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Two Thousand Years of Historical-Archaeological Observations of Bradyseism in Pozzuoli

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Abstract

The Serapeum of Pozzuoli has long served as a pivotal site for scholars seeking to integrate geology, archaeology, and historical records to study the phenomenon of ground deformation in the Campi Flegrei area. Early modern observations of slow vertical ground movements in Pozzuoli laid the groundwork for understanding a process that has persisted for millennia, leaving tangible traces in stone, inscriptions, and ancient manuscripts. The interplay between human activity and the dynamic volcanic environment is revealed through architectural remains, epigraphic evidence, and historical accounts, highlighting both the resilience and vulnerability of urban settlements to bradyseism events. This study synthesizes archaeological, historical, and geological data to reconstruct the evolution of ground deformation in Pozzuoli, emphasizing the Serapeum as a unique reference point for interdisciplinary research and for evaluating long-term hazards in volcanic regions.

Keywords: Campi Flegrei; Bradyseism; Epigraph; Serapeum; Subsidence

1. Introduction

For many scholars working on the Campi Flegrei, the so-called Serapeum of Pozzuoli has represented a foundational case study for integrating geological, archaeological, and historical evidence in the interpretation of a long-term geodynamic process extending over several millennia. The phenomenon has left clear traces both in the built environment and in written sources, preserved in inscriptions and ancient manuscripts.

The first modern observations of slow vertical ground deformation in the Pozzuoli area date to the early modern period, following the rediscovery of the monumental remains of the so-called Temple of Serapis – now correctly identified as the market (macellum) of the Roman city – at the end of the eighteenth century (Parascandola, 1947). The monument was excavated in 1750 by order of King Charles of Bourbon, shortly after the discovery of Pompeii, in an area of Pozzuoli known as the "Vigna delle Tre Colonne" (Fig. 1).

This toponym derived from the presence of three cipollino marble columns partially buried near a thermal-mineral spring known as the Cantarellum.

The excavation was directed by the military engineer Joaquín de Alcubierre, who had previously overseen the excavations at Herculaneum and Pompeii. The structure was initially interpreted as a Temple of Serapis owing to the discovery of a statue of Jupiter Serapis, now preserved in the National Archaeological Museum of Naples (Fig. 2).

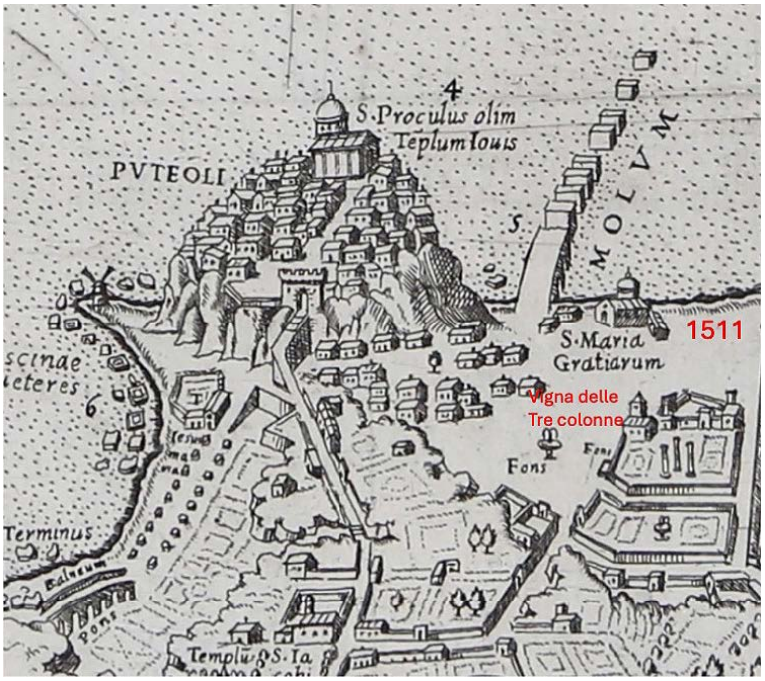

Figure 1. A section of the map of Mario Cartaro (1584) showing in the center right the so called Vigna delle tre colonne. Also shown the Church Santa Maria Gratiarum (1511).

Figure 2. The statue of Iuppiter Serapis found in the Macellum now preserved in the Archaeological Museum of Naples.

Subsequent archaeological interpretation firmly established the monument as the macellum of Pozzuoli. Early local guidebooks suggested that twelve cipollino marble columns recovered during the excavation were reused to decorate the court theatre of the Royal Palace of Caserta (Pennini, 2018; De Filippis, 1968). This hypothesis has been rejected by later studies, which identified in the Apennines the quarry supplying the columns of the theatre (Ciapparelli, 1996) and by a direct investigation at the theater.

Among the earliest visual representations of the Serapeum is the engraving by Giovanni Battista Natali and Giovanni Volpato, published in Paolo Antonio Paoli (1768), as documented by Binda (2017) (Fig. 3).

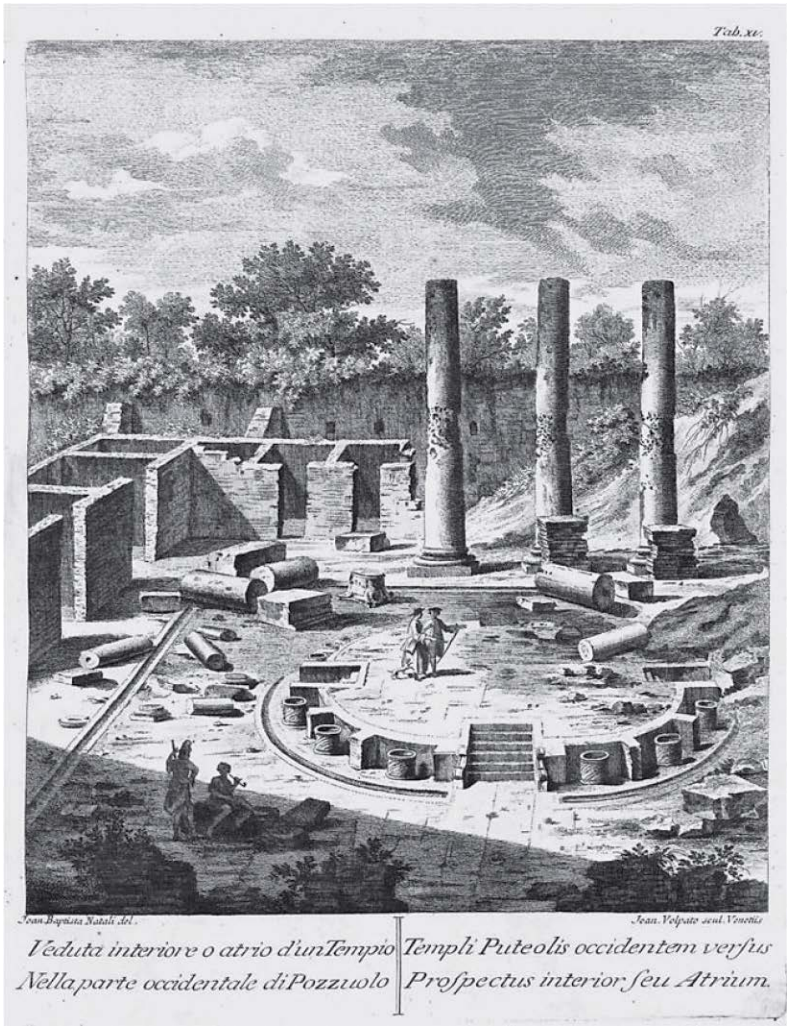

Figure 3. The excavation of the Serapeum in the drawing made by Giovanni Battista Natali and Giovanni Volpato 1760-68 (Ministero del Tesoro, Istituto Centrale per la Grafica).

