# Caldera resurgence and the case-history of Campi Flegrei

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## Abstract

Large calderas formed by explosive eruption are often characterized by a structural uplift of the caldera floor that has been named resurgent dome or block.
The analysis of recent unrest at several calderas suggests that the resurgent dome is likely formed by the intrusion of magma at shallow depth below the light caldera infill.
Campi Flegrei is an active volcano considered the highest risk volcano in Italy and Europe and has been in a state of unrest in the last 70 years. The analysis of the past volcanological history point to an unrest localized in a central resurgent block. Different or paired interpretations on the current unrest suggest either an intrusion of magma at shallow depth (3-5 km) or a deformation governed by the poro-elastic response of a shallow hydrothermal system to changes in fluid pressure and temperature. The invariance of the shape of the deformation, as well as the diffuse degassing of the Solfatara area, hint that the unrest is related with the uplift of the resurgent block driven by magma intrusion at shallow depth.

Keywords: Campi Flegrei; Caldera; Resurgence

## 1. Introduction

Large calderas are the result of the release of the highest energy processes occurring on the Earth and it is of paramount importance to understand their formation and the evolution of their activity after the formation.

In this paper we focus on a few well studied and monitored calderas that provide insights into the mechanism of post-caldera activity and unrest. Then we discuss in more detail Campi Flegrei caldera for its threatening unrest and the wealth of data collected in the last 50 years that may help to understand the behavior of other similar volcanoes.

Calderas formed by large explosive eruptions (Williams, 1941) are usually characterized by a central depression filled by pyroclastics emitted during the major eruptions. In many cases, the low-density infill causes a circular negative Bouguer anomaly concentric with the caldera boundary (Yokoyama, 1963, Scandone, 1990)

Post-caldera activity may occur by new vents scattered inside the caldera and outside with no clear statistical distribution (Walker, 1984) ranging from vents distributed along the margin of the caldera, linear distribution, central vent, random distribution. The lack of a clear pattern may be the result of complex caldera formation and subsequent activity.

**Roberto Scandone and Lisetta Giacomelli**

Silicic calderas are often characterized by a structural uplift of the caldera floor that has been named resurgent dome (Smith and Bailey, 1968).

The resurgent dome is not formed by the accumulation on the surface of viscous magma, but rather by an inflection of the floor that may involve a large fraction of the total area of the caldera. Post-caldera activity often occurs from vents located on the border of the resurgent dome (Fig. 1).



**Figure 1.** Valles caldera in the inset. In the background the resurgent dome "Redondo Peak". In the foreground a vent of post-caldera activity "Cerro La Jara" (Photo Giacomelli-Scandone).

The cause of resurgence has been variously interpreted as due to regional detumescence, or magmatic rebound, or magma pressurization (Marsh 1984). Acocella (2021) suggested the possibility of magma accumulation at shallow levels with the formation of sills or laccoliths. The resurgent portion has a larger volume with respect to the magma erupted during post-caldera activity.

Studies of the unrest of calderas provide an insight into the mechanism of resurgence and the possible volcanic activity accompanying these events (Newhall and Dzurisin, 1988, Acocella et al., 2015).

## 2. Caldera unrest at resurgent calderas

Unrest is defined as a deviation from baseline of seismicity, or ground deformation, or gas emission (Newhall and Dzurisin, 1988). The unrest is defined as volcano-tectonic when it is caused by stress deformation processes related to the accumulation, transfer and eruption of shallow magma (Acocella, 2021).

The baseline ground deformation for many large calderas is a slow subsidence possibly caused by the compaction of light material making up the caldera floor (e.g. Campi Flegrei, Yellowstone, Ischia, etc.) (Newhall and Dzurisin, 1988). On the contrary the cases of documented unrest show evidence of episodic uplift sometimes accompanied by burst of seismicity. We share the ideas of Acocella (2021) who suggests that the resurgence is caused by repeated episodes of shallow magma emplacement responsible for a net uplift alternating with episodes of stasis or subsidence governed by the cooling and degassing of the intruded magma bodies.

This idea is further sustained by the observation that the unrest episodes at several resurgent calderas are characterized by an uplift only of the resurgent dome or bloc, and seismicity distributed along the border of the resurgent dome (e.g. Long Valley, Yellowstone, Campi Flegrei).

### Yellowstone

Yellowstone caldera was formed during three separated volcanic cycle each culminating with a voluminous caldera forming eruption (Huckleberry Ridge Tuff, 2.1 Ma, Mesa Fall Tuff, 1.3 Ma and Lava Creek Tuff 630 ka. The respective volumes are 2450 km$^3$, 280 km$^3$ and 1000 km$^3$. The eruptions gave rise to a fracture zone enclosing a cauldron block 85x45 km wide (Fig. 2) (Christensen, 2001). Post collapse resurgence formed two resurgent domes.
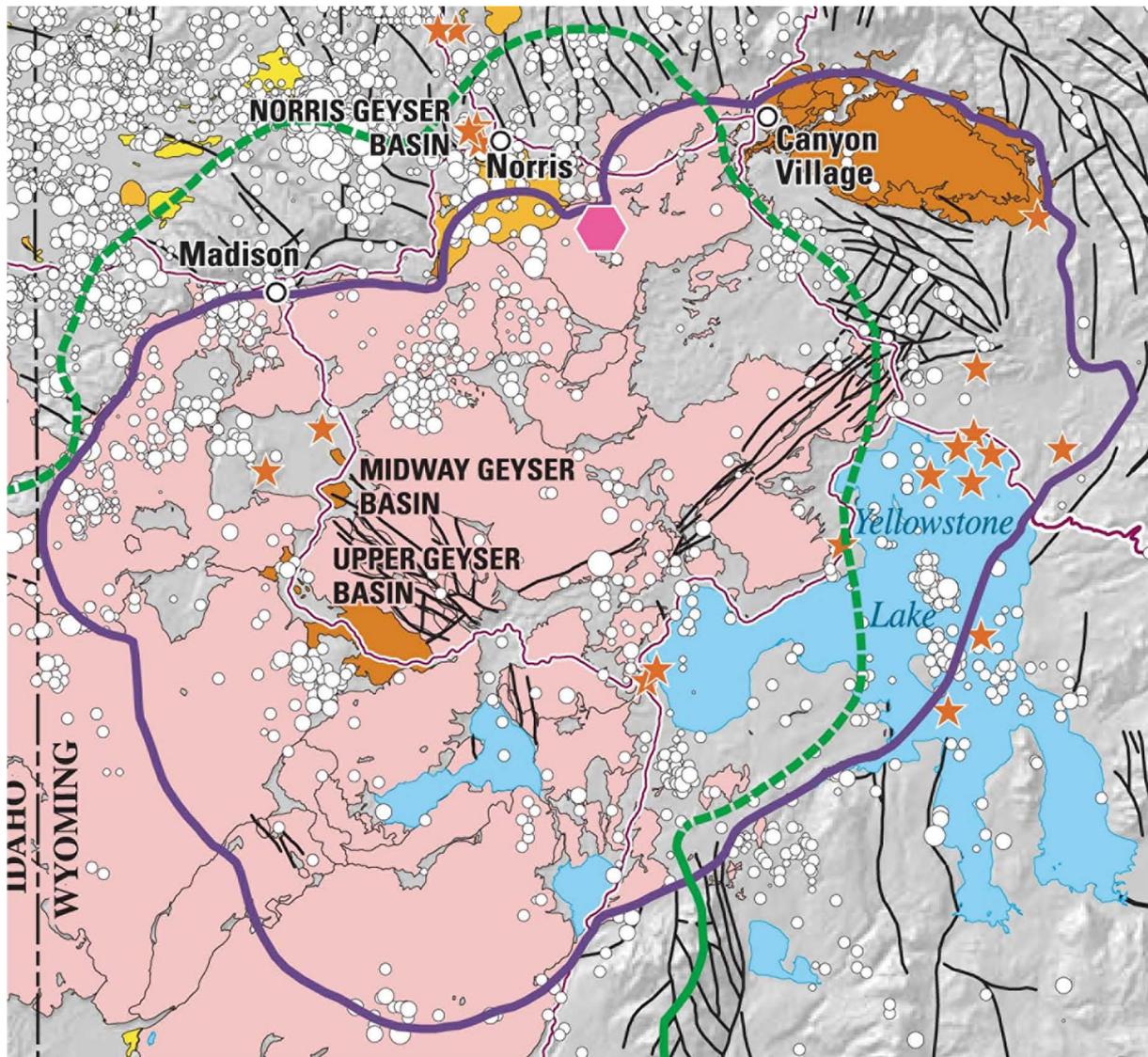


**Figure 2.** Geological sketch map of Yellowstone caldera (modified after Christensen, 2001).

The caldera displayed a recent uplift of the two resurgent domes between 1923 and 1984 followed by a period of subsidence since 1985 (Dzurisin et al., 1990). In 1995 the northern caldera rim started to inflate causing, by 1997, 30 mm uplift of the entire caldera floor, followed in 2000 by a caldera wide deflation. Wicks et al. (2006) suggest that the repeated episode of inflation-deflation at Yellowstone are caused by continuous movement of molten basalt in to and out of the Yellowstone volcanic system.

