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Evolution of anthropic coastal landscapes and ground deformation in the Campi Flegrei caldera (southern Italy) since Roman times: insights from multi-technique surveys

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***Abstract* – This study explores the long-term evolution of the coastal landscape within the Campi Flegrei caldera (southern Italy), a highly dynamic volcanic region affected by persistent ground deformation. Through an integrated, multi-technique approach combining archaeological surveys, acoustic seabed mapping, and stratigraphic and geophysical analysis, the research reconstructs relative sea-level changes and vertical ground movements since Roman times. Submerged Roman structures serve as precise sea-level indicators, revealing spatially heterogeneous patterns of uplift and subsidence over the last 2400 years. These findings shed light on the interplay between volcanic-tectonic processes and human adaptation strategies in shaping the coastal environment. The results not only enhance the understanding of past landscape dynamics in Campi Flegrei but also offer a valuable reference for evaluating future risks in coastal areas affected by geological instability.**

I. INTRODUCTION

Campi Flegrei caldera, located along the Tyrrhenian coast of southern Italy, represents one of the most active and hazardous volcanic systems in the Mediterranean. Its long and complex history of eruptive activity and volcano-tectonic ground deformation has profoundly shaped both the natural environment and the development of human settlements within its coastal zone. Despite persistent instability, including abrupt changes in ground elevation and frequent bradyseismic crises, the area has been continuously inhabited since antiquity, leaving behind a unique and well-preserved archive of submerged archaeological features.

The evolution of the Campi Flegrei caldera began with two major eruptions: the Campanian Ignimbrite (~39,000 years ago) [1] and the Neapolitan Yellow Tuff (~15,000 years ago) [2], which gave rise to its current nested structure. This was followed by three distinct epochs of post-caldera volcanic activity, dated to approximately 15–10.6 ka BP, 9.6–9.1 ka BP, and 5.5–3.5 ka [3]. These phases were marked by explosive and effusive eruptions distributed across the caldera, and were accompanied by intense volcano-tectonic ground deformation. More recently, the Monte Nuovo eruption in 1538 AD [4] signaled the onset of renewed activity, suggesting that the system remains capable of future unrest. In addition to eruptive phenomena, the caldera has experienced non-eruptive, cyclical ground movements (i.e. bradyseism) driven by magmatic and hydrothermal processes, which have repeatedly altered coastal topography.

Over the past two millennia, vertical ground movements (VGMs) and relative sea-level (RSL) changes have dramatically reshaped the coastline. Periods of tectonic stability and coastal progradation were often interrupted by subsidence events that led to the flooding of Roman-era infrastructure, including villas, harbors, fish tanks, and roads. These features, now partially or fully submerged, serve as high-precision sea-level markers and offer crucial evidence for reconstructing the historical evolution of the coastal landscape. Through integrated archaeological, stratigraphic, and geophysical analyses, it is possible to trace not only the magnitude and timing of vertical ground movements but also the ways in which ancient communities responded to environmental change.

A spatially resolved reconstruction of RSL trends and ground deformation over the last 2400 years reveals heterogeneous deformation patterns across the caldera. By analyzing submerged archaeological structures and sedimentary sequences within different coastal sectors, it is possible to distinguish localized histories of uplift and subsidence with decimetric accuracy. These reconstructions demonstrate a dynamic coastal evolution shaped by both natural forces and human adaptation, highlighting the complex interdependence between geophysical processes and cultural development.

This research provides new insight into how volcanic processes have continuously reshaped the Campi Flegrei coastline, offering a valuable case study on how past human societies adapted to persistent environmental change in one of the most dynamic volcanic settings in Europe.

II. METHODS

This research adopts a multitechnique approach to reconstruct the evolution of the anthropic coastal landscape and quantify VGMs in the Campi Flegrei caldera since Roman times. The methodology integrates direct archaeological surveys, acoustic and optical seabed mapping, stratigraphic analysis, and high-resolution spatial data processing. This interdisciplinary strategy allows for a detailed assessment of RSL change, geomorphological transformations, and human adaptation in response to ground deformation.