Another important early depiction is the drawing by Auguste Caristie (1783-1862), now preserved at the Academy of Fine Arts in Paris (Fig. 4).

One of the first scholars to recognise the significance of the lithophaga (rock-boring mollusc) holes visible on the marble columns was Scipione Breislak, who interpreted them as evidence of either fluctuations in sea level or vertical ground movements. At the beginning of the nineteenth century, the Neapolitan architect Nicolini (1829) carried out the first systematic measurements of sea level relative to the floor of the Serapeum and supported the hypothesis that shoreline changes in the Phlegraean area were primarily driven by variations in sea level.

Charles Babbage (1847) subsequently analysed the lithophaga borings on the columns to infer relative changes in both sea level and ground level, proposing that vertical movements of the land surface played a dominant role. Charles Lyell, in his Principles of Geology (1830-1833), cited the Serapeum as a paradigmatic example of slow and continuous geological processes, interpreting it as direct evidence of gradual crustal movements consistent with

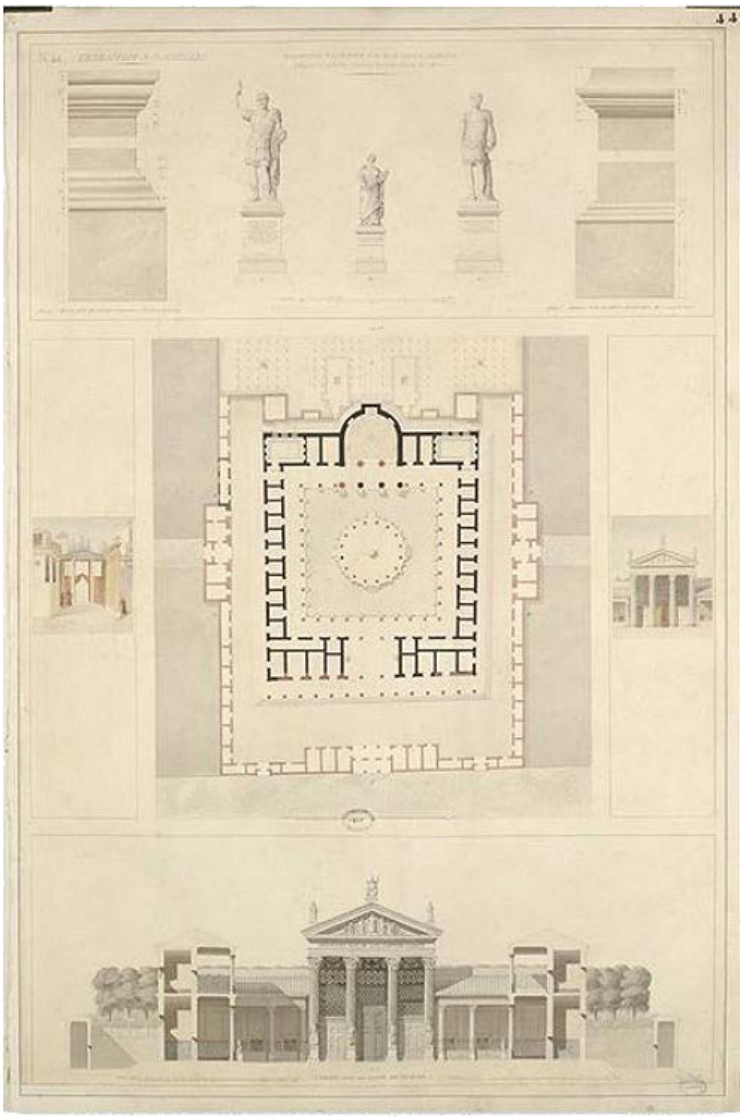

Figure 4. The reconstruction of the Serapeum made by Caristie (Academy of Fine Arts in Paris).

his uniformitarian framework. During his travels in Italy, Lyell collected measurements and eyewitness accounts documenting changes in the relative position of land and sea.

From the early nineteenth century onward, the progressive submergence of the floor of the Serapeum below sea level was repeatedly observed and measured. To describe this phenomenon, the term bradyseism was introduced, derived from the Greek bradýs ("slow") and seismós ("movement"). The term is generally attributed to Arturo Issel (1876), a geologist at the University of Genoa, who applied it to slow vertical movements of the Earth's crust in both Italian and international contexts. In the decades that followed, the Serapeum of Pozzuoli became the most frequently cited and emblematic case study illustrating bradyseism deformation.

In this paper, we do not attempt a detailed reconstruction of ground deformation across the entire Campi Flegrei caldera. Instead, we refer to the high-resolution deformation history proposed by Mattei et al. (2024), based on submarine geo-archaeological data from the Gulf of Pozzuoli, and compare it with archaeological evidence and historical chronicles preserved on land.

2. Historical and Archaeological Evidence of Bradyseism During the Roman Period

The earliest documented evidence of slow vertical ground deformation in the Pozzuoli area dates to the Roman period, when repeated maintenance and restoration works were required to counteract the progressive encroachment

of the sea along the coastal sectors of the city. These interventions implicitly record alternating phases of subsidence and uplift affecting the shoreline of the Campi Flegrei.

The earliest epigraphic reference to a Temple of Serapis, is an inscription dated to 105 before CE (CIL X, 1781), which mentions the construction of a building in proximity to the Aedes Serapis (Fig. 5).

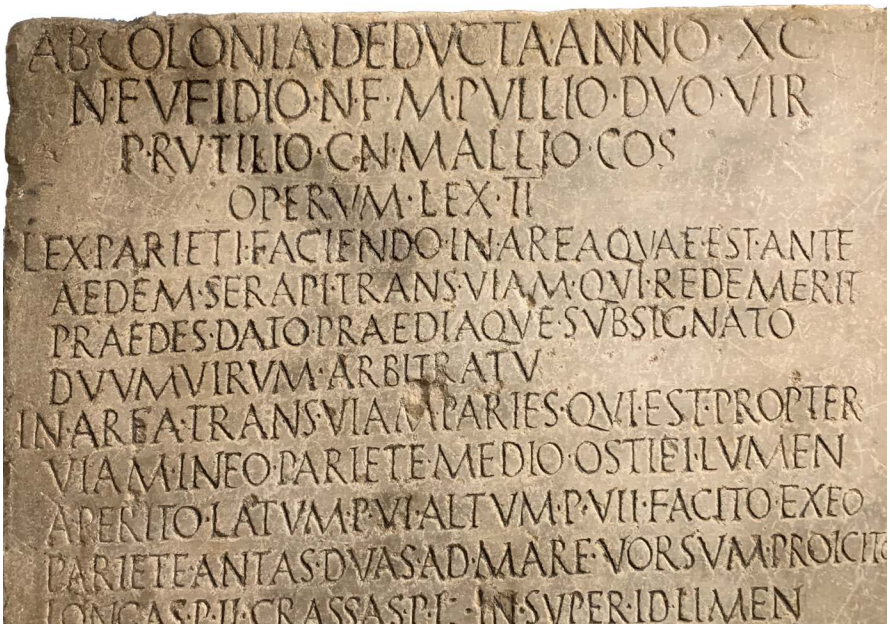

Figure 5. The epigraph of Lex Parieti faciendo found at Pozzuoli (Museo Archeologico Nazionale di Napoli).

