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Key Points:
- 20 archeological sites at Campi Flegrei show two post-1538 eruption subsidence phases, separated by an undocumented uplift in 1540–1582
- During 1540–1582, a central sill-like source (~3.5 km depth) transfers magma below Monte Nuovo, representing an aborted eruption
- From 1538 to 1650 a deeper magmatic layer (~8 km depth) experienced continuous magma supply, also during caldera subsidence

Supporting Information:
Supporting Information may be found in the online version of this article.

Correspondence to:
E. Trasatti,
elisa.trasatti@ingv.it

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Author Contributions:
Conceptualization: Elisa Trasatti, Carmine Magri, Valerio Acocella, Mauro A. Di Vito
Data curation: Carlo Del Gaudio, Ciro Ricco, Mauro A. Di Vito
Formal analysis: Elisa Trasatti, Carmine Magri, Carlo Del Gaudio
Methodology: Elisa Trasatti, Carmine Magri, Carlo Del Gaudio, Ciro Ricco
Software: Elisa Trasatti
Supervision: Valerio Acocella
Writing – original draft: Elisa Trasatti, Carmine Magri, Valerio Acocella, Carlo Del Gaudio, Mauro A. Di Vito

Magma Transfer at Campi Flegrei Caldera (Italy) After the 1538 AD Eruption

Elisa Trasatti[1], Carmine Magri[2], Valerio Acocella[2], Carlo Del Gaudio[1], Ciro Ricco[1], and Mauro A. Di Vito[1]

[1]Istituto Nazionale di Geofisica e Vulcanologia, Napoli, Italy, [2]Università Roma Tre, Roma, Italy

Abstract Shallow magma transfer is difficult to detect at poorly monitored volcanoes. Magma transfer before the last 1538 eruption at Campi Flegrei caldera (Italy) was exceptionally tracked using historical, archeological, and geological data. Here, we extend that data set to 1650 to uncover any magma transfer during post-eruptive subsidence. Results show two post-eruptive subsidence phases, separated by a previously undocumented uplift during 1540–1582. Uplift highlights the pressurization of the central (~3.5 km depth) and peripheral (~1 km depth) pre-eruptive sources, suggesting an aborted eruption. The subsidence events mainly require the depressurization of the central source and pressurization of a deeper magmatic layer (~8 km depth). Therefore, despite the overall post-eruptive deflation, after 1538 the deeper reservoir experienced continuous magma supply, with magma almost erupting between 1540 and 1582, challenging the common assumption of post-eruptive deflation. This underlies the importance of monitoring the deeper magmatic systems, also after eruptions, to properly assess their eruptive potential.

Plain Language Summary Today, volcanic activity is monitored by satellite and ground networks. However, very little is known about the pre- and post-eruptive behavior of volcanoes before the instrumental era. Here, we present a unique set of archeological records related to the elevation changes at Campi Flegrei caldera (Italy) during 1515–1650, mainly focusing on its behavior after the last 1538 eruption at Monte Nuovo. After the eruption, subsidence occurred from 1538 to 1540, followed, from 1540 to 1582, by a previously unreported uplift; the latter was followed by renewed subsidence until 1650 at least. Modeling the sources responsible for the deformation, we find that, despite the depressurization of shallow sources, after 1538, a deeper magmatic layer (~8 km depth) experienced continuous magma supply, with magma almost erupting between 1540 and 1582. This questions the common notion of post-1538 deflation at Campi Flegrei, where the depressurization of the shallower sources masks the pressurization of the deeper magmatic system for more than a century.

