15

Ground movement (bradyseism) in the Campi Flegrei volcanic area: a review

Claudia Cannatelli[1,2], Frank J. Spera[3], Robert J. Bodnar[4], Annamaria Lima[5], Benedetto De Vivo[6,7,8,9]

[1]*Department of Geology, FCFM, University of Chile, Santiago, Chile;* [2]*Andean Geothermal Center of Excellence (CEGA), University of Chile, Santiago, Chile;* [3]*Department of Earth Science and Earth Research Institute, University of California, Santa Barbara, CA, United States;* [4]*Fluids Research Laboratory, Department of Geosciences, Virginia Polytechnic Institute and State University, Blacksburg, VA, United States;* [5]*Dipartimento di Scienze della Terra, delle Risorse e dell'Ambiente, Universitá di Napoli Federico II, Naples, Italy;* [6]*Pegaso On Line University, Naples, Italy;* [7]*Adjunct Professor, Dept of Geosciences, Virginia Polytechnic Institute & State University (Virginia Tech), Blacksburg, VA, United States;* [8]*Nanjing University, Nanjing, China;* [9]*Hubei Polytechnic University, Huangshi, China*

Introduction

The Campi Flegrei volcanic district (CFVD) is an area located in Southern Italy just west of the city of Naples that has experienced intense volcanism, hydrothermal activity, and bradyseism over the past 100 ka. The CFVD, one of the most densely populated volcanically active areas in the world with about 1.5 million inhabitants, is considered one of the highest risk volcanic areas on Earth. The origin of volcanism in the CFVD and the geodynamics of the area have been the subject of intense research and heated debate for the past century (De Lorenzo, 1904; Oliveri del Castillo and Quagliariello, 1969; Casertano et al., 1976; Corrado et al., 1976; Berrino et al., 1984; AGIP, 1987; Aster and Meyer, 1988; Bonafede, 1990, 1991; De Natale et al., 1991; Cortini et al., 1991; Ferrucci et al., 1992; Cortini and Barton, 1993; Berrino and Gasparini, 1995; De Natale et al., 1995; Wortel and Spakman, 2000; Milia

Vesuvius, Campi Flegrei, and Campanian Volcanism. https://doi.org/10.1016/B978-0-12-816454-9.00015-8

and Torrente, 1999, 2003; Faccenna et al., 2001; Cubellis et al., 2002; Sartori, 2003; Todesco et al., 2003, 2004; Rolandi et al., 2003; Goes et al., 2004; Turco et al., 2006; Battaglia et al., 2006; Bodnar et al., 2007; Troise et al., 2007; Caliro et al., 2007; Lima et al., 2009; De Vivo et al., 2010).

Several hypotheses have been proposed for the origin of past volcanism in the Campi Flegrei (CF) caldera, mostly focused on its activity after the Neapolitan Yellow Tuff eruption (NYT, 15 ka, Deino et al., 2004). In general, these hypotheses involve one or more of the following: (1) magma-related intrusion or intermittent ascent, (2) heating or cooling of hydrothermal fluids, (3) various geothermal system processes, and (4) chaos theory.

The phenomenon of bradyseism (from the ancient Greek words "bradus" meaning slow," and "seism" meaning movement") has affected the CF region since at least Roman times, as testified by layers of boreholes left by marine mollusks on the marble columns of the Roman Temple of Serapis in Pozzuoli (Parascandola, 1947). In this contribution, we will compile geochemical and geophysical data from the literature and provide a review of several models proposed for bradyseism at CF over the past 40 years. Developing a correct interpretation to explain bradyseismic event at CF is not just for academic interest; it is required to develop robust hazard assessment because the evacuation of large numbers of citizens have caused financial, emotional, and physical stress on the affected population. Hence, the relationship between bradyseism and eruption probability is critically important.

Over the last 2000 years, there have been many phases of ground movements at CF, but eruptions associated with uplift have been rare. The only case documented was the eruption of Monte Nuovo in CE 1538 and perhaps a small phreatic event in CE 1198, where bradyseism was directly associated with an eruptive event. This phenomenon of ground deformation *without* eruption is quite common in other areas characterized by significant bradyseism, such as Yellowstone (Pierce et al., 2002; Lowenstern and Hurwitz, 2007) and the Long Valley caldera (Hill et al., 2002; Foulger et al., 2003). Active bradyseism not always implies recent emplacement of magma or an imminent eruption (Acocella et al., 2015), although generally the emplacement of magma at shallow depth can lead to ground displacements at the surface as documented extensively at Hawaii (e.g., Polland, 2014). Although magma emplacement has been often *inferred* for CF based on bradyseism, it has not been unequivocally demonstrated to date.

Based on geochemical/geophysical data and models proposed by several authors in the last four decades, we propose that the hydrothermal model without magmatic recharge, suggested by

Bodnar et al. (2007) and Lima et al. (2009), is most compatible with the breadth of observational data and therefore paints the most consistent picture of the bradyseism phenomenon at CF.

Geologic setting at Campi Flegrei

The Campanian margin is a tectonically active area, characterized by extensional structures that affected the Apennine fold and thrust belt and formed half-grabens during the Pleistocene (Fig. 15.1). Normal fault activity controls stratigraphic architecture,

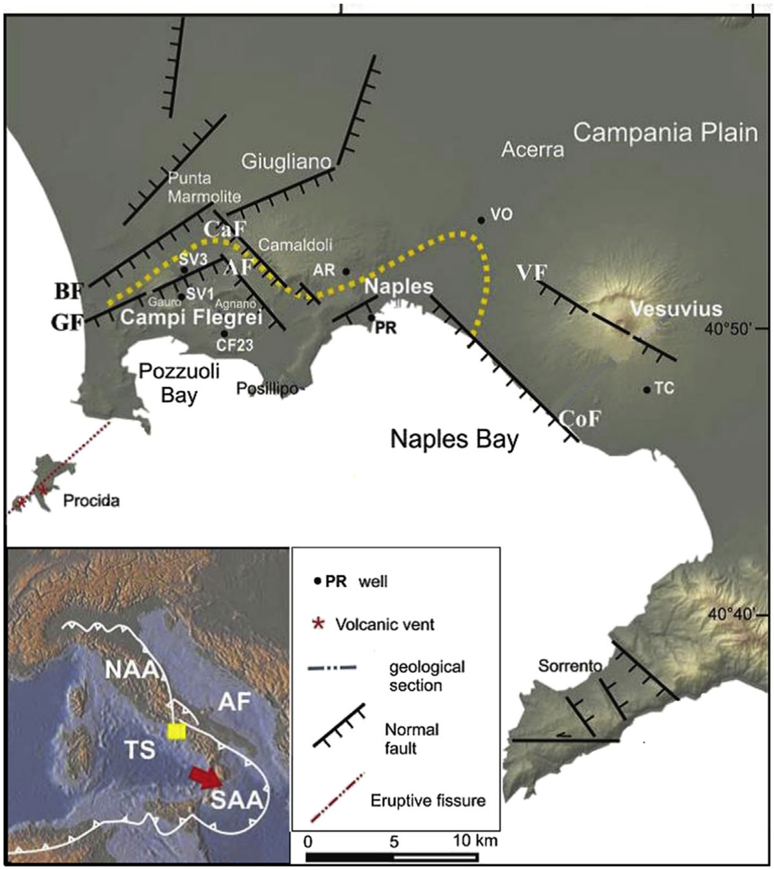

Figure 15.1 Structural map of the Campanian volcanic zone, showing location of volcanic vents (red stars), crustal sections (black lines), and deep boreholes (black dots). The yellow dotted line corresponds to the palaeoshelf edge before ignimbrite emplacement. *AF*, Adriatic Foreland; *AF*, Agnano fault; *AR*, Arenella well; *BF*, breakaway fault; *CaF*, Camaldoli fault; *CF23*, CF23 well; *CoF*, coastal fault; *GF*, Gauro fault; *NAA*, Northern Apennine Arc; *PR*, Palazzo Reale well; *SAA*, Southern Apennine Arc; *SV1*, San Vito1 well; *SV3*, San Vito3 well; *TC*, Trecase well; *TS*, Tyrrhenian Sea; *VF*, Vesuvius cone fault; *VO*, Volla well. The inset shows a schematic structural map of Italy and Campanian volcanic zone. The red arrow shows the migration of the SAA over the last 700 ka Modified from Milia A., Torrente M.M., 2011. The possible role of extensional faults in localizing magmatic activity: a crustal model for the Campanian Volcanic Zone (Eastern Tyrrhenian Sea, Italy). J. Geol. Soc. 68, 471–484.

depositional environments, and rate of subsidence in the Campanian margin (Milia and Torrente, 1999, 2003). During the late-Quaternary, active uplift and E-W left-lateral strike-slip faulting have been documented along the margin contemporaneous with normal faults activity (Milia and Torrente, 2003), whereas NW-SE extensional tectonics were responsible for the formation of several deep basins, one of which is represented by the actual CF sensu stricto (Milia and Torrente, 1999).

The boundary of the CF area both onshore and offshore is affected by high-angle normal faults, which characterize the structural framework of the CFVD. The southern part of CF, corresponding to the Bay of Pozzuoli, records active folding (Milia et al., 2000; Milia and Torrente, 2000), represented by the culmination of an anticline near the city of Pozzuoli and a syncline located in the Bay of Pozzuoli. The maximum uplift associated with bradyseism at CF is recorded at the anticline culmination, where a compressional tectonic regime is active, but the area of uplift decreases very rapidly toward the CF boundary where the main high-angle faults occur. Similarly, earthquakes associated with bradyseism are recorded close to the city of Pozzuoli (anticline culmination) and in the middle of the Bay near the locus of tectonic folding. According to Milia et al. (2003), the basement of the Campanian margin is composed of Mesozoic–Cenozoic carbonate successions forming the Apennine fold and thrust belt, overlain by terrigenous conglomerates and a marine succession of siltstones and calcarenites of the Lower Pleistocene (Fig. 15.2). Milia and Torrente (2003) associated the maximum depth of the earthquakes with the stratigraphic boundary between the carbonates of the Mesozoic–Cenozoic succession and the overlying stratified clastic succession of Pleistocene age.

According to Milia and Torrente (2011), structural, stratigraphic, and paleogeographical analyses reveal evidence for up to 750 m of subsidence, which has occurred at a mean rate of up to 4.9 mm/year over the past 154 ka, suggesting that extensional tectonics is responsible for the regional subsidence. By matching the structural and stratigraphic architecture with published geophysical and geochemical data, Milia and Torrente (2011) proposed a crustal tectonomagmatic model that shows high-angle faults rooted into a low-angle detachment, which in turn is rooted into a deep sill-like magma reservoir. Their model suggests that extensional faults play a role in localizing magmatic activity, especially during ignimbrite eruptions, as magma exploits preexisting fractures in its ascent to the surface.