Although the Macellum is generally dated to the Imperial period, recent archaeological studies have identified an earlier pavement when a phase of uplift occurred between the late Republican and Augustan periods (Amato and Gialanella, 2013). This interpretation is supported by geo-archaeological investigations documenting a phase of uplift in the central sector of the Gulf of Pozzuoli during the 1st century before CE (Marino et al., 2022; Mattei et al., 2024). The succession of pavements within the Serapeum complex is illustrated in Fig. 6

The first literary evidence for subsidence in the Phlegraean area appears in Strabo's Geography (late 1st century before CE), in a passage describing the coastal barrier separating the Lucrine Gulf from the open sea:

> "The Lucrine Gulf extends as far as Baiae; and it is shut off from the open sea by a mound eight stadia in length and broad as a wagon-road. But since it admitted the waves over its surface in times of storm, so that it could not easily be traversed on foot, Agrippa built it up higher."

This passage refers to the construction of Portus Iulius and the reinforcement of the Via Herculea, which ran along a low coastal bar. The military harbour was built in 37 before CE by Agrippa on behalf of Augustus during the civil war against Sextus Pompey. By CE 12, the naval base was transferred to Misenum, possibly due to harbour silting or progressive subsidence, while the same area subsequently developed as the commercial port of Puteoli.

The topographic reconstruction of ancient Puteoli, and of the harbour area in front of the Macellum, is informed by a diverse corpus of iconographic evidence ranging from Roman wall paintings to late-modern views, including antiquarian images. Among these, the so-called "Bellori drawing," published by Giovanni Pietro Bellori in 1673 based on an ancient fresco discovered on the Esquiline Hill, represents a key source for the depiction of the ancient harbour. Although highly stylised and partially indistinct, the image portrays a harbour city with moles, quays, and an insular feature on the left side of the scene, traditionally identified as the island of Calypso and absent from the modern coastal morphology. Transmitted through later copies and engravings, the drawing is generally accepted as a representation of the harbour of Puteoli, with public buildings and port structures labelled by ancient epigraphic captions, including the Porticus Neptuni and the Forum Olitorium (Dubois, 1907).

Comparable Roman pictorial representations of Campanian ports, such as the view of Pozzuoli from Stabiae (Gragnano Painting) preserved in Villa San Marco (Dubois, 1907), similarly emphasise rocky shorelines, moles, and

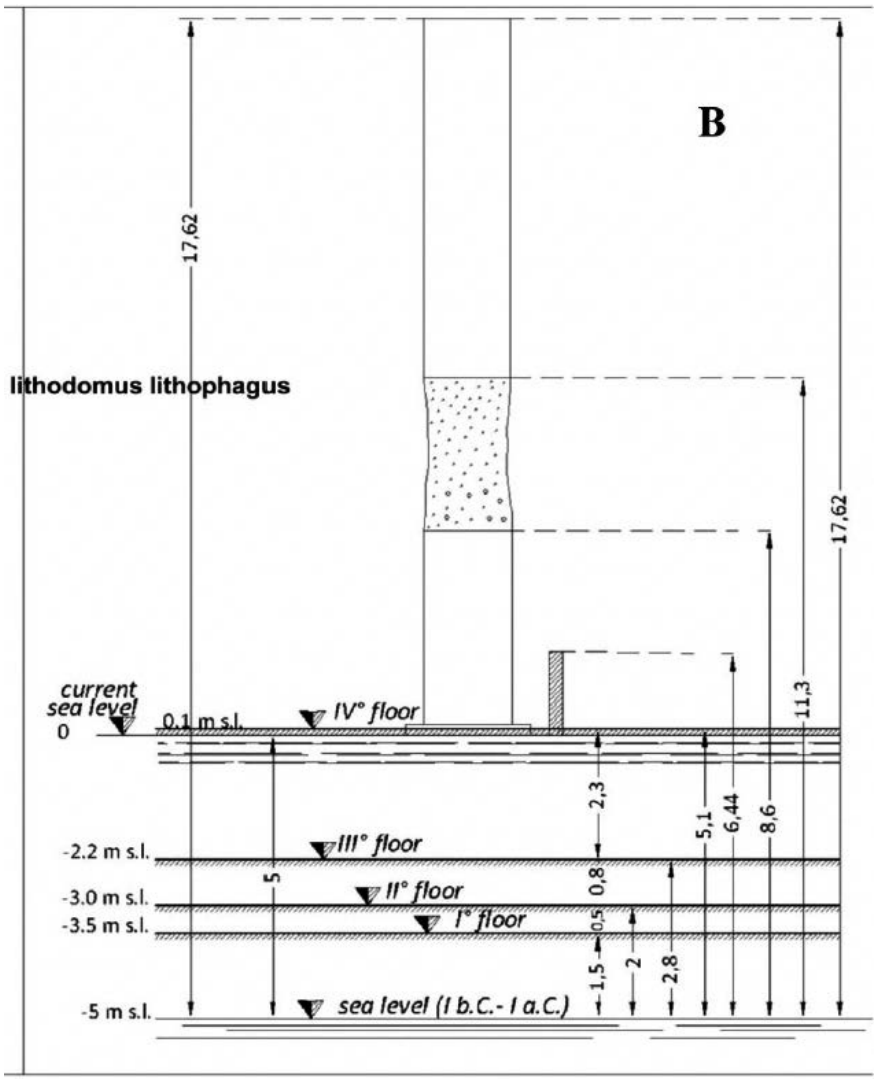

Figure 6. The succession of the floors of Serapeum and their height above sea level reconstructed by Amato and Gialanella (2013).

arched harbour structures, indicating that such coastal configurations were common motifs in Imperial-period painting.

The insular feature traditionally labelled as the island of Calypso may plausibly be identified with the area now known as the Secca delle Fumose (Gianfrotta, 2010, Mattei et al., 2024). This shallow offshore zone, located immediately in front of the ancient harbour of Puteoli, is characterised by persistent gas emissions and thermal activity, consistent with descriptions of boiling waters and difficult access found in both medieval textual sources and early visual representations. Rather than representing a stable natural island, the feature depicted in the Bellori drawing may correspond to an artificial thermal bath constructed on shallow seabed (Gianfrotta, 2010) and subject to changing exposure due to bradyseism movements and sea-level fluctuations. (Fig. 7).

Thermal Baths are mentioned by Pausanias (Description of Greece, 8.7.3):

"… and off Dicearchia, in the land of the Tyrrhenians, there is boiling water in the sea, and an island has been constructed artificially, that the water may be utilized for warm baths."

Also, Pliny the Elder (Plin., Natural History XXXI, 5) mention the thermal springs:

The baths of Baia are called Posidiane, a name taken from a freedman of Claudius Caesar, and they also cook food. They smoke in the sea itself, as do those of Licinius Crassus, and amid the waves there is something healthy for the health.

