Open-System Behaviour at the Campi Flegrei Caldera: from Evidence of Magma Mixing to pre-Eruptive Timescales

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Research Article

Keywords: Campi Flegrei Caldera, Campanian Ignimbrite, Neapolitan Yellow Tuff, mixing-to-eruption timescales, magma ascent velocity

Posted Date: June 1st, 2022

DOI: https://doi.org/10.21203/rs.3.rs-1662425/v1

Version of Record: A version of this preprint was published at Earth, Planets and Space on February 3rd, 2023. See the published version at https://doi.org/10.1186/s40623-023-01765-z.

Abstract

We review the evidence of open-system behavior in the volcanic plumbing system of the Campi Flegrei Caldera. Also, we highlight the estimates of magma residence time, magma ascent, and mixing-to-eruption timescales. In detail, we concentrate on the Campanian Ignimbrite ~ 40ka, the Neapolitan Yellow Tuff (~ 15ka), and the recent activity within the Phlegrean area. We start highlighting the evidence of magma mixing on the pyroclastic rocks deriving from different sources (e.g., crystal disequilibria, vertical zonings, and isotopic records). Then we describe geophysical and geochemical data of the magma feeding system with a focus on magma residence times and mixing to eruption timescales. Also, we link the timescales of magma ascent reported in the literature with a physically constrained model based on the magma-driven ascending dyke theory. Results show that considerably fast ascent velocities (i.e., units to tens m/s) can be easily achieved for eruptions fed by both shallow (i.e., 3–4 km) and deep (i.e., ~ 9 Km) reservoirs when characterized by large enough overpressures (i.e., > 25 MPa). Finally, we highlight the volcanological implications of timescale estimates for residence time and ascent in both open- and closed-system behavior of the volcanic plumbing system. The main aim is to provide constraints to the volcanic hazard definition of the area.

Introduction

Open system processes are not an exception in volcanic plumbing systems (Perugini, 2021). Among them, magma mixing is the dominant one (Druitt et al., 2012; Kent et al., 2010; Leonard et al., 2002), and it is associated with many of the most explosive volcanic eruptions on Earth (Druitt et al., 2012; Kent et al., 2010; Leonard et al., 2002). This being so, magma mixing represents a common factor deserving further investigations with the aim of understanding dynamics and timescales of volcanic explosions (Astbury et al., 2018; Di Renzo et al., 2011).

From the petrologic point of view, the interaction between magmas of different compositions is often described using the terms “magma mingling” and “chemical mixing” (Perugini and Poli, 2012). The first term, i.e., “magma mingling”, refers to the process of physical dispersion (with no chemical exchanges) of one or more magma in another magma. The latter, i.e., “chemical mixing” considers the chemical exchanges between the interacting magmas driven by compositional gradients (e.g., Flinders and Clemens, 1996). In Nature, it is often not easy to distinguish between magma mingling and chemical mixing processes, because they mostly occur jointly during the interaction of different magmas. Therefore, many authors utilize the general term magma mixing (*sensu latu*) to describe the interaction of two or more different magmas (Perugini, 2021).

It is widely accepted that magmas can mix effectively when they have similar viscosities (e.g., Bateman, 1995; Sparks and Marshall, 1986). These rheological conditions can occur when: (a) the interacting magmas share similar rheology since the beginning of the interaction, or (b) they achieve similar viscosities in response to evolutionary processes (e.g., Bateman, 1995; Sparks and Marshall, 1986). The mixing of magmas can therefore happen at any instant during the evolution of a magmatic system if chemical gradients occur. This means that magma mixing could coexist with other processes such as fractional crystallization, assimilation, or partial melting, which both produce thermal and chemical gradients.

From the volcanological point of view, the presence of magma mixing marks the edge between two different pre-eruptive scenarios for the volcanic plumbing system: close- and open-system evolution (Orsi et al., 2022; Rosi et al., 2022; Stock et al., 2016). The identification of magma mixing is therefore of paramount importance to provide constraints on the behavior of a volcanic plumbing system and to provide hypotheses on the definition of volcanic hazard scenarios (Orsi et al., 2022; Rosi 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. Together with two catastrophic events, i.e., the Campanian Ignimbrite (~ 40ka) and the Neapolitan Yellow Tuff (~ 15ka), the Campi Flegrei caldera has been experienced an intense eruptive activity the past 15 ka, with 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 magma mixing is widespread in the CFC. As an example, the Campanian Ignimbrite shows evidence of crystal-mush remobilization by mafic magma recharges (Civetta et al., 1997), as well as the Neapolitan Yellow Tuff (Forni et al., 2018b). Also, many of the eruptions belonging to the recent activity (i.e., past 15 ka), e.g., Averno (~ 3.7 ka; Di Vito et al., 2011), Astroni (4.8–3.8 ka; Arienzo et al., 2016; Astbury et al., 2018), Agnano Monte Spina (~ 4.1 ka; Arienzo et al., 2010), and Monte Nuovo (1538 AD; Di Vito et al., 2016), show evidence of magma mixing. Although the CFC is a widely studied area (Orsi et al., 2022; Rosi et al., 2022), an exhaustive review of the temporal evolution of the volcanic plumbing system and mixing-to-eruption timescales and magma ascent velocities is still missing.

In this work we report on the evidence of magma mixing at the CFC as an indication for open-system behavior of the volcanic plumbing system. Then we highlight the estimates of magma residence time, magma ascent, and mixing-to-eruption timescales within the CFC with the aim of providing physical constraints to the volcanic hazard definition of the area (Orsi et al., 2022; Rosi et al., 2022).