The CF stratigraphic sequence is based on data from the 3000 m deep San Vito and Mofete geothermal wells (De Vivo et al., 1989, and unpublished data), where the uppermost

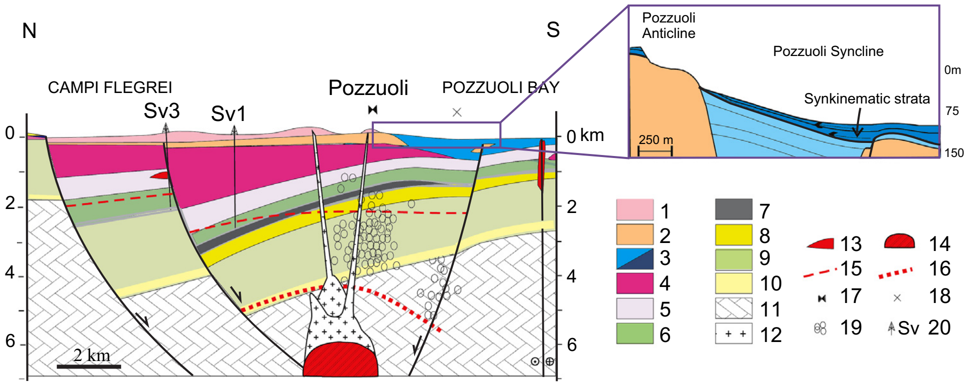

Figure 15.2 Geologic cross section across Campi Flegrei—Pozzuoli Bay. *1*, Holocene volcanics; *2*, Neapolitan Yellow Tuff; *3*, main sediments post 39 ka; *4*, Campanian Ignimbrite and pre-CI tuffs; *5*, Middle Pleistocene sandstones, siltstones, and volcanics; *6*, Middle Pleistocene marine sediments; *7*, fine-grained Middle Pleistocene marine sediments; *8*, Middle Pleistocene deep-water debris flows; *9*, Lower Pleistocene marine sediments; *10*, continental deposits and conglomerates; *11*, Meso-Cenozoic substrate; *12*, crystallized magma; *13*, volcanic bodies; *14*, magma body; *15*, thermometamorphic boundary; *16*, impermeable zone surrounding the crystallizing magma body; *17*, Pozzuoli Anticline; *18*, Pozzuoli Bay Syncline; *19*, 1983—84 earthquake hypocenters; *20*, deep geothermal wells; *21*, magmatic fluids. Inset A: north-south cross section showing Pozzuoli Anticline-Syncline
Modified from Bodnar, R.J., Cannatelli, C., De Vivo, B., Lima, A., Belkin, H.E., Milia, A., 2007. Quantitative model for magma degassing and ground deformation (bradyseism) at Campi Flegrei, Italy: implications for future eruptions. Geology 35, 791—794.

2000 m is composed of recent volcanoclastic products with minor trachytic volcanics and a low permeability cap rock that lies at a depth of about 2—3 km. A metamorphic aureole is observed below ~2 km in the San Vito boreholes, which is interpreted to represent the downward migration of magma layer from 4 to 5 km in the past to the current level of ≥6 km.

Bodnar et al. (2007) and Lima et al. (2009) proposed that the structure and magnitude of the permeability field is critical for the onset of bradyseism at the CF because low-permeability layers impede the upward movement of fluids released by magma degassing and provide a quasibarrier to the deep flow of meteoric fluids. In particular, Lima et al. (2009) describe a permeability oscillation between high and low values extending stratigraphically downward from the surface to the crystallized rind (contact aureole) of the magma body, with values ranging from high (coarse clastics and volcanoclastics) to low (transgressive siltstones and claystones) to high (debris flows) to low (marine calcarenites and siltstones) to high (fluvial conglomerates) and finally to low (carbonates, thermometamorphic, and plutonic rocks). From modeling studies, it is well known that vertical variations in permeability, strongly anisotropic permeability fields, or thermohaline hydrothermal convection can severely constrain vertical fluid trajectories in porous media (Rosenberg and Spera, 1990, 1992a,b; Schoofs et al., 2003).

Volcanism at Campi Flegrei volcanic district

Multiple eruptions have occurred in the CFVD in the last 300 ka (Pappalardo et al., 2002). The eruption of the Campanian Ignimbrite (CI) at 39 ka (De Vivo et al., 2001) is generally considered to be the dominant event in the CF (150 km^3 dense rock equivalent (DRE), Civetta et al., 1997; 200 km^3 DRE, Rolandi et al., 2003), followed by the NYT (50 km^3 DRE, Scarpati et al., 1993) that formed at 15 ka (Deino et al., 2004). Some authors relate the formation of the CF caldera to two major eruptions: the CI (VEI = 7) dated at 39 ka by De Vivo et al. (2001) and the NYT (VEI = 6, Pappalardo and Mastrolorenzo, 2012). Some authors (Rosi and Sbrana, 1987; Orsi et al., 1996; Signorelli et al., 1999) relate the CI eruption to a caldera rim fracture system located in the CFVD, while other authors (De Vivo et al., 2001; Rolandi et al., 2003) suggest that the CI originated from fractures activated along the neotectonic Apennine fault system parallel to the Tyrrhenian coastline. The latter authors argue that eruptions from >300 ka to 19 ka are not confined to a unique volcanic center or isolated vent system in CFVD as suggested by Rosi and Sbrana (1987) and Orsi et al. (1996). De Vivo et al. (2001) and Rolandi et al. (2003) argue that only the NYT erupted from vents within the CF, whereas the CI had a much wider source and dispersal area. According to Pappalardo et al. (2002), the interval between the CI and NYT eruptions is characterized by a number of small magnitude volcanic events. Since the NYT eruption, the margins of the region have been the site of at least 65 eruptions (Fig. 15.3) ($0 < \text{VEI} < 5$, Pappalardo and Mastrolorenzo, 2012), divided into three periods of activity (15–9.5, 8.6–8.2, and 4.8–3.8 ka, Di Vito et al., 1999). The only eruptive event in historical time in the CF topographic depression is the Monte Nuovo eruption (CE 1538), which represents a rather minor event in the eruptive history of this area (VEI = 2), having produced a relatively small volume of magma (about 2.5×10^7 m^3 or 0.025 km^3) and a 150 m volcanic cone near the city of Pozzuoli. The Monte Nuovo eruptive volume is approximately 10,000 times smaller than sum of the CI and NYT ignimbrites.

Bradyseism at Campi Flegrei

The occurrence of slow, vertical ground movements (bradyseism) at CF has been known since before Roman times (Parascandola, 1947). The deformation cycles of inflation (uplift) and deflation

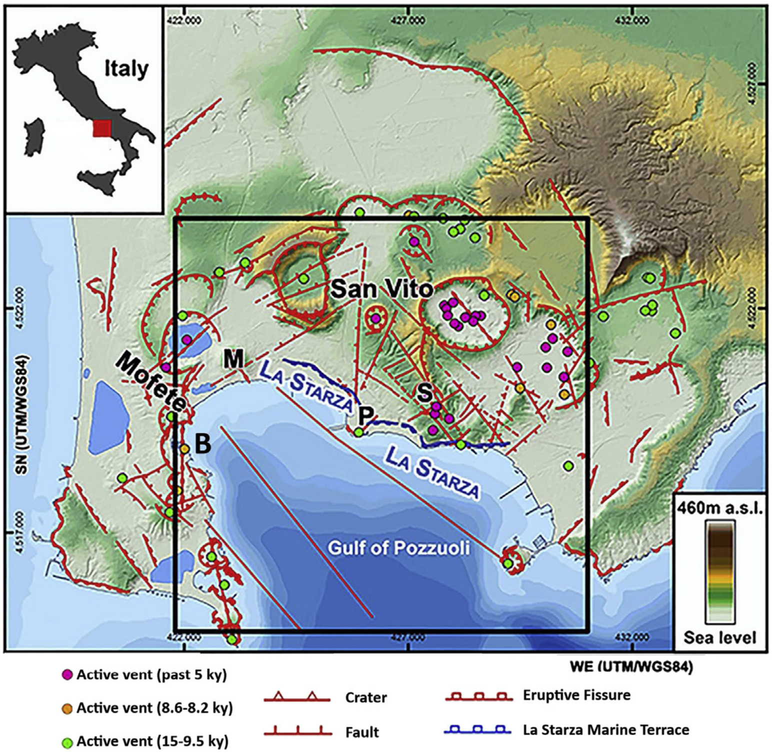

Figure 15.3 Campi Flegrei volcanic district structural map. Volcanic centers of Pozzuoli (P), Baia (B), Solfatara (S), and Monte Nuovo (M) are labeled with bold letters; volcanic vents and major faults are marked with colored circles (green, orange, and pink, according to age) and red lines, respectively, Modified from De Siena, L., Chiodini, G., Vilardo, G., Del Pezzo, E., Castellano, M., Colombelli, S., Tisato, N., Ventura, G., 2017. Source and dynamics of a volcanic caldera unrest: Campi Flegrei, 1983—84. Sci. Rep.-UK 7: 8099. https://doi.org/10.1038/s41598-017-08192-7.

