative sea level (−4.5 m MSL) that was obtained from the Early Bronze Age second order shore-platforms.

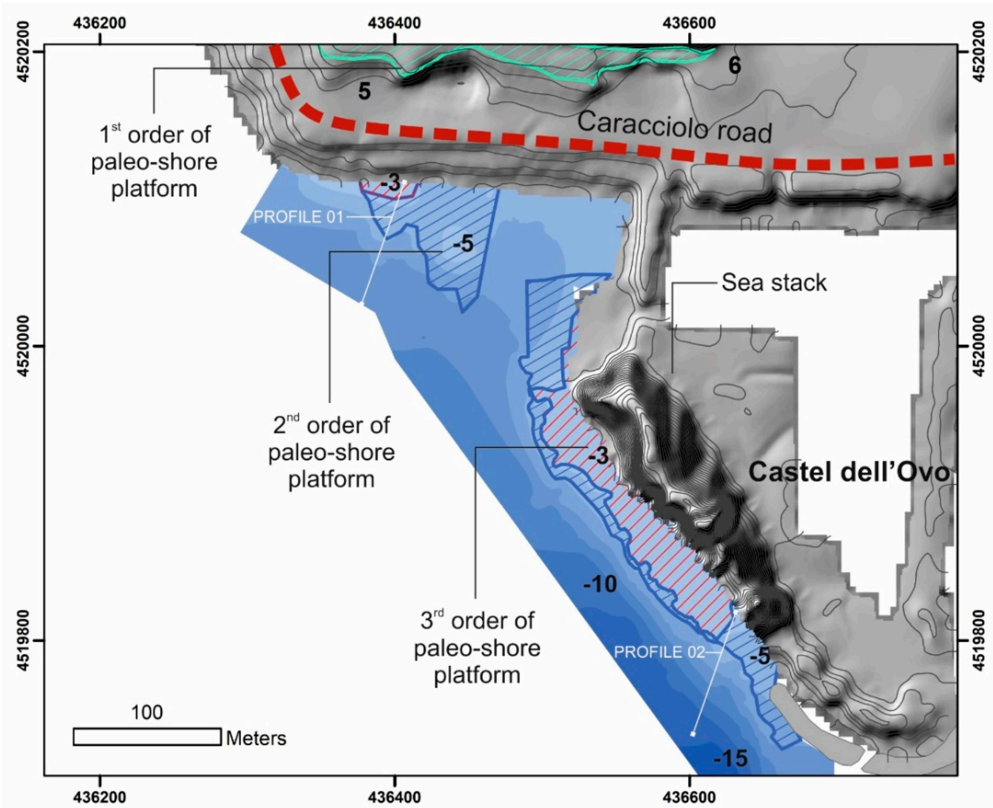
Anyway, when considering that in the Gulf of Naples, the average retreat rate of sea cliffs in tuff is around 0.04 m/year [14,98], the time that is required to abrade the Chiatamone terrace (up to 60 m wide) can be estimated in about 1500 years, under conditions of sea-level stand or low rate in sea-level rise.

4.2. Second and Third Order Paleo-Shore Platforms

The second-order paleo-shore platforms (Figure 12a) was precisely mapped at −4.5/−5 m MSL in the nearshore sector of Castel dell' Ovo islet during the morpho-acoustic survey (Figure 12a,b). The analysis of the acoustic signal, along with several direct surveys, allowed for defining that this landform is cut in NYT.



(**a**)



(**b**)

Figure 12. (**a**) Side Scan Sonar (SSS) map of the nearshore sector of Castel dell' Ovo islet; (**b**) Bathymetric map of the nearshore sector of Castel dell' Ovo islet with the precise mapping of the second (blue dashed lines) and third (red dashed lines) order submerged paleo-shore platforms (after Pappone et al. [45]).

The southern part of this platform has a very narrow shape in SW-NE direction (max 15 m) and it extends for 350 m in the NW-SE direction, with a medium slope of 2.5°. Instead, in the northernmost sector, overlooking the promontory of Pizzofalcone, the platform reaches about 100 m of extension seaward (Figure 12b). The two relicts of this paleo-shore platform are separated by a depositional surface, as demonstrated by the backscattering signal analysis [45].

