New Inferences on Magma Dynamics in Melilitite-Carbonatite Volcanoes: The Case Study of Mt. Vulture (Southern Italy)

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Key Points:

- Micro-thermometric analyses show the occurrence of high-density CO_2-rich fluid inclusions within wehrlite xenoliths
- Estimates on magma ascent rate show how a melilitite-carbonatite magma can be comparable with ascent rate of kimberlite magmatism
- Melilitite-carbonatite volcanoes can be hazardous even after long time of quiescence (> 10^5 years)

Abstract

This study provides the first micro-thermometric data of fluid inclusions in mafic loose xenocrysts and ultramafic xenoliths in explosive products of the melilitite-carbonatite Mt. Vulture volcano (southern Italy). We found within ultramafic xenoliths CO_2-dominated fluid inclusions with trapping pressures between 8.5 and 8.9 kbar, corresponding to a depth of 26-27 km, in proximity of the local crust-mantle boundary. In contrast, trapping pressures within the loose xenocrysts are up to 2.8 and 3.2 kbar (8-9 km). We estimated an ascent rate of the latest 141 ka old melilititic-carbonatitic magmas from the Moho depth to the surface in the range of few hours. Considering the ongoing degassing of mantle-derived CO_2 rich gases at Mt. Vulture, together with geophysical evidences of the presence of low amount of melts at depth, and the tectonic control of the past volcanic activity, our study opens new perspective about the hazardous nature of the "quiescent" melilitite-carbonatite volcanoes.

Plain Language Summary

The study of fluid inclusions can provide important information about the environments and magmatological processes in which the host minerals formed. Investigating their composition and trapping pressure and temperature it is possible to constrain magma ascent history. To understand the last explosive volcanic activity of Mt. Vulture volcano (southern Italy), we investigated fluid inclusions in mafic minerals, and ultramafic xenoliths brought to the surface by a melilitite-carbonatite magma. Our results show the presence of CO_2-rich fluid inclusions with trapping pressure corresponding to a depth of 26-27 km in ultramafic xenoliths, and a shallower depth (8-9 km) in mafic minerals. Estimates on magma ascent rate show rapid ascent dynamics to the surface (hours). Our study emphasizes the importance of a multidisciplinary approach that combine geophysics, geochemistry and petrology to investigate a volcanic system even if the volcano is considered "quiescent", as is the case of Mt. Vulture volcano, where currently active magmatic degassing occurs.

1 Introduction

Carbonatite magmatism is mainly associated with intraplate continental tectonic settings, with a temporal distribution from Archean to the present (*e.g.*, Jones et al., 2013; Woolley & Kjarsgaard, 2008), and currently, Oldoinyo Lengai (Tanzania) represents the only active carbonatite volcano, characterised by a natrocarbonatitic affinity. The growing number of carbonatite occurrences from unconventional tectonic settings, such as oceanic contexts (*e.g.*, Carnevale et al., 2021; Doucelance et al., 2010; Mata et al., 2010; Schmidt & Weidendorfer, 2018) or subduction zones (*e.g.*, D'Orazio et al., 2007; Li et al., 2018), received considerable attention during last two decades, given their importance as source of rare elements (Verplanck et al., 2019), and, most importantly, because they provide meaningful information about the geochemical cycle of carbon and mantle metasomatism as well (*e.g.*, Bouabdellah et al., 2010; Horton, 2021).

Mt. Vulture (southern Italy) is an isolated volcano located between the Apulia foreland and the eastern side of the Apennine orogenic belt, within the particular geodynamic context of the Apennine subduction zone (D'Orazio et al., 2007; Peccerillo, 2017). This volcano is located along the deep NE-SW lithospheric faults that represent the tear of the slab, a potential pathway for the ascent of magmatic bodies and mantle derived fluids (Caracausi et al., 2013a; D'Orazio et al., 2007; Rosenbaum et al., 2008).

