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Pre-eruptive dynamics at the Campi Flegrei Caldera: from evidence of magma mixing to timescales estimates

Maurizio Petrelli*, Mónica Ágreda López, Alessandro Pisello and Diego Perugini

Abstract

We review pre-eruptive dynamics and evidence of open-system behavior in the volcanic plumbing system beneath Campi Flegrei Caldera, together with estimates of magma residence time, magma ascent, and mixing-to-eruption timescales. In detail, we compile pre- and syn-eruptive dynamics reported in the literature for (a) the Campanian Ignimbrite ~ 40 ka, (b) the Neapolitan Yellow Tuff (~ 15 ka), and (c) the recent activity within the Phlegrean area. We first summarize geochemical and textural evidence (e.g., magma mixing, crystal disequilibria, vertical zonings, and isotopic records) of open-system behavior for the pyroclasts erupted in the last 40 ky at Campi Flegrei Caldera. We show that the fingerprint of open-system dynamics is ubiquitous in the deposits associated with the volcanic activity at the Campi Flegrei Caldera in the last 40 ky. Then, we describe the results of geophysical and petrological investigations that allow us to hypothesize the structure of the magma feeding system. We point to a trans-crustal magmatic feeding system characterized by a main storage reservoir hosted at ~ 9 km that feeds and interacts with shallow reservoirs, mainly placed at 2–4 km. Finally, we define a scenario depicting pre-eruptive dynamics of a possible future eruption and provide new constraints on timescales of magma ascent with a physical model based on magma-driven ascending dyke theory. Results show that considerably fast ascent velocities (i.e., of the order of m/s) can be easily achieved for eruptions fed by both shallow (i.e., 3–4 km) and deep (i.e., ~ 9 km) reservoirs. Comparing the results from experimental and numerical methods, it emerges that mixing-to-eruption timescales occurring at shallow reservoirs could be on the order of minutes to hours. Finally, we highlight the volcanological implications of our timescale estimates for magma ascent and mixing to eruption. In particular, explosive eruptions could begin with little physical 'warning', of the order of days to months. In this case, the onset of volatile saturation might provide pre-eruptive indicators.

Keywords Campi Flegrei Caldera, Pre-eruptive dynamics, Volcanic plumbing system, Mixing-to-eruption timescales, Magma ascent velocity

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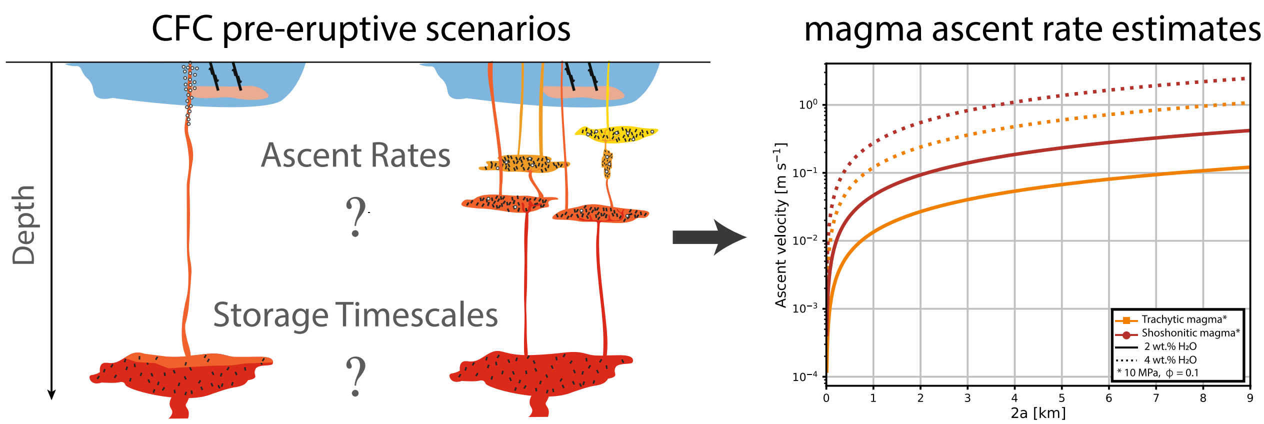
Graphical Abstract



Introduction

Open system processes are not an exception in volcanic plumbing systems (e.g., Morgavi et al. 2022, 2019; Perugini 2021). Among them, magma mixing is the most dominant, and is associated with many of the most explosive volcanic eruptions on Earth (Perugini 2021; Morgavi et al. 2019; Druitt et al. 2012; Kent et al. 2010; Leonard et al. 2002). From the petrologic point of view, open system processes also include (a) crystal exchanges between different batches of magmas, (b) volatiles transfer, and (c) the potential re-melting of a portion of the crystal cargo due to heat exchange (e.g., Astbury et al. 2018; Morgavi et al. 2022; Pelullo et al. 2022a, 2022b). From the volcanological point of view, the refilling of a shallower system by fresh magma coming from deeper crustal levels may lead to the remobilization of crystal mushes and potentially trigger a new eruption (e.g., Morgavi et al. 2022). Also, volatiles transfer from deep to shallower crustal levels may play a significant role in modulating pre-eruptive events and in controlling eruptive styles (Bachmann and Bergantz 2006; Caricchi et al. 2018; Edmonds et al. 2022; La Spina et al. 2022; Petrelli and Zellmer 2020).

Typically, open system processes act at non-equilibrium conditions, leaving a record on the resulting volcanic rocks (e.g., Costa et al. 2020; Ubide and Kamber 2018). This record includes textural evidences plus chemical and isotopic zonings in crystals (e.g., Higgins et al. 2021; Chen et al. 2020; Costa et al. 2020; Ubide and Kamber 2018). Also, chemical and isotopic variations can characterize bulk-rock analyses (Arienzo et al. 2016, 2009). Identifying the clues of open system behavior in a volcanic sequence and studying the related non-equilibrium processes is of paramount importance to constrain the evolution of a volcanic plumbing system and to provide hypotheses on the definition of volcanic hazard scenarios (Giordano and Caricchi 2022; Rooyakkers et al. 2021; Orsi et al. 2022; Rosi et al. 2022; Morgavi et al. 2022).

The focus of the present study is the Campi Flegrei Caldera (CFC; southern Italy), one of the most hazardous volcanic systems on Earth in the last 40 ky. Following two catastrophic events, the Campanian Ignimbrite (~40 ky) and the Neapolitan Yellow Tuff (~15 ky), the CFC has experienced intense eruptive activity and more than 60 eruptions (Orsi et al. 2022). The CFC is still active, posing a significant risk to the dense population living nearby (Orsi et al. 2022; Rosi et al. 2022).

Evidence of open system behavior is widespread in the products generated by eruptions within the CFC. As an example, the Campanian Ignimbrite shows evidence of crystal-mush reactivation by mafic magma recharges (Arienzo et al. 2011, 2009; Civetta et al. 1997; Di Salvo et al. 2020), as well as the Neapolitan Yellow Tuff (Pabst et al. 2008; Forni et al. 2018b). Many of the deposits belonging to the recent activity (i.e., the past 15 ky), e.g., Averno 2 (~3.7 ky; Di Vito et al. 2011), Astroni (4.8–3.8 ka; Arienzo et al. 2015; Astbury et al. 2018), Agnano Monte Spina (~4.1 ky; Arienzo et al. 2010; Pelullo et al. 2022a), Nisida (~4 ky; Arienzo et al. 2016), and Monte Nuovo (1538 AD; Di Vito et al. 2016), show evidence of magma mixing.

Although the CFC is a widely studied area (e.g., Orsi et al. 2022; Rosi et al. 2022), an exhaustive review of the clues highlighting open system behavior, magma transfer velocities from different crustal levels, and mixing-to-eruption timescales is still missing. To fill this gap, we aim to (1) highlight the evidence of open system behavior in the last ~40 ky at CFC; (2) provide an exhaustive review of magma ascent velocities, and mixing-to-eruption timescales in the last 40 ky; (3) focus on the petrologic record of the recent activity (i.e., the last 15 ky) and geophysical constraints, to define a pre-eruptive scenario and provide new constraints for magma ascent rates and warning timescales in medium- to large-class potential future eruptive events as defined by Orsi et al. (2009, 2004) and Bevilacqua et al. (2022, 2017, 2015).

Evidence of open-system behavior at the Campi Flegrei Caldera

The present review covers the volcanic activity at the CFC in the last ~ 40 ky. In detail, it first focuses on the two catastrophic events producing the Campanian Ignimbrite (~ 40 ky; Giaccio et al. 2017) and the Neapolitan Yellow Tuff (~ 15 ky; Deino et al. 2004). Then, it concentrates on the recent eruptive activity within the CFC in the past 15 ky (Fig. 1).

Campanian Ignimbrite (CI)

Many authors reported evidence of open-system evolution for the CI magma feeding system (e.g., Arienzo et al. 2011; Pabst et al. 2008; Pappalardo et al. 2008, 2002; Signorelli et al. 1999; Forni et al. 2016).