1. Introduction

Understanding how shallow magma transfer occurs at volcanoes plays a key role to depict a conceptual model of how a volcano works and, possibly, to forecast where and when an eruptive vent may open. This becomes particularly relevant in the case of calderas, characterized by volcanism resulting from complex processes of magma transfer (Acocella, 2021, and references therein). Monitoring data are essential to constrain how magma is transferred within a volcano, as it has been demonstrated for example, at Etna, Stromboli, Bárðarbunga, and Kīlauea (Neal et al., 2019; Neri et al., 2004, 2008; Sigmundsson et al., 2014). However, identifying shallow magma transfer becomes extremely challenging for volcanoes that have erupted before the instrumental epoch spanning the last decades, where monitoring data are not available. At the same time, evaluating magma transfer during historical eruptions would be valuable to better understand how a volcano that has not erupted for centuries may behave in case of pre-eruptive unrest and ultimately optimize risk mitigation efforts. This is the case of Campi Flegrei caldera (Italy), whose last eruption occurred in 1538 AD. In this case, with an exceptional data set, deriving from the merging of detailed historical, archeological, and geological information, Di Vito et al. (2016) reconstructed the path of magma transfer immediately before the 1538 eruption. These results provided the basis to also explain the location of the recent eruptive vents within the caldera through a physical model that may be used to forecast the most likely location of future vents (Rivalta et al., 2019). Here, we use an updated and extended version of the data set by Di Vito et al. (2016) to study the post-1538 dynamics of the caldera, trying to capture any magma transfer during the widely known post-eruptive deflation (e.g., Morhange et al., 2006).

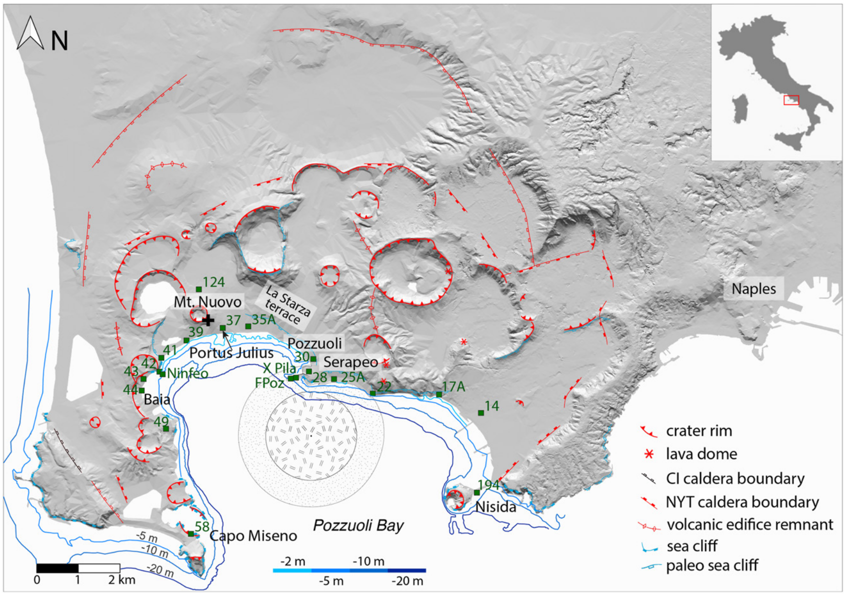

Figure 1. Morpho-structural map of the Campi Flegrei caldera (Italy), after Costa et al. (2022) and references therein. The caldera boundary and the main features of the edifices of the recent volcanism (younger than 15 ka) are marked (CI, Campanian Ignimbrite; NYT, Neapolitan Yellow Tuff). The leveling benchmarks corresponding to the measurement sites are indicated by green squares, along with their nomenclature according to Di Vito et al. (2016). The two disks are the surface projection of the central sill-like source (in-scale, radius of 1,750 m, during 1515–1536, and average radius of 1,100 m, during 1536–1650). The center of the magmatic source below Monte Nuovo is reported with a black cross. The bathymetry contour lines are from Istituto Idrografico della Marina (1987).