Evidence Of Magma Mixing At The Campi Flegrei Caldera

The present review covers the two catastrophic events producing the Campanian Ignimbrite (~40ka) and the Neapolitan Yellow Tuff (~15ka) as well as all the recent eruptive activity within the CFC in the past 12 ka (Figure 1).

Campanian Ignimbrite (CI)

Although some authors point to a mainly closed-system evolution by fractional crystallization (e.g., Fedele et al., 2008; Fowler and Spera, 2008), many others propose magma mixing (i.e., open-system evolution) as a key process for the CI magma feeding system (e.g., Arienzo et al., 2009; Civetta et al., 1997; Pappalardo et al., 2008, 2002; Signorelli et al., 1999).

As an example, (Arienzo et al., 2009; Di Renzo et al., 2011) describe the existence of two isotopically distinct CI magmas based on Pd- and Nd-isotope data. Also, (Civetta et al., 1997) proposed that the compositional variation within the CI results from a combination of crystal-liquid fractionation and 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 particular, some studies (Forni et al., 2016; Di Salvo et al., 2020) provided a detailed description of the CI feeding system, proposing the occurrence of a crystal-mush zone, characterized by a buoyant cap of evolved magma. In such scenario, the recharge of hotter and less evolved magma acted as the trigger for the CI eruption. Quantitative modeling by Forni et al., 2018 and Di Salvo et al., 2020, demonstrate that the geochemical and isotopic fingerprint of CI magmas resulted from multiple petrologic processes due to the evolution of the CI crystal-mush by fractional crystallization coupled with the physical and chemical interaction with new mafic magma that reactivated the CI system. In detail, both the cited suggested 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, then allowing the triggering of 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; 14.9 ka, Deino et al., 2004) is not straightforward (e.g., Forni et al., 2018b; Orsi et al., 1995, 1992; Scarpati et al., 1993). As an 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. At the highest level, the magma was of alkali-trachyte composition, it was highly homogeneous and probably resulted from vigorous convection. The magma filling the intermediate layer was of trachytic composition, showing heterogeneities, also experiencing 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 such scenario proposed by Orsi et al., 1995, the three magmas filled the magmatic system sequentially, with the last one approaching the system shortly before the beginning of the eruption and possibly acting as the eruption trigger. 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. In such scenario the compositional variations observed in the NYT do not reflect a vertically zoned magma chamber. Rather, it results from the complex interaction between different magmatic components stored in a heterogeneous upper crustal magma reservoir and progressively tapped. In particular, Forni et al., 2018b point to the occurrence of disequilibrium mineral phases, which suggests interaction with a less evolved recharging magma. Again, the same study indicates 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. Such a scenario is also supported by the presence of intermediate rock compositions hosting crystals deriving from both the host and the refilling magmas. In agreement with Forni et al., 2018b, mixing among all the different components (i.e., evolved host magma, the one deriving from the melting of cumulates, and the less evolved refilling magma) might also explain the broad compositional ranges observed in the Upper Member of the NYT sequence.

Recent activity of the Campi Flegrei Caldera

In the recent activity of the CFC, the evidence of magma mixing is widespread (e.g., (Arienzo et al., 2010; Astbury et al., 2018; D'Antonio et al., 1999; Di Vito et al., 1999). The isotopic record provides many clues to unravel the open-system evolution of the recent activity within the CFC (e.g., Di Renzo et al., 2011; Di Vito et al., 1999). As an example, (D'Antonio et al., 1999) pointed to three isotopically and geochemically distinct magmatic components that erupted in the past 12 ka. They are a Campanian Ignimbrite component (CIc; 87Sr/86Sr ~0.70735–0.70740), a Neapolitan Yellow Tuff component (NYTc; 87Sr/86Sr ~0.70750–0.70757), and a Minopoli component (MIc 87Sr/86Sr 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 first phase of the Campanian Ignimbrite, to the latitic–alkali–trachytic magma batches extruded the Neapolitan Yellow Tuff, and to the trachybasaltic 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 ka, 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 143Nd/144Nd and 206Pb/204Pb ratios as reported in Figure 2. In particular, two components agree with the characterization reported by D'Antonio et al., 1999. They are the NYTc (87Sr/86Sr of 0.70750–53, 143Nd/144Nd ratio of ca. 0.51246, 206Pb/204Pb of ca. 19.04 and δ11B of ca. −7.9‰) and the MIc (87Sr/86Sr of ca. 0.70860, 143Nd/144Nd ratio of ca. 0.51236, 206Pb/204Pb of ca. 18.90, δ11B value of ca. −7.32‰). The third component in the characterization proposed by Di Renzo et al., 2011 is the Astroni 6 component (A6c) characterized by lower 87Sr/86Sr values than the CIc originally proposed by D'Antonio et al., 1999: in detail, the A6c points to 87Sr/86Sr values close to 0.70726, 206Pb/204Pb of ca. 19.08, 143Nd/144Nd of ca. 0.51250, and δ11B of −9.8‰.

To mention a few specific cases, Arienzo et al., 2010, pointed to two batches of magmas that mixed during the eruption of Agnano Monte Spina. This conclusion is supported by isotope data. In detail, one component was similar to the Minopoli shoshonite (i.e., the MIc proposed by D'Antonio et al., 1999), whereas the second agrees with the NYTc reported by D'Antonio et al., 1999. As a physical scenario, 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.

Also, for the case of Averno 2 fissure eruption (Di Vito et al., 2011), isotopic evidence supports 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 87Sr/86Sr values close to 0.70750-0.70750 and 0.70753-0.70754, respectively.