(subsidence) have been well documented through time, mainly due to the geographical location and long history of habitation and construction in the area. At the beginning of the 16th century, the area between Baia and Pozzuoli (B and P, Fig. 15.2) experienced progressive ground inflation and migration of the coastline. Several seismic swarms that occurred 2 years before the eruption of Monte Nuovo accompanied the bradyseismic phenomenon. According to Guidoboni and Ciuccarelli (2011), significant ground uplift and earthquakes occurred at least 70 years before the eruption of Monte Nuovo. Starting in the 19th century, the first interpretations of bradyseismic events in the area were put forward (Breislak, 1792; Forbes, 1829; Niccolini, 1839, 1845; Babbage, 1847; Lyell, 1872; Gunther, 1903; Parascandola, 1947) by studying boreholes left by marine organisms *Lithodomus lithophagus* on

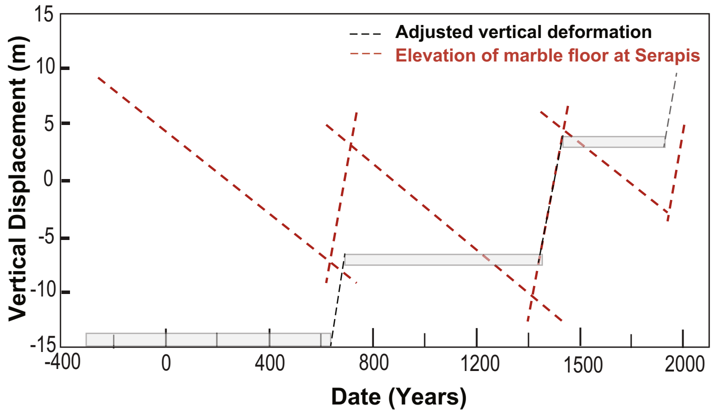

Figure 15.4 Vertical movements at Serapis (orange dotted line), showing two major uplifts, and step-like pattern of uplift (black dotted line). Black arrow indicates the Monte Nuovo eruption of 1538 AD Modified from Bellucci, F., Woo, J., Kilburn, C.R.J., Rolandi, G., 2006. Ground deformation at Campi Flegrei, Italy: implications for hazard assessment. In: Troise, C., De Natale, G., Kilburn, C.R.J. (eds), Mechanisms of Activity and Unrest at Large Calderas. Geological Society, London, Special Publications vol. 269, 141–157.

the marble columns of the Roman Temple of Serapis, an ancient market of Roman Age located near the harbor of Pozzuoli. Dvorak and Mastrolorenzo (1991) updated the work of Parascandola (1947) on the boreholes and reconstructed the history of CF vertical movements. The boreholes left by the mollusks can be traced for the past 2000 years on the ~7 m-high columns of the temple (Morhange et al., 2006) and show a trend of subsidence at a rate of ~1.5–2.0 cm/yr starting from the eruption of Monte Nuovo and centered at Pozzuoli harbor (Fig. 15.4). This subsidence is very consistent with the ultragranular data developed using modern geodetic tools at, for example, Kilauea volcano, Hawaii, USA, for the 1983–present eruptive episode.

Geodetic methods have been used to establish subannual to decadal displacements that include +0.73 m (uplift) during the period 1950–52 (Del Gaudio et al., 2010), +1.77 m (uplift) during the period 1969–72, −0.2 m (subsidence) during 1972–75 (Lima et al., 2009 and references therein), and +1.79 m in the period 1982–84 (Del Gaudio et al., 2010). This latter episode was accompanied by more than 16,000 earthquakes with magnitudes up to 4 (D'Auria et al., 2011), followed by −0.2 m (subsidence) from 1985 to 1988, and +0.13 m (uplift) in the period 1988–89 (Lima et al., 2009 and references therein). This led to the temporary evacuation of about 40,000 people from the town of Pozzuoli that lasted for several months (Barberi et al., 1984). The evacuated population was moved to two newly formed towns (Rione Toiano and Monteruscello) built a few km away from the town of Pozzuoli but still located inside the area of CF caldera that was considered to be at risk for an eruption! After 1988, the general subsidence phase has been interrupted by minor, short duration uplift phases in 1989, 1994, and 2000. After two decades of prevailing subsidence at CF, uplift resumed in November 2004 but with a highly unstable behavior, alternating between increased uplift rate and subsidence or showing constant deformation trends (D'Auria et al., 2011; De Martino et al., 2014). Very recently, between April 2012 and January 2013, an accelerating ground uplift rate was recorded at CF, with a peak rate of about 3 cm/month (De Martino et al., 2014; Trasatti et al., 2015). Also from the period 2012–13, D'Auria et al. (2015) identified renewed magmatic activity at the CF caldera. The authors propose that the driving mechanism for the accelerated ground uplift in this period is the emplacement, at shallow depth (3090 ± 138 m), of a magmatic sill (0.0042 ± 0.0002 km^3 in volume) beneath CF. The observed uplift can be explained by intermittent injections of small magma batches feeding a shallow magmatic reservoir associated with transient perturbations of the hydrothermal system. The authors also propose that the presence of melt before 2012 was probably due to the existence of a persistent structure, which has been repeatedly refilled in the last decades as suggested by the abundant layers of subvolcanic rocks that are found in various boreholes (Piochi et al., 2014) and by petrological evidence (Pappalardo and Mastrolorenzo, 2012). A recent discussion by Kilburn et al. (2017) argues that the bradyseismic events from 1950 should be considered as part of a progressive evolution. Each time a bradyseismic event occurs without an eruption, the underlying rock strata changes incrementally from a quasielastic to an inelastic regime. This may suggest that the CF volcanic-tectonic system is evolving toward conditions more favorable to eruption.

Models for ground movements at Campi Flegrei

Various models have explained ground movements at CF. In the 1980s, a mechanical model of CF attributed unrest episodes to (1) an intrusion of new magma at shallow depth (Corrado et al., 1976; Berrino et al., 1984; Bonafede et al., 1986; Bianchi et al., 1987); (2) intermittent ascent of magma between a reservoir at depths of

8–15 km or greater and a much smaller, shallower system at depths of about 3–4 km (Bellucci et al., 2006); (3) heating and expansion of fluids (Oliveri del Castillo and Quagliariello, 1969; Casertano et al., 1976; Todesco et al., 2003, 2004; Battaglia et al., 2006; Troise et al., 2007; Caliro et al., 2007); (4) fluid dynamic processes in the shallow geothermal system (Bonafede, 1990, 1991; De Natale et al., 1991, 2001; Trasatti et al., 2005); and (5) chaos theory (Cortini et al., 1991; Cortini and Barton, 1993; Cubellis et al., 2002).

Several authors, using mainly SAR data, have proposed different models to describe the source of deformation at CF, including models of tensile faults (Dvorak and Berrino, 1991), point spheres (Avallone et al., 1999), prolate spheroids (Manconi et al., 2010), horizontal circular cracks (Gottsmann et al., 2006; Battaglia et al., 2006; Amoruso et al., 2008; Woo and Kilburn, 2010), isotropic elementary sources (Camaco et al., 2011; D'Auria et al., 2012), or generic moment tensors (Trasatti et al., 2011). Some source models imply a constant deformation pattern during positive and negative bradyseismic phases, while others show a different pattern. Amoruso et al. (2014) compiled ground displacement data from 1980 to 2010 to determine if differences exist between inflations and deflations and if anomalies are concentrated in particular areas of the CF caldera. Their results show that the CF deformation pattern may have formed by two stationary parts (slightly evolving over time, based on source strength), with both of them represented by simple deformation sources. Based on ground deformation, fumarolic geochemical data (Chiodini et al., 2010 and references therein) and seismicity (De Siena et al., 2010), Amoroso et al. (2014) determined that large-scale deformations are due to a quasihorizontal elongated crack, oriented NW to SE and embedded at a depth of 3.6 km in an inelastic layered half-space with the shape of a triaxial ellipsoid. Residual deformations are confined to the area of the Solfatara fumarolic field and are represented by a small spheroid located beneath Solfatara at about 1900 m in depth.

Other authors (Corrado et al., 1976; De Natale et al., 1995) have pointed out that seismicity at CF occurs only during unrest episodes. Between 1982 and 1984, more than 16,000 earthquakes occurred, ranging from 0.4 to 4.0 in magnitude (Aster et al., 1992). Based on seismological studies, De Natale et al. (1995) proposed that this activity was generated from faults associated with an inner caldera collapse structure. A selection of seismic events recorded at CF in 1983–84 was analyzed by Guidarelli et al. (2002) to obtain Rayleigh wave group velocities and tomographic maps and was merged with cellular dispersion data for the entire

Neapolitan volcanic region by Panza et al. (2004, 2007). A structural model for CF up to a depth of about 30 km has been developed (Guidarelli et al., 2006 and references therein), revealing a low shear wave velocity layer at about 10 km depth, consistent with one found below Mt. Vesuvius at 8 km that has been interpreted to be an area of diffuse partial melts.

Ground deformation and seismicity are associated with intense fumarolic and hydrothermal activity, which are concentrated in the crater of Solfatara where CO_2 fluxes are particularly intense during uplift and reflect magmatic degassing (Chiodini et al., 2012). These same fumarolic fluids, based on their stable isotopic composition, are interpreted to be magmatic fluids that have been variably contaminated by connate and meteoric components (Allard et al., 1991; Todesco and Scarsi, 1999; Panichi and Volpi, 1999). More recently, models based on the interaction of magmatic fluids with hydrothermal systems dominated by nonmagmatic fluids have been proposed by Gaeta et al. (2003), Todesco et al. (2003, 2004), Todesco and Berrino (2005), Battaglia et al. (2006), Troise et al. (2007), and Caliro et al. (2007). Todesco et al. (2003, 2004) and Todesco and Berrino (2005) believe ground surface deformations are triggered by pressure variations in the hydrothermal system. In particular, Todesco et al. (2003) indicate that an increase in the permeability at shallow depth may have an important influence on the system condition and fluid discharge. Battaglia et al. (2006) indicate that the migration of fluids to and from the caldera hydrothermal system is the cause of ground deformation and consequent unrest. These same authors infer that the "intrusion of magma takes place at the beginning of each period of unrest" and suggest that uplift may be used to forecast eruptions at CF.

Hydrothermal activity at Campi Flegrei

Calderas are often sites of pervasive hydrothermal circulation due to their structure and morphology, and fluids can play an active role in triggering episodic unrest events (Chiodini et al., 2003, 2017). In recent years (1985–2011), the dynamics of CF have been mostly linked to its hydrothermal system (Chiodini et al., 2015 and references therein), and several authors have shown a remarkable correlation between ground deformation and fluid geochemical parameters in the 2005–11 interval. Chiodini et al. (2015) interpreted this correlation as the "signature" of transient disturbances propagating through the hydrothermal system; however, this correlation broke down in 2012, suggesting that the driving mechanism of the ground uplift changed.

The abovementioned authors found strong evidence that the recent dynamics of CF can be explained by the potential emplacement of a magma batch within a flat, sill-shaped, magmatic reservoir. By combining CF seismicity with ground deformation data and compositions of the main fumaroles located inside Solfatara, the most active zone of the caldera, Chiodini et al. (2017) conclude that the ongoing crisis at CF is controlled by a unique process represented by a thermo-fluid dynamic model, where high temperature magmatic fluids are repeatedly injected into the hydrothermal system feeding the fumaroles of Solfatara, similar to the episodic release of magmatic fluids into the hydrothermal system proposed by Bodnar et al. (2007).

