Review of Rolandi et al., The 1538 eruption at Campi Flegrei resurgent caldera: implications for future unrest and eruptive scenarios.

Summary

The revised version of the manuscript naturally divides into two parts. One part successfully highlights the meticulous reconstruction of ground movement and seismicity before Campi Flegrei's only historical eruption. The results provide an important new reference for constraining interpretations of the volcano's current unrest and deserve to be published after modest changes to the English.

The other part is more speculative and draws conclusions beyond those possible from the new reconstructions. I recommend that this part is severely edited to avoid distracting from the merits of the new data; it can then be recast as offering interpretations to be tested, rather than affirmations. As in its earlier version, the text keeps slipping into a negative approach by insisting that the ideas of others are wrong. This is not objective. A positive approach can be achieved by focussing on the merits of the authors' new reconstruction, regardless of the alternatives. I have made copious comments on the manuscript, mainly to illustrate how subediting might enhance the flow of the text. The streamlined version should be ready for publication.

Specific Comments

Please see the annotated manuscript for additional recommendations on editing the text.

Section 2. Caldera formation.

This section on the history of Campi Flegrei is more detailed than necessary. The information is fine, but doesn't follow naturally from the introduction. The main point seems to argue that prehistoric ground movements are consistent with the displacement of a central block – which is later used to interpret historic unrest. If that is correct, I would shorten this section and start around Line 78 with something like "Ground movement since caldera collapse is consistent with the centre of the caldera behaving as a single block (REFS)". The description of magma chemistry isn't obviously relevant here.

Section 3. Reconstructing ground movement before the eruption in 1538.

Lines 142-154. What type of new evidence did later studies use to modify Parascandola's 1947 reconstruction (e.g., information from additional contemporary accounts). Specific details do not need to be described: citations to papers will suffice. The authors could then note that (1) the later reconstructions were still based on partial data sets and (2) the new work uses a more comprehensive data set (and so provides a test of previous interpretations). Stating this here will simplify the later discussion of Fig. 13 and avoid repetition when comparing new and old reconstructions.

Lines 169-177. These repeat previous text. I'd consider omitting this paragraph and starting at Line 178.

Lines 491-492 (Figure 13). Fig. 13 shows only three of the five reconstructions mentioned in the text. To highlight how the new work clarifies previous ambiguities, please add the reconstructions by Dvorak & Mastrolorenzo (1991) and Bellucci et al. (2006).

Section 4*. Schematic model for the preparatory phases of the 1538 eruption.
[*Check formatting. The numbering of sections has been set back to "2".]

Lines 504-594. This section makes the case for movement along faults to be a major influence on observed patterns of ground deformation (as had previously been proposed by some of the authors). However, it loses focus by intermittently mentioning that alternative models are wrong. The assertion has not been justified. It would require a full account of the alternative models and their assumptions. I would simplify the section by concentrating on the evidence for block movement. The commentary on alternative interpretations can be omitted. This would make the text easier to follow and also allow the authors to highlight that their reconstruction demonstrates that fault-bounded movement is a realistic interpretation.

Lines 545-548. These lines can be omitted. The authors can support their interpretation, but they have NOT shown alternative views to be incorrect. That needs a separate paper in its own right. I would simply concentrate on the authors' reconstruction and their description of (and terminology for) the stratigraphy. The discussion of terms is a distraction about terminology, in that deformation models are distinguished by the values of physical properties used, such as elastic modulus, and not by their qualitative description. Moreover, the later assertions that the lithoid tuff is heavily fractured calls into question the relevance of the distinction being made here.

Lines 561-574. Try omitting these lines. I don't see they add anything new to what has previously been written. The previous and following paragraphs would then be linked through the references to Battaglia et al. (2008).

Lines 589-591. References to mush are out of place here. The rest of the section describes observations. No mush has been observed and its presence is speculative. I would omit these lines and leave speculations about mush to the final discussion.

Section 5.2. The preparatory phases of the 1538 eruption.
This section would be better placed after the reconstruction of pre-eruptive seismicity and will be discussed later.

Section 5.3. The eruption of Monte Nuovo.
It's not clear why this section has been included. I can't help feeling it belongs in another paper. The account of the eruption is interesting but, as far as I can tell, does not add to the information already available in the published literature. Unless the authors have a pressing need to keep the account, I would consider removing it, so that this paper can focus on the novelty of the new reconstructions before the eruption.

Section 6 (?) The seismicity before and after the 1538 eruption
(Please check numbering of sections; it appears as "3" at the moment)
This section nicely compares the seismicity in the century before the 1538 eruption with events recorded during the current unrest. Transforming the size of historic events from intensities to magnitudes is a neat way to compare with modern methods for characterising the size of an earthquake.

The classification into long-, medium- and short-term sequences is instructive and relevant to understanding current unrest. However, I would reorganise the text so that the characteristics of each sequence is presented before offering an overall interpretation. Thus, I would group together Lines 827-830, 835-844 and 861-865 and integrate them into the final discussion after Section 6.2.

Section 6.2. The post-eruption seismicity.
Lines 869-872 can be omitted. Start with something like "Post-eruption seismicity was recorded in…". I suggest combining this as a final paragraph to the previous section, rather than keeping it as a standalone section.

Sections 7 and 5.2
[I'm assuming Section 7 starts on Line 880]
These sections repeat themselves and could easily be combined into an interpretation of events preceding the 1538 eruption. For example, Lines 885-901 could be followed by text connecting the reconstructed ground uplift and seismicity before 1538 to a following summary of Lines 827-830, 835-844 and 861-86. This will identify water, gas and magma as favoured sources of overpressure at depth. The role of gas and water can summarised by combining Lines 622-626 and 637-646 (from Section 5.2); the role of magma can the be described succinctly in terms of ascent from a main reservoir to form shallow intrusions. The descriptions can then lead to the two scenarios (Sections 7.1 and 7.2).

The interpretations in Lines 589-621 and 626-677 are speculative at the level of detail presented. They may very well be reasonable, but the supporting evidence is superficial and so the arguments lack conviction (especially when compared with the painstaking reconstruction of behaviour before 1538): in particular, the insistence that small shallow sills can consist of magmatic mush after more than a few years is not fully justified. For example, sills intruded at depths of c. 3 km are shallow enough for their mean thicknesses to be similar to the amounts of surface uplift they produce – namely a few metres. Even under the conditions of slowest cooling by conduction, such bodies are expected to have solidified completely within years (remember the magma has only to cool below its solidus to be completely solid). For such conditions, the assumption that magma remains as mush that can be remobilised is not very strong. I thus strongly recommend the authors reduce this text by about 50-70% - or even remove it altogether. Just as for the description of the 1538 eruption, it feels as though it belongs to a separate paper.

Incidentally, in Lines 700-705, the notion of repeated intrusions of small bodies, rather than the growth of a single shallow source has been applied by several authors to the unrest since 1950

(Woo & Kilburn, (2010) and other references): applying it also to before 1538 shows how comparisons between 1430-1538 and 1950-Present may be valuable in both directions, and not only from 1430-1538 to 1950-Present.

Sections 7.1 & 7.2. Scenarios
Lines 913-920. See comments above about “mush”.

Lines 928-951. None of this text follows from the results of the current study. The arguments are generic and really need to be developed further to be convincing. They are not essential to justifying the importance of the new reconstructions. Omitting them would produce a better focussed paper.

Lines 961-967. The description of the results in Kilburn et al. (2023) is misleading. As it happens, significant seismicity resumed at Campi Flegrei in 2017 as had been expected. There is no basis for the statement in Line 967 that “the system would already have collapsed”. I suggest removing the whole comment.

Lines 968-973. The logic of the argument and its implicit assumptions need to be more clearly articulated. For instance, the authors are assuming that the crust was equally relaxed in 1430 and 1950. Maybe it was; maybe it wasn’t. The assumption, though, must be made explicit. I also don’t follow the logic that “conditions [are] too gradual to culminate in an actual eruption” (Line 971). Supporting evidence is essential here given that the statement is used to suggest that unrest may continue for another century or more. [Have the authors anticipated the notion of viscoelastic behaviour, which only appears in the conclusions?]

Conclusions
[Please check numbering of section headings]
Lines 997-1012. The text contains additional information about the scenarios. This should be moved to the earlier sections which introduce the scenarios. Viscoelastic behaviour has not previously been mentioned and ought not to appear for the first time in the conclusions. The conclusions could thus be shortened to Lines 979-996, followed by Lines 1016-1018, adding to the list (1) that the outcome of the current unrest is uncertain and two scenarios can be identified, and (2) that, in the case of an eruption, post eruptive seismicity may continue to present a significant hazard (from Section 6.2).

A

The 1538 eruption at Campi Flegrei resurgent caldera: implications for future unrest and eruptive scenarios

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Abstract

The recent unrest in the Campi Flegrei caldera which began several decades ago, poses a high risk to a densely populated area, due to significant uplift, very shallow earthquakes of intermediate magnitude and the potential for an eruption. Given the high population density, it is crucial, especially for civil defense purposes, to consider realistic scenarios for the evolution of these phenomena, particularly seismicity and potential eruptions. The eruption of 1538, the only historical eruption in the area, provides a valuable basis for understanding how unrest episodes in this caldera may evolve toward an eruption. In this paper, we provide a new historical reconstruction of the precursory phenomena of the 1538 eruption, analyzed considering recent volcanological observations and results obtained in the last few decades. This allows us to build a coherent picture of the mechanism and possible evolution of the present unrest, including expected seismicity, ground uplift and eruptions. Our work identifies two main alternative scenarios, providing a robust guideline for civil protection measures, and facilitating the development of effective emergency plans in this highly risky area.

NOT CHECKED! Rewrite after revisions.

1. Introduction

The Campi Flegrei area has been a benchmark of modern geology and volcanology since the middle XVIII century, due to the clear evidence of significant ground movements, associated with both uplift and subsidence, imprinted on the columns of the ancient Roman Market (Macellum; hereafter also called ~~Serapeum or Serapis Temple~~) in the town of Pozzuoli. These movements were famously depicted on the cover of Charles Lyell's ~~seminal book~~, 'Principles of Geology'. By the XIX century,

I'd choose just ONE term — or even use "Serapeo" today. Don't switch between different names.

it became evident that the impressive relative movements between sea level and ground were due to ground uplift and subsidence. Consequently, numerous efforts have been made to reconstruct the timeline of these movements, during the centuries. One of the most convincing reconstructions was proposed by Parascandola (1947), later modified by Dvorak and Mastrolorenzo (1991), Morhange et al. (2006), Bellucci et al. (2006) and, more recently, Di Vito et al. (2016). However, all these reconstructions exhibit evident discrepancies, and do not rely on the full body of historical evidence, as we will demonstrate. These significant ground movements have predominantly involved a long-term trend of subsidence, punctuated by occasional episodes of rapid ground uplift, culminating in the only eruption occurred in historical times, in 1538 (Di Vito et al., 2016). After the 1538 eruption, a new period of subsidence began, which was interrupted in 1950, when a new series of uplift episodes commenced (Del Gaudio et al., 2010). Two major uplift episodes occurred between 1969-1972 and 1982-1984, characterized by significant and rapid uplift (with a cumulative uplift of about 3.5 m) accompanied by intense seismicity. These events led to the evacuation of 3000 residents from the oldest part of Pozzuoli town (Rione Terra), in 1970, and the entire town of Pozzuoli comprising 40.000 people, in 1984 (Barberi et al., 1984). After approximately 20 years of subsidence, a new uplift phase began in 2005-2006, with a much lower uplift rate (less than 0.01 meters per month on average, compared to about 0.06 meters per month in the 1970s and 1980s), but long lasting and still ongoing. This new unrest has been accompanied by progressively increasing seismicity, which has substantially intensified, both in frequency and maximum magnitude (Troise et al., 2019; Iervolino et al., 2024). The maximum magnitude reached M=4.4 on May 20, 2024, once the maximum ground level attained at the end of 1984 was reached (in July 2022) and surpassed. The progressively increasing seismicity confirms the predictions of Kilburn et al. (2017) and Troise et al. (2019), who based their forecast on the correspondence of the ground level with stress levels at depth. This seismic activity represents a significant and continuous hazard for the edifices in such a densely populated area, given the very shallow depth of the earthquakes (about 2-3 km). Furthermore, the current crisis poses an even higher threat as it could potentially be a precursor to a future eruption in the area.

The present study is aimed to reconstruct and interpret the events before and after the 1538 eruption. This analysis follows three main paths: i) the accurate reconstruction, of the ground movements in this area since early historical times, using historical testimonies and documentation; ii) the accurate reconstruction of the uplift movements that evolved from 1430 to 1538, accompanied and followed by significant seismic events; iii) the analysis of stratigraphic and geophysical parameters, which, although collected in the recent era, provide important elements for the reconstruction and interpretation of the unrest related to the 1538 eruption.

Please adjust – either specify largest magnitude until (say) the end of 2024 – or change to 4.6 in March 2025.

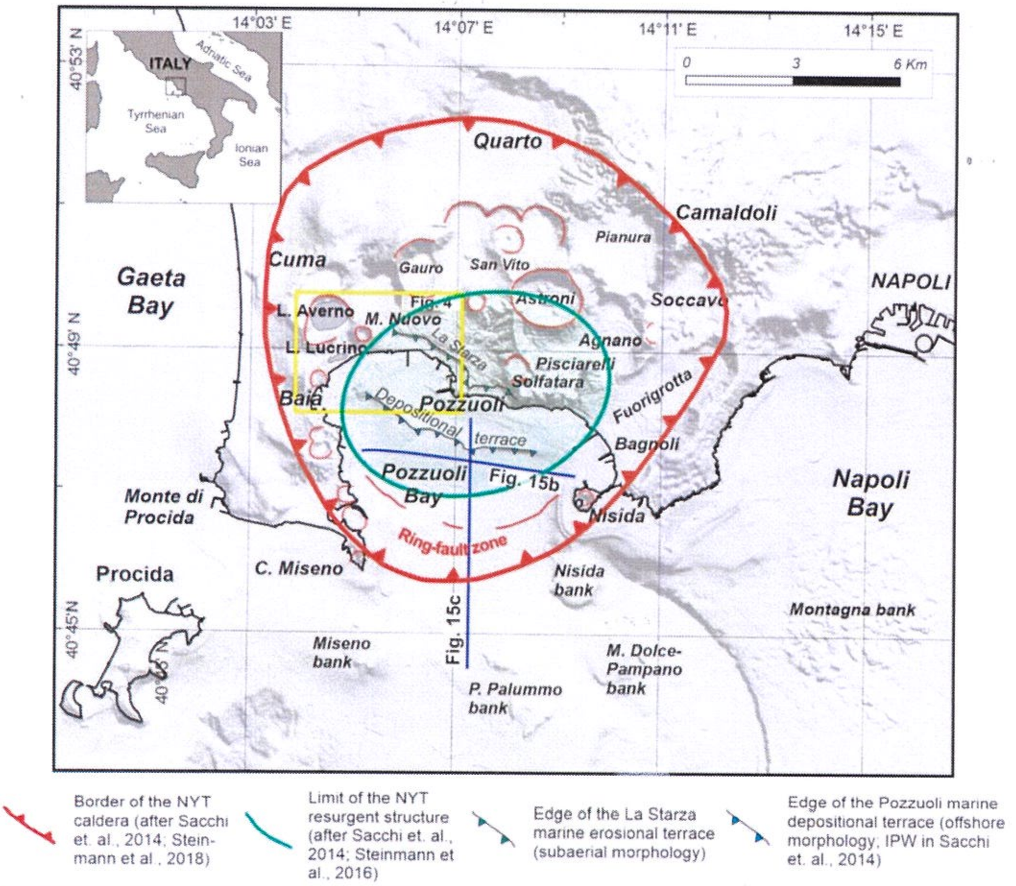
Is this truly necessary? See later.

Finally, the interpretation of the events preceding, accompanying and following the 1538 eruption is used to provide insight into possible evolution scenarios for the present unrest~~, which started in 1950 and is still in progress~~ (Troise et al., 2019; Scarpa et al., 2022)

2. Caldera formation and post-caldera volcanic activity 14 ka - 3.7 ka

Campi Flegrei is an active caldera to the west of Naples in southern Italy. About 12-14 km across, its southern third is submerged beneath the Bay of Pozzuoli. Following the most recent, and likely only (Rolandi et al., 2020a; 2020b; De Natale et al., 2016), episode of caldera formation, i.e. the Neapolitan Yellow Tuff eruption 15 ka, some 70 eruptions (linked to 35 visible vents) have occurred across the caldera floor, ranging from the effusion of lava domes to explosive hydro-magmatic eruptions (Di Vito et al., 1999; Smith et al., 2011; Isaia et al., 2015). The most recent eruption occurred in 1538, producing the cone of Monte Nuovo (Di Vito et al., 1987; 2016). The caldera collapse resulted in many new fractures, which gradually became eruptive vents. Through these vents, the eruptions continued, exhibiting the characteristics of a volcanic field (Druitt and Sparks, 1984), resulting in the so-called post-caldera activity. Dome-shaped uplift of NYT occurred after the caldera formation in the central zone of Campi Flegrei, with uplift up to hundreds of meters on the caldera floor (Rolandi et al., 2020b). The significant uplift involved a large intra-calderic NYT block, making Campi Flegrei a typical example of resurgent caldera (Luongo et al., 1991; Orsi et al., 1996; 1999; Acocella (2010); Rolandi et al., 2020b). The post-caldera activity gave rise to numerous craters, predominantly tuff cones and tuff rings (Fig. 1a,b), displaying the typical characters of monogenic volcanoes (Marti et al., 2016). Within Campi Flegrei, 35 small eruptive centers have been identified, since the NYT eruption (Di Vito et al., 1999; Smith et al., 2012), producing about 70 eruptions. The magmas associated with these eruptions are typically trachytes and alkali trachytes, with smaller amounts of latite and phonolite (Di Girolamo et al., 1984; Rosi and Sbrana, 1987; D'Antonio et al., 1999). The post-caldera eruptions can be then classified in two periods, occurring between 14 ka and 8.2 ka BP and 5.8 and 3.7 ka BP., respectively, with an interval of significant subsidence without eruptions from 8.2 to 5.8 ka BP (Rolandi et al., 2020b).