Sr isotopic data on samples belonging to the Astroni 6 eruption reported by Arienzo et al., 2015, again suggest the presence of a magma similar to the NYTc reported by D'Antonio et al., 1999, i.e., 87Sr/86Sr close to 0.70750. Also, the same samples highlight the occurrence of a magma characterized by 87Sr/86Sr values close to 0.70724, interpreted as a magmatic component that entered the CFC feeding system in the past 5 ka, and described by Morgavi et al., 2017. Also, some crystals in Astroni 6 show peculiar 87Sr/86Sr values, in the range of 0.7060–0.7068 and high 143Nd/144Nd ratios, close to Ischia isotopic compositions D'Antonio et al., 2013. Arienzo et al., 2015, proposed that these compositions may represent another common magmatic component, as they have been found in most of the Phlegrean Volcanic District products emplaced over the past 75 ka. The same study proposed that the isotopic variations found in whole rocks, the evidence of isotopic disequilibrium between minerals and glasses, and the huge variation in the Sr isotopic record within single crystals can all be accounted for magma mixing processes. In addition to these isotopic constraints, Astbury et al., 2018, performed a combined use of textural investigations, geochemical data on glasses and crystals, and high-resolution trace element maps of the A6 crystal cargo to reveal the pre-eruptive dynamics occurred before the A6 eruption. Such study disclosed the evolution of the A6 plumbing system involving two separate magma bodies: (a) an evolved magma stored in a shallow system; (b) a less evolved magma represented originally stored at a depth of ~7 km, 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 A6 eruption.

The isotopic record also points to open-system behavior for the Nisida Eruption (~ 4 ka BP; Arienzo et al., 2016). In detail, Arienzo et al., 2016, proposed the arrival of a volatile-rich, shoshonite–latite magma, close to the A6c (i.e., 87Sr/86Sr ~ 0.70730; 143Nd/144Nd ~ 0.51250) which triggered the Nisida eruption. Also, the same study 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 ka.

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. Combining analytical determinations and rhyolite-MELTS modeling, Esposito et al., 2018, highlighted a group of melt inclusions that recorded a polybaric fractional crystallization at depths ranging from ≥7.5 km to ~1 km of a volatile-saturated magma. Also, such study reported a group of melt inclusions recording the refilling of the shallow system by a less evolved magma which mixed with the resident magma before the eruption.

The only historical Eruption within the CFC, i.e., Monte Nuovo (1538 AD), also shows evidence of magma mixing: in particular, Di Vito et al., 2016, reported that the volcanic products belonging to the Monte Nuovo eruption result from the mixing between two magmas: the first stored at shallow levels, i.e., 4-5 km; the second possibly intruding the shallow reservoir.

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 (Bianco et al., 2022; Bonechi et al., 2022; De Siena et al., 2017, 2014, 2010; Di Renzo et al., 2011; Fedi et al., 2018; Vaggelli et al., 2006)

Many models agree with the presence of different magma reservoirs at ~7 km and ~2-3 km, as depicted in Figure 3, 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).

Exploring the magma feeding system at deeper levels, Fedi et al., 2018, suggested two possible scenarios: 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; the second proposes a fractal density distribution, derived by a distribution of discrete melt pockets within host rocks. Both the proposed scenarios agree with the available volcanological and seismic constraints. These two scenarios can be considered as the end members of a trans-crustal volcanic plumbing system (i.e., 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 Figure 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 2-3 km.

Magma Residence Times And Mixing-to-eruption Timescales At The Campi Flegrei Caldera

Many authors attempted the definition pre- and syn-eruptive timescales at the CFC (Table 1 and references therein). Most of the proposed estimates (e.g., mixing-to-eruptions estimates) refer to an open-system scenario that appears to be widespread within the CFC, as reported in the previous section. Mixing timescales 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. Many of the reported investigations (e.g., crystal size distributions) can be applied to both open- and closed-systems, and finally, the scenario proposed by Stock et al., 2018 is relevant for the evolution of a closed-system behavior of the volcanic plumbing system.

Modelling 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 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 constraints the timescales of open-system processes before the ∼4.7 ka Agnano-Monte Spina eruption by combining backscattered electron imaging and quantitative electron microprobe determinations on 50 sanidine crystals focusing on chemical zonations close to crystal rims. Obtained results range from 3 to 60 years.

Other studies (Arzilli et al., 2016; C. D'Oriano et al., 2005; L. Pappalardo and Mastrolorenzo, 2012; Piochi et al., 2005) focused on Cristal Size Distribution estimates, obtaining quick crystallization timescales in the order of hours to days.

Stock et al., 2016, 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 ka). In detail, Stock et al., 2016 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, Stock et al., 2016, suggested that late-stage volatile saturation probably triggered the eruptive event, with a maximum time delay between volatile saturation and eruption of the order of $10–10^3$ days.

Numerical Modelling

Montagna et al., 2022, and Montagna et al., 2015, used numerical modeling of magma mixing in the framework of the CFC to unravel magma mixing dynamics and homogenization timescales. In detail, the former of the cited study modeled the dynamics of magmas within the plumbing system of the CFC by a deep reservoir, schematized as a sill, feeding a shallow system whose geometry varied from oblate to prolate. The models reported in Montagna et al., 2022, simulated the injection of CO_2-rich, shoshonitic magma coming from the deep reservoir into the shallower system hosting a partially degassed phonolitic magma. The results of these simulations reveal several interesting issues: 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 to 50 wt% of deep components; 3) 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., 2022, 2015) highlights that, at CFC, shallow chamber replenishment shows typical mixing time scales in the order of a few hours.