Determining gas budgets during periods of unrest is fundamental to understanding the activity, evolution, and possible future eruptions of a caldera (Lowenstern et al., 2006). Aiuppa et al. (2013) measured low S (1.5–2.2 tons/day) and high CO_2 fluxes ($\approx$1560 tons/day) in the CF caldera from fumarolic and soil degassing. This elevated output of CO_2 is not in agreement with the hypothesis that current degassing unrest at CF is triggered by gas released from a relatively older, evolved (CO_2-poor), and crystallizing/crystallized magma volume (Bodnar et al., 2007; Lima et al., 2009). Aiuppa et al. (2013) propose that the degassing unrest period from 2005 to the present has been sourced by a more fertile (CO_2-rich) magma source of variable size and located between 4 and 7 km depth. The role of fluids as drivers during periods of unrest at CF is strongly supported by the temporal coincidence between changes in gas composition and uplift (Chiodini et al., 2003, 2010, 2017; Caliro et al., 2014; Gresse et al., 2016), physical simulations of episodic gas injection into the hydrothermal system (Chiodini et al., 2003, 2012; Cardellini et al., 2017; Todesco et al., 2003, 2014; Romano et al., 2018), quantitative analyses of shallow seismicity (Bianco et al., 2004, 2010; D'Auria et al., 2011), and seismic tomography data (Vanorio et al., 2005; Zollo et al., 2008; De Siena et al., 2010, 2017; De Landro et al., 2017). Although the origin of emitted fluids is unequivocally magmatic (Allard et al., 1991; Caliro et al., 2007, 2014), the volume, storage depth, and gas content of the magmatic source remains somewhat disputed (Bodnar et al., 2007; Zollo et al., 2008; Arienzo et al., 2010; Di Vito et al., 2016).

During each seismic and ground uplift crisis, the magmatic component fraction (X_{CO2}/X_{H2O}) in fumaroles increases (up to $\sim$0.5, Caliro et al., 2007; Moretti et al., 2013, 2018), suggesting that periodic injections of CO_2-rich magmatic fluids near the base of the hydrothermal system trigger bradyseismic crises. Troise et al. (2007) associate the uplift with the input of magmatic fluids from a shallow magma chamber based on the ratio of maximum horizontal to vertical displacement measured from continuous GPS data, while Moretti et al. (2018) propose that the uplift is generated by the shallow intrusion of a sill-like magmatic body and subsequent injection of hot steam-rich fluids into the hydrothermal reservoir, based on the geochemistry of gas discharge. According to these authors, small uplift events can reflect the overpressure of deeper source magmatic fluids, whereas large uplift events may represent the overpressure of shallower aquifers. As demonstrated by the models of Battaglia et al. (2006) and Troise et al. (2007), magma plays an active role in uplift and possibly eruption. Finally, in the model of Bodnar et al. (2007), fluid expelled during crystallization of preexisting magma supplies the fluids involved in bradyseism, but the intrusion of new magma does not play an active role in uplift episodes. Bodnar et al. (2007) predict that uplift between 1982 and 1984 is associated with crystallization of $\sim$0.83 km^3 of H_2O-saturated magma at $\sim$6 km depth. The latter depth is in good agreement with recent findings (Arienzo et al., 2010; Vetere et al., 2011; Esposito et al., 2018). Near the approximate depth of the magma–country rock interface indicated by Bodnar et al. (2007), seismic tomography data show that a magma sill is located at $\sim$7.5 km depth (Zollo et al., 2008). The seismic tomography results support the concept that shallow-level magma intrusion at CF is not the cause of bradyseism and uplift. According to the model of Bodnar et al. (2007), the solid–melt boundary of the mush zone of the crystallizing magma body migrates downward and fresh magma injection is not a prerequisite for bradyseism (Fig. 15.5A-C). The subsurface magmatic-hydrothermal activity at CF for the period from pre-1982 to 1984 AD is shown schematically in Fig. 15.5(A–B).

Evidence for connectivity between the deep and shallow systems is provided by CO_2/H_2O ratios of fumarolic fluids at CF (Fig. 15.6), which increase during uplift and reach a maximum shortly after deflation begins (i.e., after the low-permeability cap rock is breached).

Thermodynamic model for ground movements at Campi Flegrei

Lima et al. (2009) extend the contribution of Bodnar et al. (2007) by presenting a thermodynamic description of the earlier semi-quantitative models and proposing a new model consistent with geological, geochemical, and geophysical data. Without including

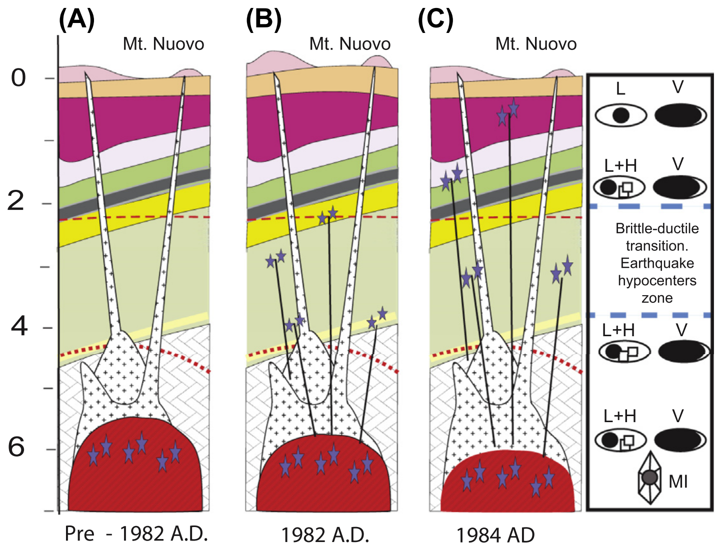

Figure 15.5 Schematic interpretation of subsurface magmatic-hydrothermal activity at Campi Flegrei. (A) After the Monte Nuovo eruption (1538 AD), the magma body became a closed system with magmatic volatiles accumulating below the impermeable crystallized carapace. (B) In 1982, the carapace fractured, allowing magmatic fluids to enter the overlying rocks beneath the low permeability cap rock, causing vertical ground deformation. (C) In 1984, the ground deformation ended and deflation began when fractures penetrated the low-permeability cap rock, allowing the deep fluids to migrate into the shallow hydrostatic aquifers and flow toward the surface. The lateral inset shows the systematic variation in the types of fluid and melt inclusions that occur at different depth (L, liquid-rich inclusion; V, vapor-rich inclusion; L + H, halite-bearing fluid inclusion; MI, melt inclusion) Modified from Lima, A., De Vivo, B., Spera, F.J., Bodnar, R.J., Milia, A., Nunziata, C., Belkin, H.E., Cannatelli, C., 2009. Thermodynamic model for uplift and deflation episodes (bradyseism) associated with magmatic-hydrothermal activity at Campi Flegrei (Italy). Earth Sci. Rev. 97, 44–58

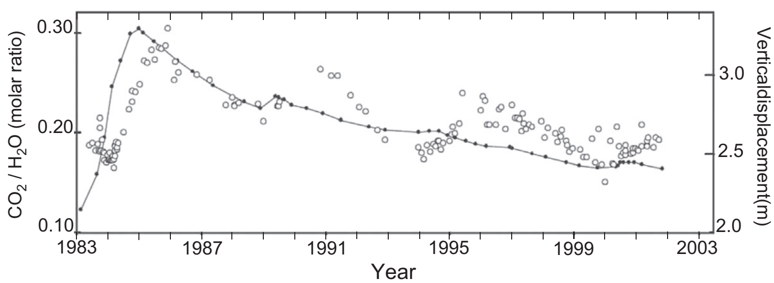

Figure 15.6 CO_2/H_2O ratios recorded during the past 20 years La Solfatara fumarole, compared with vertical displacement measured at Pozzuoli Modified from Lima, A., De Vivo, B., Spera, F.J., Bodnar, R.J., Milia, A., Nunziata, C., Belkin, H.E., Cannatelli, C., 2009. Thermodynamic model for uplift and deflation episodes (bradyseism) associated with magmatic-hydrothermal activity at Campi Flegrei (Italy). Earth Sci. Rev. 97, 44–58

the input of new magma, Lima et al. (2009) attributes the phenomenon of ground movements at CF to magmatic–hydrothermal processes driven by the crystallization of hydrous magma at depth, which leads to the exsolution and expulsion of lithostatically pressured fluids into the overlying country rock. The petrologic basis for the generation of magmatic fluids by a "second boiling" was documented in CF magmas in other areas (Fowler et al., 2007; Cannatelli, 2012). The deep fluid environment at CF is similar to that described in magmatic–hydrothermal ore deposit systems associated with porphyry copper deposits (Bodnar and Beane, 1980; Beane and Titley, 1981; Audétat and Pettke, 1993; Bodnar, 1995; Beane and Bodnar, 1995; Roedder and Bodnar, 1997; Sasada, 2000).

In the Lima et al. (2009) model, the evolution of melt (MI) and fluid inclusions (FI) in porphyry copper deposits is compared with the crystallization of intermediate to silicic volatile-bearing magmas. The authors do not believe a porphyry deposit is currently forming at CF, but instead propose that during crystallization of hydrous magmas in the upper crust, a volatile phase generally consisting of a low salinity H_2O-rich fluid is exsolved from the melt. This fluid is composed of variable amounts of volatiles (CO_2, H_2S, or SO_2) and ore metals (Cu, Au, Mo, Pb, Zn, and Ag) (Bodnar, 1995; Roedder and Bodnar, 1997) as well as major LIL fluid–soluble elements (Rb, Cs, Ba, Pb, and Sr) (Spera et al., 2007). During the initial phase of crystallization, the melt becomes saturated in volatiles due to the precipitation of anhydrous phases. As a consequence, the fluid gets trapped beneath the impermeable igneous rock/pyrometamorphic contact aureole (rind) surrounding the magma, and the local fluid pressure in the magma body increases. The CF hydrothermal system shows some similarities with porphyry copper systems, with the crystallization front migrating slowly and gradually toward the deeper part of the system and the magma becoming saturated in water and forming a carapace composed of crystals + silicate melt + magmatic fluids in the overlying intrusive magma body and immediately below the crystalline impermeable layer.

