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Key Points:
- Volcanic hazard assessment in the highest risk volcanic area worldwide, in unrest since 60 years, by innovative research
- Scientific drilling as a tool to solve crucial questions related to volcanic hazard at volcanoes
- Geochemical analysis of more than three decades of data from a caldera in long lasting unrest, to evidence magma intrusion and/or cooling

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Understanding volcanic hazard at the most populated caldera in the world: Campi Flegrei, Southern Italy

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Abstract Naples and its hinterland in Southern Italy are one of the most urbanized areas in the world under threat from volcanic activity. The region lies within range of three active volcanic centers: Vesuvius, Campi Flegrei, and Ischia. The Campi Flegrei caldera, in particular, has been in unrest for six decades. The unrest followed four centuries of quiescence and has heightened concern about an increased potential for eruption. Innovative modeling and scientific drilling are being used to investigate Campi Flegrei, and the results highlight key directions for better understanding the mechanisms of caldera formation and the roles of magma intrusion and geothermal activity in determining the volcano's behavior. They also provide a framework for evaluating and mitigating the risk from this caldera and other large ones worldwide.

1. Understanding and Mitigating Volcanic Risk: The Case of Campi Flegrei

About one billion people are threated by known active or potentially active volcanoes; in some regions, large urban areas have developed close to volcanic vents, resulting in extreme risk even from small to moderate eruptions. The area arguably at greatest risk in the world is the Neapolitan district of southern Italy, where about three million people live within 10 km of the active volcanoes of Vesuvius, Campi Flegrei, and Ischia (see map in Figure 1). Of these, Campi Flegrei is currently in unrest for the first time since its only historical eruption in 1538 [*De Natale et al.*, 2006]. An urgent goal is to understand whether the new unrest means that the volcano has returned to conditions that favor an eruption.

1.1. Formation of Campi Flegrei

Campi Flegrei is a typical example of a large collapse caldera, in which postcaldera volcanic activity is polygenetic. Such calderas represent the most explosive, yet least understood, volcanism on Earth [*Acocella et al.*, 2015]. Campi Flegrei itself is generally thought to have been formed during two large eruptions of ignimbrites: the 300 km^3 Campanian Ignimbrite (CI, 39,000 years ago) and the 50 km^3 Neapolitan Yellow Tuff (NYT, 15,600 years ago). The CI eruption was the largest to have occurred in Europe for at least 100,000 years, and has been included among the possible causes for the extinction of the Neanderthals [*Fedele et al.*, 2002]. Its caldera was initially defined as a quasicircular structure, about 12 km across, approximately centered on the coastal town of Pozzuoli [*Rosi and Sbrana*, 1987]. Its southern third was submerged beneath the Bay of Pozzuoli, and the amount of collapse associated with the eruption was estimated to have been at least 1.5 km [*Rosi and Sbrana*, 1987]. On land, its eastern margin included the westernmost suburbs of Naples that had extended beyond the promontory of Posillipo Hill. Later studies proposed that the margin instead tapered out another 10 km further east and included virtually the entire city [*Orsi et al.*, 1996].

The role of the CI eruption, however, remains controversial and has been challenged most strongly by *De Vivo et al.* [2001], who argue that Campi Flegrei's caldera was formed during the NYT eruption alone. Nevertheless, the different models agree that the caldera most evident from geophysical observations (such as gravity anomalies) reflects collapse during the NYT eruption. Yellow tuff is the most typical rock covering Naples and historically has provided one of the main construction materials for houses, churches, and other public buildings in the Neapolitan district.

Since the Neapolitan Yellow Tuff eruption, about 60 intracaldera eruptions have been recognized across the floor of the caldera [*Smith et al.*, 2011]. Each has expelled volumes of magma between about 0.01 and