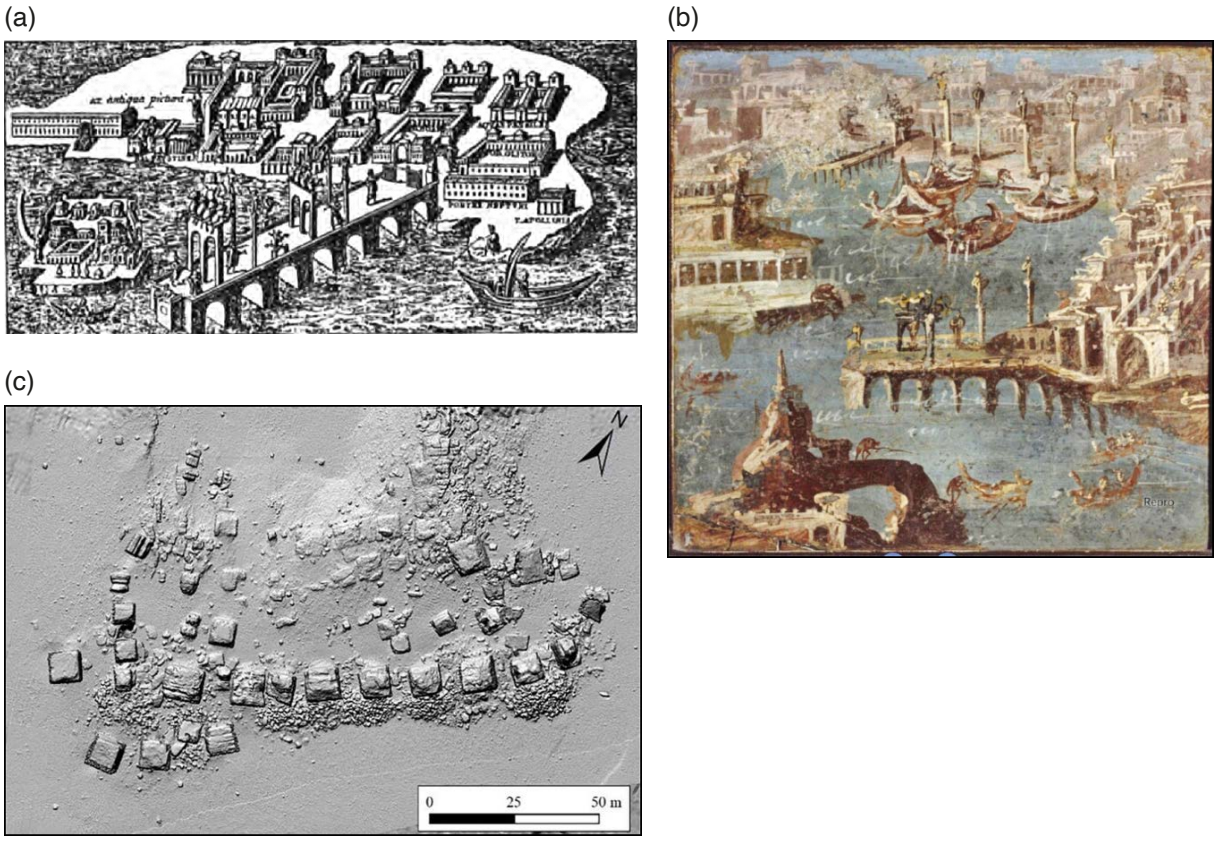

Figure 7. (a) The Bellori drawing showing the port of Puteoli with the small island on the left (Dubois, 1907); (b) the Villa San Marco fresco with the pier and an edifice to the left probably in the open sea (Museo Archeologico Nazionale di Napoli); (c) the image of the pillars of the thermal bath at Le Fumose (Gianardi et al., 2024).

Direct epigraphic evidence for engineering works intended to protect the harbour from marine incursions dates to the 2nd century CE An inscription of CE 139 (CIL X, 1640), found in the Pilae of the port pier, records restoration works ordered by Emperor Antoninus Pius:

Imp(erator) Caesar divi Hadriani fil(ius)... opus pilarum vi maris conlapsum... restituit.

The inscription commemorates the restoration of harbour piles destroyed by storm waves (vi maris conlapsum), fulfilling a promise made by Hadrian.

Later, three inscriptions dated to CE 394 (CIL X, 1690-1691; Camodeca, 1980), now preserved in the National Archaeological Museum of Naples, explicitly refer to the construction of protective barriers for the Macellum. Repairs were carried out on the ripa on both sides of the building, and the structure was shielded from storm surges by the construction of sea walls (iactis molibus propter incursione ingruentium procellarum) (Fig. 8).

These interventions mark the onset of a phase of progressive submergence of the coastal area.

Slightly earlier, in CE 324, the restoration of the Augustan aqueduct of the Serino (longa incuria et vetustate corruptum) was ordered by Constantine, with Puteoli listed first among the cities served by the system (Camodeca, 1980). Progressive subsidence in the Phlegraean area may have affected the hydraulic gradient of the aqueduct, which crossed Pozzuoli before supplying the naval base at Misenum.

To the 3rd-4th centuries CE, belong several engraved glass ampullae depicting the harbour of Pozzuoli, discovered at various European sites (Gianfrotta, 2022) (Fig. 9). Of particular importance is a 4th-century ampulla from a burial in Mérida (Spain) showing the harbour façade with the Macellum prominently standing beside the port (Bejarano Osorio, 2005).

The pier resembles that depicted in the Bellori drawing and in the Gragnano painting, with four Tritons and two tall columns. These images constitute the only surviving Roman-period representations of the Macellum and indicate that the building remained fully functional after the construction of the containment walls. The wide distribution of these ampullae all over Europe, and the contemporary archaeological remains attests to the continued importance of the port of Puteoli during Late Antiquity (Camodeca, 1980; Gianfrotta, 2022).

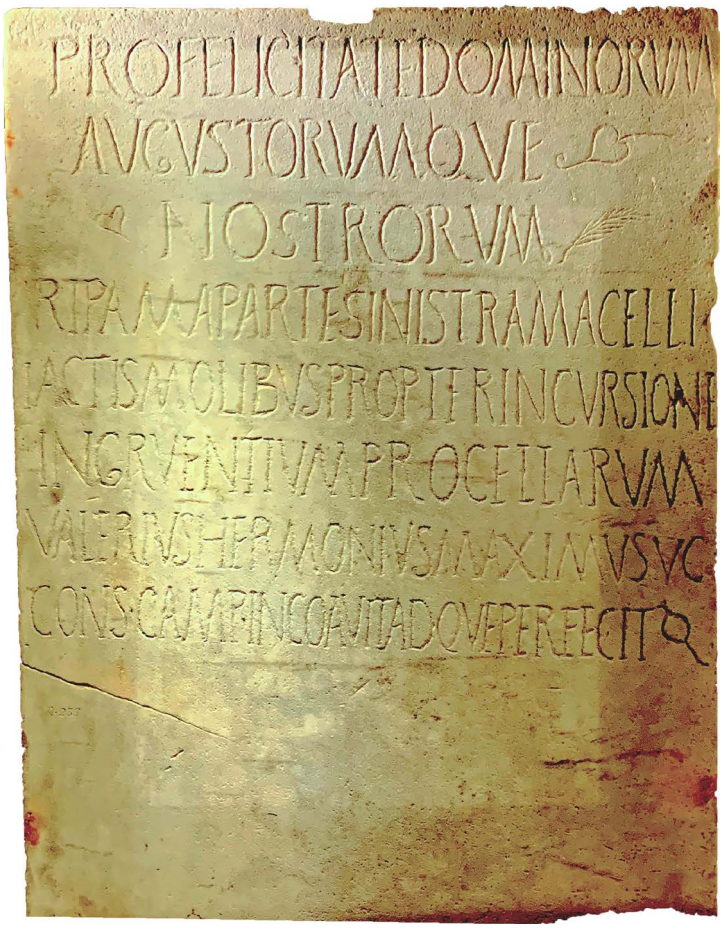

Figure 8. The epigraph documenting the construction of a barrier the prevent the ingression of sea water into the Macellum (Museo Archeologico Nazionale, Napoli).