The Mt. Vulture volcano is a relatively small volcanic complex characterised by a central vent and parasitic cones, domes, and lava plugs (Giannandrea et al., 2006). Its eruptive activity started at 730 ± 8 ka (Laurenzi et al., 1993) or 687 ± 8 ka (Villa & Buettner, 2009), and it continued until to 141 ± 11 ka (Villa & Buettner, 2009) with long inter-eruptive periods of quiescence (> 10^5 years, Buettner et al., 2006). After the initial phase of volcanic activity, represented by pyroclastic products with lava blocks and subordinate eccentric domes, the latest volcanic event was strongly explosive, erupting melilitite-carbonatite tephra from maar-type craters (Stoppa & Principe, 1997). These craters host two lakes (Monticchio Lakes) whose water dissolves mantle-derived volatiles (Caracausi et al., 2009, 2013b), supporting the active degassing of mantle volatiles from this volcano (Caracausi et al., 2009, 2015). The last volcanic activity (identified as Monticchio Lakes Formation, Stoppa & Principe, 1997), fed by a melilitite-carbonatite magma, brought to the surface some pelletal lapilli (enclosing abundant ultramafic mantle xenoliths and xenocrysts) considered juvenile component of the melilititic-carbonatitic Monticchio diatreme and volatile component (Lloyd & Stoppa, 2003). Thus, these products are particularly useful to characterize the mantle source beneath Mt. Vulture, providing important information about the melilitite-carbonatite magma and its mantle source.

Here we present the first detailed micro-thermometric analysis of fluid inclusions (FIs) hosted in the ultramafic xenolith cores of pelletal lapilli and in loose olivine and clinopyroxene xenocrysts from Mt. Vulture volcano (Monticchio Lakes Synthem, Lago Piccolo Sub-Synthem), in order to describe the way which these very particular magmas are transported to the surface and the possible implications in terms of volcanic hazard.

2 Sample Description

Were selected 29 pelletal lapilli set in a compact fine-grained carbonate-dominated matrix in the ash-tuff phreatomagmatic deposit of Lago Piccolo Sub-Synthem, with the presence of ultramafic xenoliths (dominantly wehrlitic) constituting the core of pelletal lapilli, surrounded by a variably thick rim of micro-phenocrysts (Figures 1a and 1b). We also selected about 200 olivine and 100 emerald-green Cr-diopside loose xenocrysts (Figures 1c and 1d) from the fine-grained carbonate-rich matrix, where loose xenocrysts of blackish clinopyroxene, amphibole, mica (phlogopite) and spinel, were also present together with the pelletal lapilli. These loose xenocrysts are considered as mantle debris from disaggregated nodules. In order to compare the fluid inclusions within the loose olivine and Cr-diopside xenocrysts with the fluid inclusions within the ultramafic xenolith cores of pelletal lapilli, we selected two representative wehrlite cores from the 29 pelletal lapilli, three olivines and two Cr-diopsides from the 200 and 100 loose xenocrysts respectively.