Extensive direct geoarchaeological surveys were conducted at major submerged Roman sites within the caldera, targeting architectural elements such as fish tanks, *pilae*, *nymphaea*, *crepidines*, thresholds, and floor pavements. These features were then interpreted as sea-level index points (SLIPs) and terrestrial limiting points (TLPs), providing high-resolution constraints on past RSL positions and offering a direct record of ground deformation affecting the coastal zone.

To extend the spatial coverage and resolution of the coastal mapping, morphoacoustic surveys [5] were carried out using high-frequency acoustic instrumentation. In shallow and archaeologically sensitive sectors, additional data were collected using the ARGO unmanned surface vessel (USV) [6].

All acquired datasets were integrated within a Geographic Information System (GIS) environment. A high-resolution digital terrain model (DTM) (2×2 m on land and 0.25×0.25 m underwater) was created, providing a detailed 3D representation of the coastal landscape used to map ancient shorelines, analyze changes in coastal morphology, and assess the distribution of archaeological structures.

By comparing the modern terrain with past sea-level indicators and stratigraphic records, it was possible to identify patterns of shoreline movement and reconstruct the geomorphological changes that occurred over the last 2400 years.

In terms of volcano-tectonic activity, using available GIA models for the study area[7], the SLIP data were compared to the geophysical prediction by using a statistical approach, employing Monte-Carlo simulations.

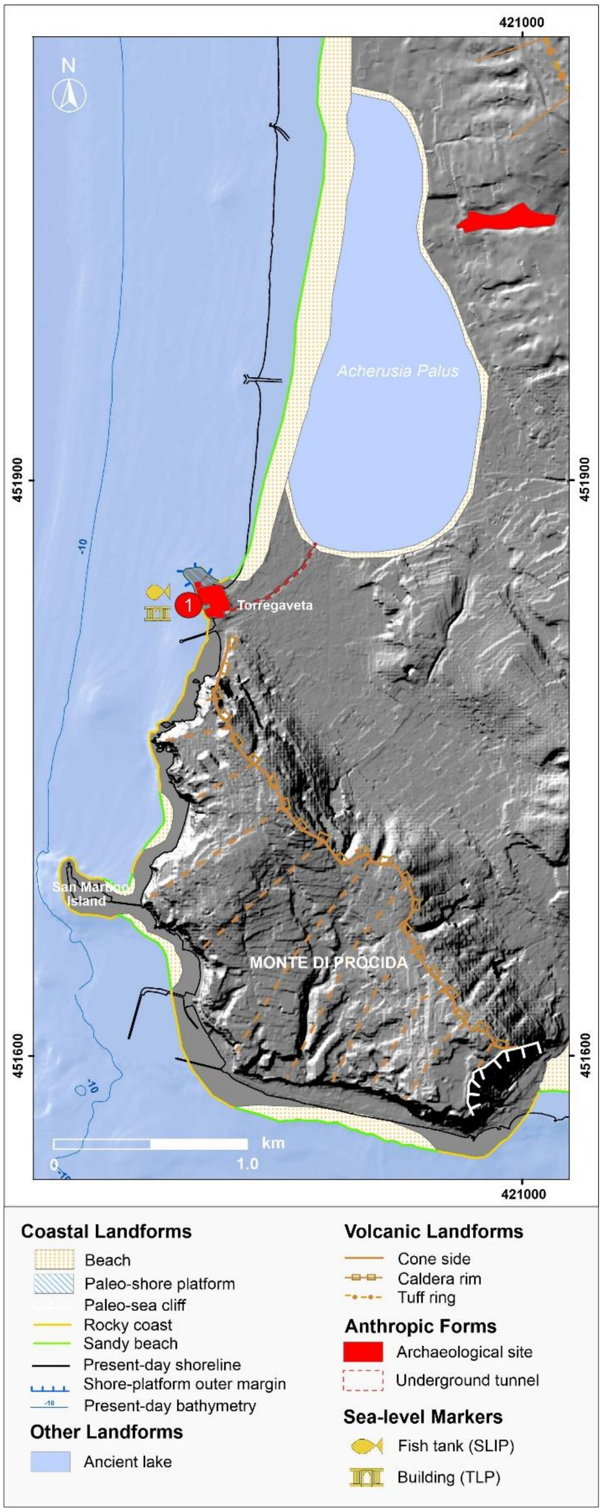

Fig. 1. Coastal landscape during Roman times between the ancient Acherusia Palus and M.te di Procida. Location ID: 1 - Vatia Villa. Modified from [8].