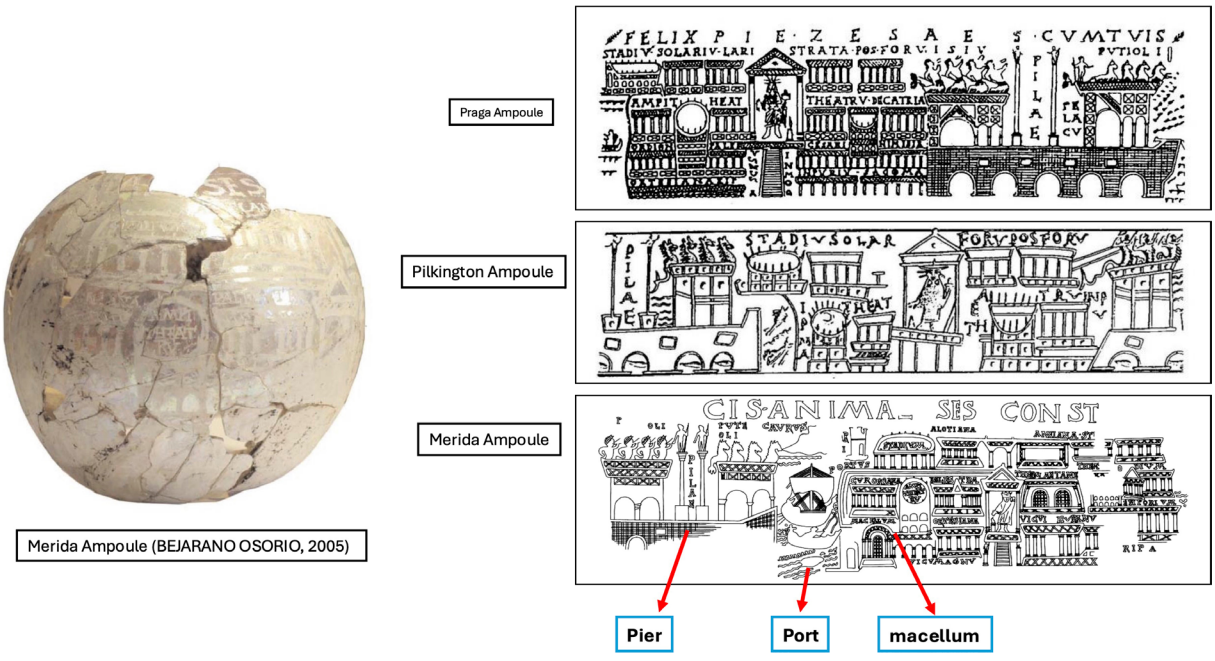

Figure 9. Different glass ampoules depicting the port of Pozzuoli, found all over Europe. The glass ampoule found at Merida (Bejarano Osorio, 2005) represents the harbour of Pozzuoli with several buildings and with the Macellum next to the port (Gianfrotta, 2022).

3. Historical Evidence of Bradyseism in the Late Middle Ages

Following the sack of Rome by Alaric in CE 410, information regarding Pozzuoli is lost, and only a few brief notes remain, drawn from manuscripts and chronicles relating to thermal and mineral springs. However geological studies offer a clue to the dynamics of Campi Flegrei. Marino et al. (2022) suggest a brief inflation episode between 600-700 CE based on the analysis of sedimentation in the gulf of Pozzuoli, confirming the study based on the dating of lithodomes of the Serapeum by Mohrange et al. (2006). Episodes of ground uplift are also suggested by Mattei et al. (2024).

A sudden acceleration of subsidence occurred after 700 CE. Frederiksen (1977) interprets a passage reported in the so-called Acta Apostolorum Apocrypha, concerning the arrival of Saint Paul in Italy, as evidence of subsidence at Pozzuoli:

> "They came to a place called Baiae; and they observed with their eyes, and they saw the city, that which is called Pozzuoli, submerged at the bottom of the sea to the depth of an arm's length. And there it remains, under the sea, as a monument up to this day. […] But those who had escaped from the city of Pozzuoli submerged by the sea, reported to Caesar in Rome that Pozzuoli had sunk with all its people."

This episode recorded in the Acta is thought to correspond to the description of the event found in an illustrated Calabrian manuscript dated to CE 890, which contains an image of a city beneath the waters and may therefore be dated to the time of the manuscript's composition (Frederiksen, 1977; Nocita, 2012). Similarly in the X century there is a complete abandon of the city of Pozzuoli, and its port has no relevance at all (Frederiksen, 1977).

The description found in the manuscript Sefer Yosefon, composed in the 10th century by a Jew from southern Italy, and similarly in the itinerary of a Jew from Spain, Benjamin of Tudela (12th century) (Toaff, 1965), which speaks of Pozzuoli (erroneously identified as Sorrento) as follows:

> "And from there to Pozzuoli, called Sorrento, the great city built by Sinsan Hadar'ezer who fled for fear of King David (may peace be upon him). Thereafter, the sea submerged two quarters of the city, and even to this day one can still see the markets and the towers half-buried. There a spring wells up from the abyss and brings forth oil, called petroleum, which is collected on the surface of the water and is used for medicinal purposes. There are also hot baths of water which issue from the ground, and these are located on the seashore."

This description corresponds well to Pozzuoli, then submerged by the sea along its shoreline, and to its thermal-mineral springs, among which one was called Oleo Petroleo, (Fig. 10) and another completely submerged by the sea (Cantarellum).

The thermal-mineral springs are extensively discussed in the work of Pietro da Eboli (1150-1220), author of the treatise De Balneis Puteolanis (or De Balneis Terrae Laboris), which describes 35 oligo-mineral springs in the Campi Flegrei, known since Roman times and widely used for thermal treatments during much of the Middle Ages (Giacomelli and Scandone, 2011; D'Amato, 2014). The Balneum Cantarellum is depicted in the oldest editions of the work (Angelica codex) as a circular container (cantarellum, in latin) in the middle of the sea. The location of the spring is traditionally placed within the Macellum.

The text accompanying the illustration is:

> Inter aquas pelagi fervens aqua manat et ipsam,
> ne fluat in pontum, fictile claudit opus.
> Cum mare fervescit, locus oppugnatur ab undis:
> vix aliquis poterit aeger adire locum.
> Cantarellum humana fruitur virtute medendi.
>
> Among the waters of the sea, a boiling spring flows forth;
> lest it pour into the open sea, a structure of baked clay confines it.
> When the sea is agitated, the place is assaulted by the waves,
> and scarcely can anyone, even when healthy, reach it.
> The Cantarellum possesses a healing power beneficial to humankind.

This description raises some doubt about the true location of the Cantarellum spring.

1) The current temperature of the spring in the Macellum, probably not much changed since middle age, is approximately 18 °C, certainly not boiling (fervens).

2) Even in the period of maximum sinking of Macellum, it cannot be defined as in the middle of the sea (Inter aquas pelagi) and difficult to reach during stormy sea.
3) There is no trace of a structure of baked clay containing the waters (Cantarellum from the Greek Kantaros-container).