Campi Flegrei, in the densely inhabited metropolitan area of Naples, is one of the most dangerous active volcanoes on Earth. It consists of a ∼12 km wide depression hosting two nested calderas formed during the eruptions of the Campanian Ignimbrite (∼39 ka) and the Neapolitan Yellow Tuff (∼15 ka) (Figure 1; Orsi et al., 1996; Rosi & Sbrana, 1987; Vitale & Isaia, 2014). In the last ∼5 ka, resurgence, with uplift >60 m in the central part of the caldera (Pozzuoli area), was accompanied by volcanism of the "III epoch" of activity (Isaia et al., 2019; ∼4.8 to ∼3.8 ka; Di Vito et al., 1999 and references therein). After ∼3 ka of quiescence, increasing seismicity and uplift preceded the last eruption at Monte Nuovo in 1538 for several decades (Di Vito et al., 1987, 2016; Guidoboni & Ciuccarelli, 2011). The most recent activity culminated in four unrest episodes between 1950–1952, 1969–1972, 1982–1984, and 2005–present, with uplift at Pozzuoli of ∼0.7, ∼1.7, ∼1.8, and ∼1 m, respectively (Chiodini et al., 2016; Del Gaudio et al., 2010). Some authors considered the unrest episodes as being magma-driven (Amoruso et al., 2017; D'Auria et al., 2015). The post-1980 deformation largely results from a magmatic oblate or sill-like source at ∼4 km depth below Pozzuoli (e.g., Amoruso et al., 2014; D'Auria et al., 2015; Trasatti et al., 2015). However, an important role for the hydrothermal system has been also proposed (Battaglia et al., 2006; Bonafede et al., 2022; Troise et al., 2019 and references therein).

Here, we extend the historical, archeological, and geological data set by Di Vito et al. (2016) to 1650, and use it to investigate any post-eruptive magma transfer. In order to place the post-eruptive dynamics at Campi Flegrei in a proper context, we briefly reconsider the immediate pre-eruptive history, from 1515 to 1538. We anticipate that the reconsidered pre-eruptive dynamics is consistent with Di Vito et al. (2016). The pre-eruptive magmatic sources have been then used to characterize the post-eruptive dynamics of the caldera, with the addition of a magmatic layer at 8 km depth, which was not accounted for in the previous reconstruction.

2. Materials and Methods

2.1. Elevation Changes From Archeological Records

The analysis of 20 sites (Figure 1 and Supporting Information S1) located along the coast of the Bay of Pozzuoli allowed reconstructing the ground displacements predating and following the 1538 Monte Nuovo eruption. The sites were selected near (<200 m) the benchmarks of the INGV - Observatorio Vesuviano leveling network, established since 1905 by the IGM (Istituto Geografico Militare), to take in account in the analysis the ground movements that occurred in the caldera since 1905 (Del Gaudio et al., 2010). Our reconstruction has been carried out integrating geomorphological, sedimentological, paleontological, archeological, and historical data, in agreement with the method described in Di Vito et al. (2016) and in the related supplementary material. The data set in Di Vito et al. (2016) consists of four measurements in 1251, 1400, 1536, and 1538. In the present study, the analysis of historical documentation and the integration with field data allowed us to extend the data set at the same sites focusing on the post-eruptive phases, obtaining elevations for the years 1515, 1536, 1538, 1540, 1582, and 1650.

Details on the reconstruction and the used material are reported in the Supplementary Material (Text, Table S1, and Figures from S1 to S6 in Supporting Information S1). In particular, the emersion/submersion of dated sources (maps, paints, engravings, etc.) along the coastline permitted their comparison with the shallower bathymetry (Figure 1; Istituto Idrografico della Marina, 1987) and to estimate ground elevation changes with respect to the sea level in the periods considered. The analysis includes sea-level indicators from ancient building, maps or historical reports, notches, marine and transitional sediments, fishponds, ancient harbors and related structures, moorings, ancient roads, buildings and related floors, maps showing the submerged or emerged position of any of these features at a given time. The presence of well-dated edifices and their modifications through time due to the variation of the relative sea level in response to the elevation changes corroborated this reconstruction (a representative example of the reconstruction is described in the supplementary text and in Figure S6 of Supporting Information S1). Table S1 in Supporting Information S1 reports the measurement details for all the 20 sites, along with the corresponding closest benchmarks of the leveling network, as also reported in Figure 1. This correspondence allowed to subtract the post-1905 (first leveling measurement by the IGM) vertical displacements from the archeological estimates and to reconstruct the complete time-series with the pre-1905 elevation changes estimates described above. The time-series of each site have been connected to those of Di Vito et al. (2016) to complete the time-loop from 35 BCE, obtaining the elevation changes reported in Table S2 of Supporting Information S1.