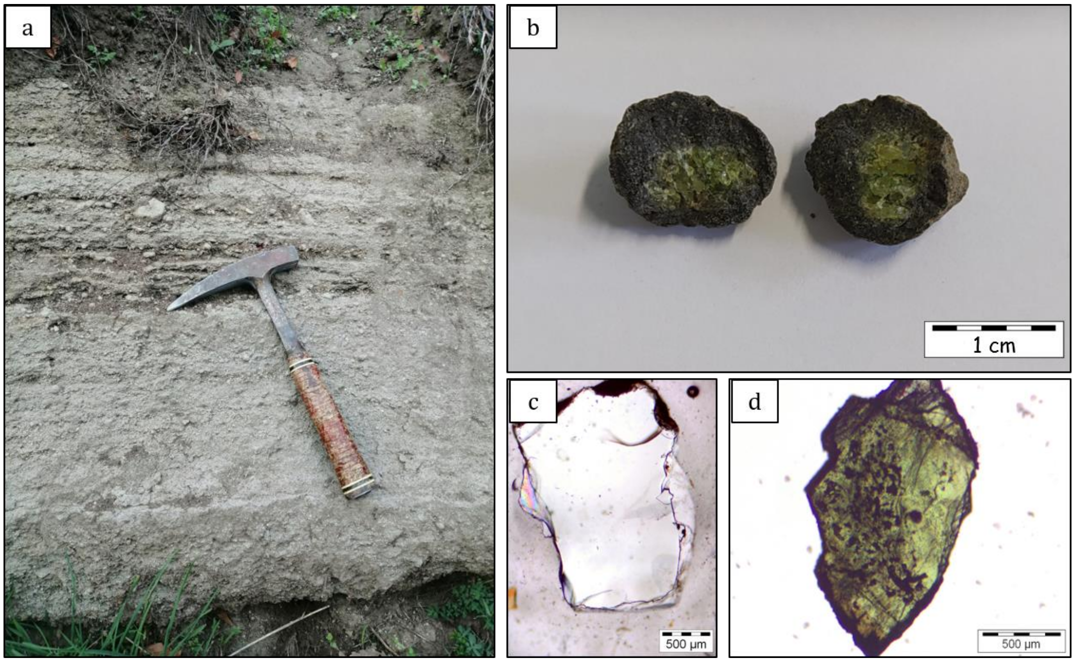

Figure 1. Sampling site and details on pelletal lapilli and loose crystals. a) Ash-rich tuff surge deposit of Lago Piccolo Sub-Synthem. b) Pelletal lapilli with ultramafic xenolith cores. c) Loose olivine xenocryst from the fine-grained matrix (parallel polars). d) Loose clinopyroxene (Cr-diopside) xenocryst from the fine-grained matrix (parallel polars).

3 Results

The ultramafic xenolith cores of pelletal lapilli (the diameter of enclaves vary from 6 to 17 mm) are characterised by the presence of Mg-rich olivine (Fo_{90-91}, NiO varying from 0.35 to 0.38 wt. %, Table S1) and Cr-rich diopside (Wo_{46-48}, En_{47-48}, Fs_{4-5}) with relatively high Cr_2O_3 content (1.3-1.5 wt. %, Table S2). The grain size of the ultramafic xenolith cores is fine- to medium-grained (300-600 µm) with equigranular holocrystalline texture, granoblastic or interlocking with randomly oriented olivine and clinopyroxene variably elongated (Figures 2a and 2b). The variably thick rim of fine-grained material is composed essentially of häuyne micro-phenocrysts, with xenocrystic debris of olivine and clinopyroxene (Figure S1).

Loose (disaggregated) olivine xenocrysts show very similar composition (Fo_{89-92}, NiO = 0.37-0.41 wt. %, Table S1) if compared with olivine from the ultramafic xenolith cores of pelletal lapilli. In the same way, almost all loose clinopyroxene xenocrysts show very similar composition (Wo_{46-48}, En_{47-48}, Fs_{4-6}, Cr_2O_3 = 0.4-1.3 wt. %) if compared with clinopyroxene from the ultramafic xenolith cores of pelletal lapilli (Table S2). Thus, interestingly, the olivine and Cr-diopside minerals from the ultramafic xenoliths (wehrlites) and loose olivine and Cr-diopside xenocrysts, show almost the same minerochemical composition. Indeed, if plotted onto Mg# vs. NiO wt. % (olivine) and Cr_2O_3 wt. % (Cr-diopside) diagrams, they show narrow ranges (Figures 3a and 3b).

All the studied fluid inclusions (FIs) are characterised by pure CO_2, with melting temperatures (Tm) ranging in a very narrow interval between -56.6 (*i.e.* the triple point of pure CO_2 at 1 bar) and -56.8 °C ± 0.1. FIs in loose olivine and Cr-diopside xenocrysts homogenized to liquid phase, with temperatures of homogenization (Th) ranging from 11.5 to 30.2 °C (ρ = 0.58-0.85 g/cm^3) and from -20.0 to 13.2 °C (ρ = 0.84-1.03 g/cm^3), respectively. FIs in the ultramafic cores of lapilli also homogenized to liquid phase, at Th ranging from -27.3 to -8.5 °C (ρ = 0.98-1.06 g/cm^3) in Cr-diopside crystals, and from -27.7 to -6.0 °C (ρ = 0.96-1.07 g/cm^3) in olivine crystals. Data of Th, densities, corrected densities and number of measures are reported in Table S3. The main geometric measurements of the aspect ratio and the internal structure of pelletal lapilli are reported in Table S4. Further details, also about analytical methods, are reported in Supporting Information S1.

