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The Campi Flegrei Deep Drilling Project (CFDDP): New insight on caldera structure, evolution and hazard implications for the Naples area (Southern Italy)

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Abstract The 501 m deep hole of the Campi Flegrei Deep Drilling Project, located west of the Naples metropolitan area and inside the Campi Flegrei caldera, gives new insight to reconstruct the volcano-tectonic evolution of this highly populated volcano. It is one of the highest risk volcanic areas in the world, but its tectonic structure, eruptive history, and size of the largest eruptions are intensely debated in the literature. New stratigraphic and $^{40}Ar/^{39}Ar$ geochronological dating allow us to determine, for the first time, the age of intracaldera deposits belonging to the two highest magnitude caldera-forming eruptions (i.e., Campanian Ignimbrite, CI, 39 ka, and Neapolitan Yellow Tuff, NYT, 14.9 ka) and to estimate the amount of collapse. Tuffs from 439 m of depth yield the first $^{40}Ar/^{39}Ar$ age of ca. 39 ka within the caldera, consistent with the CI. Volcanic rocks from the NYT were, moreover, detected between 250 and 160 m. Our findings highlight: (i) a reduction of the area affected by caldera collapse, which appears to not include the city of Naples; (ii) a small volume of the infilling caldera deposits, particularly for the CI, and (iii) the need for reassessment of the collapse amounts and mechanisms related to larger eruptions. Our results also imply a revaluation of volcanic risk for the eastern caldera area, including the city of Naples. The results of this study point out that large calderas are characterized by complex collapse mechanisms and dynamics, whose understanding needs more robust constraints, which can be obtained from scientific drilling.

1. Introduction

Extremely explosive volcanic eruptions from large calderas are the most likely hazard to generate global catastrophes [*Hill*, 2006; *Lowenstern et al*., 2006]. It is generally accepted that volcanic calderas result from the rapid magma withdrawal associated with the collapse of magma chamber roof. The collapse is typically larger with increasing magma volumes. However, some fundamental aspects of calderas—i.e., the mechanisms of collapse and the relation among eruption, magma chamber, and collapse sizes, as well as their dynamics and structure—still remain uncertain and controversial [*Geyer et al*., 2006]. This topic has received considerable attention because of the millions of people living in high-risk volcanic areas [e.g., *Druitt and Sparks*, 1984; *Lipman*, 1997, and references therein; *Gudmundsson*, 1998; *Acocella et al*., 2000; *Geyer et al*., 2006; *Acocella*, 2007, and references therein].

Currently, conceptual models for many calderas are based on an incomplete reconstruction of their system [*Lipman*, 1997; *Cole et al*., 2005; *Carlino and Somma*, 2010]. This produces an unreliable evaluation of the actual hazard of the active calderas. A well-known case study is the caldera of Campi Flegrei in southern Italy (Figure 1), which was produced by large volume eruptions at ca. 39 ka (Campanian Ignimbrite, CI, VEI = 7) [*Fedele et al*., 2008] and ca. 15 ka (Neapolitan Yellow Tuff, NYT, VEI = 6) [*Deino et al*., 2004]. The mechanism of these eruptions and the involved volume of magma (particularly for the CI eruption) are still uncertain, resulting in different interpretations related to the caldera boundary location and to the assessment of DRE (Dense Rock Equivalent) emitted during each eruption. Some authors proposed that the CI caldera boundary enclosed the central sector of Naples [*Orsi et al*., 1996; *Perrotta et al*., 2006] while other authors [*Rosi and Sbrana*, 1987; *Vitale and Isaia*, 2014] do not incorporate the central part of the city. The latter models are

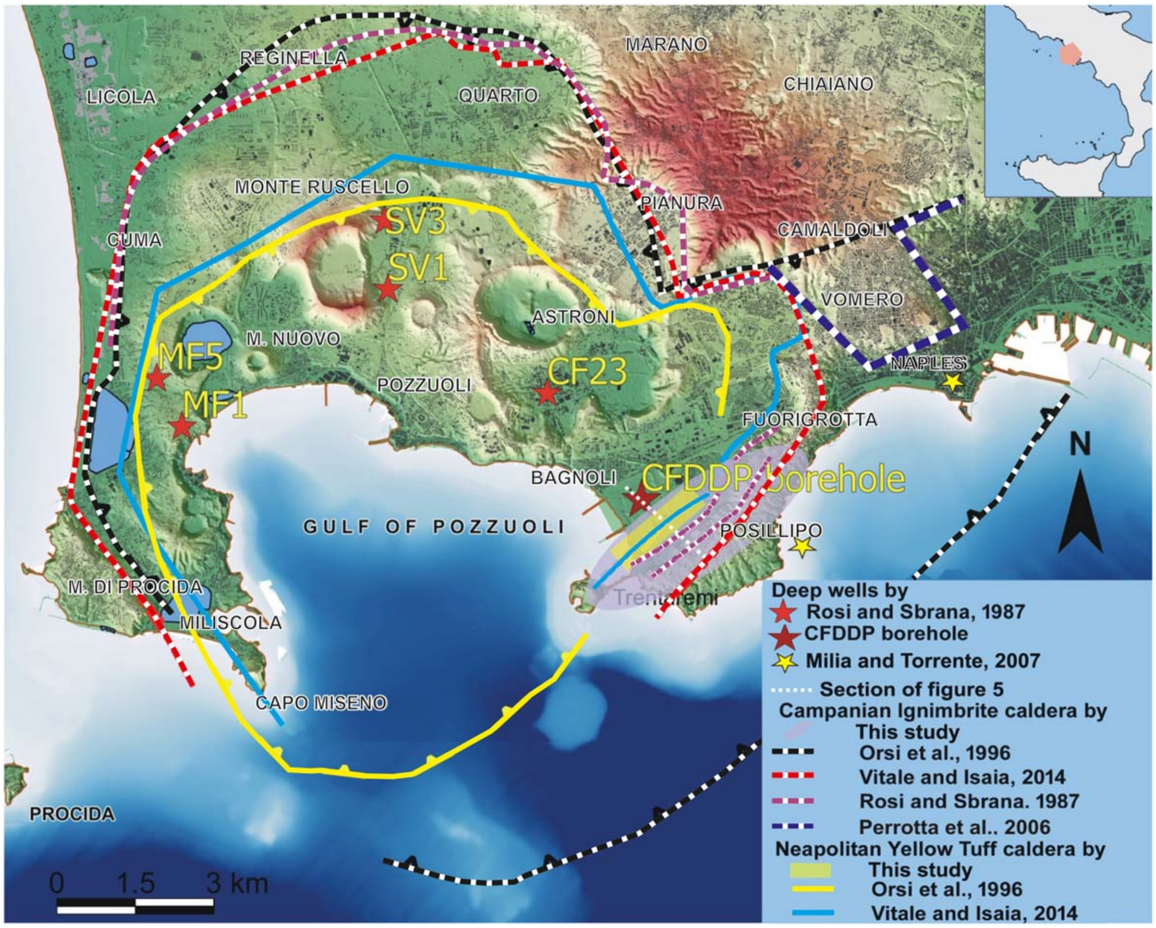

Figure 1. Morphological map of the Campi Flegrei caldera. The lines (dashed and solid, respectively, for CI and NYT) are the caldera limits as proposed by different authors. CFDDP drilling site (larger red star) is shown, together with the deep boreholes drilled by ENEL-AGIP (SV1, SV3, MF1, MF5) and SAFEN (CF23) companies (smaller red stars) and two shallower boreholes (smaller yellow stars)

mainly based on the hypothesis of partial reactivation of pre-existing regional faults along which the collapse occurred during the caldera formation.