The estimate of the error associated with the elevation changes was mainly based on the interpretation of coastal features (bathymetry) and sources (representation of the coastline), on historical maps, paintings as well as chronicles. As for the historical engravings, the error estimation considers the observer's parallax error and the image quality, assuming that the paintings were executed under favorable weather conditions. Elevation errors are, with the exception of Portus Julius (next to Monte Nuovo), between 0.5 and 0.8 m, and between 1.0 and 1.5 m in several sites in the year of the eruption, 1538. At Portus Julius the larger errors (up to 2 m) are associated with larger displacements (up to 20 m).

2.2. Modeling of the Deformation Sources

We perform geodetic data inversions using the Python tool Volcanic and Seismic source Modeling (VSM, Trasatti, 2022). The modeling is aimed at retrieving information (location, depth, and volume variation) on the sources of the plumbing system active during the uplift and subsidence phases from 1515 to 1650. We model the caldera's crust as a homogenous, isotropic, elastic half space with shear modulus $\mu = 5$ GPa and Poisson's ratio $\nu = 0.25$ (Aster & Meyer, 1988; Heap et al., 2014; Zamora et al., 1994). Because of the limitations due to the availability of only one-dimensional component of the surface displacement field (the vertical component) and of the high associated uncertainly, the inversions are carried out avoiding finding, for each phase, the best solution for all the free parameters of the sources employed. Instead, the first pre-eruptive uplift (1515–1536) is modeled as a sill-like source (Fialko et al., 2001), based on previous findings (e.g., Amoruso et al., 2014; D'Auria et al., 2015; Trasatti et al., 2015). The obtained geographical location of this central source is kept constant in the subsequent phases, while its depth, radius, and intensity (ratio between overpressure and shear modulus) are free parameters retrieved by VSM. Also, the deformation in the second pre-eruptive phase is intense not only in the caldera center but also nearby the future Monte Nuovo. Therefore, we add a second source, simply represented as an isotropic point-source (Mogi, 1958). This second source is also geographically fixed in the following phases, although keeping its depth and volume variation as free parameters, in agreement with Di Vito et al. (2016). We then consider a deep magmatic layer detected by tomographic and modeling studies (Amoruso & Crescentini, 2022; Amoruso et al., 2017; Zollo et al., 2008), placed at 8 km depth and modeled as a horizontal squared dislocation with side of 10 km (Okada, 1985). This deep reservoir allows a better description of the post-eruptive subsidence along the caldera periphery, not explained using only the central shallower source.

