Cities on Volcanoes 10

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INTRAMEETING FIELD TRIP

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FTI.1 | The Campi Flegrei caldera volcanism and the unrest phenomena

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NAPOLI - ITALIA 2018

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INTRAMEETING FIELD TRIP

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FTI.1 | The Campi Flegrei caldera volcanism and the unrest phenomena

Campi Flegrei volcanoes

The Campi Flegrei volcanic field (Fig. 1), including Procida and Vivara islands, is a volcanic area formed by small volcanic apparatus and several monogenetic volcanoes, in the form of tuff rings, tuff cones and rarely cinder cones and lava domes. These crop out outside, on the borders, and within a large polygenetic caldera formed by the eruptions of the Campanian Ignimbrite (CI) and the Neapolitan Yellow Tuff (NYT) (e.g., Armienti et al., 1983; Di Girolamo et al., 1984; Rosi & Sbrana, 1987; Orsi et al., 1992, 1995, 1996, 1999; Cole & Scarpati, 1993; Rosi et al., 1996, 1999; Di Vito et al., 1999; De Vivo et al., 200).

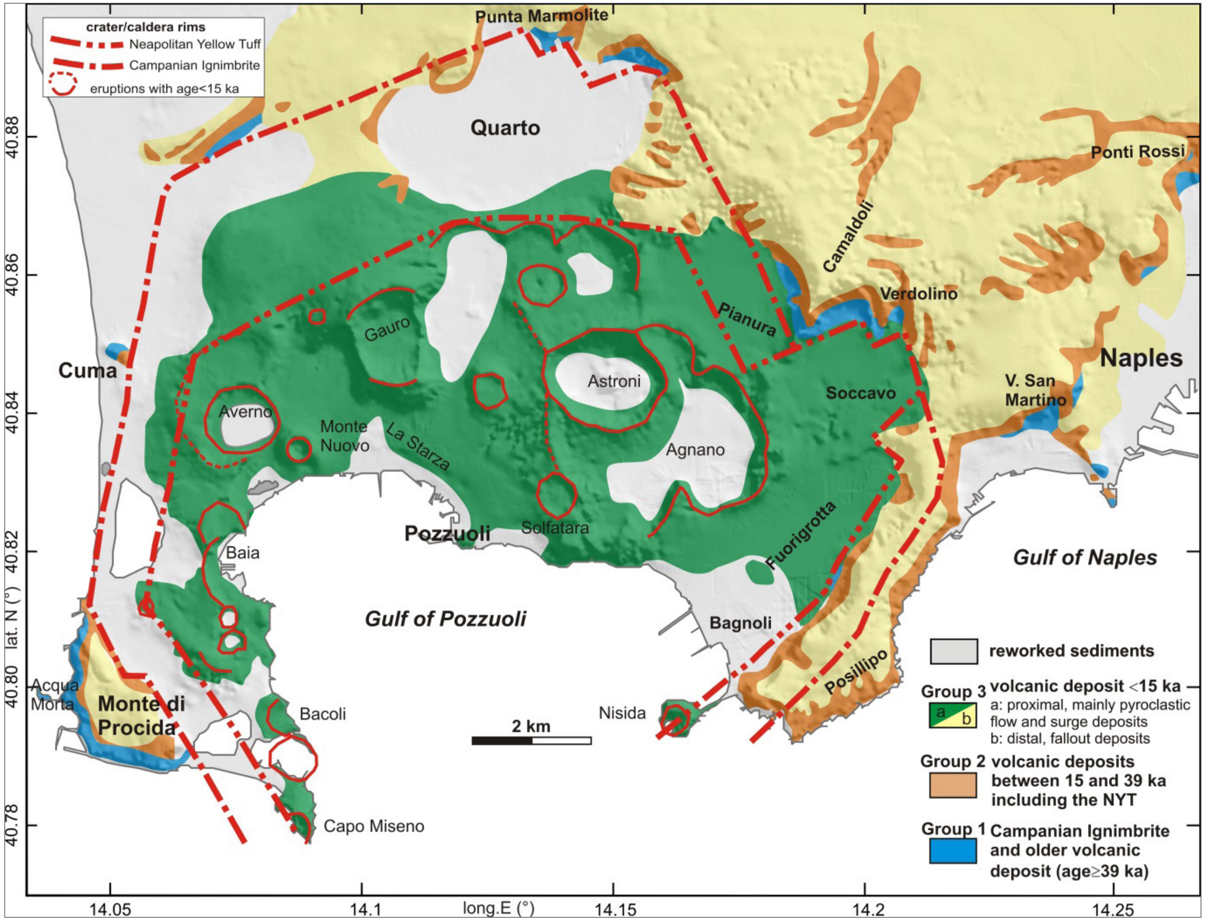


Fig. 1 - Geological sketch map of the Campi Flegrei (from Vitale and Isaia 2014)

The oldest volcanic activity date back till ~80 ka and is represented by the pre-CI deposits, which are found as loose remnants cropping out outside and on the borders of the CI caldera (Pappalardo et al., 1999; Scarpati et al., 2012). Between 80 and 40 ka scattered and monogenetic activity is recorded, including lava and scoria of San Martino, tuff cones of Miliscola and Vitafumo (Monte di Procida), lava domes of Cuma, Punta Marmolite (north of Quarto Plain), tuff cones of the city of Naples (C.so V. Emanuele, Monte Echia and Capodimonte) (e.g., Rosi and Sbrana, 1987; Scarpati et al., 2012). Thick pyroclastic sequences generated from at least 60 ka ago also occur (Orsi et al. 1996; Pappalardo et al. 1999). Other ignimbritic deposits are found in the Campanian Plain, and date back till ~21 ka (De Vivo et al., 2001) and ~29 ka (Rolandi et al., 2003). All ages mentioned since now and in the following discussion are ^{40}Ar-^{39}Ar ages, unless otherwise specified. The large volume CI (Fisher et al., 1993; Rosi et al., 1996) erupted ~300 km^3 of trachytic dense rock equivalent magma (D.R.E.), whose proximal products are found at Procida, Monte di Procida, Giugliano, Quarto, Cuma, base of Camaldoli and San Martino Hills. The CI eruption was the largest magnitude eruption to occur in the Mediterranean region during the late Quaternary, and resulted in the formation of a 14 km caldera (Rosi and Sbrana, 1987). The eruption began with a Plinian phase, during which a SE-distributed pumice fallout was emplaced. This was followed by a succession of pyroclastic density currents (PDC) that deposited ash and pumice flows and densely-welded ignimbrites that covered the Campanian Plain and surrounding hills (Barberi et al., 1978). Proximal deposits (e.g., Breccia Museo, Piperno) cropping out at the top of the eruption deposits along the caldera margins are interpreted as proximal facies related to the final caldera-forming phase (Rosi and Sbrana, 1987; Rosi et al., 1996). On these deposits, several age data were published (~37 ka, Deino et al., 2004; ~39 ka, De Vivo et al., 2001; ~38 ka, Fedele et al., 2008). A very recent and high precision ^{14}C and $^{39}Ar/^{40}Ar$ age determination of the CI yelded an age of 39.85 ± 0.14 ka (Giaccio et al., 2017).

An intense volcanic activity occurred after the formation of the CI caldera, with the formation of pyroclastic deposits from several volcanic centers. A second large eruption dates back at 15 ka (Deino et al., 2004) with the emplacement of the Neapolitan Yellow Tuff (NYT; Cole & Scarpati, 1993; Wohletz et al., 1996), whose volume has been estimated at 12 km^3 D.R.E of latitic to trachytic magma (Rosi & Sbrana, 1987).

The eruptions of the post-NYT period were confined within the structural boundaries of the caldera and comprised at least 70 known events (Di Renzo et al., 2011), dominated by low- to medium-magnitude phreatomagmatic–magmatic eruptions with volumes of <0.1 km^3 (Di Renzo et al., 2011; Orsi et al., 1995; Smith et al. 2011). The most recent volcanic activity, placed within the NYT caldera and on its borders, dates back to 1538 A.D. with the eruption of Monte Nuovo (e.g., de Vita et al., 1999; Isaia et al., 2004; D'Oriano et al., 2005; Di Vito et al., 2016). At present, the only activity is represented by fumarolic and bradyseismic activity.

Campi Flegrei magma compositions

The generation of melt beneath the Campanian region is related to the northwest subduction of the Ionian oceanic plate beneath the Eurasia plate (e.g., Faccenna et al., 2007), with the slab (Wadati–Benioff zone) located at a depth of around 350 km (Giardini and Velonà, 1991). The primary magmas produced have a mid-ocean ridge basalt (MORB)-like asthenospheric mantle wedge composition, and these are modified by aqueous fluids, oceanic sediment, and continental crust (Tonarini et al., 2004; D'Antonio et al., 2007). Trench roll-back has resulted in a region of back-arc extension in the Campanian region and it is in this thinner and fractured crust that the magmas ascend and erupt (e.g., Patacca and Scandone, 1989).

The mafic melts that make it into the crust (upper 25 km) at Campi Flegrei are K-basalts (e.g., Webster et al., 2003). These mafic compositions are preserved as melt inclusions in antecrystic Mg-rich olivines and clinopyroxenes in some eruption deposits (e.g., Cannatelli et al., 2007). The composition of the erupted melts range from shoshonitic through to phonolitic and trachytic, with the most differentiated compositions dominating (e.g., Mangiacapra et al., 2008; Smith et al., 2011; Tomlinson et al., 2012). The phenocrysts in these Campi Flegrei magmas are predominantly plagioclase + K-feldspar + clinopyroxene ± biotite. Magnetite and apatite occur as accessory phases and eruptions occasionally contain olivine or rare feldspathoids.

The SiO_2 and Na_2O contents of the magmas increase with differentiation, whereas CaO, FeO, MgO, and P_2O_5 contents decrease (e.g., Civetta et al., 1991b). There is a noticeable inflection in K_2O melt compositions, denoting K-feldspar-in, at ~60 wt% SiO_2 (Fowler et al., 2007; Smith et al., 2011; Tomlinson et al., 2012). The Sr, Ba, and Eu contents behave compatibly, and reflect the significant amount of felspar fractionation. Other REE (excluding Eu), Y, Nb, Zr, Rb, Th, and Ta are all incompatible (e.g., Civetta et al. 1997; Bohrson et al. 2006, Arienzo et al., 2010; Tomlinson et al., 2012). These major and trace element compositions follow an evolutionary trend that could be generated through fractional crystallization of a single parental melt (e.g., Civetta et al., 1991; D'Antonio et al., 1999; Fourmentraux et al., 2012) but isotopic variations indicate that the melt that erupt are derived from different batches of magma (Pappalardo et al., 1999, 2002; D'Antonio et al., 2007; Di Renzo et al., 2011).

Samples from Campi Flegrei eruption deposits suggest that only evolved magmas were erupted in the early history (Pappalardo et al., 1999) and it was only after the last caldera-forming ~15 ka NYT eruption that more compositionally diverse melts were erupted (e.g., D'Antonio et al., 1999; Smith et al., 2011). The isotope (Nd, Pb and Sr) and occasionally the major and trace element glass compositions of the magmas indicate that the eruptions tap distinct batches of melt, and some have interacted at depth (e.g., Di Renzo et al., 2011). This has been well documented for the large caldera-forming events (e.g., Forni et al. 2018) and for eruptions in the last 15 ka (e.g., Tonarini et al., 2009; Fourmentraux et al., 2012). The general trend between 60 and 10 ka is that Nd and Pb isotopic compositions the erupted magmas became progressively less radiogenic ($^{143}Nd/^{144}Nd$ - 0.51252 to 0.51236 and $^{206}Pb/^{204}Pb$ - 19.2 to 18.9) while the Sr-isotope composition became more enriched (0.70700 to 0.70864) over time (Pabst et al., 2008; Di Renzo et al., 2011). These changes in the isotopic compositions are consistent with an increase in crustal contamination. However, the Campi Flegrei liquid line of descent and extent of Sr and Pb isotopic heterogeneity is compatible only with very minor assimilation (D'Antonio et al., 2007; Fowler et al., 2007).

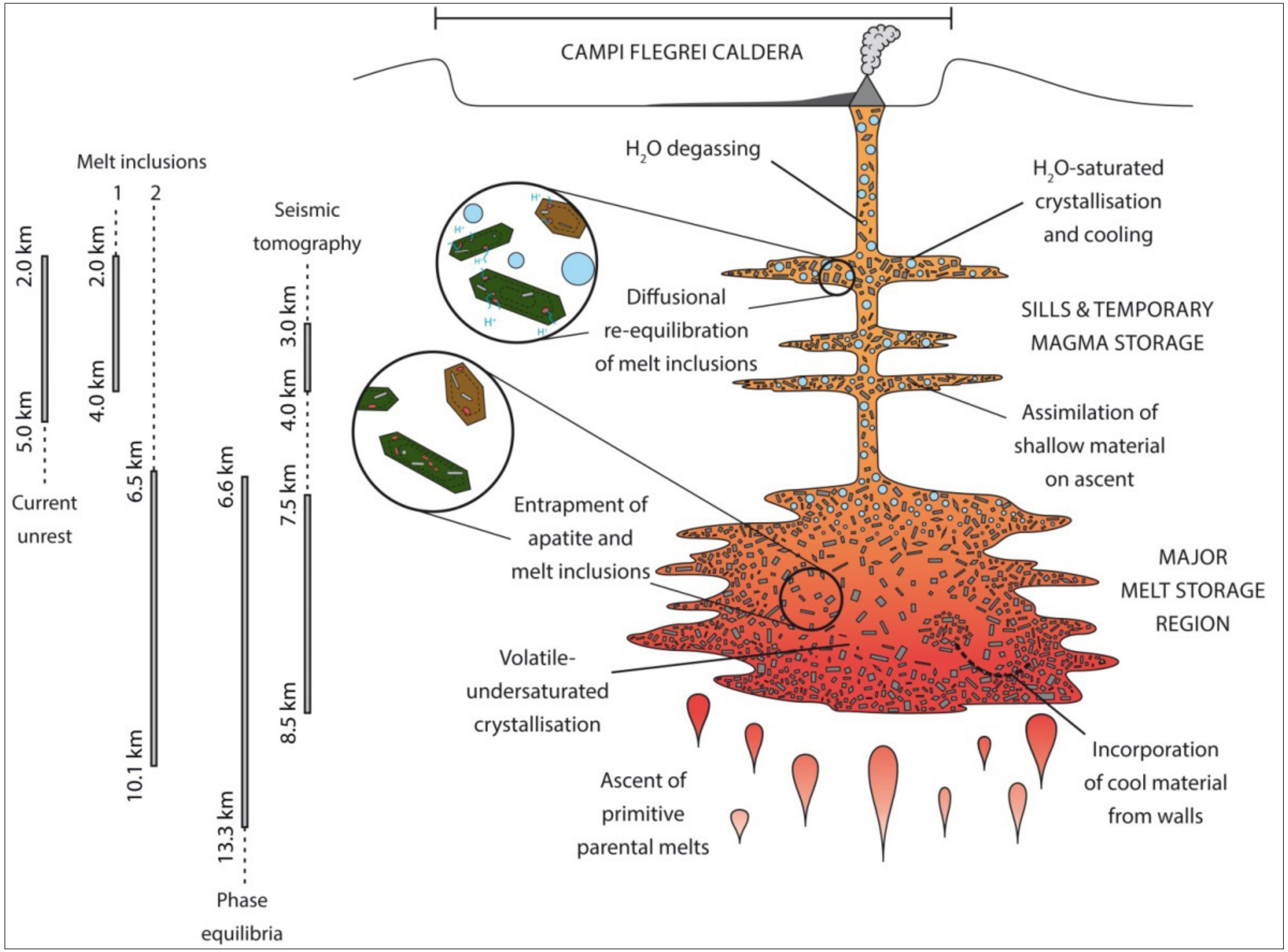


Fig. 2 - Schematic diagram of magmatic storage at Campi Flegrei, modified from Stock et al., (2018). The grey bars on the left show the estimates of magma storage depths, which have been derived from: recent ground deformation ('current unrest'; e.g., Woo & Kilburn, 2010; Amoruso et al., 2014); melt inclusions (e.g., 1-Fourmentraux et al., 2012, 2-Arienzo et al., 2016); phase equilibria constraints (Fowler et al., 2007, Bohrson et al., 2006; Cannatelli 2012); and seismic tomography data (Zollo et al. 2008; De Siena et al., 2010).