Also the magma volume involved in the CI eruption has been evaluated by various authors, producing estimates that range from 80 to more than 300 km^3 of DRE [*Costa et al*., 2012, and references therein]. These different interpretations have important implications for the assessment of both the eruptive mechanism and the risk for people living in the area. The above uncertainties have been encountered for many large caldera-forming eruptions worldwide [e.g., Toba, Indonesia; Yellowstone, US; Long Valley, US; Lake City, US; Creede, US; Chegem, Russia; see *Lipman*, 2000, and references therein], for which geologic records, are, in many cases, obliterated by subsequent volcanic activity and erosional processes. In this case, deep drilling provides the best means to obtain direct information on processes occurring at depth and represents a key tool for reconstructing the caldera structure and understanding the volcano dynamics [e.g., *Eichelberger and Uto*, 2007; *Rosi and Sbrana*, 1987; *Carlino et al*., 2012, 2015]. Scientific drilling at Campi Flegrei caldera is of particular interest, because it improves the amount and the quality of data for evaluating several important pending questions, such as those mentioned above. This is fundamental in volcanic risk assessment. The caldera is, in fact, highly urbanized and has been experiencing decades of unrest, with uplift rates up to 1 m/yr, thousands of microearthquakes per year [*De Natale and Zollo*, 1986; *De Natale et al*., 2006; *Troiano et al*., 2011] and geochemical anomalies [*De Natale et al.*, 1991; *D'Auria et al*., 2011; *Chiodini et al*., 2010], leading to evacuation of Pozzuoli town in 1982–1983. At the present time, the alert level for the caldera has been moved from "base" (ordinary activity of volcano) to "attention" status. However, any existing hazard planning requires a continuous implementation of geological data acquired with new research, to attain a more reliable knowledge of the structure and dynamics of the volcano.

2. Caldera Drilling and Data Recovering

Among several scientific experiments in the caldera [see *Piochi et al*., 2014, for a review], the most recent one is the Campi Flegrei Deep Drilling Project (CFDDP), endorsed by ICDP (International Continental Scientific Drilling Programme) [*De Natale and Troise*, 2011; *Carlino et al*., 2015] and targeted the eastern caldera sector with a borehole achieving a depth of 501 m below sea level (bsl). The drilling project was initially aimed to gather information about the stratigraphy, rock properties, in situ stress field, and borehole temperature profile of the area in order to evaluate the possibility of a deeper drill hole down to 3500 m bsl [*De Natale and Troise*, 2011; *Carlino et al*., 2015]. The CFDDP core/cuttings analyses were performed with the aim to provide new constraints on the volcanic setting in the eastern sector of the caldera, filling the "information gaps" from previous deep exploration work for geothermal purposes in the western, northern, and central sectors of the caldera [*Rosi and Sbrana*, 1987; *Piochi et al*., 2014].

Here we report the main results from lithological, paleontological and geochronological studies on both cores and cuttings, showing that deposits from the two caldera-forming eruptions (NYT and CI) are shallower and thinner than expected. Our findings raise new questions about the structure and genesis of the caldera and the level of volcanic hazard for the Neapolitan area. The obtained results demonstrate the effectiveness of drill holes in providing reliable constraints on caldera dynamics.

The borehole was drilled in 2012 in the 2 km^2 old steel factory site in Bagnoli (western Naples) and nearby the Posillipo hill (Figure 1), which represents one of the most well-recognized morphological limit of the caldera, possibly related to the collapse during the caldera-forming eruptions.

The chosen location for the pilot hole deserves some comments. In all the available literature, it is considered to be inside both the Campanian Ignimbrite and the Neapolitan Yellow Tuff calderas. According to *Rosi and Sbrana* [1987] the Posillipo hill represents the structural limit of the CI caldera. *Di Girolamo et al*. [1984] and *Lirer et al*. [1987] attributed the caldera collapse and its eastern structural boundary, along the Posillipo hill, at the NYT eruption. According to these papers, the Campanian Ignimbrite was fed through and arcuate fracture along the northern edge of Campi Flegrei and the relative collapse affected a large area including the Campi Flegrei and part of the Gulf of Naples. *Orsi et al*. [1996] and almost all the subsequent literature [i.e., *Orsi et al*., 1999; *Perrotta et al*., 2006] moved the limit of the CI caldera much more eastward, to include the city of Naples. Recently, such eastward extension of the caldera limits has been confuted by *Vitale and Isaia* [2014]. Moreover, inversion of multidisciplinary geophysical data led *Capuano and Achauer* [2003] to highlight the lack of evidence for any collapse overcoming the border of the Posillipo hill. In addition, some researchers [*Scandone et al*., 1991; *Rolandi et al*., 2003] suggested the only caldera collapse in the area, the one clearly visible also from geophysical (mainly gravity) data, had been caused by the NYT eruption, whereas the CI would have been erupted from the central part of the Campania Plain. It is worthy of note, however, that the collapse signature from gravity and seismic tomography data [*Rosi and Sbrana*, 1987; *Capuano and Achauer*, 2003; *Vinciguerra et al*., 2006], which involves an area smaller than the limits of the caldera as seen in the Northern sectors, is substantially in agreement with the Posillipo hill being the eastern border of the collapse. An important NE-SW trending fault corresponding to the Posillipo alignment was also detected through seismic survey [*Judenherc and Zollo*, 2004]. So, from all the literature and geophysical data it appears to be a true structural limit of the Campi Flegrei caldera. On the other hands, some previous drillings located very close to Posillipo hill, reaching 100–150 m, put in evidence a dislocation of the NYT, found in the range 30–150 m, with respect to the outcrops of the hill. Hence, the drilling location was chosen because it seems to be surely within the NYT caldera and also within the limits of the CI caldera as reported in the literature, which include also the hypothesis of faults reactivation through time in this area. The location of the drilling site possibly close to a caldera border was aimed to study in detail the east side of the caldera, the most crucial because involving the city of Naples. Previous drillings operated in the mid 1970s and 1980s of the last century for geothermal research purposes, in fact, sampled only the west side (Mofete area) and the northern side (S. Vito area) of the caldera, down to 3 km of depth. Obviously, the drilling site, being located very close but inside a caldera border, provides also new information to discriminate among the different hypotheses on the caldera limits, particularly for the extension of the Campi Flegrei caldera collapse associated to the CI eruption, which is the most debated question in the literature.

Drilling operations were carried out through technical and logistical mud services, thus allowing the collection of mud cuttings and cores (see supporting information 1). Two cores (of about 1 m) were extracted