When considering that the main storms and prevailing waves in the area coming from the S and SW sectors [87–94], it is possible to assume that the underwater channel separating the two landforms was shaped by the erosive effects of the wave action that also induced the formation of the sea-stack, where Castel dell' Ovo is now located.

In the close Chiaia plain, a buried landform at the same elevation range was detected during the geoarchaeological excavations that were related to the subway construction [37]. This buried landform is cut into Agnano Monte Spina and Astroni tephras (4.5 and 4.0 ky BP, respectively) and it is covered by archaeological remains, leading to suppose that it was shaped between the 4.0 ky BP and 600 BC.

It is reasonable to assume that submerged landform at −5 m MSL near Castel dell' Ovo was shaped in the same period.

The RSL in this period was deduced at −4 m MSL by measuring the present elevation of the inner margin in a well-preserved part, as described in the method section.

The spatial analysis of the morpho-acoustic data also allowed the detection of the third order paleo-shore platform at −3 m MSL (Figure 12).

This landform extended seaward 25–30 m in the nearshore sector close to Castel dell' Ovo and has a slope up to 2.2° (Profile 02 in Figure 13). Indeed, only a small witness is still visible in the northern area, as the platform was buried by an anthropogenic infill during modern times (Profile 01 in Figure 13).

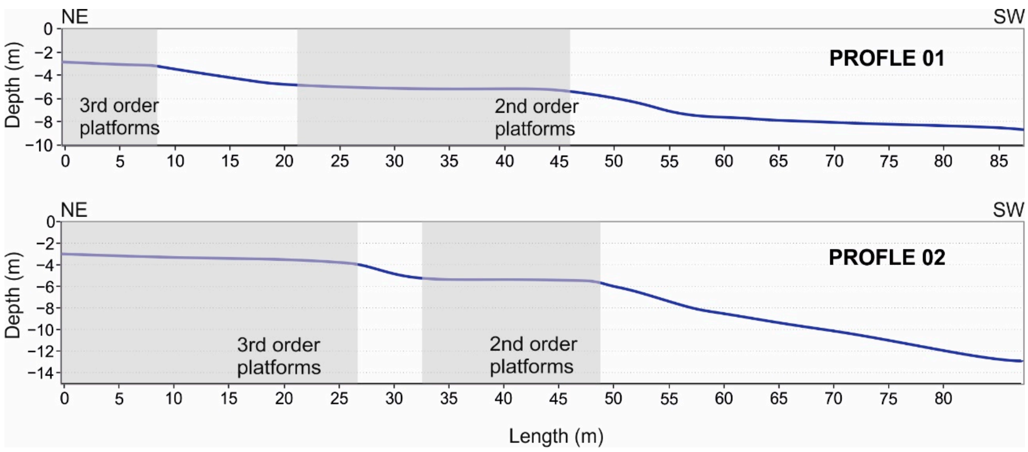


Figure 13. NE–SW profiles of the two relicts of the submerged paleo-shore platforms; for their location see Figure 11b.

The dating of this landform was possible thanks to the geoarchaeological study that was carried out by Pappone et al. [45] on the submerged archaeological remains laid on this platform. During direct and indirect surveys, several submerged targets were detected on a complex structure sculpted in tuff and extending along the outer margin of the third order of platform. The archaeological interpretation of these targets led to suppose that the structure was an ancient fish tank related to the Lucullus villa built on the Castel dell' Ovo islet during the 1st century BC [99]. The fundamental structural element that was used to evaluate the relative seal level (RSL) in this period was a well-preserved walkway, nowadays positioned at −1.8 m MSL. When considering that the functional clearance of this element with respect the ancient high tide (MHW, *sensu* Shennan, [24]) has been evaluated in 0.2 m by several authors (Aucelli et al. [53] and reference therein), a RSL at −2.2 m during the first century BC was deduced.

Moreover, this paleo-sea level is perfectly compatible with that obtained from the present elevation of the inner margin of the third order paleo-shore platforms measured in the best-preserved part.

Consequently, we can deduce that this shore platform, what was probably widened by human activity, was active during the Roman period.

5. Discussion

The interpretation of new data coming from direct and indirect surveys carried out in the coastal sector between Chiaia plain and Pizzofalcone promontory, corroborated by the analysis of bibliographic data and historical pictures, led to the detection of emerged and submerged terraces, testifying three Holocene episodes of relative sea-level stand, at +8 m, −4.5 m, and −2.2 m MSL, respectively.