## Roberto Scandone and Lisetta Giacomelli

### Long Valley

Long Valley caldera. (Fig. 3) formed because of the voluminous eruption of Bishop Tuff, 0.76 Ma ago.
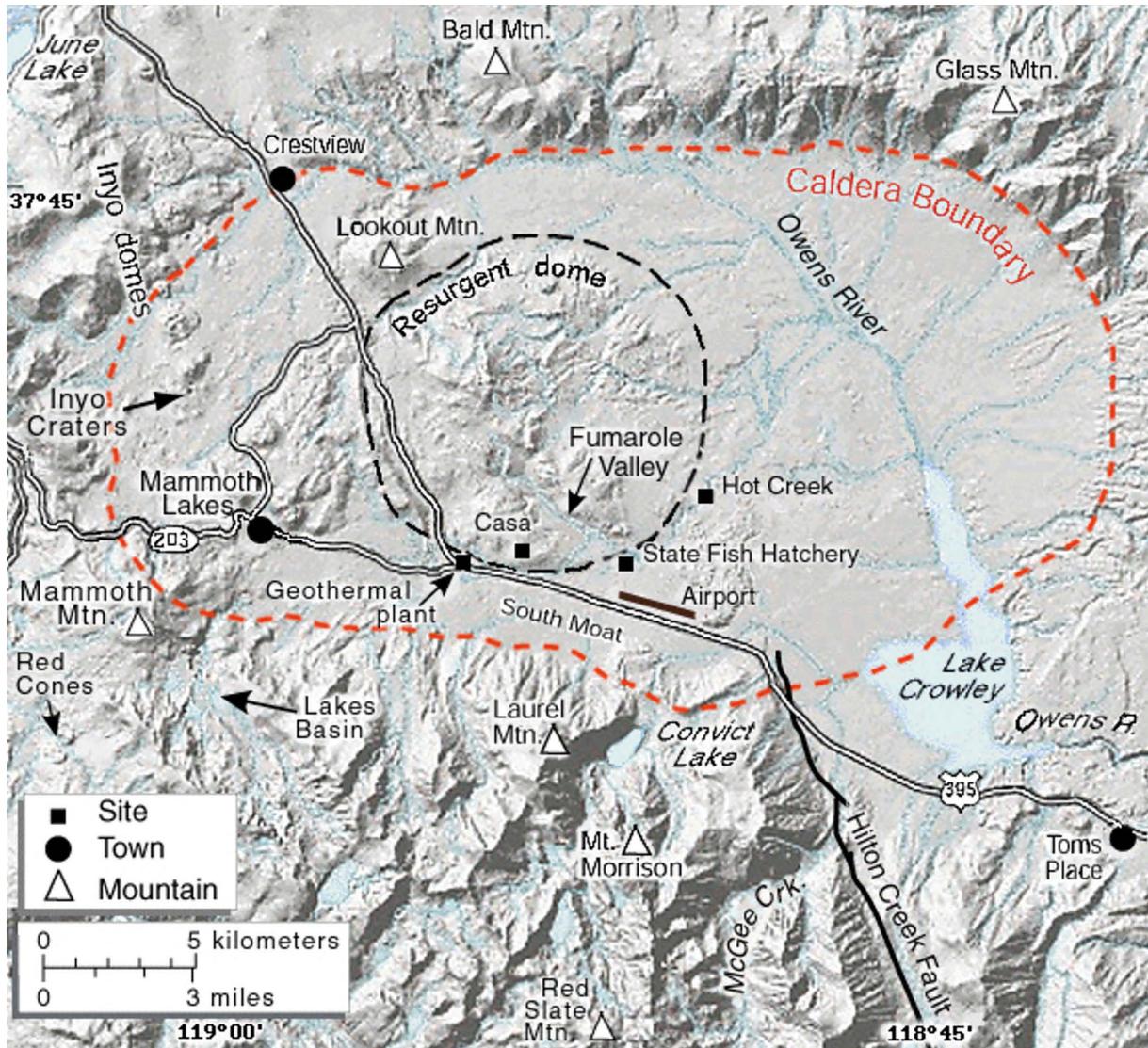


**Figure 3.** Relief map of Long Valley caldera. The center relief is the resurgent dome. The Inyo domes form the alignment crossing the northwestern border of the caldera (USGS).

Post caldera activity occurred both inside and outside the caldera along the Mono-Inyo volcanic chain, which produced some 20 eruptions over the last 5000 years, with the most recent eruption in Mono Lake just 200-300 a BP (Hill, 2006), An episode of uplift was first detected in 1980 along a leveling line first measured in 1975. This occurrence raised concern because it was preceded by 4 M = 6+ earthquakes occurring outside the caldera boundary and numerous earthquake swarms in the south moat of the caldera. An inflation of the resurgent dome by more than 50 cm till 1984 (Hill, 1984), was followed by a period of relative quiescence till 1990 when there was a renewal of the uplift with peak rates of 0.2 cm/day and 1000 M > 1.2 events/day over several days. The earthquake-swarm activity was concentrated at depths between 3 and 8 km beneath a broad, 15-km-long zone spanning the so-called South Moat Seismic Zone at the southern margin of the resurgent dome. In 1990, the crisis was accompanied by the emission of large quantities of gases, essentially $CO_2$ released by a cooling magma. This high gas flux led to the 'death' of a forest. Inflation of the resurgent dome and seismicity substantially declined in 1998 but resumed in 2002-2003 and again in 2014 totaling a cumulative uplift of 80 cm. Battaglia et al. (1999, 2003) and Montgomery-Brown (2015) suggest that the inflation can be justified by a magma intrusion below the resurgent dome.

### Rabaul

The activity at Rabaul dates to 0.12 Ma with at least two major ignimbritic eruption at 0.1 and 0.05 Ma. The better-preserved record of the last 20 ka suggests the occurrence of at least 5/9 ignimbritic eruption with volumes exceeding 1 km$^3$ (Nairn et al., 1995). The last caldera forming eruption, previously referred as the 1400 BP eruption has been recently dated at AD 667-699 (Mckee et al., 2015).

At least eight intra-caldera eruptions have occurred since the last caldera forming event, building small pyroclastic and scoria cones within the caldera (Nairn et al., 1995). The last eruptions occurred in 1878, 1937-43, 1994-2014.

Between 1973 and 1982, the seismicity of Rabaul caldera consisted essentially of shallow, short-period, volcano-tectonic earthquakes originating from about 6 km to near-surface depths. The earthquakes were distributed over a circular area within the caldera boundary. The strongest earthquakes registered at $M_L$ 5.2 and 5.1 respectively (Global volcanism, 1982). In this period a maximum uplift of 1 m was measured at the center of the caldera through a leveling network. The uplift rapidly decreased toward the edge of the caldera in correspondence with the limits of the annular seismic zone.

A seismic crisis occurred between 1983 and the first half of 1984 with a over 8000 earthquakes in a month and an uplift rate of 50 mm/month compared with a rate of 8 mm/month of the previous period (Global Volcanism, 1984).