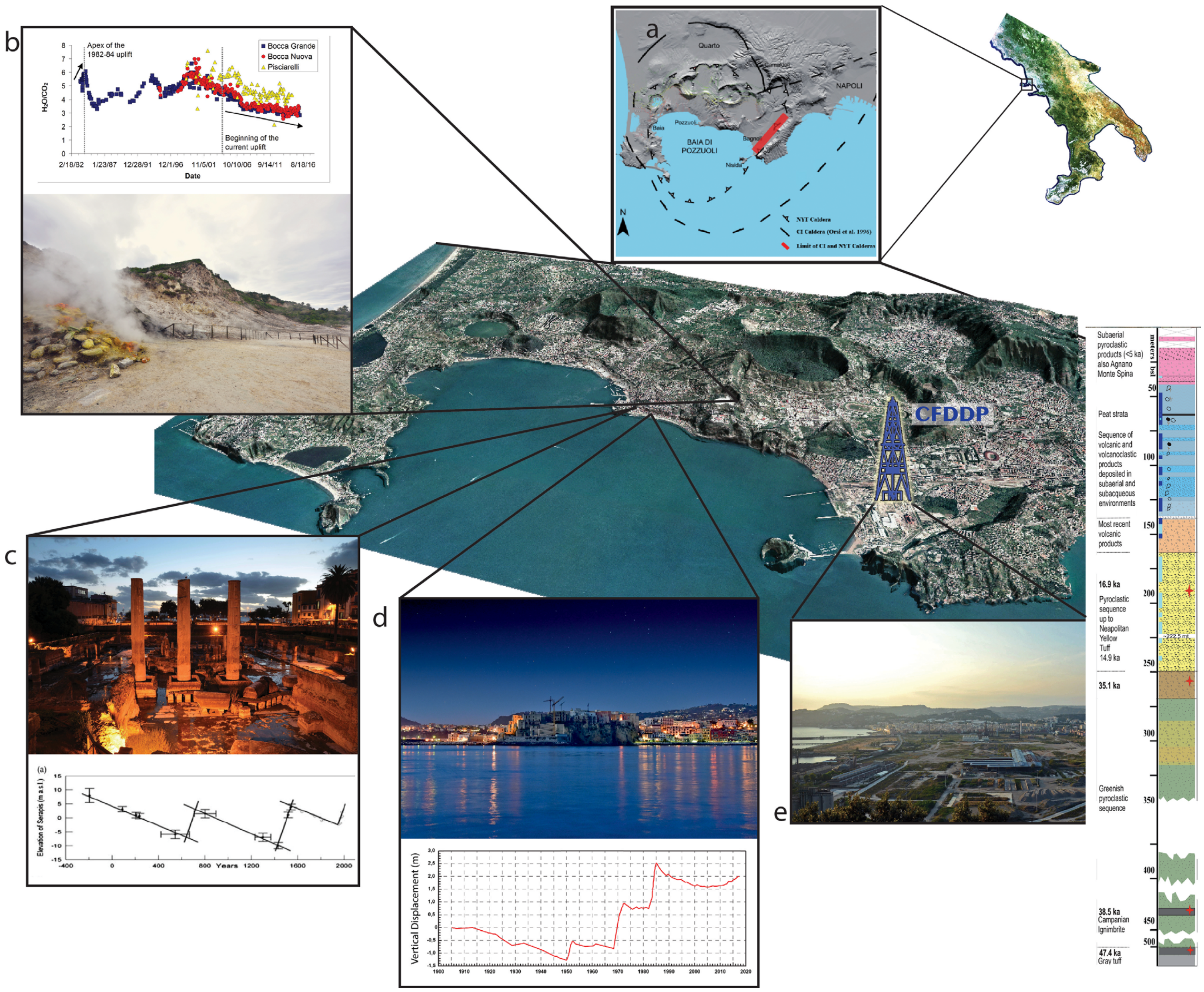

Figure 1. Campi Flegrei caldera (orthophoto on DEM) with key data and results mentioned in this paper: (a) sketch map of the caldera with the two previously hypothesized caldera collapses; the red bar shows the actual limits of both calderas as inferred by *De Natale et al*. [2016]; (b) picture of fumarole emissions at Solfatara, analyzed by *Moretti et al*. [2017]; the ratio between H_2O and CO_2, determined in the last 34 years by these authors, is shown; (c) picture of the Roman Market (Macellum) in Pozzuoli town, with the marble columns of the "Serapis" Temple which, with their bores (caused by molluscs) indicating the marine ingression levels during the time, allowed to reconstruct the secular variations of the ground level since Roman times (shown in this frame, from *Bellucci et al*., 2006); (d) picture of the tuff cliff of Rione Terra, at the center of Pozzuoli town and the Port; this is the site of maximum measured deformation at Campi Flegrei, whose trend since 1905 to present is shown below the picture, as measured by precision levellings until 2000 and by continuous GPS after this date; (e) picture of the dismissed steel factory of Bagnoli (ILVA), which hosted the drilling site CFDDP; on the right side, the stratigraphic sequence recovered in the well is shown with recovered ages and depths of main samplings (red stars). (Figures and composition by Claudio Serio, photos by Alessandro Fedele).

1 km^3. The majority have been explosive and produced significant ash fall and pyroclastic flows. The area most exposed to possible pyroclastic flows hosts about 600,000 people, including the western suburbs of Naples that lie inside the caldera. In addition, because the dominant wind direction is toward the east, downtown Naples (a city of one million people) is also vulnerable to ash falls of thicknesses large enogh to damage buildings [*Mastrolorenzo et al*., 2006, 2008].