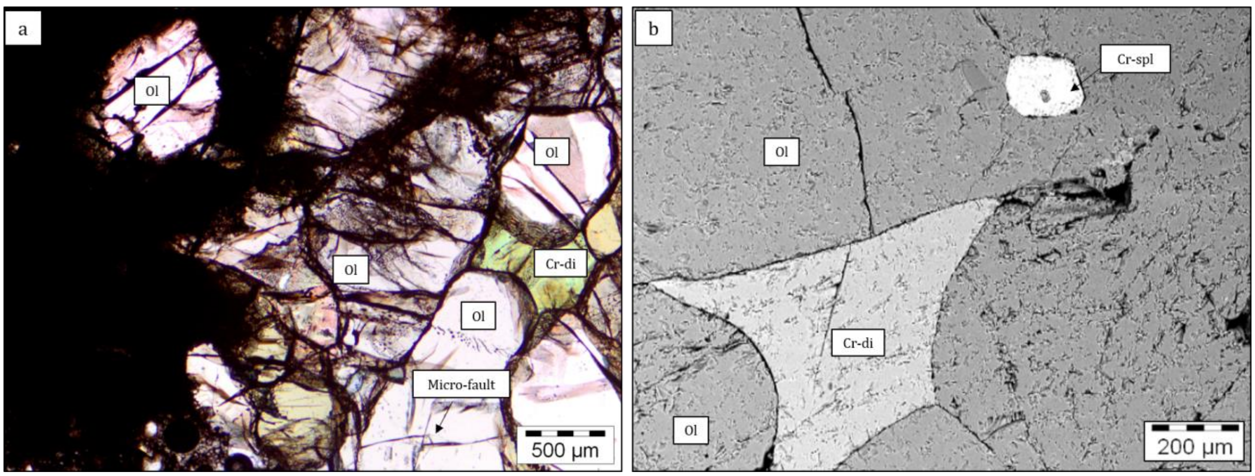

Figure 2. Photomicrographs of the ultramafic core of pelletal lapilli from Vulture volcano. a) Sub-idioblastic texture with Cr-diopside (emerald green) and elongated olivine crystal with

intracrystalline deformations (parallel polars). b) BSE image showing Cr-diopside and olivine crystal with Cr-spinel inclusion.

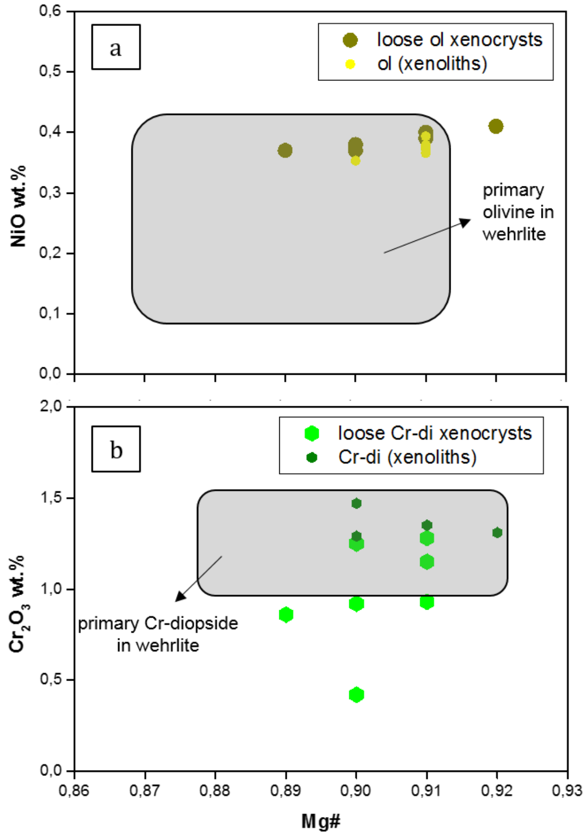

Figure 3. Minerochemical composition of olivine and Cr-diopside from the ultramafic xenoliths (wehrlites) and loose olivine and Cr-diopside xenocrysts from Vulture volcano. a) Mg# vs. NiO wt. % in olivine crystals. b) Mg# vs. Cr_2O_3 wt. % in Cr-diopside crystals. The field of the primary olivine and Cr-diopside in wehrlite are from Jones et al. (2000).