After several years of mild seismic activity, and uplift of the order of centimeters/year (Fig. 4), Vulcan and Tavurvur, two vents on opposite sides of Rabaul Caldera erupted on the morning of 19 September 1994 and formed an eruptive column 18 km high asl.
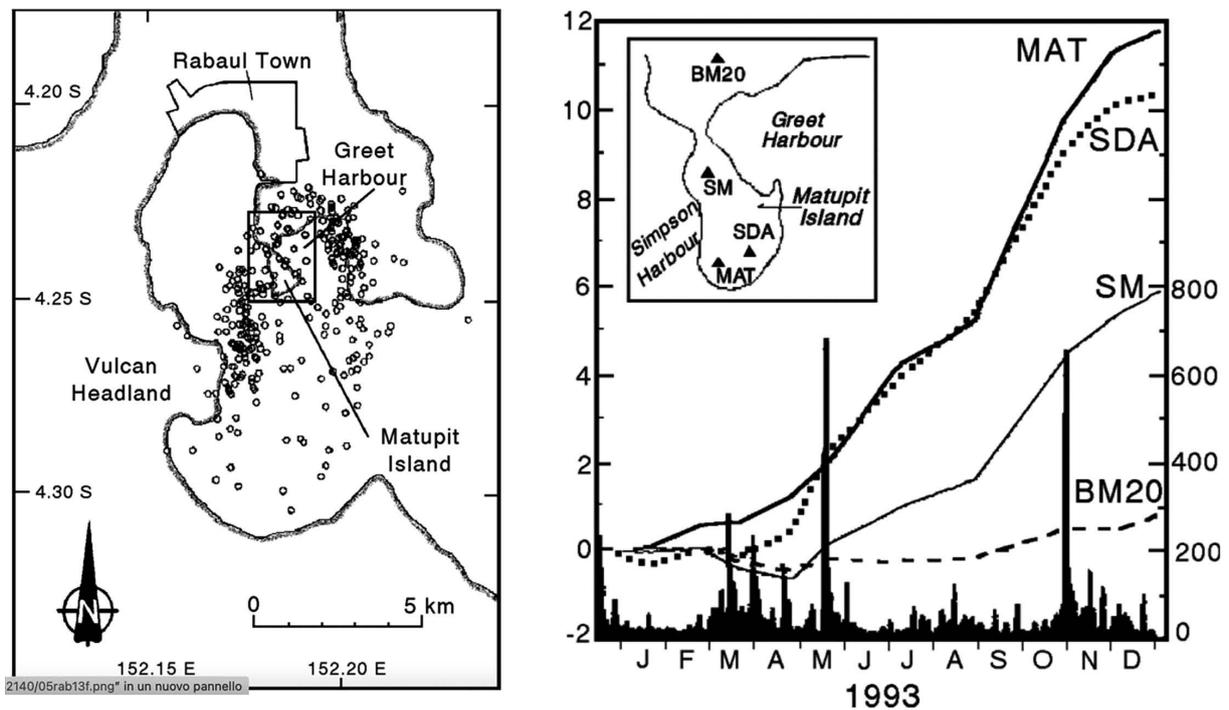


**Figure 4.** The distribution of the earthquakes occurred in 1993 (left) and the vertical ground uplift (cm) measured during 1993 (redrawn after Global Volcanism Program, 1994).

The eruption was preceded by 27 hours of unusual seismicity. On 18 September, a M 5.1 earthquake occurred beneath the harbor and was followed by an intensifying swarm of high-frequency (A-type) earthquakes, with a peak number around 2400 that night, with ~2 felt events/minute, which decreased toward morning. By 06:00 on 19 September the eruption had begun (Global volcanism, 1994).

A recent three-dimensional seismic tomography imaging (Finlayson et al., 2003) identifies a 30-35 km$^3$ low-velocity region at 3-6 km depth beneath the central Rabaul caldera, interpreted as a shallow magma chamber. The seismicity above the magma chamber can be interpreted as the rim of the plug that is deforming the central floor of the caldera because of the shallow intrusion.

## 3. Calderas with a resurgent block

Calderas with a small aspect ratio ($A_r = 1$) between the lateral extent of the uplifted dome to the depth of the magma chamber, build a resurgent block which may be tilted (Acocella, 2021). Subsequent activity occurs on the border of the uplifted block. Typical examples are Ischia and Pantelleria (Orsi et al., 1991).

The first hypothesis of a caldera with a resurgent block has been proposed by Rittmann (1930) who suggested that the central part of Ischia Island, Mount Epomeo, was a block raised because of a shallow magma intrusion and called the central part of the island, a volcano-tectonic horst (Fig. 5).
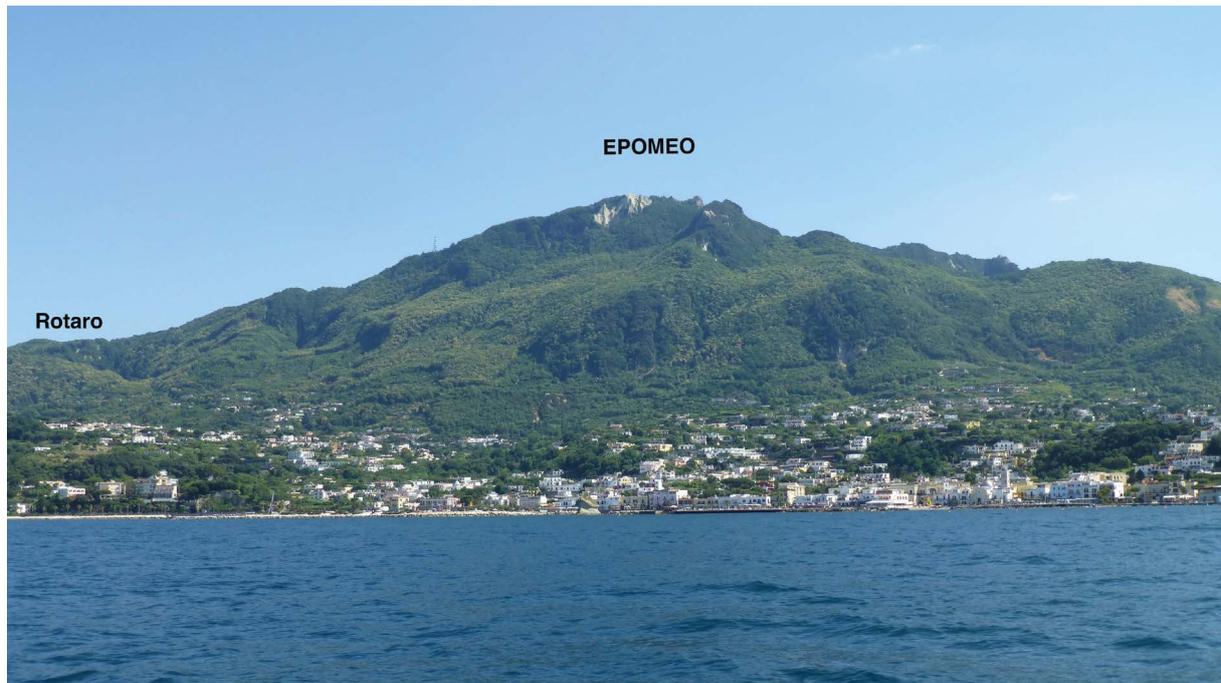


**Figure 5.** The resurgent block of Monte Epomeo at Ischia. To the left the post caldera dome of Monte Rotaro. (photo Giacomelli-Scandone).

A recent interpretation of geophysical and geological data has been recently put forward by Marotta et al. (2022) who provide a detailed structural model of the island. The most interesting aspects are the multiple magma intrusion at shallow depth causing the uplift of the central block, Monte Epomeo (Fig. 6). The intrusions are layered below a low-density layer made up by pre-caldera volcanics or volcanoclastic deposit.

To better understand the mechanism of intrusion that may be common even for many large calderas formed by explosive eruption, we must recall the mechanism of magma ascent.