As an example, Civetta et al. (1997) proposed that the compositional variation within the CI results from a combination of crystal–liquid fractionation and the syn-eruptive magmatic interaction between magmas with different degrees of evolution, accounting for the disequilibrium evidence in crystals and the chemical heterogeneity of glass compositions. In detail, some pumice samples show evidence of mineralogic disequilibria such as the co-occurrence of sanidine and diopside of variable composition and a bimodal distribution of trace-element in Fe-rich diopside (Civetta et al. 1997). Glass compositions also record a bimodal distribution (Civetta et al. 1997).

In addition, Arienzo et al. (2011) and Di Renzo et al. (2011) describe the existence of two isotopically distinct CI magmas based on Sr-, Nd-, Pb- and B-isotope data. In this scenario, the least evolved magma crystallized during ascent a few ky before mixing, possibly favoring eruption.

Some studies, e.g., Forni et al. (2016) and Di Salvo et al. (2020), propose the occurrence of a crystal-mush zone, coexisting with a buoyant cap of evolved magma. In such a scenario, the recharge of hotter and less-evolved magma triggered the CI eruption. This

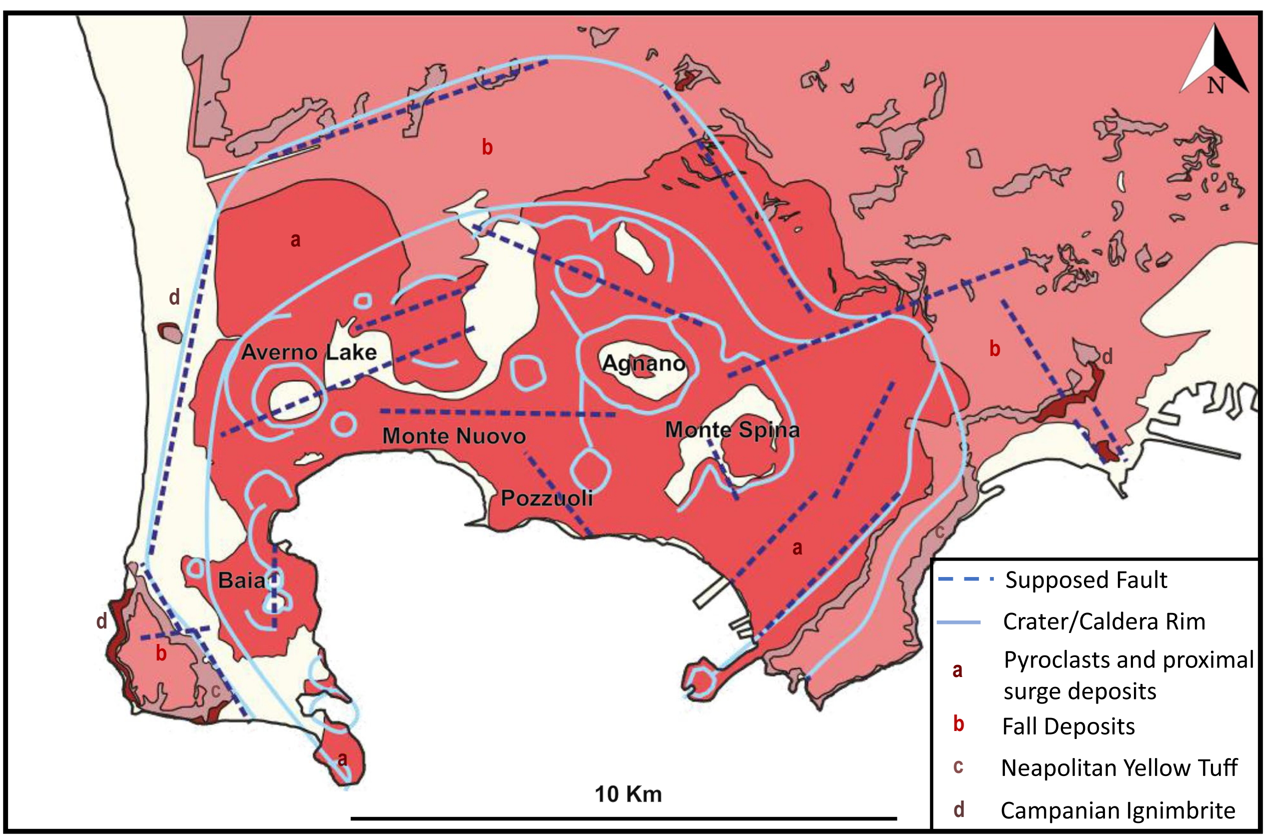


Fig. 1 Map of the CFC area with main pyroclastic products, fault system and craters. Modified after Ciarcia and Vitale 2018

idea is in agreement with other studies including Di Renzo et al. (2011) and Arienzo et al. (2011). Moreover, Moretti et al. (2019) discussed the role of volatiles by proposing an over-pressurized CO_2-dominated gas cap at the top of the magma chamber, possibly favoring the CI eruption.

Quantitative modeling by Forni et al. (2016) and Di Salvo et al. (2020) demonstrate that the geochemical and isotopic fingerprint of CI magmas (e.g., a marked compositional and isotopic variation in the juveniles of the topmost crystal-rich deposits erupted just after the caldera collapse, the high Ba and Sr contents and positive bulk-rock Eu anomalies observed in crystal-rich units, the positive Eu anomalies in the matrix glass of the crystal-rich units, the Ba and Sr-rich rims in the feldspars and positive Eu anomalies in clinopyroxene rims, and the presence of An-rich plagioclase) resulted from multiple petrologic processes, including the occurrence of a crystal-mush physically and chemically interacting with new mafic magma that reactivated the CI system. In detail, both studies suggest that the arrival of less-evolved and hotter magmas at the base of the CI crystal-mush system produced the melting of low-Or sanidine and low-An plagioclase. In the scenario proposed by Di Salvo et al. (2020), the melting of sanidine and plagioclase reduced the crystallinity of the mushy system, triggering a sequence of complex petrologic processes including mixing and crystallization.

Neapolitan Yellow Tuff (NYT)

As for the CI, the interpretation of the petrologic processes driving the pre-eruptive history of the Neapolitan Yellow Tuff (NYT) is not straightforward (e.g., Forni et al. 2018b; Orsi et al. 1995; Orsi et al. 1992; Pabst et al. 2008; Scarpati et al. 1993). For example, Orsi et al. (1995) hypothesize three main magma compositions, separated by gaps in the eruptive sequence and interpreted the architecture of the magmatic system as a chamber filled with three distinct and stratified magmas. The uppermost layer, with magma having alkali-trachyte composition, was highly homogeneous and probably resulted from vigorous convection. The magma filling the intermediate layer was of trachytic composition, showing compositional heterogeneities. Orsi et al. (1995) suggested that the intermediate layer also experienced convection, but less intense than that of the uppermost level. The magma at the bottom of the system was compositionally zoned ranging from alkali-trachyte to latite downward. In the scenario proposed by Orsi et al. (1995), the three magmas filled the magmatic system sequentially, with the last one entering the system shortly before the beginning of the eruption and possibly acting as the eruption trigger. Pabst et al. (2008) suggested the presence of multiple and isolated magma chambers with distinct compositions before the NYT eruption. Then, a new large-volume magma input of intermediate composition recharged one of these reservoirs, possibly coalescencing the previously separated reservoirs into one large chamber that fed the NYT eruption. Recently, Forni et al. (2018b) reported a detailed micro-analytical investigation of the mineral phases and matrix glasses collected at different stratigraphic positions along the NYT pyroclastic sequence highlighting at least three compositionally distinct magmas that fed the NYT eruption. They were (a) an evolved magma characterized by low Ca–Mg–Ba–Sr and negative Eu anomalies; (b) a more mafic magma showing high Ca–Mg–Ba–Sr, low K and slightly negative Eu anomalies, and (c) an intermediate magma with low Ca–Mg, high-K, intermediate Ba and Sr and slightly negative-to-positive Eu anomalies. Based on their results, Forni et al. (2018b) suggested that the compositional variations observed in the NYT do not reflect a vertically zoned magma chamber. Rather, they result from the complex interaction between different magmatic components stored in a heterogeneous upper crustal magma reservoir and progressively tapped. The occurrence of disequilibrium mineral phases further suggests interaction with a less-evolved recharging magma. They also indicate that the recharge of the magmatic system by a less-evolved and hotter magma activated the convection and promoted the mixing between the refilling and host magmas. This is supported by the presence of intermediate rock compositions hosting crystals derived from both the host and the refilling magmas.