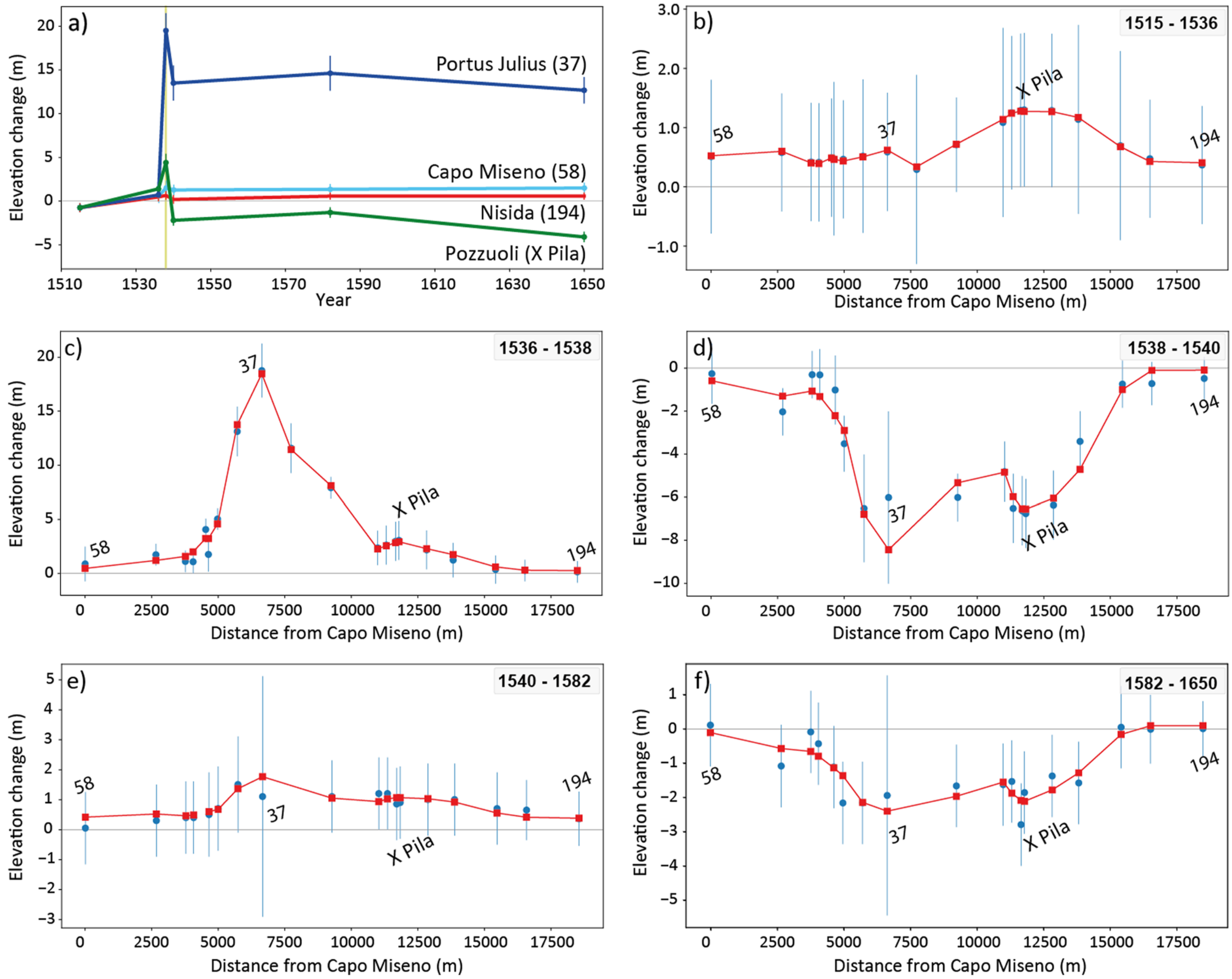

Figure 2. (a) Time series of the elevation changes since 1515 at reference sites (with benchmarks specified) in the Campi Flegrei caldera. The yellow vertical line indicates the Monte Nuovo eruption in 1538. (b–f) Elevation changes during the different periods considered in this study in the sites along the coastline of the Pozzuoli Bay. Blue: data and associated error; red: modeling results.

Also, this reservoir at 8 km depth is the top of the deeper portion of the plumbing system at Campi Flegrei, as constrained by petrological and geochemical data (Buono et al., 2022).

3. Ground Deformation Data

The integrated analysis of the multidisciplinary data set collected along the coast of the Bay of Pozzuoli allowed us to reconstruct the evolution of ground deformation at variable distance from Monte Nuovo and from the Roman market Serapeo (caldera center; Figure 1). Both sites are characterized by the largest ground deformation from 1515 to 1650 (Figure 2). The elevation changes within the caldera highlight four periods, characterized by alternations of predominant uplift (1515–1538 and 1540–1582) or subsidence (1538–1540 and 1582–1650). Here, we further divide the first uplift (the pre-Monte Nuovo uplift) in two phases, due to the different vertical ground velocities and deformation patterns. The resulting phases of elevation changes are subdivided as follows:

1. 1515–1536 (pre-eruptive central uplift): with maximum uplift of 1.4 ± 1.3 m at Pozzuoli, close to the Serapeo. The average uplift rate in this period is 4.0 ± 1.5 cm/yr.
2. 1536–1538 (pre-eruptive peripheral uplift): characterized by accelerated uplift, with average rate of 2.1 ± 1.8 m/yr. In this period, the area of maximum uplift, amounting to 18.8 ± 2.5 m, is located near the future eruptive center of Monte Nuovo (Portus Julius).