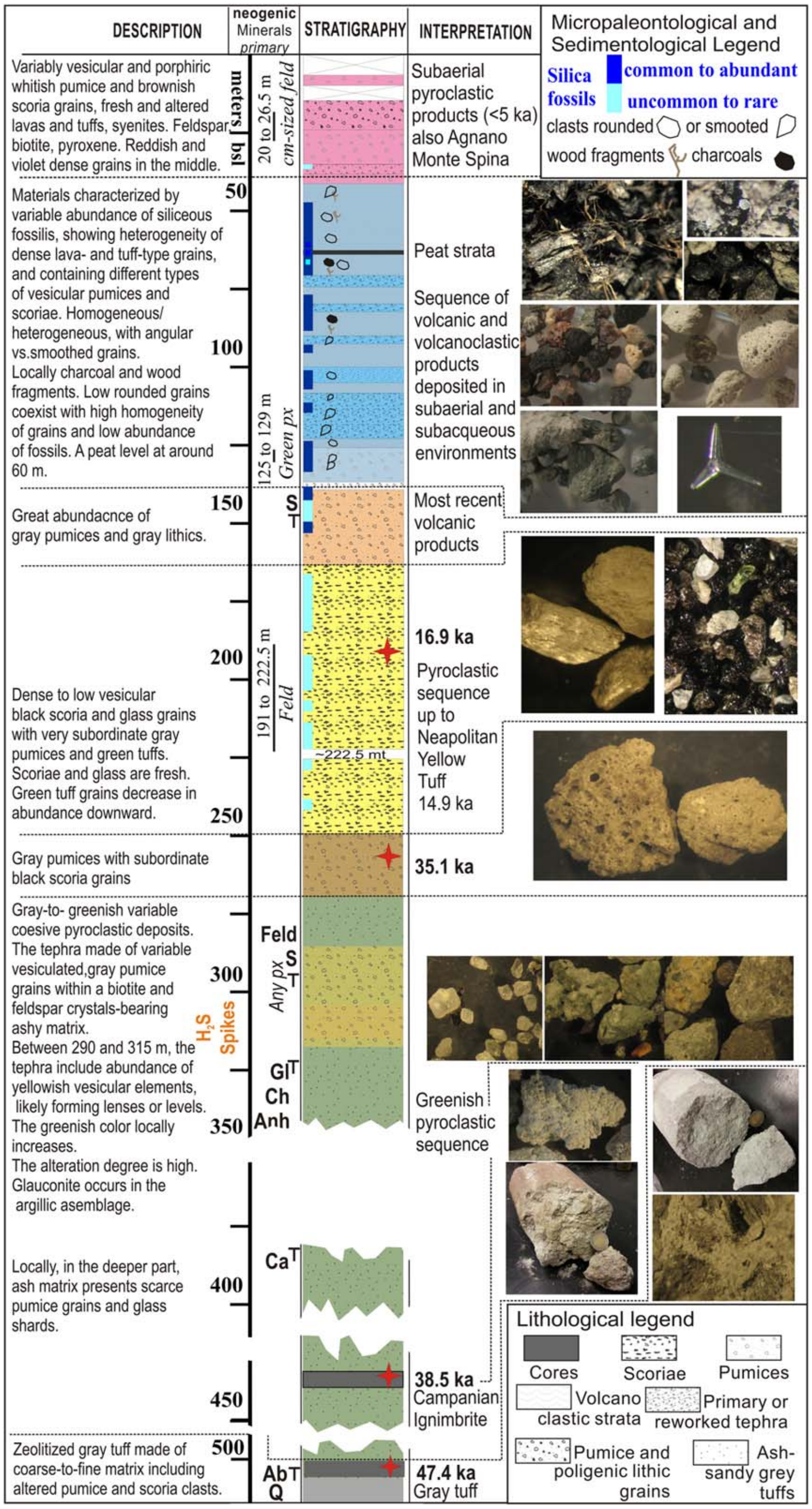

Figure 2. Synthetic stratigraphic reconstruction along the CFDDP drill hole as derived from lithological (description on the left) and micropaleontological (occurrence of fossils within the main column, i.e., sponge spicules that, only between 61 and 67 m of depth, associate with diatoms) analyses of samples (see methods in the supporting information 1). Primary and neogenic mineral assemblage, and H_2S spike are also indicated. The photos show the representative sampled materials (size between 2000 and 63 μm) and the cores (439 m and 501 m). Stars locate the Ar-dated feldspars. Shaded colors allow rapidly distinguish each stratigraphic unit; CI is related to the 439 core but we infer that the CI deposit can extend up to the 35.1 ka deposit. Feld = feldspar, Px = pyroxene, S = sulfur, Gl = glauconite, Anh = anhydrite, Ca = carbonate, Q = quartz, Ab = albite, $\top$ = appearance and $\perp$ =disappearance of phases. Depths of Feld and Px occurrence are indicated in the mineral column.

from 439 and 501 m. The supporting information 1 reports data about mud sampling and analytical techniques. In particular, ^{40}Ar/^{39}Ar geochronology was performed on feldspars from selected mud cuttings from the 191 m scoria and the 260 m pumice-rich levels, and the two cores. Feldspars (sanidine) were isolated using the method of *Mark et al*. [2011a, 2014]. Crystals were prepared as detailed in the supporting information 1 for irradiation with Alder Creek Tuff sanidine (ACs, 1.2056 $\pm$ 0.0019 Ma) [*Renne et al*., 2011]. *J* values and irradiation interference correction values are presented in the raw ^{40}Ar/^{39}Ar data file, together with ideograms (data set in the supporting information 2). Individual sample crystals were analyzed by single-crystal total fusion with a focused CO_2 laser. Isotope measurements were made using a MAP 215-50 noble gas mass spectrometer operated in peak jumping mode (as described in *Mark et al*. [2014] and in the supporting information 1). The Ar isotope data were corrected for backgrounds, mass discrimination, and reactor-produced nuclides and processed using the BGC *MassSpec* software. The atmospheric argon ratios of *Lee et al*. [2006], the latter independently verified by *Mark et al*. [2011b], were employed.

3. Analytical Results

The lithological, mineralogical, and micropaleontological analyses of cuttings and coring from CFDDP drilling are reported here and summarized in Figure 2. Texture, mineralogical assemblage, and chemistry of cores are reported in *Mormone et al*. [2015]. The sequence is fully composed of pyroclastic materials. The uppermost sequence (down to 36 m) consists of subaerial pyroclastic deposits composed of variably vesicular and porphyritic fragments (magenta in Figure 2); we recognize the Agnano Monte Spina tephra [ca. 5 ka; *de Vita et al*., 1999] at the base. It covers a 130 m thick sequence of sponge spicules and diatoms-bearing deposits, locally including organic carbon remains, wood fragments, and peat deposits. In particular, from about 45 to 165 m, the grains are subrounded or rounded, vesicular to dense, heterogeneous pyroclastic fragments, with heterogeneity and rounding shape directly correlated to the microfossil abundance. Diatoms occur only within the peat deposits (three samples at depth of 61, 64, and 67 m). These deposits are soft, blackish, and biogenic, with rare pumiceous grains. The diatoms occurrence within a narrow depth interval suggests limited cross-contamination between different rock strata and gives support to the reconstruction. Below, the sequence shows a ca. 100 m thick (161–245 m depth interval) nearly monotonous deposit mainly composed by brown dense (obsidian-like) to vesicular glass fragments, mostly scoriae, and greenish dense clasts, beige pumices, and tuffs, with minor amount of sponge spicules. The glassy matrix of obsidian and vesicular scoriae contains rare very thin feldspar and apatite microlites.

At 255 m of depth, the scoriae disappear and the 53 lowermost samples collected down to the bottom of the borehole are all devoid of fossils; materials from 255 to 265.5 m are barren and can be attributed to an about 20 m thick grayish pumice deposit.

The remaining underlying sequence is composed of greenish tuffs overlying a gray tuff at the bottom of the hole, both containing very low abundances of feldspars; the transition between the two tuffs is likely gradual and starts to occur at ca. 450 m. Samples from the greenish tuffs are very homogeneous and strongly comparable to the core at 439 m, with only local (i.e., 290.5–318 m) increases of yellowish vesicular and low-crystalline pumice sand layers. The 439 m core [see *Mormone et al*., 2015, for details] is representative of a fine-grained to coarse-grained heterogeneous fossil-free tuff, gray-green in color with stretched and subrounded vesicular pumices, strongly altered by clays minerals.

The core at 501 m is a chaotic tuff with coarse-grained to fine-grained ash matrix hardened by zeolitization and includes cm-sized iridescent gray-to-silvery and grayaphyric juvenile vesicular fragments with devitrification of the glass matrix [*Mormone et al*., 2015].

The ^{40}Ar/^{39}Ar age constraints are shown for the four dated samples at the specific depth and provide the absolute chronology of the sequence.^{40}Ar/^{39}Ar data are plotted in the diagrams of Figure 3 and listed in the supporting information 2. All data are reported at the 1-sigma confidence level (unless otherwise stated) and uncertainties are reported as $\pm X/Y$, where *X* is the analytical precision and *Y* is the full external precision (including decay constant uncertainty). All data are reported relative to the optimization model of *Renne et al*. [2010] using the parameters of *Renne et al*. [2011] and corrected as in the Analytical methods section. Sample INGV 439 yielded a single-crystal ^{40}Ar/^{39}Ar age population whereas the other samples yielded complex ideograms owing to mixing of crystals of different ages. Only sample INGV 260 yielded data with a clearly discernible juvenile age population. The other two samples (INGV 191 and 501) yielded single-crystal