Recent activity of the Campi Flegrei Caldera

In the products derived from the recent activity of the CFC (i.e., the last 15 ky; Table 1), the evidence of magma mixing is widespread (e.g., Arienzo et al. 2010, 2015, 2016; Astbury et al. 2018; D'Antonio et al. 2022; Di Vito et al. 2011; Voloschina et al. 2018; Di Renzo et al. 2011). The isotopic record provides many clues to unravel the open-system evolution of the recent activity within the CFC (e.g., D'Antonio et al. 2022 and references therein). As an example, D'Antonio et al. (1999) used Sr-isotopic composition of the erupted products to isolate three isotopically and geochemically distinct magmatic components that erupted in the past 15 ky. They are the Campanian Ignimbrite component (CIc; $^{87}Sr/^{86}Sr \sim 0.70735–0.70740$), the Neapolitan Yellow Tuff component (NYTc; $^{87}Sr/^{86}Sr \sim 0.70750–0.70757$), and the Minopoli component (MIc $^{87}Sr/^{86}Sr$ of ~ 0.7086), respectively. These three components (i.e., CIc, NYTc, and MIc) are similar to the trachytic magma that has been erupted during the final phase of the CI eruption, to the latitic–alkali–trachytic magma batches extruded during

Table 1 Eruptions at the CFC in the last 15 ky. Modified from Bevilacqua et al. (2022)

ID	Eruption	Epoch	ID	Eruption	Epoch
70	Monte Nuovo	AD 1538	35	Fondi di Baia	2
69	Nisidia	3b	34	Baia	2
68	Fossa Lupara	3b	33	Porto Miseno	1
67	Astroni 7	3b	32	Bacoli	1
66	Astroni 6	3b	31	Casale	1
65	Astroni 5	3b	30	Pisani 3	1
64	Astroni 4	3b	29	Pignatiello 1	1
63	Astroni 3	3b	28	Montagna Spaccata	1
62	Astroni 2	3b	27	Concola	1
61	Astroni 1	3b	26	Fondo Riccio	1
60[?]	Capo Miseno	3b	25	Pisani 2	1
59[a]	Averno 2	3b	24	Pisani 1	1
58	Solfatara	3b	23	Soccavo 5	1
57[b]	Academia Lava Dome	3b	22	Minopoli 2	1
56	Monte Olibano Tephra	3b	21	Paleo-San Martino	1
55	Solfatara lava dome	3b	20	Soccavo 4	1
54	Paleo-Astroni 3	3b	19	S4s3_2	1
53[b]	M.te Olibano Lava Dome	3b	18	S4s3_1	1
52	S.ta Maria delle Grazie	3b	17	Soccavo 3	1
51	Agnano-Monte Spina	3a	16	Soccavo 2	1
50	Paleo-Astroni 2	3a	15	Paleo-Pisani 2	1
49	Paleo-Astroni 1	3a	14	Paleo-Pisani 1	1
48b	Monte Sant'Angelo	3a	13	Pomici Principali	1
47	Pignatiello 2	3a	12	Gaiola	1
46	Cigliano	3a	11	Soccavo 1	1
45	Agnano 3	3a	10	Paradiso	1
44	Averno 1	3a	9	Minopoli 1	1
43	Agnano 2	3a	8	Torre Cappella	1
42	Agnano 1	3a	7	La Pigna 2	1
41	San Martino	2	6	La Pigna 1	1
40	Sartania 2	2	5	La Pietra	1
39	Pigna San Nicola	2	4	Santa Teresa	1
38	Costa San Domenico	2	3	Gauro	1
37	Monte Spina Lava Dome	2	2	Mofete	1
36	Sartania 1	2	1	Bellavista	1

the NYT, and to the shoshonitic magma of the Minopoli 2 eruptions, respectively. In agreement with D'Antonio et al. (1999), mixing processes occurred among the three components. In detail, the cited study proposes that the CIc and NYTc represent the residual portions of the long-lived and large-volume magmatic reservoirs developed since at least 60 and 5 ky, respectively, in agreement with Pappalardo et al. (1999). Finally, MIc could represent a magma coming from a deeper reservoir.

Di Renzo et al. (2011) further refined the isotopic characterization of the end-members involved in mixing events during the recent activity of the CFC, hypothesizing three end-members defined by Sr, Nd, Pd and B isotopes. In particular, two components agree with the characterization reported by D'Antonio et al. (1999). They are the NYTc ($^{87}Sr/^{86}Sr$ of 0.70750–0.70753, $^{143}Nd/^{144}Nd$ ratio of ca. 0.51246, $^{206}Pb/^{204}Pb$ of ca. 19.04 and $\delta^{11}B$ of ca. –7.9‰) and the MIc ($^{87}Sr/^{86}Sr$ of ca. 0.70860, $^{143}Nd/^{144}Nd$ ratio of ca. 0.51236, $^{206}Pb/^{204}Pb$ of ca. 18.90, $\delta^{11}B$ value of ca. –7.32‰). The third component in the characterization proposed by Di Renzo et al. (2011) is the Astroni 6 component (A6c; Fig. 2). The A6c points to $^{87}Sr/^{86}Sr$ values close to 0.70726, $^{206}Pb/^{204}Pb$ of ca. 19.08, $^{143}Nd/^{144}Nd$ of ca. 0.51250, and $\delta^{11}B$ of − 9.8‰. Based on the new Sr, Nd, Pb, and B isotopic analyses, performed on the same samples previously investigated by D'Antonio et al. (1999), Di Renzo et al. (2011) proposed that the A6c (one of the components that fed the volcanic activity in the last 5 ka) was not a residue of CIc but a new and distinct component.

In a few specific cases, Arienzo et al. (2010) pointed to two batches of magmas that mixed during the eruption of Agnano Monte Spina (A-MS). This conclusion is supported by whole rock chemical data, isotopic data, mineral–melt disequilibria and melt inclusion investigations. In detail, one component was similar to the MIc (D'Antonio et al. 2022; Di Renzo et al. 2011), whereas the other component was similar to the NYTc reported by D'Antonio et al. (2022) and references therein. Arienzo et al. (2010) proposed that the mixing between the MI and NYT components was pushed by a gas phase which drove the ascent of magmas. In agreement with Arienzo et al. (2010), Pelullo et al. (2022a) pointed to the existence of at least two, physically separated, magmatic environments for the A-MS plumbing system. Based on textural features and the chemical composition of the A-MS clinopyroxenes, Pelullo et al. (2022a) highlight two end-member populations. The first of these is marked by very high Mg# (> 91). This population is interpreted as representative of a mafic magma (i.e., ME0) that likely derived from the partial melting of the local mantle source. The second end-member population is characterized by more-evolved compositions (*Mg#* = 70–78) interpreted as representative of trachytic and phonolitic magmas (ME2), probably stationed in a shallower crustal reservoir. An intermediate population (*Mg#* = 80–84) is interpreted as representative of a magma (ME1) resulting from the mingling between ME0 and ME2. Pelullo et al. (2022a) proposed that these magmatic environments were connected with the transfer of magma between them over

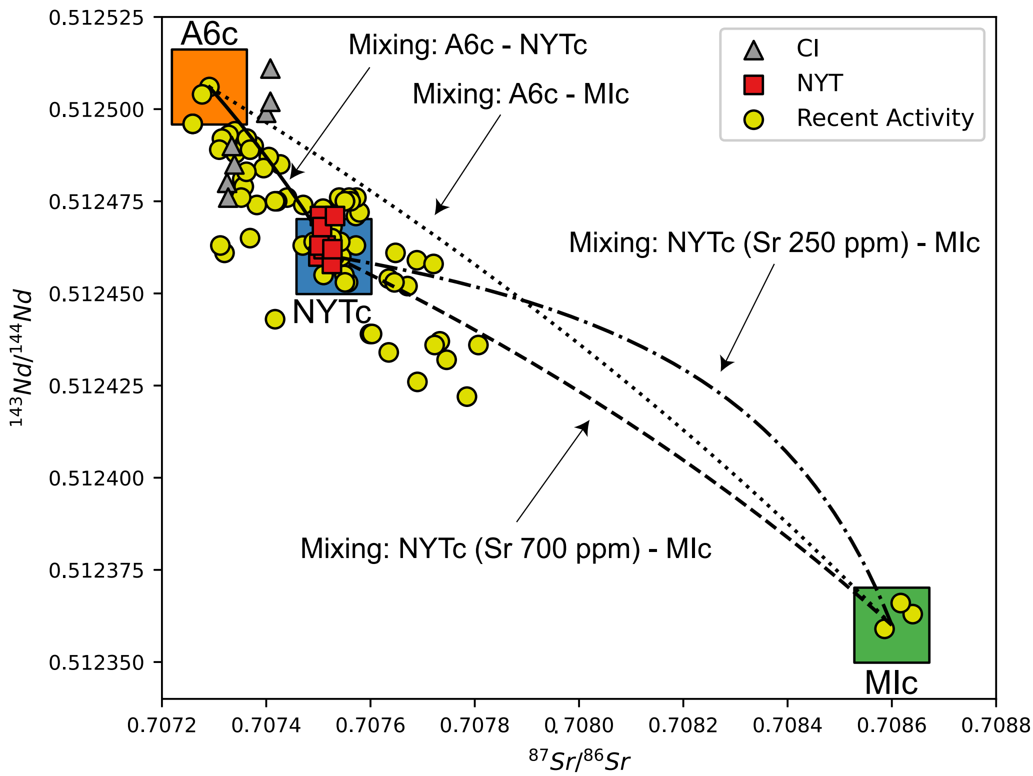


Fig. 2 Representation of the three main magmatic components (big squares) and mixing models (lines) as defined by Di Renzo et al. 2011. CI component as defined by D'Antonio et al. 1999 is not reported as end-member, but it can be individuated by the clustering of triangle datapoints. Lines were obtained using a binary mixing model by the hyperbolic equation Ax + Bxy + Cy + D = 0 (Langmuir et al. 1978). The two mixing curves between the NYTc and Mic consider different Sr concentrations for the NYTc, i.e., 250 and 700 ppm, respectively. Error bars are smaller than datapoints. Modified after Arienzo et al. 2016

decadal, and perhaps even centennial, timescales. More evolved environments (e.g., ME3: $Mg\# = 60–69$) were interpreted as resulting from degassing-induced crystallization shortly (e.g., days to hours) before the eruption.