Experimental Constraints

Many experiments in the field of experimental petrology have been developed in order to provide constraints about the evolution of magma mixing within the CFC (Arzilli et al., 2016; Fabbrizio et al., 2006; Fabbrizio and Carroll, 2008; Perugini et al., 2015)

As an example, Perugini et al., 2015, performed magma mixing experiments using a Cryofuge 8500i centrifuge (Heraeus InstrumentsTM), modified to host a high-temperature furnace (up to 1200 °C). The temperature has been monitored by three Pt–PtRh10 (type S) thermocouples, positioned at the top, middle, and bottom of the Pt-capsule containing the samples, respectively. The natural end-members, utilized 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 in the order of minutes to hours.

Arzilli et al., 2018, reported new experimental data on element partitioning between alkali feldspar and trachytic melt. In detail, such 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. This investigation is relevant from the present study since natural 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 from 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.

Fabbrizio and Carroll, 2008, investigated phase relations of samples of the Breccia Museo Eruption (BME; ~20 ky), an explosive event that occurred during the caldera-forming phase of the Ignimbrite Campana eruption. In detail, experiments were conducted in temperature and pressure ranges of 700 to 885 °C and 50 to 200 MPa, respectively. Also, the crystallization experiments were performed at fO_2 = NNO + 1 log unit, and the water contents from 3.4 to 8 wt.% (H_2O saturation). These authors compared the experimental products with natural samples to unravel the pre-eruptive conditions of the BME and they suggest that the journey of the magma from the reservoir at 150 MPa to the surface was very fast requiring hours to a maximum of 1–2 days.

Magma Ascent Velocities

To investigate magma ascent velocities, we utilized a model based on the magma-driven ascending dyke theory for incompressible fluids (Rubin, 1993). In this model, whose methodology is explained in the supplementary material, the excess pressure of a reservoir connected to a dyke is accounted, jointly with rheological parameters, to estimate how fast the magma can travel through the crust towards the surface. In detail, we modelled four different magmas (i.e., phonolitic, trachytic, latitic and shoshonitic) moving from a depth of 9 km with a water content of 2 wt.% (as in Stock et al., 2018) and an average crystalline content of 10% in volume. This choice is motivated by the fact that that Agnano-Monte Spina pyroclasts show a crystalline content in the range of 5 and 10 vol.% (Iovine et al., 2017) whereas crystalline content in magmatic reservoir is generally modelled between 5 and 30 Vol.% (Stock et al., 2018; Vona et al., 2013). Finally, three different values of overpressure within the magmatic system were accounted (i.e., 5, 20, and 50 MPa).

Figure 4 shows the results of the modelling. With an overpressure of 5MPa, final ascent velocities are of the order of $2x10^{-2}$ m/s and $7x10^{-2}$ m/s for Phonolityc-Trachytic and Latitic-Shoshonitic magmas, respectively. Increasing the overpressure to 25MPa, final ascent velocities are of the order of 10^{-0} m/s and $5x10^{-0}$ m/s for Phonolityc-Trachytic and Latitic-Shoshonitic magmas, respectively. Finally, for a value of overpressure of 25 MPa, final ascent velocities are of the order of $2x10^{-1}$ m/s and $7x10^{-1}$ m/s for Phonolityc-Trachytic and Latitic-Shoshonitic magmas, respectively.

We can compare our estimates with those reported in Table 1. 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 hours and up to 9 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 and 10^{-2} m/s. Such velocity, as displayed in Figure 4, can be accounted for all compositions with an overpressure of 5MPa. An overpressure of 25 MPa, for example, would allow to achieve a velocity of 10^0-10^{-2} m/s even more rapidly. Among the studies reported in Table 1, Perugini et al., 2015, reports a possible ascent timescale in the order of minutes, which translates into an ascent rate in the order >10 m/s. By looking at Figure 4, it is possible to see that such ascent velocities require an overpressure of ca. 50 MPa at the reservoir.

The hypothesized overpressure values might appear relatively high if compared with the ones used to model general magmatic systems (Rivalta et al., 2015). However, we relied on the studies proposed by Trasatti et al., 2005 and Trasatti and Bonafede, 2008, which, for the 1982–1984 unrest episode (De Siena et al., 2017) calculated a possible overpressure of 50 MPa at the shallow (3-4 Km) magmatic reservoir, based on the visco-elastic deformation of the host rocks which caused an uplift of more than 1.5 meters in the area of the Pozzuoli city center.

Nevertheless, such a model does not exhaustively describe the scenario of ascending magma, since ascent rates can be heavily influenced by two factors: vesiculation and crystallization. The former contributes to lowering melt density and therefore increasing the buoyancy of the magmatic system (Taisne and Jaupart, 2011). As an example, Petrelli et al., 2018, reported an increase in the ascent velocity up to a factor of 10, on a ~10 Km path of ascent. On the other hand, decompression-driven crystallization is capable of lowering the ascent rate by increasing the viscosity of the magmatic system (Annen, 2009). However, crystal growth also depends on many factors, including the degree of equilibrium of the system (La Spina et al., 2016). Also, crystal growth could be strongly inhibited in fast ascending magmas, i.e., when the average ascent velocity is larger than ~1 m s^{-1} (La Spina et al., 2016; Petrelli et al., 2018).