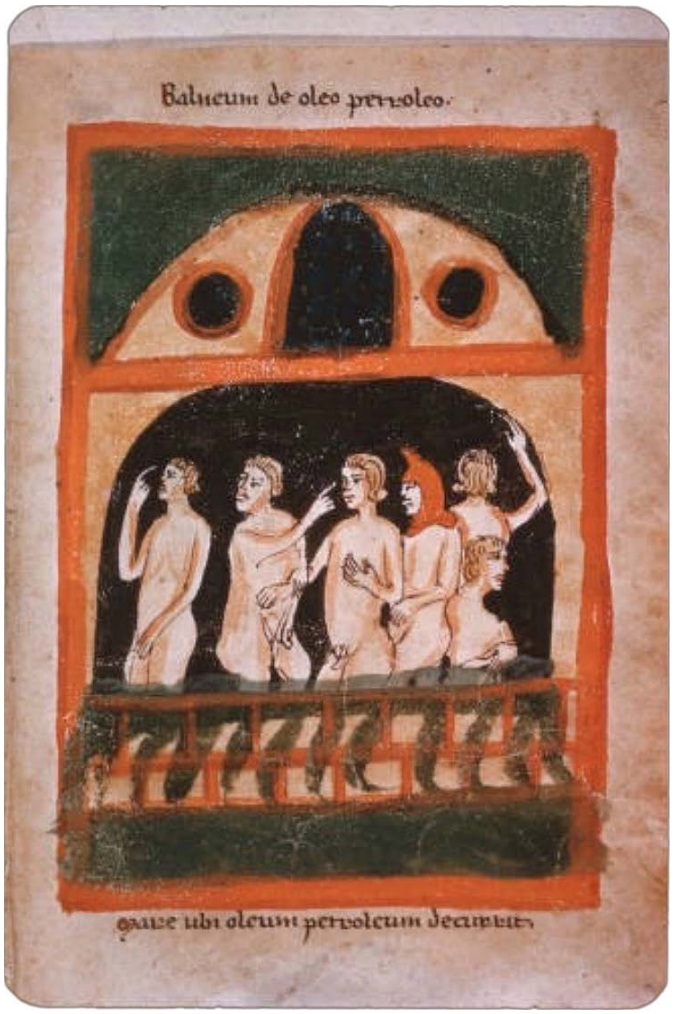

Figure 10. A representation of the bath Oleo Petroleo in the De Balneis Puteolanis (Vatican codex).

A possible different location could be the Fumosa bank, with a spring temperature of 60°C, which during middle age could have been only partially submerged. The early edition of the De Balneis Puteolanis show an island in the middle of the sea which could be reached only by boat (Fig. 11).

The Fumosa shoal was well known to the fishermen of Pozzuoli for its abundant fish stocks and was leased using the "candle method," whereby bids could be submitted until a candle had burned down.

It is only the later tradition that locates the Cantarellum in the proximity of the Macellum like the 15th-century Edinburgh Codex, showing two columns partially submerged by the sea, with the Rione Terra of Pozzuoli, Misenum, and the coastline of the Gulf of Pozzuoli in the background (Kauffmann, 1959; D'Amato, 2014).

Similarly, reference to Cantarellum is found in the edict of Queen Joanna II of 1429 (Diplomi Regi 73, 1429), granting land in Pozzuoli to the Hospital of the Annunziata:

> Original diploma of Queen Joanna II, issued at Castel Capuano on 20 April 1429, by which she grants to the Hospital of the Annunziata a demesne territory in Pozzuoli, beginning from the Bath Cantarellum to the wells, and from the public road to the sea, to make a garden and plant fruit trees and domestic herbs (Comune di Napoli).

The geographical reference suggests that the so-called Bath Cantarellum was at least partially emergent, and that from this land there later originated the area called the Vigna delle Tre Colonne.

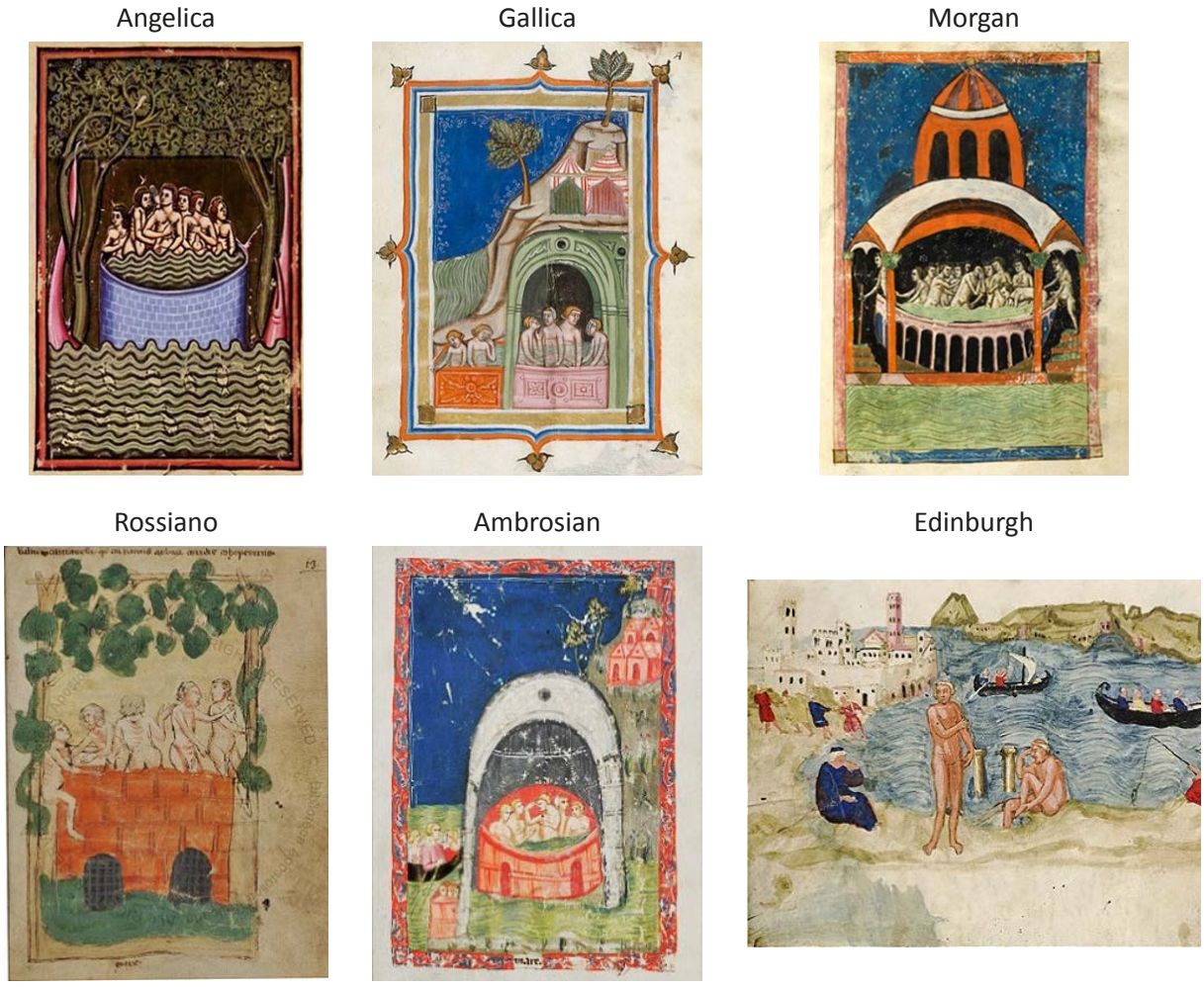

Figure 11. Different representations of the Balneum Cantarellum. All, but the Edinburgh codex show a container (Cantarellum) in the middle of the sea. On the top of each picture is shown the original codex. The codex Edinburgh, middle XV century shows two columns emerging from the sea and the Pozzuoli landscape.

We suggest the possibility that the Cantarellum, represented in the older edition of the De Balnea Puteolana, was the old thermal complex of the Fumose bank, still partially emerging from the sea and the different identification occurred in the XV century when the Macellum and its associated spring started to emerge.

A more definitive uplift is dated to 1503, with an edict of 6 October 1503:

> "The Catholic King and Queen (Ferdinand and Isabella) had ceded to the Municipality of Pozzuoli the demesne of that Municipality, which demesne is that which the sea is drying up within the land."