At CF, volatiles exsolved from the magma at variable depths between 4 and 10 km are composed of high-salinity brine and vapor (Fig. 15.7A) in the deeper portions of the system and a lower salinity, low-viscosity vapor phase in the shallower levels of the system. Fracturing of the overlying impermeable rocks allows the low salinity fluid to move toward the surface and interact/mix with meteoric water present in fractures and pores at

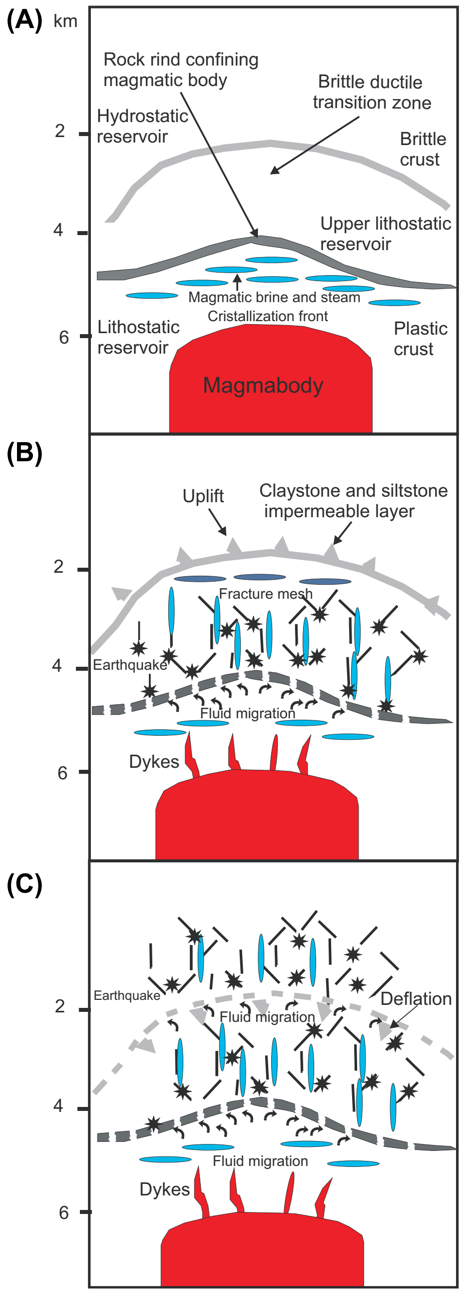

Figure 15.7 Schematic representation of magma, fluids, and crustal deformation at Campi Flegrei. (A) Sealed magmatic–hydrothermal system showing the plastic and brittle domains separated by an intermediate lithostatic–hydrostatic reservoir. (B) The impermeable carapace confining the magmatic system allows magmatic fluids to enter the overlying rocks beneath the low-permeability cap rock, causing ground uplift. (C) Ground uplift ends and deflation begins when fractures penetrate the surficial low-permeability cap rock, allowing the fluids to migrate into the shallow aquifers and flow toward the surface Modified from Lima, A., De Vivo, B., Spera, F.J., Bodnar, R.J., Milia, A., Nunziata, C., Belkin, H.E., Cannatelli, C., 2009. Thermodynamic model for uplift and deflation episodes (bradyseism) associated with magmatic-hydrothermal activity at Campi Flegrei (Italy). Earth Sci. Rev. 97, 44–58.

shallower depths (Fig. 15.7C). This interaction produces a low salinity boiling assemblage so that trapped FIs are low salinity liquid rich or vapor rich at room temperature (Bodnar, 1995; Bodnar and Student, 2006), and MIs and FIs are trapped in phenocrysts and veins as the system evolves (De Vivo et al., 1989, 1995, 2006). Crystals + silicate melt + magmatic fluid coexists in the deepest part of the system, as recorded in coexisting MI and FI from crustal xenoliths at CF (Fedele et al., 2006). According to the thermodynamic transport model of Lima et al. (2009), bradyseism is driven by the transient connection between the deeper lithostatic reservoir and the overlying permeable hydrostatic reservoir. The long timescale (10^3–10^4 yr) of the model by Lima et al. (2009) is associated with the crystallization of a volatile-bearing magma at ~6 km depth and the release of magmatic fluids (as also shown by Cannatelli et al., 2007 and Cannatelli, 2012) into a deep aquifer with high lithostatic pressure, separated from a shallower hydrostatic aquifer by a low-permeability barrier zone (~2.5–3.0 km depth). Lima et al. (2009) show that the shorter timescale (1–10 yr) of their model is intrinsically episodic in nature and associated with transient fracture propagation events that connect the lower lithostatic reservoir with the upper hydrostatic one (Fig. 15.7) until connectivity is dampened by mineral precipitation accompanying irreversible fluid decompression with concomitant mineral precipitation that alters the local permeability.

At CF, vertical ground deformations are produced by the breaching of the rock "rind" confining the magmatic system (at about 4 km depth, similar to earthquake hypocenters), which in turn allows magmatic fluids to escape and enter the overlying rocks beneath the low permeability cap rock (~2.5–3.0 km) (Fig. 15.7A). The fracture of the crystallized rind produces a pressure quench of additional magma that leads to the release of CO_2 (Lima et al., 2009). Evidence of this last phenomenon is the ratios of CO_2/H_2O in fumarolic fluids at CF (Fig. 15.4), which increase during uplift and reach a maximum shortly after deflation begins (i.e., after the low-permeability cap rock is breached). Uplift ends and deflation begins when fractures penetrate the low permeability cap rock (Fig. 15.7B), allowing the deep magmatic fluids to migrate into the shallow aquifers and ascend toward the surface (Lima et al., 2009).

The above-described process may culminate in a steam blast if water at shallow depths is heated to its flash point. A magmatic eruption may follow if the reduced confining pressure on the magma leads to a runaway process of bubble formation in the melt, ascent, and growth (as was the case for the Monte Nuovo eruption at CF). A hydraulic surge can be triggered by tectonic activity that characterizes the CF area, disrupting the transition seal and allowing magmatic geopressured fluids to invade the country rock. According to Lima et al. (2009), ground movements at CF are driven by the ongoing cooling of magma at depth. According to this model, the probability that an eruption will occur at CF is decreasing, and today it is the lowest as it has been in the last 500 years. The scenario may change and the possibility of an eruptive event will increase should new magma enter the deep feeding system of CF (6 km depth).

Conclusions

Several models have been proposed to explain the phenomenon of bradyseism at CF, but the topic is still the subject of intense debate. Some authors propose a "magmatic model" to explain bradyseism at CF, suggesting that there is a continuous (or intermittent) intrusion of new magma at shallow depth for every uplift event recorded in the area, with subsequent eruption alerts being unjustified. Other authors, such as Bodnar et al. (2007) and Lima et al. (2009), propose a "hydrothermal model" based on petrological, geochemical, and geophysical observations and suggest that magmatic-hydrothermal processes at CF are driven by the crystallization of a volatile-bearing magma at depth (~6 km), which release magmatic fluids into a deep aquifer separated from a shallower one by a low permeability zone (~3 km depth). According to this model, uplift and seismicity at CF are produced by the fracture of the rock rind confining the magmatic system, which in turn leads to the release of CO_2. Evidence of this phenomenon is the increase of CO_2/H_2O ratios in fumaroles during uplift at CF. Vertical ground movements end, deflation begins when fractures penetrate the low permeability zone, and the deep magmatic fluids migrate and flow toward the surface. Models that explain bradyseismic events at CF without including magma are preferable as there is no evidence (geochemical or geophysical) of new magma entering the feeding system. Detailed studies in several volcanic areas of the world, which experience bradyseismic phenomena similar to those at CF (such as Rabaul in New Guinea, Long Valley in California, and Yellowstone National Park in Wyoming), have demonstrated that active bradyseism does not necessarily reflect recent emplacement of magma or that an eruption is imminent, with the latter being a very exceptional event.

Acknowledgments

The authors would like to thank reviewers M. Steele-McInnis and H.E. Belkin for their thoughtful and thorough comments and J. T. Buscher for his further comments and thorough editing work.

References

Acocella, V., Di Lorenzo, R., Newhall, C., Scandone, R., 2015. An overview of recent (1988 to 2014) caldera unrest: knowledge and perspectives. Rev. Geophys. 53, 896–955.

Agip, 1987. Geologia e geofisica del sistema geotermico dei Campi Flegrei, internal report. Milan, Italy, p. 17.

Aiuppa, A., Tamburello, G., Di Napoli, R., Cardellini, C., Chiodini, G., Giudice, G., Grassa, F., Pedone, M., 2013. First observations of the fumarolic gas output from a restless caldera: implications for the current period of unrest (2005–2013) at Campi Flegrei. Geochem. Geophys. Geosyst. 14, 4153–4169.

Allard, P., Maiorani, A., Tedesco, D., Cortecci, G., Turi, B., 1991. Isotopic study of the origin of sulfur and carbon in Solfatara fumaroles, Campi Flegrei Caldera. J. Volcanol. Geotherm. Res. 48, 139–159.

Amoruso, A., Crescentini, L., Berrino, G., 2008. Simultaneous inversion of deformation and gravity changes in a horizontally layered half-space: evidences for magma intrusion during 1982–1984 unrest at Campi Flegrei caldera (Italy). Earth Planet. Sci. Lett. 272, 181–188.

Amoruso, A., Crescentini, L., Sabbetta, I., 2014. Paired deformation sources of the Campi Flegrei caldera (Italy) required by recent (1980–2010) deformation history. J. Geophys. Res. Solid Earth 119, 858–879.

Arienzo, I., Moretti, R., Civetta, L., Orsi, G., Papale, P., 2010. The feeding system of Agnano–Monte Spina eruption (Campi Flegrei, Italy): dragging the past into present activity and future scenarios. Chem. Geol. 270, 135–147.

Aster, R.C., Meyer, R.P., 1988. Three-dimensional velocity structure and hypocenter distribution in the Campi Flegrei caldera. Italy. Tectonophysics 149, 195–218.

Aster, R.C., Meyer, R.P., De Natale, G., Zollo, A., Martini, M., Del Pezzo, E., Scarpa, R., Iannaccone, G., 1992. Seismic Investigation of Campi Flegrei Caldera. Volcanic Seismology. Proc. Volcanol. Series, vol. III. Springer Verlag, New York.

Audétat, A., Pettke, T., 1993. The magmatic–hydrothermal evolution of two barren granites: a melt and fluid inclusion study of the Rio del Medio and Canada Pinabete plutons in northern New Mexico (USA). Geochim. Cosmochem. Acta 67, 97–121.

Avallone, A., Briole, P., Delacourt, C., Zollo, A., Beauducel, F., 1999. Subsidence at Campi Flegrei (Italy) detected by SAR interferometry. Geophys. Res. Lett. 26, 2303–2306.

Babbage, C., 1847. Observation on the Temple of Serapis at Pozzuoli Near Naples. R. and J. E. Taylor, London, p. 35.

Barberi, F., Corrado, G., Innocenti, F., Luongo, G., 1984. Phlegraean fields 1982-84: brief chronicle of a Volcano emergency in a densely populated area. Bull. Volcanol. 47–2.