Volcanological Implications Of Timescale Estimate For Open And Closed System Evolution

Pre eruptive scenarios of the CFC, as discussed in the previous sections, has been often described as an open system of connected magma reservoirs at different depths (Akande et al., 2019; De Siena et al., 2017, 2010; Zollo et al., 2008; Bonechi et al., 2022), or as a locally closed system (Stock et al., 2018). These two end-member scenarios are depicted in Figure 5. The final ascent velocities reported in Figure 4, fit well a closed system scenario with a magma reservoir stored at ~9Km (Fig 5, left scenario; Stock et al., 2018). However, given that modelled velocity increases rapidly at the beginning of the ascent path, such velocities are also close to those of shallower reservoirs, i.e., up to 3-4 Km. As an additional consideration, shallower systems are expected to host more evolved magmas (i.e., phonolitic and trachytic) than deep seated reservoirs, where the probability to find less evolved magmas progressively increases with the depth (Bonechi et al., 2022). Therefore, under the same boundary conditions, the ascent velocities are expected to be lower for shallower systems than for deep seated reservoirs.

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) if characterized by large overpressures (i.e., > 25 MPa). The question is: will these eruptions be announced by significant pre-eruptive warning signals? Recording ground deformation and monitoring the seismicity of shallow systems during unrests can successfully monitor long- to mid-term magma assembly (Druitt et al., 2012) and magma migration (De Siena et al., 2017). However, monitoring ground and shallow seismic records alone could not be effective to intercept fast-rising events from deep magmatic systems (e.g., Petrelli et al., 2018). Also, considering the current deformation state of the CFC, being at the maximum since the beginning of the instrumental monitoring that started ~50 years ago, with significant unrests (e.g., the inflating that occurred in 1984; De Siena et al., 2017), followed by a significant deflate, we can state that the vertical deformation alone, could led to misleading conclusions. Moreover, in the case of fast refilling events, investigations should be targeted at monitoring not only shallow systems, but the efforts should focus on deeper systems, possibly characterized by over-pressurized magmas, that might rapidly evolve toward explosive eruptions.

Regarding the closed-system evolution of shallow portions of the CFC volcanic plumbing system, the progressive concentration of dissolved H_2O in the silicate melt could trigger eruption after saturation was eventually achieved (e.g., Petrelli et al., 2018; Stock et al., 2016). Under this scenario, the refilling of the system by a new batch of magma could 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. 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.

As for the volcanological implications, the results reported by Stock et al., 2016, highlight that the volcanic plumbing systems could stay under volatile-undersaturated for a long time, e.g., decadal to centennial timescales reported by Druitt et al., 2012. As reported by Stock et al., 2016, the potential for persistent magmatic volatile undersaturation has significant implications for the monitoring of restless volcanoes. As an example, explosive eruptions could begin with little physical 'warning', on the order of days to months. In this case, the onset of volatile saturation might provide pre-eruptive indicators (Stock et al., 2016). Clues could be the leakage of magmatic volatiles, and an increased magmatic component in fumarolic gases at the surface (Chiodini et al., 2012; Stock et al., 2016).

Declarations

Availability of data and materials

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

Competing interests

We declare no competing interests

Funding

PRIN2020 Dynamics and timescales of volcanic plumbing systems: a multidisciplinary approach to a multifaceted problem (202037YPCZ_001)

Authors' contributions

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

Acknowledgement

The authors kindly acknowledge the EPS staff and editors for the editorial handling of the manuscript.

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Tables

Table 1 is available in the Supplementary Files section.