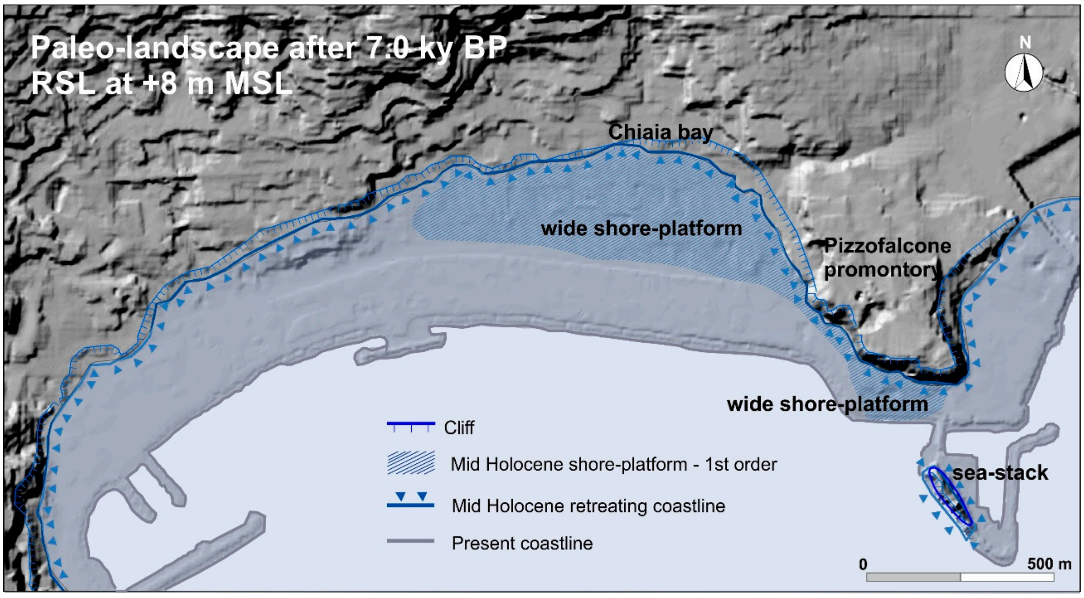
On the promontory of Pizzofalcone and in the proximity of the islet Castel dell' Ovo, the three orders of paleo-shore platforms are represented by wave-cut platforms, while, in the adjacent bays (Chiaia plain and Piazza Municipio), also by sedimentary bodies.

The geomorphological evolution of the study area during the Holocene can be summarized, as follows (Figure 14).

During the Holocene, maximum marine ingression in the area occurred 6000 years ago, and the decrease of the sea-level rise rate favoured a sea cliff retreat in the whole coastal sector-characterized at that time by active sea cliffs—and the formation of the first order paleo-shore platform nowadays uplifted at 7–9 m MSL. In the same period, the sea stack nowadays hosting Castel dell' Ovo probably formed (Figure 14a).

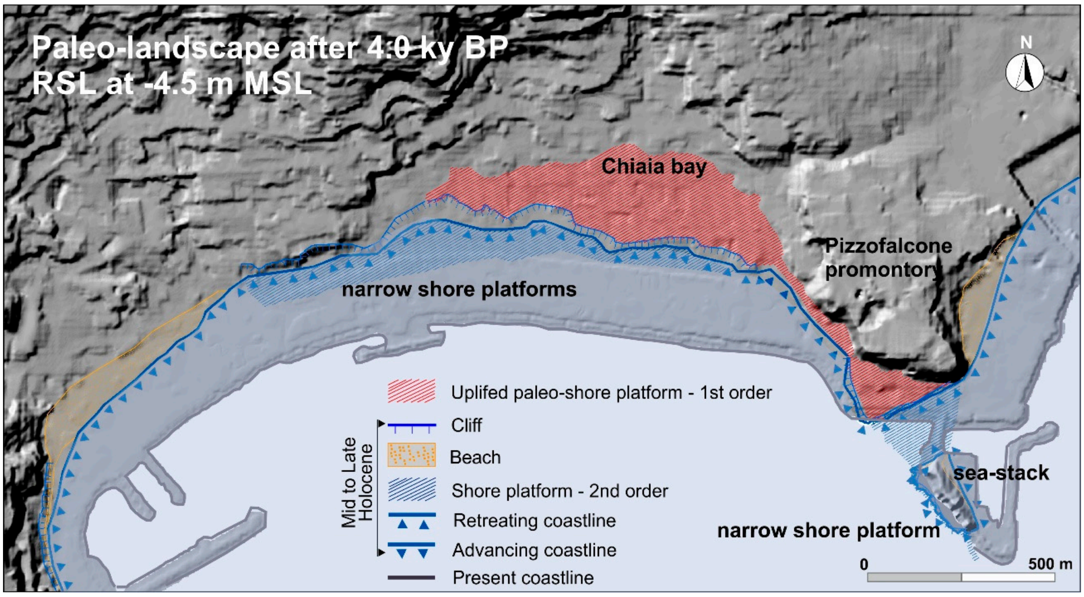
Later on (between 4.0 ky BP and 2.2 ky BP), after an uplift of a metric entity, the RSL stood at about −4 m MSL, which was long enough to allow the wave action to partially dismantle that raised platform and form a new one below it (2nd order platform; Figure 14b).