Battaglia, M., Troise, C., Obrizzo, F., Pingue, F., De Natale, G., 2006. Evidence for fluid migration as the source of deformation at Campi Flegrei caldera (Italy). Geophys. Res. Lett. 33, L01307. https://doi.org/10.1029/2005GL024904.

Beane, R.E., Bodnar, R.J., 1995. Hydrothermal fluids and hydrothermal alteration in porphyry copper deposits. Ariz. Geol. Soc. Digest 20, 83–93.
Beane, R.E., Titley, S.R., 1981. Porphyry copper deposits. Part II. Hydrothermal alteration and mineralization. Econ. Geol. 75th Anniversary Vol. 235–263.
Bellucci, F., Woo, J., Kilburn, C.R.J., Rolandi, G., 2006. Ground deformation at Campi Flegrei, Italy: implications for hazard assessment. In: Troise, C., De Natale, G., Kilburn, C.R.J. (Eds.), Mechanisms of Activity and Unrest at Large Calderas, vol. 269. Geological Society, London, Special Publications, pp. 141–157.
Berrino, G., Corrado, G., Luongo, G., Toro, B., 1984. Ground deformation and gravity changes accompanying the 1982 Pozzuoli uplift. Bull. Volcanol. 47–2, 187–200.
Berrino, G., Gasparini, P., 1995. Ground deformation and caldera unrest. Cah. Cent. Eur. Geodyn. Seismol. 8, 41–55.
Bianchi, R., Cordini, A., Federico, C., Giberti, G., Lanciano, P., Pozzi, J.P., Sartoris, G., Scandone, R., 1987. Modeling of surface ground deformation in volcanic areas: the 1970–1972 and 1982–1984 crises of Campi Flegrei, Italy. J. Geophys. Res. 92 (B13), 14139–14150.
Bianco, F., Castellano, M., Cogliano, R., Cusano, P., Del Pezzo, E., Di Vito, M.A., Fodarella, A., Galluzzo, D., La Rocca, M., Milana, G., Petrosino, S., Pucillo, S., Riccio, G., Rovelli, A., 2010. Seismic background noise characterization at Campi Flegrei volcanic area (napoli): the “UNREST” experiment. Quaderni Geofisc. 86, 21.
Bianco, F., Del Pezzo, E., Saccorotti, G., Ventura, G., 2004. The role of hydrothermal fluids in triggering the July–August 2000 seismic swarm at Campi Flegrei, Italy: evidence from seismological and mesostructural data. J. Volcanol. Geotherm. Res. 133, 229–246.
Bodnar, R.J., 1995. Fluid inclusion evidence for a magmatic source for metals in porphyry copper deposits. Miner. Assoc. Can. Short Course 23, 139–152.
Bodnar, R.J., Beane, R.E., 1980. Temporal and spatial variations in hydrothermal fluid characteristics during vein filling in pre-ore cover overlying deeply buried porphyry copper-type mineralization at Red Mountain, Arizona. Econ. Geol. 75, 876–893.
Bodnar, R.J., Cannatelli, C., De Vivo, B., Lima, A., Belkin, H.E., Milia, A., 2007. Quantitative model for magma degassing and ground deformation (bradyseism) at Campi Flegrei, Italy: implications for future eruptions. Geology 35, 791–794.
Bodnar, R.J., Student, J.J., 2006. Melt inclusions in plutonic rocks: petrography and microthermometry. In: Webster, J.D. (Ed.), Melt Inclusions in Plutonic Rocks. Mineral. Assoc. Canada, Short Course, vol. 36, pp. 1–26.
Bonafede, M., 1990. Axi-symmetric deformation of a thermo-poro-elastic half-space: inflation of a magma chamber. Geophys. Int. 103.
Bonafede, M., 1991. Hot fluid migration: an efficient source of ground deformation: application to the 1982–1985 crisis at Campi Flegrei-Italy. J. Volcanol. Geotherm. Res. 48, 187–198.
Bonafede, M., Dragoni, M., Quareni, F., 1986. Displacement and stress fields produced by a centre of dilatation and by a pressure source in visco-elastic half-space: application to the study of ground deformation and seismic activity at Campi Flegrei, Italy. Geophys. J. R. Astron. Soc. 87, 455–485.
Breislak, S., 1792. Essai mineralogiques sur le Solfatare de Pouzzole. Part 3, Observations sur l’exterieur du crater de la Solfatare. Giaccio, Naples 170–177.

Caliro, S., Chiodini, G., Moretti, R., Avino, R., Granieri, D., Russo, M., Fiebig, J., 2007. The origin of the fumaroles of La Solfatara (Campi Flegrei, south Italy). Geochem. Cosmochim. Acta 71, 3040–3055.

Caliro, S., Chiodini, G., Paoni, A., 2014. Geochemical evidences of magma dynamics at Campi Flegrei (Italy). Geochim Cosmochim Ac 132, 1–15.

Camacho, A.G., González, P.J., Fernández, J., Berrino, G., 2011. Simultaneous inversion of surface deformation and gravity changes by means of extended bodies with a free geometry: application to deforming calderas. J. Geophys. Res. 116, B10401. https://doi.org/10.1029/2010JB008165.

Cannatelli, C., 2012. Understanding magma evolution at Campi Flegrei (Campania, Italy) volcanic complex using melt inclusions and phase equilibria. Mineral. Petrol. 104, 29–42.

Cannatelli, C., Lima, A., Bodnar, R.J., De Vivo, B., Webster, J.D., Fedele, L., 2007. Geochemistry of melt inclusions from the fondo riccio and minopoli 1 eruptions at Campi Flegrei (Italy). Chem. Geol. 237, 418–432.

Cardellini, C., Chiodini, G., Frondini, F., Avino, R., Bagnato, E., Caliro, S., Lelli, M., Rosiello, A., 2017. Monitoring diffusing volcanic degassing during volcanic unrest: the case of Campi Flegrei (Italy). Sci. Rep. 7, 6757. https://doi.org/10.1038/s41598-017-06941-2.

Casertano, L., Oliveri del Castillo, A., Quagliariello, M.T., 1976. Hydrodynamics and geodynamics in the phlegraean fields area of Italy. Nature 264, 154–161.

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

Chiodini, G., Caliro, S., De Martino, P., Avino, R., Ghepardi, F., 2012. Early signals of new volcanic unrest at Campi Flegrei caldera? Insights from geochemical data and physical simulations. Geology 40, 943–946.

Chiodini, G., Selva, J., Del Pezzo, E., Marsan, D., De Siena, L., D'Auria, L., Bianco, F., Caliro, S., De Martino, P., Ricciolino, P., Petrillo, Z., 2017. Clues on the origin of post-2000 earthquakes at Campi Flegrei caldera (Italy). Sci. Rep. 7, 4472. https://doi.org/10.1038/s41598-017-04845-9.

Chiodini, G., Todesco, M., Caliro, S., Del Gaudio, C., Macedonio, G., Russo, M., 2003. Magma degassing as a trigger of bradyseismic events; the case of Phlegrean Fields (Italy). Geophys. Res. Lett. 30, 1434. https://doi.org/10.1029/2002GL016790.

Chiodini, G., Vandemeulebrouck, J., Caliro, S., D'Auria, L., De Martino, P., Mangiacapra, A., Petrillo, Z., 2015. Evidence of thermal-driven processes triggering the 2005–2014 unrest at Campi Flegrei caldera. Earth Planet. Sci. Lett. 414, 58–67.

Civetta, L., Orsi, G., Pappalardo, L., Fisher, R.V., Heiken, G., Ort, M., 1997. Geochemical zoning, mingling, eruptive dynamics and depositional processes - the Campanian Ignimbrite, Campi Flegrei caldera. Italy. J. Volcanol. Geotherm. Res. 75, 183–219.

Corrado, G., Guerra, I., Lo Bascio, A., Luongo, G., Rampoldi, R., 1976. Inflation and microearthquake activity of phlegraean fields, Italy. Bull. Volcanol. 40, 3.

Cortini, M., Barton, C.C., 1993. Non linear forecasting analysis of inflation–deflation patterns of an active caldera (Campi Flegrei, Italy). Geology 21, 239–242.

Cortini, M., Cilento, L., Rullo, A., 1991. Vertical ground movements in the Campi Flegrei caldera as a chaotic dynamic phenomenon. J. Volcanol. Geotherm. Res. 48, 103–114.

Cubellis, E., Di Donna, G., Luongo, G., Mazzarella, A., 2002. Simulating the mechanism of magmatic processes in the Campi Flegrei area (southern Italy) by the Lorenz equations. J. Volcanol. Geotherm. Res. 115, 339–349.

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

D'Auria, L., Giudicepietro, F., Martini, M., Lanari, R., 2012. The 4D imaging of the source of ground deformation at Campi Flegrei caldera (southern Italy). J. Geophys. Res. 117, B08209. https://doi.org/10.1029/2012JB009181.

D'Auria, L., Pepe, S., Castaldo, R., Giudicepietro, F., Macedonio, G., Ricciolino, P., Zinno, I., 2015. Magma injection beneath the urban area of Naples: a new mechanism for the 2012–2013 volcanic unrest at Campi Flegrei caldera. Sci. Rep.-UK 5, 1–11.

De Landro, G., Serlenga, V., Russo, G., Amoroso, O., Festa, G., Bruno, P.P., Gresse, M., Vandemeulebrouck, J., Zollo, A., 2017. 3D ultra-high resolution seismic imaging of shallow Solfatara crater in Campi Flegrei (Italy): new insights on deep hydrothermal fluid circulation processes. Sci. Rep.-UK 7, 3412. https://doi.org/10.1038/s41598-017-03604-0.

De Lorenzo, G., 1904. L'attività vulcanica nei Campi Flegrei. Rend. Acc. Sc. Fis. Mat., Napoli 3, 203–211.

De Martino, P., Guardato, S., Tammaro, U., Vassallo, M., Iannaccone, G., 2014. A first GPS measurement of vertical seafloor displacement in the Campi Flegrei caldera (Italy). J. Volcanol. Geotherm. Res. 276, 145–151.

De Natale, G., Pingue, F., Allard, P., Zollo, A., 1991. Geophysical and geochemical modelling of the 1982–1984 unrest phenomena at Campi Flegrei caldera (southern Italy). J. Volcanol. Geotherm. Res. 48, 199–222.

De Natale, G., Troise, C., Pingue, F., 2001. A mechanical fluid-dynamical model for ground movements at Campi Flegrei caldera. J. Geodyn. 32, 487–571.