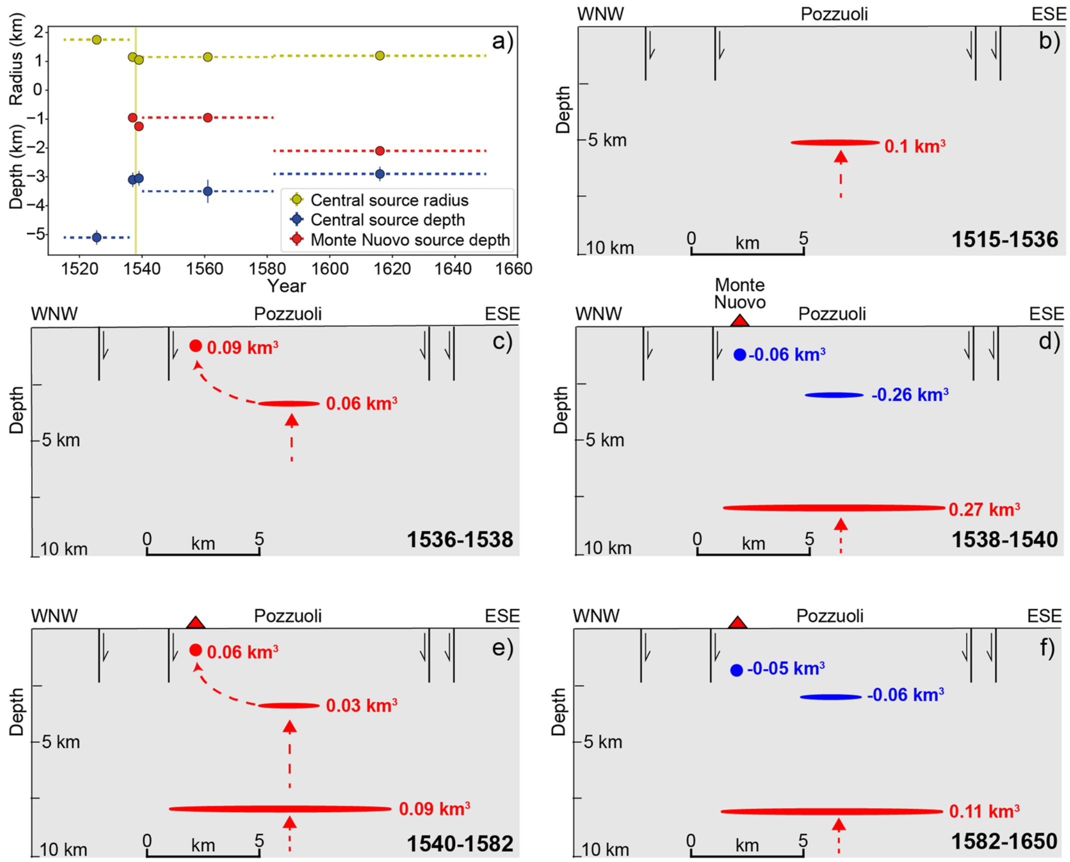

Figure 3. (a) Depth variations for the sill-like central source and the Monte Nuovo peripheral source, and radius variation for the sill-like source. The horizontal dashed line indicates the time window. The yellow vertical line is the Monte Nuovo eruption in 1538. (b–f) Sketch of the section of the plumbing system at Campi Flegrei during 1515–1650. The volume variation of the sources at each phase are reported (red for inflation, blue for deflation; dashed arrows highlight likely magma paths). The profile is approximately WNW - ESE and not to scale.

3. 1538–1540 (post-eruptive subsidence): characterized by subsidence at average rate of −1.7 ± 1.2 m/yr, culminating both at Pozzuoli (−6.7 ± 1.6 m) and close to the newly formed Monte Nuovo vent (−6.5 ± 2.5 m).
4. 1540–1582 (post-eruptive uplift): this previously unrecognized uplift, culminating at Pozzuoli (1.2 ± 1.2 m) and Monte Nuovo (1.5 ± 1.6 m), has an average rate of 2.0 ± 0.8 cm/yr.
5. 1582–1650 (post-eruptive subsidence): characterized by subsidence with rate of −2 ± 1 cm/yr, culminating both in Pozzuoli (−2.8 ± 1.2 m) and close to Monte Nuovo (−2.2 ± 1.2 m). The southern periphery of the caldera records minor uplift at benchmarks 58, 14 and 194 (Figures 1 and 2f).