This seems out of place.
It does not follow naturally from the introduction.
What do we need all the details that are not used later on?
Go STRAIGHT to point that the distribution and timing of eruptions since the Neapolitan Yellow Tuff are consistent with a resurgent block: THIS is the key point for later discussion.



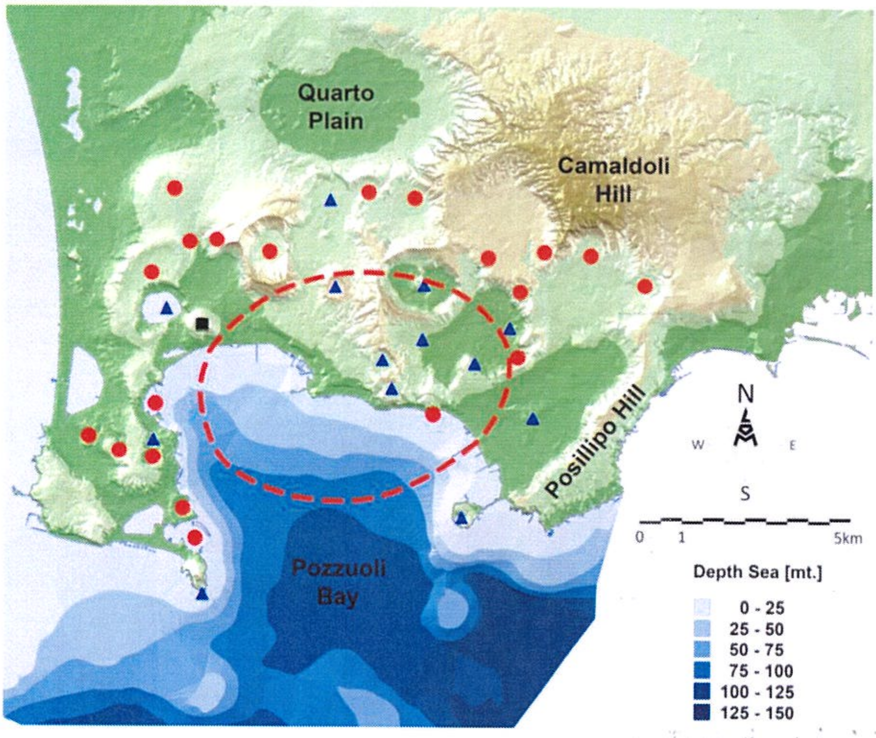


Fig. 1 – ***Top***: **Location map of the study area with indication of relevant toponyms and major volcano-tectonic and morpho-structural lineaments associated with the Campi Flegrei caldera.** ***Bottom***: **Map of Campi Flegrei caldera. Red circles indicate the craters of the first post-caldera volcanic phase, blue triangles indicate the craters of the second phase. The red hatched area represents the resurgent block of NYT extended in the Pozzuoli Bay.**

? Isaia et al. 2009 GL040513 (GRL)

The second post-caldera eruptive phase was preceded by the uplift of 30m, above sea level, of La Starza marine terrace (Cinque et al., 1983; Rolandi et al., 2020b). The distribution of eruptive centers reveals that, during the first post-caldera phase, they were distributed around the resurgent block. In the second phase, among thirteen volcanic edifices, seven occurred within the resurgent area (Fig. 1).

It seems likely that the second post-caldera phase (5.8 - 3.7 ka) can be considered the primary reference for defining possible future eruptive scenarios, following the eruption of 1538 AD.

3. Subsidence and uplift evolution before the 1538 eruption

3.1 Previous interpretations

Modern research on ground movements at Campi Flegrei caldera started with the detailed studies by Parascandola (1943; 1947), the latter drawing mainly on earlier work by Niccolini (1846). The 1943 study primarily focused on historical documents describing the subsidence of the ancient Greek-Roman road known as 'Via Herculea', which was located near the Averno volcano, and contributed to the formation of Lake Lucrino. (Fig. ?)

The Via Herculea, in use since Greek times (beginning in the 8th century BC) and remaining important throughout the Roman times, serves as fundamental historical marker for assessing ground movements west of Pozzuoli. The detailed history of this road, reconstructed from numerous historical sources and included in the supplementary material, provides insights into its subsidence over the centuries.

The road ran along a narrow strip of land, ~~likely~~ probably formed by coastal aggradation of volcaniclastic sandy deposits (Parascandola, 1943) primarily from the 5 ka and 3.7 ka eruptions of the Averno and Capo Miseno volcanoes (Insinga et al., 2006; Di Vito et al., 2011; Sacchi et al., 2014; Di Girolamo et al., 1984)**.** The deposits ~~which~~ eventually created a lake (Fig. 2a). Given its elevation just a few meters above sea level, subsidence significantly affected its usability, with frequent disruptions documented in historical records. These records provide crucial evidence of the evolution of ground subsidence in this area over the centuries.

The Greeks arriving from Euboea in the 8th century BC, initially settled on the island of Ischia (Pithecusa), before founding the polis of Cuma, the first Greek colony in Magna Graecia and the entire western Mediterranean. From this time the narrow land strip served as a road known as the Via Herculea, providing access to the cultivated countryside around Pozzuoli (Fig. 2b).

Lucrino?

Rephrase

Rewrite. This sentence jumps from Cuma to the via Herculea. New paragraph?

Parascandola (1943) emphasized the continuous subsidence of the Via Herculea, using historical accounts from Petrarca (1341) and Boccaccio (1355-1373) to establish that the road had already sunk below sea level by their time. He also noted that Via Herculea did not re-emerge during the uplift accompanying the 1538 eruption, suggesting that the ground uplift in this area was insufficient to compensate for the secular subsidence.

In his later work, Parascandola (1947) presented a detailed reconstruction of ground movements in Pozzuoli, ~~based on evidence fundamental reference~~ for subsequent studies on this subject. According to Parascandola (1947) the maximum subsidence occurred during the IX century.

The first paper to propose an alternative model for ground movements at Campi Flegrei was published by Dvorak and Mastrolorenzo (1991). They propose simplified and constant rates of subsidence and uplift, suggesting that the maximum subsidence occurred at the end of 15th century.

Morhange et al. (1999; 2006), based on radiocarbon dating of ~~lithodome shell~~s, identified an additional episode of ground uplift between 650 and 800 AD. Bellucci et al. (2006) later integrated the ground deformation model of Dvorak and Mastrolorenzo (1991) with the findings of Morhange et al. (1999; 2006) into a unified framework.

More recently, Di Vito et al. (2016) proposed a new reconstruction of ground movements, which will be discussed in more detail ~~in the following paragraphs~~. Their model suggests that the maximum subsidence occurred in 1251 AD. They also ~~hypothesized~~ that subsidence at Campi Flegrei began around 35 BC, and that the ground at the Monte Nuovo vent uplifted by approximately 19 meters immediately before the 1538 eruption.

3.2 Reconstructing the ground movements with the whole available data set

~~As inferred from historical chronicles, as well as from studies on the incrustations and traces of bioerosion on the Pozzuoli Serapeum marble columns (Parascandola 1947; Bellucci et al. 2006), after the two post-caldera phases previously defined, large ground uplift and subsidence in the order of tens of meters occurred.~~ Historical documents allowed us to precisely reconstruct such ground movements in Pozzuoli area (central part of the caldera) and in the Averno area (3 km west of Pozzuoli, close to the area where the 1538 eruption occurred. ~~The reconstruction reported here, based on all reliable historical documents, is the most complete and rigorous~~, allowing to ~~put strong~~ constraints ~~on~~ the reconstruction of past ground movements, ~~whose interpretation is presently very unconstrained and hence variable among the different authors~~..

Repeating previous text. Try starting on Line 178

3.2.1 Ground movements at Averno

The first evidence of subsidence in the Campi Flegrei area dates back Greek times, as reported by Diodoro Siculo (VIII century BC) and is related to the area in front of the Averno Lake, and of the 1538 eruption which generated the Monte Nuovo cone. We will start to describe the historical documents to shed light on the ground movements in this area, then we will reconstruct ground movements in the most deformed, central Pozzuoli area.

A fundamental historical marker for inferring the ground movements west of Pozzuoli, as already mentioned, is the Via Herculea. Diodoro Siculo (see Appendix 1) reported that, already at the times of first Greek settlements, i.e. 8th century BC, continuous subsidence affected this area, thus generating problems to the practicability of Via Herculea.

In Roman times, since the beginning of the 1st century BC, the body of water enclosed by the Via Herculea, purchased by Sergio Orata, played an important role in fish-farming since 90 BC, taking the name of Lucrino, much larger than the present-day Lake Lucrino. After his death, ~~due to~~ continuous subsidence ~~which~~ menaced both the practicability of the Via Herculea and the fish farming activities. The new owners around 50 BC turned to the Roman Senate calling for appropriate interventions. For this purpose, in the period 48-44 BC Julius Caesar was commissioned, then building a barrier (*Opus Pilarum*) and special shutters to protect the road and the Lucrino Lake from sea ingression (see Appendix 1). Towards the end of the same century, for military purposes, in 37 BC Agrippa cut both the Via Herculea and the barrier with the crater of Avernus. Having understood, unlike Julius Caesar, the continuous subsidence of the Via Herculea, which at the end of the century was only few meters above sea level (Fig. 2c), Agrippa also ***increased its height*** (Strabo, 1st century BC). About four centuries later, Theodoric (King of the Ostrogoths), upon request for the protection of fish farming, restored the dam by increasing again the height of via Herculea with respect to the sea level (Parascandola, 1943).

~~Due to continuous subsidence~~, The Via Herculea finally sank below the sea level between 6th - 7th century A.D, when the sea penetrated the crater of Averno, the Lake Lucrino having disappeared (Fig. 2d). Proof of the disappearance of the Via Herculea and of the Lucrino Lake was also testified by Boccaccio, who lived in the Naples area from 1327 to 1341 AD and described the Averno area in its geographical book 'De montibus' (*…to Avernus, connected in ancient times with the nearby lake Lucrino where it recalls the waters of portus Iulius*).

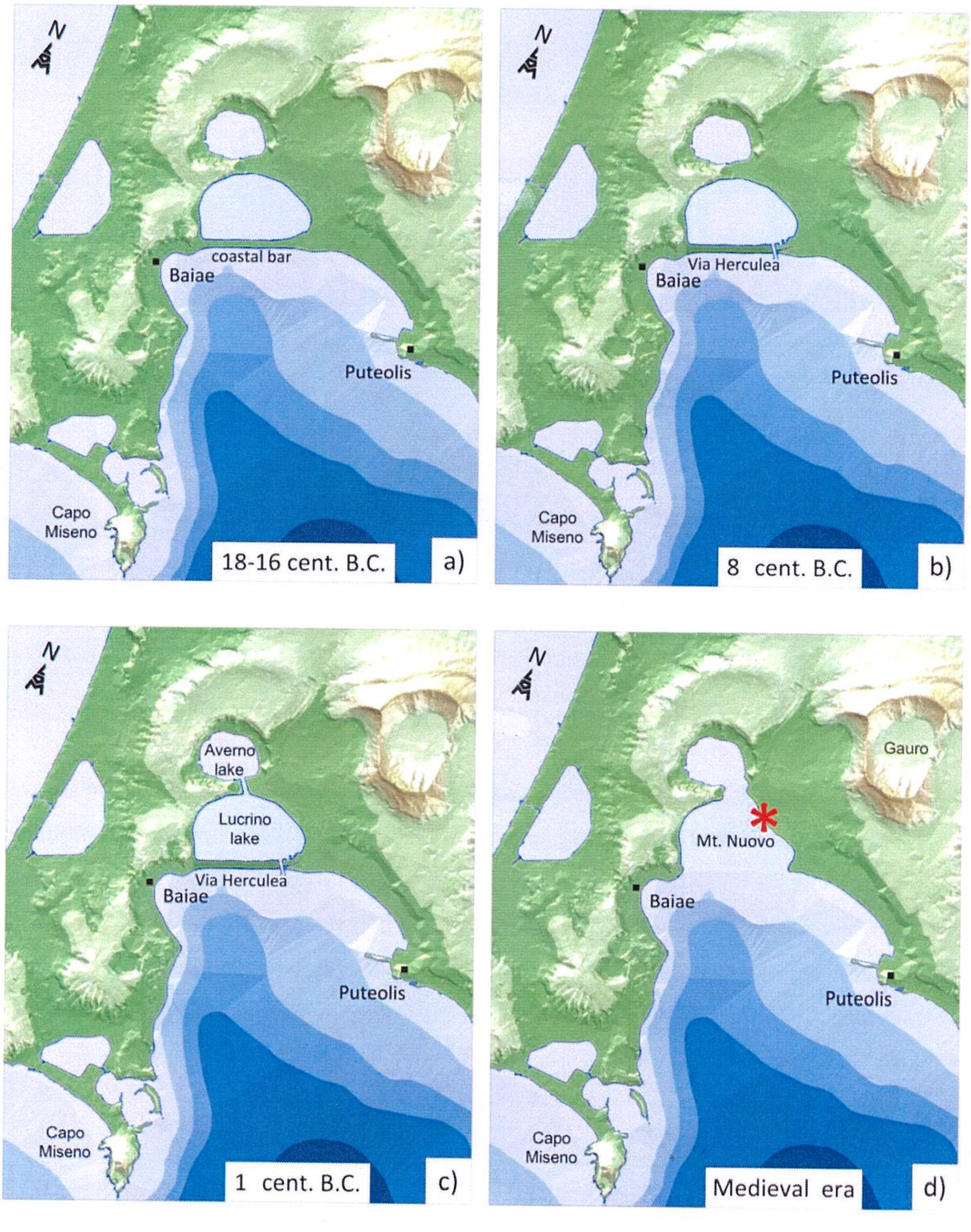


Fig. 2 - a,b,c,d) position and shape of the via Herculea, Lucrino and Averno lakes,along 33 centuries. The red star indicates the central point around which the volcanic edifice of 1538 was formed.

Via Herculea never rose above the sea level again, despite the large uplift phase occurred before and during the 1538 eruption (see Fig. 2d).

The tentative reconstruction of the level of Via Herculea, approximately shown in Fig. 2 as briefly described above, is shown in detail in Fig. 3, where each point of the curve refers to a specific documented historical period, starting from the Greek age (8th century BC), through the Roman era and the late Middle Ages, until the eruptive event of 1538 (see Table 1, and Appendix 1). Note that on the Via Herculea, at the end of the 1st century BC and at the end of the 4th century AD, works were carried out to increase its height above sea level due to the incipient submersion. Due to these works, the submersion of the structure was delayed from ca. the 3rd, 4th century BC up to the 7th century AD (Fig. 3). The date of submersion around 6-7th century is also consistent with the observations reported by Parascandola (1943), indicating that the land strip of Via Herculea still emerged above sea level for much of the 6th century.

It is fundamental to note that Via Herculea never emerged again, not even immediately before and during the eruptive phase of 1538 (Parascandola, 1943). The submerged relicts of the Via Herculea are still visible today, located at about 4.5 meters bsl, as shown in the high-resolution bathymetry (Fig.4) recently obtained by Somma et al. (2016).

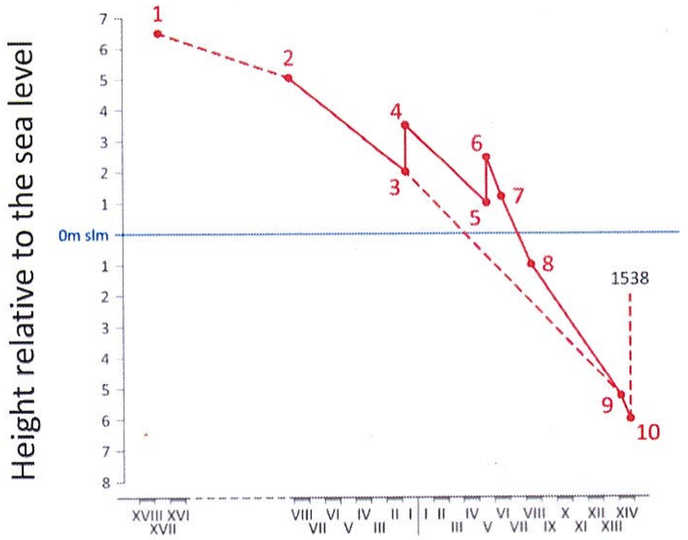


Fig. 3 – Diagram showing the trend of ground movements at the Via Herculea, as referred to sea level, along 33 centuries. Numbers on the curve indicate the times of references for the inferred level: they are synthetically reported in Table 1 and extensively explained in Appendix 1. Dashed lines represent hypothesized subsidences: the first one connecting to the likely initial elevation, the second one showing the likely subsidence path in absence of the restoration works (points 4 and 6), the third one showing the likely uplift linked to 1538 eruption.