De Natale, G., Zollo, A., Ferraro, A., Virieux, J., 1995. Accurate fault mechanism determinations for a 1984 earthquake swarm at Campi Flegrei caldera (Italy) during an unrest episode: implications for volcanological research. J. Geophys. Res. 100 (B12), 24167–24185.

De Siena, L., Chiodini, G., Vilardo, G., Del Pezzo, E., Castellano, M., Colombelli, S., Tisato, N., Ventura, G., 2017. Source and dynamics of a volcanic caldera unrest: Campi Flegrei, 1983–84. Sci. Rep.-UK 7, 8099. https://doi.org/10.1038/s41598-017-08192-7.

De Siena, L., Del Pezzo, E., Bianco, F., 2010. Seismic attenuation imaging of Campi Flegrei: evidence of gas reservoirs, hydrothermal basins, and feeding systems. J. Geophys. Res. 115 https://doi.org/10.1029/2009JB006938.

De Vivo, B., Belkin, H.E., Barbieri, M., Chelini, W., Lattanzi, P., Lima, A., Tolomeo, L., 1989. The Campi Flegrei (Italy) geothermal system: a fluid inclusion study of the Mofete and San Vito fields. J. Volcanol. Geotherm. Res. 36, 303–326.

De Vivo, B., Lima, A., Kamenetsky, V.S., Danyushevsky, L.V., 2006. Fluid and melt inclusions in the sub-volcanic environments from volcanic systems: examples from the Neapolitan area and Pontine islands (Italy). In: Webster, J.D. (Ed.), Melt Inclusions in Plutonic Rocks. Min. Ass. Canada Short Course, Montreal, Quebec, vol. 36, pp. 211–237.

De Vivo, B., Petrosino, P., Lima, A., Rolandi, G., Belkin, H.E., 2010. Research progress in volcanology in the Neapolitan area, southern Italy: a review and some alternative views. Mineral. Petrol. 99, 1–28.

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

De Vivo, B., Torok, K., Ayuso, R.A., Lima, A., Lirer, L., 1995. Fluid inclusion evidence for magmatic/saline/CO_2 immiscibility and geochemistry of alkaline xenoliths from Ventotene Island, Italy. Geochim. Cosmochim. Acta 59, 2941–2953.

Deino, A.L., Orsi, G., de Vita, S., Piochi, M., 2004. The age of the Neapolitan Yellow Tuff caldera-forming eruption (Campi Flegrei caldera - Italy) assessed by $^{40}Ar/^{39}Ar$ dating method. J. Volcanol. Geotherm. Res. 133, 157–170.

Del Gaudio, C., Aquino, I., Ricciardi, G.P., Ricco, C., Scandone, R., 2010. Unrest episodes at Campi Flegrei: a reconstruction of vertical ground movements during 1905–2009. J. Volcanol. Geotherm. Res. 195, 48–56.

Di Vito, M.A., Acocella, V., Aiello, G., Barra, D., Battaglia, M., Carandente, A., Del Gaudio, C., de Vita, S., Ricciardi, G.P., Ricco, C., Scandone, R., Terrasi, F., 2016. Magma transfer at Campi Flegrei caldera (Italy) before the 1538 AD eruption. Sci. Rep. UK 6, 32245. https://doi.org/10.1038/srep32245.

Di Vito, M.A., Isaia, R., Orsi, G., Southon, J., de Vita, S., D'Antonio, M., Pappalardo, L., Piochi, M., 1999. Volcanism and deformation since 12000 years at the Campi Flegrei caldera (Italy). J. Volcanol. Geotherm. Res. 91, 221–246.

Dvorak, J., Berrino, G., 1991. Recent ground movement and seismic activity in Campi Flegrei, southern Italy: episodic growth of a resurgent dome. J. Geophys. Res. 96 (B2), 2309–2323. https://doi.org/10.1029/90JB02225.

Dvorak, J.J., Mastrolorenzo, G., 1991. The mechanism of recent vertical crustal movements in Campi Flegrei caldera. Southern Italy. Geol. Soc. Am. Spec. Pap. 263.

Esposito, R., Badescu, K., Steele-McInnis, M., Cannatelli, C., De Vivo, B., Lima, A., Bodnar, R.J., Manning, C.E., 2018. Magmatic evolution of the Campi Flegrei and Procida volcanic fields, Italy, based on interpretation of data from well-constrained melt inclusions. Earth Sci. Rev. 185, 325–356.

Faccenna, C., Funiciello, F., Giardini, D., Lucente, P., 2001. Episodic back-arc extension during restricted mantle convection in the central Mediterranean. Earth Planet. Sci. Lett. 187, 105–116.

Ferrucci, F., Hirn, A., Virieux, J., De Natale, G., Mirabile, L., 1992. P-SV conversions at a shallow boundary beneath Campi Flegrei caldera (Naples, Italy): evidence for the magma chamber. J. Geophys. Res. 97 (B11), 15351–15359.

Forbes, J.D., 1829. Physical notice in the Bay of Naples. Number 5, on the temple of jupiter Serapis at Pozzuoli and the phenomena which it exhibits. Edin. J. Sci. New Ser. 1, 260–286.

Foulger, G.R., Julian, B.R., Pitt, A.M., Hill, D.P., Malin, P.E., Shalev, E., 2003. Three-dimensional crustal structure of Long Valley caldera, California, and evidence for the migration of CO_2 under Mammoth Mountain. J. Geophys. Res. 108, 2147–2163.

Fowler, S.J., Spera, F.J., Bohrson, W.A., Belkin, H.E., De Vivo, B., 2007. Phase equilibria constraints on the chemical and physical evolution of the Campanian ignimbrite. J. Petrol. 48, 459–493.

Gaeta, F.S., Peluso, F., Arienzo, I., Castagnolo, D., De Natale, G., Milano, G., Albanese, C., Mita, D.G., 2003. A physical appraisal of a new aspect of bradyseism: the miniuplift. J. Geophys. Res. 108, 2363. https://doi.org/10.1029/2002JB001913.

Goes, S., Giardini, D., Jenny, S., Hollenstein, C., Kahle, H.G., Geiger, A., 2004. A recent tectonic reorganization in the south-central Mediterranean. Earth Planet. Sci. Lett. 226, 335–345.

Gottsmann, J., Folch, A., Rymer, H., 2006. Unrest at Campi Flegrei: a contribution to the magmatic versus hydrothermal debate from inverse and finite element modeling. J. Geophys. Res. 111, B07203. https://doi.org/10.1029/2005JB003745.

Gresse, M., Vandemeulebrouck, J., Byrdina, S., Chiodini, G., Bruno, P., 2016. Changes in CO2 diffuse degassing induced by the passing of seismic waves. J. Volcanol Geoth Res 320, 12–18.

Guidarelli, M., Saraò, A., Panza, G.F., 2002. Surface wave tomography and seismic source studies at Campi Flegrei (Italy). Phys. Earth Planet. In. 134, 157–173.

Guidarelli, M., Zille, A., Saraò, A., Natale, M., Nunziata, C., Panza, G.F., 2006. Shear-wave velocity models and seismic sources in Campanian volcanic areas: Vesuvius and Phlegraean Fields. In: Dobran, F. (Ed.), VESUVIUS 2000: Education, Security and Prosperity. Elsevier, pp. 287–309.

Guidoboni, E., Ciuccarelli, C., 2011. The Campi Flegrei caldera: historical revision and new data on seismic crises, bradyseism, the Monte Nuovo eruption and ensuing earthquakes (twelfth century 1582 AD). Bull. Volcanol. 73, 655–677.

Gunther, R.T., 1903. The submerged Greek and Roman foreshore near Naples. Archaeologia 58, 62.

Hill, D.P., Pollitz, F., Newhall, C., 2002. Earthquake–volcano interactions. Phys. Today 41–47.

Kilburn, C.R.J., De Natale, G., Carlino, S., 2017. Progressive approach to eruption at Campi Flegrei caldera in southern Italy. Nat. Commun. 8, 15312. https://doi.org/10.1038/ncomms15312.

Lima, A., De Vivo, B., Spera, F.J., Bodnar, R.J., Milia, A., Nunziata, C., Belkin, H.E., Cannatelli, C., 2009. Thermodynamic model for uplift and deflation episodes (bradyseism) associated with magmatic-hydrothermal activity at Campi Flegrei (Italy). Earth Sci. Rev. 97, 44–58.

Lowenstern, J.B., Hurwitz, S., 2007. Monitoring a supervolcano in repose: heat and volatile flux at the Yellowstone caldera. Elements 4, 35–40.

Lowenstern, J.B., Smith, R.B., Hill, D.P., 2006. Monitoring super-volcanoes: geophysical and geochemical signals at Yellowstone and other large caldera systems. Philos. Trans. R. Soc. A 364, 2055–2072.

Lyell, C., 1872. In: Murray, J. (Ed.), Principles of Geology. London, pp. 164–179.

Manconi, A., Walter, T.R., Manzo, M., Zeni, G., Tizzani, P., Sansosti, E., Lanari, R., 2010. On the effects of 3D mechanical heterogeneities at Campi Flegrei caldera. Southern Italy. J. Geophys. Res. 115, B08405. https://doi.org/10.1029/2009JB007099.

Milia, A., Torrente, M.M., 1999. Tectonics and stratigraphic architecture of a pery- Tyrrhenian half-graben (Bay of Naples Italy). Tectonophysics 315, 297–314.

Milia, A., Torrente, M.M., 2000. Fold uplift and syn-kinematic stratal architectures in a region of active transtensional tectonics and volcanism, Eastern Tyrrhenian Sea. Geol. Soc. Am. Bull. 112, 1531–1542.

Milia, A., Torrente, M.M., 2003. Late quaternary volcanism and transtensional tectonics in the Bay of Naples, campanian continental margin. Italy. Miner. Petrol. 79, 49–65.

Milia, A., Torrente, M.M., 2011. The possible role of extensional faults in localizing magmatic activity: a crustal model for the Campanian Volcanic Zone (Eastern Tyrrhenian Sea, Italy). J. Geol. Soc. 68, 471–484.

Milia, A., Torrente, M.M., Giordano, F., 2000. Active deformation and volcanism offshore Campi Flegrei, Italy: new data from high-resolution seismic reflection profiles. Mar. Geol. 171, 61–73.

Milia, A., Torrente, M.M., Russo, M., Zuppetta, A., 2003. Tectonics and crustal structure of the Campania continental margin: relationships with volcanism. Mineria Pet. 79, 33–47.

