THE CAMPI FLEGREI DEEP DRILLING PROJECT (CFDDP): CALDERA STRUCTURE AND HAZARD

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ABSTRACT

The recent investigation carried out on the west bound of the Naples metropolitan area and inside the Campi Flegrei caldera as part of the Campi Flegrei Deep Drilling Project provided new insight in order to reconstruct the volcano-tectonic evolution of this extremely populated area. Campi Flegrei represents the highest risk volcanic areas in the world, although its volcano-tectonic structure, eruptive history and eruptive style of the largest eruptions are intensely debatedby scientists since several decades. We present here a summary of stratigraphic and geochronological dating (40Ar/39Ar) allowing to define the age of intra-caldera deposits belonging to the two highest magnitude caldera-forming eruptions (i.e. Campania Ignimbrite, 39÷40 ka, and Neapolitan Yellow Tuff, 14.9 ka) and to evaluate the amount of collapse of the eastern sector of the caldera.

These results point out: (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 characterised by complex collapse mechanisms and dynamics, whose understanding needs more robust constraints, which can be obtained from scientific drilling.

Keywords: Ar dating, caldera dynamic, caldera-forming eruptions, Campi Flegrei caldera, CFDDP drilling, volcanic hazard

1 INTRODUCTION

Extreme volcanic eruptions from large calderas are the most likely hazard to generate global catastrophes [1, 2]. This topic has received considerable attention because of the millions of people living in high-risk volcanic areas [3].

Actually, conceptual models for many calderas are based on an incomplete reconstruction of their system [4]. A well-known case study is the caldera of Campi Flegrei in Southern Italy (Fig. 1), which was produced by large volume eruptions at c. 39 ka (Campanian Ignimbrite, CI, VEI=7) and c. 15 ka (Neapolitan Yellow Tuff, NYT, VEI=6) [5].

The mechanism of the above eruptions and the involved volume of magma (particularly for the CI eruption) are still uncertain. Recently, some authors proposed that the CI caldera limit enclosed the central sector of Naples [6, 7] while other authors [8, 9] do not incorporate the central part of the city. The latter models are 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 in a range of 80 to more than 300 km^3 of DRE. These different interpretations have important implications on the assessment of both the eruptive mechanism and the risk for people living in the surroundings. In this case, deep drilling provides the best mean to obtain direct information on processes occurring at depth and represents a key tool for reconstructing the caldera structure and understanding the volcano dynamic and volcanic risk assessment [10]. The highly urbanised Campi Flegrei Caldera have been experiencing decades of unrest, with uplift rates up to 1 m/y,

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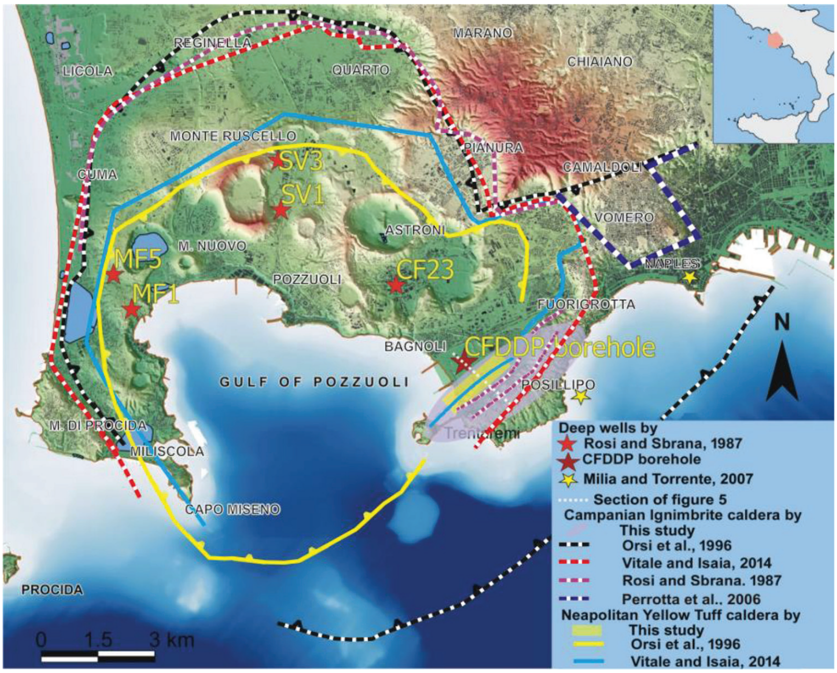

