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Morphological responses to relative sea-level changes along Procida coast (Gulf of Naples, Italy) during the last 6.5 Ky

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Abstract –
In this research, the morpho-evolutive trend of sea cliffs placed in the volcanic island of Procida was investigated. The entire perimeter of the island is bordered by cliffs, which in some cases are connected to narrow shore platforms sloping slightly towards the sea. The presence of different orders of submerged paleo-shore platforms suggests different phases of sea-level stand and related coastal response. Mapping these platforms, together with the interpretation of archaeological and geomorphological markers allowed defining the shoreline evolution of Procida Island during the last 6.5 ky.
The paleo sea levels deduced from these indicators were compared with the eustatic sea-level curve proposed by [1] demonstrating that Procida coastal area was affected by an overall subsiding trend since the Mid-Holocene, which probably occurred intermittently or with variable intensity over time.
By reconstructing the position of the ancient shorelines related to the three orders of platforms, the retreating rates of the cliffs bordering the area were calculated.

I. INTRODUCTION

Procida Island belongs to the insular part of the Campi Flegrei (CF) volcanic area and owes its formation to several explosive eruptions related to the CF volcanic activity started more than 60 ky BP [2]. The Campi Flegrei volcanic area, still active today, represents one of the two main hazardous volcanic areas in the Gulf of Naples (southern Italy) [3-17].
In detail, the island is characterised by steep cliffed coasts and articulated in a succession of headlands and small embayments [18]. The cliffs are generally cut into pyroclastic deposits showing a height of 10 to 40meters and an inclination of over 40°. Small and narrow pocket beaches, such as Ciraccio and Chiaia beaches, represent the main tourist attraction of the island.
This study aims to reconstruct the coastal response to relative sea-level rise since the mid-Holocene, by analysing the submerged features of the coast [19-22]. Geomorphological and geo-archaeological interpretations obtained from the GIS elaboration of a multi-scale dataset led to evaluate the modification of the coastal landscape during the last 6500 years.

II. METHODS

The coastal sector of the study area was investigated by using a multi-techniques approach based on direct and indirect methods. Several on-site investigations were integrated with the geomorphological study of aerial photos.

A. Geomorphological and GIS analysis

The 3D elaboration of the topo-bathymetric data, concerning Procida coastal area, followed a specific procedure.
The first step was the calculation of an onshore-offshore DTM by interpolating the LIDAR (from the Ministry of Environment, 0 – 200 m msl) and bathymetric data (from the CARG project [23], 0 – 20 m msl), with a Topo to Raster interpolator (1 × 1 m grid).
The second step was the slope analysis of the above-mentioned DTM in order to classify the submerged area in sub-horizontal and steep slope sectors.
By integrating the above-mentioned GIS analysis with data derived from direct surveys, several sub-horizontal submerged surfaces (0-5% of slopes) were detected and interpreted as ancient shore platforms [24-25]. Consequently, the higher sloping sectors (slope > 20%) adjacent to the sub-horizontal surfaces were interpreted as related paleo-cliffs.
Finally, the mapped paleo-shore platforms were reclassified depending on their depth in three orders and subsequently dated by means of the archaeological

evidence from bibliographic sources and our geomorphological interpretations.
The last step was the morphometric analysis applied to these landforms to evaluate the retreat rates of sea cliffs and the vertical ground movements that have affected the Procida costal sector in the last six thousand years.

B. Shore platforms as sea level index points

Paleo-shore platforms can be used as indicators of ancient sea levels if their morphology can be reconstructed [26]. While some platforms are incised above sea level, others are incised in intertidal or slightly subtidal areas [27]. According to [28], the outer margin (i.e. the termination point of the platform towards the sea) is the point where active erosion of the bedrock ends.
However, the most relevant feature useful for sea-level interpretations certainly is the inner margin of the platform (*Fig. 1*), considering that it is located at the same level of the mean higher high water (MHHW - average of the higher high water height of each tidal day observed over a Tidal Datum Epoch) [27]. The Relative Sea Level (RSL) associated with this indicator is equal to:

$$RSL = E - MHHW \quad (1)$$

Where E is the present elevation of the platform at issue with respect to the mean sea level (msl).