Figures

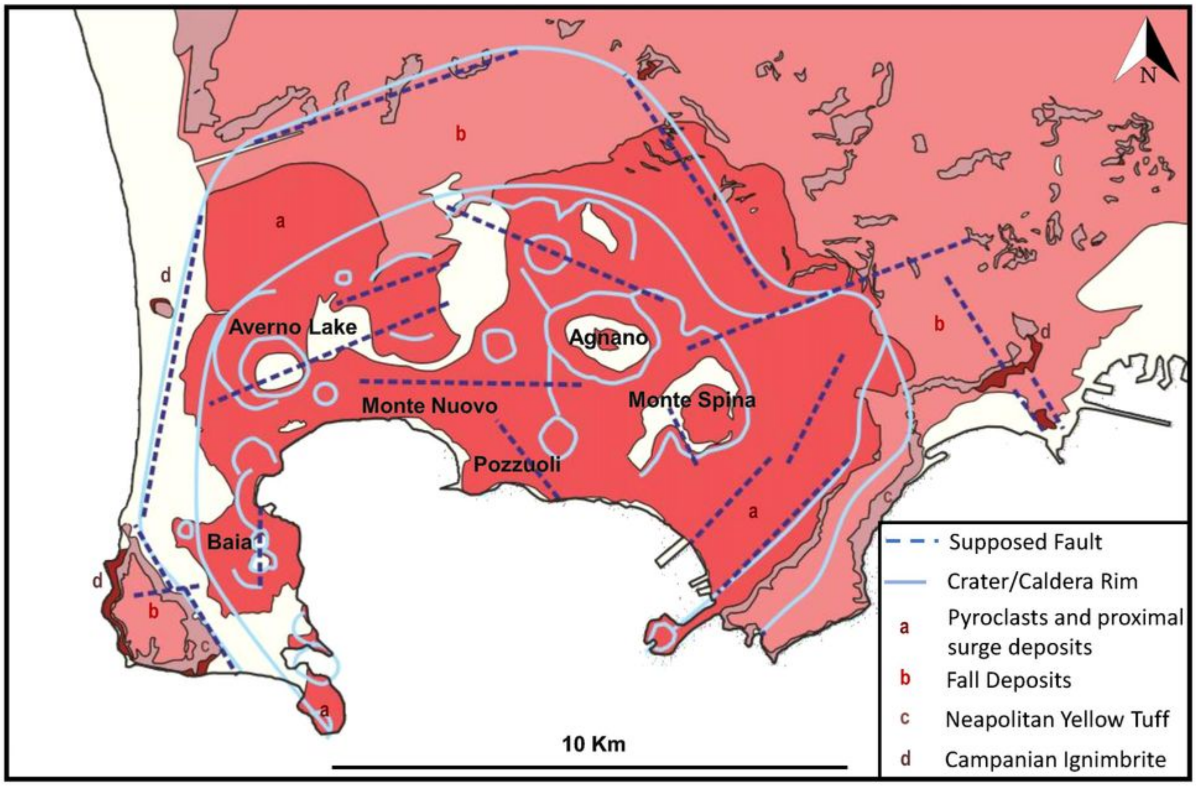

Figure 1

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

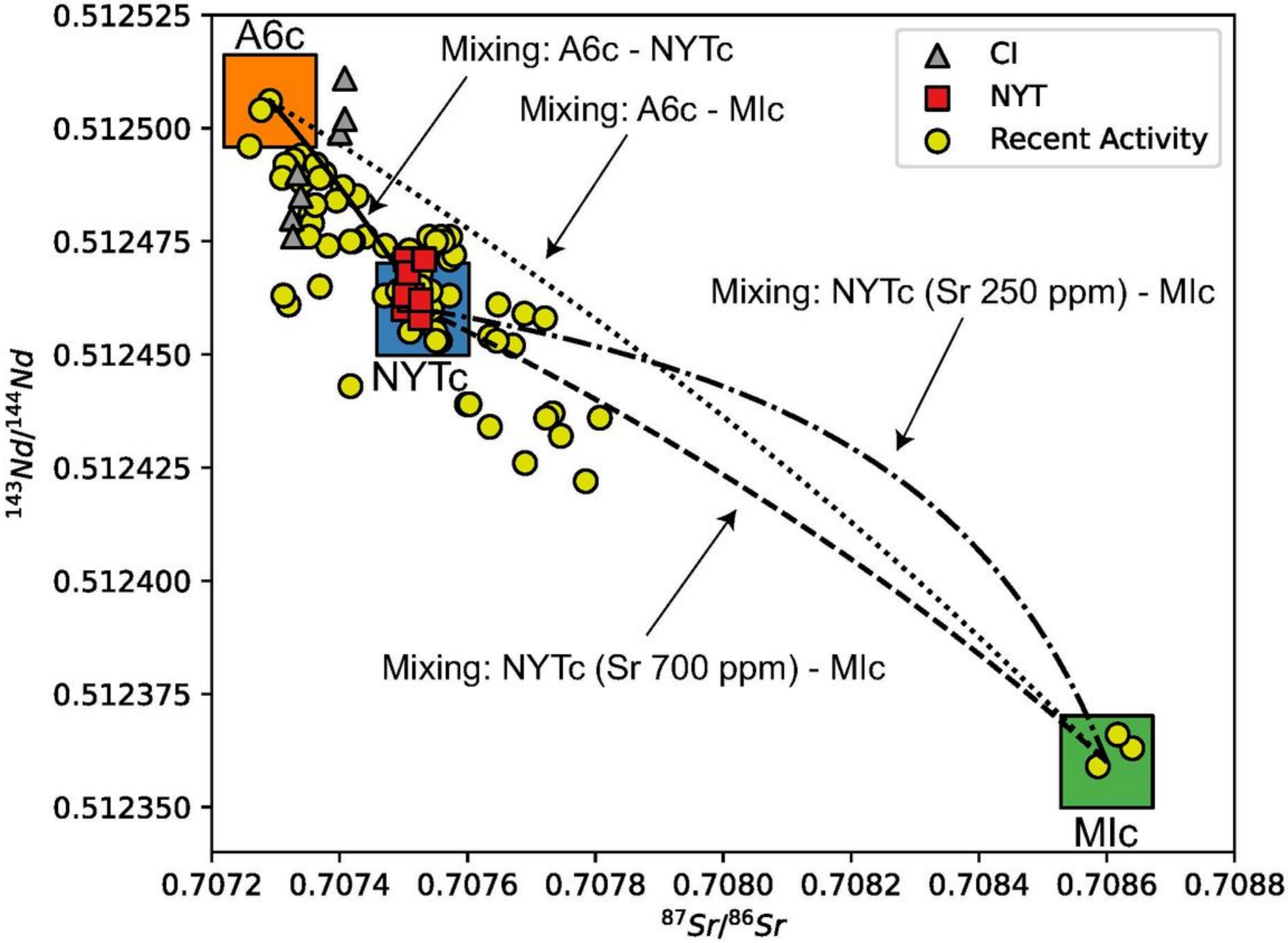

Figure 2

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). Error bars are smaller than datapoints. Modified after Arienzo et al., 2016.