Also, for the case of the Averno 2 fissure eruption, chemical, isotopic and melt inclusion data support the idea that magma mixing occurred between a more-evolved and less-radiogenic magma hosted in a shallow reservoir intruded by a less-evolved and more-radiogenic magma that triggered the eruption. In detail, the two components have been characterized by $^{87}Sr/^{86}Sr$ values close to 0.70750–0.70751 and 0.70753–0.70754, respectively (Di Vito et al. 2011; Fourmentraux et al. 2012).

Sr-isotopic data on samples belonging to the Astroni 6 eruption suggest the occurrence of mixing among chemically and isotopically distinct magmatic components (Di Renzo et al. 2011). Detailed analytical investigations allow the authors to refine the geochemical features of the magmatic components involved in Astroni 6 pre-eruptive dynamics (Arienzo et al. 2015). One is the Astroni 6 component (the same defined in Di Renzo et al. 2011), the other is chemically similar to some of the products extruded during the A-MS and Pomici Principali eruptions or, more in general, to the NYT component.

In addition to these isotopic constraints, Astbury et al. (2018), combined textural investigations, geochemical data on glasses and crystals, and high-resolution trace-element maps of the Astroni 6 crystal cargo to reveal the pre-eruptive dynamics occurred before the A6 eruption. Such study disclosed the evolution of the Astroni 6 plumbing system involving two separate magma bodies: (a) an evolved magma stored in a shallow system; (b) a less-evolved magma originally stored at a depth of ~ 7 km that then raised to shallow levels. Also, Astbury et al. (2018) emphasized that a single recharge and mixing event occurred just before the beginning of the Astroni 6 eruption.

The isotopic record, chemical data, and investigations on melt inclusions also points to open-system behavior on the volcanic plumbing system feeding the Nisida eruption (~ 4 ky BP; Arienzo et al. 2016). Arienzo et al. (2016), proposed that the arrival of a volatile-rich, shoshonite–latite magma, isotopically similar to the A6c (i.e., $^{87}Sr/^{86}Sr \sim 0.70730$; $^{143}Nd/^{144}Nd \sim 0.51250$), triggered the

Nisida eruption. They also suggested that emplacement of the A6c component activated the resurgence of the caldera floor, feeding most of the volcanic eruptions at CFC in the past 5 ky.

The geochemistry of melt inclusions also points to the open system evolution of the activity within the CFC. Esposito et al. (2018), focused on melt inclusions hosted in sanidine, clinopyroxene, plagioclase, biotite, and olivine belonging to the recent activity of the CFC (also including the NYT) and the Island of Procida volcanic systems. Esposito et al. (2018) interpreted the selective enrichment of major and trace elements recorded by melt inclusions as the result of dissolution-reaction-mixing (DRM) in a mush zone at the interface between a magma body and wall rock (Danyushevsky et al. 2004). As an example, the enrichment of Al_2O_3 could result from DRM between plagioclase and melts at various stages of evolution. The DRM interpretation is in agreement with micro-scale heterogeneities that result when a less-evolved melt ascends and interacts with a pre-existing mush zone (Esposito et al. 2018). Also, combining analytical determinations and rhyolite-MELTS modeling, Esposito et al. (2018) highlighted a group of melt inclusions that recorded polybaric fractional crystallization of a volatile-saturated magma at depths ranging from ≥ 7.5 km to ~ 1 km (see the next section for a detailed description of magma storage depths).

The only historical Eruption within the CFC is Monte Nuovo (1538 AD), characterized by volcanic rocks of K-phonolitic composition at the limit of the peralkaline field (SiO_2 = 58.7–59.6 wt%, $Na_2O + K_2O$ = 13.8–14.7 wt%, K_2O/Na_2O ~1 and Agpaitic Index = 0.92–1; D'Oriano et al. 2005; Piochi et al. 2005). Di Vito et al. (2016) suggested that these products resulted from the mixing between two magmas: the first stored at shallow levels, i.e., 4–5 km, and the second possibly intruding the shallow reservoir.

The architecture of the volcanic plumbing system at the Campi Flegrei Caldera

Information about the architecture of the volcanic plumbing system can be achieved by combining geophysical data with petrological and volcanological constraints (De Siena et al. 2010, 2014; Giordano and Caricchi 2022; Orsi et al. 2022, and references therein).

The architecture over the last 40 ky: petrologic constraints

The investigation of melt inclusions (MIs) provides essential constraints on magma geochemical evolution, volatile contents, and storage depths (Arienzo et al. 2016, 2010; Cannatelli et al. 2007; Fourmentraux et al. 2012; Mangiacapra et al. 2008; Moretti et al. 2019, 2013; Mormone et al. 2011; Voloschina et al. 2018). Therefore, they are of paramount importance to reconstruct the architecture of a volcanic plumbing system, and its evolution over time. In particular, the modeling of H_2O plus CO_2 saturation surfaces (e.g., Papale et al. 2006) can provide us MI entrapment pressures, that can be easily converted to magma storage depths. For the CFC, MIs often highlight a complex pre-eruptive evolution and they point to a trans-crustal magmatic system with different reservoirs hosted at different crustal levels (Arienzo et al. 2016, 2010; Cannatelli et al. 2007; Fourmentraux et al. 2012; Mangiacapra et al. 2008; Moretti et al. 2019, 2013; Mormone et al. 2011; Voloschina et al. 2018). This hypothesis well agrees with the geochemical record, pointing to different magmas that interact in the volcanic plumbing system before an eruption (e.g., D'Antonio et al. 2022, and references therein).

As an example, MIs from the CI equip us with information on the architecture of the CFC volcanic plumbing system at 40 Ky. H_2O and CO_2 contents measured in MIs belonging to the CI eruption range from 0.4 to 4.2 wt% and from 184 to 1100 ppm, respectively (Moretti et al. 2019). Estimated CI entrapment pressures range from ~ 50 to ~ 400 MPa, which correspond to a depth range of ~ 2–16 km (Moretti et al. 2019).

Mormone et al. (2011) investigated MI from the Solchiaro Eruptive sequence (Procida Island Eruption; 18 ky), located just outside the CFC. Maximum H_2O and CO_2 contents achieved 2.69 wt.% and 2653 ppm, respectively. Recalculated entrapment pressures range from ~ 350 MPa to < 50 MPa. As a consequence, Mormone et al. (2011) proposed the occurrence of a CO_2-rich magma source, originally stored at a depth of ~ 13–14 km (i.e., 350 MPa). Fanara et al. (2015) performed experimental investigations on H_2O–CO_2 solubility surfaces in natural magmas that erupted during the CI and Solchiaro (Procida Island) eruptions. Then, they combined these results with H_2O–CO_2 contents analyzed in melt inclusions [i.e., the results reported by Mormone et al. (2011) and Esposito et al. (2011)], in glass matrices, and in bulk rocks. Combining experimental and natural data, Fanara et al. (2015) suggested that the Campanian Ignimbrite magma could have been stored or ponded during ascent at two different levels: a deeper one corresponding to a depth of ~ 8–15 km, and a shallower one at about ~ 1–8 km. Also, the magma feeding the Solchiaro eruption pointed to a deep reservoir at ~ 11 km depth with a storage or ponding level at ~ 2–8 km depth (Fanara et al. 2015).

Voloschina et al. (2018) investigated MIs from Baia–Fondi di Baia eruption (9525–9696 BP). These MIs show an average SiO_2 content of 59.6 ± 0.7 wt.%, a total alkali content of 12–13 wt.%, and a broad range of halogen concentrations (up to 0.70 wt.% Cl and 0.23 wt.% F). Water contents range from 1.1 to 4.2 wt.%. Combining mineral, melt inclusions, and Sr isotope data, Voloschina et al. (2018) suggest the presence of a magma reservoir located at 6–9 km depth and a complex evolution for the plumbing system feeding the eruption with the involvement of three magma batches.