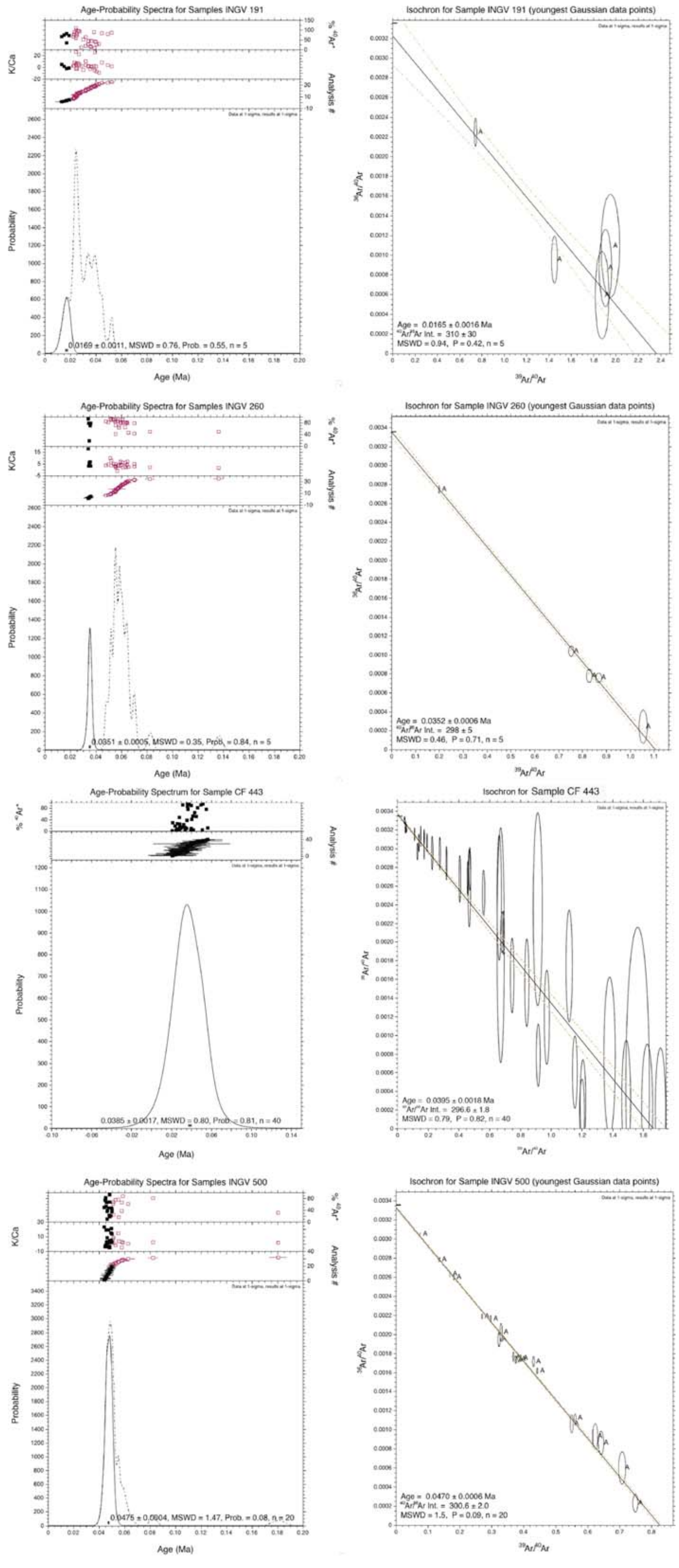

Figure 3. $^{40}Ar/^{39}Ar$ geochronological data presented on ideograms (left) and isotope correlation plots (right) for samples INGV 191, 260, 443, 500. The ideogram show the age distribution for single crystals from each sample plotted against the K/Ca ratios and percentage radiogenic ^{40}Ar ($^{40}Ar^*$). The data show that a range of feldspars with variable compositions were dated. Owing to the presence of xenocrysts within each sample a statistical filter of choosing the youngest coherent Gaussian distribution of data was selected. This was the only accurate way to determine the ages of the rocks in this situation. The isotope correlation plots for all samples (showing crystals selected as a part of the youngest Gaussian distribution criteria) all define inverse isochrons that overlap at 95% confidence with the age defined by the ideograms and the modern day $^{40}Ar/^{39}Ar$ value for atmosphere, as expected. Supporting information 1 provides details of methodology, and supporting information 2 provides the full raw data.

$^{40}Ar/^{39}Ar$ ages that overlapped a large temporal range suggesting xenocrystic contamination. This is expected given that samples were recovered from a proximal location to the volcanic vents and high-energy emplacement mechanisms probably recycled older erupted material in to younger flows. Furthermore, because the samples from the CFDDP borehole were recovered as cuttings rather than core and we cannot rule out cross contamination between horizons during the drilling, although we consider this unlikely or strongly limited, as already stated above. Therefore, we analyzed the data using statistical filters—asking the *MassSpec* software to choose the youngest Gaussian peak with MSWD probability cut off (0–1) = 0.05. Although not an ideal approach, the statistical filter returned ages that makes sense in terms of the stratigraphy of the selected samples. The single-crystal data from each Gaussian profile were plotted on an isotope correlation plot with all samples defining an inverse isochronous. Ages calculated from the ideograms are indistinguishable from the inverse isochrones with all samples defining an initial trapped component indistinguishable from modern day atmosphere.

The $^{40}Ar/^{39}Ar$ age for each sample (see also Figure 2), therefore, is:

INGV 191: 16.9 $\pm$ 1.1/1.2 ka

INGV 260: 35.1 $\pm$ 0.5/0.6 ka

INGV 439: 38.5 $\pm$ 1.7/1.8 ka

INGV 500: 47.5 $\pm$ 0.8/0.9 ka.

4. Discussion

The CFDDP lithological sequence, in contrast with previous Campi Flegrei wells [*Rosi and Sbrana*, 1987; *Piochi et al*., 2014], has age-based constraints that can be very useful to detail the collapse features and the evolution of the volcano, also by comparison with outcrops.

The scoriae sample at 191 m, dated at ca. 17 ka, is part of the monotonous scoriaceous deposits drilled between 161 and 245 m. Based on the age and lithologic similarity, it can be attributed to the NYT sequence and/or the pyroclastic sequence immediately below it. The closest NYT outcrop mostly constitutes the tectonic cliff of the Posillipo hill, <1 km east of the CFDDP site (Figure 1). Here the NYT is a ca. 100 m thick pyroclastic sequence that, consistently, also (i) includes a few tens of meters of scoria levels or lenses and greenish tuff clasts [*Rittmann*, 1950] and (ii) overlaps the Trentaremi volcano [ca. 21 kyr: *Scarpati et al*., 2013]. Therefore, the borehole shows that the base of the NYT within the caldera is not more than 250 m deep, while it is located roughly at the sea level along the Posillipo cliff. This depth is comparable with the 180–200 m determined in the bay of Pozzuoli [submerged sector of Campi Flegrei, e.g., *Sacchi et al*., 2014] and suggests that it was modest and likely on the order of 250 m.

Furthermore, the volcanic rocks at 260, 439, and 501 m show age of ca. 35, 39, and 48 ka, respectively, and are found at shallow depths. This sequence records an important period of volcanism around the CI, as generally recorded along the other sides of the caldera. The pumiceous deposit at 260 m below the NYT (Figure 2) is part of several pyroclastic sequences produced before the NYT (*Rittmann*, 1950; *Pappalardo et al*., 1999; *Scarpati et al*., 2013]. This sequence does not generally exceed a few tens of meters. Our borehole data, in agreement with distal outcrops, also suggest that, between 18 and 35 ka, volcanic activity was mostly consisted of small eruptions.

The hydrothermal alteration [*Mormone et al*., 2015] of the two cores (439 and 501 m) makes a correlation with deposits exposed throughout the caldera difficult. However, the age data of the 439 m tephra are consistent with the age for the CI eruption sequence [e.g., *Fedele et al*., 2008]. Consistently, the tuff at the bottom of the core has been dated at 47.5 $\pm$ 0.8/0.9 ka. Additional support for the chronology presented here derives from the Sr-isotope ratio of the bottom of the core as already reported and suggested by *Mormone et al*. [2015]. The ratio is, in fact, 0.707528 $\pm$ 4, i.e., comparable with ratios known for the lava domes underlying the CI at the Mofete wells (see MF5 and MF1 in Figure 1 for location). Therefore, based on previous qualitative reconstructions [*Rosi and Sbrana*, 1987; *Piochi et al*., 2014], the depth of the CI is possibly deeper (700 m) at Mofete than it is at the Bagnoli drilling site, ca. 439 m. Also, despite the absence of sedimentological features derived by the mud cutting sampling, the textural and mineralogical similarity of the samples