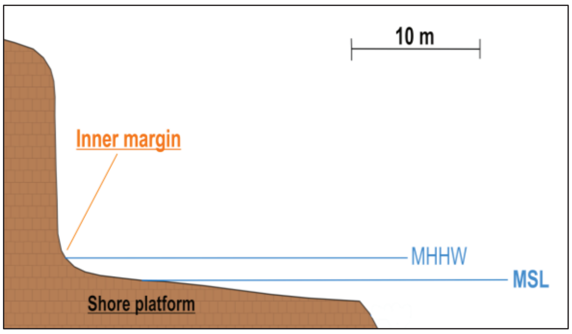

Fig. 1. Shore platforms as sea level index points (modified from [27]).

III. RESULTS

The present sea cliffs bordering the coasts of Procida island were precisely mapped and classified in two types: Type 1 -cliffs with narrow shore platforms slightly sloping towards the sea [29]; Type 2 - near-vertical slopes that rise abruptly from the deepwater (plunging cliff [29]).
The presence of three orders of submerged paleo-shore platforms highlight as many paleo sea-level stands (*Fig. 2*). The first-order platforms are positioned at -25/-23 m msl, cut in the volcanic formation of Tufo di Solchiaro [30] emplaced during the last most important eruptive phase of Procida (22 ky BP). Therefore, these platforms were modelled after that date.
By analysing the eustatic sea-level curve [30] relevant to the last 22 ky, the most favourable morphogenetic conditions for their formation started about 6.5 ky BP, when the decrease of the rate of sea-level rise was compatible with platform formation and related sea cliff retreat.
Accordingly, the age of these platforms can be likely comprised between about 6.5 ky and the age of the second order of platforms. The RSL here calculated was positioned at -23 m msl (*Fig. 2*).

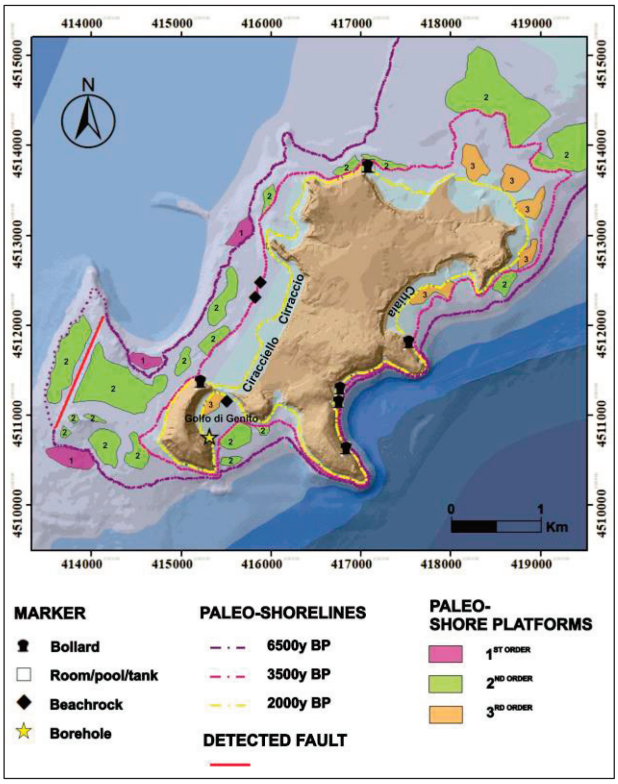

Fig. 2. Map showing the distribution of the three orders of analyzed submerged paleo-shore platforms.