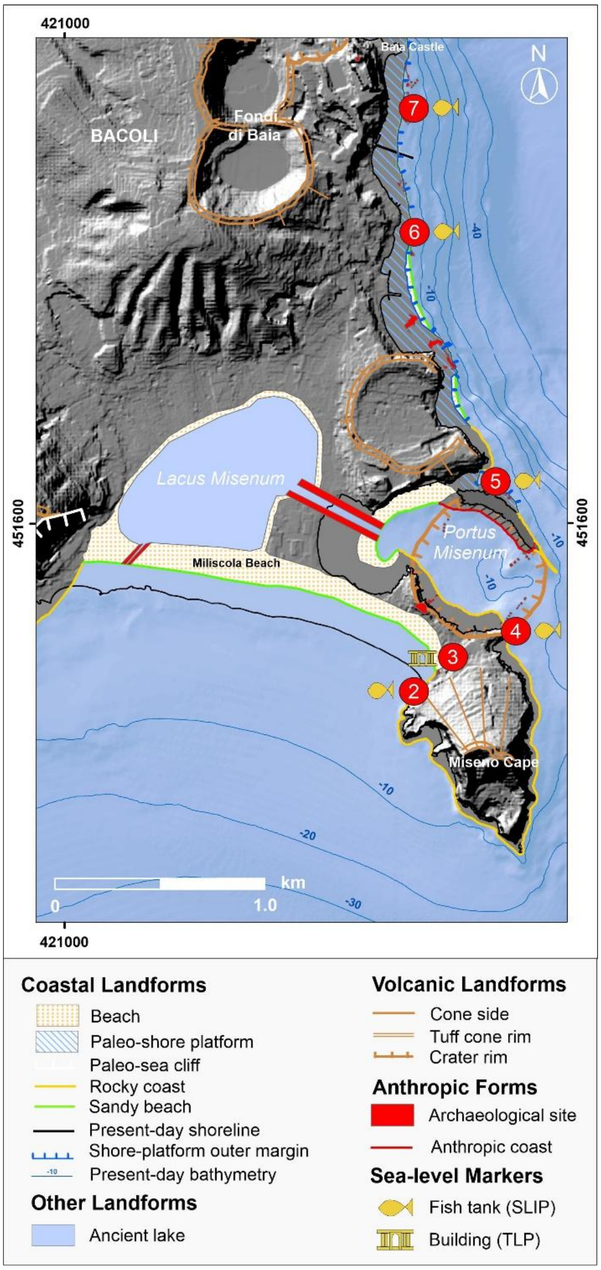

Fig. 2. Coastal landscape during Roman times between M.te di Procida and Baia's Castle. Location ID: 2 - Vatia Villa; 3 - Misenum Thermae; 4 - P.ta Terone fishtank; 5 - Pt.a Pennata fishtank; 6 - Hortalus Villa; 7 - Caesar Villa. Modified from [8].

III. RESULTS

In the 1st century BC, the coastline extending from the ancient *Acherusia Palus* (corresponding to present-day Fusaro Lake) to Capo Miseno displayed a varied geomorphology, alternating between low- and high-relief sectors (Figure 1).

The area near the ancient *Acherusia Palus* featured a low-lying coastal zone approximately 3 km long, shaped by a sandy spit barrier about 180 m wide that separated the coastal lagoon from the open Tyrrhenian Sea [9] (Figure 1).

Eastward, beginning at the Torregaveta promontory, a high coastal section extended for nearly 4 km. This stretch was marked by the presence of a luxurious Roman maritime villa (site 1 in Figure 1), attributed to the consul *Publius Servilius Vatia Isauricus* and dated to the early 1st century BC [10]. Associated with the villa were a fish tank and a *nymphaeum*, located on a rock platform partially shaped by human activity. Analysis of these archaeological features enabled estimation of a long-term retreat of the sea cliff by approximately 130 m over the past two millennia.

Field measurements at this site revealed the submerged remains of the fish tank, including a well-preserved *lower crepido*. The current depth of submersion of this feature indicates a RSL of −3.3 m for the early 1st century BC, from which a VGM of −2.56 ± 0.46 m was derived [11].