Number	Time	Event	Reference source	Reported by
1	3.7 ka and after	Formation of the coastal bar	This paper	
2	8th century BC	Subsidence of the via Herculea	Diodorus Siculus (Book IV)	Parascandola, 1943

3	60 BC	Sergio Orata, owner of the 'Lucrino' lake fish farm, asked the Senate to have via Herculea repaired, because at around 2 m asl. Cesare repaired it	Parascandola, 1943	
4	37 BC	Agrippa raised the level of via Herculea	Strabone	Parascandola, 1943
5	12 BC	Abandonment of Portus Julius and Lucrino fish farming, because of accelerated subsidence of via Herculea	Aucelli, 2020	
6	496 AD	Theodoric, King of Gotes, repaired and raised level of via Herculea	Cassiodorus, Varia Book I	Parascandola, 1943
7-8	556 AD	Failed attempts to restore fish farming in the Lucrino lake: the level of Dam was too low	Parascandola, 1943	
9	1341-1348	Petrarca and Boccaccio writings indicate via Herculea was about 5-6 m bsl	Boccaccio, 1355-1373	Parascandola, 1943
10	15th century	Uplift starts, but Lucrino lake however disappeared and via Herculea never re-emerged	Several chroniclers of the time	Parascandola, 1943

Table 1 - Sinthetic sketch of the main historical sources used to reconstruct the ground deformations shown in Fig.3 (see Appendix 1 for more details).

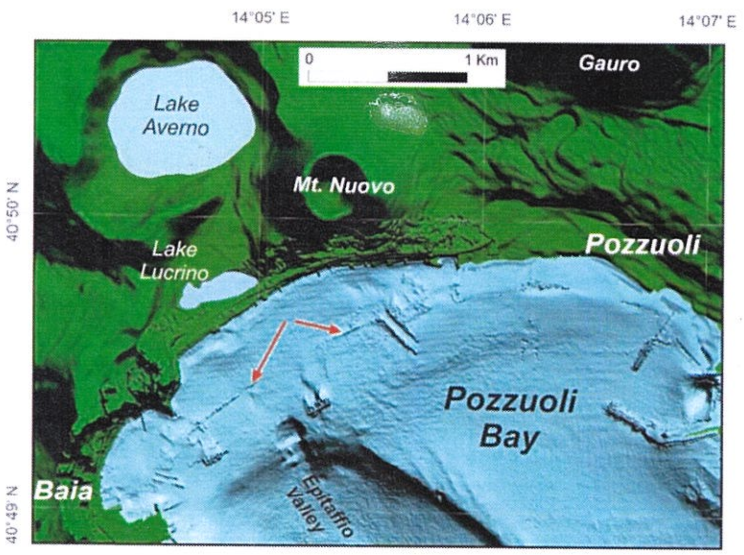


Fig. 4 – Shaded reflief map of the coastal area of the Pozzuoli Bay based on high resolution multibeam bathymetry (Somma et al., 2016). Arrows indicate the submerged remains of the breakwater pilae of the via Herculea.

3.2.2 Ground movements at Pozzuoli

MeanWhile Via Herculea records the most ancient subsidence in the whole area, the best evidence for subsidence in the Pozzuoli area, where maximum ground movements are recorded, comes from the historical-archaeological elements linked to the Serapis Temple (Macellum), although subsidence in the Pozzuoli area is also testified since Greek times (Gauthier, 1912).

Recently, Amato and Gialanella (2013) discovered, by drilling into Serapeum area, four successively superimposed floors, ranging from the Augustan age (31 BC-14 AD) to that of the Severi (193-235 AD), thus indicating the progressive subsidence of the manufact (Fig. 5). The most elevated 4th floor was built in the Severi Age, indicating at that time the previously built three floors where all below the sea level, and from this epoch we will follow the historical traces of further subsidence and subsequent uplift. The resulting time evolution of the approximate level of the 4th floor of the Serapeum is reported in Fig. 6. Also in this figure, as for the Fig. 3, each number refers to a given historical document supporting that level (see Table 2, and Appendix 2). From historical information we know that the 4th floor subsided below the sea level in the 5th century, i.e., about 200 years after its construction during the Severi Age. When the 4th floor reached a level of 3.6 m bsl, around the 7th century AD, the columns were wrapped by layers of sedimentary materials, which formed the so-called "fill" (Parascandola, 1947). Then, due to the impact of the relative sea-level change on the coastal area, colonies of lithodomes attached the part of column at the mean sea level (between 3.6 and 6.30 water depth (see the two red arrows in Fig. 7c) and created a pitted band above the sedimentary materials, for a thickness of 2.70m. This process occurred until the 9th century AD, when the fourth floor was located to a depth of 6.3 m below sea level. Such a depthwas considered by some authors (Parascandola 1947, Amato and Gialanella, 2013) to be the maximum submersion.. In the same period, however, the ground subsidence caused the flooding, by thermal and rain waters of the Agnano plain, an area located to east of Pozzuoli, and resulted in the formation of a lake (Annecchino, 1931). This event indicated a general persistence of subsidence in the Pozzuoli area, which was in fact confirmed very clearly even in the following centuries, as highlighted by numerous historical documents, resumed here (Fig. 7a) and reported in detail in Appendix 2. Such data also contradict the conclusions by Morhange et al. (1999; 2006), who hypothesized a significant uplift, of several meters, in the period 7th-8th century.

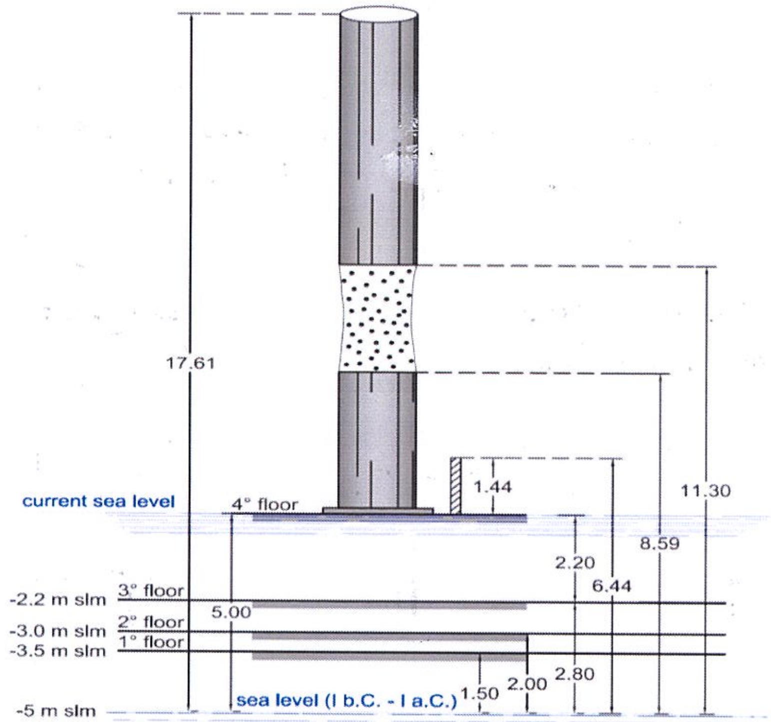


Fig. 5 – Floors underlying columns of Serapeo (redrawn from Amato and Gialanella, 2013). The dotted part of the column indicates the boring due to colonies of *Lithodomus Litophagus*.

Further Evidence for persistent subsidence comes from the Arab geographer Idrisi (11th century) and the historians Benjamin --- (12th century) and Nicolò J--- (13th century), which

In the 11th century the Arab geographer Idrisi and other historians of 12th century (Benjamin ben Yonah de Tudela) and 13th century (Nicolò Jamsilla), clearly highlighted describe the morphology of Rione Terra as a medieval castle surrounded by the sea on three sides, due to the continuation of the subsidence, which was still underway at that time (Costa et al., 2022; (see points 6 and 7 in Appendix 2). Moreover, in 14th century there is the account of Boccaccio (1355-1373), as reported by Parascandola (1943), who wrote that the fisherman's wharf in the Bay of Pozzuoli became had become completely submerged (point 8 in Table 2 and Appendix 2). (Parascandola 1947; Table 2 & Appendix 2).

We can prove again the subsidence continued further in the following century, since it is possible to get obtain a more precise estimate of the depth below sea level reached by the 4th floor of the Serapeum, by observing Serapeo's from the painting "Bagno del Cantariello" (Fig. 7a), part of the famous Balneis Puteolanis of the Edinburgh Codex of 1430 AD (Di Bonito and Giamminelli, 1992). The painting depicts the Rione Terra encircled by vertical yellow tuff walls, from which the beach of Marina Della Postierla extends (towards the observer) to the base of the S. Francesco hill, the source of the thermal spring Cantariello (foreground) near the coast northeast of the submerged Serapeum Serapeo. Behind the visitors of the thermal spring, the painting clearly shows the upper part of the three marble columns of Serapeum emerging from the sea the Serapeo above sea level. Also depicted are People are also shown fishing directly from the shore (Fig. 7b). From this painting

THIS WAS SHOWN IN Bellucci et al. (2006). Their work MUST be referenced. The significance of Fig. 7 is NOT a new discovery.

Bellucci et al (2006) !!!

we can make a rough estimate of the portion of columns below the sea level at that time, taking into account that a significant part of the columns is submerged. Historical records from the 1750 excavations, ~~(see further)~~ indicate that the buried part of the columns amounted to about 10 m ~~(see Parascandola, 1947); the shallowest 2 meters of the excavations were formed by pyroclastic~~ flow ~~deposits of the 1538 eruption (see further paragraphs)~~.

Honestly, not citing previous studies here is wholly unacceptable. The authors are FULLY AWARE of this paper.

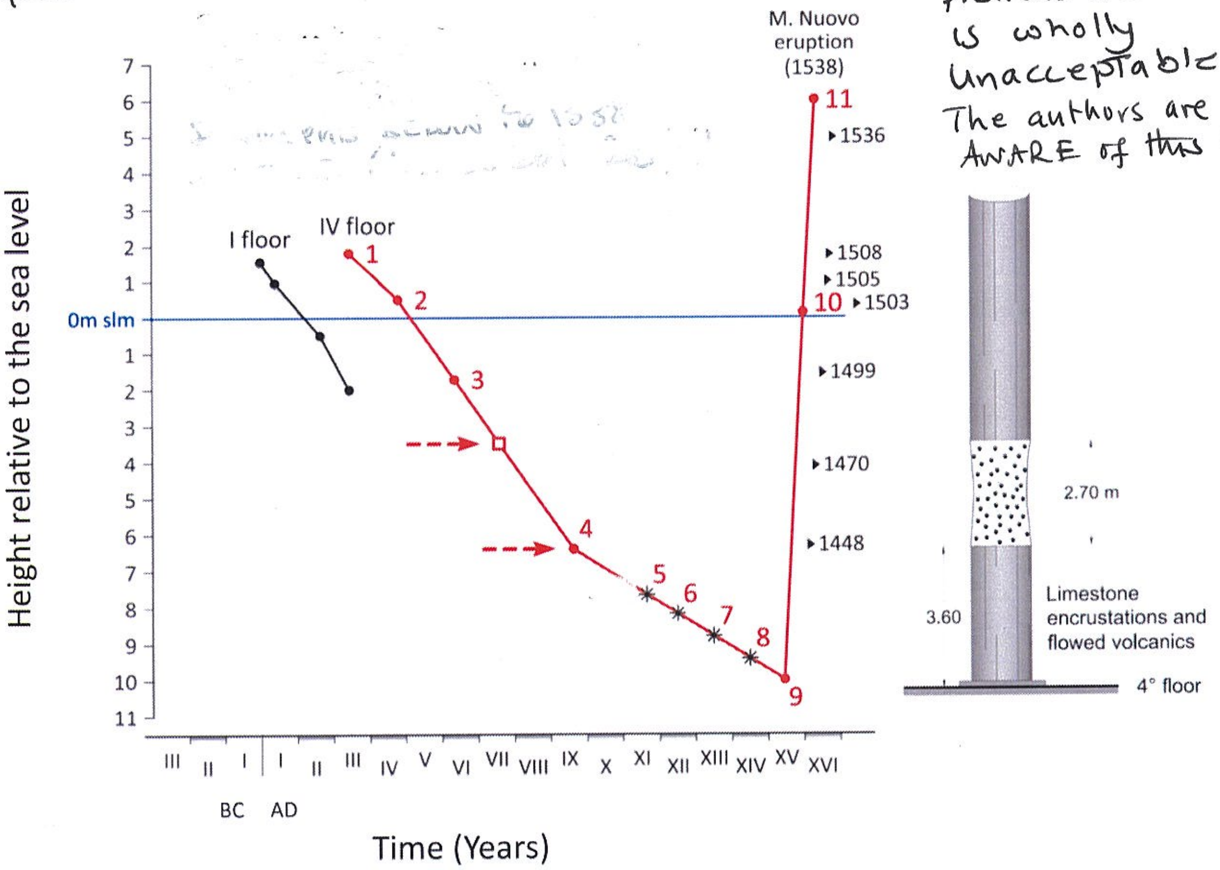


Fig. 6 – Diagram of the level of first (until the building of the fourth floor) and fourth floor of the Serapeum The arrows indicate the limits of the submersion corresponding to the part of the columns bored by lithodomes. Numbers on the curve indicate the times of references for the inferred level: they are synthetically reported in Table 2 and extensively explained in the Appendix 2. Dates marked on the right indicate the times of occurrence of major earthquakes.

Number	Time	Event	Reference source
1	230 AD	The third floor of Serapeum was at a level of only about 1 m asl, often invaded by water: it was then built the fourth floor, located at 2 m asl	Amato and Gialanella, 2013
2	394 AD	The fourth floor is invaded by the sea. Important works to	Camodeca, 1987; Caruso, 2004

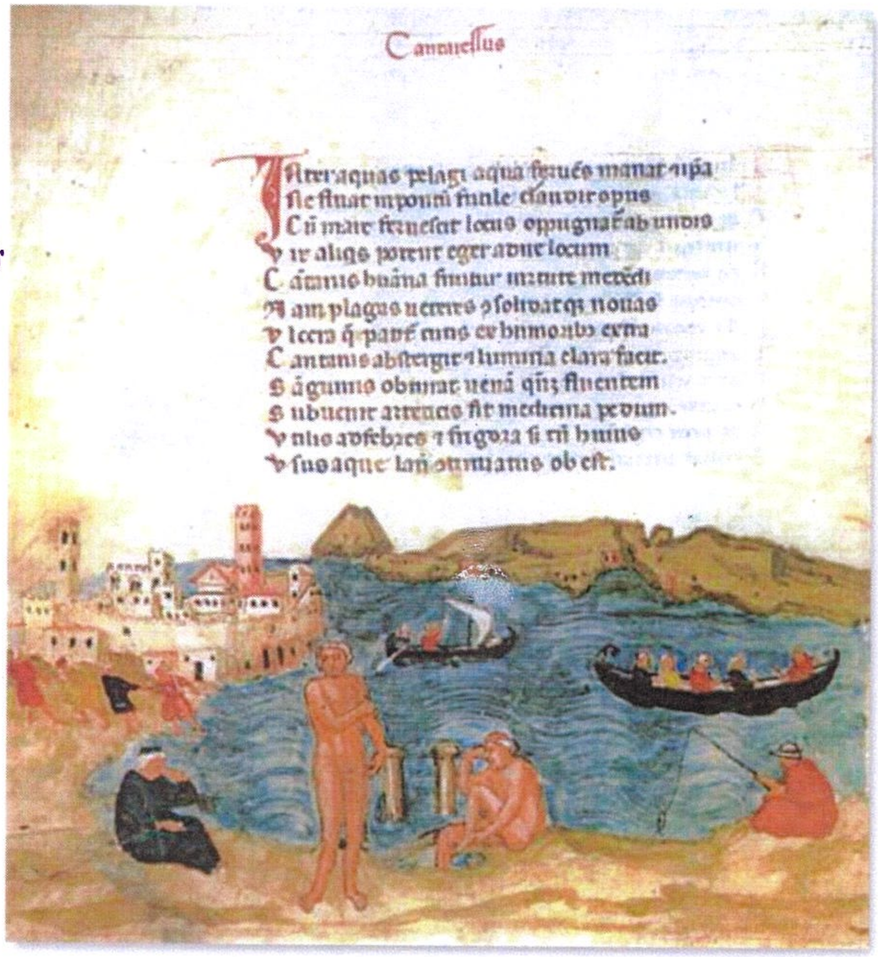
		restore the banks and protect them by coastal embankments	
3	VI-VII century	Puteoli almost depopulated. People refuged in a fortified citadel, surrounded by sea: the Acropolis of Rione Terra	Varriale, 2004
4	VIII-X century	Due to continuous subsidence, Agnano Plain was invaded by water, transforming into a lake	Annecchino, 1931
5	XI century	The sea increasily surrounded Rione Terra, which appeared like a castle. The Arab geographer ***Idrisi*** in his ***Opus Geographicum***, describing Pozzuoli as a ***"castle"***	Varriale, 2004
6	XII century	Subsidence continues: Benjamin ben Yonah de Tudela, passing through Pozzuoli, described: ***turres et fora in acqua demersa quae in media quondam fuerant***	Russo Mailer C., 1979; Caruso, 2004
7	XIII century	Subsidence continues: Niccolò Jamsilla (***Historia de rebus gestis Frederici II imperatoris ejeusque filorum Corradiet Manfredi Apuliaeet Siciliae regnum)*** describes the places between Agnano and Pozzuoli as follows: …***videlicet Putheolum mari mantibusque inaccessibilius circumquaque conclusum…***	Fuiano, 1951
8	1327-1341	Boccaccio reported descriptions as the lower part of Puteoli being completely submerged	Mancusi, 1987
9	1430	The 1430 gouache 'Bagno del	Di Bonito and Giamminelli, 1992

		Cantariello' shows the Serapeum columns submerged for about 10 meters. A	
10	1441	A description indicates that 'the sea covered the littoral plain, today called Starza'	De Jorio, 1820

Table 2: Sinthetic sketch of the main historical sources used to reconstruct the ground deformations shown in Fig.6 (see Historical Appendix 2 for more details).