The second-order platforms (-20/-11 m msl) were dated to 3.5 ky BP through coring data coming from the Genito Gulf, where abundant fragments of archaeological finds were identified and dated by [32] to 3.5 ky BP, and through several beachrocks detected at a depth of -13m msl and -11,8m msl. The RSL calculated was positioned at -11 m msl.
The third-order platforms (-10/-4 msl) were dated through ring bollards detected at a depth of -4.5 m msl and beachrocks detected at a depth of -6,2 m msl and dating back to 2000 and 1000 years ago [32-33]. The RSL calculated was positioned at -4.5 m msl.
The paleo sea-levels deduced from these indicators were compared with the eustatic sea-level curve proposed by Lambeck [1] (*Fig. 3*) demonstrating that this area was affected by an overall subsiding trend since the Mid-Holocene, which probably occurred intermittently or with variable intensity over time. By subtracting the RSL data

from the eustatic values, the vertical displacements for Procida coastal area were evaluated.
By reconstructing the position of the ancient shorelines related to the inner margin of the three orders of platforms, the cliff retreat rates related to the erosion of second- and third-order platforms were evaluated.
In particular, in the Ciraccio-Cirracciello sector,for location see *Fig. 2*, the retreat rate of the second order platform of about 0.14 m/y was calculated in the last 3.5 ky BP. In addition, a subsidence rate of about 0.002 m/y was obtained. In the same sector, the RSL at -4.5 m msl dated to 2.0 ky BP allowed calculating a subsidence rate of about 0.001 m/y.
In the Chiaia coastal sector, a cliff retreat rate of 0.12 m/y in the last 3.5 ky BP was evaluated by measuring the extension of the second-order paleo-shore platform. Instead, by analysing the historical platform dated between 2.0 ky BP and 1.0 ky BP a cliff retreat trend of about 0.16 m/y was evaluated for this time span. A related subsiding trend of about 0.001 m/y in the last two thousand years was measured.

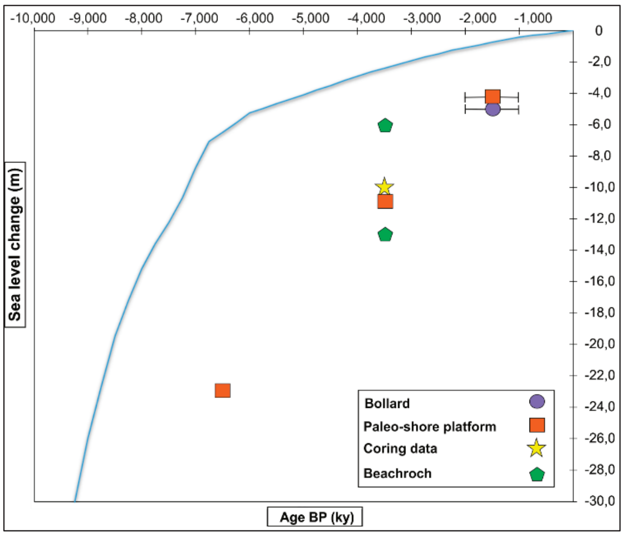

Fig. 3. Eustatic sea-level curve including the archaeological and geomorphological indicators found offshore the coast of Procida. They are represented with relative uncertainty bars (modified from [1]).

IV. CONCLUSIONS

In this research, the morpho-evolutive trends of the Procida coastal area since the mid-Holocene were evaluated.
For this purpose, three orders of submerged paleo-shore platforms were used as morphological markers of ancient sea-level stands.
The geomorphological interpretation of these three orders of paleo-shore platforms, formed between 6.5 and 1.0 ky BP, provided the reconstruction of as many ancient shorelines. In addition, the cliff retreat rates over the last 6500 years along the Cirraccio-Cirracciello and Chiaia sectors were evaluated.
The precise mapping of these ancient platforms at various depths allowed establishing that an overall subsidence has certainly contributed to the polyphasic Holocene coastal evolution of the island, which was characterized by three main phases of relative sea-level stability (or strong decreasing in the rate of sea-level rise) that occurred during the last 7 ky.
A volcano-tectonic origin, related to the activity of the Campi Flegrei volcanic area, can be assumed as the main cause of this subsidence, even if the analysis of remote sensing data demonstrates that the island is nowadays stable [34]. The observed subsidence cannot be escluded that was influenced by the eruptions occured in the phlegrean area in the same span, anyway this issue needs further accurate evaluation.

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