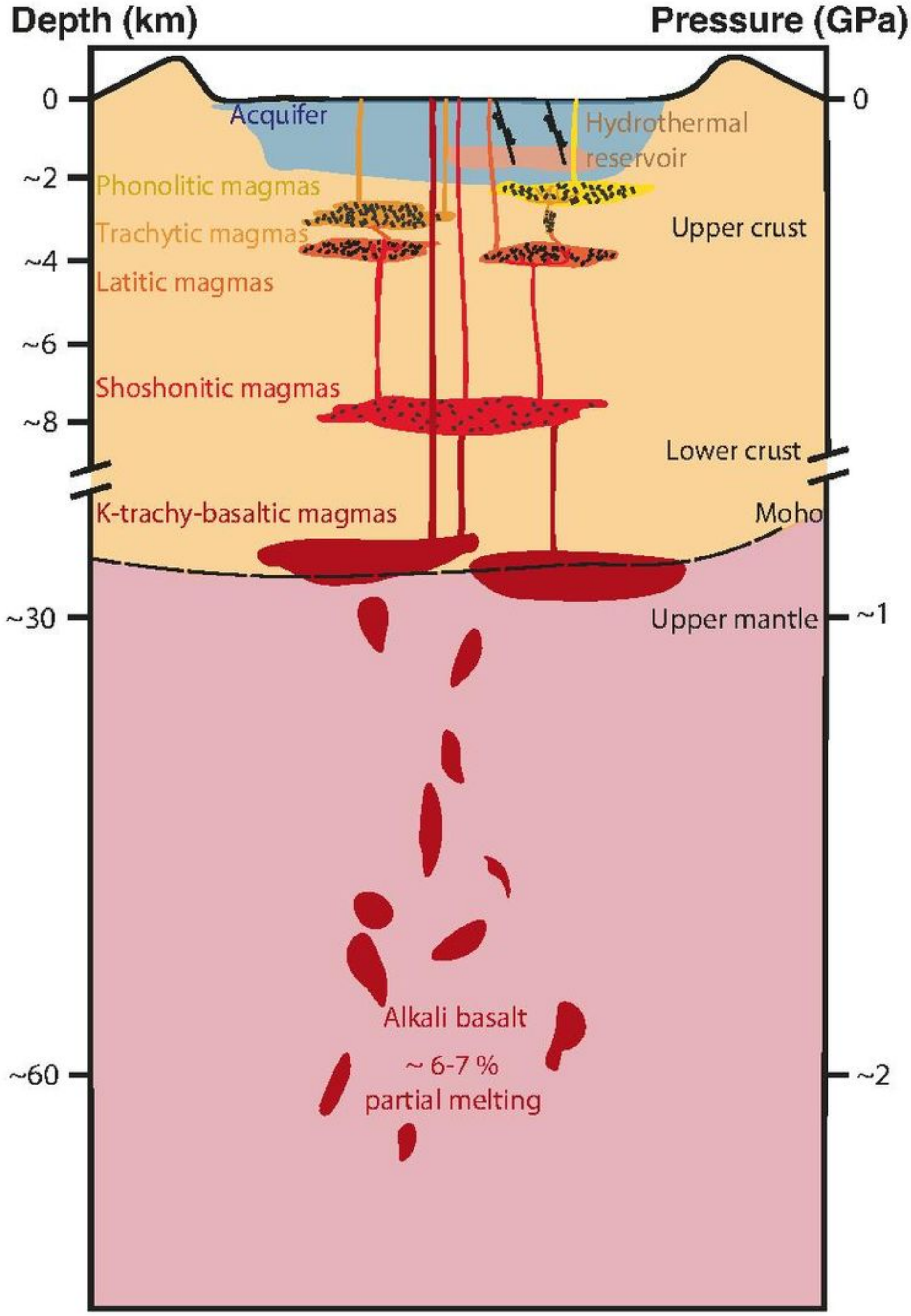

Figure 3

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

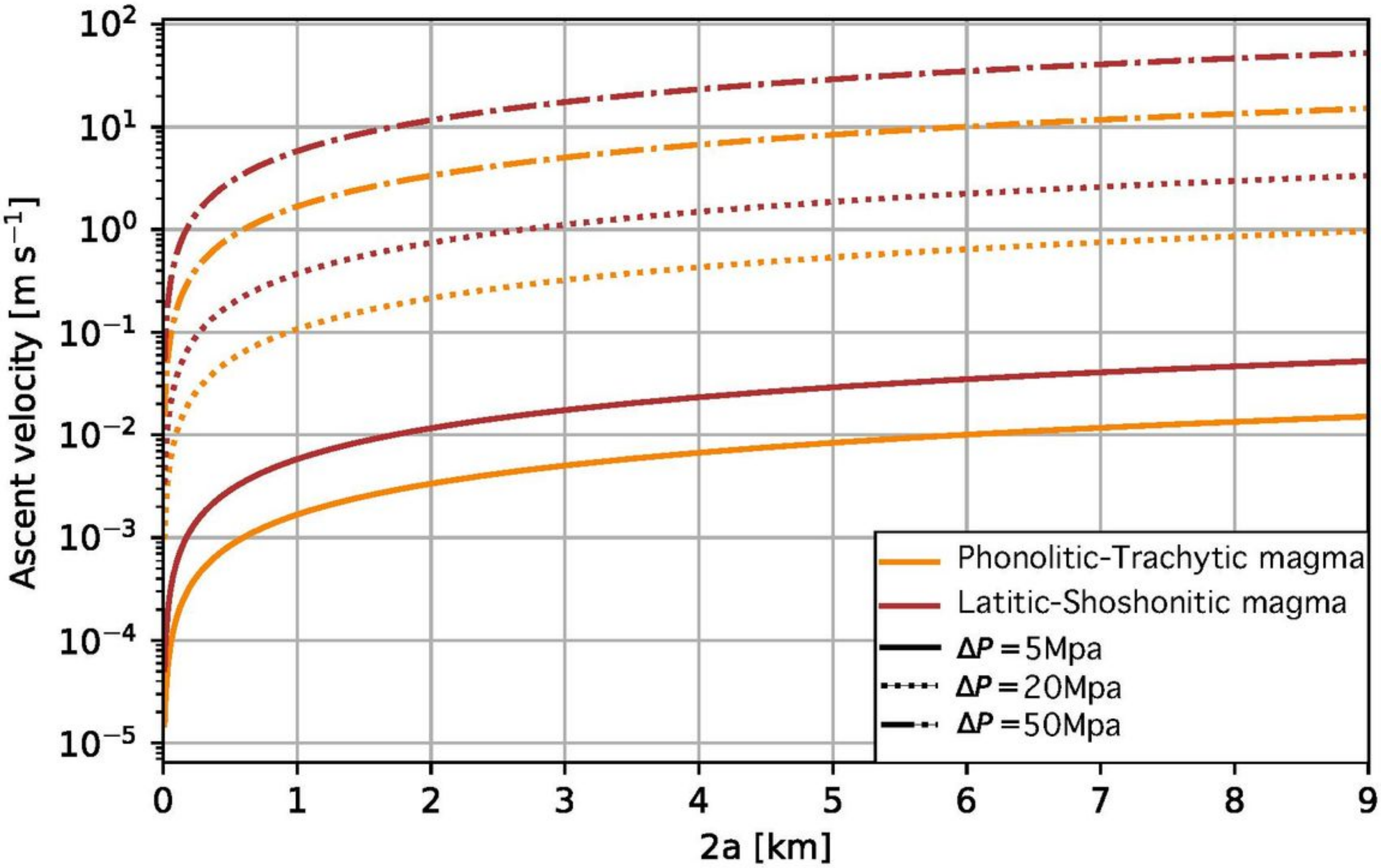

Figure 4

Modelled 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.