The relicts of these platforms are nowadays buried by recent littoral sands in Chiaia plain and sculptured in tuff in the submerged sector of Castel dell' Ovo. Other erosional traces of the palaeo-sea level at −4.5/−5 m MSL were detected in the nearby Posillipo coastal sector [43], where they mainly consist of abandoned sea cliffs in NYT. In this sector, several port-like landing structures dated at the 1st century BC were built on these platforms, demonstrating that during the Roman period these platforms were already completely submerged [43,44].

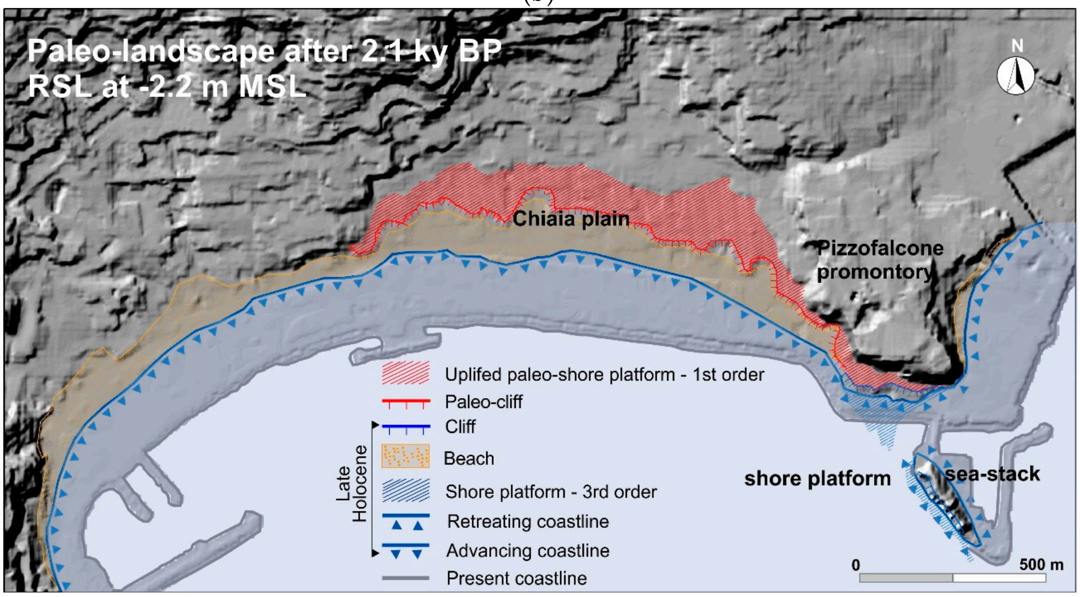


(**a**)

Figure 14. *Cont.*



(**b**)



(**c**)

Figure 14. Morpho-evolution of Naples coastal sector since the mid-Holocene (**a**) Paleo-landscape after the Holocene marine transgression (6.5 ky BP); (**b**) Paleo-landscape after the volcano-tectonic uplift occurred 5.0–4.5 ky BP; and, (**c**) Paleo-landscape during the Roman period.