Mangiacapra et al. (2008) analyzed the Minopoli 2 shoshonite and Fondo Riccio latite products (10.2 to 9.5 ky). There, MIs record H_2O and CO_2 contents in the range 0.2–2.84 wt.% and 172–1100 ppm, respectively. The modeling of H_2O–CO_2 pairs suggests entrapment pressures ranging from 61 to 212 MPa, corresponding to ~ 2 and ~ 9 km, respectively (Mangiacapra et al. 2008).

Melt inclusions belonging to the Agnano–Monte Spina eruption (4.1 ky; Arienzo et al. 2010) span H_2O and CO_2 contents of 0.8 to 3.0 wt.% and 150 to 500 ppm, respectively. The reported H_2O and CO_2 contents point to yield entrapment pressures between 107 and 211 MPa, corresponding to depths between 4 and 8 km (Arienzo et al. 2010).

MIs hosted in latite pumice samples from the Nisida eruption (~ 4 ka BP; Arienzo et al. 2016) display a water content in the range from ~ 1 to ~ 4.5 wt.%, with a mode at around 2 wt.%, whereas Sulfur (S) and chlorine (Cl) contents range from ~ 0.02 to ~ 0.11 wt.% and from ~ 0.5 to ~ 1.1 wt.%, respectively. A few MIs show detectable dissolved CO_2, around 400–500 ppm. Arienzo et al. (2016) estimate entrapment pressures, calculated for the H_2O–CO_2 pairs (Papale et al. 2006), in the range from 200 to 230 MPa, corresponding to depths of ~ 9 km and suggesting a relatively deep provenance for the latite magma feeding the Nisida eruption.

Melt inclusions in phenocrysts of the Vateliero and Cava Nocelle shoshonite–latite eruptive products (Ischia, just outside the CFC, sixth to fourth centuries BC, Moretti et al. 2013) show H_2O and CO_2 contents ranging from 0.9 to 4.3 wt.% and from 170 to 4,600 ppm, respectively. Entrapment pressures calculated for the H_2O–CO_2 pairs range from 70 to 430 MPa, corresponding to depths between 2.8 and 17.2 km. These results suggest a vertically extended magmatic plumbing system, characterized by a major region of magma stagnation and gas fluxing at ~200–250 MPa (~ 8–10 km; Moretti et al. 2013).

Melt inclusions belonging to the Averno 2 Eruption (3.7 ky; Fourmentraux et al. 2012) record significant variations in H_2O (from 0.4 to 5 wt.%), S (from 0.01 to 0.06 wt.%), Cl (from 0.75 up to 1 wt.%), and F (from 0.20 to > 0.50 wt.%). Carbon (CO_2 or carbonates) was not detected in melt inclusions ($CO_2 \leq 40$ ppm). Estimated entrapment pressures vary from 50 to 100 MPa, corresponding to depths ranging between 2 and 4 km, respectively.

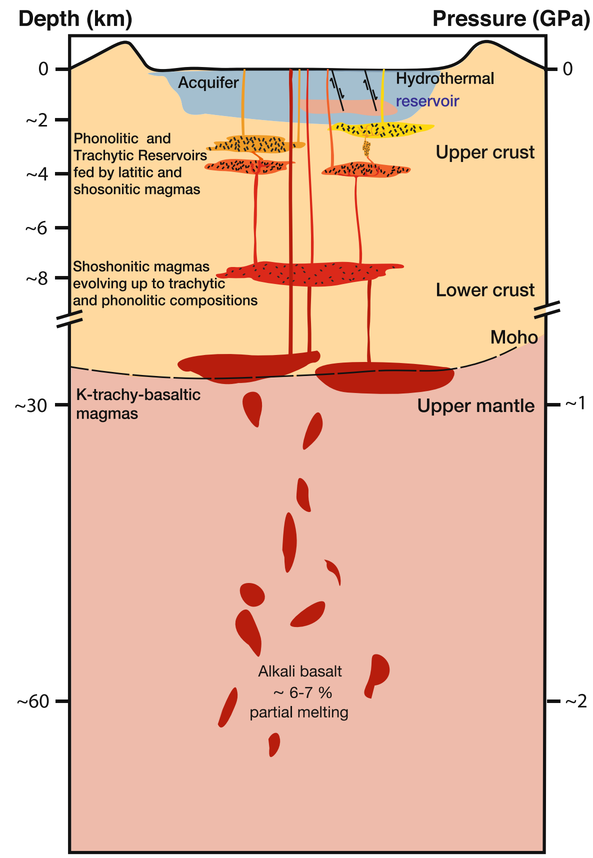


Fig. 3 Possible plumbing system of the CFC area, modified after Bonechi et al. 2022

The current architecture: combining petrological data with geophysical constraints

Many models (e.g., Bianco et al. 2022) agree with the presence of a magma reservoirs at ~ 7–10 km and with the rising and accumulation of magmatic fluids at ~ 2–3 km, as depicted in Fig. 3 and in agreement with geophysical constraints, e.g., coda-attenuation anomalies (Akande et al. 2019), seismic reflection surveys (Zollo et al. 2008), seismic tomography, and rock-physics (e.g., Calò and Tramelli 2018; De Siena et al. 2017; Vanorio and Kanitpanyacharoen 2015). The current presence of a shallow magmatic reservoirs depicted by petrological investigations has been often investigated, but not yet fully supported by data (e.g., Akande et al. 2019; Zollo et al. 2008).

Fedi et al. (2018) interpreted a wide gravity low at the CFC as being produced by a large and deep source distribution of partially molten, low-density material from about 8 to 30 km depth. Also, they combined gravity data with petrological constraints (e.g., Pappalardo and Mastrolorenzo 2012; Melluso et al. 2014; Arienzo et al. 2016) providing two models: the first assumes the presence, at intermediate to deep crustal levels (i.e., 8–24 km), of large amounts of melts and cumulates besides country rocks (Fig. 3); the second reflects a fractal density distribution, based on the scaling exponent estimated from the gravity data. The latter model suggests that the gravity low would be related to a distribution of melt pockets within solid rocks. These two scenarios can be considered as the end-members of a trans-crustal volcanic plumbing system feeding the eruptive activity of the CFC and extending from very shallow crustal levels to up to ~ 25 km (Fedi et al. 2018). The trans-crustal system is fed by melts of alkali basalt composition that originate within the underlying mantle at ca. 60 km as shown in Fig. 3 (Bonechi et al. 2022). Potassic magmas (shoshonitic basalts and subordinately K-basanites) progressively evolve within the trans-crustal system, eventually feeding ephemeral shallow systems at 2–4 km (Fedi et al. 2018; Pelullo et al. 2022b).

Pre-eruptive scenarios for possible future eruptions

Many studies, mainly based on statistical investigations of post-NYT occurrences (i.e., the last 15 ky), provide a definition for possible scenarios for future eruptions at CFC (e.g., Orsi et al. 2004, 2009; Bevilacqua et al. 2015, 2017, 2022).

As an example, Orsi et al. (2009) define three main scenarios with reference eruptions: large- medium- and small-class events. These are Agnano Monte Spina (trachytic composition) as a large event and Astroni 6 (mostly of trachytic and phonolitic composition) as a medium-size event. For the small-size class, Orsi et al. (2009) selected the Monte Nuovo (K-phonolitic) and Averno 2 (alkali-trachyte) eruptions. In addition, Agnano Monte Spina eruption has been taken as a reference eruption scenario for the next large-scale eruption at Campi Flegrei by the Italian Civil Protection Agency (e.g., Orsi et al. 2004, 2009; Bevilacqua et al. 2015, 2017, 2022). Moreover, Bevilacqua et al. (2015, 2017, 2022), point on the Astroni, Agnano Monte Spina, and Solfatara delimited area, as the most probable zone for a future eruptive vent opening.

Combining the reference scenarios for future eruptions, geophysical constraints depicting the current state of the volcanic plumbing system, and the geochemical and petrological record of the volcanic products, we provide new models and discussion on magma ascent velocities and mixing-to-eruption timescales. The main conceptual model consists of a trans-crustal magmatic system (e.g., Giordano and Caricchi 2022) characterized by a main storage reservoir hosted at ~ 9 km that interacts with shallow (as they are depicted by petrologic studies), maybe ephemeral (as there in not clear geophysical evidence for the presence of magma at shallow crustal levels) reservoirs, mainly placed at 2–4 km. In this framework, we discuss of magma residence times and mixing-to-eruption timescales in the last 15 ky. Also, we provide new modeling and discussion of magma ascent from the main storage reservoir located at ~ 9 km directly to the surface.

Magma residence times and mixing-to-eruption timescales at the Campi Flegrei Caldera in the last 15 ky

Many authors attempted to define pre- and syn-eruptive timescales at the CFC (Table 2 and references therein). Most of the proposed estimates (e.g., mixing-to-eruptions estimates) refer to an open-system scenario that appears to be common within the CFC, as reported in the previous sections. Timescales of magmatic processes have been derived using different methods applied to natural samples, such as the study of molecular diffusion in chemically zoned crystal phases or the investigation of crystal size distributions, numerical modeling and newly designed magma mixing experiments using natural melts under different fluid dynamics conditions (Table 2 and references therein).