Continuing southeast beyond the Monte di Procida cliff, the coast transitions into the Miliscola beach (Figure 2), a low-lying sandy spit that extends to Miseno Cape. Since the 1st century BC, this sector has undergone net progradation of roughly 130 m, whereas Miseno Cape experienced a minor coastal retreat of about 40 m over the same period.

On the western side of Miseno Cape, lies another complex of Roman fish tanks, traditionally linked to the Roman consul *Lucullus* [12] and archaeologically dated to the latter half of the 1st century BC (site 2 in Figure 2). At this location, the lowest *crepido* was surveyed, yielding an RSL estimate of −3.2 ± 0.29 m. Based on this, a VGM of −2.47 ± 0.45 m was calculated using a Monte Carlo simulation.

Next to *Lucullus* fish tanks are the remains of the Roman *Thermae* of *Misenum* (site 3 in Figure 2) [13, 14], constructed in the 2nd century AD near the close *Portus Misenum*.

Excavations at the site have exposed two well-preserved rooms from the thermal complex, now entirely buried beneath a sequence of sedimentary deposits. Ceramic fragments found within these layers document two reoccupation events dated to the 6th–7th and 11th–12th centuries that followed the first abandonment during the 4th century AD, possibly as a result of marine transgression and partial inundation [13].

Here, stratigraphic evidence places the RSL at the time of its construction below 0.5 m MSL, while subsequent sedimentary accumulation and archaeological markers indicate a sea-level that rose to approximately 5 ± 1 m MSL between the 8th and 11th centuries AD [14].

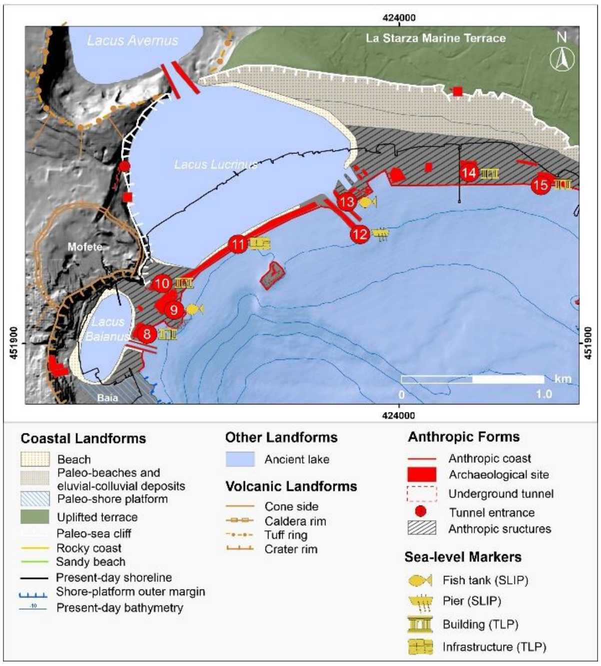

Fig. 3. Coastal landscape during Roman times between Baia's Castle and Pozzuoli. Location ID: 8 - Protiro Villa; 9 - Pisoni Villa; 10 - Claudius Nymphaeum; 11 - Via Herculanea; 12, 13 – Portus julius; 14 - Vicus Annianus; 15 - Vicus Lartidianus. Modified from [8].

The coastal section stretching from the eastern flank of Miseno Cape to the northern extremity of Punta Pennata Island is characterized by a predominantly rocky shoreline, approximately 2.5 km in length.

This coastline is interrupted by a small bay, historically identified as the location of the ancient harbour of *Portus Misenum* [15], artificially connected to the inland *Lacus Misenum* (modern Miseno Lake).

The southern limit of the inlet is defined by the Punta Terone promontory, where archaeological findings point to the presence of a fish tank likely belonging to a seaside villa that predates the harbor's construction, and which can be dated to the late 1st century BC (site 4 in Figure 2). Here, the lower *crepido* level suggested a RSL of −4.1 ± 0.3 m [5, 14] from which a VGM of −3.35 ± 0.44 m was derived.