Since that time, a subsiding trend—which was also recorded in La Starza sequence [62]—affected the area bringing the relative sea-level up to −2.2 m during the Roman age. In this period, a low rate in sea level change favoured the formation of the third order paleo-shore platforms in the Castel dell' Ovo sector at −3 m MSL, as a result of sea cliff retreat. The effect was different inside the adjacent bay of Chiaia [37]. Being a coastal reach with a positive sedimentary budget, a prograding trend prevailed, as demonstrated by the littoral sands dated thanks to pottery remains of Greek–Roman (Figure 14c).

The natural evolution of the area ended in 1800 with the construction of coastal gardens and streets.

A new curve of Mid-Holocene relative sea-level variation was proposed for the Naples coastal sector as a result of our geomorphological interpretations (Figure 15).

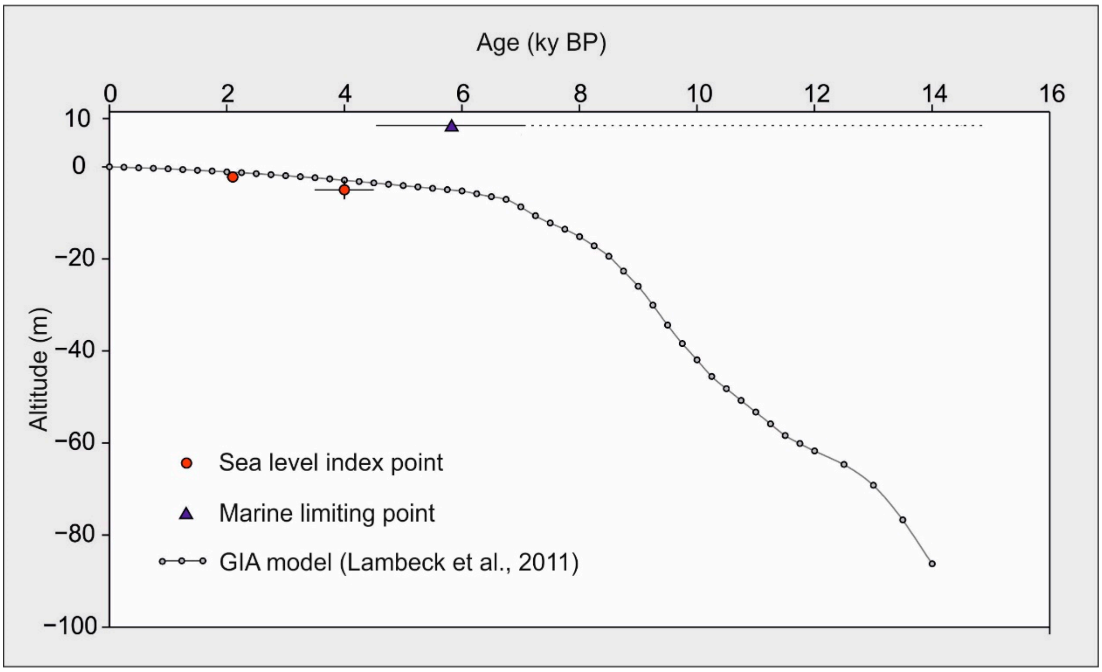


Figure 15. Relative sea-level curve for Naples in the last 6000 years. Black lines indicate the bi-directional uncertainty, but in the case of the marine limiting point related to the first order paleo-shore platform, the temporal uncertainty between 15 and 7 ky BP is a dotted line, because our interpretations led to discarding those millennia during which the rate of post-glacial sea-level rise was too fast to permit the formation of sub-horizontal wave-cut platforms.

Some novelties emerged by comparing our data with the framework of knowledge that was acquired during the underground excavations [36–41]. In the first instance, the geoarchaeological studies that were carried out in Chiaia and Municipio coastal plains precisely reconstructed the landscape modifications and the relative sea-level variations occurred in the last 4000 years, but no specific data have been acquired until now on the coastal palaeo-morphologies detectable along the interposed Pizzofalcone promontory, which separates the two coastal plains. In particular, such studies mainly measured the differential rate of a subsiding trend that occurred in the same period, but any evidence had been highlighted on the mid-Holocene uplift of a metric entity described in this study. On the other hand, the overlay between this result, previous studies, and several morpho-acoustic surveys of the underwater sector allowed for reconstructing the main morpho-evolutive trends of Naples coasts in the last 6000 years.