Constraints on the architecture of the magma storage at Campi Flegrei

The architecture of the crustal magma plumbing system at Campi Flegrei has recently been constructed based on the integration of all existing petrological and geophysical datasets (Fig. 2; Stock et al., 2018).

Seismic tomography data show that there are currently two main zones of magma storage at Campi Flegrei: a major magma storage region at 7-8 km and small melt pockets at approximately 2 and 4 km (Zollo et al., 2008; De Siena et al., 2010). The shallower magma storage region correlates with the depth of sill emplacement during recent seismic crises (e.g. Woo & Kilburn, 2010). Phase equilibrium models indicate that most of magma crystallisation and phenocryst formation before past eruptions of Campi Flegrei occurs between 150 and 300 MPa (i.e. 6.6–13.3 km; Bohrson et al., 2006; Fowler et al., 2007; Cannatelli, 2012; Arienzo et al., 2016), which correlates with the deeper magma storage region. Crystallisation within these two zones of magma storage has recently been further corroborated by clinopyroxene-melt geobarometry (Astbury et al., in review).

Apatite inclusions and microphenocrysts have been used to provide a long-term history of volatile behaviour in the Campi Flegrei system, utilising the fact that the volatile contents of apatite inclusions cannot be reset post-entrapment. These data indicate that magmas in the deep Campi Felgrei storage region experience protracted volatile-undersaturated crystallization until late in magmatic evolution (Stock et al., 2016; Stock et al., 2018). Rhyolite-MELTS fractional crystallisation models (Gualda et al., 2012) support the fact that the system only becomes volatile saturated after biotite starts to crystallise approximately ~910 °C (at 150-200 MPa; Stock et al., 2016). Once the melts become H_2O saturated, only a small amount of crystallisation would result in a substantial increase in the amount of gas, which could easily generate overpressures that exceed the fracture criterion and result in eruption (Stock et al., 2016). It is likely that many of the eruptions from Campi Flegrei are triggered through this 'internal' mechanism, with diffusion timescales indicating these processes can occur within years of the eruption (Stock et al., 2016).

The volatile compositions of the Campi Flegrei melt inclusions range from 1 to 4 wt % H_2O, and CO_2 concentrations are typically low with <250 ppm (e.g., Marianelli et al., 2006; Arienzo et al., 2016; Stock et al., 2016, 2018). Phonolite and trachyte solubility data from CO_2-free melts at 850–950 °C (e.g. Carroll & Blank, 1997; Webster et al., 2014) indicate that melt inclusions typically became saturated at pressures of 25–75 MPa, which equates to a depth of around 1-3.5 km (Stock et al., 2018). These depths are much shallower than the main zone of magma storage determined using geophysical and petrological techniques. Furthermore, there is no relationship between H_2O and MgO concentrations in many clinopyroxene-hosted melt inclusions (Arienzo et al., 2016), which would be anticipated during volatile-undersaturated crystallisation. This implies that the H_2O contents of the melt inclusions may have been diffusively reset post-entrapment, consistent with the short experimental timescales of H^+ diffusion (e.g., Reubi et al., 2013). The melt inclusion data therefore only provide information on the last phase of magma storage and crystallisation at Campi Flegrei, where the magmas ascending from depth interact and mix with small, volatile-saturated magma bodies.

The Campanian Ignimbrite sequence

The CI sequence includes a basal Plinian fallout deposit surmounted by PDC units, which in proximal areas are intercalated by densely welded ignimbrite (Piperno; Fig. 4) and lithic-rich breccia units (Museum Breccia), related to the final caldera-forming phase.

The basal Plinian deposit (Rosi et al., 1999), dispersed towards the east, consists of a well-sorted and reversely-graded lower portion, followed by a well- to poorly-sorted crudely-stratified upper portion. The PDC deposits, which covered an area of about 30,000 km^2, show homogeneous sedimentological characteristics in medial and distal areas (10 to 80 km from the source) (Fisher et al., 1993; Fig. 3). More than 300 km^3 of magma and volcanic ash were emitted during this eruption, with deposits extending eastward up to Russia (Fig. 3; Giaccio et al., 2008; Costa et al., 2012; Smith et al., 2016).

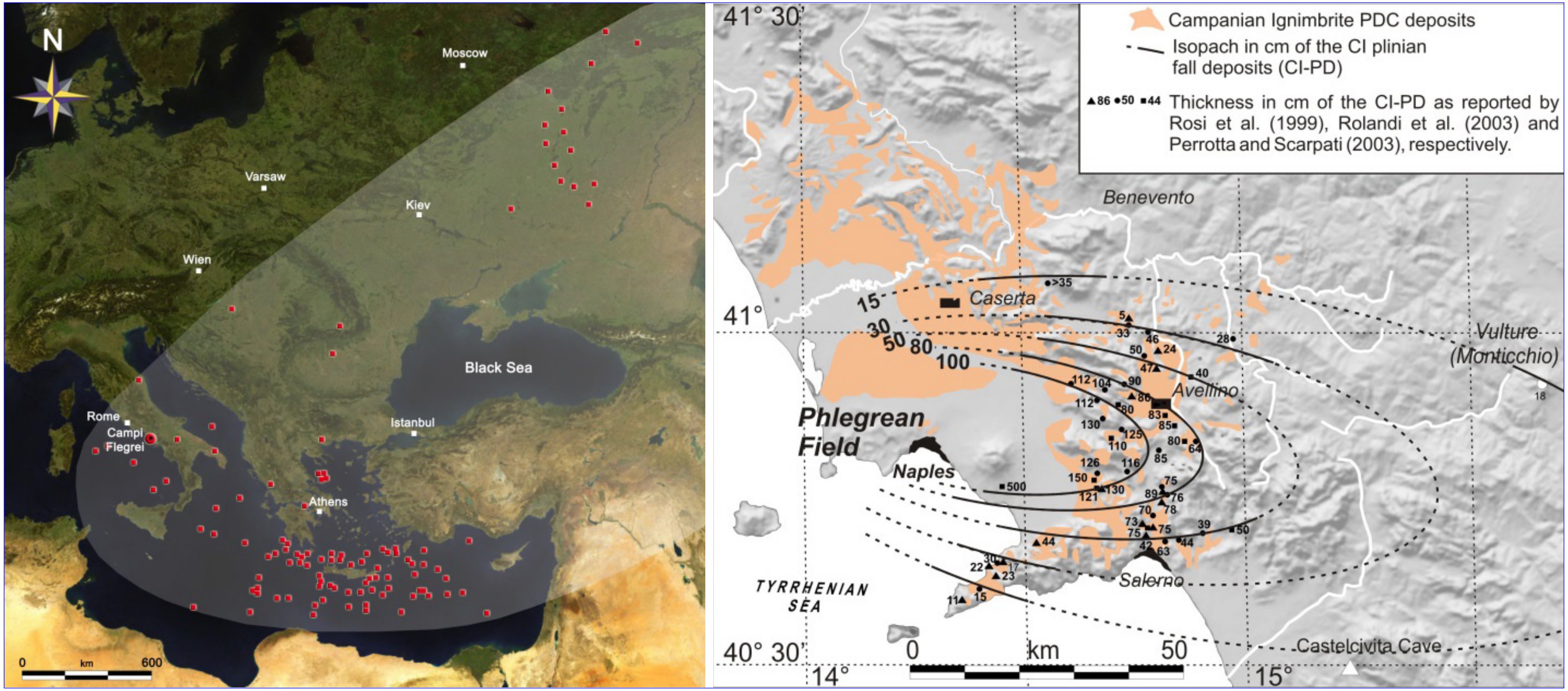


Fig. 3 - Distribution of the Campanian Ignimbrite distal tephra (left) and its intermediate-proximal deposits (right); modified from Giaccio et al., 2008 and Smith et al., (2016).

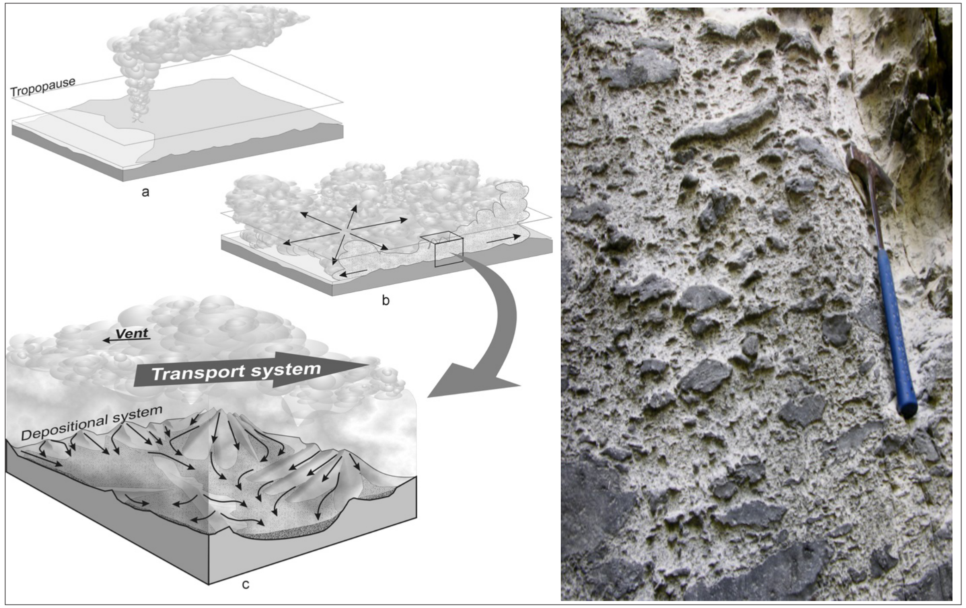


Fig. 4 - Left: CI eruption phases (a, b) and model of the trasport and depositional system of the PDCs (c). a) sustained plinian eruption column; b) expanding PDCs; c) block diagram showing the movement of the PDCs over the topography (after Fedele et al., 2003). Right: grey welded tuff facies (Piperno) of Campanian Ignimbrite

The CI show a slightly compositional variability of pyroclastics from trachytic to trachytic-phonolitic (eg. Melluso et al., 1995; Civetta et al., 1997; Signorelli et al., 1999; Pappalardo et al., 2002; Marianelli et al., 2006; Giaccio et al., 2008).

In particular, Civetta et al. (1997), who investigated mainly the PDCs deposits, described three main composition groups, not systematically arranged according to the stratigraphy of deposits, but distinguished based on their areal distribution and distance from the vent. In terms of major element composition, the difference among these groups mainly concerns the K_2O/Na_2O ratio and the relative abundance of CaO, Fe_2O_3, MgO and Cl. The study of the interstitial glasses and melt inclusions of the CI fallout and breccia deposits (Signorelli et al., 1999; Marianelli et al., 2006) indicates a similar compositional variability also for these eruptive units. The analyses of the Breccia Museo, outcropping in the western sector of the Campi Flegrei, revealed a systematic compositional variability with the stratigraphy parallel to an upward increase of the less evolved products (Melluso et al., 1995), a connection that was later recognised by Pappalardo et al. (2002) in another proximal sequence of the CI at Ponti Rossi, east of the Phlegrean Fields. As a whole, the variability in the CI rock composition indicates that the CI eruption was fed by a trachytic magma chamber which included two chemically different magmatic members: a more evolved upper magma layer, and a less evolved lower layer (e.g. Civetta et al., 1997).

The magma chamber that fed the eruption was located between 6 and 8 km depth (Marianelli et al., 2006), and its partial depletion led to the formation of the Campi Flegrei caldera. The caldera margins have been the subject of various interpretations in recent literature (e.g., Rosi and Sbrana 1987; Orsi et al. 1996; Perrotta et al. 2006; Acocella 2008) that mainly differ in the definition of the eastern sector of the collapsed area, with particular reference to the inclusion or exclusion of the city of Naples in the area affected by the collapse. Some authors (Lirer et al. 1987; Rolandi et al. 2003), moreover, exclude the formation of a caldera in relation to the CI eruption, identifying caldera formation at around 15 ka linked to the NYT (Deino et al. 2004) and other previous eruptions.

The CI tephra is found all across the central and eastern Mediterranean (Fig. 3), on land to the east of Italy and in an area including northern Libya in the south and River Don river valley, Russia in the northeast.

Costa et al. (2012) estimated that the eruption column was ~37-40 km and the total volume of fallout material, associated with both the Plinian column and the co-ignimbrite plume, to be 250-300 km^3, corresponding to 104-125 km^3 of magma (dense rock equivalent, DRE). Once the volume of the PDC (Pyle et al., 2006) is considered, the total bulk volume for the CI eruption is estimated in 430-680 km^3, which is equivalent to 180-280 km^3 DRE (Costa et al., 2012).

Using the glass compositional data, Smith et al. (2016) clearly indicates that most of the ultra-distal dispersal during the CI eruption was associated with the late co-ignimbrite plume that was generated during caldera collapse. Authors highlight that the dominance of the co-ignimbrite component is likely to be linked to the fact that the flows are the most voluminous component of the eruption, and estimated that the Plinian column dispersed approximately 17-20% of the volume erupted, with 45-67% that was dispersed by the co-ignimbrite plume, and 13-38% emplaced as flows. The area over which the ash was dispersed increased due to co-ignimbrite plume would have been transported by both tropospheric and stratospheric winds, which could have been in different directions (Smith et al., 2016).

The Neapolitan Yellow Tuff sequence

The NYT eruption was the last dramatic event in the history of the caldera. The eruption was a phreatoplinian to phreatomagmatic event which erupted about 40 km^3 of magma (Orsi et al., 1992; Scarpati et al., 1993). The tuff (Fig. 5), which covered an area of about 1,000 km^2, is generally zeolitized and is commonly used as building material forming the skeleton of the City of Naples.

The NYT sequence was divided into a Lower Member (LM) and an Upper Member (UM), on the basis of textural characteristics, dispersal and occurrence of an angular unconformity which separates the two units. LM is the product of the largest known trachytic phreato-Plinian eruption. Its thickness varies from 11 m in the most proximal exposures, to 85 cm at Sant'Angelo in Formis, at the foot of the Apennine mountains, 35 km from the vent area. In contrast, the characteristics of UM are typical of a phreatomagmatic eruption. Its thickness varies from about 100 m in the Quarto Plain, to 7 m in the Caserta Plain. The NYT composition varies from latite to alkali trachyte. Phenocrysts (<3% by volume) are sanidine, plagioclase, clinopyroxene, biotite, magnetite, in order of decreasing abundance, and rare apatite. Sanidine in latite, anorthitic plagioclase in trachyte and alkali trachyte, reversely zoned plagioclase and two clinopyroxene (diopside and salite) are evidence of mineralogical disequilibrium. The magma chamber was composed of three discrete layers: an upper alkali trachyte, an intermediate trachyte and a lower alkali trachyte to latite magmas separated by compositional gaps (Orsi et al., 1995). The NYT event led to a further collapse of Campi Flegrei caldera (Orsi et al. 1992; Scarpati et al. 1993) whose margin is probably exposed only along the eastern edge of the Bagnoli plain. With this relatively massive eruption, probably the CI caldera was reactivated with further collapse in its center.

Fig. 5 - Neapolitan Yellow Tuff deposit (loc. Trentaremi, Napoli).

Post-NYT activity

Following the eruption of the NYT, activity within the caldera generated at least 70 volcanic eruptions mainly concentrated in discrete periods alternating with periods of quiescence of variable length (Di Vito et al., 1999; Isaia et al., 2009; Fig. 6).