Mixing-to-eruption timescales and magma residence times by crystal zonations, saturation, and crystal size distribution on natural samples

The investigation of natural samples can provide a robust estimate of the timescales of pre- and syn-eruptive processes, as an example, Astbury et al. (2018) provide mixing-to-eruption timescales for the Astroni 6 eruption by measuring the thickness of the most recently recorded zones in crystals enriched in incompatible elements. These zones are interpreted as final recharge zones, in agreement with Ubide and Kamber (2018). The determinations reported by Astbury et al. (2018) were obtained in the maximum growth direction along the c-axis of the crystal. Noteworthy is the fact that, due to potential sectioning effects, the resulting timescale estimates should be considered as maxima [see Astbury et al. (2018) for further methodological details]. These results point to mixing-to-eruption timescales in the order of hours to days.

Iovine et al. (2017) applied the modeling of chemical diffusion (i.e., Fick's second law-based geospeedometry) to constrain the timescales of open-system processes before the ~4.7 ky Agnano-Monte Spina eruption. They combined backscattered electron imaging and

Table 2 Résumé of the latest studies regarding ascent mechanisms and velocities

References	Time	Process	Magnetic system	Method
Mixing-to-eruption timescales				
Pelullo et al. (2022a)	Decades	Mafic recharge of evolved shallow reservoir	Agnano-Monte Spina eruption (~4.7 ka)	Compositional zoning in clinopyroxene crystals
Iovine et al. (2017)	2–60 years	Shoshonite injection in phonolitic reservoir	Agnano-Monte Spina eruption (~4.7 ka)	Diffusion chronometry performed on sanidine crystals
Perugini et al. (2015)	Minutes to hours	Shoshonite injection in phonolitic reservoir	Agnano Monte Spina (~4.7 ka), Astroni 6 (4.1–4.3 ky), and Averno 2 (~3.7 ka)	Concentration Variance Decay
Astbury et al. (2018)	Hours to days	Shoshonite injection in phonolitic reservoir	Astroni 6 (4.1–4.3 ky)	Thickness of final recharge zones and outermost rims
Perugini et al. (2010)	2 and 9 days, respectively	Shoshonite injection in phonolitic reservoir	Astroni 6 (4.1–4.3 ky) and Averno 2 (~3.7 ky)	Diffusive Fractionation Method
Magma residence times and non-mixing-related timescales				
Fabbrizio and Carroll (2008)	Hours to a max of 1–2 days	Evolution of trachy-phonolite magma during ascent	Breccia Museo Eruption (40 ky)	Dissolution rate data of biotites
Pappalardo and Mastrolorenzo (2012)	Hours to a max of 1–2 days	Volatile-rich trachytic layer at the top of a wide magma reservoir by magmatic differentiation, which could then erupt explosively	Campanian Ignimbrite (40 ky)	Cristal Size Distribution (CSD)
Arienzo et al. (2011)	6.4 ± 2.1 ka	Magma assembly prior the CI caldera forming eruption	Campanian Ignimbrite (40 ky)	U–Th isotopic dating
Arzilli et al. (2018)	Days	Magma residence time under non-equilibrium conditions	Campi Flegrei Caldera (last 40 ky)	Element partitioning between alkali feldspar and trachytic melts
D'Oriano et al. (2005)	Days	Syn-eruptive crystallization	Monte Nuovo (1538 AD)	Cristal Size Distribution (CSD)
Piochi et al. (2005)	Few days to tens of days	Evolution magmas falling near the trachyte-phonolite boundary	Monte Nuovo (1538 AD)	Cristal Size Distribution (CSD)
Arzilli et al. (2016)	Hours to two days	Evolution of trachy-phonolite magma	Monte Nuovo (1538 AD)	Cristal Size Distribution (CSD)
Stock et al. (2016, 2018)	Days to years	Volatile recharge and pressurization of the deep system (7.5–8.5 km)	Astroni 1 (4.1–4.3 ka)	Volatile variations in apatite and hydrous glasses
Di Vito et al. (2016)	~ 300 years	Pre-eruptive magma residence times	Monte Nuovo (1538 AD)	Based on the Uplift history
Bonechi et al. (2022)	~ 10 ka	Filling of the deep reservoir at 25 km from the mantle source by a melt of alkali basalt composition supposed at ~ 50 km	Campi Flegrei Caldera (last 40 ky)	Mobility by density contrast between the melt and the surrounding permeable crystalline matrix

quantitative electron microprobe determinations on 50 sanidine crystals focusing on chemical zonations close to crystal rims, obtaining results ranging from 3 to 60 years.

Pelullo et al. (2022a) characterized the compositional zoning of clinopyroxene crystals belonging to the Agnano-Monte Spina eruption. They highlighted that the chemical zoning for Fe–Mg plus other elements (e.g., Al, Ti) often shows two or more compositional plateaus with sharp or slightly diffuse boundaries between them. Combining textural and chemical investigations with diffusion modeling methods, Pelullo et al. (2022a) pointed to deep and shallow reservoirs beneath the CFC that were connected to each other over several tens of years. Also, they suggest that the amount of mafic recharge increased during the last 10–15 years before the Agnano-Monte Spina eruption. They suggest that the input of mafic magma by itself does not always trigger eruptions. On the contrary, Pelullo et al. (2022a) suggest that eruptions are triggered only when a threshold is exceeded such that degassing and related events are set in motion.

Other studies (Arzilli et al. 2016; D'Oriano et al. 2005; Pappalardo and Mastrolorenzo 2012; Piochi et al. 2005) focused on crystal size distribution to obtain magma residence and ascent time estimates. They often point to obtaining quick crystallization timescales in the order of hours to days (Table 2).

Stock et al. (2018) analyzed fluorine, chlorine, and water in apatite crystals, and in melt inclusions from clinopyroxene and biotite crystals belonging to the Astroni 1 eruption (4.3–4.1 ky). They combined geochemical determinations and thermodynamic modeling to reveal the evolution of the volcanic plumbing system before the eruption, highlighting that the magmatic system remained water-undersaturated throughout most of its lifetime and that the melt reached volatile saturation at low temperatures, just before the eruption. Finally, they suggested that late-stage volatile saturation probably triggered the eruptive event, with a maximum time delay between volatile saturation and eruption on the order of $10–10^3$ days.

Experimental constraints

Many studies in the field of experimental petrology have been developed to constrain the evolution of pre- and syn-eruptive dynamics within the CFC (e.g., Arzilli et al. 2016; Perugini et al. 2015; Iezzi et al. 2008; Fabbrizio and Carroll 2008; Calzolaio et al. 2010; Arzilli and Carroll 2013; Preuss et al. 2016; Vetere et al. 2011; Campagnola et al. 2016; Montanaro et al. 2016; Fanara et al. 2015; Bonechi et al. 2020, 2022). Here we focus on those experiments that allow extraction of magma ascent, residence times, and mixing-to-eruption timescales (i.e., Perugini et al. 2015; Arzilli et al. 2018; Calzolaio et al. 2010; Bonechi et al. 2022).

As an example, Perugini et al. (2015) performed magma mixing experiments using a high-temperature centrifuge where tendrils of basalt are injected into the phonolite, triggering a "fountain-like" process of mingling. The resulting mixing dynamics are intended to simulate the triggering of magma mixing in nature via injection of mafic magmas into felsic magma chambers. The natural end-members used in the experiments were an Agnano Monte-Spina phonolitic tuff and an alkali-basalt from Minopoli (CFC). The results point to: (1) the production of complex mixing patterns of filaments, swirls, and bands from mm to μm length scales; (2) morphologies of mixing patterns produced during the experiments similar to those observed in natural rock samples; (3) estimated mixing-to-eruption timescales are on the order of minutes to hours.

Calzolaio et al. (2010) performed a series of decompression experiments on samples of trachytic composition to investigate pre- and syn-eruptive growth rates of alkali feldspars in the volcanic plumbing system feeding the Monte Nuovo eruption and unravel magma ascent times. Results suggested magma ascent times ranging from several hours to 1–2 days.

Arzilli et al. (2018) reported new experimental data on elemental (i.e., Sr and Ba) partitioning between alkali feldspar and trachytic melt. The study performed short disequilibrium and long near-equilibrium experiments at 500 MPa, 870–890 °C to investigate the influence of diffusive re-equilibration on trace-element partitioning during crystallization. In detail, Arzilli et al. (2018) highlighted that the magmatic systems can rapidly pass from equilibrium to disequilibrium conditions (e.g., magma mixing and fast ascent). The application of the method proposed by Arzilli et al. (2018) to alkali feldspar in rocks erupted at the CFC constrain the magma residence time at subliquidus conditions in a reservoir to a maximum of 6 days under disequilibrium conditions and to a minimum of 9 days upon approaching near-equilibrium conditions.