Figure 1: Morphological map of the Campi Flegrei caldera.The lines are the caldera limits as differently proposed. CFDDP drilling site (larger red star) is shown with the deepest boreholes realised by AGIP (SV1, SV3, MF1, MF5) andSAFEN (CF23) companies (smaller red stars).

thousands of microearthquakes per year [11] and strong geochemical anomalies [12], leading to people evacuation of Pozzuoli town in 1982–1983. At the present, 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 researches, 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, the most recent and important one is the Campi Flegrei Deep Drilling Project (CFDDP), endorsed by ICDP [13, 14] and targeted to the eastern caldera sector with a borehole achieving a depth of 501 m below sea level (bsl). The CFDDP core/cuttings analyses were performed with the aim to provide new constraints to the volcanic setting in the eastern sector of the caldera, filling the 'information gaps' from previous deep exploration work in the western, northern and central sectors of the caldera.

Here, we report a summary of 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 [14]. 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 drillings in providing reliable constraints in the understanding of 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 (Fig. 1), which represents a morphological limit of the caldera, possibly related to the collapse during the caldera-forming eruptions.

Drilling operations were carried out through technical and logistical mud services, thus allowing the collection of mud cuttings and cores. Two cores were extracted from 439 m and 501 m. In particular, 40Ar/39Ar 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.

3 ANALYTICAL RESULTS

Stratigraphy and volcanology of the drilled sequence as deduced by lithological, mineralogical and micropaleontological analyses are reported in Figure 2.

The sequence is fully composed of pyroclastic materials. The upper most part consists of subaerial pyroclastic deposits composed of variably vesicular and porphyritic fragments including Agnano Monte Spina tephra (c. 5 ka) at the base. Below, the sequence shows a c. 100m-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 remaining underlying sequence is composed of greenish tuffs overlying a gray-tuff at the bottom hole, both containing very low abundances of feldspars. The transition between the two tuffs is likely gradual and starts to occur at c. 450 m. Samples from the greenish tuffs are very homogeneous and strongly comparable to the core at 439 m representative of a fine- to coarse-grained heterogeneous fossil-free tuff, gray-green in colour. The core at 501 m is a chaotic tuff with coarse- to fine-grained ash matrix hardened by zeolitisation.

The 40Ar/39Ar age constraints for the four dated samples at the specific depth provide the absolute chronology of the sequence ranging between 16.9 ± 1.1/1.2 ka and 47.5 ± 0.8/0.9 ka (see Fig. 2).

Figure 2 shows a 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 (primary and neogenic mineral assemblage, and H2S 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 colours 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.

4 RESULTS AND DISCUSSION

The stratigraphic sequence obtained and the 40Ar/39Ar dating constraints at the CFDDP borehole provide new insights on the eastern Campi Flegrei caldera deep structure and evolution. Based on the CFDDP data, we can point out the following main results in comparison with recent scientific literature. It is evident a reduction of the area affected by collapse and a surprisingly smaller volume of the infilling caldera deposits, particularly for the CI eruption, with respect to the previous hypothesis [7]. Therefore, it is possible to re-evaluate the collapse amounts and mechanisms related to the CI and NYT eruptions.

The obtained data do not support a collapse extending toward the Naples metropolitan areas and Gulf of Naples with a hypothesised drop of ~1500 m and show that the drilling site is very close to the caldera border (see Fig. 1). 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