The 70 post-NYT eruptions are grouped into three eruptive epochs, separated by periods of quiescence: Epoch 1 (15.0–10.6 ka BP), Epoch 2 (9.6–9.1 ka BP), and Epoch 3 (5.5–3.5 ka BP) (Di Vito et al., 1999; Isaia et al., 2009; Smith et al. 2011). The eruption of Monte Nuovo in 1538 A.D. represents the last eruption of the caldera. This period of volcanic activity at Campi Flegrei was characterized mainly by explosive eruptions with less frequent effusive events. During the last 15,000 years, there have been only two high-magnitude eruptions characterized by Plinian phases (Agnano Pomici-Principali and Agnano-Monte Spina; Di Vito et al. 1999; De Vita et al. 1999), while eruptive events of medium and low magnitude were predominant. The variability of the events is evidenced by the different areal distributions of deposits and by different volumes of magma emitted during eruptions that only for the highest magnitude event exceeded 1 km^3 (Orsi et al., 2004; Di Renzo et al., 2011). Indeed, volume estimates of magma erupted during many post-NYT events represent generally an underestimation due to the lack of proximal deposits for many of the recognized eruptions. The largest post-15 ka events that erupted >>0.1 km^3 D.R.E. of magma, and dispersed ash over wide areas. Deposits of these eruptions indicate that they had phases that were either subplinian to Plinian with eruption columns that extended well into the stratosphere. The Plinian and subplinan column were generally widespread toward east-northeast, while low height column laid down fallout deposits in

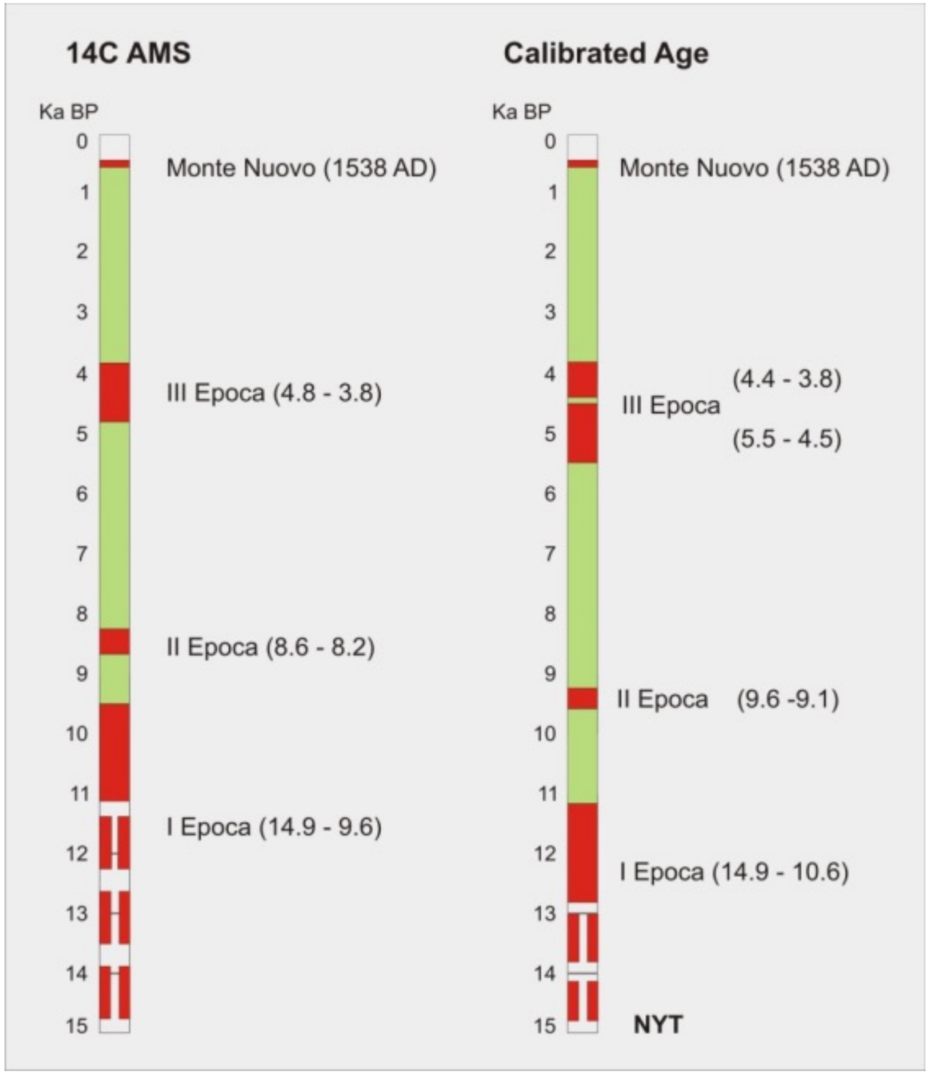


Fig. 6 - Chronostratigraphyc scheme of the volcanism younger than 15 ka at the Campi Flegrei caldera (after Isaia and Smith, 2013).

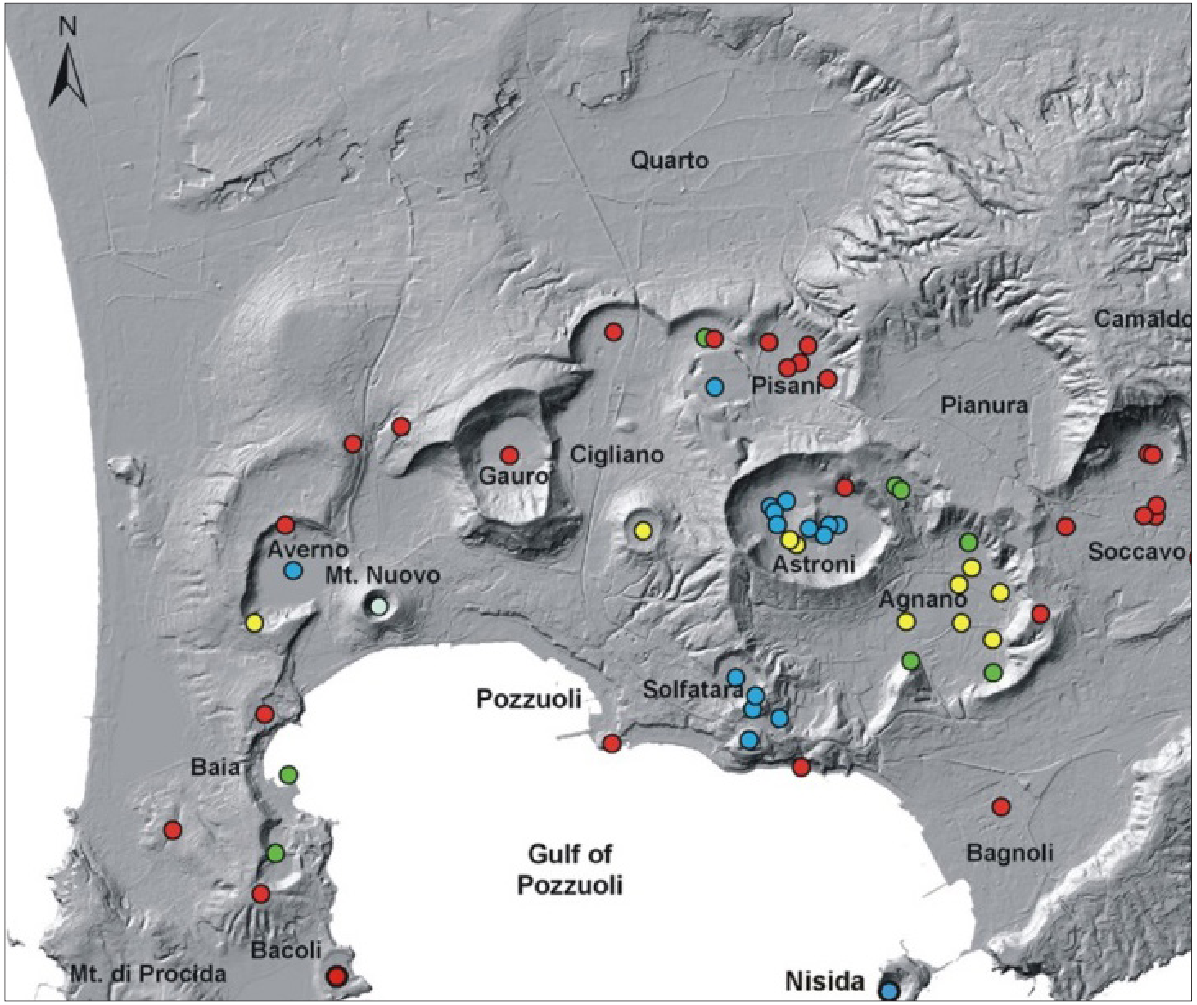


Fig. 7– Location of eruptive vents of the last 15 ka at Campi Flegrei caldera (after Isaia and Smith 2013)

variable directions.

The location of eruptive vents (Fig. 7) has changed over time, most recently being concentrated in the central-eastern part of the caldera, with respect to the western sector (Isaia et al. 2009; Vilardo et al. 2010; Bevilacqua et al., 2015). During Epoch 1, vents were mainly aligned along the structural boundaries of the NYT caldera, but Epoch 2 was mainly characterized by eruptions from the NE sector of the caldera, with the exception of the Baia–Fondi di Baia eruption (Fig. 7). This occurred at onset of Epoch 2 and was located in the western sector of the NYT caldera. Finally, Epoch 3 vents were hosted mainly in the central-eastern sector of the caldera, at the western margin of the Agnano collapse area (Isaia et al. 2009, Bevilacqua et al., 2015).

Simultaneous eruptions in the two different sectors of the caldera were also highlighted at 4.3 ky BP, when Solfatara and Averno volcanoes erupted simultaneously (Isaia et al., 2009; Pistolesi et al., 2016).

The caldera was also characterized by ground deformation during the last 10,500 years which resulted in a total uplift greater than 100 m in its central part. The main epochs of volcanism were anticipated by resurgence episodes resulting in meters to tens of meters of uplift (Di Vito et al., 1999; Isaia et al., 2009) in response to magma movements at depth. Even over several decades before the Monte Nuovo eruption ground uplift attained several meters (e.g., Dvorak and Gasparini, 1991; Morhange et al., 2006; Guidoboni and Ciuccarelli, 2011; Di Vito et al., 2016).

Recently, slow ground movement (bradyseism) has occurred in the area, with two major bradyseismic crises (1970-72 and 1982-84) accompanied by hundreds of earthquakes and 3.5 m of ground uplift, leading to the partial evacuation of the town of Pozzuoli. Different episodes of 'micro-uplift' with maximum displacement of a few tens of cm occurred in the last 30 years and are currently underway (Fig. 8).

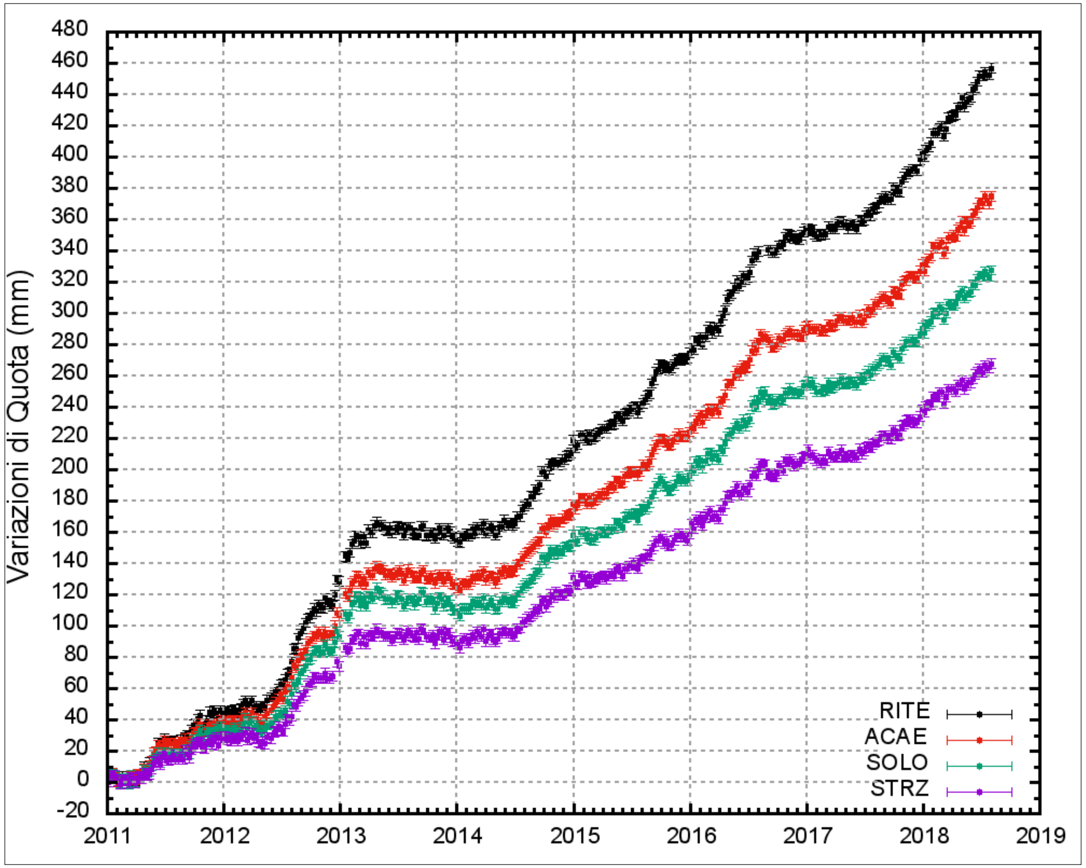


Fig. 8– Time series of changes in elevation of the RITE stations (Pozzuoli – Rione Terra), ACAE (Accademia Aeronautica), SOLO (Solfatara) e STRZ (Pozzuoli - Cimitero) from January 1, 2011 to August 4, 2018 (Weekly Bulletin of Surveillance at Campi Flegrei; INGV – OV)

Campi Flegrei – Itinerary

Fig. 9 - Aerial view of the central part of the Campi Flegrei with the field trip stops

The itinerary (Fig. 9) in the Campi Flegrei caldera allow us to observe some of the main volcanic structures of the area as well as tephra deposits of representative recent eruptions. This will give us the opportunity to illustrate and discuss about the volcanic history of the Campi Flegrei, the ground deformation dynamics, and to focus on the possible future scenario and the risk related to a possible resumption of the eruptive activity at Campi Flegrei. Stops to look at the fumarolic field of the Solfatara area, as well as to the Pozzuoli harbour and Serapeo Roman archaeological ruins, will allow discussing in depth volcanic hazards related to unrest episodes and the relationships between unrest episodes and eruptions. Visit to archaeological sites allow us also to assess from inside the volcano the physical relationship between volcanic and human activities since romans time and discuss about the volcanic risk perception by residents including a large part of the city of Napoli. Fig. 9 shows the location of the stops.

Stop A – The volcanic structure of the Campi Flegrei. Panoramic view from the hill of Posillipo in Naples

Significance. - A general view of the Campi Flegrei caldera structure and the densely inhabited western sector of Naples city.

The caldera. - From this site it's possible to have a general view of the Campi Flegrei (Fig. 10). Towards North there is the Camaldoli hill, whose slopes are constituted by thick successions of pyroclastic deposits with age from about 50 ka. The high-angle slopes that form the top of Camaldoli represent the edge of the Campi Flegrei caldera and along these a thick Campanian Ignimbrite sequence is exposed. This eruption formed the Campi Flegrei caldera and changed the landscape of large part of the Campania Plain. In the upper part of the scarp are well visible the yellowish tuff deposits laid down by the second largest eruption of the Campi Flegrei named Neapolitan Yellow Tuff (NYT). The Camaldoli hill are the highest point of the Neapolitan-Phlegraean area (434 m asl).

Fig. 10- Overview of the Campi Flegrei seen from the Posillipo Hill (G. Vilardo Lab. Geomatica e Cartografia, Osservatorio Vesuviano)

The Vomero-Arenella saddle was a preferential pathway for PDC erupted in the present Soccavo plain where many vents were active during the I epoch (9.5-15 ka) of volcanism following the NYT eruption (15 ka; Deino et al., 2004). The largest part of the morphological boundaries of both CI and NYT calderas, are visible. The scarp bordering the Posillipo hill towards the northwest, is the only exposed part of the NYT caldera margin. The densely urbanized Fuorigrotta-Bagnoli and Soccavo plains, have been the site of eruption vents during the I epoch (15 - 9.5 ka).

Seeing toward the inner part of the caldera the articulated morphology of the landscape can be noted, mainly due to presence of several volcanic edifices. However these edifices, in many cases are only partially preserved due to both subsequent explosive activity and erosion process mainly by the sea water, which in some cases have formed marine terraces (La Starza, Pozzuoli) or coastal plains as the Bagnoli area just below us. It's worth to note that this stop is on top of the scarp bordering the Posillipo hill towards the northwest the only visible scarp related to the collapse occurred during the NYT eruption.

Looking towards the west, one can have a view of the central volcanic vents of the caldera with the hill bordering the Agnano plain and the Astroni tuff ring. The former results from a volcano-tectonic collapse during the Agnano-Monte Spina eruption. The Astroni volcano, a well preserved elliptical edifice with axes of about 2 and 1 km, (Fig. 9), formed during the most recent epoch of activity of the Campi Flegrei caldera (Di Vito et al., 1999, Isaia et al., 2009).