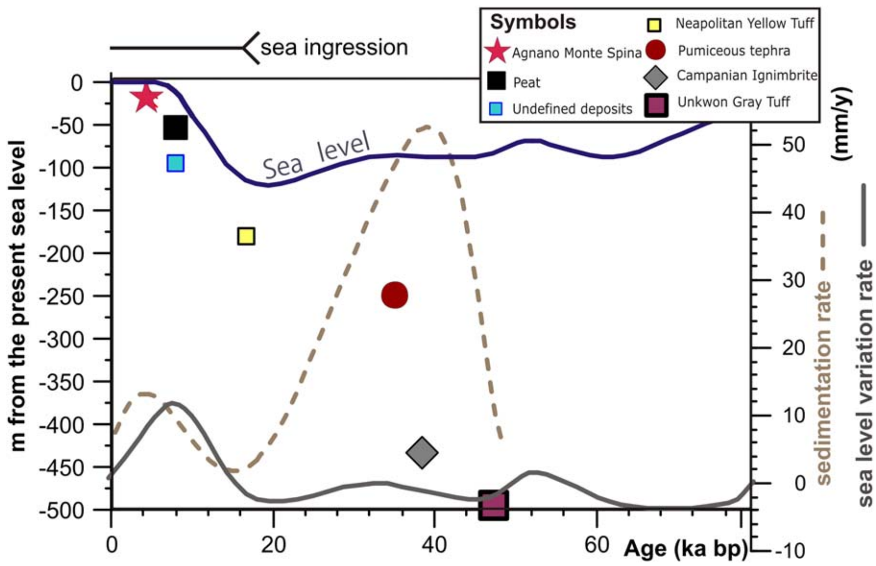

Figure 4. Depth of drilled fossiliferous and subaerial tephra (symbols in the diagram) compared with the sea level variation (blue line) as reconstructed by Antonioli et al. (2004), at the age of their formation. The rates of sea level variation (dashed green line) and of sedimentation (dashed brown line), calculated using the available data (thickness deposits/time interval), are displayed evidencing the huge amount of products deposited between 38.5 and 35.1 ka (orange colored box). The Wurmian sea ingression started at 18 ka is colored in cyan; to note the similarity of sedimentation and sea ingression rates in this period and up to 5–8 ka.

in the 265–450 m depth interval suggests (as we display in Figure 2) that the CI deposits could extend from the bottom gray tuff up to the gray pumice layers.

We merged ages, microfossils occurrence and the local sea level curve [*Antonioli et al.*, 2004] in order to recover information and discuss the main questions concerning the volcano evolution, at least in the eastern part of Campi Flegrei (Figure 4).

The drilled sequence between 250 and 501 m (ca. 35–48 ka) is fossil-free and we hypothesize that it was deposited in a continental environment. By considering the sea level at that time (blue line in Figure 4), it must have been at least 350 m above its present elevation. Similarly, the 35 ka pumice layer was deposited at about 180 m above its present elevation. Also, fossils indicative of a marine environment are found only in the sediments shallower than 250 m between ca. 35–17 ka (Figure 4) when the sea level is slightly decreasing and later on, when this marine environment is contemporaneous to the sea ingression (blue line in Figure 4). The position of peat deposits nearly plotting on the sea level curve supports our reconstruction in Figure 4.

The inferred minimum drop of 350 m includes the contributions of the collapse of both CI and NYT (and any other collapse subsequent to CI). A relative evaluation of the collapse related to the NYT can be inferred by taking into account, as a reference point, the base of NYT sequence outcropping out along the inner (western) side of Posillipo hill. It stands roughly at the sea level and thus the net drop related to NYT eruption is equal to about 250 m. Thus, subtracting the amount of NYT collapse from the total drop of 350 m, we found a collapse of about 100 m that can be related to the CI. This evaluation neglects the possible minor collapses due to minor eruptions, which possibly are less significant. However, these estimates are conservative as they consider the deposition of the CI and 35 ka rocks just at the time-related sea level and the absence of erosional and uplift processes. It is then worthy to note that the ratio between the measured collapses related to NYT and CI is 2.5, which appears unreliable because CI was a much larger eruption (with erupted volume about 10 times larger). The environmental reconstruction at this time is represented in Figure 5a, which shows the caldera evolution is characterized by a subsidence progressively determining the marine ingression and sedimentation recorded between 35.1 and 16.9 ka in the Bagnoli area [*Rosi and Sbrana*, 1987; *Orsi et al.*, 1996; *Perrotta et al.*, 2006; *Piochi et al.*, 2014]. The scoriae deposits correlated to the NYT are characterized by presence or absence of fossils at the different depths (Figure 2); the site at this time was submerged (Figure 4). We therefore suggest that the NYT sequence was deposited in an environment oscillating from submarine to subaerial, possibly in relation to the dynamics of the eruption. Based on the type of drilled deposits, i.e., scoriaceous, an eruptive vent of the NYT could be proximal to the drilling site.

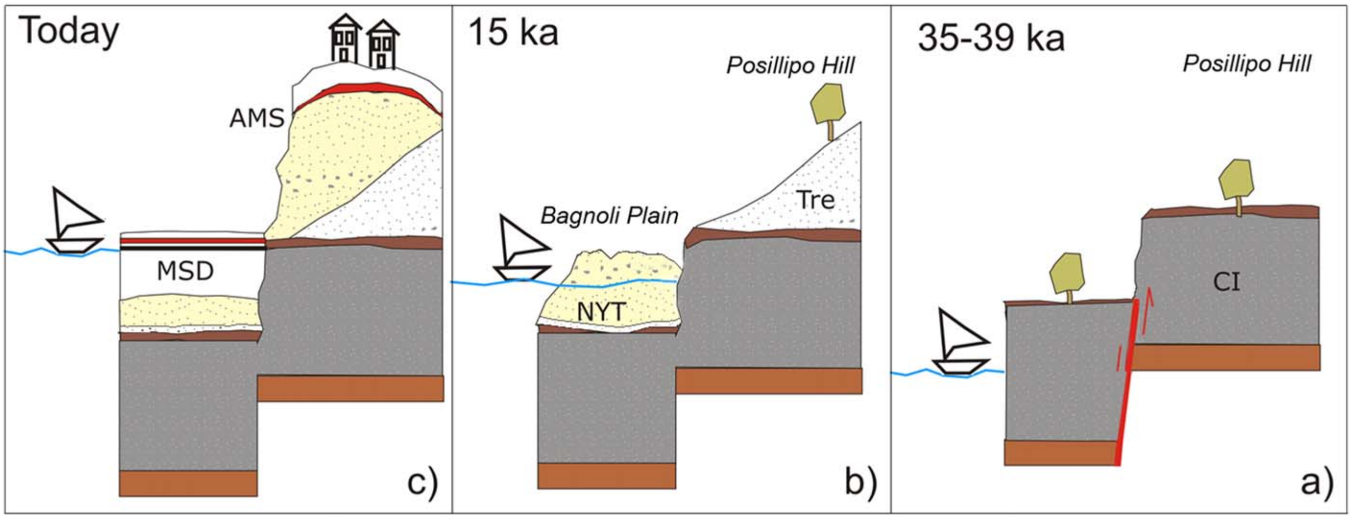

Figure 5. Sketch showing the evolution of the eastern side of the Campi Flegrei caldera following the 47.5 ka tuff. This sketch was drawn not to scale and considering only the well constrained deposits, thus it does not provide information about the layering shape, but only the relative position during the evolution of the drilled site. (a) The situation after the Campanian Ignimbrite (CI) volcanism and just after the deposition of the 35 kapumiceous deposit, both in a subaerial environment; (b) the area at the time and during the Neapolitan Yellow Tuff (NYT) eruption; note the local vent in a marine and/or transitional environment and the Trentaremi (Tre) volcano; (c) the Bagnoli Plain and the Posillipo hill at the present time; the Agnano Monte Spina Tephra (AMS) was deposited on the marine to transitional sequence (MTD or MSD) that includes the peat layer (black layer). Refer to Figure 4 for sea level.

The overlying sediments are similar to the sequence cropping out along the La Starza marine cliff in Pozzuoli emplaced during the marine ingression, following the low sea level stand of ca. 18–14 ka. The uppermost 160 m borehole sequence contains variable fossil abundances and grains shapes, suggesting transitions among marine—coastal—continental depositional environments with the presence of peat layer deposits likely related to the emergence phase recorded at La Starza at about 8.5 ka (*Di Vito et al*., 1999). The $<$5 ka borehole sequence, lacks of marine fossils and is presently below sea level, also suggesting slow subsidence during the past 5 ka. Based on the age and thickness of deposits, rates of sedimentation and sea ingression were on the same order of magnitude (Figure 4). This suggests, after the NYT eruption, a slow and continuous dominant subsidence process in this area producing the present geological setting (Figure 5c). This differs from what recorded on La Starza [*Rosi and Sbrana*, 1987; *Isaia et al*., 2009], where uplift events occurred. However, the peat deposits suggest a variable subsidence rate, at least in the most recent period, with an increase of subsidence just after the peat deposition.