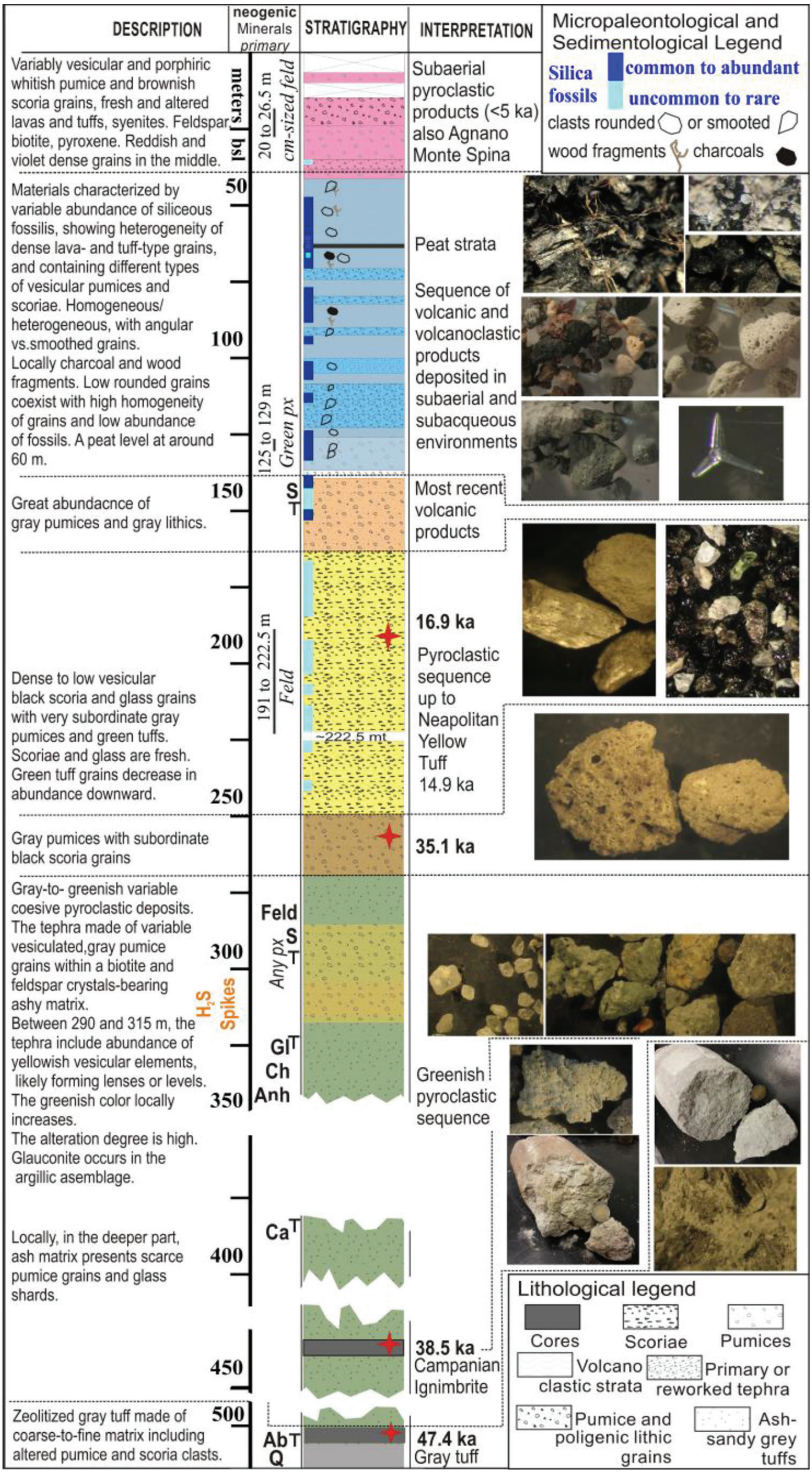

Figure 2: Synthetic stratigraphic reconstruction along the CFDDP drill hole.

favour of NYT with respect to CI, is largely unexpected because of the higher VEI of CI. This is a very crucial finding, which favour the hypothesis that CI was possibly erupted from vents also outside the Campi Flegrei caldera. An alternative model, which anyway should be reconciled with the low thickness of CI deposits, would be that a very large regional uplift occurred related to the CI, approximately several hundred meters.

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 do not extend in the central part of the city of Naples as stated by the most of recent literature.

The results of this study point out, in a more general way, that large calderas are characterized by complex collapse mechanisms, in which the collapse progressively deepens going from the borders towards the central part. Such a complex mechanism also emerges as the most likely one in recent theoretical studies on caldera formation. Finally, this study shows the importance of age-based correlation between intra-caldera and extra-caldera tephra in defining the eruptive mechanisms at the origin of collapse. This problem is common to several calderas worldwide [15]; for the above reasons, scientific drilling demonstrates as one of the most powerful tool to reconstruct the structure, the collapse mechanism and the volcanic history of calderas.

5 TABLE OF ABBREVIATIONS

ka	=	kilo annum;
bsl	=	below sea level;
40Ar	=	Argon 40 (Ar Isotope, used to compute, from relative radioactive decay, the absolute age of the sample);
39Ar	=	Argon 39 (Ar isotope, used to compute, from relative radioactive decay, the absolute age of the sample);
VEI	=	Volcanic Explosivity Index;
NYT	=	Neapolitan Yellow Tuff Eruption;
CI	=	Campanian Ignimbrite Eruption;
ICDP	=	International Continental Drilling Program (World Organization to promote and support scientific drilling);
DRE	=	Dense Rock Equivalent (Volume of pyroclastic erupted material compressed to a density equivalent to the corresponding rock);
CFDDP	=	Campi Flegrei Deep Drilling Project.