Behind the Astroni and Gauro volcanoes, looking toward the south west are visible the Averno-Capo Miseno alignment of tuff cones and tuff rings, which marks the western margin of the Neapolitan Yellow Tuff caldera. At the end of the town of Pozzuoli is visible the Mt. Nuovo cone formed during the only hystorical eruption of the caldera.

Looking towards the south-west, one can have a view of the Gulf of Pozzuoli, and of the volcanoes of the western sector of the caldera, with the clearly visible Capo Miseno volcano at the end corner of the Gulf. On the back of this edifice it's possible to look at volcanic islands of Procida and Ischia.

The general view of the Campi Flegrei caldera structure highlights how large and densely populated districts of Naples are developed entirely inside the caldera and contemporaneously to have an idea about the huge work has to be done to mitigate and manage the volcanic risk in this area. At the same time the overall look of the caldera allows us also to make an immediate comparison in terms of structure and morphology with the other active volcano of Somma Vesuvius.

Posillipo Hill

This site stand on the highest point of the Campi Flegrei caldera and allow to have a look at the main structure of the caldera as well as to the very dense urbanisation of the area, providing an immediate idea of the associated volcanic risk. From this point it is also interesting highlight the complex morphology of Campi Flegrei volcanoes and how this features are not easily perceived as a "volcano" by the local population.

Stop B The Agnano Monte Spina Plinian eruption

Significance. - Agnano-Monte Spina eruption, the large-scale event of the Campi Flegrei caldera in the past 5.5 ka.

Agnano Monte Spina eruption (AMS) - The AMS is the highest-magnitude eruption that occurred over the past 5.5 ka within the CFc (de Vita et al. 1999; Di Vito et al., 1999; Dellino et al. 2001; Orsi et al. 2004; Costa et al., 2009; Smith et al., 2011). de Vita et al. (1999) presented a detailed reconstruction of the pyroclastic sequence and obtained a radiocarbon age of the eruption to 4.1 ka, which successively has been calibrated and modelled by Smith et al (2011) providing an age of about 4.5 ka. Authors subdivided the whole sequence into six members (A through F) mainly based on variation of lithological features (Fig. 10).

Members are further subdivided into sub-members upon sedimentological characteristics. Plinian/sub-Plinian fallout deposits generated by magmatic explosions frequently alternate with base-surge beds of phreatomagmatic origin (de Vita et al. 1999; Dellino et al. 2004). During some eruption phases the contrasting eruption dynamics were almost contemporaneous (Dellino et al., 2004). Mele et al., (2015) studied the PDC generated during the AMS eruption with the aim of assessing the potential impact of similar events in the future. Laboratory analyses on samples from the main layers of deposits allowed obtaining the input data for the PYFLOW code, which was used for reconstructing the flow dynamic characteristics of the currents. In the large-scale even like AMS, the dynamic pressure ranges from 9.38 to 1.00 kPa (integrating the basal 10 m of the current) at distances of 1.5 and 4.0 km from the vent, respectively. These values are highly influenced by the local topography. provide important information on the potential impact that similar PDCs could cause to buildings, infrastructures and population.

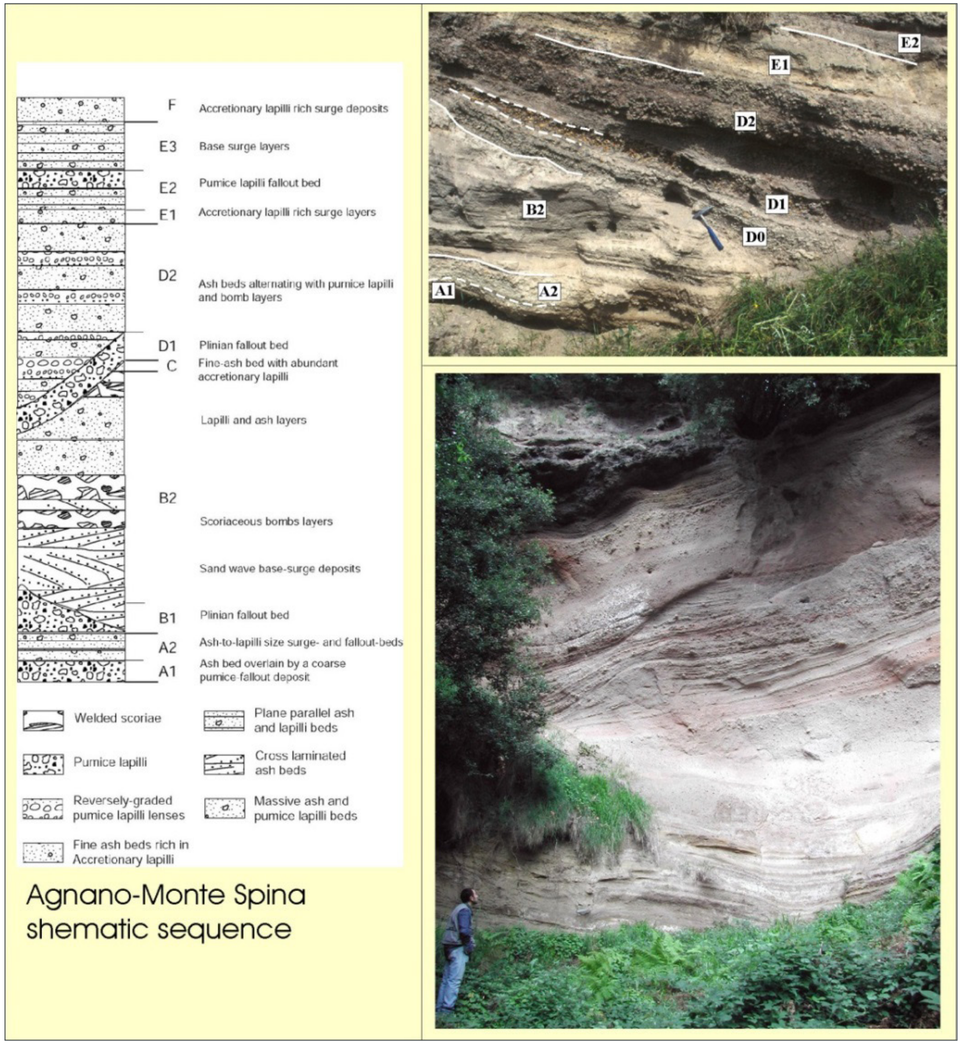


Fig. 10 - Agnano Monte Spina reconstructed stratigraphyc sequence; photos on the right refers to proximal deposits (below; Agnano area) and medial-proximal deposits (above; Pianura area)

Only two of the six members of the AMS pyroclastic sequence comprise coarse fallout layers produced during Plinian phases. The stratigrafically lowest Plinian fallout deposit of the entire AMS sequence was recognized at the base of Member B (sub-Member B1). It is composed of a coarse pumice-fallout layer laid down by a pulsating column reaching a maximum height of about 23 km. Isopach maps indicate that B1 was dispersed towards the east up to 45 km from the vent area (Fig. 11). Another coarse pumice-fallout deposit (sub-Member D1) was recognized in the lower portion of the Member D. This fallout layer generated during magmatic explosions was deposited by a Plinian column that reached a maximum height of about 30 km. Layer D1 is a pumice-fallout deposit with a northeastward oriented dispersal axis. Isopachs are quite regular elliptical curves covering an area of at least 700 km^2 (Fig. 11). According to de Vita et al. (1999), thickness of AMS Tephra varies from a maximum estimated value of about 70 m in the Agnano plain, which is the inferred vent area, to a few centimetres over a distance of about 50 km (Fig. 11). The total volume of the erupted magma was 1.2 km^3 (DRE), while a volume of 0.11 and 0.10 km^3 (DRE) was here estimated for B1 and D1 fallout deposits, respectively.

The Agnano-Monte Spina Tephra range in composition from trachyte to alkali-trachyte. Pumice and scoria fragments are porphyritic, with phenocrysts of feldspar, clinopyroxene, black mica, apatite and opaques in order of decreasing abundance. Olivine is present only in few samples. Arienzo et al. (2010) on the base of chemical and isotopic data on whole rocks and glasses suggest that at least two magma batches mixed during the course of the eruption, whereas melt inclusion data highlight the pre-eruption storage conditions of two magmatic end-members The H_2O and CO_2 contents in pyroxene-hosted melt inclusions yield entrapment pressures between 107 and 211 MPa, corresponding to depths between 4 and 8 km.

Glass chemistry data and information on the eruptions have been used to correlate eruption units in a proximal and distal locations (Smith et al., 2011). The chemical and physical characteristics of the uppermost Lago di Monticchio layers with a Campi Flegrei chemical affinity indicate that they are from the AMS eruption, and reveal that AMS comprised two separate plinian eruptions separated by 40 years (based on varve counts). These detailed information on volcanism enable also to use this data for hazard assessments of the Campi Flegrei active caldera.

The Agnano Plain overview

From the entrance of the Astroni crater it is possible to have a view of the Agnano Plain, the structure resulted from the caldera collapse accompanying the AMS eruption. The borders of the Plain are made up by old volcanic edifices cut by faults reactivated during the collapse phase. The morphological sign of the volcano-tectonic lineaments are represented by deep valleys, filled mainly by proximal deposits of AMS, and triangular facets, oriented mainly NE-SW and NO-SE.

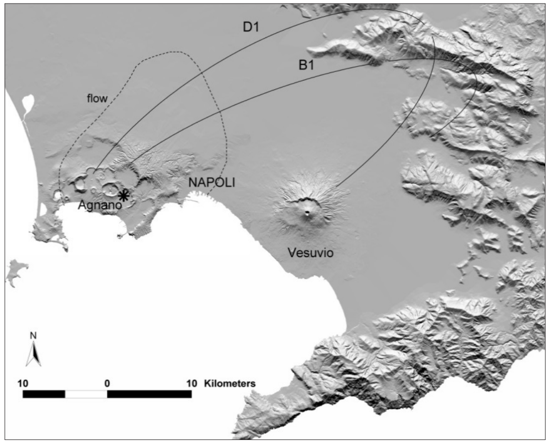


Fig - 11 Areal distribution of Agnano Monte Spina deposits; the dashed line delimits the area of the PDC dispersion, the solid lines encompass the isopachs of 10 cm for the main fallout deposits, the asterisk indicates the vent area. After de Vita et al. (1999).

Stop B - The Astroni volcano

Significance. - The sequence of 7 close eruptions in the same area during a period of very intense volcanism

The Astroni volcano is a well preserved elliptical edifice with axes of about 2 and 1 km, and maximum elevation of 253 m a.s.l. (Fig. 12). This volcano formed during the III and most recent epoch of activity (5.5-3.8 ka) of the Campi Flegrei caldera (CFc) (Di Vito et al., 1999; Isaia et al., 2009; Smith et al., 2011).

The activity of the volcano was dominated by explosive, mostly phreatomagmatic eruptions, with only subordinate lava effusions. Isaia et al. (2004) have defined 7 depositional units, their internal stratigraphy and areal distribution, and their relationships with the other volcanic units of the Campi flegrei caldera. The entire Astroni sequence is found between the deposits of Solfatara and Averno 2 Tephra (Isaia et al., 2009; Pistolesi et al., 2016) and Fossa Lupara tephra (Fig. 13).

Fig. 12 - View of the Astroni crater seen from the south (G. Vilardo Lab. Geomatica e Cartografia, Osservatorio Vesuviano)

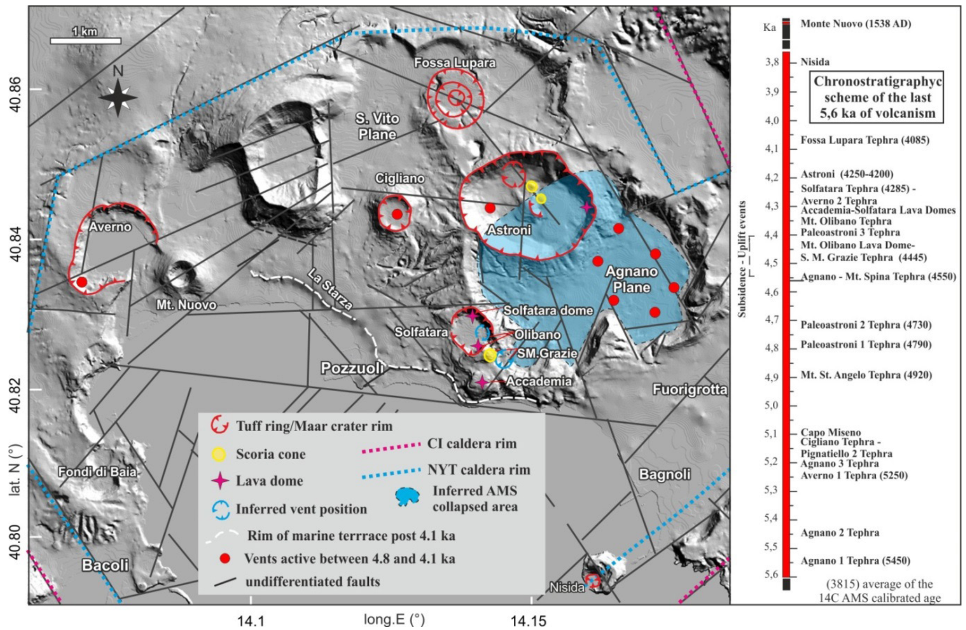


Fig. 13 - Vent location within the central sector of the Campi Flegrei caldera and chronostratigraphy between 5.6 ka and 1538 AP (from Isaia et al., 2015).

The recognized Units have been named 1 through 7 from base upwards and are delimited by either thin paleosols or erosional unconformities. They are composed of pyroclastic deposits generated by phreatomagmatic with subordinate magmatic explosions. Only two (Units 5 and 7) include products of late low-energy explosions and lava extrusion. All phreatomagmatic explosions have generated large amount of ash widely dispersed in the Campanian Plain (Fig.14).

The texture of the deposits of such explosions varies according to distance from the vent, from coarse and wavy to plane-parallel, to fine and plane-parallel to massive. The magmatic explosions produced strombolian fallout layer intercalated to the surge bed (Fig. 15). In some cases, the particle fallout was contemporaneous to the surge flowage. The base of Unit 6 is the only Plinian fallout deposit of the entire Astroni sequence, deposited by a column which reach a maximum height of 20 km (Fig. 16).

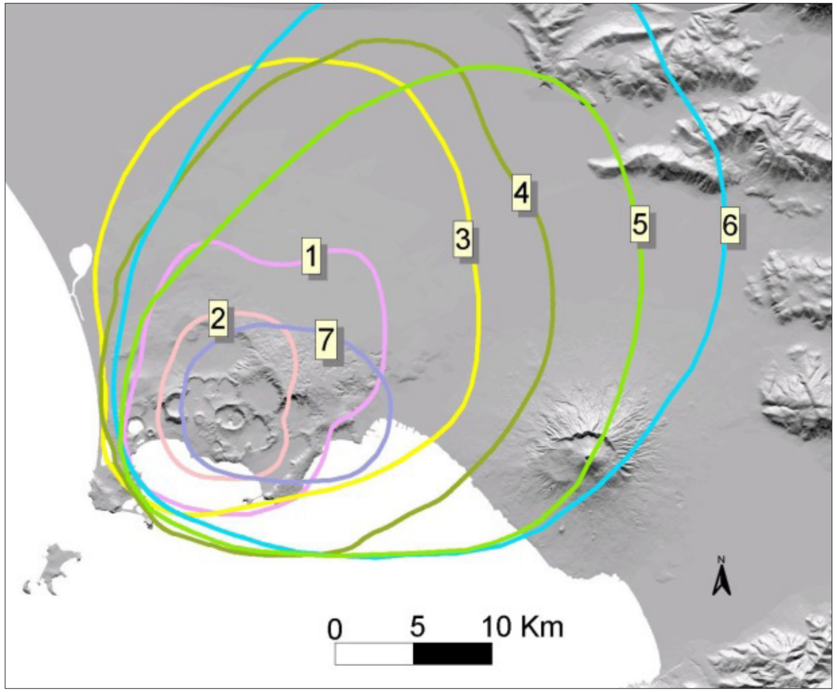


Fig. 14 - Isopachs maps of 10 cm thick tephra layers of the 7 Astroni units (from Isaia et al., 2004).

Fig. 15 – Sandwave beds deposits typical of the Astroni units, exposed along the Crater wall.

Facies and thickness variation of the deposits indicate that the eruption vents, although confined in the present crater, migrated from NW to SE during the course of the eruption.