4. Modeling Results

The inversions are carried out using the VSM tool implemented in Jupyter Notebooks. Data, inversion workflows and result products are stored in Trasatti et al. (2023). The modeling results are shown in Figure 2, and in the Supplementary Material (1D and 2D marginal distributions for all the phases in Figures S7–S11, and Table S3 in Supporting Information S1 summarizing the optimal parameters and related uncertainties). A synthesis of the dynamic variations of the plumbing system is shown in Figure 3. During the first pre-eruptive uplift (1515–1536), a central sill-like source is retrieved at 5.1 km depth beneath the caldera center, slightly offshore, with radius of ~1,800 m and volume change of 0.1 km^3. The second pre-eruptive phase (1536–1538) shows uplift culminating at the caldera center and, mostly, close to the future Monte Nuovo vent. This is explained by the pressurization of a central sill-like source at 3.1 km depth, with radius of 1,150 m and volume change of 0.06 km^3, and a peripheral spherical intrusion beneath Monte Nuovo, at 950 m depth with volume change of 0.09 km^3. The shallower depth of the central source respect to the previous phase can reflect the pressurization of the shallowest level of the magma chamber and/or the magma transfer from the central source to shallower depths for the incoming eruption. The 1538–1540 post-eruptive subsidence is explained by three sources: a first, depressurized central sill-like source, at 3 km depth with radius of ∼1,000 m and volume change of −0.26 km^3; a second peripheral depressurized spherical source, at 1,250 m depth beneath Monte Nuovo, with volume change of −0.06 km^3; a third pressurized deep layer at 8 km depth, with positive volume change of 0.27 km^3; this pressurized source is required to model the substantially stable elevation of the peripheral part of the caldera. The volume variations of the sill and the deep layer are similar, although with opposite sign. The volume decrease for the peripheral source below Monte Nuovo is comparable with the erupted DRE volume, amounting to 0.025 km^3 (Di Vito et al., 1987). The 1540–1582 uplift is modeled with the pressurization of the central sill-like source at 3.5 km depth, with radius of 1,150 m and volume change of 0.03 km^3 and with the pressurization of a source at 950 m depth beneath Monte Nuovo, with volume change of 0.006 km^3. The magmatic layer at 8 km depth is also pressurized, with volume variation of 0.09 km^3. The 1582–1650 subsidence is modeled with the depressurization of the central sill-like source at 2.9 km depth beneath the caldera center, with radius of 1,200 m and volume change of −0.06 km^3. The source beneath Monte Nuovo lies at 2,100 m depth, with volume change of −0.05 km^3. In addition, despite the clear subsidence of the central part of the caldera, a minor uplift is observed along the southern portion; this can be only modeled with the pressurization of the magmatic deep layer, which undergoes a positive volume change of 0.11 km^3.

5. Discussion and Conclusions

The location and depth of the 1515–1536 sources are consistent, within associated uncertainties, with those of recent unrest episodes (Figures 1 and 3; Amoruso et al., 2014; D'Auria et al., 2015; Trasatti et al., 2015) and with the source responsible for the 1400–1536 uplift (Di Vito et al., 2016). Apart from the pre-eruptive 1536–1538 period, all these short-term (months to decades) uplift episodes at Campi Flegrei culminate in this central area. The caldera center also corresponds to the maximum uplift of the resurgence (Acocella, 2010; Di Vito et al., 2016; Natale et al., 2022; Sacchi et al., 2014), suggesting a connection between the short- and longer-term deformation, implying that the central source has been active in the last 5 ka at least (Acocella, 2019; Di Vito et al., 2016; Natale et al., 2022). During the pre-eruptive 1536–1538 uplift, the depths (in average and within uncertainties) and volume changes of the sources are compatible with previous results by Di Vito et al. (2016). The central source is shallower with respect to the previous period (1515–1536), suggesting the rise of the accumulated magma. Accordingly, the lateral migration of magma from the central reservoir to the peripheral intrusion beneath the future Monte Nuovo might be driven by caldera unloading (Di Vito et al., 2016; Rivalta et al., 2019). In fact, the mass removal due to the presence of the caldera depression and the lighter caldera infilling is inferred to produce a subvertical direction of minimum compression below the caldera, responsible for lateral magma propagation.