1.2. Historic Unrest at Campi Flegrei

Ground movements at Campi Flegrei have been exceptionally large in the last 2000 years, as shown by variations in elevation with respect to sea level at coastal archaeological sites dating back to Roman times. We know from such observations that the ground during that time underwent almost continuous subsidence, which was interrupted at least once, in the early Fifteenth century, about 100 years before the 1538 eruption of Monte Nuovo, the only eruption to have occurred in historical times [*Dvorak and Mastrolorenzo*, 1991; *Bellucci et al*., 2006]. The mean rate of subsidence was approximately 1.5–2 cm/yr at the site of modern Pozzuoli, near the center of the caldera [*Bellucci et al*., 2006]; during the century of uplift before 1538, Pozzuoli rose by some 17 m. After 1538, the ground at Pozzuoli again subsided at 1.5–2 cm/year until 1950 [*Del Gaudio et al*., 2010], after which it rose by about 4.5 m during three intervals: 1950–1952, 1969–1972, and 1982–1984. The last uplift was first followed by a slow subsidence of about 0.8 m until 2000–2005, followed by slower uplift, which continues today [*Kilburn et al*., 2017; *Moretti et al*., 2017]. The two rapid uplifts between 1969 and 1984 were accompanied by swarms of earthquakes of small magnitude (up to $M_L = 4.0$) and movements since at least 1982 have been accompanied by marked changes in the geochemistry of fumarolic gases [*Chiodini et al*., 2016; *Moretti et al*., 2017].

The renewed unrest since 1950 has raised serious concern about a possible eruption. It highlights the need for research into the evolution and structure of the caldera to better understand the significance of the present unrest. Such understanding will help to reduce the risk from volcanic activity not only at Campi Flegrei, but insights can be applied to unrest at similar collapse calderas worldwide.

2. Crucial Scientific Questions for Risk Mitigation and the Importance of Scientific Drilling

The immediate questions to be addressed at the Campi Flegrei caldera include:

1. What are the relative contributions of magmatic and hydrothermal processes to ground uplift? How does this relate to the repeated uplift episodes that resulted in a cumulative uplift of several meters, and how can we place this in the context of evolving volcanic unrest?
2. How can we forecast the possible evolution of volcanic unrest leading up to an eruption?
3. How and when did the caldera form, and what part of the Neapolitan urban area does it encompass?

To meet these goals, and provide detailed data regarding the caldera, the International Continental Scientific Drilling Program (ICDP) supported a drilling project into the caldera. The Campi Flegrei Deep Drilling Project (CFDDP) [*De Natale and Troise*, 2011] was launched in 2012, with the drilling of a "pilot hole" to a depth of 500 meters, in an abandoned steel works at Bagnoli in the eastern part of the caldera – and the westernmost part of Naples.

2.1. How Many Calderas Have Produced Campi Flegrei?

A primary aim of the pilot hole was to test the performance of borehole monitoring instrumentation under the harsh conditions expected within the volcano (hot, acidic, and corrosive ground water), and to measure crucial parameters like rock permeability and tectonic stress at depth [*Carlino et al*., 2015]. An unexpected bonus was that the borehole samples revealed an impressive record of the caldera's collapse, discovering volcanic products as old as 48,000 years. Argon-argon dating of core samples revealed that the pilot hole had penetrated deposits from both the NYT and CI eruptions [*De Natale et al*., 2016]. The NYT was found about 250 m below subaerial outcrops in the adjacent Posillipo Hill and the CI was encountered at a depth of only 439 m [*De Natale et al*., 2016].

Both levels were shallower than expected. The shallow depth of the NYT in this area, compared to the mean collapse of about 700 m, suggests that the collapse was uneven and probably deeper toward the center of the caldera. In the case of the CI, previous studies had inferred a collapse of 1.5 km or more [*Rosi and Sbrana*, 1987; *Orsi et al*., 1996]. The shallow depth of the CI deposits at the drill hole site imply that the collapse was much smaller. After taking in account changes in sea level (which, at the time of eruption, was about 100 m lower than today) and collapse of the NYT caldera, the depth of the CI deposits imply a collapse at that location of only about 100 m. Even including that the collapse extended beneath the whole of Naples, the erupted volume can only be explained with an overall mean subsidence of 1 km, which is 10 times larger than we found. According to the extended caldera model, the pilot hole is located well within the area of main collapse. Unless the borehole happens to have been drilled in an unrepresentative area of small subsidence, the new data raise doubts about whether the CI significantly shaped the Campi Flegrei caldera. These result would support the view that collapse at Campi Flegrei only occurred during the NYT eruption, and CI only marginally affected this area [*De Vivo et al*., 2001]. It also implies that most of Naples does not lie within the Campi Flegrei caldera. The implications of such new findings for volcanic hazard assessment in the city of Naples are crucial.