The total volume of erupted magma is 0.45 km^3 (DRE), while the total mass is 1.12*10^{12} kg. The magma feeding the first 5 eruptions was alkali-trachytic and slightly zoned, while the last two eruptions tapped a magma batch resulting from mixing of the previously extruded alkali-trachytic and a less evolved trachytic magma.

The volcano grew at the northwestern edge of the polygonal volcano-tectonic collapse, NW-SE elongated, which accompanied the Agnano-Monte Spina eruption (4.5 ka), the largest of the III epoch. Stratigraphical data and calibrated radiometric dates constrain the age of the volcano between 4.25 and 4.2 ka. This implies that the 7 eruptions followed each other at very short time intervals, soon after the eruptive activity of Solfatara maar system and slightly before the formation of the Fossa Lupara volcano. The sequence of 7 close eruptions in the same area during a period of very intense volcanism, makes the Astroni volcano peculiar in the recent history of the CFc, and provide also very important clue to understand the eruptive scenarios of the caldera, as relevant elements to forecast its behavior.

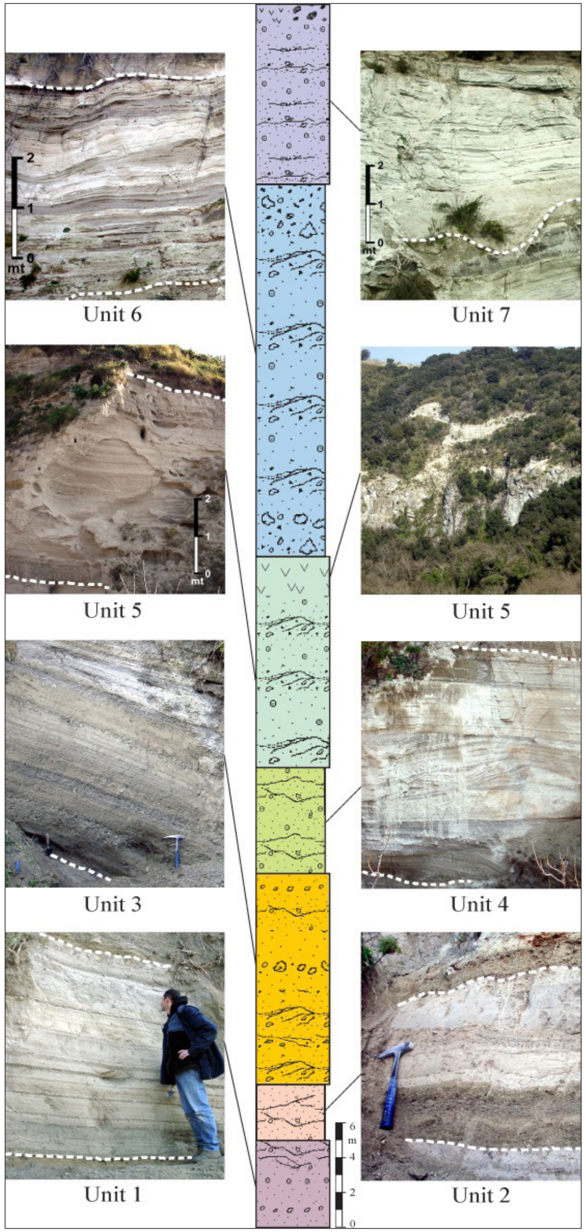


Fig. 16 - Reconstructed type sequence of the Astroni Units (from Isaia et al. 2004)

The Crater of Astroni

A viewpoint close to entrance of the Natural reserve of Astroni allow us to look at the well preserved crater of the tuff ring generated after 7 distinct eruptive event. Along the internal flanks of the volcano, pyroclastic sequences crop out showing very interesting structures of proximal PDC deposits. The north-eastern sector of the edifice exposed the remnant of the lava dome (La Caprara) ending the eruptive event 5 of the sequence. The floor of the crater hosts different small scoria cone and a tuff cone, and among them small lakes.

The Crater of Astroni is presently a WWF Natural Reserve of 247 hectare near Napoli city centre. Most of the crater is covered in forest. At the bottom of the crater there are three lakes (Lago Grande, Cofaniello Piccolo e Cofaniello Grande) and a number of small hills (Colle dell'Imperatore and Colle della Rotondella) formed after the volcanic eruptions.

The whole area is an environmental mosaic of considerable complexity and the composition of the vegetation is the result of inverted plant zonation. This particular type of plant zonation, whereby high altitude species are found at lower altitudes and low altitude species grow at higher altitudes, is the result of the particular micro-climatic conditions of the crater.

The remarkable biodiversity of the Reserve favoured the establishment of a very diverse animal community. Birds are the most interesting wildlife presence: there are approximately 130 different species that come to rest and/or nest during migration and the winter season.

Moreover, at the reserve Environmnent Education Centre (CEA) WWF staff organise educational activities both for schools and visitors, and specific labs during the Spring and Summer months for children and teenagers.

Stop C - Baia-Fondi di Baia eruptive sequence

Significance. - Migration of the eruptive vents for small eruptions occurred close to the sea level in short time.

The Baia–Fondi di Baia eruption is one of the sporadic events that have occurred in the western sector of the Campi Flegrei caldera. It dates back to 9525–9696 BP and opened Epoch 2 of the caldera activity after a 1000-year-long period of quiescence. Although relatively small in terms of erupted volume with respect to most of the events of the past 15 ka, the Baia–Fondi di Baia eruption was characterized by a complex series of events. The stratigraphic succession has been related to two distinct eruptive episodes (Baia and Fondi di Baia). These were separated by a short time interval, and each was characterized by different eruptive phases (Pistolesi et al. 2017). The Baia eruptive episode started in a shallow-water environment with an explosive vent-opening phase that formed a breccia deposit (Unit I), rapidly followed by alternating fallout activity and dense, PDC deposits generation (Unit II).

Sedimentological features and pumice textural analyses suggest that deposition of Unit II coincided with the intensity peak of the eruption, with the fallout deposit being identified up to 20 km north of the Baia crater. This peak phase waned to turbulent, surge-like activity possibly associated with Vulcanian explosions and characterized by progressively lower intensity (Unit III). This first eruptive episode was followed by a short quiescence, interrupted by the onset of a second eruptive episode (Fondi di Baia) whose vent opening deposited a breccia bed (Unit IV) which at some key outcrops directly overlies the fallout deposit of Unit II. The final phase of the Fondi di Baia episode strongly resembles Unit II, although sedimentological and textural features, together with a more limited dispersal, suggest that this phase of the eruption had a lower intensity (Fig. 17).

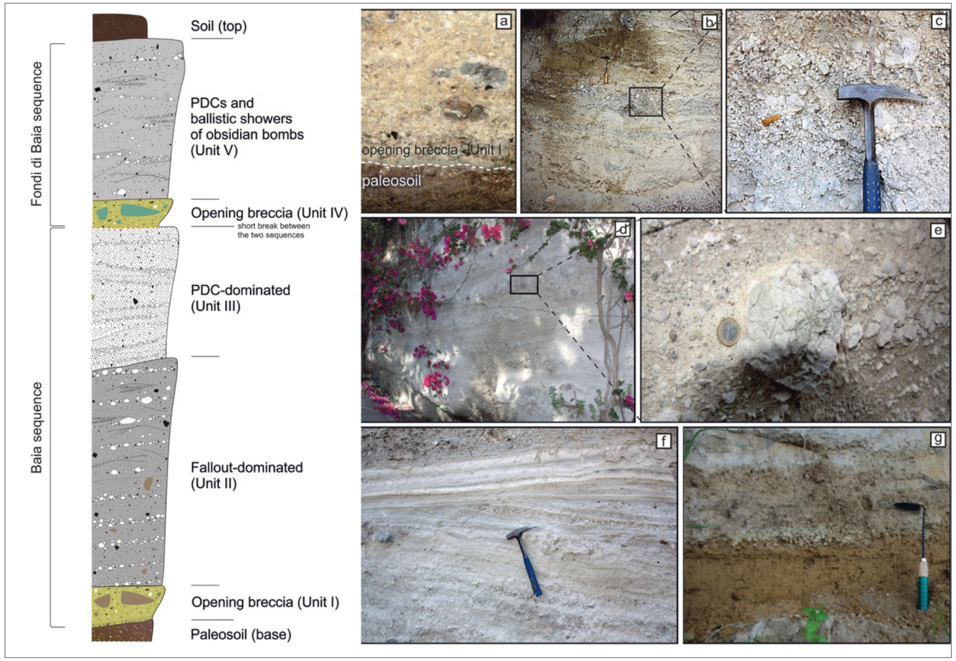


Fig. 17 - Pictures of the Baia succession. (a) Opening breccia (Unit I) which overlies the basal paleosoil. (b) Fallout and PDC deposits of Unit II. (c) Detail of a pumice layer shown in (b). (d) PDC layers of the upper part of Unit II. (e) Detail of a breadcrust bomb shown in (d). (f) Cross-bedding of surge deposits of Unit III. (g) Pumice fallout deposit of Unit II overlying a paleosoil 20 km north of the vent. On the left, idealized composite stratigraphy of the different phases of the eruption. Modified after Pistolesi et al. (2017).

From the Baia Castle, on the southern side of the vent area, we have a complete overview of the inferred source location of the Baia-Fondi di Baia eruption. The Baia vent can be placed within the Baia harbor, today partially invaded by the sea. During the eruption, the source area migrated southward, and the inferred vent of the Fondi di Baia event coincides with the southernmost crater (Fig. 18).

The Baia Sequence

The key section of the Baia sequence is exposed on the western side of Baia's harbor. In this area, we have a complete overview of the >20-m thick tephra succession (Fig. 17). By walking on the internal rim of the Baia vent, we will access all the stratigraphic sequence, from the altered, opening breccia, to the fallout-dominated deposits, to the PDC-dominated, surge-like deposits.

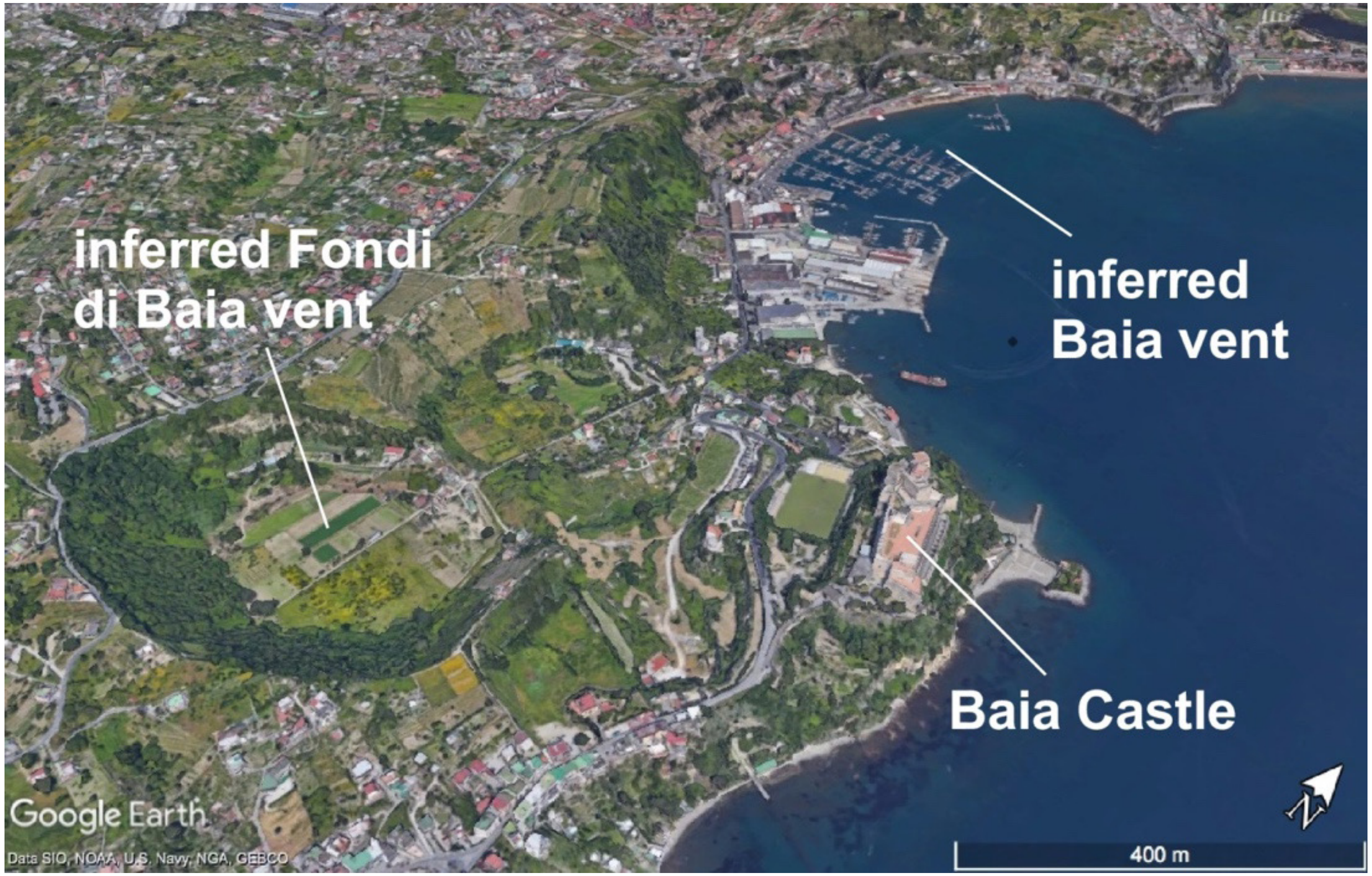


Fig. 18 - General overview of the source area, characterized by the presence of three circular depressions. The Baia harbor, vent of the Baia event today partially invaded by the sea, and the southernmost crater, vent of the Fondi di Baia eruptive episode. The central depression was unlikely the FdB eruptive center because its floor is covered by the soil over which Units II and III are emplaced and which form the crater walls. The depression possibly pre-dated the eruption or was formed by post-eruption collapse along the same N-S structure along which the vents are aligned.

The Archaeological Museum of Baia

The Archaeological Museum of Campi Flegrei, which opened in 1993, is housed inside a fortress dating back to the Aragonese period, which has been specially restored and adapted to full its new role as an exhibition venue. It is located on the top of the high promontory southern closed to the gulf of Baia, and from which the entire bay of Pozzuoli and the islands of Capri, Ischia and Procida are visible.

In its splendid landscape setting, which can be admired from the Aragonese fortress, the museum reconstitutes dispersed contexts of Flegrean origin, thus reuniting objects found long ago that up until now have been kept in storage at the Museo Archeologico Nazionale di Napoli, with objects discovered in recent excavations, following a logical exhibition layout organized by topography and by theme such as: Cuma, Puteoli, Baiae, Misenum e Liternum.

The tour begins with the Cuma Section on the second floor, housed in the former barrack- rooms used by the fortress soldiers: twenty-four rooms illustrate the history of the site from the 9th century B.C. Opican settlement to the 8th – 5th century B.C. Greek city, to the 4thcentury B.C. Samnite city, to the Roman city, to the final Byzantine period.

The Pozzuoli Section consists of twenty rooms on the first floor, illustrates the history of the site: the first urban expansion of the Augustan colony (theatre buildings, aqueduct, cosmopolitan city such as Grotta del Wady Minahy in the Egyptian desert), the Neronian colony and the new urban conformation imposed by the emperors, the late-ancient revival, the suburban villas and the necropolises.

The Rione Terra Section located in the Piazza d'Arme exhibits remains came from recent excavations related to the Capitolium architectural decoration and the sculpted decoration of other public buildings in the Augustan forum: ideal statues, including the head of Athena Lemnia, portraits of Julio-Claudian age and fragments of statues of caryatids and clipei, reminiscent of the attic in the forum of Augustus in Rome, which has been reconstructed as it might be looked.

The Baiae and Misenum reconstruct the Sacello degli Augustali da Misenum, the Ninfeo of Punta Epitaffio and the ancient plaster casts made from Greek originals of classical and Hellenistic age, presents the findings of the ancient Roman maritime villa late Republican, discovered under the Castle and the Knight Pavilion, with splendid mosaic floors and cocciopesto decorated, and frescoes fragments of late Pompeii style.

Liternum, a maritime colony founded in 194 b.C., shows finds (sculptures, inscriptions, tomb goods and various types of artefacts) recovered in old and new excavations performed by the Superintendency in urban areas, in the Forum area, in the amphitheater and in the necropolises.