4 Significance of Fluid Inclusions Data

In loose olivine and Cr-diopside xenocrysts FIs are usually rounded or with a slight negative crystal shape (Figures 4a and 4b), and in some cases form trails of variable length lined in healed fractures (Figure 4c). As regards FIs in the ultramafic cores of lapilli, they form fluid inclusions assemblages (FIAs) (Figure 4d), suggesting single events of entrapment.

The histograms of homogenization temperatures (Figure 5a) and densities (Figure 5b) essentially show a bimodal distribution, except in some cases where are almost unimodal, depending mainly on different trapping events of different products. The highest corrected density values of FIs are in the olivine and Cr-diopside within the ultramafic cores of pelletal lapilli (1.10-1.11 g/cm^3), corresponding to trapping pressures between 8.46 and 8.96 kbar (26-27 km). In the loose Cr-diopside xenocrysts trapping events occurred at 8.20-8.65 kbar (25-26 km) and at 6.72-7.22 kbar (21-22 km). Conversely, loose olivine xenocrysts show lower density values with a clear density peak at 0.63 g/cm^3 and another at 0.75 g/cm^3, with trapping pressures of 2.80-3.12 kbar (8-9 km) and 4.05-4.49 kbar (12-13 km), respectively. The peak at 0.63 g/cm^3 is also slightly registered by olivine within the ultramafic cores.

Combining textures, densities and relative distribution of FIs within the ultramafic cores of pelletal lapilli and loose xenocrysts, it is possible to figure out the different fluid trapping events that occurred during the transfer of the magmas from crust-mantle boundary to the surface. Olivine and Cr-diopside within the ultramafic cores of pelletal lapilli, together with loose Cr-diopside xenocrysts, register the first fluid trapping event at depths corresponding approximately to the Moho beneath Mt. Vulture (about 32 km, Kelemework et al., 2021). Olivine composition (Fo %, NiO), clinopyroxene Cr content and spinel Cr/Cr+Al, strongly suggest that the wehrlitic cores are of mantle origin. Thus, wehrlitic cores of pelletal lapilli are not considered cumulates produced in shallow level magma chambers and subsequently entrained by the erupting melilitite-carbonatite magma during ascent to the surface (Beccaluva et al., 2002), but trapping pressures of FIs constrained the wehrlitic cores of pelletal lapilli to a minimum depth of 26-27 km, near the crust-mantle boundary. On the contrary, loose olivine xenocrysts record a different fluid trapping event at much shallower depths, hosting late stage CO_2-dominated fluids. It is therefore likely that olivine and Cr-diopside within the ultramafic xenolith cores of pelletal lapilli and loose Cr-diopside xenocrysts have different histories of fluid trapping events if compared with loose olivine xenocrysts, although these latter show very similar minerochemical composition if compared with olivine within the ultramafic xenolith cores of pelletal lapilli (see Table S1).

A continuous magma ascent translates in a density distribution of FIs with a single frequency maximum at high-density values, and depending also on parameters such as the ascent velocity, the original density should be recognizable as the upper limit of measured density values (Hansteen & Klügel, 2008). On the contrary, if the magma experiences multibaric ponding stages, the density distribution should show a multi-modal profile (*e.g.*, Zanon et al., 2003). Considering the very low viscosity of a melilitite-carbonatite magma (*e.g.*, Stagno et al., 2020) and one of the basic assumptions for the interpretation of FIs (*i.e.* that they have behaved as an isochoric system), it seems that no fluid re-equilibrating event was registered by studied Mt. Vulture products, simply showing different histories of fluid trapping events. Thus, we suggest that the melilitite-carbonatite magma transported from Moho depth to the surface the ultramafic mantle xenoliths and Cr-diopside loose xenocrysts, while loose olivine xenocrysts were incorporated at shallower depths.

It is worthy of note that trapping pressures of volatiles in FIs from loose olivine xenocrysts (2.80-4.49 kbar, corresponding to depth of 8-13 km) overlap the depth (6-15 km) of a mafic body within the Vulture plumbing system (Improta et al., 2014), suggesting the occurrence of a magma stagnation and ponding level before eruption at this depth.