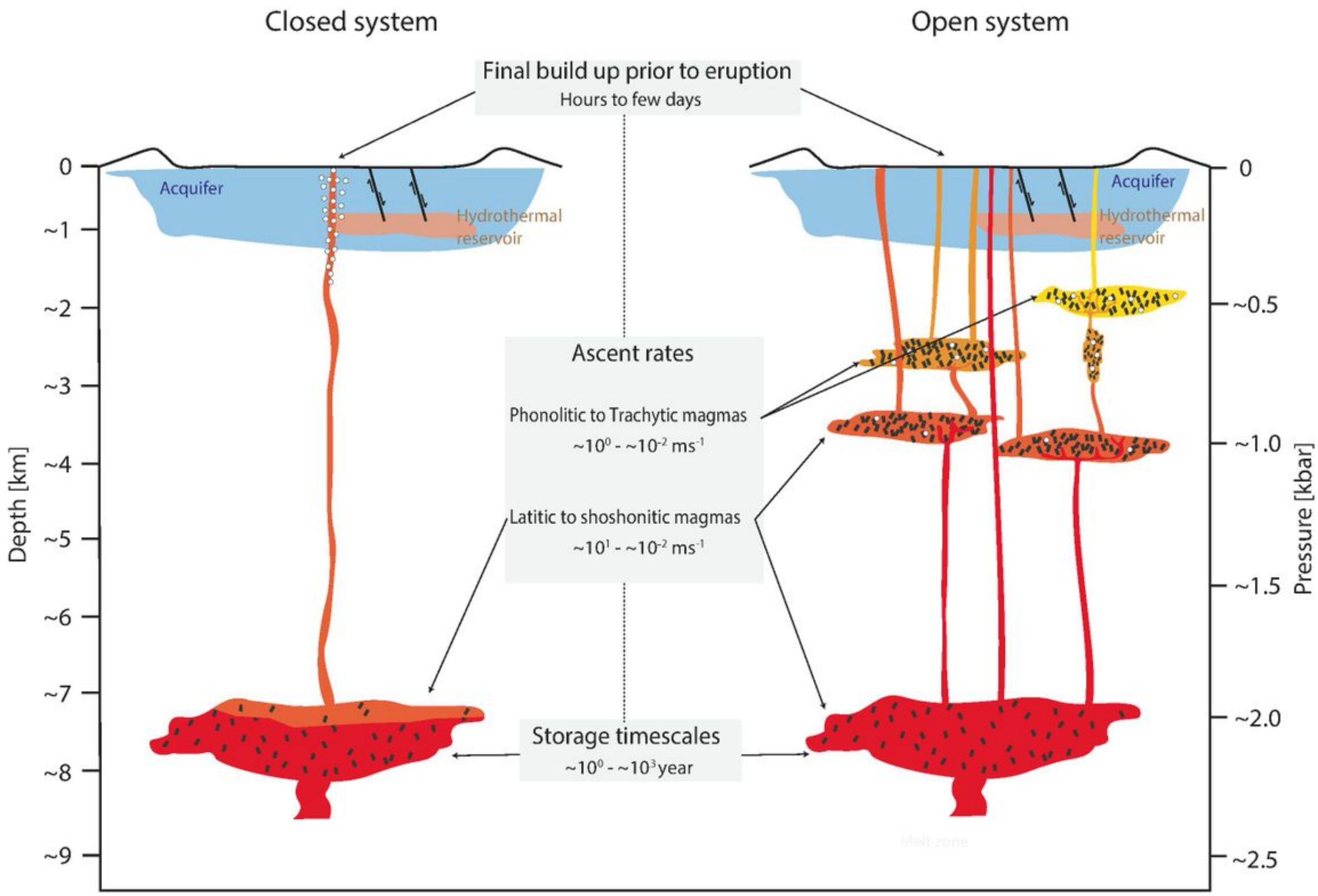

Figure 5

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

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- Table1.jpg
- SupplemetaryInformationFile.docx
- graphicalabstract.pdf