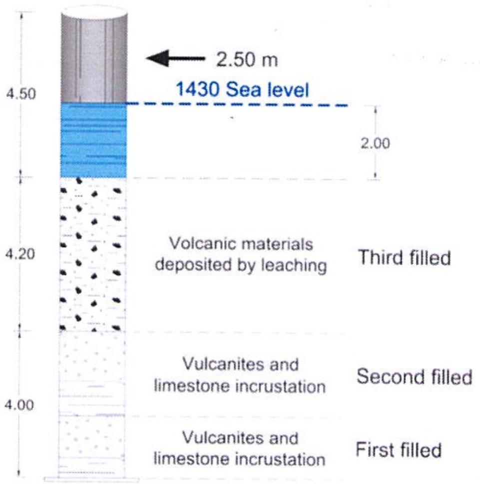
This observation constitutes an indication that during the time of the painting (1430), in the absence of 1538 products, the buried part of the columns should then have been approximately 8 meters. Moreover, the presence of trawling fishermen in the scene (Fig. 7b) suggests that sea depth there did not exceed 2 m (the maximum water depth for this type of fishing not far from the beach). Given that the total height of the columns is 12.7 m, we estimate that the emerged part of the column in 1430 was around 2.0-3.0 m (Fig. 7a,c).

Reference Bellucci et al. (2006).



a)

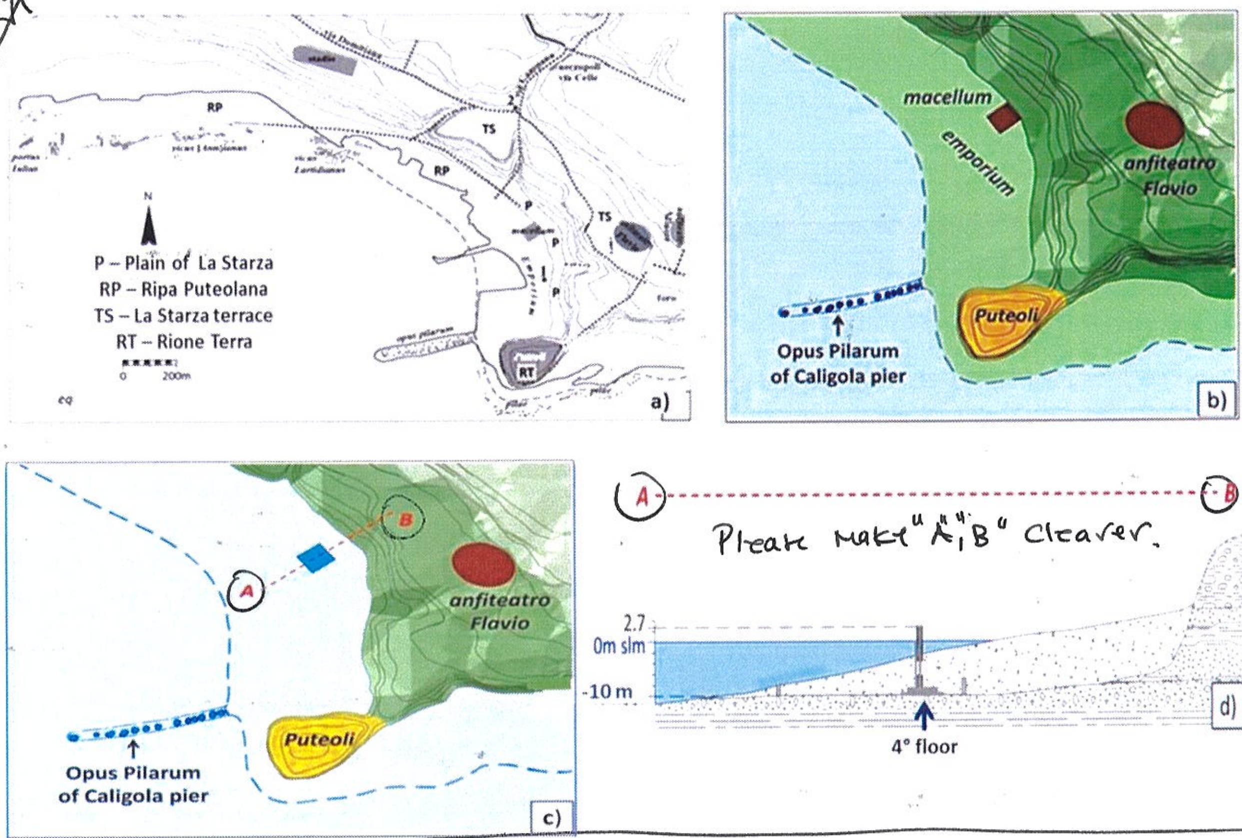
b)



c)

Fig. 7 – Gouache of de' Balneis Puteolanum from 1430: a) Stumps of the Serapeum columns that protrude from the sea to a height of 2-3m, b) Fishing from the shore, highlighted in the

box, indicates a draft depth of approximately 2m of sea, c) Reconstruction of the submerged, emerging and buried parts of the columns (see text for complete explaination).



Consequently, We infer that in 1430 AD the floor was about 10 m (+/-1 m) below sea level (Fig. 6). Such deduction, derived from the context represented in Fig.7a, can be explained in even greater detail with the help of the topographic map of the Pozzuoli area in Roman times (Soricelli, 2007) (Fig. 8a).

therefore and is consistent with a Fig 8a.

Fig. 8 – a) Map of Pozzuoli from the Roman era (III-IV century). The map shows the lower part of the emporium which extends along the Puteolana bank (RP), until reaching the base of the hill, the so-called Starza plain (P) and the upper part of the Rione Terra cliff (RT) which, in turn, connects with the upper hilly part of the Starza terrace area (TS). b) Part of the previous map, limited to the Emporium Area, in the Middle Age (after Aucelli et al., 2020, and Taravera, 2021). c) the same area shown in b around 1430, during which the hill areas (TS, RT) were surrounded at the base by the sea, according to a description of the lower area of Pozzuoli from 1441 "*the sea covered the littoral plain, today called Starza*" (after De Jorio, 1820; Dvorak and Mastrolorenzo, 1991). d) sketch of the profile A-B shown in c: the sea extended behind the

Add your reference to Soricelli (2007) to caption for 8a.

Serapeum on the plain of La Starza hill, intersecting the columns at a height of 10m (also shown).

"We therefore infer that ... (Sorcelly, 2007)".

The map (contour lines of 5m), shows that in the period of greatest development the city included the Greek Acropolis (the ancient Dicearchia nowadays called Rione Terra), with a maximum height of 40 m asl, the lower part of the city, i.e. the western area overlooking the ~~ancient emporium and the Serapeum (Roman macellum) placed near the bay area~~ Serapeo, and the upper city on the Starza terrace, with an elevation between 30-50 m asl. The latter was the site of ~~the ancient monumental edifices~~ major public works, such as an amphitheatre, stadium, forum and necropolis~~, etc~~. From this map, ~~considering only the area of the Emporium (lower part) and amphitheater (upper part)~~, a sketch of topographical relief above the sea level (in Roman times, Fig. 8b) and underlying sea level (in 1430 AD, Fig. 8c) has been obtained ~~and described~~ as follows:

- from profile A-B ~~of Fig. 8c, as reported in Fig. 8d~~, the 4th floor of the ~~Serapeum~~ Serapeo can be located at ~~a depth of~~ 10m bsl, packed in the sediments that form the Ripa Puteolana (RP), with the columns protruding from the same sediments for 4.5m, of which approximately 2m are sea water. ~~It is indicated, ultimately, that the~~ Sea level intersects the columns ~~of the Serapeum~~ at a height of approximately 10 m, connecting with the contour line of 10 m on the La Starza Plain (P) (Fig. 8c,d).
- Fig. 8c also ~~allows us to~~ highlights the morphological conditions of the Rione Terra, which, as we have already observed, has been described by the chroniclers who visited this place from the 11th to the 13th century as *"an unapproachable mountain completely surrounded by the sea"* (Fuiano, 1951; Varriale, 2004, in Appendix 2).

The historical data presented here ~~highlight an evolution~~ indicate several differences from previous reconstructions of ~~the~~ ground movements ~~in the area very different fromhypotheses appeared in previous literature. They mainly confute resultspublished in~~ the most recent work on such an argument (Di Vito et al 2016), who made the following claims:

1) the subsidence in the area started in 35 BC;

2) the local uplift in the area of the 1538 vent, from 1536 to 1538, amounted to about 19 m.;

3) the maximum subsidence was reached in 1251.

The first claim is in contrast with ~~at least two strong evidences, coming from~~ the historical ~~documents~~ evidence: that already at the time of Greek colonization (end of 8th century BC) the Via Herculea ~~used by Greeks~~, showed signs of subsidence (see Diodoro Siculo in Appendix 1) (Fig. 2); ~~limiting ourselves to the documents of 1st century BC, it is sufficient to observe that, due to the subsidence of this dam,~~ Giulio Cesare himself was sent by the Roman Senate in 48 BC to fix the problem, which was eventually (?) resolved

Move text.
Put the comparison with previous models AFTER section of chronology
What happen after 1538.

more constructively by Agrippa in 37 BC, raising the surface of the Via Herculea with respect to the sea level (see again detailed explanation in Appendix 1).

Claim 2) can be easily demonstrated to be not realistic, because in case of uplift in the Monte Nuovo area higher than few meters, the Via Herculea would have risen back above the sea level (Fig.3d). Claim 3), finally, is not confirmed by the testimonies collected until 1430, which instead indicate the continuation of this phenomenon (Di Bonito and Giamminelli, 1992; Bellucci et al., 2006).

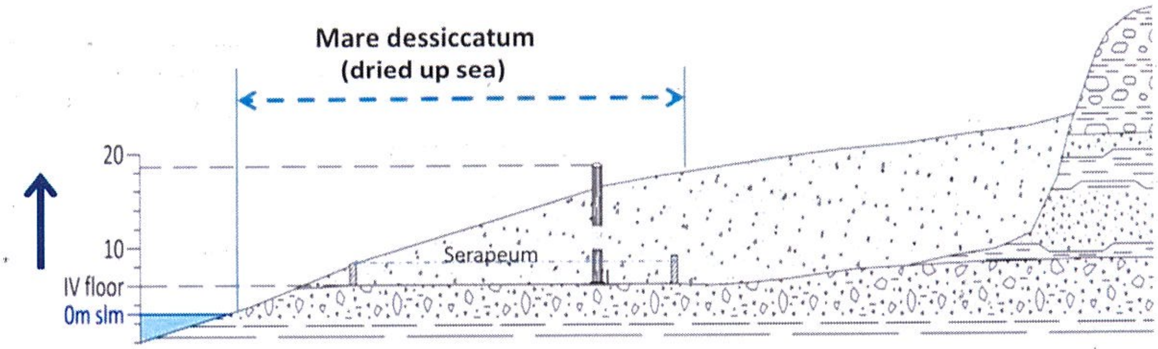


Fig. 9 – The uprise of the land (marked by the two arrows on the sides) was observed and described by Loffredo Ferrante in 1530: *"the sea was very close to the plain which was at the foot of the Starza hill"*. In this context, the 4th floor of the Serapeum had reached a height of approximately 4 m above sea level.

From our reconstruction, based on reliable historical documentation, we demonstrate that the hypothesis that maximum submergence depth of the 4th floor of the Serapeum was reached in the 9-10th century, proposed by Parascandola (1947) and Amato and Gialanella (2013), is not realistic. Nor it is the hypothesis by Di Vito et al. (2016), who place the date of the transition between subsidence and uplift in the 13th century and precisely in 1251.

Our findings dating the starting phase of uplift around 1430, are also supported by the documented occurrence of the first documented powerful earthquake in 1448 (Colletta, 1988: see also next paragraph), which induced King Ferdinand I of Aragon to suspend the so-called "fuocatico" (a mediaeval tax collected for each fire lit by a family unit; see Colletta, 1988). We know in fact, from recent unrests, that earthquakes only occur during the uplift phases at Campi Flegrei (Troise et al., 2019). It is also well known that, between 15[illegible] and 1511, the municipality of Pozzuoli granted the lands that emerged, as a result of the increasingly "drying up sea" (Fig. 9), expanding the available land, to citizens requesting them (Parascandola, 1947). Bellucci et al. (2006) and Dvorak and Mastrolorenzo (1991), however, also reported a date around 1430 or later for the beginning of the uplift phase; so, the data presented here (partly already used by Bellucci et al., 2006 and Troise et al.,

NEW HEADING:
Uplift before the 1538 eruption.

2007), support their interpretation~~, although making it more precise and robust by the addition~~ of new data. [When did uplift begin before the eruption of M. Nuovo in 1538.] [In particular,]

The next important question is ~~then~~: was the 4th floor of the Serapeum above sea level as early as at the beginning of 16th century? Parascandola (1947) answered this question through a sentence found in an account by Loffredo Ferrante from 1580: *In 1503 the sea was very close to the plain which was at the foot of the Starza hill* (Fig. 8). So, it can be deduced that the floor of the Serapeum ~~in the 1503~~ [in 1503,] was just above sea level, that is, it had risen about 10m in about 73 years, with a rate of 136 mm/y. There is clear evidence that the uplift phase continued until 1538, when the eruption occurred. The maximum uplift occurred in the Pozzuoli area, close to the Rione Terra cliff, ~~that up to the 1538 eruption reached an elevation in the order of 5-6 m asl (Fig. 6)~~ [and had reached as much as 5-6 m by 1538 (Fig. 6)]. ~~In the nearby area facing~~ [At] Averno to the west, ~~the~~ uplift~~, as already said~~, was unable to ~~cause emersion~~ [raise] ~~of~~ the Via Herculea [above sea level]. ~~So, the vent area could be affected by an additional uplift, occurred just before the eruption, however such that the total uplift since 1430 resulted lower than about 7m. In the eastern sector of the caldera,~~ At Nisida island, [to the east of Pozzuoli,] the pier did not emerge above sea level (Parascandola 1947). ~~It is then very~~ [Hence it is very] likely that the uplift phase had a bell-shaped trend, very similar to what we [have] seen in the recent unrests. ~~except for a marked additional uplift at the vent site, just before the eruption (Parascandola, 1943), however limited to a total of about 7 m maximum, possibly due to upward migration of the dyke feeding the eruption.~~

[→ NEW CLOSING PARAGRAPH: Local large uplift at future site of M. Nuovo immediately (48 hours?) before the eruption (Parascandola, 1947) --- dyke.]