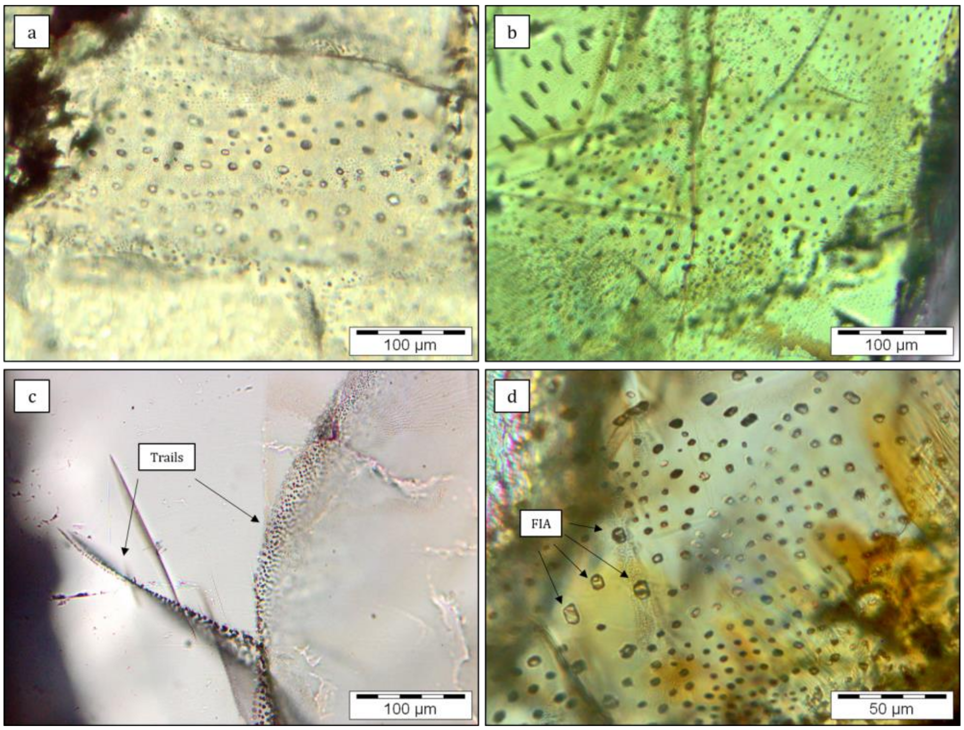

Figure 4. Thin section photomicrographs (parallel polars) of fluid inclusions and their arrangement. FIs within loose a) olivine and b) Cr-diopside xenocrysts. c) Intragranular trails of FIs in loose olivine xenocryst. (d) Fluid inclusions assemblage (FIA) in Cr-diopside from the ultramafic core of a pelletal lapillus.