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

Moretti, R., Troise, C., Sarno, F., De Natale, G., 2018. Caldera unrest driven by CO_2-induced drying of the deep hydrothermal system. Sci. Rep.-UK 8, 8309. https://doi.org/10.1038/s41598-018-26610-2.

Morhange, C., Marriner, N., Laborel, J., Todesco, M., Oberlin, C., 2006. Rapid sea-level movements and non eruptive crustal deformations in the Phlegrean Fields caldera. Italy. Geology 43, 93–96.

Niccolini, A., 1839. Tavola cronologico-metrica delle varie altezze tracciate dal mare fra la costa di Amalfi ed il promontorio di Gaeta nel corso di diaciannove secoli. Flautina, Napoli 11–52.

Niccolini, A., 1845. Descrizione della gran terna puteolana volgarmente detta Tempio di Serapide. Napoli, Stamperia Reale.

Oliveri del Castillo, A., Quagliariello, M.T., 1969. Sulla genesi del bradisismo flegreo. In: Atti Associazione Geofisica Italiana, 18th Congress, Napoli, pp. 557–594.

Orsi, G., Di Vito, M., De Vita, S., 1996. The restless, resurgent Campi Flegrei nested caldera (Italy): constraints on its evolution and configuration. J. Volcanol. Geotherm. Res. 74, 179–214.

Panichi, C., Volpi, G., 1999. Hydrogen, oxygen and carbon isotope ratios of Solfatara fumaroles (Phlegraean Fields, Italy): further insights into source processes. J. Volcanol. Geotherm. Res. 91, 321–328.

Panza, G.F., Peccerillo, A., Aoudia, A., Farina, A., 2007. Geophysical and petrological modeling of the structure and composition of the crust and upper mantle in complex of geodynamic setting: the Thyrrenian Sea and surrounding. Earth Sci. Rev. 80, 1–46.

Panza, G.F., Pontevivo, A., Saraò, A., Aoudia, A., Peccerillo, A., 2004. Structure of the lithosphere–asthenosphere and volcanism in the Tyrrhenian Sea and surroundings. From seafloor to deep mantle: architecture of the tyrrhenian backarc basin. In: Marani, et al. (Eds.), Mem. Descr, vol. 64. Carta Geologica d'Italia, pp. 29–56.

Pappalardo, L., Mastrolorenzo, G., 2012. Rapid differentiation in a sill-like magma reservoir: a case study from the Campi Flegrei caldera. Sci. Rep.-UK 2, 712. https://doi.org/10.1038/srep00712.

Pappalardo, L., Piochi, M., D'Antonio, M., Civetta, L., Petrini, R., 2002. Evidence for Multi-stage Magmatic Evolution during the past 60 kyr at Campi Flegrei (Italy) Deduced from Sr, Nd and Pb Isotope Data. J. Petrol. 43, 1415–1434.

Parascandola, A., 1947. I fenomeni bradisismici del Serapeo di Pozzuoli, Napoli. Privately published, p. 156.

Pierce, K.L., Cannon, K.P., Meyer, G.A., Trebesch, M.J., Watts, R., 2002. Post-glacial Inflation–Deflation Cycles, Tilting and Faulting in the Yellowstone Caldera Based on Yellowstone Lake Shorelines. U.S. Geological Survey Open-File. Report 02-0142.

Piochi, M., Kilburn, C., Di Vito, A., Mormone, A., Tramelli, C., Troise, C., De Natale, G., 2014. The volcanic and geothermally active Campi Flegrei caldera: an integrated multidisciplinary image of its buried structure. Int. J. Earth Sci. 103, 401–421.

Polland, M.J., 2014. Time-averaged discharge rate of subaerial lava at Kilauea Volcano, Hawaii, measured from TanDEM-X interferometry: implications for

magma supply and storage during 2011-2013. J. Geophys. Res. Solid Earth 119, 5464–5481.
Roedder, E., Bodnar, R.J., 1997. Fluid inclusion studies of hydrothermal ore deposits. In: Barnes, H.L. (Ed.), Geochemistry of Hydrothermal Ore Deposits, third ed.
Rolandi, G., Bellucci, F., Heizler, M.T., Belkin, H.E., De Vivo, B., 2003. Tectonic controls on the genesis of ignimbrites from the Campanian Volcanic Zone, southern Italy. Mineria Pet. 79, 3–31.
Romano, V., Tammaro, U., Riccardi, U., Capuano, P., 2018. Non-isothermal momentum transfer and ground displacements rates at Campi Flegrei caldera (Southern Italy). Phys. Earth Planet. In. 283, 131–139.
Rosenberg, N.D., Spera, F.J., 1990. Role of anisotropic and/or layered permeability in hydrothermal convection. Geophys. Res. Lett. 17 (3), 235–238.
Rosenberg, N.D., Spera, F.J., 1992a. Thermohaline convection in a porous medium heated from below. Int. J. Heat Mass Transf. 35, 1261–1274.
Rosenberg, N.D., Spera, F.J., 1992b. Convection in porous media with thermal and chemical buoyancy: a comparison of two models for solute dispersion. In: Yuen, D. (Ed.), Chaotic Processes in the Geological Sciences, IMA Volume in Mathematics and Its Applications, 41. Springer-Verlag, pp. 319–333.
Rosi, M., Sbrana, R., 1987. Phlegraean Fields, Quad. Ric. Sci., vol. 114. CNR Rome, p. 175.
Sartori, R., 2003. The Tyrrhenian back-arc basin and subduction of the Ionian lithosphere. Episodes 26, 217–221.
Sasada, M., 2000. Igneous-related Active Geothermal System versus Porphyry Copper Hydrothermal System. Proceeding World Geothermal Congress 2000, Kyushu– Tohoku, Japan. May 28–June 10, 1691–1693.
Scarpati, C., Cole, P.D., Perrotta, A., 1993. The Neapolitan Yellow Tuff—a large volume multiphase eruption from Campi Flegrei, southern Italy. Bull. Volcanol. 55, 343–356.
Schoofs, S., Spera, F.J., Hansen, U., 2003. Chaotic thermohaline convection in low-porosity hydrothermal systems. Earth Planet. Sci. Lett. 174, 213–229.
Signorelli, S., Vaggelli, G., Francalanci, L., Rosi, M., 1999. Origin of magmas feeding the Plinian phase of the Campanian Ignimbrite eruption, Phlegrean Fields (Italy): constraints based on matrix-glass and glass-inclusion compositions. J. Volcanol. Geotherm. Res. 99, 199–220.
Spera, F.J., Bohrson, W.A., Till, Christy, B., Ghiorso, M.S., 2007. Partitioning of trace elements among coexisting crystals, melt, and supercritical fluid during isobaric crystallization and melting. Am. Mineral. 92, 1881–1898.
Todesco, M., Berrino, G., 2005. Modeling hydrothermal fluid circulation and gravity signals at the Phlegrean Fields caldera. Earth Planet. Sci. Lett. 240, 328–338.
Todesco, M., Rutqvist, J., Chiodini, G., Pruess, K., Oldenburg, C.M., 2004. Modeling of recent volcanic episodes at Phlegrean Fields (Italy): geochemical variations and ground deformation. Geothermics 33, 531–547.
Todesco, M., Chiodini, G., Macedonio, G., 2003. Monitoring and modeling hydrothermal fluid emission at La Solfatara (Phlegrean Fields, Italy). An interdisciplinary approach to the study of diffuse degassing. J. Volcanol. Geotherm. Res. 125, 57–79.
Todesco, M., Scarsi, P., 1999. Chemical (He, H_2, CH_4, Ne, Ar, N_2) and isotopic (He, Ne, Ar, C) variations in the Solfatara crater (southern Italy): mixing of different sources in relation to seismic activity. Earth Planet. Sci. Lett. 171, 465–480.

Trasatti, E., Bonafede, M., Ferrari, C., Giunchi, C., Berrino, G., 2011. On deformation sources in volcanic areas: modeling the Campi Flegrei (Italy) 1982-84 unrest. Earth Planet. Sci. Lett. 306, 175–185.
Trasatti, E., Giunchi, G., Bonafede, M., 2005. Structural and rheological constraints on source depth and overpressure estimate at the Campi Flegrea caldera. Italy. J. Volcanol. Geotherm. Res. 144, 105–118.
Trasatti, E., Polcari, M., Bonafede, M., Stramondo, S., 2015. Geodetic constraints to the source mechanism of the 2011-2013 unrest at Campi Flegrei (Italy) caldera. Geophys. Res. Lett. 42, 3847–3854.
Troise, C., De Natale, G., Pingue, F., Obrizzo, F., De Martino, P., Tammaro, U., Boschi, E., 2007. Renewed ground uplift at Campi Flegrei caldera (Italy): new insight on magmatic processes and forecast. Geophys. Res. Lett. 34, L03301. https://doi.org/10.1029/2006GL028545.
Turco, E., Schettino, A., Pierantoni, P.P., Santarelli, G., 2006. The Pleistocene extension of the Campania Plain in the framework of the southern Tyrrhenian tectonic evolution: morphotectonic analysis, kinematic model and implications for volcanism. In: De Vivo, B. (Ed.), Volcanism in the Campania Plain: Vesuvius, Campi Flegrei and Ignimbrites. Series Developments in Volcanology, vol. 9. Elsevier, pp. 27–51.
Vanorio, T., Virieux, J., Capuano, P., Russo, G., 2005. Three-dimensional seismic tomography from P wave and S wave micro-earthquake travel times and rock physics characterization of the Campi Flegrei caldera. J. Geophys. Res. 110, B03201. https://doi.org/10.1029/2004JB003102.
Vetere, F., Botcharnikov, R.E., Holtz, F., Behrens, H., De Rosa, R., 2011. Solubility of H_2O and CO_2 in shoshonitic melts at 1250°C and pressures from 50 to 400 MPa: implications for Campi Flegrei magmatic system. J. Volcanol. Geotherm. Res. 202, 251–261.
Woo, J.Y., Kilburn, C.R.J., 2010. Intrusion and deformation at Campi Flegrei, southern Italy: sills, dikes, and regional extension. J. Geophys. Res. 115, B12210. https://doi.org/10.1029/2009JB006913.
Wortel, M., Spakman, W., 2000. Subduction and slab detachment in the mediterranean–carpathian region. Science 290, 1910–1917.
Zollo, A., Maercklin, N., Vassallo, M., Dello Iacono, D., Virieux, J., Gasparini, P., 2008. Seismic reflections reveal a massive melt layer feeding Campi Flegrei caldera. Geophys. Res. Lett. 35, L12306. https://doi.org/10.1029/2008GL034242.