Baia Roman Thermal Site

"No gulf in the world is as marvellous as Baia's". Wrote the poet Orazio at the end of the Ist century B.C.. In that period Baia was a residential centre with villas and thermal buildings built facing the little gulf, which was similar to a lake (*lacus Baianum*) connected by a canal to the open sea. The beauty of the panorama, the local springs of natural warm water and sulphurous steam coming from the volcanic subsoil, had attracted the Roman nobility here since the 2nd century B.C. They loved to spend their otia (spare time) in

these villas by the sea.

With the coming of the Empire, Baia became the imperial family's residence and in the next three centuries the building of structures for entertainment rose to such an importance that these buildings became models for roman ones. One example is the majestic dome of the thermal room, best known as "Truglio" or "Mercury Temple" or "Echo Temple" for the acoustic effect produced here. This dome, built at the end of the I century B.C., was way ahead of its building techniques used a century later in the building of the Pantheon in Rome.

The imperial palace (*Palatium Baianum*) extended over all the mountain facing the gulf including the already existing villas and the thermal buildings. Its remains are identified by the big building known as Baia's thermal baths, because of the presence of many thermal rooms. These rooms extend on the longitudinal line of the hill, on different levels of terracing, but due to the bradisism, the lower level, which was at the mountainsides till the ancient coast line, is today submerged. Long and steep flights of steps cut the buildings orthogonally to connect the various levels.

It is not a unitary monument but it's composed of five sectors that have not the same orientation, which is the sign of a different chronological construction. They are known as the Terrace complex, the Mercury thermal baths, the lower thermal baths, the Sosandra thermal baths and the Venus thermal baths.

Baia - Bath of Mercury

Apart from the Terraces Complex which is the lonely nucleus appearing as a villa, all the other buildings are composed of thermal baths, nymphaeums, fountain tubs, lodges and residential buildings open onto gardens. In the Sosandra thermal baths there is also a hemicycle nymphaeum - theatre, used as a relaxing place and as *cavea* for performances.

The complex is dated between the Ist century B.C. and the 3rd A.D.. Later because of the bradisism, a quiet but progressive decaying of the area started but not the celebrity of the Baia thermal baths, whose structures survived until the age of the Spanish viceroy Pedro Antonio di Aragona in the 17thcentury.

Thanks to the recently concluded POR project, which dealt with the restoration and development, the entire monument has been restored, the Diana sector has been recovered and is now accessible also from the new lower entrance. In fact thanks to the relocation of the old train station, in agreement with Bacoli town council, a new entrance from the lower side of the monument has been opened. The improvement of the monument has been completed thanks to the two other POR projects which have dealt with the institution of a route for disabled people and the link to the Monumental Park by a winding naturalistic path along the hill.

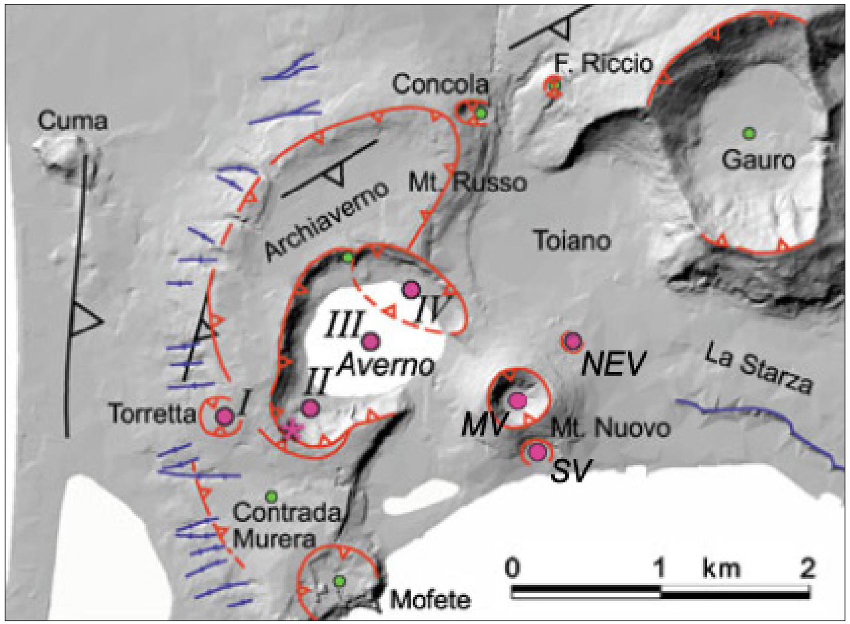
Baia - Nymphaeum - theatre

Stop D - The Averno 2 crater

Significance. - The activity of a tuff ring generated contemporaneously to the Solfatara volcano far about 5 km on the eastern sector of the caldera.

The Averno 2 eruption was contemporaneous to the Solfatara one, which vent is located in the eastern sector of the Campi Flegrei cadera (Isaia et al., 2009).

The Averno 2 eruption history and dynamics have been reconstructed by Di Vito et al. (2011) using structural, stratigraphical and sedimentological data. The eruption was characterized by three explosive phases, with variable dynamics and dispersal of the pyroclastic products.



The first phase of the eruption began with dominant magmatic and minor phreatomagmatic explosions from a vent located SW of the present Averno lake (I in Fig. 19). These explosions generated a very low eruption column, and then turbulent PDC, that together formed the fall and surge deposits of the A0 sequence of Member A (Fig. 20). The eruption continued from a new vent opened in the southwestern concave sector of the Averno lake depression (II in Fig. 19) with generation of an 8 km high eruption column, fed mainly by magmatic explosions, that laid down the A1 sequence, composed of a fall deposit (Fig. 20) overlain by minor surge beds. At this stage the vent further shifted toward the center of the present lake (III in Fig. 19) and the eruption reached its climax, producing an oscillating eruption column that reached the maximum height of 10 km, with a mass discharge rate of $3.2*10^6$ kg/s. Contemporaneous to this magmatic column, sporadic phreatomagmatic explosions also took place, probably through an unlocated but nearby secondary vent. This explosive activity produced the A2 sequence, the most widely distributed of the AV2 sequence (Fig. 20), including a fall deposit overlain by, and interbedded with minor surge beds. The eruption continued in the central part of the present lake depression with magmatic and a few phreatomagmatic explosions, generating an eruption column that reached a maximum height of about 9 km. This activity generated the subsequent A3, A4 and A5 sequences, composed of dominant fall deposits with minor surge beds.

Fig. 19 - Morpho-structural sketch map of the Averno – Monte Nuovo area (after Di Vito et al., 2011). In red the crater rims, in purple the vents of Averno and Monte Nuovo, in blue the valleys and green vents of the I epoch of activity.

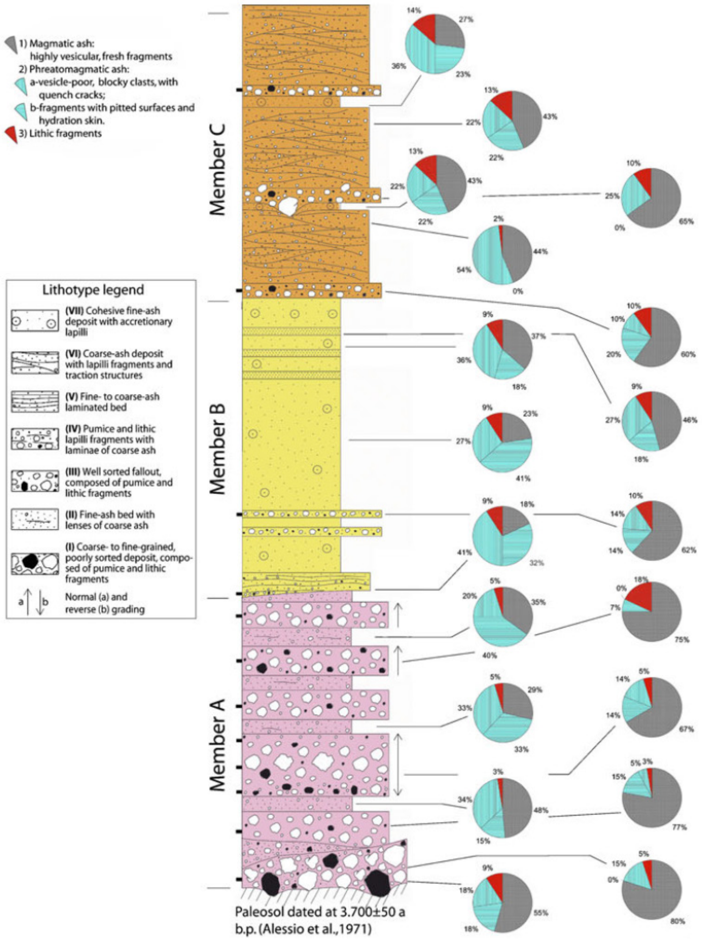


Fig. 20 - Stratigraphic type-section of the Averno 2 Tephra, with indication of the stratigraphic levels sampled for petrographic and geochemical studies in the left side of the section, as short dashes. Pie charts show the results of component analysis performed with SEM at the indicated levels; 1–3 are the types of fragments grouped according to their features (modified after Di Vito et al., 2011)

During emplacement of the A4 sequence, fractures appear to have opened, as suggested by the increase in lithics content, allowing ground- and/or sea-water to enter the shallow feeding system. This change in structural conditions produced a change in eruption dynamics and triggered onset of the second phase of the Averno 2 eruption. This phase was dominated by explosions driven by a very efficient water/magma interaction, with only a few episodes of magmatic explosivity, which generated low, short-lived eruption columns during the later stages of the activity. This second phase deposited Member B, a sequence dominated by wet surge beds, with minor fall deposits, dispersed preferentially northward from a vent still located in the center of the present lake (Fig. 19). The pre-existing Archiaverno tuff ring acted as a geomorphic barrier to the surge currents.

Another change in vent location and eruption characteristics marked the onset of the third phase of the eruption, which generated Member C. The eruption vent shifted towards the N-NE arched sector of the Averno lake depression (IV in Fig. 19), as suggested by distribution of the proximal facies of the pyroclastic deposits, distribution and geometry of impact sags by ballistic blocks and bombs, and Member C deposits draping the southern crater walls. This activity was dominated by phreatomagmatic explosions generated by efficient water-magma interaction, alternate with episodic magmatic explosions.

In summary, Member A was produced by three vents progressively active from SW toward the center of the present lake. During emplacement of this Member the eruption, dominated by magmatic explosions, reached its climax (sub-member A2), although the total erupted volume (0.020 km^3—DRE) was only about 1/3 of the total volume of the eruption. The eruption phases which produced Members B and C were dominated by phreatomagmatic explosions generating variably distributed pyroclastic surges from vents progressively shifting toward NE. These explosions were fed by more and more crystallized and degassed magma, which accounted for the remaining 2/3 of the total volume (Member B: 0.022 km^3; Member C: 0.025 km^3—DRE).

Notwithstanding the small volume of erupted magma (ca. 0.07 km^3 DRE), the products of this eruption show a slight variability of mineralogical, geochemical and Sr-isotopic characteristics, that sheds light on pre- and syn-eruption magmatic processes. The small range of composition, and the detected co-variations of major oxide and trace element concentrations, shown by the Averno 2 products (CaO from 2.4 to 1.8 wt.%), could result from a fractional crystallization process of a silica-rich magma, involving the mineral phases present in the rocks. This process is suggested by regular variation through the erupted sequence of major oxide and trace element contents with CaO as differentiation index. Sr-isotopic variations, however, indicate that open system processes, such as crustal contamination or magma mingling/mixing, operated in the magmatic system, rather than simple fractional crystallization.

Therefore, in order to explain all the detected geochemical and isotopical variations, Di Vito et al. (2011) proposed that two isotopically distinct magma batches were involved in the Averno 2 eruption. The first-erupted magma (A0 and A1 is the most evolved, least radiogenic batch (87Sr/86Sr ca. 0.70751), while the second is slightly less evolved and more enriched in radiogenic Sr ($^{87}Sr/^{86}Sr$ ca. 0.70754). These two end-members mingled/mixed before and/or during extrusion of Member A. In fact, this member is slightly chemically zoned and characterized by the widest range of both chemical and Sr-isotopic composition of the whole sequence.

Belvedere di Averno, along the Domitiana road.

General view of the Averno crater filled by a perennial lake. The view is located near the vent IV, active at the end of the eruption. From the Belvedere it is possible to see the sequence of member A, dominated by coarse fallout beds, overlain by member B, dominated by ash surge deposits. This sequence is visible all around the crater walls. Looking towards the north the sequence of deposits continues with products of member C, composed by and alternation of laminated and undulated coarse and fine ash surge beds.

STOP E - THE MONTE NUOVO VOLCANO

Significance. - Precursor and eruptive phenomena associated to the only historic eruptions of Campi Flegrei.

The Monte Nuovo eruption, the most recent event of the Campi Flegrei caldera, has been reconstructed through both geological, volcanological and petrological investigations, and analyses of historical documents (Di Vito et al., 1987; and references therein; D'Oriano et al., 2005).

The eruption lasted one week and was fed by three vents (Fig. 19). The main vent (MV) was located in the present crater of the Monte Nuovo tuff cone, whereas two minor vents were along the southern (SouthV) and northeastern (NEV) slopes of the Monte Nuovo tuff cone. The eruption was characterized by three phases separated by pauses in the activity. The entire sequence of deposits has been subdivided in 5 members named A through E, from base upsection.

The eruption began on September 29, 1538, at 7 p.m., and its first phase, which was the main phase of the entire event, lasted two days, until the night of September 30. This phase generated almost continuous phreatomagmatic with subordinate magmatic explosions, producing PDC and minor short-lived, low eruption columns, which deposited members A and B. Member A, composed of a sequence of plane-parallel to undulated fine- to coarse-ash beds forms the largest part of the Monte Nuovo tuff cone, and was erupted in about 12 hours through the MV. Phreatomagmatic explosions at the SV produced mainly PDC that deposited Member B. This member, composed of wavy fine-ash deposits containing coarse pumice and lithic fragments, is distributed only in the southern sector of Monte Nuovo and overlies unconformably member A. Strombolian explosions at the SouthV and NEV deposited the sequence of coarse scoria fallout deposits dispersed over narrow areas around the eruption vents, which form Member C. This activity marked the end of the first phase of the eruption and was followed by a pause that lasted two days.

The eruption resumed on October 3 at 4 p.m. and lasted until the next night. This second phase of the eruption was characterized by a discontinuous sequence of low-energy phreatomagmatic and magmatic explosions at the MV, which deposited the sequence of Member D. The phreatomagmatic explosions produced laminated to massive ash surge deposits, while the magmatic events produced coarse pumice and scoria fallout deposits.

Following a brief pause, the third phase of the eruption began at 4 p.m., October 6, and lasted few hours. This last phase was characterized by low-energy magmatic explosions from the MV. This activity was likely characterized by the explosion of a small dome grown during the preceding pause, followed by minor, very low-energy events at the crater of the MV, which produced Member E. This member includes fallout beds composed of dense to low-vesiculated, angular dark clasts. During this phase, 24 people died while climbing the slopes of the newly formed cone at the end of the second pause in the activity. The total emitted magma volume was 0.03 km^3 (DRE) and the maximum Mass Discharge Rate was $2.0*10^6$ kg/sec (Orsi et al., 2009).

The juvenile products of the Monte Nuovo eruption are phenocryst-poor rocks containing alkali feldspars and subordinate clinopyroxene and Fe-Ti oxides. They are light-coloured pumice and dark scoria fragments, and represent the most evolved magma erupted over the past 15 ka at Campi Flegrei caldera. It extruded fairly homogeneous phonolitic magma ranging in Sr-isotope composition from 0.70741 to 0.70744,with $^{143}Nd/^{144}Nd$=0.51247–49 (Di Renzo et al., 2011).

For the volcanic hazards assessment of the Neapolitan area, the Monte Nuovo eruption is considered as the low-magnitude type event among those expected in case of renewal of volcanism.