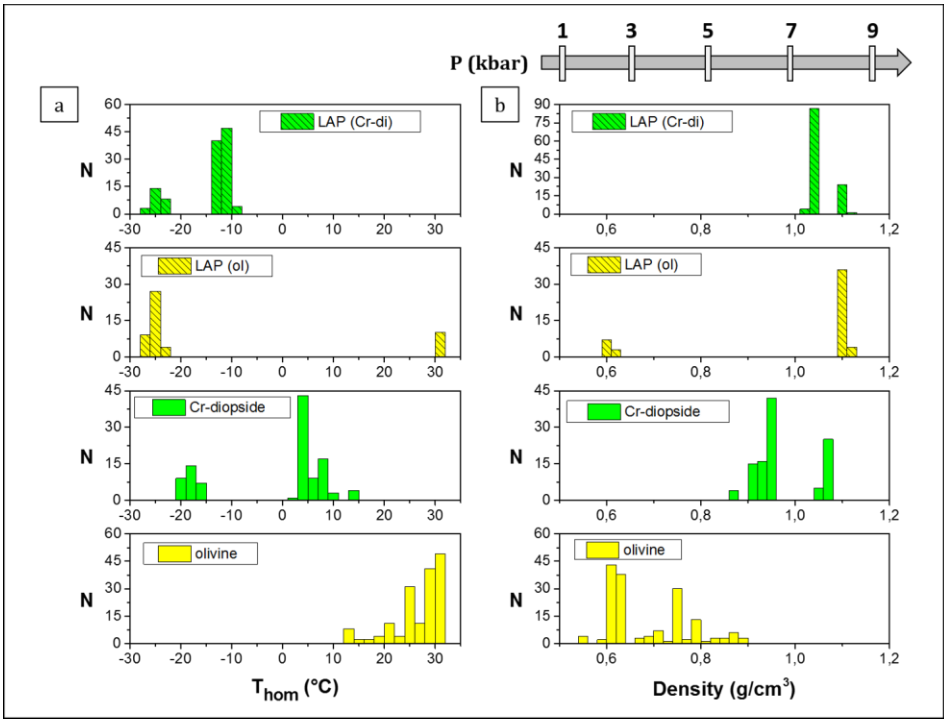

Figure 5. Frequency distribution of a) homogenization temperatures and (b) densities of FIs hosted in loose olivine and Cr-diopside xenocrysts and in ultramafic cores of pelletal lapilli from Vulture volcano.

5 Carbonatite Metasomatism and Magma Ascent Rate

The study of mantle xenoliths represents a great tool to understand the composition and possible modification of a mantle source influenced by metasomatic fluids, especially in subduction zones. In this framework, the increase of modal clinopyroxene at the expense of orthopyroxene has been interpreted as a result of the interaction of ultramafic material with carbonatite melts, and carbonatite metasomatism is accompanied by the formation of secondary clinopyroxene formed during the reaction of carbonatite melts with orthopyroxene (the melt with the lowest SiO_2 activity dissolves the highest SiO_2 mantle mineral) (Dalton & Wood, 1993; Russell et al., 2012). Therefore, the process of "*wehrlitization*" is considered a consequence of carbonatite metasomatism in the lithospheric mantle.

Among the Mt. Vulture mantle products, the presence of wehrlite enclaves is widely recognized (*e.g.*, Beccaluva et al., 2002; Downes et al., 2002; Jones et al., 2000) and is corroborated by our findings where pelletal lapilli cores are largely wehrlitic. Furthermore, according to Zong and Liu, (2018), specific crystallochemical patterns in clinopyroxenes (*e.g.*, Mg# vs. Ca/Al; Ca/Al vs. $^{87}Sr/^{86}Sr$) fall into the mantle-related carbonate metasomatism field (Figure S2). Rosatelli et al. (2007) also suggest carbonatite melts as the main metasomatism agent of Mt. Vulture mantle source region, emphasizing the role of silicate-carbonatite magma immiscibility during the carbonated melt ascent to the surface (Solovova et al., 2005), this latter point supported by a number of experimental constrains underlying melilititic magma (the last erupted at Mt. Vulture) as the best candidate to exsolve an immiscible carbonatite melt (Brooker & Kjarsgaard, 2011). Further evidence of metasomatism by carbonatite-like melts is given by the presence of interstitial calcite associated with Fe-Ni-sulfides between olivine grains in a mantle xenolith from Mt. Vulture (Blanks et al., 2020).

Despite the last eruptive event of Mt. Vulture dates back to 141 ± 11 ka (Villa & Buettner, 2009), geochemical evidences support that active magmatic degassing of mantle-derived volatiles is still ongoing in Mt. Vulture area (Caracausi et al., 2009, 2013a), also showing how the relationship between the deep CO_2 release and the time of its last eruption could be an important tool for evaluating the state of current activity (Caracausi et al., 2015). Moreover, recent studies show how the source of CO_2 degassing in Mt. Vulture area is related to the presence of a subcontinental lithospheric mantle (SCLM), that sequesters large amounts of CO_2 due to the infiltration of fluids and melts during carbonatite-like metasomatism (Bragagni et al., 2022). In this scenario the He isotopic signature in fluid inclusions of the Vulture mantle xenoliths (<6.1Ra; Ra is the He isotopic signature in air) overlap the range of the SCLM He end member (6.1 ± 0.9; Gautheron & Moreira, 2002).