The shallow depth of both the CI sequence and ca. 48 ka tuff, along with the sediment depositional environment and the sea level variation (Figure 4), cannot be unequivocally interpreted, but it anyway opens some interesting questions related to the caldera formation. First, we must recall that several researchers [*Di Girolamo et al*., 1984; *De Vivo et al*., 2001] based on different stratigraphic observations, argued the CI did not erupt from Campi Flegrei caldera, but from a series of fractures mainly located north of Campi Flegrei, with maximum emissions in the central part of the Campanian Plain and only marginally involving the Campi Flegrei area [*De Vivo et al*., 2001]. The very low amount of collapse in the Bagnoli area, mainly if compared with the NYT, as computed in the hypothesis that the original elevation was close to the sea level, would agree with a model with little or no collapse related to CI in the drilling area. As an alternative hypothesis, the CI collapse could have been preceded by a large uplift (several hundreds of meters) so that the original elevation of the caldera, at the eruption time, was much higher than the sea level. Large regional tumescence before the CI eruption has been actually hypothesized by *Luongo et al*. [1991]. In the hypothesis a CI collapse occurred here, it is clear from our data that the drilling site would be anyway very close to the caldera structural rim, as formerly hypothesized by *Rosi and Sbrana* [1987] (Figure 1) and supported by seismic data and gravimetric anomalies [*Capuano and Achauer*, 2003]. In this case, the small amount of collapse, basically related to NYT, would further indicate a differential collapse mechanism, in which the amount of collapse progressively increases from the borders towards the centre caldera, likely in the late phases of the eruption. This idea is also in agreement with previous models based on petrological inference [*Rosi and Sbrana*, 1987; *Piochi et al*., 2014]. Regarding the ca. 17 ka scoria deposits, they indicate the base of the NYT at a depth of $\sim$250 m of depth and, allowing for subsidence within the last 3.5 ka, the CFDDP provides no evidence for a large volcano-tectonic collapse at ca. 15 ka. It appears to indicate that the NYT eruption produced a small vertical displacement, in agreement with the above cited seismic reflection data highlighting 150–200 m of volcanic sinking in the Pozzuoli Bay [*Bruno*, 2004].

The collapsed area for CI eruption, as from our data, should be reduced by 64 km^2 at least, moving the east CI caldera rim about 8 km inward with respect to the models that incorporate the main part of the city of Naples [i.e., *Orsi et al*., 1996]. The CI caldera rim inferred from our drilling data is possibly closer to that proposed by *Rosi and Sbrana* [1987] or *Vitale and Isaia* [2014] (Figure 1). The lack of co-ignimbrite breccia locally, cannot be unambiguously interpreted, due to the spatial limitation of drilling and/or the drilling technique, which does not favor the identification of such rock types. However, beyond the indicated limitations, we can argue that the co-ignimbrite breccia is not present in this part of the caldera because of the modest amount of volcano-tectonic collapse that occurred in the late phase of the eruption [*Rosi et al*., 1996]. A computation of the ignimbrite volumes inside the caldera can be performed, taking into account the limits of this estimation. Well-constrained stratigraphic information on the inner caldera and a reliable knowledge of the relative role of erosion versus deposition and of subsidence versus tumescence processes are needed for this estimate. Taking into account a thickness of ca. 250 m for the $<$47.4 to 35.1 ka deposits as observed at the CFDDP and also in surrounding outcrops [see *Rosi and Sbrana*, 1987; *Orsi et al*., 1996; *Fedele et al*., 2008], we estimate a rock volume less than 16 km^3. For the ca. 17–39 ka sequence, a possibly comparable thickness of few tens of meters at both the CFDDP and the above mentioned peripheral outcrops suggests few km^3 of magma erupted by several vents. A similar volume [see *Smith et al*., 2011a, 2011b; *Mormone et al*., 2011], for the last $<$15 ka of volcanic history, could be considered representative of the intracaldera behavior at the Campi Flegrei system.

Finally, considering the accepted mechanisms of caldera-forming-eruptions [*Lipman*, 1997; *Cole et al*., 2005], the modest amount of CI collapse cannot be easily reconcilable with the very large erupted magma volume (e.g., $\geq$250 km^3 in *Costa et al*., [2012]), as already discussed. Furthermore, the very thin deposits observed here, are equally difficult to reconcile with such a large volume eruption generated from Campi Flegrei caldera. For such a reason, our data cannot exclude the hypothesis that CI was also erupted from fissural vents extending also outside the caldera margins, so that what seen here could be a bit of collapse peripheral to the main eruption.

As a whole, our findings, indicating complex mechanisms of caldera collapse, agree with the recent view of caldera collapses representing very complex and far from homogeneous (e.g., simple piston-like) mechanisms [*Kennedy et al*., 2008].

5. Conclusions

The stratigraphic sequence and the $^{40}Ar/^{39}Ar$ dating constraints at the CFDDP borehole provide new insights on the eastern Campi Flegrei caldera deep structure and evolution. The CFDDP sequence cannot be directly correlated with nondated rocks drilled elsewhere, which prevent a confident reconstruction of the Campi Flegrei caldera at a wider scale. However, based on the CFDDP data, we can point out the following main results in comparison with the recent scientific literature: (i) a reduction of the area affected by collapse with respect to the hypothesis of other authors (e.g., *Orsi et al*., 1996; *Perrotta et al.,* 2006]; (ii) a surprisingly small volume of the infilling caldera deposits, particularly for the CI eruption; and (iii) a reassessment of the collapse amounts and mechanisms related to the CI and NYT eruptions.

The borehole data do not support a collapse extending toward the central city and Gulf of Naples with an hypothesized drop of $\sim$1500 m and also show that the drilling site is very close to the caldera border (Figure 1). The low amount of collapses recorded here, with a maximum drop of 250 m for the NYT eruption, indicates a complex mechanism of collapse that cannot be attributed to a simple piston-like model. Furthermore, the inferred shallow depth of the CI layer, which in terms of hypothetical amount of collapses would indicate a ratio of 2.5 in favor of NYT with respect to much larger-volume CI, is unexpected. This is a very crucial finding, which favors the hypothesis that CI was possibly erupted from vents also outside the Campi Flegrei caldera. An alternative model, which would explain such an anomalous ratio but not the very thin deposit of a so large volume eruption, would be that a very large regional uplift occurred related to the CI, on the order of several hundred meters, and/or a much larger collapse in the central sector of the caldera.

The new findings are also helpful in orienting the future studies of the problem of risk posed to the city of Naples, indicating the Campi Flegrei caldera is delimited eastward by the Posillipo hill, and does not extend into the central part of the city of Naples as stated by most of the recent literature.

The results of this study point out, in a more general way, that large calderas are likely to be characterized by complex collapse mechanisms, in which the collapse progressively deepens going from the borders toward the central part. In particular, collapse mechanisms could be proven in detail by further drillings closer to the caldera centre. Such a complex mechanism, which is suggested by our data, also emerges as the most likely one in recent theoretical studies on caldera formation [*Kennedy et al*., 2008]. Finally, this study shows the importance of age-based correlation between intracaldera and extracaldera tephra in defining the eruptive mechanisms at the origin of collapse. This problem is common to several calderas worldwide [*Lipman*, 1997]; for the above reasons, scientific drilling demonstrates as one of the most powerful tools to reconstruct the structure, the collapse mechanism and the volcanic history of calderas.

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References

Acocella, V. (2007), Understanding caldera structure and development: An overview of analogue models compared to natural calderas, *Earth Sci. Rev*., *85*(3), 125–160, doi:10.1016/j.earscirev.2007.08.004.

Acocella, V., F. Cifelli, and R. Funiciello (2000), Analogue models of collapse calderas and resurgent domes, *J. Volcanol. Geotherm. Res*., *104*, 81–96, doi:10.1016/S0377-0273(00)00201-8.

Antonioli, F., E. Bard, E. K. Potter, S. Silenzi, and S. Improta (2004), 215-ka History of sea-level oscillations from marine and continental layers in Argentarola Cave speleothems (Italy), *Global Planet. Change*, *43*, 57–78, doi:10.1016/j.gloplacha.2004.02.004.