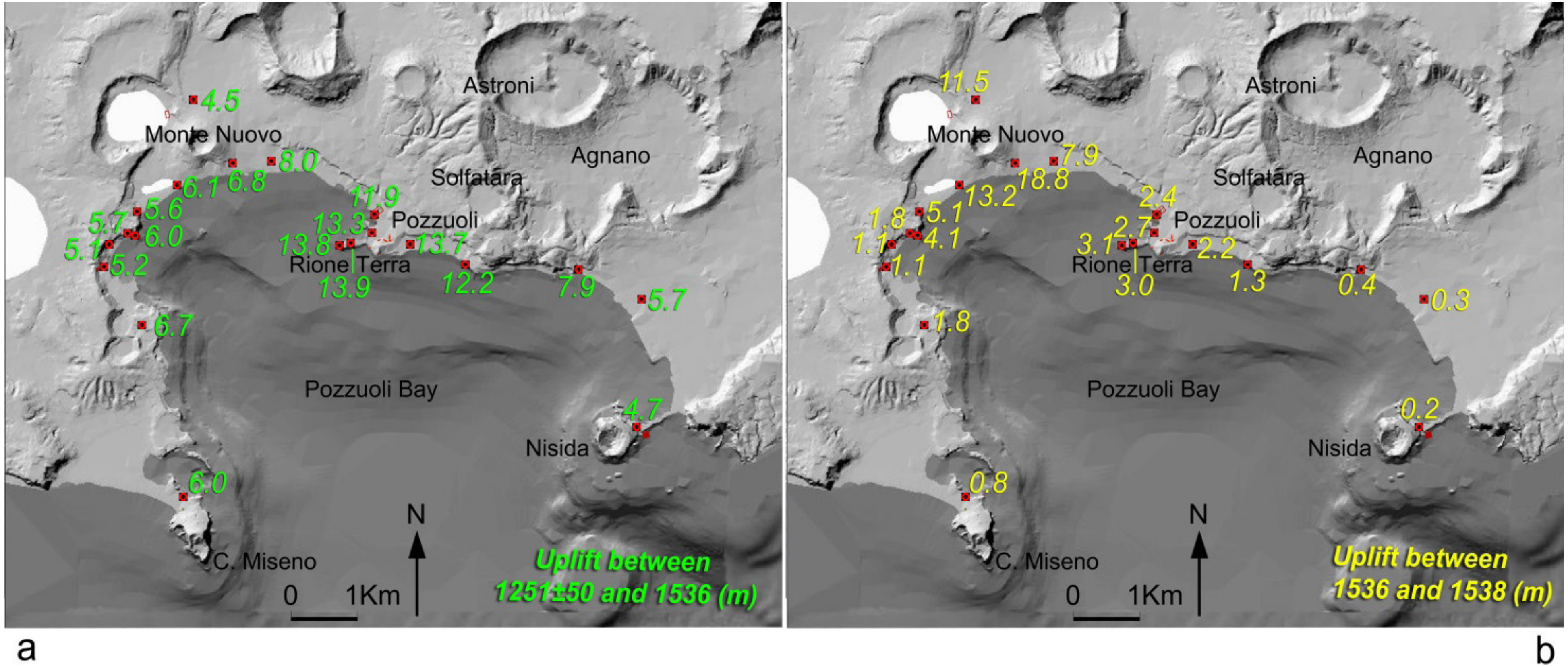


Fig. 21 - Distribution of the surface uplift preceding the Mt. Nuovo eruption. From 1251 to 1536 (a) the uplift affects the whole caldera, with a maximum in the Pozzuoli area. From 1536 to 1538 (b) the uplift is centred in the area of the future eruption (Monte Nuovo) (After Di Vito et al., 2016).

Ground movements preceding the eruption

A detailed and quantitative reconstruction of the ground displacements predating the Mt. Nuovo eruption has been carried out by Di Vito et al. (2016). The authors integrated geomorphological, sedimentological, paleontological, archaeological and historical data of sites located along the entire coastline of the Pozzuoli Bay. The general results of their analysis are summarized in Fig. 21, which shows the historical elevation changes, from 35 BC to Present, at the studied sites along the coastline of Pozzuoli Bay. These data show that in 35 BC the coastline extended outward into what is now the Pozzuoli Bay. However, since then all the area started to be affected by a quick subsidence, which resulted in progressive submersion of the coastline until 1251. The amount of subsidence in the investigated area varies from place to place. A subsequent progressive emersion of the area started during the 13th century, as suggested by historical and urban planning sources, archaeological evidence and geological data. The lower time limit for the caldera uplift is given by historical documents describing the Pozzuoli promontory of Rione Terra as an island in 1251, whereas at the end of the XIII and beginning of the XIV century the previously submerged area around the promontory is reported as the location of three new churches, testifying to the expansion of Pozzuoli on new land formed by the coastline regression, confirming the onset of a long-term uplift. The emersion of the area from the 13th to the 16th century was due to the ground uplift, with maximum values recorded in the Pozzuoli area.

The uplift rate was quite low (0.3 to 1 cm/yr; Fig. 21) from the middle of the 13th to the end of the 14th century, and increased to 2.9 to 9.1 cm/yr from 1400 to 1536. During this latter time-span, all the coastal strip emerged in response to the generalized uplift of the caldera floor, whose maximum of 12.3 m has been recorded again in the Pozzuoli area (Fig. 21).

Since the end of the 15th century this uplift was accompanied by strong seismicity (Guidoboni et al., 2010). A new and stronger uplift, with a rate of 10 to 940 cm/yr, followed the previous one between 1536–1538, reaching a maximum value of 18.8 m in the future vent-opening area (Mt. Nuovo; Fig. 21). This highest-rate uplift was accompanied by very intense seismicity, which affected all the Pozzuoli area and was felt also in the city of Naples (Guidoboni et al., 2010 and references therein). Furthermore all the historical sources coeval to the eruption report an evident uplift accompanied by continuous seismicity and opening of fractures in the vent area during the two days that preceded the eruption.

Monte Nuovo southern slope

Along the road of the “Monte Nuovo Oasis” it is possible to observe the Member C, composed by very coarse scoriae fallout emitted by the SouthV and overlying unconformably Members B and A, emitted by the SouthV and MV respectively.

Monte Nuovo crater (MV)

The crater rim is asymmetrical in response to the syneruptive ground deformation of the vent area (Di Napoli et al., 2017). The crater walls show the products of the member A, composed almost exclusively by a sequence of plane-parallel to undulated fine- to coarse-ash beds forming the largest part of the Monte Nuovo tuff cone, overlain by scoriae and minor ash layers of the member D and E, both erupted by the MV.

Stop F - The volcanic and hydrothermal activity in the volcano Solfatara

Significance. - Structural setting and intense fumarolic activities in a maar volcano.

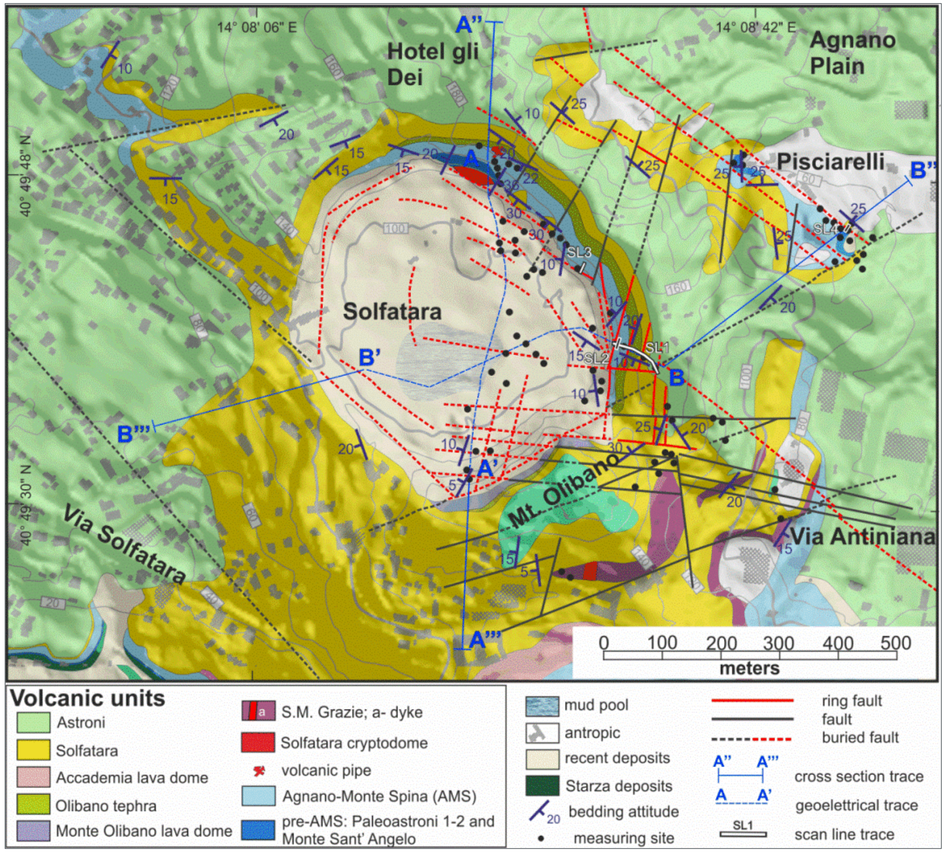


Fig. 22 - Geological map of the Solfatara area (from Isaia et al., 2015).

The Solfatara volcano, located in the central sector of the Campi Flegrei caldera, is one of the most recent volcanic edifices with an age of about 4,200 years BP. It is located about 2 km east-northeast of Pozzuoli, and characterised by a sub-rectangular (0.5x0.6 km) crater, shaped by prevailing NW-SE and SW-NE trending faults (Fig. 22) (Isaia et al. 2015).

Solfatara grows after the effusive eruptions of Monte Olibano lava dome, Olibano phreatic eruption and Accademia lava dome-forming eruption. The eruptive activity of Solfatara was mainly characterized by initial phreatic explosions with scarce juvenile material which emplaced low-dispersed PDC. This initial activity was followed by magmatic phases, with generation of PDC and tephra fallout.

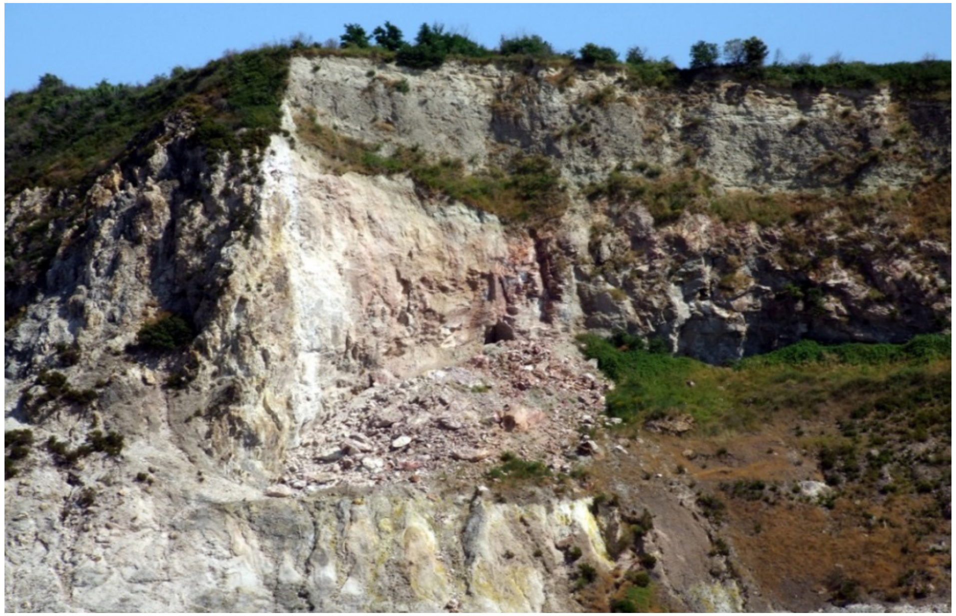


Fig. 23 - Sequence of volcanic rocks exposed along the inner wall of the eastern crater of Solfatara

The deposits consist of prevailing massive coarse to fine ash beds in the lower part and alternating fine-to-coarse ash and pumice layers (Figs. 23, 24), with surge-like lenses rich pumice clasts and ballistics in proximal to medial areas. Thin fallout deposits dispersed to the NE up to around seven km from the eruptive center were associated with the Solfatara eruption.

Fig. 24 - Pyroclastic deposits of the volcano Solfatara.

At 4.3 kyr B.P., the Solfatara and Averno vents, 5.4 km apart, erupted simultaneously

A stratigraphic section, located at ~2 km northwest of Solfatara crater and 4 km northeast of Averno lake, shows a tephra succession 100 cm thick which consists of alternating greenish to light-gray ash beds containing accretionary lapilli (Fig. 25). Light-colored and white coarser ash beds with scattered pumice clasts are interlayered at various heights. The section has been subdivided into five main units (U1 to U5), mainly based on tephra sedimentological characteristics (color and grain-size variations), consisting of an alternation of accretionary lapilli–bearing ash layers with scattered pumice fragments. Based on geochemistry of matrix glasses, and through a comparison with source tephra chemical characteristics, the light parts were associated to the Averno eruption while the greenish material to the Solfatara event (Fig. 25).

The crater of the Solfatara has been the site of an intense hydrothermal activity since Greek times (Fig. 26). It is the most impressive manifestation of the present hydrothermal activity of the caldera, which includes both focused vents, with a maximum temperature of about 160°C (Bocca Grande fumarole), and large areas of hot steaming ground. The average molar composition of the fluids is H_2O about 82 wt. %, CO_2 17.5 wt.%, H_2S 0.13 wt.% and minor amounts of N_2, H_2, CH_4 and CO.

The isotopic compositions of H_2O, CO_2 and He suggest the involvement of magmatic gases in the feeding system of the fumaroles (Chiodini et al., 1997). Subsequently the original magmatic gases are condensed by an aquifer system as suggested by the absence of the soluble acid gases SO_2, HCl and HF, typical of the high-temperature volcanic gas emissions. Boiling of this heated aquifer(s) generates the Solfatara fumaroles. At the present, the Solfatara is the main object of the geochemical surveillance of the caldera. In particular, both the chemical compositions of the fumarolic fluids and CO_2 fluxes from the soil of the crater are monitored.

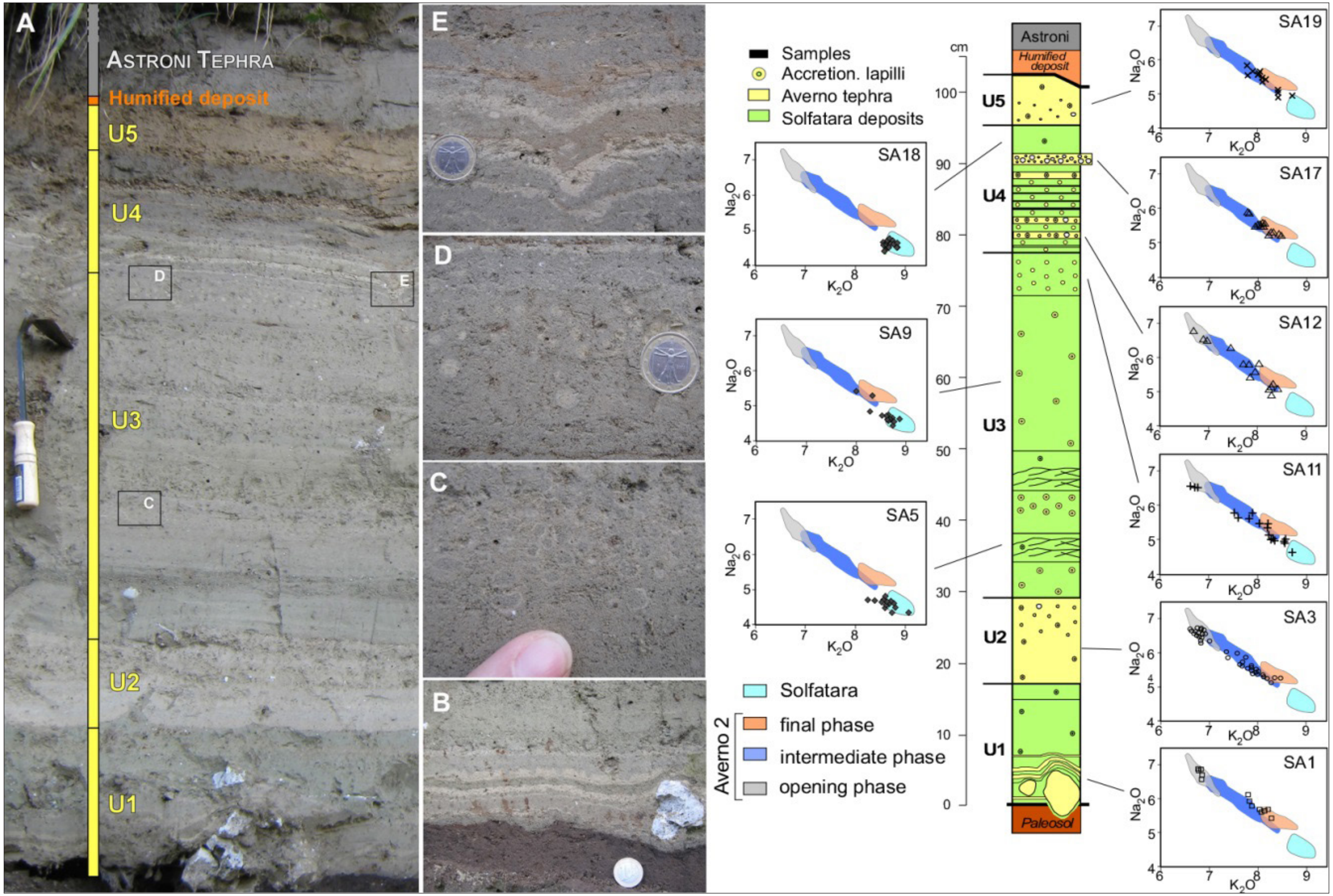


Fig. 25 - Stratigraphic section showing the interlayering among Solfatara and Averno products. Glass geochemistry fingerprinting the two sources Modified after Pistolesi et al. (2016).