Weertmann (1971) first suggested that fluid-filled cracks can propagate within the crust and demonstrated that a liquid lighter than the surrounding rocks injected into a fracture could cause it to propagate upwards. This mechanism hypothesizes that an accumulation of magma at the base of the crust, or in a magma chamber can create an overpressure sufficient to generate a fracture in the presence of a uniform tensile stress. The magma forms a fracture and fills the void thus created until the fracture reaches a characteristic length, called critical length. Once the critical length has been reached, the fracture begins to propagate upwards, always tending to open the upper end and closing the lower one.

The force that causes the displacement (Peach-Koehler force) is analogous to the Archimedean one and the same magnitude, although if it is conceptually different.

Several authors Spence and Turcotte (1990), Cashman (2004), Scandone et al. (2007), and reference cited there, suggest that magma enriched in $H_2O$ have a positive buoyancy until the surrounding rocks are denser than the gas-rich magmas. Scandone et al. (2007) further propose that magma chamber may leak single batches of magma rising because of density contrast. The light caldera infill is a formidable density barrier to the ascent of magma batches that eventually ponds at the base of the caldera floor.
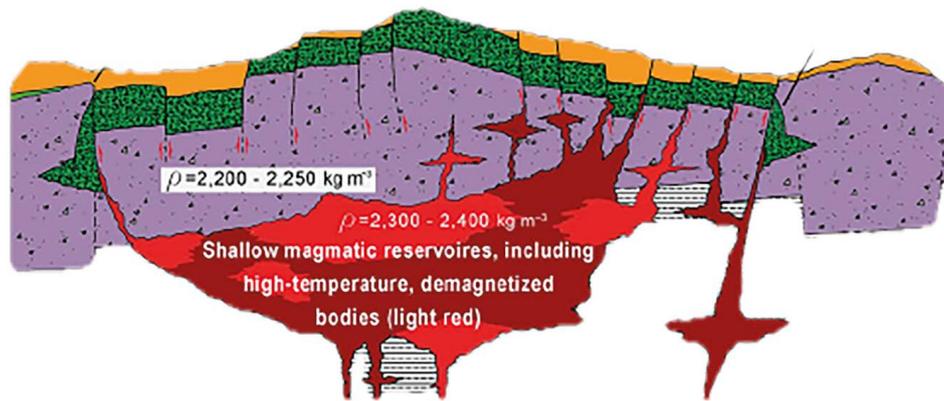
**Figure 6.** The interpretative scheme by Marotta et al. (2022) illustrating the multiple sill and laccoliths that caused the resurgence of the central block (redrawn after Marotta et al., 2022).

In this view the unrest is the result of the arrival of magma batches (magma filled cracks) at the neutral buoyancy level. Here it may cause the formation of laccoliths that deform the overlying rocks causing earthquakes and the degassing. The rise of magmatic fluids causes changes in temperature and pressure of the hydrothermal system resulting in variations in the chemistry of fumaroles and gas fluxes.

# 4. The case history of Campi Flegrei

Among the restless calderas, Campi Flegrei is of particular interest for many reasons:
– It is in a densely inhabited area since 2500 years
– The volcanological history is known in detail
– Has a long and documented history of unrests
– Part of the caldera is bordered by the sea thus providing a fixed reference of the absolute movement of the caldera floor

The volcano is active and has the highest volcanic risk in Italy and Europe (Scandone et al., 2016).

The caldera formed because of two large eruptions that occurred 39,000 and 15,000 years ago. The second eruption caused a depression bordered by circular faults with the sinking of the floor below sea water (Rosi and Sbrana, 1987, Lirer et al., 1987, Scandone et al., 1991)

The first eruption called Campanian Ignimbrite (CI) erupted a volume of 100-300 km$^3$ of magma and covered the Campanian plain with a deposit of welded ash 30-40 m thick. The most recent eruption called the Neapolitan Yellow Tuff (NYT), from the name of its deposit, which emerges mainly at the edges of the caldera, erupted a volume of 20-50 km$^3$ of magma and resulted in a less broad area of collapse than the previous one, but with a deeper drop (Scandone et al., 1991). The boundaries of the NYT caldera are shown in Fig. 7.

After the eruption of the NYT there were three periods of intense volcanic activity which were defined as epochs: the first epoch from 14,900 to 10,600 BP; the second Epoch from 9,600 to 9,100 years ago, and the third from 5,500 to 3,800 years (Di Vito et al., 1999). The last eruption was in 1538 which built the cinder cone of Monte Nuovo.

The range of eruptions in different epochs varies from highly explosive events with an Explosivity Index of 5-6 (Pomici Principali, Agnano Monte Spina eruptions) to effusive events with the emission of extremely viscous lava which gave rise to the formation of lava domes (Monte Olibano, Accademia).

The eruptions of the first Epoch occurred from emission centers near the faults bordering the NYT caldera, while the more recent ones occurred from centers towards the center of the caldera. All the volcanic activity was mainly located in the northern area or along the faults bordering the caldera to the east and west. No post-caldera activity occurred in the southern area occupied by the Gulf of Pozzuoli. Only the eruption of Nisida and Cape Miseno occurred from vents located on the border of the caldera.

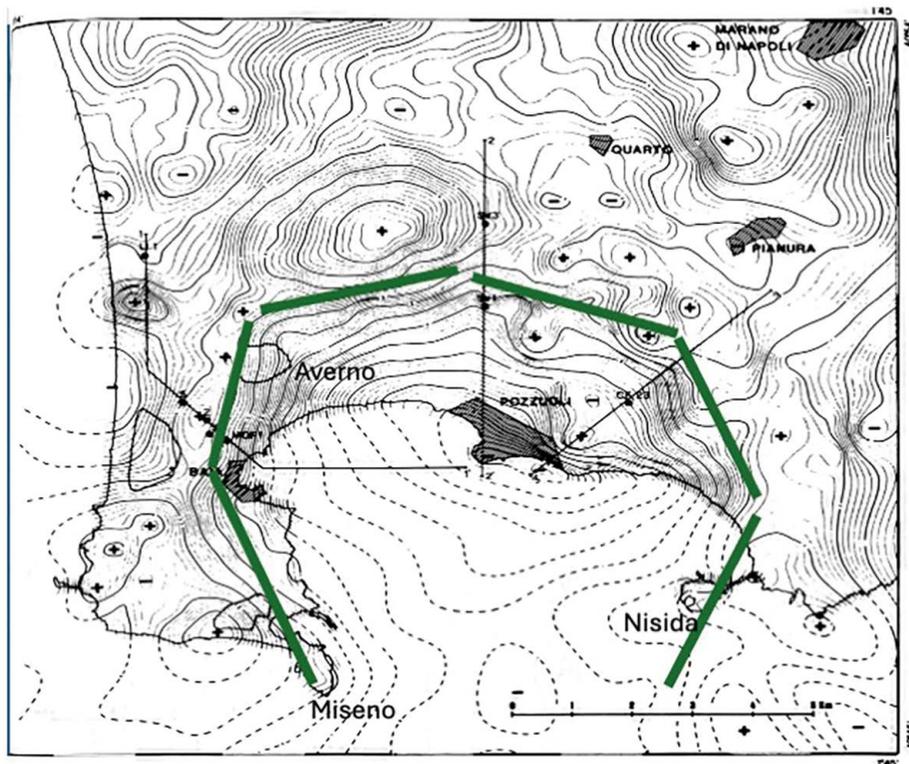The last eruption of Monte Nuovo occurred in 1538.

**Figure 7.** The NYT caldera boundaries derived by the gravity Bouguer anomaly (1 mgal interval-thick lines) based on the data of Cassano and La Torre, 1987. The caldera is smaller than that proposed basing on geological data (Vitale and Isaia 2014), suggesting a possible enlargement due to marine erosion after the caldera collapse.

With the formation of the NYT caldera, a vast gulf was formed. The post-caldera tuff cones of Epoch 1 show signs of marine erosion, which dismantled the buildings on the seaward side.

Subsequently, there was an uplift of the northern part of the caldera before Epoch 2 and Epoch 3. Both episodes, after a flare of volcanic activity, were followed by a deflation phase which, however, did not recover the initial uplift (Isaia et al., 2009).