By comparing our study at a wider Mediterranean scale, it demonstrates the efficiency of an integrated interpretation of geomorphological and historical elements in terms of former sea-level indicators in tectonically complex sectors, as various authors similarly proposed for the Greek coasts, another Mediterranean coastal area. This sector suffered a subsiding trend during the Holocene with some episodes of uplift related to seismic activities [20,100–105]. In particular, Crete Island and the Perachora Peninsula recorded several geomorphological and archaeological traces of a nine-metre coseismic uplift that occurred in the historical period and were related to the tectonic activity of North-Eastern Aegean Sea [104,106]. Even in this case, historical sources allowed for interpreting this event, leading to obtaining some substantial information on the effect that the 8.5-magnitude earthquake occurred in 365 AD had the fasten landscape changes also occurred in the surrounding areas [104,105].

This comparison between Greek and Neapolitan coasts demonstrates the high reliability of multidisciplinary studies in interpreting past geological events that strongly changed coastal landscapes, thus inducing fast RSL variations.

6. Conclusions

In this study, some novelties were proposed for the Late-Holocene morpho-evolution of Naples coast. The main result obtained is the unveiling of a raised paleo-shore platform, ranging between 7 and 9 m MSL. nowadays almost undetectable due to the massive urbanization. No absolute chronological constraints were found; nevertheless, some regional geological dynamics and eustatic considerations led to suppose that it formed between 7 ky BP and 4.5 ky BP.

The mentioned strong urbanization of the area with the consequent lack of outcrops, and the absence of recent stratigraphic records on the raised platform, prevented from obtaining direct evidence on sedimentological and/or palaeo-ecological characters of deposits that are associated to this sea-level stand. Consequently, landform was interpreted as a paleo-shore platform by interpreting the morphological properties of the platform itself and the scarp above it, obtained from the interplay between historical sources, direct inspection of the few outcrops still visible, and a morphometric analysis of the high-resolution DTMs, as discussed in the Results section. Although that platform is not yet precisely dated and the details of its original morphology are obscured by the heavy urbanization of the area, that landform is very important because it is the first appeared evidence that the Naples area also experienced some uplift during the Holocene.

In the underwater domain of the study area, we identified two orders (second and third) of wave-cut platforms at −4.5 and −3 m MSL, respectively, by integrating the high-resolution morpho-acoustic and direct surveys. The second order was shaped between the 4.0 ky BP and 600 BC, when considering that, in the Chiaia plain, it is cut into Agnano Monte Spina and Astroni tephras (4.5 and 4.0 ky BP, respectively) and covered by archaeological remains. The third order, separated from the previous one by a 1.5-m high scarp, was dated at the Roman period due to the presence of the remnants of a fish tank.

By comparing our measurements of ancient relative sea levels with the Glacio-Hydro-Isostatic Adjustment (GIA) model that was proposed by Lambeck et al. [19], the vertical ground movements of the area during the Holocene can be reconstructed, as follows:

(T1) period of substantial stability between 7.0 and 5.0 ky BP during which the first order platforms formed;
(T2) an uplift of 10 to 13 m occurred shortly before the formation of the second order platforms about 5.0 ky BP;
(T3) short period of stability during which the second order platform was abraded; and,
(T4) period of prevailing subsidence covering the last 4 ky, which accelerated before the second century BC, considering that the RSL changed from −4.5 to −2.2 m MSL. This trend totalled about 2 m of lowering and was interrupted by a brief pause during the second century BC, when the third order platform formed, and the fish tank of the maritime villa at Castel dell' Ovo was constructed on it.

The subsiding movements at issue can be interpreted as the background regional trend due to the extensional tectonics of the whole Campania Plain and Gulf of Naples [106,107]. On the contrary, the uplift characterizing the period T2 is interpreted as a volcano-tectonic event that is probably related to the Campi Flegrei volcanic complex. According to this attribution, there is the fact that—about 5 ky BP—the area around Pozzuoli (central part of Campi Flegrei) experienced a phase of strong and fast volcano-tectonic uplift that raised the La Starza marine terrace. There, the displacement was in the order of tens of meters (up to about 100 m according to Isaia et al. [62], while Naples could have been more slightly affected due to its peripheral position.

In conclusion, this research, which belongs to a wider framework of studies concerning the Holocene landscape evolution of the Gulf of Naples [42–45,53,54,79,108,109], on one hand, improved the knowledge on the coastal landscape evolution of Naples and, on the other hand, provided new data on the VGM affecting this area and referable to the CF recent activity.

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