Bruno, P. P. G. (2004), Structure and evolution of the Bay of Pozzuoli (Italy) by marine seismic Reflection data: Implications for collapse of the Campi Flegrei caldera, *Bull. Volcanol*., *66*, 342–355, doi:10.1007/s00445-003-0315-9.

Capuano, P., and U. Achauer (2003), Gravity field modeling in the Vesuvius and Campanian area, in *The TomoVes Seismic Project: Looking Inside Mt. Vesuvius*, edited by A. Zollo et al., Cuen, Naples, Italy.

Carlino, S., and R. Somma (2010), Eruptive versus non-eruptive behaviour of large calderas: The example of CampiFlegrei caldera (southern Italy), *Bull. Volcanol*., *72*, 871–886, doi:10.1007/s00445-010-0370-y.

Carlino, S., R. Somma, C. Troise, and G. De Natale (2012), The geothermal exploration of Campanian volcanoes: Historical review and future development, *Renew. Sustainable Energy Rev*., *16*, 1004–1030, doi:10.1016/j.rser.2011.09.023.

Carlino, S., C. R. J. Kilburn, A. Tramelli, C. Troise, R. Somma, and G. De Natale (2015), Tectonic stress and renewed uplift at Campi Flegrei caldera, southern Italy: New insights from caldera drilling, *Earth Planet. Sci. Lett*., *420*, 23–29, doi:10.1016/j.epsl.2015.03.035.

Chiodini, G., S. Caliro, C. Cardellini, D. Granieri, R. Avino, A. Baldini, M. Donnini, and C. Minopoli (2010), Long-term variations of the Campi Flegrei, Italy, volcanic system as revealed by the monitoring of hydrothermal activity, *J. Geophys. Res*., *115*, B03205, doi:10.1029/2008JB006258.

Cole, J. W., D. M. Milner, and K. D. Spinks (2005), Calderas and caldera structures: A review, *Earth Sci. Rev*., *69*, 1–96, doi:10.1016/j.earscirev.2004.06.004.

Costa, A., A. Folch, G. Macedonio, B. Giaccio, R. Isaia, and V. C. Smith (2012), Quantifying volcanic ash dispersal and impact of the Campanian Ignimbrite super-eruption, *Geophys. Res. Lett*., *39*, L10310, doi:10.1029/2012GL051605.

D'Auria, L., F. Giudicepietro, I. Aquino, G. Borriello, C. Del Gaudio, D. Lo Bascio, M. Martini, G.P. Ricciardi, P. Ricciolino, and C. Ricco (2011), Repeated fluid-transfer episodes as a mechanism for the recent dynamics of Campi Flegrei caldera (1989–2010), *J. Geophys. Res*., *116*, B04313, doi:10.1029/2010JB007837.

Deino, A. L., G. Orsi, S. de Vita, and M. Piochi (2004), The age of the Neapolitan Yellow Tuff caldera-forming eruption (CampiFlegrei caldera—Italy) assessed by ^{40}Ar/^{39}Ar dating method, *J. Volcanol. Geotherm. Res*., *133*, 157–170, doi:10.1016/S0377-0273(03)00396-2.

De Natale, G., and A. Zollo (1986), Statistical analysis and clustering features of the Phlegraean Fields earthquake sequence, May '83-May '84, *Bull. Seismol. Soc. Am*., *76*, 801–814, doi:10.1785/01.20120036.

De Natale, G., and C. Troise, C (2011), The 'Campi Flegrei Deep Drilling Project': From risk mitigation to renewable energy production, *Eur. Rev*., *19*, 337–353, doi:10.1017/S1062798711000111.

De Natale, G., C. Troise, F. Pingue, G. Mastrolorenzo, L. Pappalardo, and E. Boschi (2006), The Campi Flegrei Caldera: Unrest mechanisms and hazards, in *Mechanisms of Activity and Unrest at Large Calderas*, vol. 269, edited by Troise et al., pp. 25–45, Geol. Soc. Spec. Publ., London, U. K.

De Vivo, B., G. Rolandi, P. B. Gans, A. Calvert, W. A. Bohrson, F. J. Spera, and H. E. Belkin (2001), New constraints on the pyroclastic eruptive history of the Campanian volcanic Plain (Italy), *Mineral. Petrol*., *73*(1), 47–65.

de Vita, S., et al. (1999), The Agnano-Monte Spina eruption (4100 years BP) in the restless Campi Flegrei caldera (Italy), *J. Volcanol. Geotherm. Res*., *91*(2–4), 269–301, doi:10.1016/S0377-0273(99)00039-6.

Di Girolamo, P., M. R. Ghiara, L. Lirer, R. Munno, G. Rolandi, and D. Stanzione (1984), Vulcanologia e petrologia dei Campi Flegrei, *Boll. Soc. Geol. Ital*., *103*(2), 349–413.

Di Vito, M. A., R. Isaia, G. Orsi, S. de Vita, M. D'Antonio, L. Pappalardo, and M. Piochi (1999), Volcanism and deformation since 12,000 years at the Campi Flegrei caldera (Italy), *J. Volcanol. Geotherm. Res*., *91*, 221–246, doi:10.1016/S0377-0273(99)00037-2.

Druitt, T. H., and R. S. J. Sparks (1984), On the formation of calderas during ignimbrite eruptions, *Nature*, *310*, 679–681, doi:10.1038/310679a0.

Eichelberger, J. C., and K. Uto (2007), Active volcanic systems, in *Continental Scientific Drilling*, edited by U. Harms et al., pp. 213–234, Springer, Berlin.

Fedele, L., C. Scarpati, M. Lanphere, L. Melluso, V. Morra, A. Perrotta, and G. Ricci (2008), The Breccia Museo formation, Campi Flegrei, Southern Italy: Geochronology, chemostratigraphy and relationship with the Campanian ignimbrite eruption, *Bull. Volcanol*., *70*, 1189–1219, doi:10.1007/s00445-008-0197-y.

Geyer, A., A. Folch, and J. Martí (2006), Relationship between caldera collapse and magma chamber withdrawal: An experimental approach, *J. Volcanol. Geotherm. Res*., *157*, 375–386, doi:10.1016/j.jvolgeores.2006.05.001.