Subsequently, King Ferdinand issued a new edict on 23 May 1511, granting to the city of Pozzuoli the territories created by the advance of the coastline (quoddam demaniale territorium mare dessiccatum circum circa prefatam civitatem Puteolarum) as compensation for the damages caused by earthquakes:

> "Since the Municipality itself, on account of earthquakes, from which each year it is accustomed to suffer the greatest inconvenience and loss, as well as considerable ruin of houses…" (Parascandola, 1947; Guidoboni and Ciucarelli, 2011; Scandone and Giacomelli, 2013).

In 1511 was built the church of Santa Maria Gratiarum in the dried land created by the advance of the coastline near the ancient pier, shown in Fig. 1.

The reversal of bradyseism marks a prolonged phase of precursor phenomena leading up to the 1538 eruption of Monte Nuovo (Di Vito et al., 2016), and with this event a new uplift of the coastline occurred, recorded in contemporary images of the eruption in the pamphlet by Marco Antonio Delli Falconi (1538). The contemporary

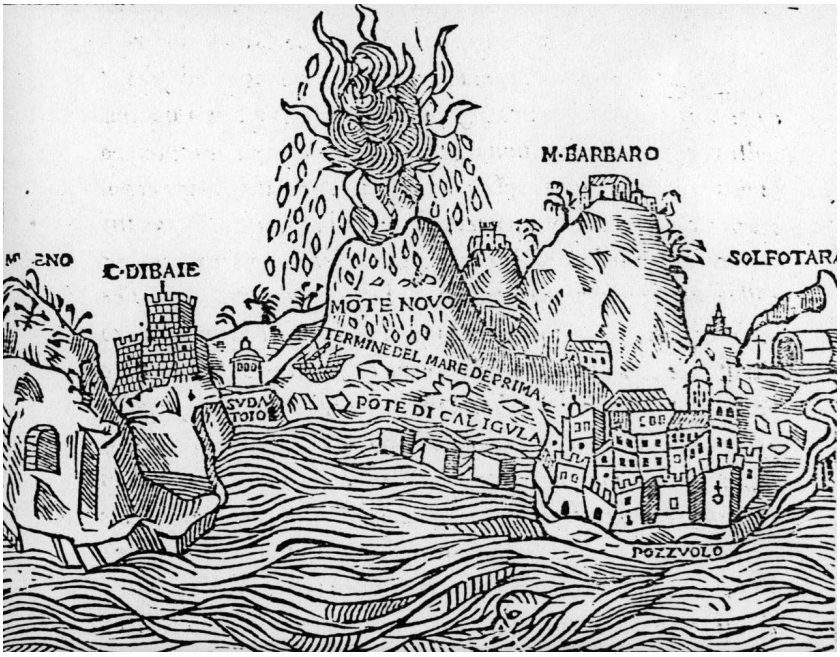

Figure 12. The image of the eruption of 1538 with indication of the previous sea level (termine del mare di prima), (Delli Falconi 1538).

image of the eruption (Fig. 12) shows the earlier more landward coastal line. It is also important to emphasise that a witness of the eruption makes explicit reference to the Secca delle Fumose which appear to have raised above sea level:

> *"And at about one or two hours into the night, a fiery vent opened near the said Hospital, in the place called la Fumosa, from within the sea, and it hurled a great quantity of pumice stones and ash; loud thunder and flashes of lightning were heard, and instead of water, ash fell like rain. This fiery vent opened so close that it approached the Castle and the Hospital of Tripergole."* (Scandone and Giacomelli, 2013).

The limit of the land and the port before the eruption is also evidenced in the map of Mario Cartaro of 1584 (Fig. 13)

A synthesis of ground movements preceding the 1538 eruption, based on observations of prominent coastal points and altimetric benchmarks, is found in Di Vito et al. (2016), while a detailed description of geodetic measurements made between 1900 and 2006 is given by Del Gaudio et al. (2010).

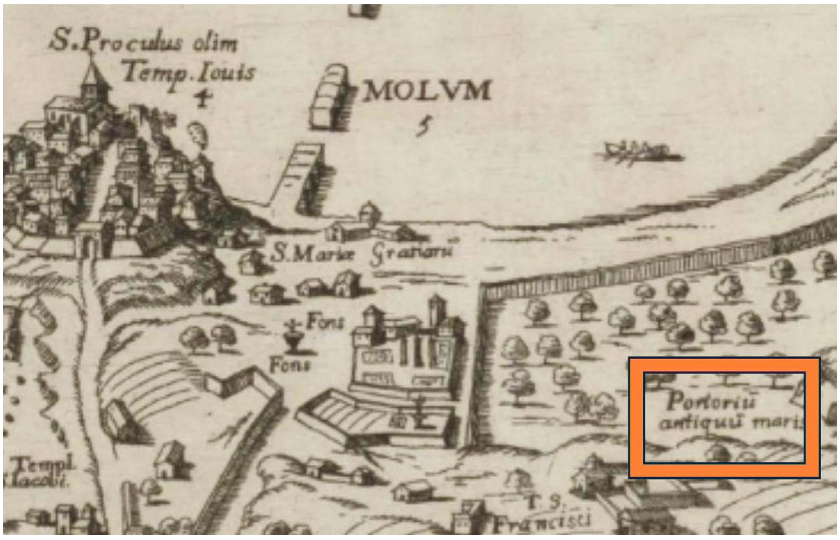

Figure 13. The map of Mario Cartaro of 1584 shows the limits of the land before the eruption of 1538 (Portoriu antiqui maris).

4. Discussion

Figure 14 illustrates the curve of ground movements for 2500 years ago after Mattei et al. (2024). For comparative purposes, the curve has been specular rotated to allow direct comparison with ground-movement reconstructions proposed by other authors. The reconstruction by Mattei et al. (2024) shows a strong agreement with archaeological evidence and historical chronicles, providing a coherent framework for interpreting the long-term vertical movements affecting the coastal area of Puteoli.

The data indicate that the construction of the military ports took place during a phase of relative subsidence. In this context, the new harbour barrier built under Agrippa would have offered effective protection against marine incursions during storm events. A subsequent phase of uplift likely favoured the construction of the Macellum and the major urban expansion of the coastal zone. This uplift was followed by a renewed subsidence phase, which necessitated the repair works on the harbour ordered under Antoninus Pius. The urban expansion was also probably connected with the arrival of refugees from Pompeii after the eruption of 79 CE (Tuck, 2025). The onset of the decline of the port area appears to coincide with the restoration works at the Macellum in 394 CE marking the beginning of the progressive submergence of the coastal sector.