Bonechi et al. (2022) investigated the effect of pressure (0.7–7.0 GPa) and temperature (1335–2000 °C) on the viscosity of anhydrous primitive alkaline basalts. They have been assumed as a proxy of possible magmas from a deep system feeding shallower reservoirs in the CFC volcanic plumbing system at the present day. Also, Bonechi et al. (2022) used the obtained results, i.e., viscosities in the order of 0.5–3.0 Pa s, to estimate ascent velocities in the range 1.5–6.0 m yr^{-1}. Finally, Bonechi et al. (2022) point at the CFC as a critical volcanic district, currently undergoing a gradual magma recharge at depth.

Numerical modeling of pre- and syn-eruptive dynamics

New modeling on magma ascent velocities

To investigate magma ascent velocities in the magmatic feeding system before the eruption, we used a model based on the magma-driven ascending dyke theory for incompressible fluids (Rubin 1993). In this model, whose methodology is explained in the Additional file 1, the excess pressure of a reservoir connected to a dyke is accounted for, along with rheological parameters, to estimate how fast the magma can travel through the crust towards the surface. After the opening of a new vent, modeling based on steady-state magma flow through vertical and cylindrical conduits open to the surface should be used (e.g., Romano et al. 2020) since they account for additional factors like magma vesiculation and magma fragmentation in the shallower system. Also, fluid dynamic modeling (e.g., Montagna et al. 2022), could provide essential information on pre-eruptive dynamics and mixing timescales.

Using the model proposed by Rubin (1993), we modeled the ascent of shoshonitic and trachytic magmas moving from a depth of 9 km, characterized by different water contents, i.e., 2 and 4 wt.% (as in Stock et al. 2018), and an average crystallinity of 10% in volume. The latter choice is motivated by the fact that the Agnano-Monte Spina pyroclasts show a crystal content in the range of

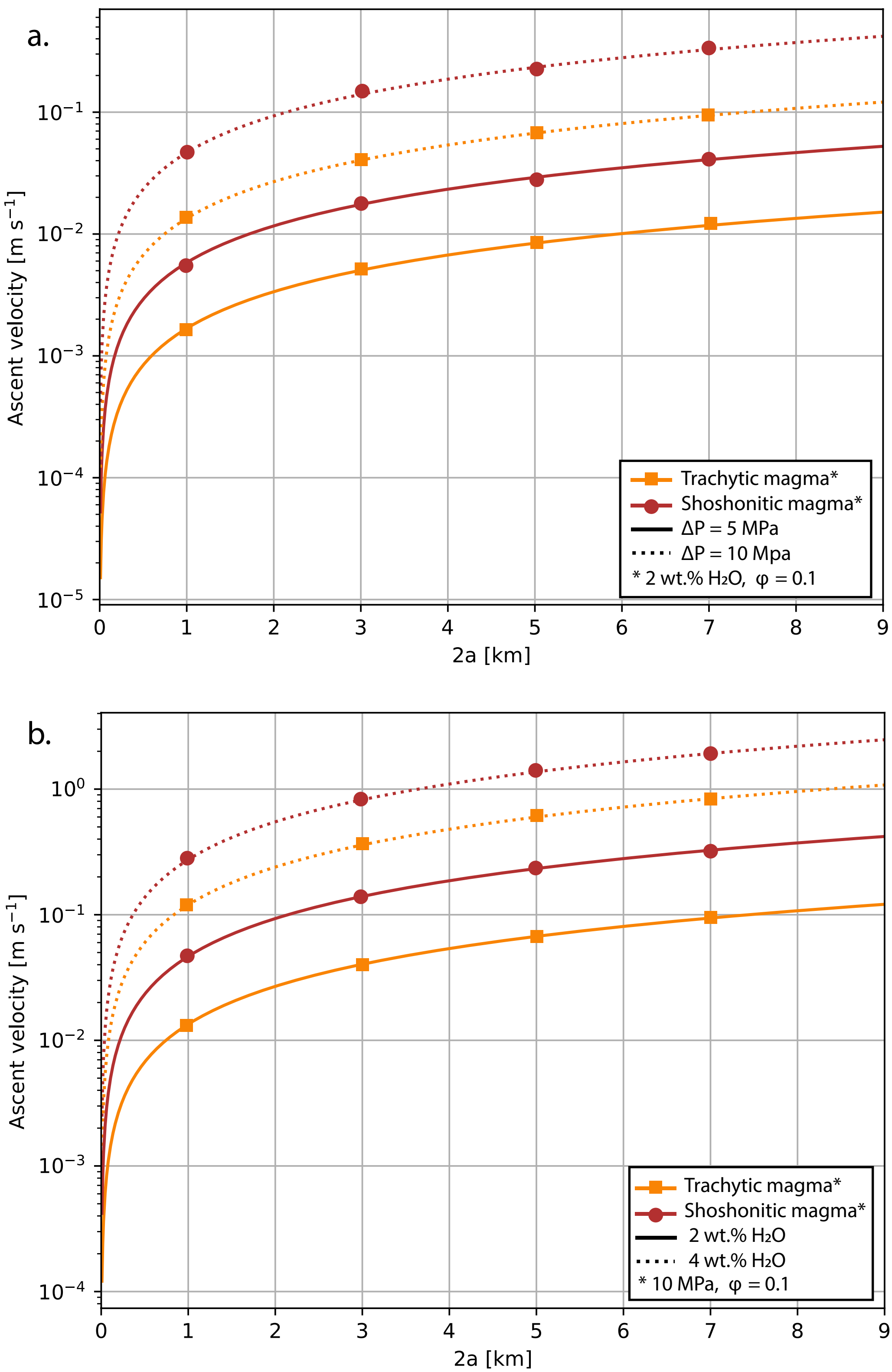


Fig. 4 Modeled ascent velocities of magmas from a 9 km reservoir, calculated after Rubin 1993 for different magmatic compositions and different values of overpressure at the reservoir

5 and 10 vol.% (Iovine et al. 2017) and crystal content in magmatic reservoir is generally modeled between 5 and 30 Vol.% (Vona et al. 2013; Stock et al. 2016, 2018). Finally, two different values of overpressure within the magmatic system were accounted (i.e., 5 and 10 MPa; e.g., Gudmundsson 2012; Geshi et al. 2020).

Figure 4a shows the results of the modeling for overpressures of 5 and 10 MPa for trachytic and shoshonitic magmas with a fixed water content of 2 wt.% and crystal volume fraction (Φ) of 0.1. With an overpressure of 5 MPa, ascent velocities are of the order of 1.5×10^{-2} m/s and 5.3×10^{-2} m/s for trachytic and shoshonitic magmas, respectively. Increasing the overpressure to 10 MPa gives final ascent velocities of the order of 1.2×10^{-1} m/s and 4.2×10^{-1} m/s for trachytic and shoshonitic magmas, respectively. Figure 4b compares the results of the modeling at 10 MPa for water contents equal to 2 and 4 wt.%, respectively. Observing Fig. 4b, it emerges that increasing the water content from 2 to 4 wt.% caused an increase of the ascent velocities of about one order of magnitude (i.e., up to velocities larger than 10^{0} m/s), due to a drop in the magma viscosity.

We can compare our estimates with those reported in Table 2. Many studies hypothesize very short timescales of magma ascent, based on estimations built on different processes that could happen during magma ascent or could cause the ascent itself. As an example, short timescales for magma ascent, i.e., in the range between a few hours and up to ~ 10 days, have been estimated by many authors (Arzilli et al. 2016; Astbury et al. 2018; D'Oriano et al. 2005; Fabbrizio and Carroll 2008; Pappalardo and Mastrolorenzo 2012; Perugini et al. 2010). Considering a reservoir at a depth of ~ 9 km, the reported timescales translate into ascent rates between 10^{0} (i.e., a magma that rises in 2 h and half) and 10^{-2} m/s (i.e., for a magma that rises in ~ 10 days). As displayed in Fig. 4, a velocity in the order of 10^{-2} m/s can account for all compositions with an overpressure of 5 MPa. Increasing the overpressure to 10 MPa magmas would easily achieve velocities on the order of 10^{-1} m/s and on the order of $\times 10^{0}$ m/s with an increase in the water content.

Role of volatiles in syn-eruptive dynamics

The evolution of the Agnano Monte Spina Eruption (i.e., the reference eruption for large-size events) after its onset has been detailed and modeled by Romano et al. (2020). They combined field, chemical, and sedimentological investigations to constrain a numerical model investigating the role of volatiles on the different transitions between sustained and collapsed columns. In detail, Romano et al. (2020) found that changes in the initial water content and minor compositional changes mainly explain different intensities and different volumes observed through the eruptive sequence characterizing the Agnano Monte Spina eruption. Also, changes in the magma water content explain a sudden drop in magma ascent rates and column collapse episodes that occurred during the A-MS eruptions.