REFERENCES

[1] Hill, D. P., *Unrest in Long Valley Caldera, California, 1978–2004, in Mechanisms of activity and unrest at large calderas*, edited by Troise *et al*., **269**, pp. 1–24, Geological Society, London, Special Publication, 2006.

[2] Lowenstern, J.B., Smith, R.B. & Hill, D.P., Monitoring super-volcanoes: geophysical and geochemical signals at Yellowstone and other large caldera systems. *Philosophical Transaction of the Royal Society A*, **364**, pp. 2055–2072, 2006. https://doi.org/10.1098/rsta.2006.1813

[3] Carlino, S. & Somma, R., Eruptive versus non-eruptive behaviour of large calderas: the example of CampiFlegrei caldera (southern Italy). *Bulletin of Volcanology*, **72**, pp. 871–886, 2010. https://doi.org/10.1007/s00445-010-0370-y

[4] Carlino, S., Somma, R., Troise, C. & De Natale, G., The geothermal exploration of Campanian volcanoes: historical review and future development. *Renewable and Sustainable Energy Reviews*, **16**, pp. 1004–1030, 2012.
https://doi.org/10.1016/j.rser.2011.09.023

[5] Deino, A.L., Orsi, G., de Vita, S. & Piochi, M., The age of the Neapolitan Yellow Tuff caldera-forming eruption (CampiFlegrei caldera - Italy) assessed by 40Ar/39Ar dating method. *Journal of Volcanology and Geothermal Research*, **133**, pp. 157–170, 2004.
https://doi.org/10.1016/S0377-0273(03)00396-2

[6] Rosi, M. & Sbrana, A., PhlegreanFields: Petrography. *Quaderni de La Ricerca Scientifica*, **114**, pp. 60–79, 1987.

[7] Perrotta, A., Scarpati, C., Luongo, G. & Morra, V., The CampiFlegrei caldera boundary in the city of Naples, in Volcanism in the Campania Plain: Vesuvius, CampiFlegrei and Ignimbrites, edited by De Vivo, B., pp. 85–96, Elsevier, Special Publication, 2006.

[8] Orsi, G., de Vita, S. & Di Vito, M., The restless, resurgent CampiFlegrei nested caldera (Italy): constraints on its evolution and configuration. *Journal of Volcanology and Geothermal Research*, **74**, pp. 179–214, 1996.
https://doi.org/10.1016/S0377-0273(96)00063-7

[9] Vitale, S. & Isaia, R., Fractures and faults in volcanic rocks (CampiFlegrei, southern Italy): insight into volcano-tectonic processes. *International Journal of Earth Sciences*, **103**, pp. 801–819, 2014.
https://doi.org/10.1007/s00531-013-0979-0

[10] Carlino, S., Kilburn, C.R.J., Tramelli, A., Troise, C., Somma, R. & De Natale, G., Tectonic stress and renewed uplift at CampiFlegrei caldera, southern Italy: new insights from caldera drilling. *Earth and Planetary Science Letters*, **420**, pp. 23–29, 2015.
https://doi.org/10.1016/j.epsl.2015.03.035

[11] De Natale, G., Troise, C., Pingue, F., Mastrolorenzo, G., Pappalardo, L. & Boschi, E., *The CampiFlegrei Caldera: unrest mechanisms and hazards, in Mechanisms of activity and unrest at large calderas*, edited by Troise *et al*., Geological Society, London, Special Publication, **269**, pp. 25–45, 2006.

[12] Moretti, R., De Natale, G. & Troise, C., A geochemical and geophysical reappraisal to the significance of the recent unrest at CampiFlegrei caldera (Southern Italy). *Geochemistry, Geophysics, Geosystems*, **18**, pp. 1244–1269, 2017.
https://doi.org/10.1002/2016GC006569.

[13] De Natale, G. & Zollo, A., Statistical analysis and clustering features of the Phlegraean Fields earthquake sequence, May ‘83–May ‘84. *Bulletin of the Seismological Society of America*, **76**, pp. 801–814, 1986.
https://doi.org/10.1785/01.20120036

[14] Lipman, P.W., Subsidence of ash-flow calderas: Relation to caldera size and magma-chamber geometry. *Bulletin of Volcanology*, **59**, pp. 198–218, 1997.
https://doi.org/10.1007/s004450050186