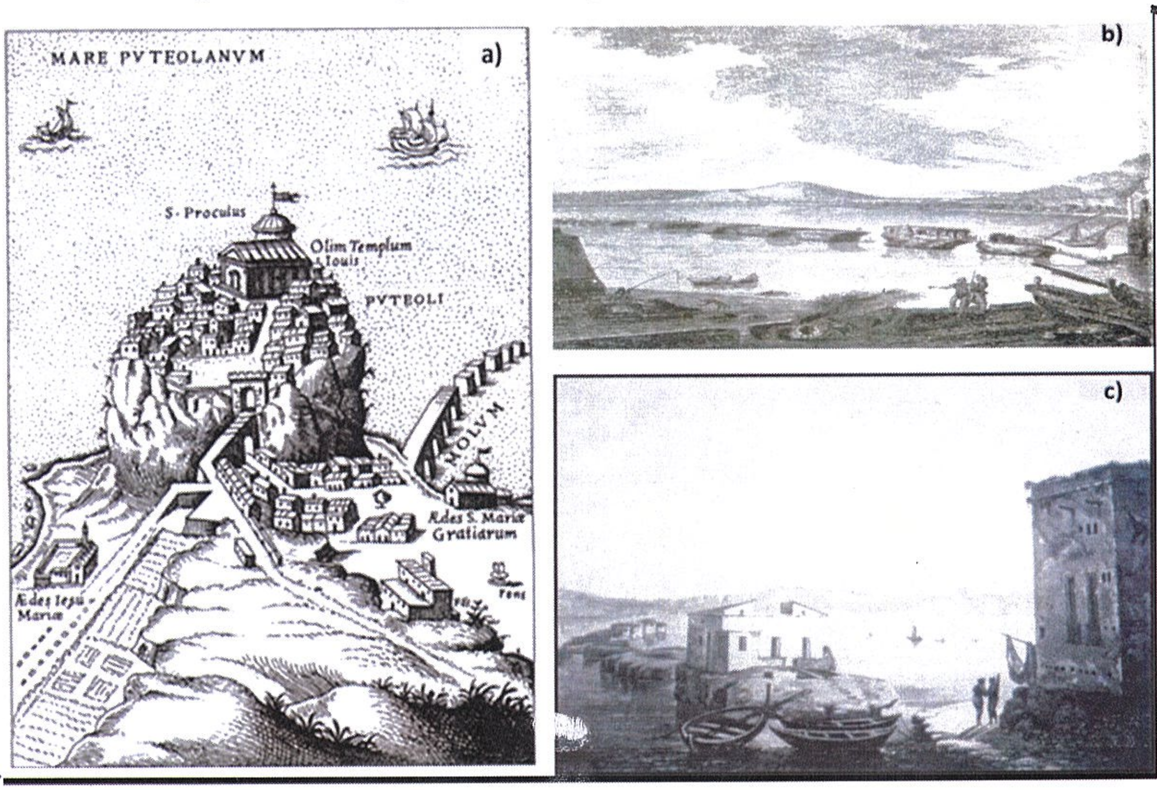
1. Ground movements after the 1538 eruption

The period between the end of the 16th century and the beginning of the 17th century lacks ~~any~~ written ~~historical document testifying the~~ [documentation about] ground movements at Pozzuoli. It is likely that ~~after the 1538 eruption a~~ subsidence ~~phase~~ started [after the eruption], ~~probably after the last post-eruption, seismic phase ended in 1580, as it will be shown in the following paragraphs~~. ~~We can anyway learn something from some paintings,~~ [Contemporary paintings provide constraints on when subsidence began.] The ~~oldest one~~ [earliest,] by Cartaro, ~~dated~~ [in] 1584 (Fig. 10a), ~~which highlights~~ [shows] the Rione Terra in the foreground,

[* Cite Dvorak & Mastrolorenzo (1991).]

TEXT MISSING. Check

with the Neronian pier which emerges almost completely above sea level, which means for about 5-6 M.?



m.

Fig. 10 – a) Engraving by Cartaro (1584) showing the Neronian pier at the base of the Rione Terra, emerging from the sea for 5-6m, showing 10 of the 15 piles of which it was made up in roman epoch, b) The remains of the pier piles, without the upper arches, highlighted in an engraving from the mid-18th century, c) Detail of the same piles highlighted in another engraving from the same period, where the height of the 1-2m piles is observed in more detail, subject to marked erosion

The pier also It also appears still partially complete, with about half pylons still connected with arches (*Opus Pilarum*). In comparison, paintings from the middle XVIII century (Fig. 10b,c) show report the pier completely destroyed, and clearly almost completely submerged. The painting in of Fig. 10c represents shows the pylons in more detail, allowing to estimate the height of the emerging part asl around 1-2 m. an their height to be estimated at 1-2 m asl. Fig. 11, from Hamilton ( ), shows another famous painting of 1776, by Hamilton, which shows the similar ruins of for the Neronian pier almost the same way than in Fig. 10b,c and, in addition, shows that the columns floor of Serapis Temple, with the Serapeo its floor almost at the same level than as the Neronian pier. (LATER)

was

Hence it appears that the pier subsided by about 4-5 m from 1580 to 1750.

Fig. 11 – a) View of the Gulf of Pozzuoli and the Cape Miseno peninsula (Hamilton 1776). Both the remains of the Neronian pier and the newly excavated Serapeo are also visible

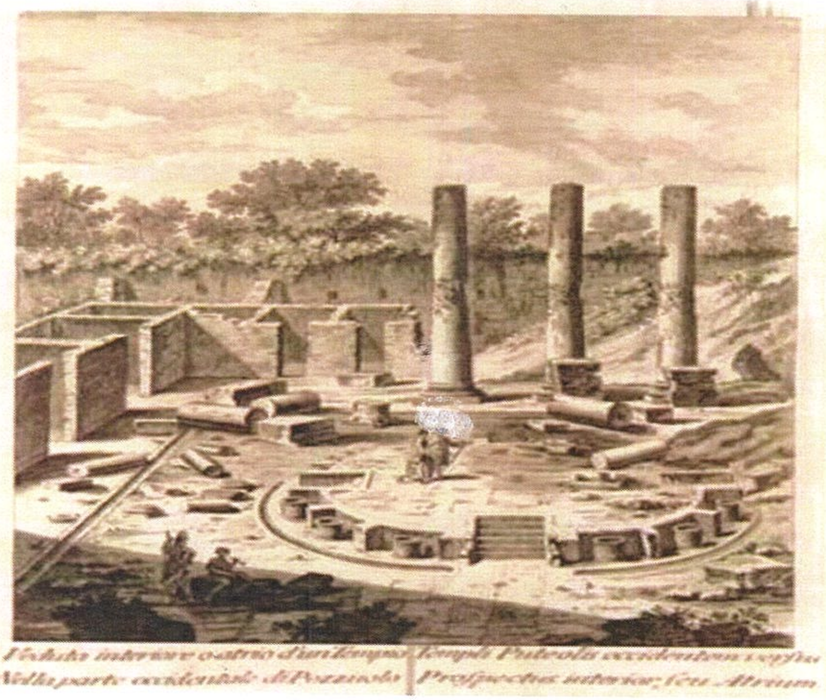


Fig. 12 – Illustration of Serapeum, as excavated in the three-year period 1750-1753. It can be noted that the height of the lighter parts of the columns, including the pitted band of the lithodomes, is preserved by oxidation, because packed by the just removed sediments. The darker upper part, oxidized since staying outside the cover, has a height of approximately 2.50m, estimated on the same figure. This leads us to consider that the pack of sediments removed had a thickness of approximately 10m, that is, the height of the hill where the *vineyard of the three columns* was located before the excavation (Niccolini, 1842).

Fig. 11 also indicates that the floor of the Serapeo was almost at the same

~~From the comparison of Fig. 10a with10b and 10c it can be deduced that the Roman opus pilarum underwent a subsidence of about 4-5 m. from 1580 to 1750~~. level as the pier in 1750.

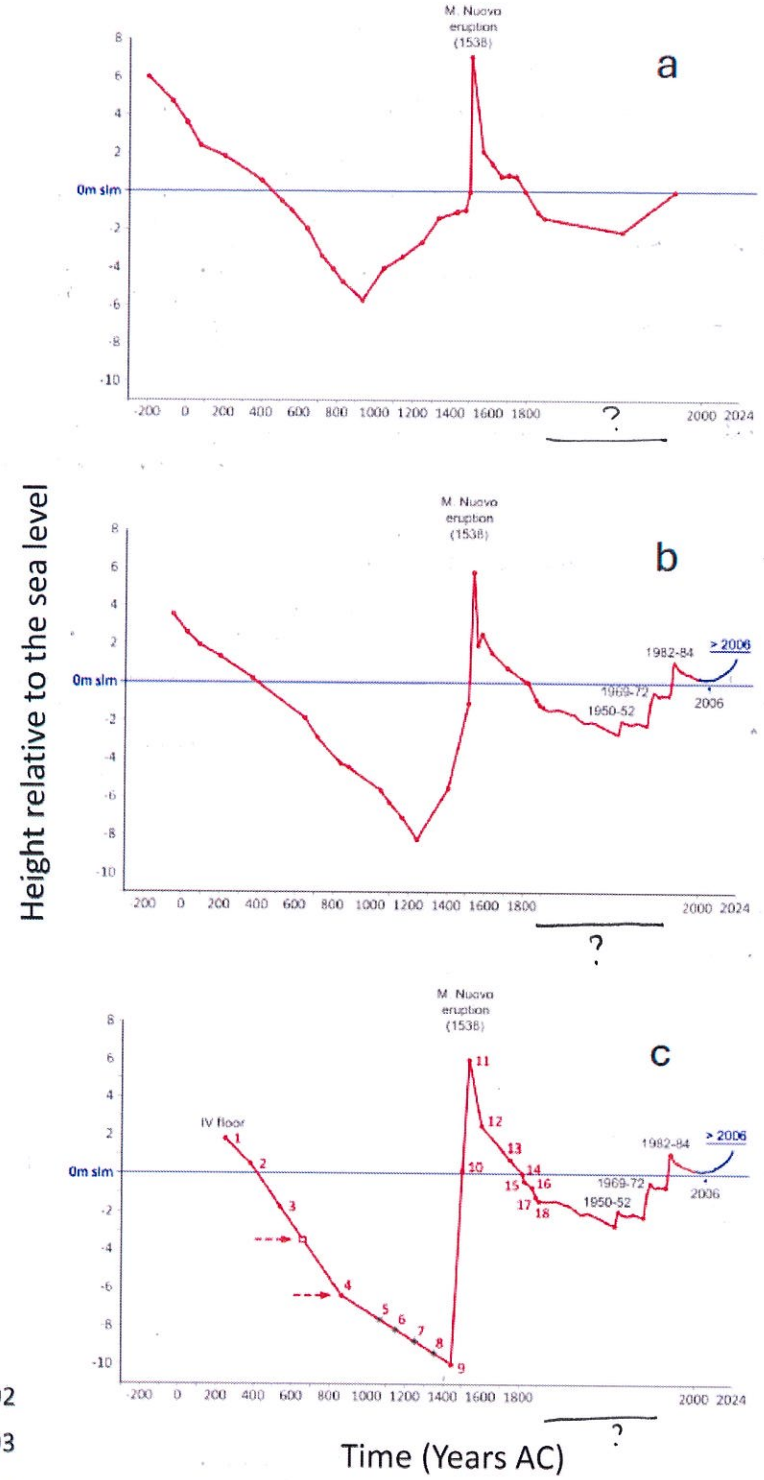
~~Since the floor of the Serapis Temple appears to be at the same level than the pier,~~ Its level in 1538 can therefore be estimated at 5 – 6 m. above sea level (Fig. 6), ~~while in 1750 it should be at~~ and about 1m ~~above sea level~~ asl in 1750, with an estimated subsidence in 1580 -1750 of about 4-5 m. This ~~approximate~~ estimate ~~is however confirmed by Parascandola (1947), who reports some~~ consistent with measurements by Niccolini (1846) reported by P--- (1947), who found the 4th floor of Serapeo to have a height above sea level varying in the range 0.9 - 0.6m throughout the 18th century. ~~It can then be deduced that~~ During the ~~three years of the~~ excavations (Fig. 12) ~~the~~ of DATE - DATE, therefore, the floor ~~could have been~~ was at approximately at 0.7 m above sea level.

~~Finally, we want to highlight, in agreement with Parascandola (1947), that the subsidence of 4 - 5 m,~~ The initial 4-5 m of subsidence ~~started~~ after 1580, ~~could~~ may have ~~evolved at higher initial rate, in such a way that~~ oc. may have slowed, around the middle of the 17th century, after it ~~already~~ may had a value of 2 - 3 m, ~~and then slowed down towards~~ until ~~the end of the century, until the~~ 1750. WHAT IS YOUR EVIDENCE?? This conclusion has appeared ~~from where~~? CHECK FIG. 13.

It is also interesting to compare the average subsidence rate before 1430 with that observed ~~after~~ between 1538 ~~till~~ and 1950. The overall rate of subsidence after 1538 is about 2 cm/year, almost double with respect to that observed before 1430. However, when excluding the first phase of sharp subsidence occurred just after the 1538 eruption, the subsidence rate becomes very similar to that observed since the roman era until 1430. – See comment on Fig 13.

~~We are hence able to describe in more detail the whole evolution of ground movements at the Pozzuoli area since Roman times, including the period following the 1538 eruption and until today. Such a reconstruction is shown in Fig. 13c.~~ In particular, regarding the post-1538 subsidence phase, the data shown, ~~starting from the 17th century, have been combined with those obtained by the most significant measurements carried out by numerous researchers who dealt with this phenomenon during the 1800s, as reported by Parascandola (1947), who suggested the reconstruction shown in Fig. 13a.~~ ~~High precision, frequent measurements started to be collected since 1905, initially based on leveling surveys carried out by the Military Geographic Institute (IGM).~~ Data from the levelling surveys were still provided also during the occurrence of the most recent unrest phases, i.e. in 1950 - 52, 1969 – 72, 1982 – 84 and until 2001. Since 2001, continuous measurements ~~are~~ have been provided by GPS stations, including station RITE ~~(RITE, see Fig. 13b,c)~~ installed at Rione Terra (Del Gaudio et al 2010; Fig. 13)

? ← Since the 1800s, survey ~~meas~~ data have recorded ~~the~~ ground movements at Campi Flegrei with increasing precision. ~~In particular,~~ ~~The~~ Military Geographic Institute (IGM), in particular, started frequent high precision levelling surveys in 1905.



PLEASE ADD TRENDS FROM DVORAK & MASTROLORENZO (1991) and BELLUCCI et al (2006) Since both have been compared with new interpretation here.

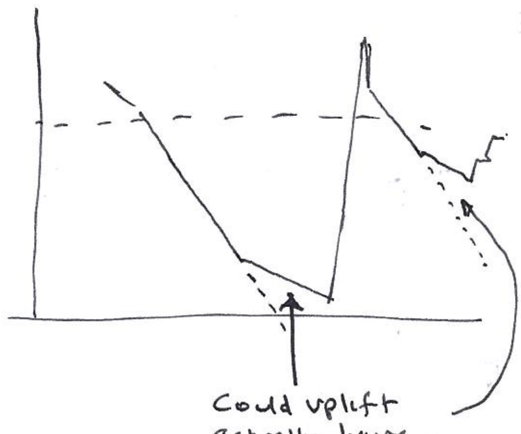


Fig. 13 a) Reconstruction of the ground level of the Serapeum floor, with respect to the mean sea level (blue line), as proposed by Parascandola (1947); b) Reconstruction of the Serapeum floor ground level, recently proposed by Di Vito et al. (2016); c) Reconstruction of the ground level of the Serapeum IV floor, since III century A.D. to present, inferred by this study. Each

point in the diagram corresponds to an appropriate historical indication reported in Table 1 and in the Appendix 2.

2. Schematic model for the preparatory phases of the 1538 eruption

2.1 Dynamics of the resurgent block in response to temperature and pressure perturbations

The ground deformation at Campi Flegrei, during the phases preceding and following the 1538 eruption, has been likely very concentrated in a small area, of few km of radius, around Pozzuoli, just as during the recent unrests (De Natale et al., 2001; 2006; 2019). Such a concentration agrees with the presence of a resurgent block.

Evidence for the involvement in the Campi Flegrei unrest episodes of a resurgent block comes from the first observations and modeling by De Natale and Pingue (1993). These authors pointed out that the concentration of the uplift in a small area, the high uplift values, and the invariance of the uplift and subsidence shape, as well as of the seismic area, indicated the up and down movement of a resurgent block, bordered by ring faults focusing the occurrence of earthquakes (see also De Natale et al., 1997; Beauducel et al., 2004; Troise et al., 2003; Folch and Gottsmann, 2006). Some authors proposed that ground deformations could be explained also without any effect of bordering faults (Berrino et al., 1984; Bianchi et al., 1987; Amoruso et al., 2008, 2014; Woo & Kilburn, 2010); however, most of these models required some 'ad hoc' distribution of rock rigidity, sometimes not realistic (see De Natale et al., 1991), or required an unrealistic constancy of the source geometry able to explain the remarkable constancy, during several decades or centuries, of the shape of deformation during both uplift and subsidence (see De Natale et al., 2006). All of these models, in addition, do not explain the peculiar shape of the seismic area, being almost elliptical around the most uplifted area. In recent times, new evidence has been collected about the location and limits of the resurgent block (Rolandi et al. 2020b). Furthermore, active high-resolution reflection seismic surveys have pointed out and imaged the presence, in the Gulf of Pozzuoli, of an inner resurgent antiformal structure or "block" bounded by a 1-2 km wide inward-dipping ring fault system associated with the caldera border, whose limits have been also documented by the survey (Sacchi et al., 2014 Steinmann et al, 2016; Sacchi et al., 2020a). Further constraints for the extent on-land of the resurgent block come from stratigraphic evidence. In particular, the old well CF-23, drilled in the Agnano area, presents about 900 m of NYT deposits, topped by only [illegible] m of more recent deposits (Rolandi et al. 2020b). The presence of uplifted, thick layers of NYT, characterizes the stratigraphy of all the wells contained in the resurgent block (Fig.14a,b,e), thus allowing to map its extent on-land, although only the CF-

Just show your evidence to support a resurgent block. Your point is that the interpretation is consistent with observation. Don't worry about other models.

Move to Line 515

23, by far the deepest one, clarifies the whole thickness of the NYT deposits in the resurgent area (Fig. 14a,c,d).