A marine terrace called "La Starza" in the central part of the caldera, raised by 20-55 m, was formed during this phase (Fig. 8) and partially eroded by the action of the sea during the subsidence phase.

The uplift affected the central part of the caldera, delimiting a resurgent block like those of Ischia and Pantelleria.



**Figure 8.** The uplifted marine terrace of La Starza in the central part of Campi Flegrei. (Photo Giacomelli-Scandone).
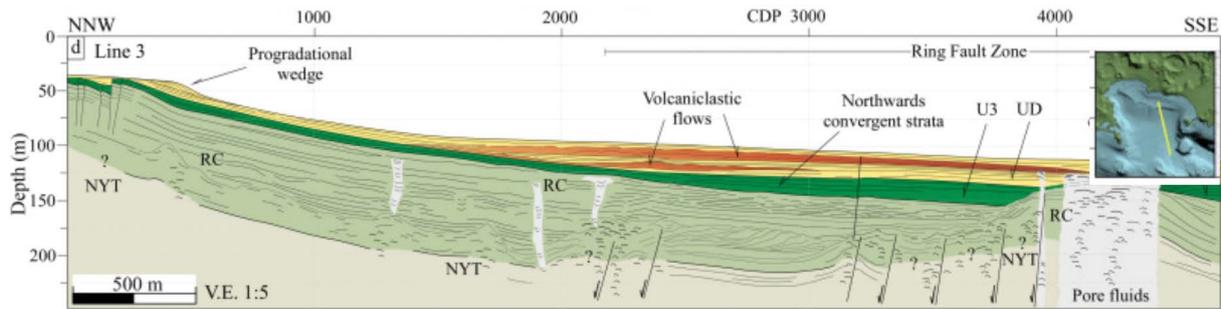
**Figure 9.** Interpretative section of seismic reflection profile of the marine portion of the NYT caldera with the resurgent, uplifted and tilted block, and moat-like features. (redrawn after Corradino et al., 2021).

The movement of the block occurred with a tilt which led to the emergence of the northern part of the caldera (Corradino et al., 2021), and a substantial modification of the eruptive styles (Fig. 9).

The uplift caused tensional fractures in the northern area which allowed the magma to rise, and the following eruptions occurred from vents located towards the center of the caldera, along the borders of the resurgent block. The emergence of the northern part of the caldera prevented the interaction between the magma and sea water and eruptions occurred in a sub-aerial environment with Plinian eruptions, strombolian eruptions or the emission of lava domes. The only exceptions to this rule were the phreato-magmatic eruptions of Miseno and Nisida which occurred on the faults bordering the caldera with magma erupting in contact with sea water.

## 5. Bradyseism and recent activity

Bradyseism is the local term used to indicate the slow ground movement. With the end of the activity of Epoch 3 (3800 years ago), the ground in the center of the caldera began to sink again with average speeds of the order of cm/year in the Pozzuoli area.

The Romans realized the problem by moving their main military port (the Portus Iulius) from Lucrino to Miseno. The civil structures of Puteoli (roman name of Pozzuoli) were also damaged and then abandoned due to the slow subsidence of the ground.

The market (Macellum) of Pozzuoli, currently known as Serapeum (Fig. 10), built in 101 BC, underwent renovation works, first with the filling and construction of a new floor in the 1st century CE (Parascandola, 1947), and subsequently (in 394-395 CE) with the construction of shelters and barriers to prevent the sea from entering during storms (Fig. 11).

Its location on the sea front of Pozzuoli is evidenced in the so-called Merida glass-flask representing the seafront of Pozzuoli, dated III-IV century CE (Camodeca, 1977, Bejarano Osorio, 2002) (Fig. 12).

The average rate of sinking in Pozzuoli was approximately 1 cm/year and the maximum submergence was reached at the beginning of the 1400s. In fact, there are images contained in a reprint of a literary work on the Phlegraean thermal springs, the "De Balneis Puteolanis" which depict the columns of the Serapeum almost completely submerged by the sea (Fig. 13).

From 1429 there were a series of royal edicts which acquired the lands where the sea was drying up for the property of the town of Pozzuoli, suggesting a renewed phase of uplift (De Vito et al., 2016).

The uplift was accompanied by episodic seismic crises which at times (1507) caused considerable damage to the cathedral of Pozzuoli. The seismicity had a more intense phase in the years 1536-1538 and culminated before and during the eruption of Monte Nuovo (Guidoboni and Ciuccarelli, 2011).

Contemporary chronicles report the main phases that led to this eruption (Scandone and Giacomelli, 2013):

*"For two years (1536-38) this region of Campania has been afflicted by earthquakes and the part surrounding Pozzuoli much more than the others: but on 27 and 28 September the earthquakes were felt continuously night and day in the city of Pozzuoli: the plane located between Lake Averno, Monte Barbaro and the sea rose…"* (Pietro Giacomo Toleto)

*-And when it was about an hour in the morning (8 pm), a mouth of fire came out, near the said hospital, in the place called the Fumosa from inside the sea, and brought out a great multitude of pumice stones, and sand, and great thunder*