The role of shallow reservoirs

As we reported above, shallow magma reservoirs have been identified as actively involved in pre-eruptive dynamics at the CFC (e.g., Arienzo et al. 2009, 2010; Fourmentraux et al. 2012; Astbury et al. 2018; Fedele 2022; D'Antonio et al. 2022). They often point to mixing events whereby the feeding of a shallow reservoir by volatile-rich, less differentiated magma from deeper crustal levels shortly precede the eruption. The dynamic evolution of a shallow magma chamber (2–4 km) fed by shoshonitic magmas has been numerically investigated by Montagna et al. (2022) and Montagna et al. (2015). The main aim was to unravel magma mixing dynamics and homogenization timescales. They modeled the two magmatic reservoirs hosted at a depth (considering the top of the reservoir) of 8 and 3 km, respectively. The modeling reported in Montagna et al. (2022) simulated the injection of a CO_2-rich, shoshonitic magma coming from the deep reservoir into the shallower system hosting a partially degassed phonolitic magma. These simulations reveal several interesting results: (1) soon after the beginning of the simulations, discrete plumes of light magma start rising through the shallow reservoir developing complex velocity fields and then reaching the top of the system; (2) the rising plumes are produced by the mixing of the two magmas, i.e., with 30–50 wt.% of deep components; (3) a complex pattern developed during the simulations, allowing the rapid mixing between the magmas; (4) compositional, density, and gas volume stratification occur inside the shallow system, with the maximum gas volumes at the top of the chamber; (5) the numerical modeling proposed by (Montagna et al. 2015, 2022) highlights that, at the CFC, shallow chamber replenishment shows typical mixing time scales on the order of a few hours.

Volcanological implications

Table 2 and Fig. 5 point to a wide spectrum of proposed timescale estimates for pre-eruptive dynamics occurring at the CFC. They range from minutes to hours for fast evolving mixing-to-eruption events (e.g., Perugini et al. 2015) to ~ 10 ky for the building up of eruptible magmas feeding large eruptions (e.g., Arienzo et al. 2011;

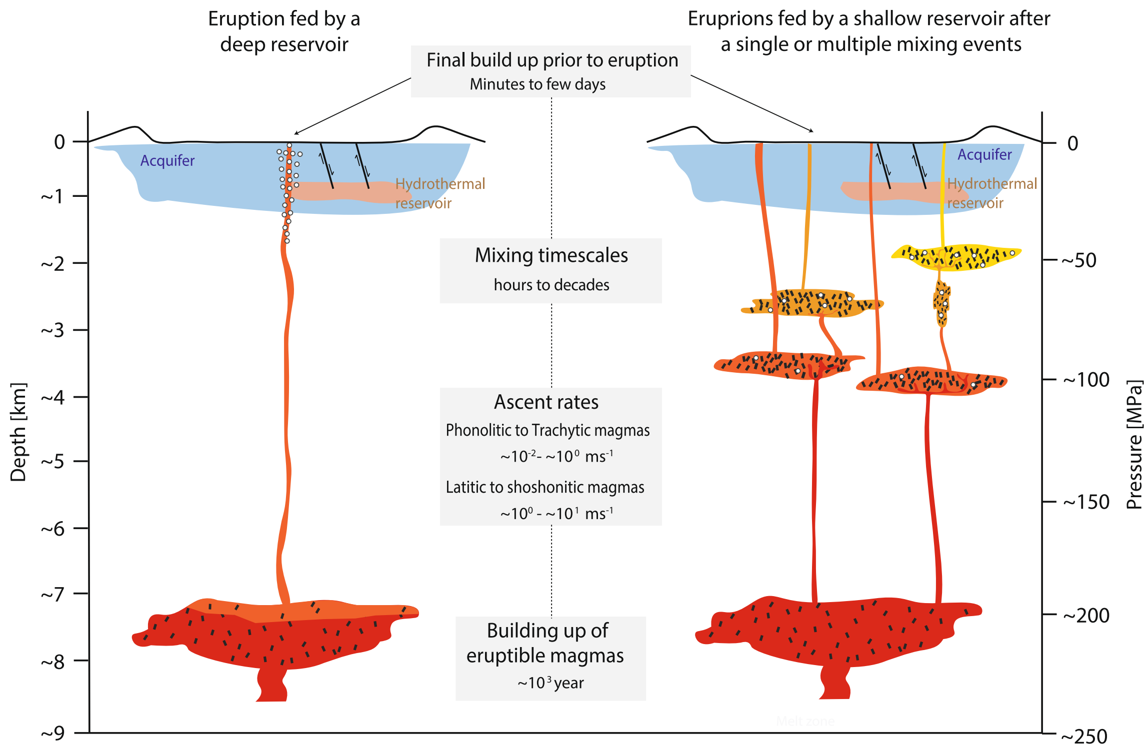


Fig. 5 Analogies and differences between two possible models for plumbing system of CFC. The two scenarios can be seen as end-members of an intermediate, variable actual arrangement of the plumbing system

Bonechi et al. 2022). These timescales agree with a trans-crustal magmatic system whereby the assembly of eruptible magmas occurs at long timescales but pre-eruptive processes may occur at medium (e.g., years to decades; Pelullo et al. 2022a; Iovine et al. 2017) or short timescales (e.g., Perugini 2021; Astbury et al. 2018).

As an example, Fig. 5 assumes magma ascent velocities as resulting from our modeling based on the magma-driven ascending dyke theory. Figure 5 depicts a magma plumbing system characterized by a main deep magma reservoir stored at ~ 8–9 km. The deep magmatic reservoir could directly feed an eruption (Fig. 5, left scenario) or interact with shallow magmatic systems (Fig. 5, right scenario). To note, the results of our modeling point to a rapid increase of ascent velocity at the beginning of the ascent path followed by a plateau. Therefore, final ascent velocities are close for both deep (~ 9 km) and shallow (3–4 km) reservoirs. As an additional consideration, shallower systems are expected to host more-evolved magmas (i.e., phonolitic and trachytic) than deep-seated reservoirs (where magmas tend to evolve from shoshonitic to phonolitic and trachytic compositions; Bonechi et al. 2022). Therefore, the results of modeling under the same boundary conditions point to higher ascent velocities for deep-seated reservoirs, where magmas are expected to be less viscous, than for shallower systems. The above considerations lead to a first conclusion: considerably fast ascent velocities (i.e., units to tens m/s) can characterize eruptions fed by both shallow (i.e., 3–4 km) and deep (i.e., ~ 9 km) reservoirs, if characterized by both shoshonitic and trachytic magmas with an excess of pressure of at least 10 MPa and H_2O content of ~ 4 wt.%. The volatile budget also plays a significant role in modulating syn-eruptive dynamics as reported by Romano et al. (2020). Changes in the volatile budget allow explain the variations in intensities and volumes observed through the eruptive sequence (Romano et al. 2020; Moretti et al. 2019).

Regarding the evolution of shallow portions of the CFC volcanic plumbing system, the progressive concentration of volatiles in the silicate melt could trigger an eruption after saturation was eventually achieved (e.g., Stock et al. 2016; Petrelli et al. 2018). Under this scenario, the refilling of the system by a new batch of magma would not necessarily culminate in an eruption because the arrival of a new mafic magma might be more volatile-undersaturated than the evolved melts within the upper crustal reservoir (Stock et al. 2016). As a result, the process of magma mixing would 'dilute' the dissolved volatile content of the silicate melt, returning the system to a more undersaturated state (Stock et al. 2016). However, as we have summarized, many records point to a direct involvement of magma mixing in pre-eruptive dynamics at CFC which suggests a role as eruption trigger (e.g., Perugini et al. 2015). Fast ascent velocities and short timescales of mixing-to-eruption events also suggest that explosive eruptions could begin with little physical 'warning', on the order of hours to days. Diffusion modelings in crystals also point to longer timescales on the order of years to decades (Iovine et al. 2017; Pelullo et al. 2022a). To reconcile these large heterogeneities in mixing-to-eruption timescales, we propose, in agreement with Pelullo et al. (2022a), that deep and shallow reservoirs were connected with the transfer of magma between them over decadal timescales. Different recharging events, over decadal timescales, have been recorded by crystal zoning as reported by Pelullo et al. (2022a). In agreement with Pelullo et al. (2022a) and Stock et al. (2016), a single mixing event does not necessarily trigger an eruption. Notably, volatiles always play a significant role (e.g., Mastrolorenzo and Pappalardo 2006; Chiodini et al. 2015; Montagna et al. 2015; Stock et al. 2016; Astbury et al. 2018; Forni et al. 2018a; Pelullo et al. 2022a). Finally, rapid mixing-to-eruption timescales (i.e., minutes to days) refers to the last recharging event that destabilizes the magmatic system if acting in conjunction with an associated degassing event, creating the ideal conditions for an eruption to be triggered (e.g., Pelullo et al. 2022a).

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s40623-023-01765-z.

Additional file 1: Table S1. Physical parameters used in the magma ascent velocities calculations. **Table S2**. Viscosities calculated and used for the magma ascent velocity modeling.

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Author contributions

MP conceived and supervised the work. MAL and AP did the estimations of ascent velocities. All the authors worked on and contributed to writing the manuscript. All authors read and approved the final manuscript.

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Availability of data and materials

All the data and codes will be made available on an open-source repository.

Declarations

Competing interests

The authors declare no competing interests.

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