The extent of the resurgent block on-land appears also reasonably well defined by a ~~clear relative~~ gravimetric maximum (Capuano et al., 2013). ~~It is crucial to emphasize that the differential movement of the~~ resurgent block, mostly detached from the external caldera rocks, ~~is responsible~~ would also favour for the almost constant, highly concentrated shape of ground displacement, during both uplift and subsidence. ~~The resurgent structure is also associated with distinct seismicity along the bordering ring fault zone (see also Troise et al., 2003)~~. Fig. 15a-c shows how the resurgent block is well ~~evidenced~~ shown by passive seismic data (Fig. 15b, c) and by earthquake locations (Fig. 15a). (Troise et al., 2003)

The presence of the central, resurgent block significantly affects the dynamical behavior in response to temperature and pressure perturbations. This is particularly evident in the central, most deformed and seismic area, where the shallow crust involves approximately 1.5 km of lithoid tuff. This contradicts substructure models proposed by various authors (Rosi and Sbrana, 1987; Vanorio et al., 2002; Lima et al., 2021; Kilburn et al., 2017, 2023), which ~~often~~ assume a thick shallow layer of loose pyroclastics from recent eruptions, typically represented by the stratigraphy of well SV1 (see Fig. 14e). BUT THESE STILL USE THE SAME PHYSICAL PROPERTIES AS OTHERS!

The physical state of the shallow structure within the resurgent block can be inferred by seismic tomography analyses presented by several authors (e.g. Aster and Mayer, 1998; Vanorio et al., 2005; Vinciguerra et al., 2006; Battaglia et al., 2008; Calò and Tramelli, 2018). These analyses consistently indicate a high Vp/Vs ratio centered below Pozzuoli town down to 1-2 km, interpreted as highly water saturated tuff.

Please clarify. You state that the upper 1-2 km consist of water-saturated tuff. ~~This is consistent with the models you are criticizing. Descriptions of "loose pyro~~ Are you saying that the material did NOT come from recent eruptions? Be careful. The key feature – as far as deformation is concerned – is the physical resistance of those layers. The specific terminology can ~~change~~ be changed ~~"loose pyroclastics~~ without questioning the validity of the analyses. "Loose pyroclastics" does NOT mean ~~unconsolidated. Perhaps~~ unconsolidated layers to depths of 1-2 km! I agree the ~~ter~~ description is misleading and ought to be changed. The previous interpretations work even when changing the name to "water saturated tuff."

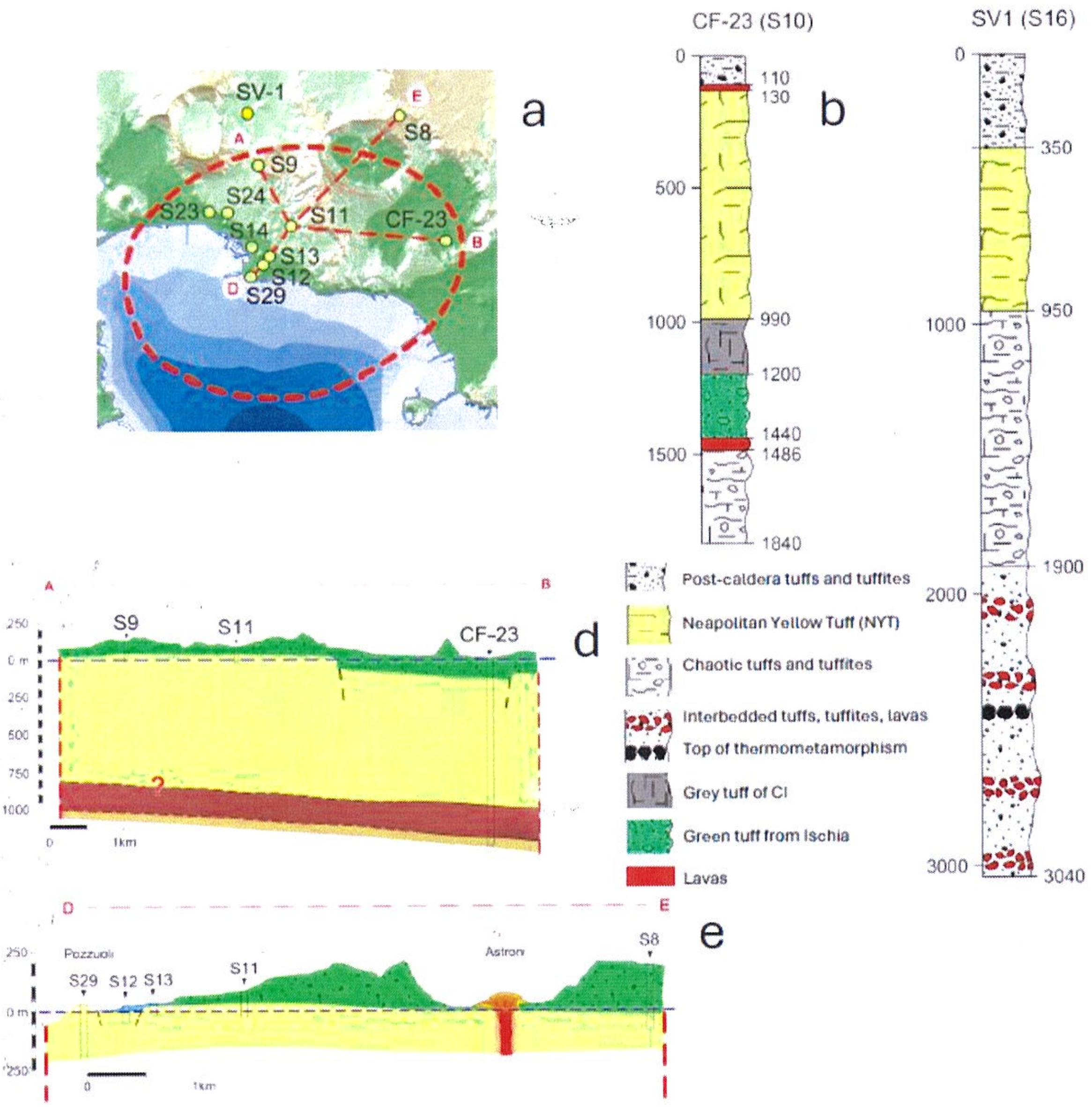


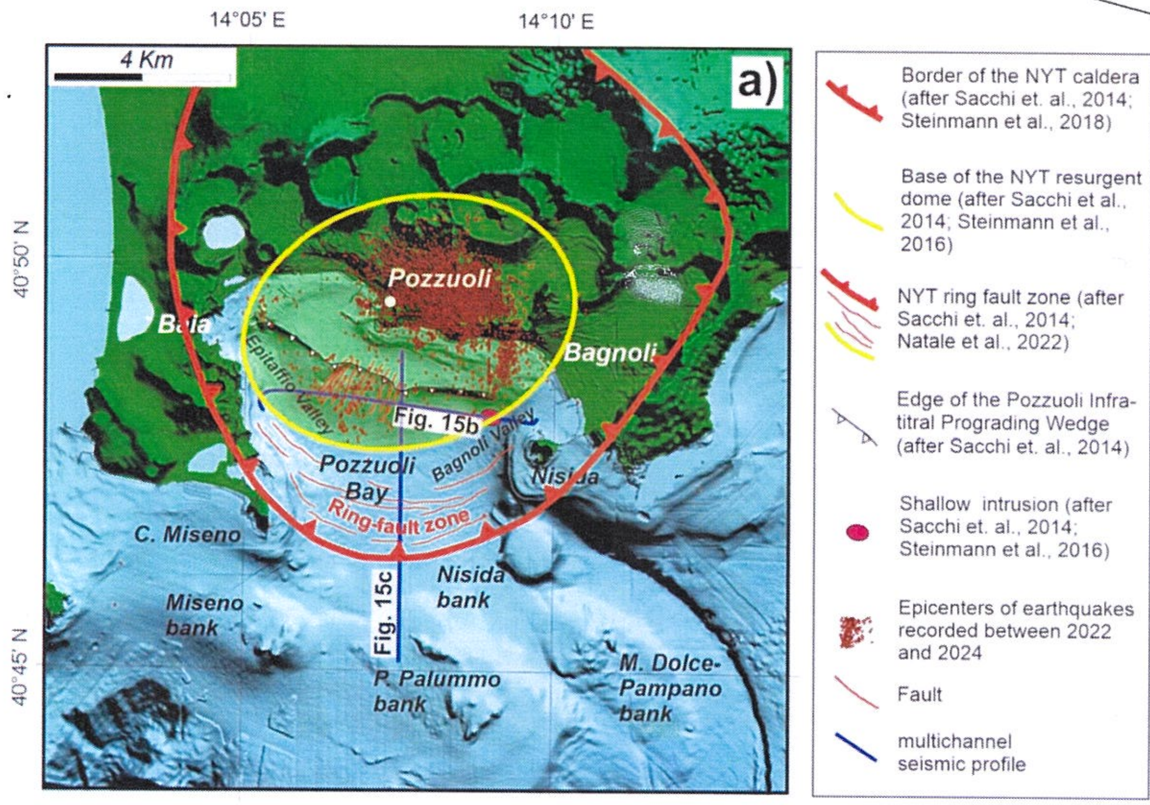
Fig. 14 - a) Location of the wells explored within the resurgent tuff block, as reported in literature; b) Stratigraphy of the CF23 (S10) well, within the resurgent block; c) Stratigraphy of the SV-1 well, outside the resurgent block, which highlights a stratigraphy where the NYT tuff blocks are not present with significant thicknesses; d-e) Profiles in the resurgent block which highlight the shallow depth of NYT because of the resurgence.

Of particular significance is the work by Vinciguerra et al. (2006) which compared the results of seismic tomography with laboratory tests. They demonstrated that the tuffs present in the central area of the Campi Flegrei caldera can be either water or gas saturated, and that inelastic pore collapse and cracking produced by mechanical and thermal stress can significantly alter the velocity properties of Campi Flegrei tuffs at depth. The effect on velocities becomes significant when the temperature rises

I don't see the added significance of Lines 561–574. Vinciguerra et al. (2006) could be added to references cited on Line 551.

sufficiently to induce physical changes, such as volume change and the generation of free water associated with the dehydration of zeolite phases. This can lead to thermal crack damage (see also Chiodini et al., 2015; Moretti et al., 2018), further affecting the dynamic behavior of the area. At higher depths, the well CF-23 indicates the presence of pyroclastic deposits from a depth of approximately 1.5 km to at least 1.8 km, where a temperature of 300°C was measured (Fig. 14b). Likely, at even greater depths of about 3km, marine silt and clay layers induce silica mineralization and the formation of low-permeability horizons. Due to the high temperatures, estimated to be at least 400°C, these layers undergo thermal alteration, forming a thermo-metamorphosed layer (Fournier, 1999; Lima et al., 2021; Cannatelli et al., 2020).

~~Is important to note that~~ Battaglia et al. (2008) interpreted a low Vp/Vs body, extending to about 3–4 km of depth, as due to the presence of fractured overpressured gas-bearing formations, confirming the data of Vanorio et al. (2005). This depth range of 3-4 km likely represents a primary accumulation zone



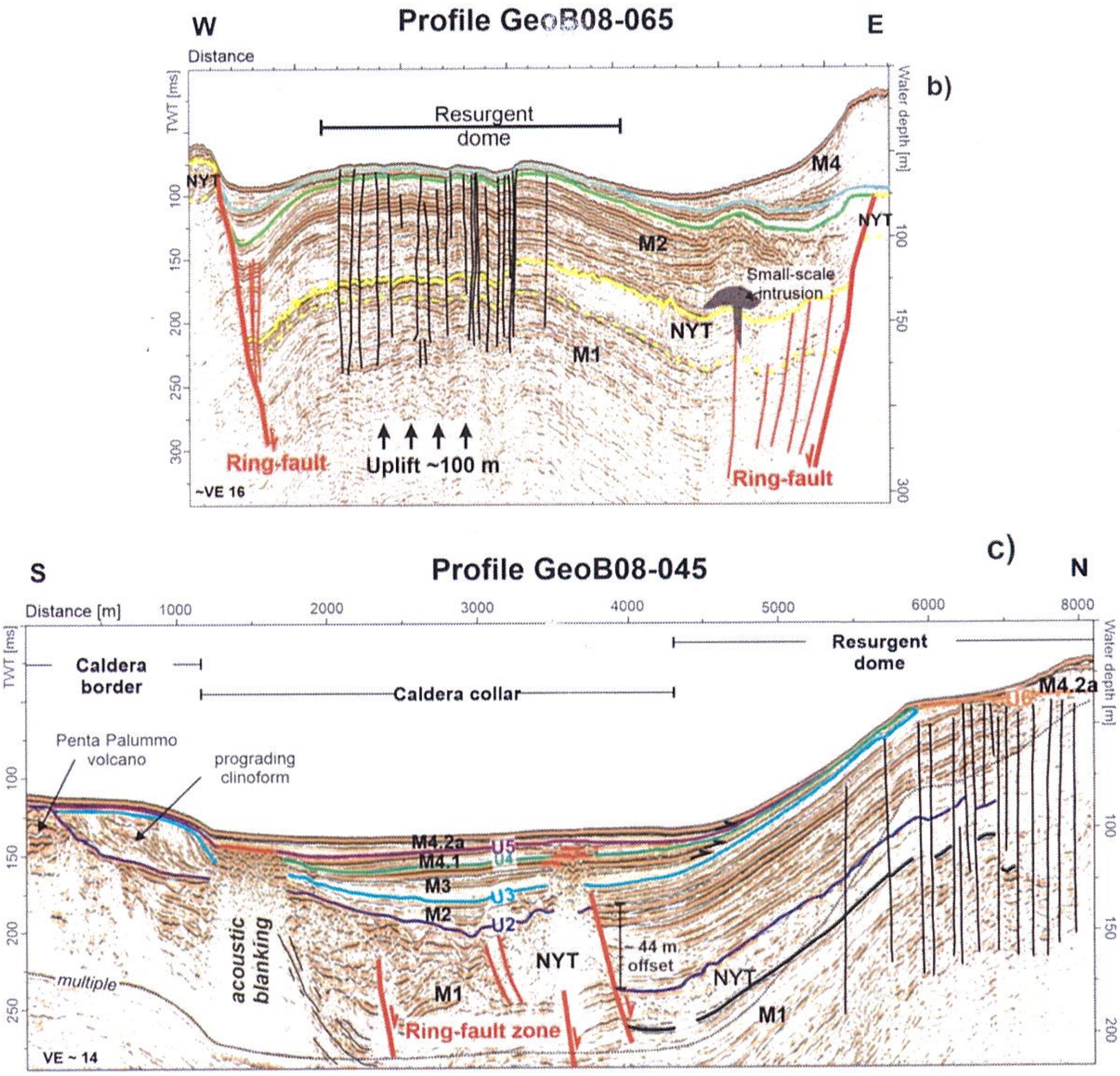


Fig. 15 – a) Campi Flegrei map showing the approximate limits of the resurgent block (area in the yellow ellipse), which concentrates ground deformation and seismicity. b) The N-S and c) W-E profiles of the high-resolution seismic survey, showing the offshore signature of the NYT ring fault system and resurgent structure (from Sacchi et al., 2014, 2020a, 2020b; Steinmann et al., 2016).

? → MISSING TEXT ← ?

for shallow intruded magma, which is unable to reach the surface and instead forms magma sills (Woo and Kilburn, 2010; Di Vito et al., 2016; Troise et al., 2019; Kilburn et al., 2023). The magma at this depth is likely to be in a mush state, i.e. solidified but still at temperature high enough to be remobilized by the inflow of new magma or hot magmatic fluids (De Natale et al., 2004).

At even greater depths, approximately between 7 - 8 km, the main magma chamber is located. This chamber contains both liquid magma and residual mush from past eruptions (Judenherc and Zollo, 2004).

Zollo et al.?

Why? This is a guess - so at best "could be" in a mush state, NOT "likely". If sills are only metres thick, then will be solid now. What thickness are you considering?

5.2 The preparatory phases of the 1538 eruption

A tentative model can be now constructed for the preparatory phases of the 1538 eruption, which accounts for all available data. It is shown in Fig. 16, and can be summarized as follows: the Pozzuoli area experienced a long period of subsidence, beginning at the end of the second phase of post-caldera volcanism (3.7 ka B.P.) and lasting until 1430 AD. This subsidence was likely triggered by the collapse of the upper and middle crustal blocks into the underlying magma chamber, situated deep within the limestone basement at depths of 7-8 km (~~Judenherc and Zollo,~~ 2004). ~~The~~ viscoelastic behavior of the shell encasing the magma chamber may have also contributed to the subsidence, along with the decrease in magma volume due to cooling and crystallization (Fig. 16a).