The 1538–1540 post-eruptive subsidence is described by the deflation of both the central and peripheral sources, plus the pressurization of the deeper magmatic layer. Indeed, despite the overall post-eruptive deflation, the deeper magmatic system continued to be recharged immediately after the eruption.

In the 1540–1582 post-eruptive uplift, the constrained sources depths and volume variations suggest new magma influx at all levels below the volcano. The fact that the 1 km deep source was also pressurized just after the eruption suggests an aborted (or failed) eruption in this period (Moran et al., 2011, and references therein). The aborted eruption may be explained by an insufficient magma overpressure (e.g., Werner et al., 2011).

The second phase of post-eruptive subsidence occurred in 1582–1650, following the depressurization of the central sill-like source and the peripheral source below Monte Nuovo. Again, the modeling data in this period require the additional pressurization of the deeper magmatic layer at 8 km depth.

The elevation changes are affected by uncertainties that may lead to different modeling solutions similarly fitting the data. In this work, we propose an active plumbing system during 1515–1650 as described above and shown in Figure 3, based on previous multidisciplinary studies regarding past and recent volcanic activity at Campi Flegrei. In this evolutionary frame, some parameters of the sources remain quite stable despite the different surface deformation patterns (Figure 3a). The central sill-like source lies at about 5 km depth beneath Pozzuoli in the first pre-Monte Nuovo uplift (1515–1536), while its depth is between 3,000 and 3,500 m in all the following phases, either during uplift or subsidence. Its radius is 1,750 m in the first pre-Monte Nuovo uplift, while in the following phases is between 1,050 m and 1,200 m, suggesting a contracting reservoir. The peripheral source below Monte Nuovo remains shallow, between 950 and 1,250 m depth; it is represented as a sphere, to simplify the modeling due to the limited available data, although it may be also interpreted as the centroid of the dike path nucleated from the central source to the surface (e.g., Rivalta et al., 2015). This source deepens at 2,100 m depth during the second phase of subsidence (1582–1650), possibly suggesting the contraction due to cooling of the deeper portion of the magma pathway feeding the Monte Nuovo eruption.

Overall, the results highlight the continuous pressurization of the deeper magmatic system throughout the entire investigated post-eruptive period (1538–1650) and the pressurization of the shallower system in the 1540–1582 period, implying the uninterrupted deep inflow of magma at Campi Flegrei also short after the last eruption. This behavior has been accompanied by felt seismicity and gas emissions after 1538 and until the end of the XVI century, as reported in chronicles (Ricciardi, 2009). These features are in contrast with any common belief that the post-1538 period has been a "quiet" post-eruptive period, as tentatively suggested by the previously documented evidence of long-term post-eruptive deflation (Di Vito et al., 2016; Morhange et al., 2006). However, what appears important here is not only the detection of the continuous post-eruptive inflow of magma within the deeper magmatic system, but mostly the fact that Campi Flegrei has been uninterruptedly fed by magma from well before the 1538 eruption (approximately from the XIII century; Di Vito et al., 2016) until 1650 at least. Estimates of the volumes injected within the shallow and deeper magmatic system suggest that at least ~1.8 km^3 of magma has been intruded from approximately 1400 to 1650, compared to the negligible 0.025 km^3 DRE of magma that has been erupted during the Monte Nuovo event (Di Vito et al., 1987). This leads to a ratio of nearly 100:1 between the recently intruded and erupted magma at Campi Flegrei, providing a worrisome balance for its eruptive potential. More detailed investigations of the dynamics or the caldera in the period before the XIII century and after 1650 are needed to properly assess the magma influx that has been accompanying the activity of the caldera since Roman times to present and, indirectly, the current eruptive potential of the caldera.

On a more general frame, this study underlines the importance of monitoring the deeper portion of a magmatic system at active volcanoes, especially after eruptions, to assess the real eruptive potential. Post-eruptive deflation of shallow sources may in fact mask a deeper magmatic recharge that significantly increases the eruptive hazard.

Data Availability Statement

The elevations at each site are available in the Supplementary Material. The VSM code (https://doi.org/10.5281/zenodo.7950408) is published in Trasatti (2022) and available at https://github.com/EliTras/VSM. The inversions are carried out using Jupyter Notebooks. Data, inversion workflows and result products are stored in Trasatti et al. (2023).

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