**Roberto Scandone and Lisetta Giacomelli**



**Figure 10.** The Serapeum of Pozzuoli. The black mark on the columns of the roman market shows the maximum sinking of the edifice during middle age. (Photo Giacomelli-Scandone).
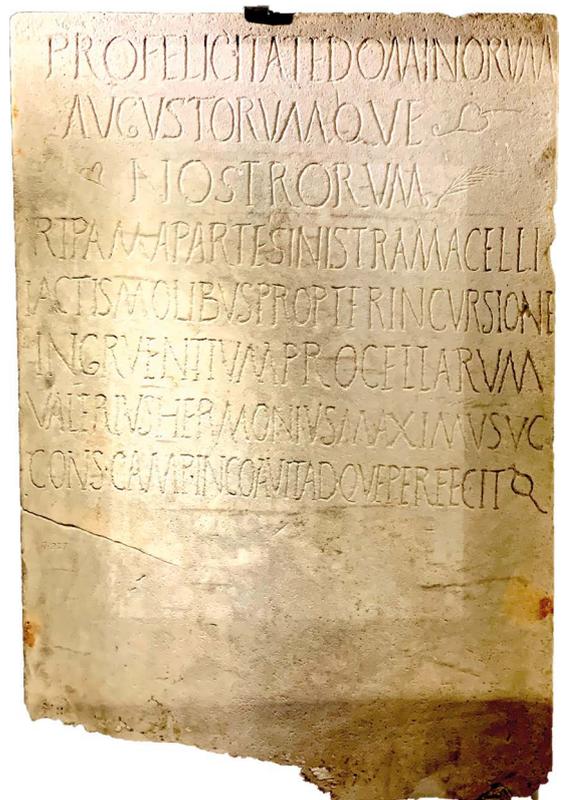
**Figure 11.** One of the two inscriptions found at the Serapeum for the repair work for the sea entrance into the Serapeum area – National Archaeological Museum of Naples, Marble, 394/395 AD. Pozzuoli Macellum Inv. 3266 "*For the happiness of our lords and Augusti, Valerius Hermonius Maximus, a most noble man, governor of Campania began and completed the work on the dock on the left side of the market (Macellum) also providing for the erection of embankments to prevent the violence of the waves*" (Photo Giacomelli Scandone).
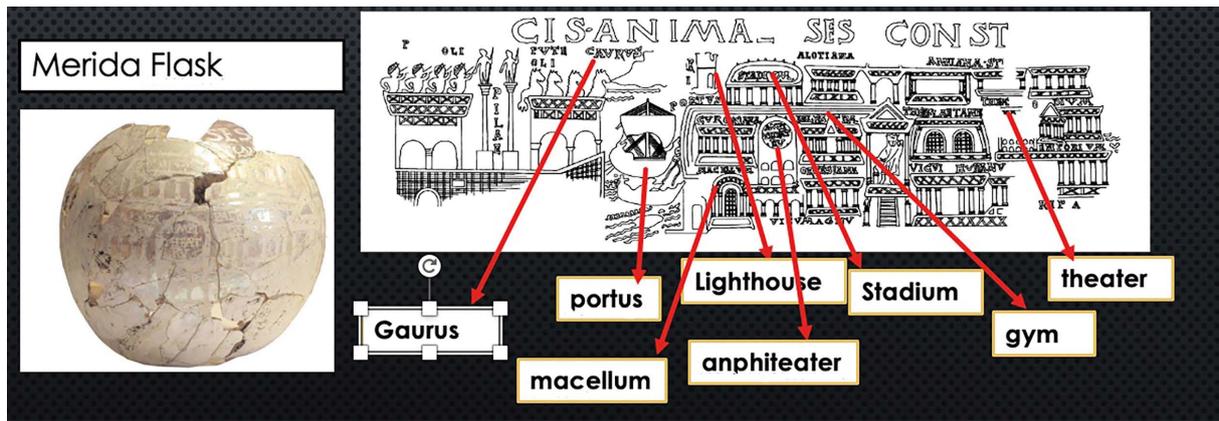
**Figure 12.** The Merida Flask (on the left) described by Bejarano Osorio, (2002) where is drawn up the seafront of Pozzuoli during III-IV century CE. (Right) reconstruction of the plane of the city. Note the relative position of the Macellum (Serapeum) and Portus. Currently the Portus is 6-8 m bsl.
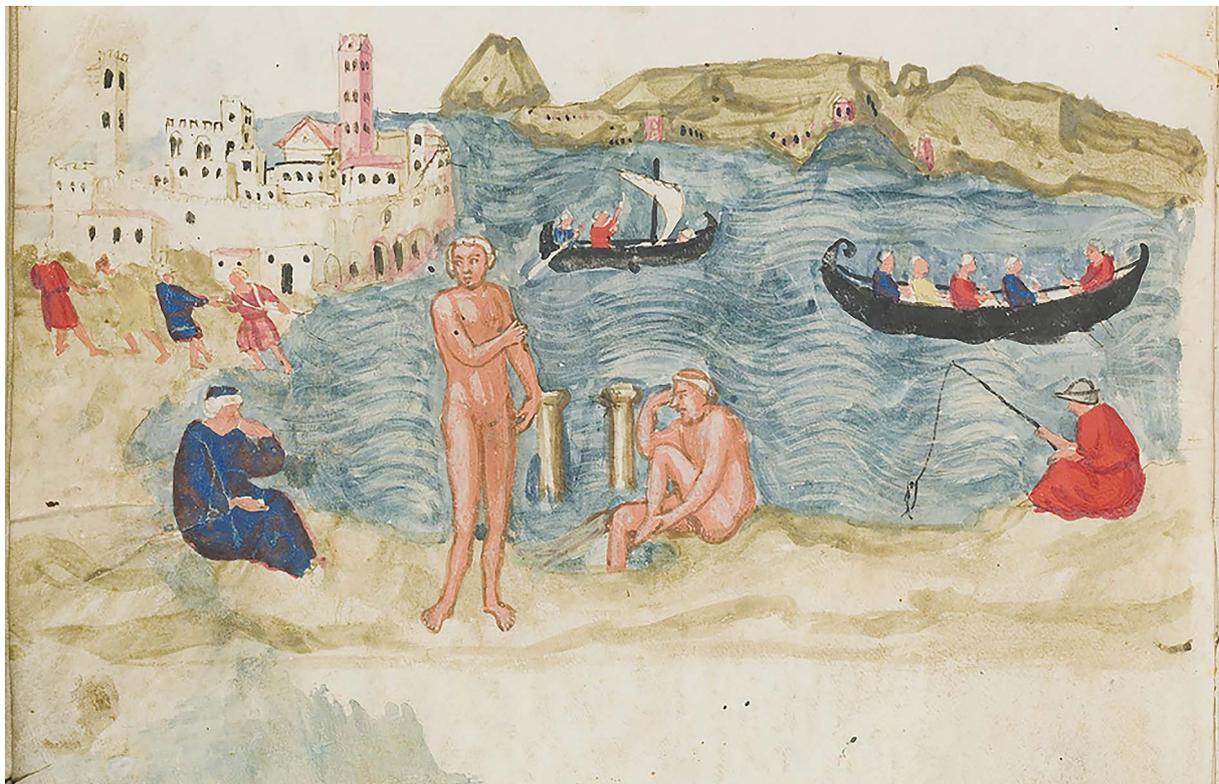


**Figure 13.** An image of the Edinburgh edition of the Balneis Puteolanis representing the Balneum Cantarellus located within the Serapeum. At the time of the reprint, at the beginning of the XV century, the columns of the Serapeum are almost submerged by the sea.

*and lightning could be heard; and in exchange for water it rained sand, and it was called a mouth of fire near the Castle and Hospital of Tripergole"* (Antonio Russo).

The eruption was characterized by an initial medium explosive phase due to the interaction between the magma and sea water, and subsequently by a low explosive phase (Strombolian) when the construction of the cone prevented the interaction between magma and sea water.

The uplift of the ground that preceded and accompanied the eruption dried up Lake Lucrino almost completely, greatly reducing its size. A contemporary print illustrates the eruption and the uplift of the ground (Fig. 14).
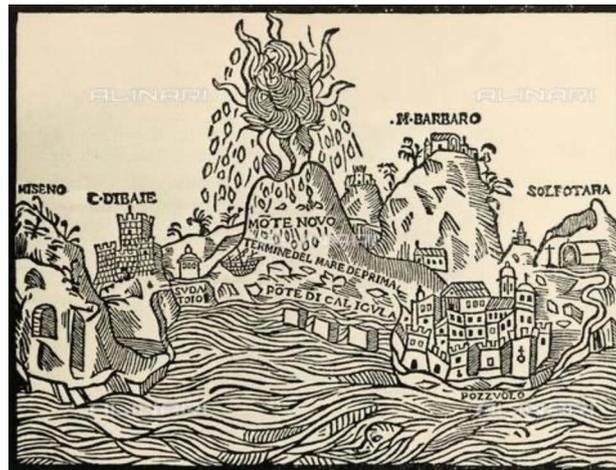
**Figure 14.** The representation of the eruption of Monte Nuovo in the pamphlet of Delli Falconi (1538). Note the writing Termine del mare di prima (limits of the sea before) indicating the uplift occurrred just before the eruption.

The magma intrusion at shallow depth, occurred since a century before the eruption, caused a first phase dominated by an elastic deformation of the bottom of the caldera, followed by a fragile deformation (earthquake occurrence) with the sin-eruptive unblocking of the resurgent block and the rapid displacement of several meters.

The resurgence of the block occurred differentially with the lifting of the northern part (trapdoor lifting) (Fig. 15).
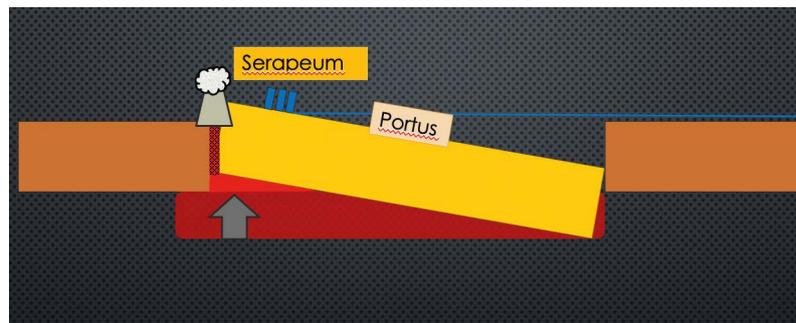


**Figure 15.** Scheme of the mechanism of tilting of the caldera floor during the eruption of Monte Nuovo in 1538, raising the northern part of the resurgent block with the Serapeum and the sinking of the southern part with the ruins of the roman port.

This phenomenon is demonstrated by the fact that with the eruption of Monte Nuovo the coastal area of the gulf was raised by about 10-14 m (Di Vito et al., 2016), bringing the Serapeum back to the level it had in the Roman period, while the port area of Portus Iulius remained submerged at a depth of 6-8 m. meters (Fig. 16).