Gudmundsson, A. (1998), Formation and development of normal-fault calderas and the initiation of large explosive eruptions, *Bull. Volcanol.*, *60*, 160–170.
Hill, D. P. (2006), Unrest in Long Valley Caldera, California, 1978–2004, in *Mechanisms of Activity and Unrest at Large Calderas*, vol. 269, edited by Troise et al., pp. 1–24, Spec. Publ. Geol. Soc., London, U. K.
Isaia, R., P. Marianelli, and A. Sbrana (2009), Caldera unrest prior to intense volcanism in Campi Flegrei (Italy) at 4.0 ka B.P.: Implications for caldera dynamics and future eruptive scenarios, *Geophys. Res. Lett.*, *36*, L21303, doi:10.1029/2009GL040513.
Judenherc, S. and A. Zollo (2004), The Bay of Naples (Southern Italy): Constraints on the volcanic structures inferred from a dense seismic survey, *J. Geophys. Res.*, *109*, B10312, doi:10.1029/2003JB002876.
Kennedy, B. M., A. M. Jellinek, and J. Stix (2008), Coupled caldera subsidence and stirring inferred from analogue models, *Nat. Geosci.*, *1*, 385–389, doi:10.1038/ngeo206.
Lee, J. Y., K. Marti, J. P. Severinghaus, K. Kawamura, H. S. Yoo, J. B. Lee, and J. S. Kim (2006), A redetermination of the isotopic abundances of atmospheric, *Geochim. Cosmochim. Acta*, *70*(17), 4507–4512, doi:10.1016/j.gca.2011.09.042.
Lipman, P. (2000), Calderas, in Encyclopedia of Volcanoes, edited by H. Sigurdsson, et al., pp. 643–662, Academic Press, San Diego, Calif.
Lirer, L., G. Luongo, and R. Scandone (1987), On the volcanological evolution of Campi Flegrei, EOS, Trans. *Am. Geophys. Union*, *68*, 226–234.
Lipman, P. W. (1997), Subsidence of ash-flow calderas: Relation to caldera size and magma-chamber geometry, *Bull. Volcanol.*, *59*, 198–218, doi:10.1007/s004450050186.
Lowenstern, J. B., R. B. Smith, and D. P. Hill (2006), Monitoring super-volcanoes: Geophysical and geochemical signals at Yellowstone and other large caldera systems, *Philos. Trans. R. Soc. A*, *364*, 2055–2072, doi:10.1098/rsta.2006.1813.
Luongo, G., E. Cubellis, F. Obrizzo, and S. M. Petrazzuoli (1991), The mechanics of the Campi Flegrei resurgent caldera—A model, *J. Volcanol. Geotherm. Res.*, *45*(3–4), 161–172.
Mark, D. F., C. M. Rice, M. R. Lee, A. E. Fallick, A. Boyce, N. H. Trewin, and J. K. W. Lee (2011a), ^{40}Ar/^{39}Ar dating of hydrothermal activity, biota and gold mineralization in the Rhynie hot-spring system, Aberdeenshire, Scotland, *Geochim. Cosmochim. Acta*, *75*, 555–569, doi: 10.1016/j.gca.2010.10.014.
Mark, D. F., F. M. Stuart, and M. de Podesta (2011b), New high-precision measurements of the isotopic composition of atmospheric argon, *Geochim. Cosmochim. Acta*, *75*, 7494–7501, doi:10.1016/j.gca.2011.09.042.
Mark, D. F., M. Petraglia, V. C. Smith, L. E. Morgan, D. N. Barfod, B. S. Ellis, N. J. Pal, and R. Korisettar (2014), A high-precision ^{40}Ar/^{39}Ar age for the Young Toba Tuff and dating of ultra-distal tephra: Forcing of Quaternary climate and implications for hominin occupation of India, *Quat. Geochronol.*, *21*, 90–103, doi:10.1016/j.quageo.2012.12.004.
Mormone, A., A. Tramelli, M. A. Di Vito, and M. Piochi (2011), Secondary hydrothermal alteration minerals in buried rocks at the CampiFlegrei Caldera, Italia: A possible tool to understand the rock-physics and to assess the state of the volcanic system, *Period. Mineral*., 80, 385–406, doi:10.2451/2011PM0027.
Mormone, A., C. Troise, M. Piochi, G. Balassone, M. Joachimski, and G. De Natale (2015), Mineralogical, geochemical and isotopic features of tuff from the CFDDP 506 m hole: Hydrothermal activity in the eastern side of the Campi Flegrei volcano (southern Italy), *J. Volcanol. Geotherm. Res.*, *290*, 39–52, doi:10.1016/j.jvolgeores.2014.12.003.
Orsi, G., S. de Vita, and M. Di Vito (1996), The restless, resurgent Campi Flegrei nested caldera (Italy): Constraints on its evolution and configuration, *J. Volcanol. Geotherm. Res.*, *74*, 179–214, doi:10.1016/S0377-0273(96)00063-7.
Pappalardo, L., L. Civetta, M. D'Antonio, A. Deino, M. A. Di Vito, G. Orsi, A. Carandente, S. de Vita, R. Isaia, and M. Piochi (1999), Chemical and Sr-isotopical evolution of the Phlegraean magmatic system before the Campanian Ignimbrite and the Neapolitan Yellow Tuff eruptions, *J. Volcanol. Geotherm. Res.*, *91*(2–4), 141–166, doi:10.1016/S0377-0273(99)00033-5.
Perrotta, A., C. Scarpati, G. Luongo, and V. Morra (2006), The Campi Flegrei caldera boundary in the city of Naples, in *Volcanism in the Campania Plain: Vesuvius, CampiFlegrei and Ignimbrites*, edited by B. De Vivo, pp. 85–96, Elsevier, Amsterdam.
Piochi, M., C. R. J. Kilburn, M. A. Di Vito, A. Mormone, A. Tramelli, C. Troise, and G. De Natale (2014), The volcanic and geothermally active Campi Flegrei caldera: An integrated multidisciplinary image of its buried structure, *Int. J. Earth Sci.*, *103*(2), 401–421, doi:10.1007/s00531-013-0972-7.
Renne, P. R., R. Mundil, G. Balco, K. Min and K. R. Ludwig (2010), Joint determination of 40K decay constants and 40Ar*/40K for the Fish Canyon sanidine standard, and improved accuracy for 40Ar/39Ar geochronology, *Geochim. Cosmochim. Acta, 74*, 5349–5367.
Renne, P. R., G. Balco, K. R. Ludwig, R. Mundil, and K. Min (2011), Joint determination of ^{40}K decay constants and ^{40}Ar*/^{40}K for the Fish Canyon sanidine standard, and improved accuracy for ^{40}Ar/^{39}Ar geochronology'': Response to the comment, *Geochim. Cosmochim. Acta*, *75*, 5097–5100, doi:10.1016/j.gca.2010.06.017.
Rittmann, A. (1950), Sintesi geologica dei Campi Flegrei, *Boll. Sot. Geol. Ital.*, *69*, 117–177.
Rosi, M., and A. Sbrana (1987), Phlegrean Fields: Petrography, *Quad. Ricerca Sci.*, *114*, 60–79.
Rosi, M., L.Vezzoli, P. Aleotti, and M. De Censi (1996), Interaction between Caldera collapse and eruptive dynamics during the Campanian Ignimbrite eruption, Phlegrean Fields, Italy, *Bull. Volcanol.*, *57*, 541–554, doi:10.1007/BF00304438.
Rolandi, G., F. Bellucci, M. T. Heizler, H. E. Belkin, and B. De Vivo (2003), Tectonic controls on the genesis of ignimbrites from the Campanian Volcanic Zone, southern Italy, *Mineral. Petrol.*, *79*, 3–31, doi:10.1007/s00710-003-0014-4.
Sacchi, M., F. Pepe, M. Corradino, D. D. Insinga, F. Molisso, and C. Lubritto (2014), The Neapolitan Yellow Tuff caldera offshore the Campi Flegrei: Stratal architecture and kinematic reconstruction during the last 15 ky. 2014, *Mar. Geol.*, *354*, 15–33, doi:10.1016/j.margeo.2014.04.012.
Scandone, R., F. Bellucci, L. Lirer, and G. Rolandi (1991), The structure of the Campanian Plain and the activity of the Neapolitan volcanoes (Italy), *J. Volcanol. Geotherm. Res.*, *48*, 1–31.
Scarpati, C., A. Perrotta, S. Lepore, and A. Calvert (2013), Eruptive history of Neapolitan volcanoes: Constraints from ^{40}Ar/^{39}Ar dating, *Geol. Mag.*, *150*, 412–425, doi:10.1017/S0016756812000854.
Smith, V. C., R. Isaia, and N. J. G. Pearce (2011a), Tephrostratigraphy and glass compositions of post-15 kyr Campi Flegrei eruptions: Implications for eruption history and chronostratigraphic markers, *Quat. Sci. Rev.*, *30*, 3638–3660, doi:10.1016/j.quascirev.2011.07.012.
Smith, V. C., et al. (2011b), Toward establishing precise ^{40}Ar/^{39}Ar chronologies for Late Pleistocene palaeoclimate archives: An example from the Lake Suigetsu (Japan) sedimentary record, *Quat. Sci. Rev*., 2845–2850, doi:10.1016/j.quascirev.2011.06.020.
Troiano, A., M. G. Di Giuseppe, Z. Petrillo, C. Troise, and G. De Natale (2011), Ground deformation at calderas driven by fluid injection: Modelling unrest episodes at Campi Flegrei (Italy), *Geophys J. Int.*, *187*, 833–847, doi:10.111/j.1365-246X.2011.05149.x.
Vinciguerra, S., C. Trovato, P. G. Meredith, P. M. Benson, G. De Luca, C. Troise, and G. De Natale (2006), Understanding the seismic velocity structure of Campi Flegrei caldera (Italy): from the laboratory to the field scale, *Pure App. Geophys.*, *63*(10), 2205–2221, doi:10.1007/s00024-006-0118-y.
Vitale, S., and R. Isaia (2014), Fractures and faults in volcanic rocks (Campi Flegrei, southern Italy): Insight into volcano-tectonic processes, *Int. J. Earth Sci.*, *103*, 801–819, doi:10.1007/s00531-013-0979-0.