Solfatara Crater

The Solfatara volcano gives a peculiar example of the of low energy eruptions dynamics, and allows to understand the influence of tectonic structures influence in generating different volcano shapes. On the cratere floor, but also along the internal and external flanks of the Solfatara Maar we can also have a look at the intense fumarolic manifestations.

Fig. 26 - Fumarolic and hydrothermal vents in the crater of Solfatara.

Stop G - the Serapeum and the bradyseism

Significance. - Short-term deformation and ongoing ground deformation within an active caldera.

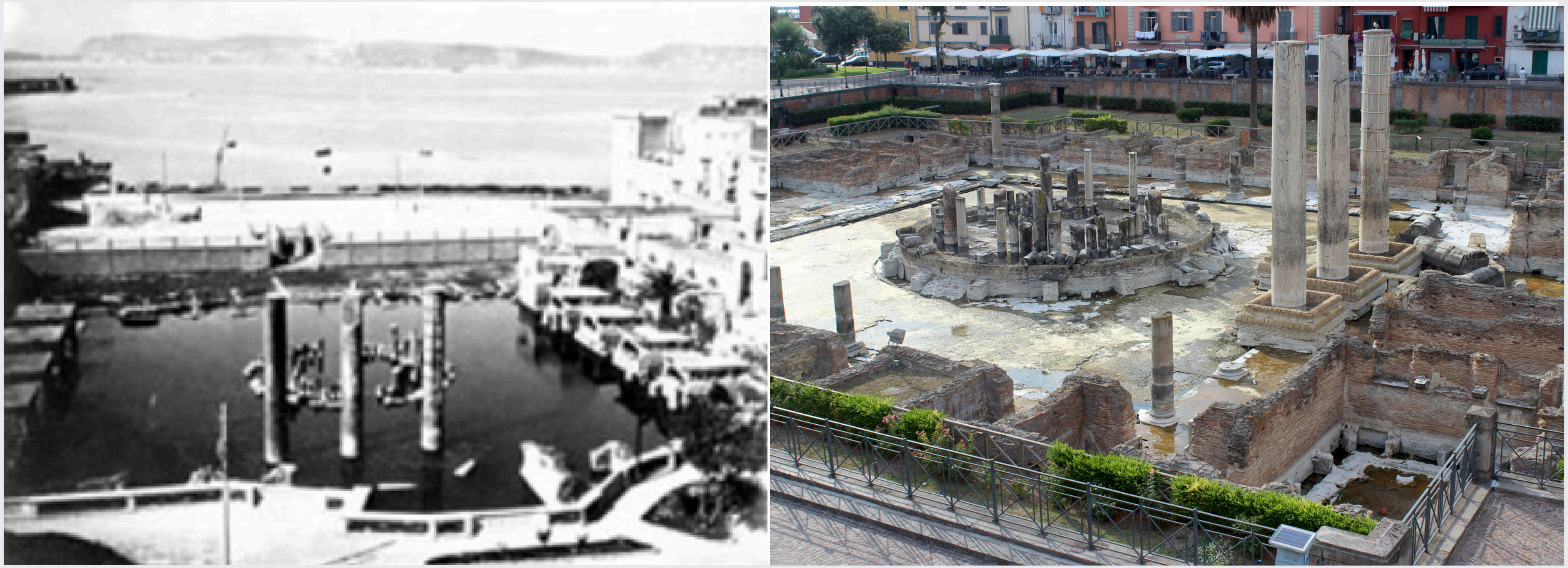
The ground deformation is a particular sign that reveals the breath of a volcanic active area. Historical documentary sources report that slow movement of the ground in the area of Campi Flegrei is a well-known phenomenon since Roman times. In the Baia area several Roman age buildings are now under the sea due to continuous subsidence of central-western sector of the caldera. In addition, there are documentary sources reporting a consistent uplift of the ground in the area of the ancient Roman harbour of Averno before the 1538 AD eruption, which brought to the build-up of the Monte Nuovo cinder cone. The uplift started at least 30 years before the eruption and constantly increased with the approach of the eruptive event. The marine regression that occurred arose disputes on the attribution of ownership of new lands emerged from the sea, until the eruption started and covered all new lands.

The most famous example that helps to reconstruct the slow ground deformation (bradyseism) in the Campi Flegrei Volcano is the so called Serapeum (i.e., Temple of Serapis) of Pozzuoli (40°49'35"N – 14°07'15"E). The Serapeo, located few tens of meters inland at Pozzuoli, was first supposed to be a temple devoted to the Egyptian god Serapis, from which the name. Only at the beginning of the last century it was recognized as a marketplace. Excavation of the monument began in 1750, by order of Charles of Bourbon the king of Naples, in an area called "the vineyard of the three columns" because three marble columns were coming out of the ground. After excavation, the columns showed lythodomes holes up to 7 m above the floor of the monument, testifying the maximum subsidence of the area. The first scholar to analytically set the problem of how the columns of the Temple of Serapis were perforated by lithodomes was the abbot Scipione Breislak in the eighteen century. Indeed, he believed that such phenomenon had occurred either as the result of the sea level variations, or to changes in the level of the ground (Giudicepietro & D'Auria, 2013).

Since then the Temple of Serapis became the object of several study and measurements of the ground uplift and lowering in the Campi Flegrei. Intense comparative measurements of benchmarks located into the Temple of Serapis and along the Pozzuoli promenade, nearby the "Rione Terra" area starting on 1905 allow the definition of the continuous experimental curve of the ground deformation of the Pozzuoli area through the entire twentieth century (Fig. 27), through the bradyseismic crisis of 1980-82 AD (Del Gaudio et al., 2010). In Fig. 27 the variation of the elevation in meters with respect the sea level from 1905 AD (green line) of both Serapeum floor and topographic benchmark, respectively, is reported. It is noteworthy the strong correlation existing between the values of the benchmark (red stars) and the values of the Serapeum floor (blue dot) that argue for an elevation related with a general slow uplift of the entire Pozzuoli area rather than an eustatic variation.

The Serapeum

Looking at the monument, constructed between the end of the I and the beginning of the II century, will be possible discuss of long- and short-term deformation in an active caldera and the evolution of these phenomena, as sign of unrest crises and also their relationships with eruptions, in quiescent volcano.



The two photos show the Serapeum invaded by water (left) and completely dry (right) respectively before and after the 1980-82 uplift crisis.

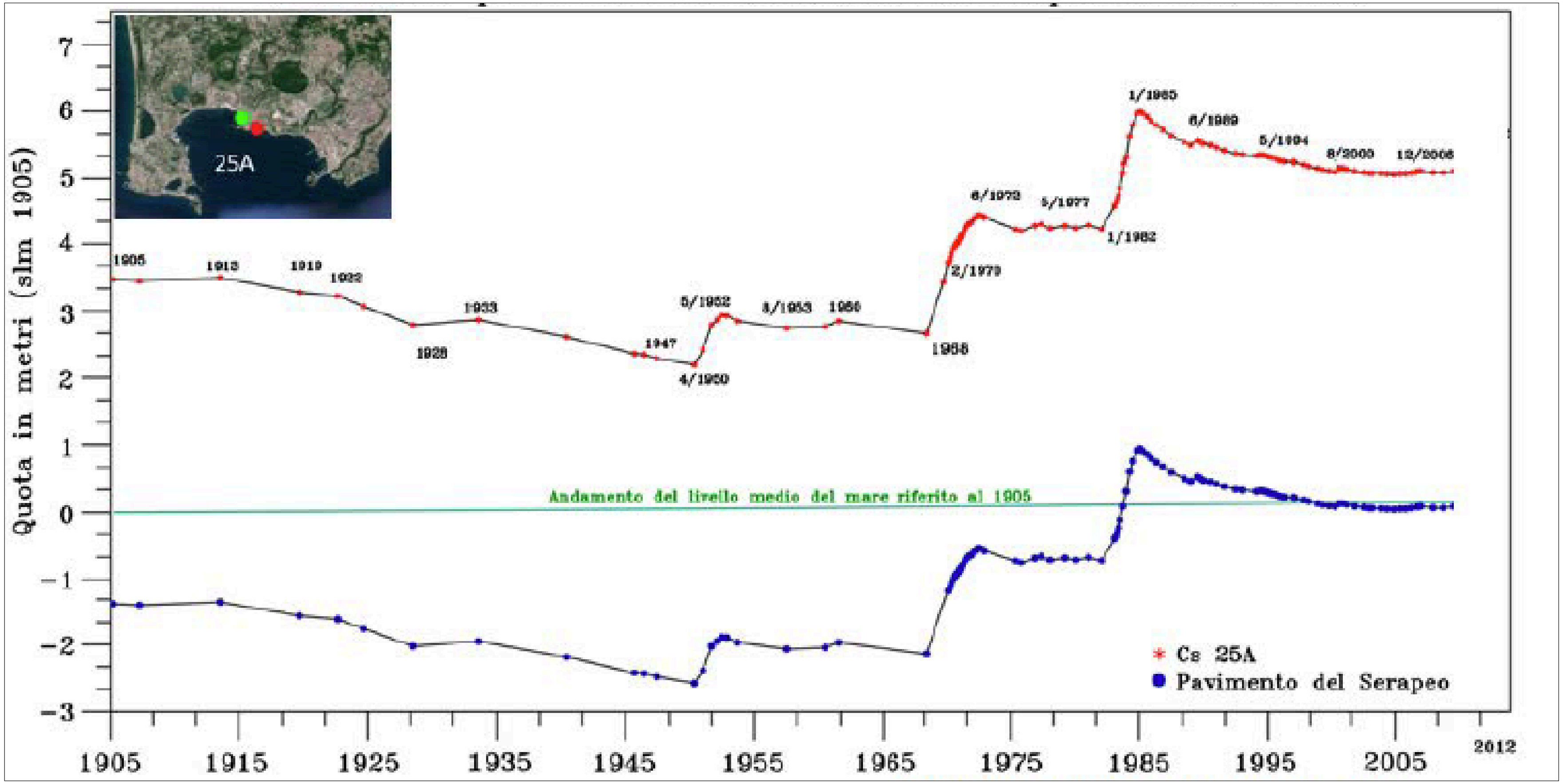


Fig. 27 - Elevation changes of the floor level in Pozzuoli measure at the "Serapeum" and at the benchmark BM 25A, sited along the promenade near the "Rione Terra". On horizontal axis years from 1905 to 2012 AD are reported. Green and red dots in the inset are the position of the Serapeum and of the benchmark, respectively (from Giudicepietro & D'Auria, 2013).

Stop H – Rione Terra

The old part of the town of Pozzuoli (Fig. 28), deeply affected by the recent bradeyseismic crises of 1969-1972 and 1982-84, host an interesting archaeological site of romans time.

The underground archaeological tour of Rione Terra (Fig. 29) is a journey in the ancient Roman colony, *Puteoli*, founded in 194 BC and soon become the commercial port of Rome. The course is located below the tuff rock overlooking the Gulf of Pozzuoli, between Nisida and Baia, and runs along the principal axes of the Roman city, hinges and decumani. The visitor, strolling along the streets of *Puteoli*, will be fascinated by the architecture of many buildings, the granaries, the oven for processing and baking bread (pistrinum) with millstones almost intact, from cryptoporticos, the workshops and warehouses. The archaeological itinerary is enriched by multimedia installations that guide the audience to discover the activities that took place in ancient *Puteoli*.

Fig. 28 - Rione Terra, Pozzuoli

Fig. 29 - View form the archaeological tour of Rione Terra, Pozzuoli

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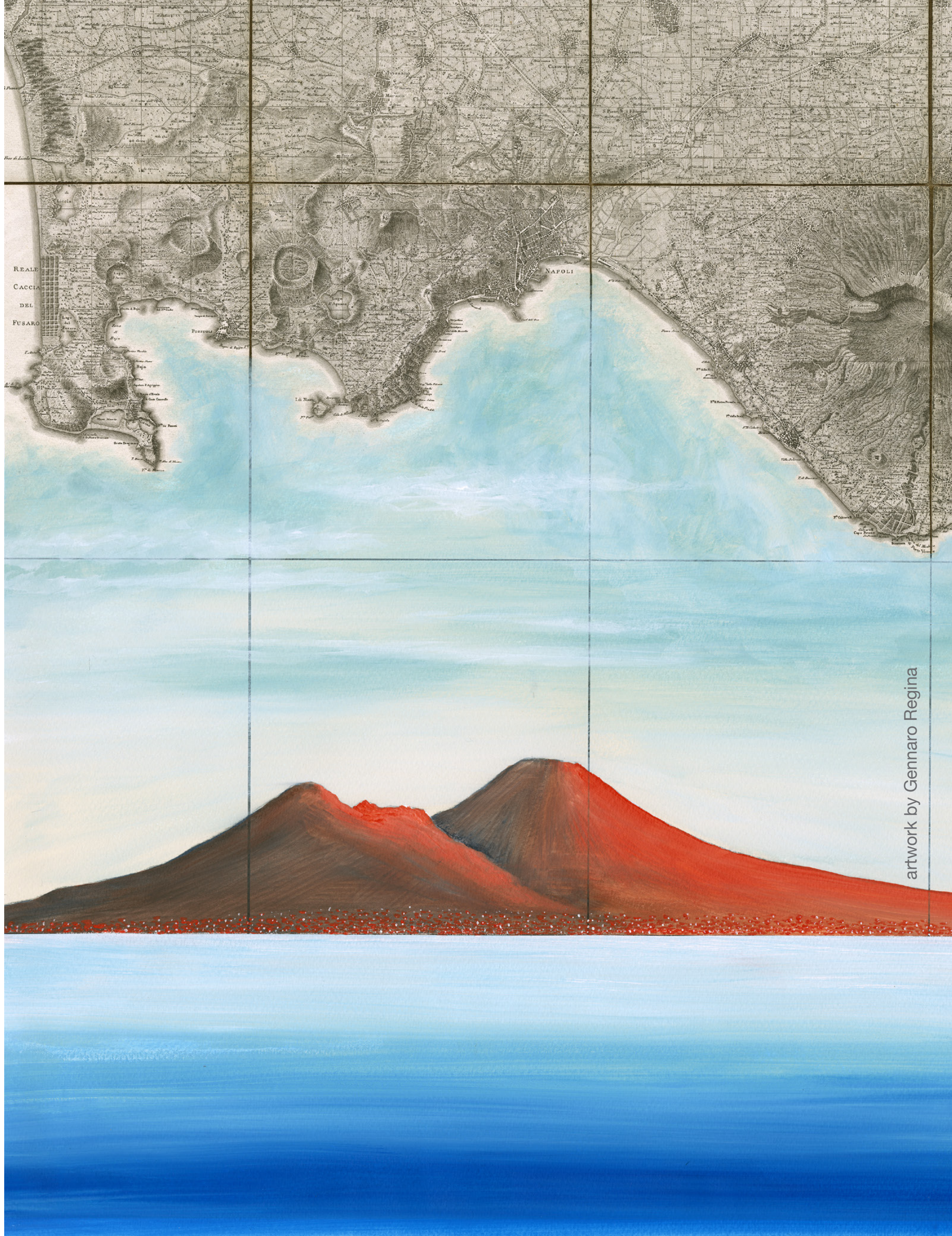

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