2.2. New Interpretations of Campi Flegrei Unrest

Designing the CFDDP program stimulated a reappraisal of geochemical data that had been collected from fumarolic emissions over the course of more than three decades [*Chiodini et al*., 2012, 2016]. The results confirmed that as much as 0.1 km^3 of magma was intruded at depths of about 3–4 km during or before the unrest of 1982–1984 and that most of it likely cooled and solidified by 2000 [*Moretti et al*., 2013, 2017]. However, in contrast to interpetations suggesting that the slow uplift since 2005 can also be attributed to the shallow intrusion of magma [*Chiodini et al*., 2016], the new analysis indicates that conditions are instead returning, after shallow magma cooled by 2000–2005, to those that prevailed before the 1982–1984 unrest [*Moretti et al*., 2017], with gas emissions coming directly from the deeper magma chamber, located at a depth of about 8 km. Understanding whether new magma is being intruded to shallower depths is crucial for evaluating the potential for eruption. By allowing additional gas sampling at depth, the CFDDP program will provide an exceptional opportunity for future monitoring.

Although the new geochemical studies indicate a lack of shallow magmatic intrusions over the last few decades, an evaluation of the full sequence of unrest since 1950 indicates an underlying long-term evolution in the state of stress in the crust [*Kilburn et al*., 2017]. The three episodes of rapid uplft between 1950 and 1984 have been characterized by an increase in the number of microearthquakes, or volcano-tectonic (VT) events, recorded per meter of uplift. The majority of VT events occurred in the shallow crust, above the inferred level of magma intrusion. The change in uplift rate and seismicity is thus consistent with the crust being uplifted and stretched by successive intrusions and deforming as a partly elastic, partly brittle material, with the brittle component, which produces VT events, becoming progressively larger with time. It also implies that the slow and nearly aseismic subsidence and uplift at Campi Flegrei since 1984 reflect corresponding decreases and increases in pore-pressure in the geothermal system, consistent with arguments from gas analyses [*Moretti et al*., 2017]. The overall picture that emerges is that stress is accumulating in the crust along a trend toward bulk failure. Such an event, in turn, may provide a new pathway along which the deeper magma could escape to the surface. Although an eruption is not guaranteed, the potential for eruption seems to be now significantly greater than before previous unrests [*Kilburn et al*., 2017]. The CFDDP will provide measurements of deformation and VT event rates at depth [*Carlino et al*., 2015] and these, combined with surface measurements, will provide better constraints on where brittle failure is most likely to occur in the crust. Clearly, close monitoring of this situation is essential, and will be made more effective by the new borehole instruments installed in the framework of CFDDP and related projects.

3. Conclusions

Analyses of the recent unrest at Campi Flegrei have highlighted key topics to be investigated to improve assessments of the caldera's potential for eruption. These include extended monitoring of gas geochemistry, detailed analysis of the rheological behavior and accumulation of stress in the crust, and their applications to understanding the behavior of the geothermal system and mechanisms of shallow-level magma intrusion. Analyses to date have been confined to geodetic, geophysical, and geochemical measurements made at the surface. Major advances are expected by incorporating new data from borehole measurements below the surface. At Campi Flegrei, a new offshore drilling program is being designed to augment the onshore CFDDP program. Beyond Campi Flegrei, data from both these initiatives will be likely complemented by those from parallel deep drilling programs planned in other volcanically active regions, including the Krafla Magma Drilling Project in Iceland, the Newberry Volcano Deep Drilling Project in the USA, and the Japan Beyond Brittle Project. Thus, the next decade may lead to a transformational change in our understanding not only of large calderas, such as Campi Flegrei, but also of the mechanisms that drive eruptions at volcanoes worldwide.

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References

Acocella, V., R. Di Lorenzo, C. Newhall, and R. Scandone (2015), An overview of recent (1988-2014) caldera unrest: Knowledge and perspectives, *Rev. Geophys.*, *53*, 896–955, doi:10.1002/2015RG000492.

Bellucci, F., J. Woo, C. R. J. Kilburn, and G. Rolandi (2006), Ground deformation at Campi Flegrei, Italy: Implications for hazard assessment, in *Mechanisms of Activity and Unrest at Large Calderas*, edited by C. Troise, G. De Natale, and C. R. J. Kilburn, Geol. Soc., Spec. Publ., 269, 141–158.