After the eruption, probably after 1582 (the date of a last seismic crisis), the ground began to sink again and since 1800 the Serapeum was once again invaded by sea water. Sea level measurements in the Serapeum gave indications of a subsidence speed of the order of 1 cm/year. Starting from 1905, geodetic measurements began, which confirmed the observations obtained by measuring the height of sea level on the floor of Serapeum.

At the beginning of the 1900s, the coastal part of Pozzuoli was often invaded by the sea when high tide and wind conditions occurred. In 1911 the government allocated a loan for the rehabilitation of the hygienic conditions of Pozzuoli through a fill of the lower part of the city. The fill reached up to the first floor of the buildings (Scandone and Giacomelli, 2018).

Meanwhile, the geodetic measurements carried out along the coastal road from Naples to Miseno gave for the first time a measure of the extent of the subsidence which increases regularly from Naples to Pozzuoli and then decreases again up to Miseno (Lirer et al., 1987).

**Figure 16.** The Roman port (Portus Iulius) remained submerged even after the uplift of the area which occurred before and during the eruption of Monte Nuovo, testifying to the inclination of the resurgent dome with the uplift of the northern part of the block.

**Recent bradyseism crises 1950-2024** Subsidence continued regularly until 1950, the year in which the movement reversed for the first time after more than four hundred years.

The uplift was almost completely ignored at the time as it was not accompanied by any seismic crisis. Only one researcher was able to identify the event through local leveling measurements (Ranieri, 1952). This observation, initially discarded, was subsequently validated by a careful analysis of the available documentation (Del Gaudio et al., 2010).

Starting from 1952 the slow subsidence of the ground resumed and lasted until 1969 when a new phase of uplift began.

The uplift of 1970 was accompanied by a mild seismic crisis. The authorities, made aware of the phenomenon, ordered the evacuation of the oldest part of the town, the Rione Terra, due to the dilapidated conditions of the buildings. The inhabitants were settled in a new settlement, the Toiano district, north of the historic center of Pozzuoli. Mild ground subsidence followed this phase between 1972 and 1982.

Since 1982, a new phase of ground inflation began, this time accompanied by a seismic crisis with numerous earthquakes felt by the population.

The largest magnitude earthquake (4-4.2) occurred on 4 October 1983 and led to the decision to evacuate the historic center of Pozzuoli. The people were later housed in the new settlement of Monte Ruscello (Scandone and Giacomelli, 2018).

The measurements taken by the Osservatorio Vesuviano along the leveling line showed the constancy of the shape of the deformation (Fig. 17).

The crisis ended in early 1985 when subsidence resumed, and earthquakes stopped. This phase lasted until 2006 with occasional mini-uplift and burst of mild seismicity. Since this date, a new phase of uplift began which continues to this day (Fig. 18).

The current distribution of earthquakes is like that of the 1982-84 period.

The uplift at the point of maximum deformation now exceeds the maximum level of 1984. Initially the uplift occurred without appreciable seismic activity. The picture progressively changed, starting from 2020, with an acceleration in 2023 and the occurrence of several earthquakes with magnitude greater than 3, and 4 (the maximum of the 1982-84 crisis) (Fig. 19).
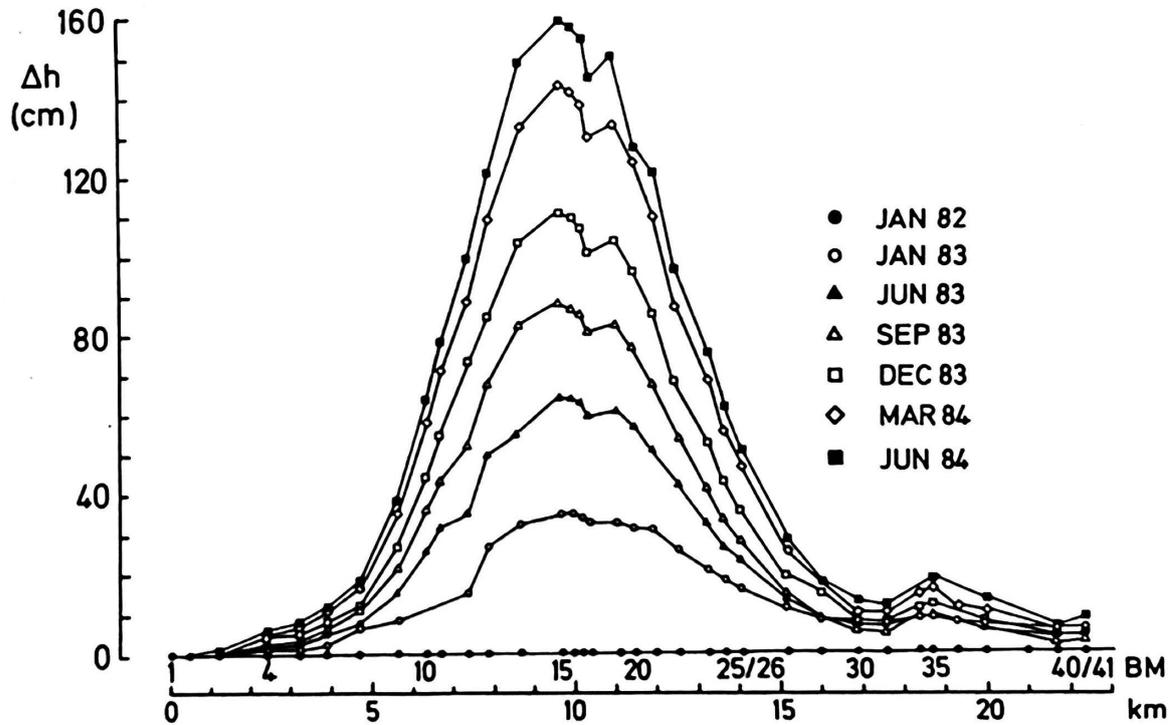


**Figure 17.** Different levelling survey performed by Osservatorio Vesuviano in the period 1983-84 on the levelling line along the coast of Pozzuoli. The increasing deformation does not affect the size of the deformed area.
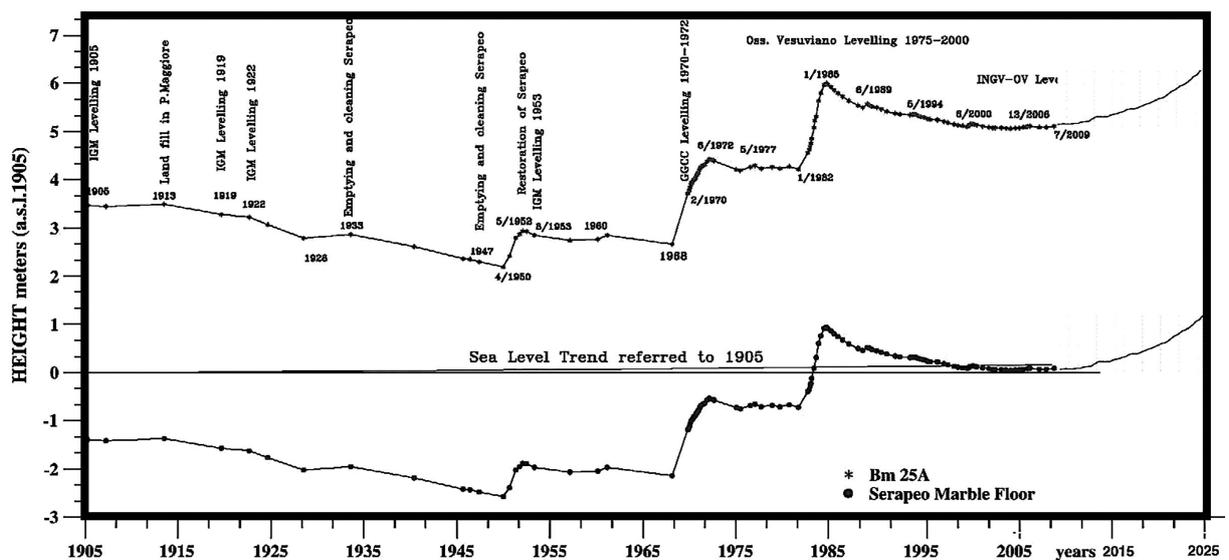