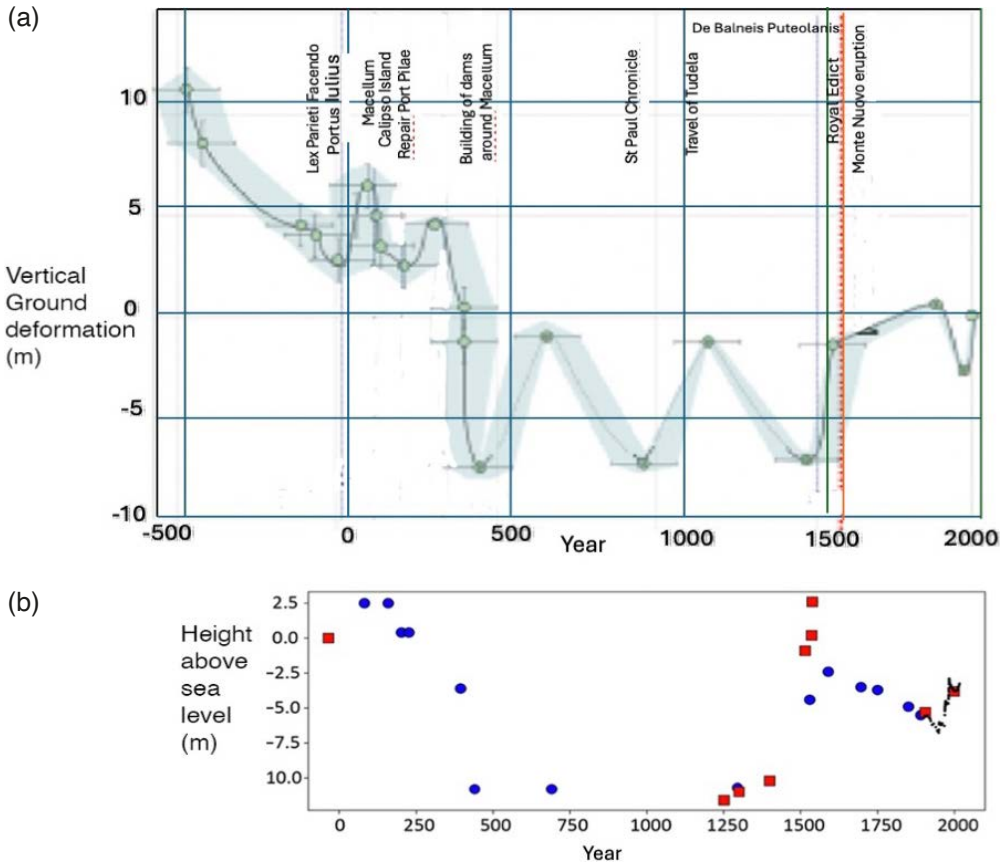

Figure 14. The curve of ground movement (a) proposed by Mattei et al. (2024). We added the main archaeological information from this work); (b) Trasatti (2022).

Compared with other reconstructions of ground movements, such as that proposed by Trasatti (2022), which integrates data from multiple sources, the curve of Mattei et al. (2024) offers a higher temporal resolution. Notably, it identifies several previously undocumented uplift episodes that were not followed by volcanic eruptions, and accounts for the phase of submergence during the Middle Ages. However, there is an apparent uplift lasting from 1538 to the excavation of Serapeum in 1750. Instead, we do know that the subsidence began already in the 1600, when the Convent of Cappuccini on the coast of Pozzuoli was progressively surrounded by the sea. In this respect the curve of Trasatti (2022) appears more reliable. This observation has important implications and calls for a reassessment of volcanic hazard conditions in the Campi Flegrei area.

The uplift that preceded and accompanied the Monte Nuovo eruption raised landward buildings above the previous sea level. However, this uplift did not affect the still-submerged sectors of Portus Iulius in the same manner (Fig. 15).

Structures built contemporaneously – such as the Macellum, the pilae of Portus Iulius, and the thermal installations at the Secca delle Fumose – are today found at markedly different elevations relative to their original construction levels. While coastal buildings remain close to their initial elevation, seaward structures lie at significantly lower heights. This pattern is best explained by differential ground movement affecting the central block of the Campi Flegrei caldera, which experienced tilting and uplift of its northern sector (Scandone and Giacomelli, 2024).

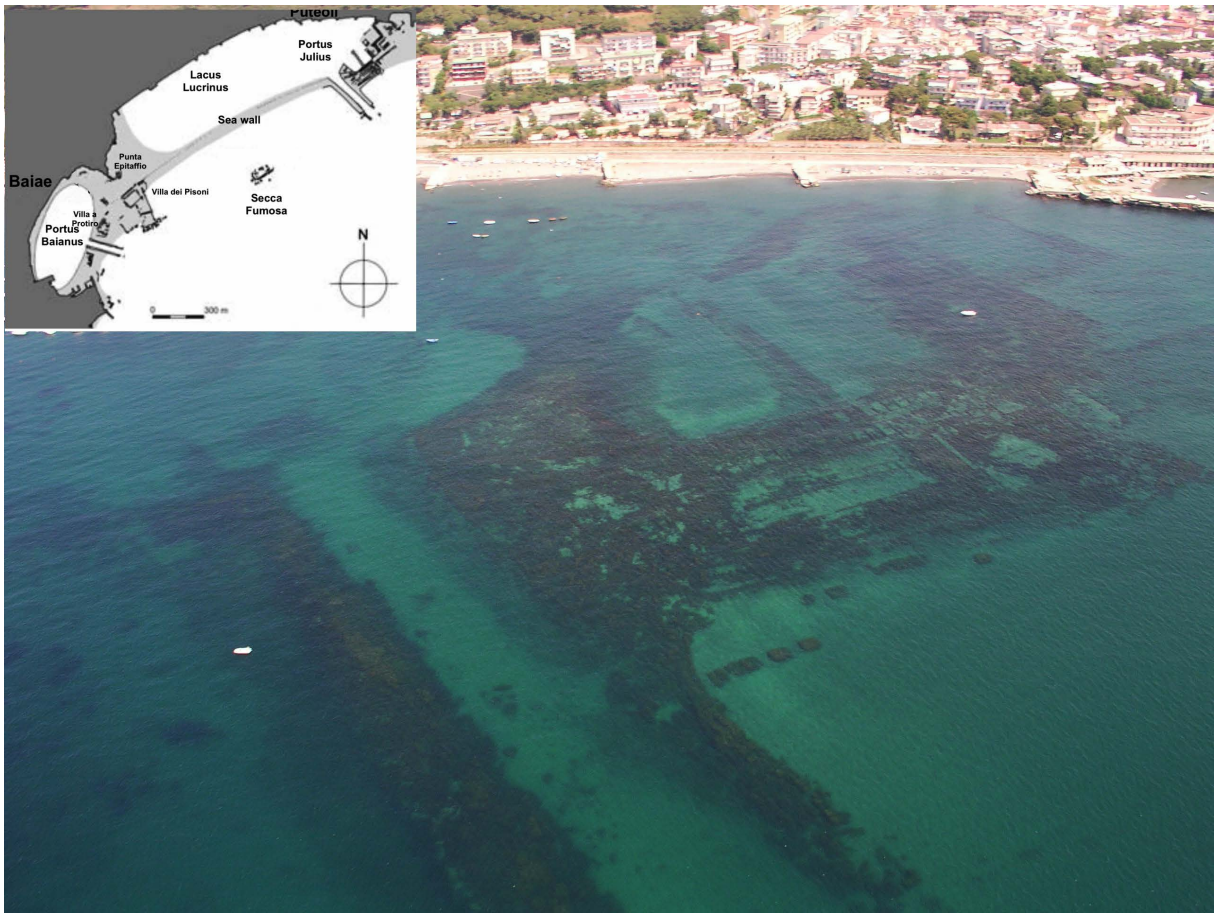

Figure 15. The submerged entrance channel to Portus Iulius. In the inset the map of the roman port (photograph of the authors).

5. Conclusions

Observations of ground movements in the Campi Flegrei provide a unique record spanning more than 2,500 years, unparalleled in any other volcanic system. This exceptional dataset is made possible by the continuous human occupation of the area and by the presence of long-lived coastal settlements repeatedly affected by alternating phases of submergence and emergence driven by vertical ground displacements. The long-term history of the Campi Flegrei demonstrates that volcanic systems may undergo prolonged cycles of relative quiescence punctuated by phases of intensified activity, characterised by rapid uplift and increased seismicity. Such phases can exert profound impacts on human settlements and land use, yet they do not necessarily constitute unambiguous precursors to eruptive activity.

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