On the eastern side of Miseno Bay, near Punta Pennata Island, a raised paleo-shoreline platform extends to the present-day harbor of Baia (Figure 2). This ancient platform formed during the third eruptive phase of the Campi Flegrei volcanic complex, between 5.5 and 3.5 ka BP [3], when volcano tectonic subsidence, combined with glacio-isostatic sea-level rise during the Late Holocene, led to the flooding of the Neapolitan Yellow Tuff caldera [16].

The elevated platform, that witnessed a coastal retreat of approximately 100 m before Roman occupation, later hosted several coastal structures, including a maritime villa dating to the 1st century AD near Punta Pennata [11] (site 5 in Figure 2). Submersion analysis of the associated fish tank sluice gate indicates that the RSL at the time of construction was −2.3 ± 0.3 m MSL, resulting in a VGM of −1.65 ± 0.43 m.

Further north, along the coastline from Garibaldi dock to the Baia Castle headland, additional Roman coastal structures were constructed on the uplifted surface of the platform, including the fish tank attributed to the Villa of *Hortensius Hortalus* (site 6 in Figure 2) and the one belonged to *Caesar's Villa* (site 7 in Figure 2), both dated to the 1st century BCE.

Their submerged remains support a consistent RSL estimation between −4.00 and −4.20 ± 0.29 m MSL, aligning with the values obtained at Punta Terone [8, 14], and VGM values between −3.27 ± 0.45 and −3.30 ± 0.44 m, respectively.

In the 1st century BCE, the area north of Baia Castle was flanked by the ancient port basin known as *Lacus Baianus* (Figure 3), a naturally protected inlet formed by marine erosion acting upon the exposed flanks of the Fondi di Baia volcano [17, 18].

This portion of the coast was densely built-up with luxurious maritime structures, among them the Protiro [19] (site 8 in Figure 3) and Pisonis Villas [19, 20, 21] (site 9 in Figure 3) and the *Nymphaeum* of Emperor Claudius, located at Punta Epitaffio [22, 23] (site 10 in Figure 3).

These buildings, dating to the 1st century AD, have provided critical SLIP at -6.9 ± 0.29 m MSL [5, 8], suggesting that the more central sector of the Campi Flegrei caldera experienced greater vertical subsidence than nearby areas during the same period with VGM values of −6.22 ± 0.43 m.

One of the largest engineering projects of the time involved the construction of a massive breakwater (site 11 in Figure 3), today misattributed to the ancient *Via Herculanea,* erected over shallow marine deposits to isolate from the sea the *Lacus Lucrinus* (modern Lucrino Lake), used for oyster cultivation and hydraulically connected to the inner *Lacus Avernus* (modern Averno Lake).

At its center, the breakwater was interrupted to allow access to the harbour of *Portus Julius*, constructed between the second half of the 1st century BC and the beginning of the 1st century AD, where direct measurements carried out along the *pilae* (site 12 in Figure 3) located at the entrance and the inner fish tank (site 13 in Figure 3) assessed volcano-tectonic stability for the reference period and a RSL stand at −3.10 ± 0.29 m MSL [5, 8, 24].

Further inland, the coastal plain to the east underwent major transformations due to extensive landfilling efforts [25]. This anthropogenic modification led to an average progradation of about 200 m, on which the Roman harbor neighborhoods of *Vicus Annianus* (site 14 in Figure 3) and *Vicus Lartidianus* (site 15 in Figure 3) were subsequently established.

IV. DISCUSSION AND CONCLUSION

The presented paleoenvironmental reconstruction highlights the intricate interplay between volcano-tectonic dynamics and glacio-hydro-isostatic sea-level rise in shaping the coastal landscape of the Campi Flegrei caldera. Together, these processes have repeatedly reshaped the coastal interface, influencing human occupation patterns and prompting adaptive responses such as land reclamation, harbor modification, and the reoccupation of previously abandoned areas over the last two millennia.

The spatially and temporally resolved analysis of submerged Roman structures, stratigraphic records, and geomorphological features reveals a highly heterogeneous pattern of VGMs, reflecting localized episodes of subsidence and uplift superimposed on broader regional trends in sea-level change.

By illustrating the coupled influence of endogenic and exogenic forces on coastal evolution, this research advances the understanding of past landscape dynamics in the Campi Flegrei area, offering a valuable reference for assessing future coastal vulnerability in tectonically and volcanically active regions.

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