Since the end of the second phase of post-caldera volcanism, approximately 3.7 ky ago, the primary magma chamber, located at 7-8 km of depth, likely contains a mixture of liquid magma and mush. It's important to note that mush refers to a non-eruptible phase of trachytic magma, composed of 25%–55% volume by crystals (Marsh, 1996; Bachmann and Huber, 2016; Cashman et al., 2017; Edmonds et al., 2019). When heated by several tens of degrees, typically through the injection of hotter magma, mush can revert to a liquid state, thereby regaining the ability to trigger a volcanic eruption (e.g. De Natale et al., 2004; Caricchi et al., 2014). However, the way the mush is rejuvenated by intrusion plays a fundamental role in this mechanism (Parmigiani et al., 2014). One plausible scenario is that the new magma from the deeper crustal levels forms sills at the base of the mush, revitalizing it through the supply of heat, but not of magmatic mass, i.e. only exsolution occurs (Bachmann and Bergantz, 2006; Bergantz, 1989; Burgisser and Bergantz, 2011; Huber et al., 2011; Bachmann and Huber, 2016; Cashman et al., 2017; Carrara et al., 2020). To explain the rapid uplift observed in the interval between 1430 and 1538, the temperature contrast between the two layers could play a fundamental role: the mafic melt positioned at the base, being hotter than the overlaying layer, undergoes cooling and crystallization, leading to an increase in the volatile content (primarily H_2O and CO_2) of the residual melt (Fig. 16b). Lower ductile rocks tend to deform gradually, allowing magmatic gases to permeate into the brittle zone above, thereby inducing a thermo-metamorphic separation layer.

A seismic anomaly displaying low Vp/Vs at approximately 4 km depth (Battaglia et al., 2008) indicates the presence of supercritical fluids. Earthquakes are clustered above such a depth, suggesting the presence of fractured rocks rich ~~in overpressured gas~~. This condition likely results in triggering additional earthquakes (Fig. 16a): a similar condition has been often hypothesized to occur in the Yellowstone volcano (Shelly and Hurwitz, 2022), and is explained in the following. Intense degassing from the main magma chamber would lead to increased pressure in the shallow aquifers forming the large hydrothermal system, just as hypothesized for recent unrest (Moretti et al., 2017;

Zollo et al. Any

This is pure SPECULATION and not a consequence of new data here.

I think you are over-interpreting ~~other~~ data from other sources. Think about removing this paragraph.

Earthquakes ⇒ fractures ✓ but not overpressured gas.

Well – it was 3-4 km on lines 575/6. CLARIFY

Near the base of the hydrothermal system?

Really – distinguishing the a difference from 3 to 2.5 km is well within observational error.

The proposed depth of c 3 km is to be consistent with the ground deformation data.

2018); moreover, the rise in temperature would cause the water contained in the tuffs' zeolites to convert into steam, generating additional overpressure. Such a situation is shown by the CF-23 well, where its stratigraphy indicates the presence of a magmatic layer approximately 30 m thick beneath the overlying tuff blocks, which are approximately 1.5 km thick (Fig. 14b).

It is noteworthy, when considering the correct stratigraphy of the resurgent block as represented by the CF-23 well, that some previous models suggesting the presence of two low-permeability layers at depth (Vanorio and Kanitpanyacharoen, 2015; Kilburn et al., 2023), inferred from the SV1 well (which is situated outside of the resurgent block) (Fig. 14a), can be questioned. Therefore, magmatic gases may not necessarily be restricted to below the thermo-metamorphic horizon (Kilburn et al., 2023), but may instead accumulate at shallower levels beneath the "summit" magma intrusion at a depth of about 2.5-3.0 km.". Consequently, at the base of the magma body, conditions of high temperature and pressure result in widespread brittle deformation of this layer due to uplift, making it highly permeable by fracturing (Fig. 16b).

c.3 km

Not much different.

I don't see what is NEW here.

Finally, super-compressed magmatic gases were likely contained within an approximately 2.5 km thick fragile zone, while a limited release of the increased pressure occurred directly through the fractures connecting the intermediate depth area with the Solfatara and Pisciarelli areas, resulting in the escape of CO2-rich vapor. A similar mechanism has been evidenced in the recent unrest, by the reported increase in fumarolic activity and in the CO_2/H_2O ratio (Chiodini et al. 2021).

You mean from the surface to 2.5 km?

Following this hypothesis, it is noteworthy that, at a depth of 1.8 km, the CF23 drill-hole indicates a very high temperature of 300°C, not far from the supercritical temperature. It is plausible that, if the temperature significantly increases, due to the supply of deeper, hot magmatic fluids, the water contained in the basal part of the tuff block could reach supercritical conditions, leading to thermal fracturing within the tuff block (Vinciguerra et al., 2006), over a certain thickness (Fig. 16b).

As previously mentioned, the increase of pressure resulting from such intense heating caused by deeper magmatic fluids should be attributed to both the overpressure of shallow aquifers and the vaporization of water contained in the zeolites, likely in the form of superheated steam.

This is interesting but SPECULATIVE. How does it follow from your observations of ground movement?

WHERE? 8 km?

The pressure increase in the main magma chamber, resulting from the input of new magma and/or magmatic fluids as explained, can also trigger the formation of magma dykes (Troise et al., 2019). The progressive intrusion of several magma dykes likely leads to the ascent of magma towards the surface. This process may be further facilitated by phreatic explosions caused by the heating of shallow aquifers, resulting in depressurization pulses. Intruding magma may encounter layers that are more resistant to penetration at certain depths. In this case further magma intrusion may be inhibited and lateral expansion, to form sills, may occur (Gretener, 1969). Previous studies of recent unrests

PURE SPECULATION AND NOT A CONSEQUENCE OF THE NEW RECONSTRUCTION. I'D BE CAREFUL HERE, BECAUSE YOU RISK DILUTING THE IMPORTANCE OF THE NEW RECONSTRUCTION.

have indicated that depths between 2.5 and 4 km, close to the upper limit of the ductile zone, are locations where magma intrusions can halt (Woo and Kilburn, 2010; Troise et al., 2019). Before the 1538 eruption, a small plumbing system, in the form of flattened intrusions near the contact between a lower ductile zone and an upper brittle zone in a high-pressure environment, was hypothesized (Fig. 16b) (Pasquarè et al., 1988). From such a shallower magma chamber, magma can further progress upward towards the surface. A dynamic in which early intrusions in the shallow crust create small plumbing systems (i.e. stalled intrusions), from which a dyke later propagates, bringing a small quantity of magma to the surface, is typical of monogenic volcanoes (Marti et al., 2016). The ability of intruded magma sills to erupt at surface is also influenced by the relatively short timescale of sill solidification, typically in the order of few tens of years (Troise et al., 2019).

Shallow solidified magma sills, in the form of mush, can be remobilized due to the arrival of new magma and/or of hot deeper magma fluids. The significant uplift preceding the 1538 eruption, amounting to more than 16 meters in the initial phase involving the entire resurgent block, if interpreted solely in terms of magma intrusion, would suggest a total intruded volume, in the shallow plumbing system, on the order of some cubic kilometers of magma (Bellucci et al., 2006).

No. This is confusing solid ROCK with mush.

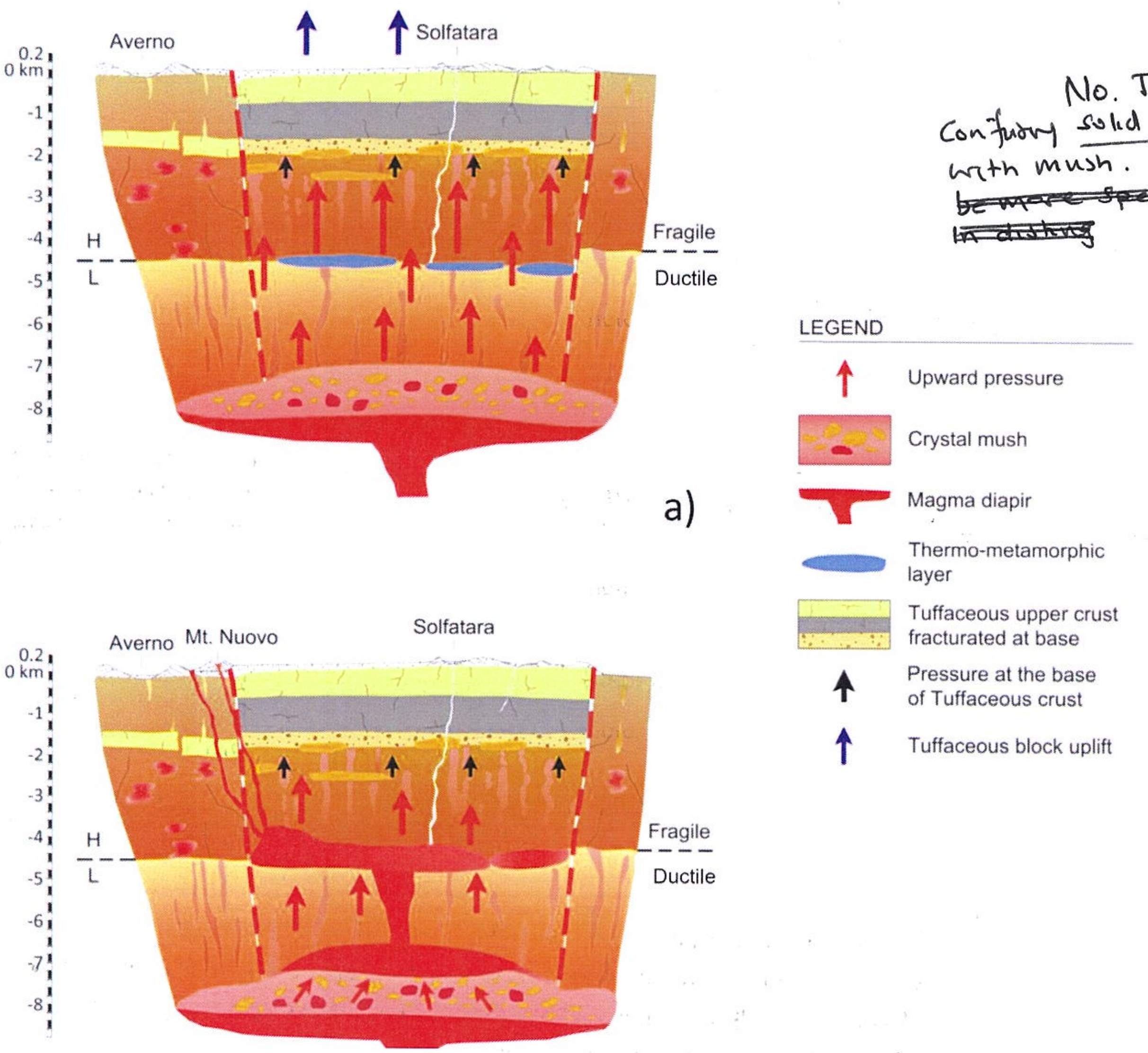


Fig. 16 – Schematic cross sections of the hydrothermal and magmatic systems underlying the Campi Flegrei resurgent block in the 1538 AD, showing:

a) Process of gas sparging according to Bachmann and Bergantz (2006) model, related to the transfer of hot gas from a mafic intrusion underplating the trachytic mush and the hypothesized relation with earthquake swarms of the exsolved fluids, accumulated at lithostatic pressures in the ductile region and episodically injected into the brittle crust at very high strain rates. The sudden increase of fluid pressure, in the brittle region, can trigger earthquake swarms in the 2-4 km depth range.

b) Remobilization of mush by mafic magmas then occurs, so the magma remobilized from the mush accumulates at the top, fueling its rise upward to accumulate, in a sill-like shape, along the ductile-brittle transition surface. Eruption from the magma sill is then likely to occur at the faulted borders of the resurgent block.

Yes. But where is the "mush" now?

However, despite such a large uplift, suggesting however high volumes of shallow intruded magma, the eruption of 1538 only produced about 0.03 km^3 of pyroclastic deposits (see next section). This discrepancy likely suggests that multiple sill intrusions occurred over more than one century, with most of them solidifying without contributing to the eventual eruption. Only the most recent intrusion events~~, and/or some portion of~~ magma mush from prior intrusions remobilized by subsequent heating, would have fed the eruption.

Also interesting is to note that, after the 1538 eruption, ground subsidence recovered only 8 meters, i.e. one half of the former total ground uplift. This means that about one half of the total uplift ~~was likely~~ may have been caused by thermally pressurized gas and water (shallow aquifers), perturbed by hot fluids coming from the deeper (7-8 km) magma chamber; the remaining, unrecovered uplift, should have been caused by shallow magma intrusion. It is the same process hypothesized for recent unrests: in particular, the 1982-1984 uplift showed a subsequent subsidence about one half than the former uplift, interpreted as the deflation of formerly pressurized water and gas (Troise et al., 2019).

Another characteristic of eruptions from small monogenic volcanoes is their difficulty to be forecasted, as they occur at unexpected locations (Marti et al., 2016). Both distinctive traits were evident in the eruption of Monte Nuovo, which represents a prototype of a small monogenic volcano

~~6.1 The seismic phases that accompanied the ground uplift and the eruption~~

We can classify the ~~precursory~~ earthquake sequences into ~~three categories:~~ long-term, medium-term and short-term precursors.

- The ~~phase of~~ ***long-term seismic precursors*** started in 1448 ~~and was well documented since~~ 1468 - 1470 ~~when a paroxysmal seismic phase occurred~~ (Io = VII) (Guidoboni and Ciuccarelli, 2011; Francisconi et al., 2019) (Fig. 19a – interval A) ~~resulting from a progressive increase in fracturing.~~ ~~This~~ culminated ~~into intense~~ fumarolic-hydrothermal activity ~~recorded~~ at ~~the~~ Solfatara ~~volcano. The historical chronicles report~~ widespread damage to the vegetation ~~both spontaneous and cultivated, in all the areas surrounding the volcano~~. This a~~ppears to be an important piece of information, indicating~~ a broadening of the area affected by intense degassing (Francisconi et al., 2019). ~~In 1475,~~ another seismic phase was reported (Guidoboni, 2020), with maximum intensity Io = IV - V. ~~Over the following twenty years~~, ground uplift ~~continued at an accelerated~~ rate. This period ~~culminated~~ with a strong seismic phase ~~occurring~~ in October 1498, reaching ~~considerable~~ maximum intensity (Io = VII). A low-intensity seismic ~~phase~~ then followed ~~during the period~~ 1499 - 1503 (maximum intensity Io = V) (Fig. 19a – interval A). Such a long-term precursory phase ~~could likely be interpreted a~~s mainly ~~due~~ ~~to intense~~ degassing ~~coming from~~ the deep magma chamber ~~and progressively~~ increasing pressure in the shallow layers of the geothermal system, without significant contribution from ~~direct~~ magma intrusion at shallow depth.

- ~~After this first initial long-term precursory ph~~... a new phase of *Medium-term precursors* ~~followed.~~ ~~This phase was characterized by stronger~~ seismic events in 1505 and 1508 ~~which were~~ of higher intensity ~~with respect to the previous ones~~ (maximum intensity Io = VIII) (Guidoboni and Ciuccarelli, 2011). ~~Additionally, there was a~~ faster ground uplift ~~during this period~~, resulting in serious damage to buildings and several casualties. This seismic phase could have been caused by either a higher stress associated with increased uplift ~~level~~ or magma intrusion from the deep magma chamber into shallower levels. This intrusion could have produced higher stress resulting in seismic activity of greater intensity. Although it is obviously difficult to identify, from historic sources alone, the respective roles of the deep degassing into the hydrothermal system versus shallow magma intrusion, we believe that the reported evidence of vegetation damage and increased degassing in the first phase, and the increase of earthquake intensity in the second phase, indicate respectively a main contribution of degassing perturbing the hydrothermal system, in the first phase, and of shallow magma intrusion in the second phase. This phase ended in 1520, ...h a medium intensity earthquake (Io = V-VI) (Fig. 19a – interval B)..