**Figure 18.** Elevation changes of the floor of Serapeum and benchmark Benchmark 25A (m asl) from 1905 to 2024 referred to the sea level in 1905. The graph from 2009 to 2024 is extrapolated by the GPS data of RITE station monitored by INGV-OV which is the nearest to benchmark 25A (Modified from Del Gaudio et al., 2010).
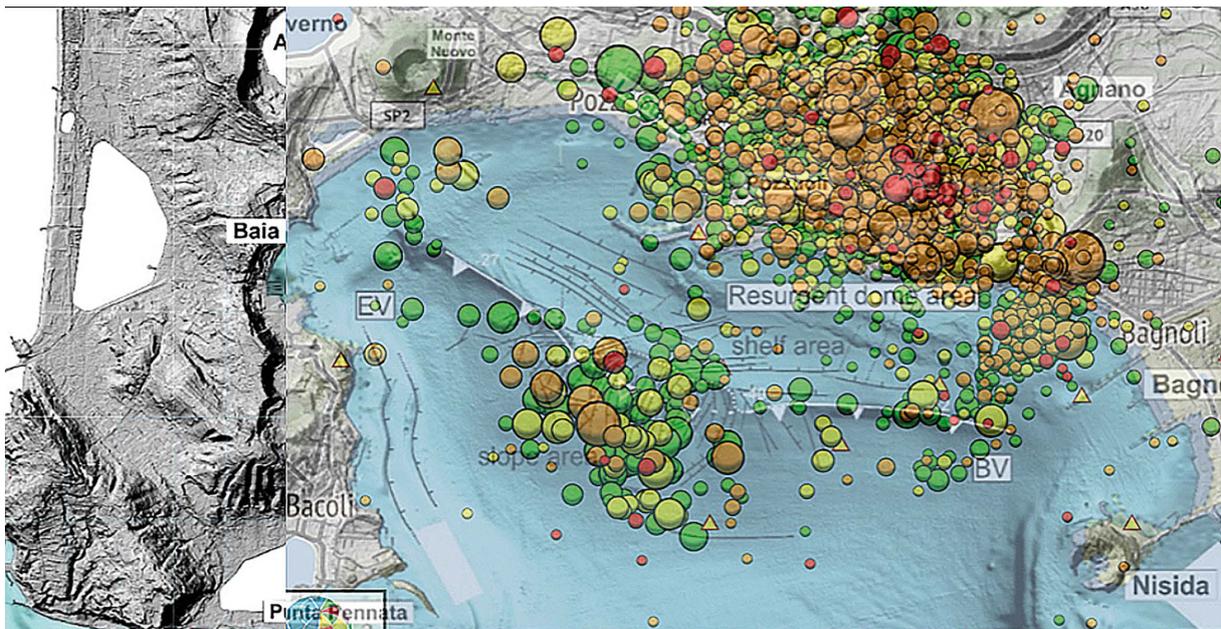
**Figure 19.** Distribution of earthquakes that occurred in the period 2022-2023 overlapped on the structural map of the caldera. The earthquakes are distributed along the edges of the resurgent block. Those at sea, have hypocenters that are on average deeper than those on land, with an inverse fault plane solution while those on land have a normal one compatible with the inclined uplift of the resurgent block. (Seismic data from INGV-Vesuvius Observatory, Structural model from Sacchi et al., 2014).

# 6. Analysis and Interpretation of phenomena

There is general agreement in the scientific community that the uplifts observed before and during Epochs 2 and 3 as well as those observed before 1538, were due to a shallow (3-5 km) magma intrusion that caused the uplift of the resurgent block (Isaia et al., 2009). The trend before 1538 provides further details on the uplift mechanism: the first phase is dominated by an elastic deformation of the bottom of the caldera followed by a fragile deformation (occurrence of earthquakes) with a rapid displacement, measuring several meters.

After the resurgence phases, slow subsidence is observed. There is no unanimous opinion on the origin of this phenomenon. For some, it is linked to the contraction and cooling of the intruded magmatic mass (Macedonio et al., 2014 and reference therein), while for others it is the effect of the degassing and contraction of the porous matrix of the rocks that make up the caldera floor (Casertano et al., 1976, De Natale et al., 2006).

Similarly, for the current unrest there are different hypotheses on the source of deformation. Several authors (see Todesco 2021 and reference therein) suggest that the deformation is governed a poro-elastic response of a shallow hydrothermal system to changes in pore pressure and fluid content. Corrado et al. (1977), Berrino et al. (1984), Berrino, (1993) suggest that the unrest of 1970-72 and 1982-84 were governed by the intrusion of a magma body at shallow depth. Amoruso et al. (2011), D'Auria et al. (2015), hypothesize that a magma intrusion is responsible also for the unrest since 2006 at Campi Flegrei.

To better focalize the causes of the current unrest we must recall some peculiar features:
– Constancy with time of the shape of the deformation
– Constancy of the depth of the deformation source (3-5 km)
– Repetitiveness of the spatial distribution of earthquakes and their focal mechanisms during the 1982-84 crises and the current one.

The constancy of the shape of the deformation, both during uplift and subsidence, first evidenced by Lirer et al. (1987), is restricted to the lateral extension of the resurgent block. This feature is well evidenced also by the distribution of the earthquakes around the border of the resurgent dome and inside it. The constancy of shape during the uplift episodes suggests a constant source of both deformation and pressure, since a change in either one of these

variables would result in a change of shape. Amoruso and Crescentini (2022) infer that most deformation is related to the activity of a 3-4 km deep sill-like source, which is inflated by magma and/or magmatic fluids during periods of unrest and deflates during periods of subsidence. On the other hand, Giacomuzzi et al. (2024), performing a non-linear 4D (in space and time) seismic tomography on the seismic data recorded till 2022, evidenced the ascent of magma batches at shallow depth, which could have started in 2019. These arrivals may have perturbed the hydrothermal circulation.

Earthquakes with the higher magnitude are localized in the deepest portion of the caldera floor at depth ranging between 3-5 km. Tramelli et al. (2024) observe the smallest b-values for the deepest seismicity where there is the higher stress/strain concentration, in the so-called caprock, and the largest b values where the porosity of the medium allows the passage of the volcanic gases toward the surface. Further on, the earthquakes occurring in the southern part of the caldera, occupied by the sea, at major depth, have an inverse focal mechanism contrary to those occurring on land (Gaudiosi and Iannaccone, 1984, La Rocca and Galluzzo, 2019, Macedonio et al., 2024).

All these features can be explained as due to the trapdoor movement of the resurgent block because of the intrusion of magma below it.

Currently the resurgent block is not yet unlocked with respect to the surrounding rocks but is deformed elastically and causes a stress accumulation at its edges with associated the earthquakes. Additionally, the other seismic zone within the resurgent block around the Solfatara indicate a surficial fracturing which favors an enhanced degassing of the intruded magma. Chiodini et al. (2021) and references therein, show a pivotal role of fluids in the bradyseismic crises. However, the highly cracked state of the surficial crust and the degassing, point against the gas pressure accumulation in the solid matrix of the rocks as responsible of the stress accumulation at the base of the resurgent block.

## 7. Conclusions

Episodes of unrest of large calderas are often linked with episodes of resurgence of the central dome or block. Seismicity occurs mostly along the edges of the dome (Long Valley, Rabaul, Campi Flegrei) whereas the uplift is mostly in the central part of the caldera. The uplift is likely linked with intrusion of magma at shallow depth forming laccoliths that not always erupt. The crisis at calderas in the last century resulted only rarely with an eruption at the edges of the resurgent block (Rabaul). Eruptions of this type are preceded by a long-term deformation and seismicity culminating with an energetic short-term seismic crisis and a rapid uplift (Rabaul and Monte Nuovo).

We do not have examples of caldera-forming eruption at large calderas, and we do not know the pattern of precursors, if any different, that may warn such events. If the caldera forming eruption is preceded by a plinian eruption, as is often the case, we may not be able to discern this precursory trend from that of a "normal eruption", and the plinian event may be the only discernible precursor to the caldera forming one.

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