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, 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, P. De Martino, R. Avino, and F. Gherardi (2012), Early signals of new volcanic unrest at Campi Flegrei caldera? Insights from geochemical data and physical simulations, *Geology*, *40*, 943–946.

Chiodini, G., A. Paonita, A. Aiuppa, A. Costa, S. Caliro, P. De Martino, V. Acocella, and J. Vandemeulebrouck (2016), Magmas near the critical degassing pressure drive volcanic unrest towards a critical state, *Nat. Commun.*, *7*, 13712, doi:10.1038/ncomms13712.

Del Gaudio, C., I. Aquino, G. P. Ricciardi, C. Ricco, and R. Scandone (2010), Unrest episodes at Campi Flegrei: A reconstruction of vertical ground movements during 1905–2009, *J. Volcanol. Geotherm. Res.*, *195*(1), 48–56, doi:10.1016/j.jvolgeores.2010.05.014.

De Natale, G., and C. Troise (2011), The ''Campi Flegrei Deep Drilling Project'': From risk mitigation to renewable energy production, *Eur. Rev.*, *19*(3), 337–353, doi:10.1017/S1062798711000111.

De Natale, G., C. Troise, F. Pingue, G. Mastrolorenzo, L. Pappalardo, M. Battaglia, and E. Boschi (2006), The Campi Flegrei Caldera: Unrest mechanisms and hazards, in *Mechanisms of Activity and Unrest at Large Calderas*, edited by C. Troise, G. De Natale, and C. R. J. Kilburn, Geol. Soc. Spec. Publ., 269, 25–45.

De Natale, G., C. Troise, D. Mark, A. Mormone, M. Piochi, M. A. Di Vito, R. Isaia, S. Carlino, D. Barra, and R. Somma (2016), The Campi Flegrei Deep Drilling Project(CFDDP): New insight on caldera structure, evolution and hazard implications for the Naples area (Southern Italy), *Geochem. Geophys. Geosyst.*, *17*, 4836–4847, doi:10.1002/2015GC006183.

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.

Dvorak, J.J., and G. Mastrolorenzo (1991), The mechanisms of recent vertical crustal movements in Campi Flegrei caldera, southern Italy, *Geol. Soc. Am. Spec. Pap.*, *263*, 47 p.

Fedele F., B. Giaccio, R. Isaia, and G. Orsi (2002), Ecosystem impact of the Campanian Ignimbrite eruption in Late Pleistocene Europe, *Quat. Res.*, *57*, 420–424.

Kilburn, C. R. J., G. De Natale, and S. Carlino (2017), Progressive approach to eruption at Campi Flegrei caldera in southern Italy, *Nat. Commun.*, doi:10.1038/ncomms15312, in press.

Mastrolorenzo, G., L. Pappalardo, C. Troise, S. Rossano, A. Panizza, and G. De Natale (2006), Volcanic hazard assessment at Campi Flegrei caldera, in *Mechanisms of Activity and Unrest at Large Calderas*, edited by C. Troise, G. De Natale, and C. R. J. Kilburn, Geol. Soc. Spec. Publ., 269, 159–171.

Mastrolorenzo, G., L. Pappalardo, C. Troise, A. Panizza, and G. De Natale (2008), Probabilistic tephra fall-out hazard maps in Neapolitan area from quantitative volcanological study of Campi Flegrei eruptions, *J. Geophys. Res.*, *113*, B07203, doi:10.1029/2007JB004954.

Moretti, R., I. Arienzo, L. Civetta, G. Orsi, and P. Papale (2013), Multiple magma degassing sources at an explosive volcano, *Earth Planet. Sci. Lett.*, *367*, 95–104.

Moretti R., G. De Natale, and C. Troise (2017), A geochemical and geophysical reappraisal to the significance of the recent unrest at Campi Flegrei caldera (Southern Italy), *Geochem. Geophys. Geosyst.*, *17*, 4836–4847, doi:10.1002/2015GC006183.

Orsi, G., S. de Vita, and M. Di Vito (1996), The restless, resurgent CampiFlegrei nested caldera (Italy): Constraints on its evolution and configuration, *J. Volcanol. Geotherm. Res.*, *74*, 179–214, doi:10.1016/S0377-0273(96)00063-7.

Rosi, M., and A. Sbrana (1987), Phlegrean fields: Petrography, *Quad. Ric. Sci.*, *114*, 60–79.

Smith, V. C., R. Isaia, and N. J. G. Pearce (2011), 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.