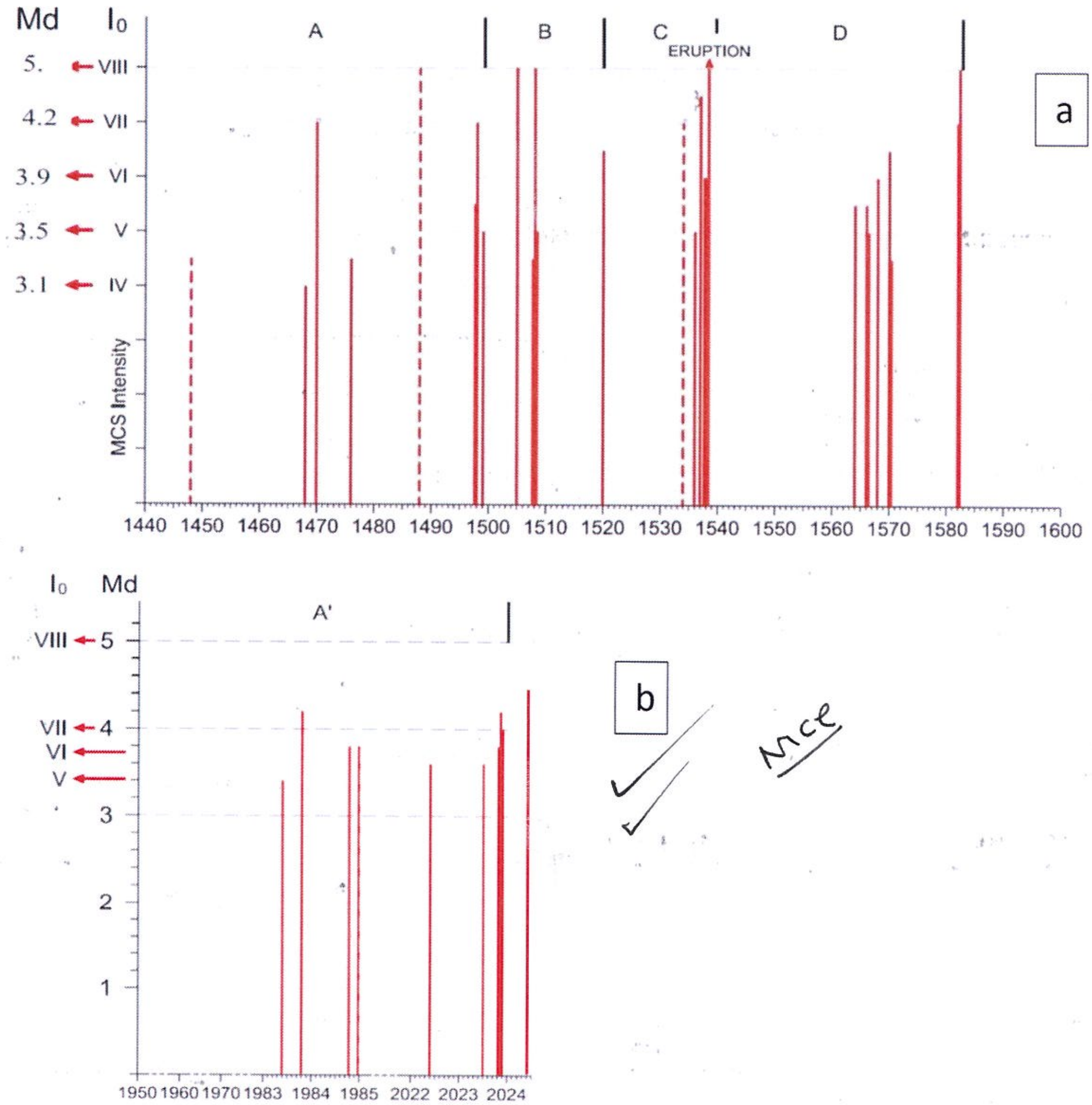


Fig. 19 – a) Reported earthquakes occurred before and after the 1538 eruption (after Guidoboni and Ciuccarelli, 2011). The computed intensities of these earthquakes have been converted in magnitudes using the considerations made in the appendix 3. b) Highest magnitude earthquakes (M≥3.5) occurred since 1950 to present.

After 16 years of relative seismic quiescence, ~~likely~~ possibly characterized by low-intensity earthquakes not reported in chronicles, a short-term precursory phase began in 1536. It started with continuous seismicity, without major damage (Io = III -IV), continuing with similar features until the early 1537. It is possible that this last seismic phase, characterized by relatively low magnitude, was caused by low-frequency seismicity, resulting from magma oscillations during the fractures opening (see Chouet, 1996). This seismicity became more frequent just before the eruption. In February of the same year, the seismic activity peaked with stronger events (Io = VI - VII), accompanied by an increase in the fumarolic activity at Solfatara. This provides evidence that this seismicity could be again related to perturbations in the hydrothermal system. A final increase in seismic activity (Io = VIII), began in mid-June 1538, accompanied by a localized, significant additional ground uplift at the eruption site, located 3 km away from the center of previous maximum uplift (Fig. 19a – interval C) (Parascandola, 1943, Rolandi et al., 1986; Guidoboni and Ciuccarelli, 2011; Guidoboni, 2020).

-

6.2 The post-eruption seismicity

We will now consider the seismic phase following the eruption just described, which we will indicate as the ***aftereffect of the 1538 eruption***. This phase was likely triggered by continuing degassing from the deep magma chamber, and/or by new episodes of shallow magma intrusion not reaching the surface to erupt. It began in 1564 with earthquakes of medium intensity (Io = V - VI), followed by a phase of lower intensity 2 years later. In 1570 seismic intensity increased (Io = VI - VII), causing damage to the buildings of the city of Pozzuoli. Between 1575 and 1580 a new phase of low seismic intensity began, culminating, in 1582, with two earthquakes, respectively of intensity Io = VII – VIII. These earthquakes caused partial collapses in several houses and serious damage to churches and buildings, as well as numerous casualties (Parascandola, 1943; Guidoboni e Cucciarelli, 2010; Guidoboni, 2020).

4. Comparison of precursory phases of 1538 eruption with current unrest

This study is mainly aimed at understanding how the evolution of the ground movement and seismicity phases linked to the 1538 eruption can help build realistic scenarios for the evolution of the same recent phases at the Campi Flegrei caldera. Common features between the medieval and present-day unrest phases are described in the following:

The main similarity is that the seismicity, in the past and in the recent unrest, has been clearly correlated both with the total uplift and the uplift rate; it is practically absent in periods of subsidence (Dvorak and Gasparini, 1991; Kilburn et al., 2017; Troise et al., 2019).

We found, in particular, that seismicity of period 1950-2024 is on the same order than the period 1430-1503, whereas the latter, as we have previously observed, was the first phase of preparation of the 1538 eruption. Although the total amount of uplift in the period 1430-1503, about 10 m, was more than double than the total uplift recorded since 1950-2023, of about 4.1 m., the seismicity in the two periods has been remarkably comparable. The maximum magnitude, M=4.4 recently occurred on May 20th, 2024, is in fact very similar to the maximum magnitude reconstructed for the period 1430-1503 (Fig.19a interval A and Fig.19b interval A').

It is also interesting to compare the average uplift rate before the 1538 eruption with that observed since 1950 to present. In particular, we can compare the average uplift rate occurred in the first 70-73 years, since 1430 to 1503, with that observed since 1950 till now. In the period 1430-1503 maximum ground uplift was about 10 m, thus implying an average uplift rate of about 13.5 cm/year; actually, the average ground uplift since 1950 has been less than half [at] 6.1 cm/year, It is anyway interesting to note that, in the last years, the continuous uplift period still ongoing is characterized by [although it has since (DATE), it has been increasing to] an average uplift rate of about 12-20 cm/year.

Another common feature is that both seismic phases, as well as ground uplift, can be mostly ascribed to the effect of pressurized hydrothermal fluids (Moretti et al., 2017; 2018; Troise et al., 2019). So, till now there is a close analogy between the 'long term precursory phase' preceding the 1538 eruption and the recent unrest 1950-2023; the only clear difference is, as we already noted, the much lower cumulative uplift (and consequently average uplift rate) of the recent unrest.
Such observations led us to consider two possible scenarios for the evolution of the present unrest.

ADD MORE RECENT PAPERS HERE.

Not convincing. One possibility Surely the stretching of crust is also important?

7.1 First scenario

The first scenario would imply that the present unrest progresses towards a new eruption. Although there is, presently, no evidence for shallow magma intrusions occurring during the present unrest since 2006 (see Moretti et al., 2017, 2018; Troise et al., 2019), a new shallow magma intrusion, in the near future, cannot be ruled out. Another possibility is that the mush, which should be present at low depth, could be re-mobilised by hot fluids coming from the main magma chamber, the way we explained in the previous paragraphs. Troise et al. (2019), showed in fact evidence for a likely shallow magma intrusion occurred at about 3 km of depth, during the 1982-1984 unrest, with a volume of about 0.03 km^3, i.e. the same order of magnitude of the erupted volume in the 1538 event. The same authors calculated, in agreement with other authors (Woo and Kilburn, 2010; Moretti et al., 2013; Moretti et al., 2018), that such a sill intrusion should have solidified, in form of mush, after about 20 years, i.e. around 2003. If the actual unrest will progress towards an eruption, it is also very likely that seismicity will increase, in frequency and magnitude, possibly reaching magnitudes around 5 or even higher. Earthquakes of magnitude 5, in this area, would occur at very shallow depths (not higher than about 3 km), so producing high intensities (higher than VIII MCS, see Fig. 19). Finally, from a civil protection perspective, we must also take into account the possible onset of a post-eruptive seismic phase, which after the 1538 eruption lasted more than about 40 years. In conjunction with the prefigured scenario, the problem of forecasting the position of a new eruptive vent is also extremely relevant because, in principle, it could be opening in any sector of the caldera. Despite the indications contained in several probabilistic studies on the subject (Alberico et al., 2002; Selva et al., 2011), we

No — SOLIDIFIED as rock.
The claim for 'mush' here is weak.
Do you really need it?

No! This is not correct. Go straight to large deformation before 1538.

of cumulative number of earthquakes as a function of cumulative uplift, that such critical value would have been reached and overcome in 2015. Besides any speculation on their interpretations, it is clear that, if the internal stress had really overcome the critical level in 2015, considering the large additional uplift cumulated since then (about 0.90 m.), and hence the considerable incremental stress, the system would have already collapsed, and an eruption occurred. The very high deformation occurred before the 1538, namely 16 m plus the localized uplift occurred just at the vent site before the eruption, seems to indicate that the critical stress level, at that time, was may have been much higher than the one presently reached. So, if it could be assumed the medium strength today is similar, there is a possibility that the progression towards eruption conditions is too gradual to culminate in an actual eruption, and the unrest may cease before reaching that point; or, however, that the time to reach the critical stage will be much longer (200-250 years, instead of about 100).

Why longer if strength lower?

5. Conclusion

In this paper, we have presented a detailed reconstruction of the ground deformation, and a comprehensive analysis of the main observations characterizing the events before, during and after the 1538 Monte Nuovo eruption, the only eruption occurred at Campi Flegrei caldera in historical times. This reconstruction, based on clear historical evidence, has allowed us to correct some widely diffused but questionable reconstructions, found in the past and recent literature.. Specifically, we demonstrated that subsidence in the area began, at least, during the Greek colonization (VIII century BC) and persisted through Roman times, with documentation dating back to 90 BC. Additionally, we reconstructed the evolution of ground deformation at Pozzuoli harbor during the Middle Age, demonstrating that maximum subsidence occurred around 1430. We also tracked the ground level from 1430 until the first half of the 19th century, using historical data on the height of the Serapeum floor relative to sea level.

Furthermore, by reconstructing the subsidence and uplift of the Via Herculea, based on ancient chronicles, we provided clear evidence indicating that the local uplift preceding the eruption at the Monte Nuovo site, situated near Via Herculea, did not exceed 5-7 meters, since Via Herculea never re-emerged from sea before and during the eruption. This evidence disproves claims in recent literature (Di Vito et al., 2016), that suggested local uplift around M. Nuovo reached elevations as high as 19 m immediately before the eruption.

Our reconstruction of geophysical anomalies (mainly ground displacement and seismicity) preceding and following the 1538 eruption has been tentatively interpreted in comparison with observations and data collected during the recent unrests. This approach enables the formulation of two possible scenarios for the evolution of the present unrest, which, so far, has shown notable similarities to the long-term precursors of the 1538 eruption.

This needs further study. It doesn't ~~really~~ follow from the new analysis and could be omitted.

must consider they are biased by the assumption of stationary conditions, which is implied in any probability computation based on the frequency of past events; they just rely on the most frequent vent locations of the past. As the most evident example that such probabilistic determinations have a poor reliability, it is enough to note that, on the basis of similar calculations, the site of the 1538 Monte Nuovo eruption would have never been predicted. A more reliable indication of the most likely future vent could come from the most seismic areas, because they reflect the areas of maximum shear stress. In this perspective, the Solfatara-Agnano area (see Fig. 15a), which is by far the most seismically active one, could be the most probable site for future vent opening. However, the most effective way to address this problem would be the prompt determination of localized uplift in addition to the usual bell-shaped one centered on Pozzuoli harbor. Although some recent eruptions (e.g. at Hekla volcano: Wonderman, 2000) show that the rise of magma from several km to the surface can be so fast to be practically useless for civil protection purposes, localized and considerable ground uplift was actually observed before the 1538 eruption, making it likely that this precursor will be observed before a future eruption in the area.

We must however consider the possibility that, even without new shallow magma intrusions, ~~and/or in absence of mobilized mush eruption,~~ the increase of pressure for aquifer heating above the critical threshold could produce a phreatic eruption. Phreatic eruptions are in general very difficult to forecast, and also to detect from the past geological record. However, there is some robust indication for at least one phreatic eruption occurred in the area, in 1198 (Scandone et al., 2010); it is also realistic that most of the phreatomagmatic eruptions in the area started as phreatic eruptions, as explained in previous paragraphs. The phreatic scenario deserves maximum attention for the current evolution of the CF unrest, because of its serious implications for civil defense purposes, and for the even higher difficulty to be forecasted, with respect to a magmatic eruption.

7.2 Second scenario

As an alternative scenario, we should consider the one which stops sometimes without evolving towards an eruption. Despite the similarity of the recent unrest with the first phase leading to the 1538 eruption, we could in fact consider the notable difference in the cumulative uplift between the past and present unrests: 10 m., as compared with less than 4.5 m. The level of ground uplift is critical, because it indicates the level of stress accumulated underground. As pointed out by Kilburn et al. (2017), when the level of stress reaches a critical value, the medium rheology becomes totally fragile and any small amount of incremental stress can cause the collapse (i.e. the catastrophic fracturing) of the shallow crust, thus producing the eruption. Actually, we don't know the critical stress level for the shallow crust at Campi Flegrei. Kilburn et al. (2023) claimed, from the observation of the trend

But the idea is still valid. Indeed, 2015-2017 saw the return of significant seismicity, ~~the crust~~ consistent with a greater "fragility".

The first scenario involves the progression of phenomena towards an eruption, suggesting that, in the near future, earthquakes with magnitude up to 5 or slightly higher may occur, both preceding the eruption and persisting for several decades afterward. Conversely, the alternative scenario, implies that the unrest may cease before an eruption occurs. This possibility is supported by the fact that ground uplift observed from 1950 to 2024, compared with the uplift occurred over an equivalent period from 1430 to 1503, is significantly lower (4.3 m as compared to 10 m). Since the overpressure in the system is somewhat proportional to the amount of uplift, it is plausible that the recent unrest has not reached the critical value for catastrophic fracture of shallow rocks. In addition, if cumulative stress increases too slowly, a substantial amount of previous stress can be cleared depending on viscoelastic relaxation and its characteristic times. While the exact critical threshold and viscoelastic relaxation time remain unknown, they can be tentatively inferred from the maximum deformation observed before the 1538 eruption. The bell-shaped cumulative vertical displacement centered at Pozzuoli, before the 1538 eruption, was much larger, reaching 16 m., compared to the about 4.5 m recorded from 1950 to 2024. This substantial difference, assuming the rheology and strength of shallow rocks in the 0-3 km depth range remain unchanged, would suggest that we are currently far from reaching the critical stress threshold necessary for an eruption.

A further, important consideration, coming from the observation that pyroclastic flows from 1538 reached the centre of Pozzuoli, is that even a very small eruption (as the 1538 one) can produce pyroclastic flows travelling some km on flat ground.

Finally, this work put in evidence that the most critical events, with civil defense implications, we could reasonably expect in case of a future eruption, are the following:

1) increasing seismic activity and M 5 events

~~2) phreatic eruption~~

~~3) phreatic eruption followed by a phreato-magmatic one~~

~~4) pyroclastic flows travelling more than 3 km, inside the caldera, even in case of a small, VEI=2 eruption like the 1538 one.~~

Data availability

All raw data can be provided by the corresponding authors upon request.

Author contributions

GR, GDN and CT analyzed historical and volcanological data; GDN and CT analyzed earthquake intensity/magnitude data; MS analyzed seismic data; GR, MS and MDL wrote the manuscript draft and prepared the figures; GDN, CT and MS reviewed and edited the manuscript.

Competing interests

The authors declare that they have no conflict of interest.

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References

Acocella V., 2010. Evaluating fracture patterns within a resurgent caldera: Campi Flegrei. Italy. Bull. Volcanol., 72, 623-638.

Acocella V., 2019. Bridging the gap from caldera unrest to resurgence. Front. Earth Science, 7, 173. https://doi.org/10.3389/feart.2019.00173.

AGIP, 1987. Geologia e geofisica del sistema geotermico dei Campi Flegrei. Servizi Centrali per l'Esplorazione, SERG-MMESG, San Donato

Alberico, I., Petrosino, P., and Lirer, L., 2011. Volcanic hazard and risk assessment in a multi-source volcanic area: the example of Napoli city (Southern Italy), Nat. Hazards Earth Syst. Sci., 11, 1057–1070, https://doi.org/10.5194/nhess-11-1057-2011, 2011.

Altaner, S., Demosthenous, C., Pozzuoli, A., Rolandi, G., 2013. Alteration history of Mount Epomeo Green Tuff and a related polymictic breccia, Ischia Island, Italy: Evidence for debris avalanche. Bulletin of Volcanology 75, 5, https://doi.org/10.1007/ s00445-013-0718-1

Amato, L. and Gialanella, C., 2013. New evidences on the Phlegraean bradyseism in the area of Puteolis harbour. Conference: Geotechnical Engineering for the Preservation of Monuments and Historic Sites. https://doi.org/10.13140/2.1.2326.0482

Amoruso, A., Crescentini, L., Berrino, G., 2008. Simultaneous inversion of deformation and gravity changes in a horizontally layered half-space: Evidences for magma intrusion during the 1982–1984 unrest at Campi Flegrei caldera (Italy). Earth Planet. Sci. Lett., 272, 181–188. https://doi.org/10.1016/j.epsl.2008.04.040.