Considering, 1) the active degassing of mantle-derived fluids in Mt. Vulture area (Caracausi et al., 2009, 2015), 2) the explosive behaviour associated with a maar-diatreme system of the Monticchio Lakes Synthem (MLS; Solovova et al., 2005; Stoppa & Principe, 1997), 3) the occurrence of small amounts of magma at the Moho depth (< 1.6 %, Tumanian et al., 2012), in absence of mantle upwelling or extensional tectonics that could favour decompression melting (Peccerillo & Frezzotti, 2015), 4) the role of tectonics in the transfer of the mantle-derived magma and volatiles and its control of the Vulture volcanism and outgassing (*e.g.*, Caracausi et al., 2013a; D'Orazio et al., 2007; Rosenbaum et al., 2008), 5) the long inter-eruptive periods (> 140 ka, Buettner et al., 2006) and 6) the recognized occurring of volatiles rich magmas at the mantle-crust boundary (Section 4, Significance of Fluid Inclusions Data), we focused on modelling melilitite-carbonatite magma ascent rate with its cargo of xenoliths and loose xenocrysts to the surface. In order to constrain the ascent velocity of the melilitite-carbonatite magma, we used the equation from Lister and Kerr (1991) and applied by Sparks et al. (2006) in their physical model.

Taking into consideration (i) a closed system during the magma ascent with a constant dike width of 1 m, (ii) a magma density of 2500 kg/m^3, (iii) a constant viscosity of 0.6 Pa s, and (iv) a mean density of the crust of 2600 kg/m^3, we obtain ascent rate of about 17 m/s (equation (8) from Sparks et al. 2006), assuming that the buoyancy is the main driving force. Magma viscosity value is taken from experimental studies of a representative melilitite synthetic melt (Stagno et al., 2020). Magma density is calculated using the model of Ochs and Lange (1999) at 1100 °C and 10 kbar, assuming a bulk composition from Stoppa and Principe (1997) with SiO_2 = 37 wt. %, and a mean CO_2 value of 7.5 wt. %, obtained from the H_2O-CO_2 solubility model proposed by Moussallam et al. (2016). Indeed, if we consider their model for a low SiO_2- and H_2O-free melts (our fluid inclusions study indicates the presence of pure CO_2 as the main volatile phase, with no presence or very scarce of H_2O), at about 30 km depth (crust-mantle boundary beneath Mt. Vulture area), we obtain CO_2 values between 5 and 10 wt. %. The model of Moussallam et al. (2016) is applied to a kimberlite magmatism with 25 wt. % ≤ SiO_2 ≤ 32 wt. %, and it is comparable to the melilitite-carbonatite magmatism of Monticchio Lakes Syntheme with SiO_2 < 40 wt. % (Stoppa & Principe, 1997).

Our result of the ascent rate of the melilitite-carbonatite magma is in the same order of the ascent rates of kimberlite magmatism described by Moussallam et al. (2016). The direct effect of ascent dynamics is that the melilitite-carbonatite magma could reach the surface from the depth of 30 km in less than an hour. Considering also recent studies showing how volcanic systems where activity has remained dormant for protracted periods (> 100 ka) still have the potential for reactivation (Harangi et al., 2015a; Molnár et al., 2018, 2019), and in Mt. Vulture there is a possible link between the development of tear faults, magmatism and related magma ascent along these tectonic pathways (Peccerillo, 2017; Rosenbaum et al., 2008), our study supports that volcanic hazard in melilitite-carbonatite volcanoes, even after long time of quiescence, should be carefully evaluated.

6 Conclusion

We analysed fluid inclusions (FIs) hosted in the wehrlitic cores of pelletal lapilli and in loose xenocrysts of olivine and clinopyroxene brought to the surface by a melilitite-carbonatite magma from the last eruption of Mt. Vulture volcano (Monticchio Lakes Syntheme, Lago Piccolo Sub-Synthem). We found CO_2-dominated FIs with different trapping pressures (from 2.80 to 8.96 kbar) that correspond to magma storage at different depths within the volcano plumbing system (from 8 to 27 km). The deeper reservoir is close to the local Moho (32 km), while the shallower corresponds to a solidified magmatic body imaged by geophysical investigations (Improta et al., 2014). Modeling magma ascent rate results in quite high velocity for melilitite-carbonatite magma from the crust-mantle boundary to the surface, in the order of 15-20 m/s. These evidences, coupled to (i) the outgassing of magmatic volatiles at Mt. Vulture, which isotopic signature correspond to those in the fluid inclusions of the last activity of the volcano (Caracausi et al., 2009, 2013a), and to (ii) the presence of small amounts of melt (< 1,6%) at the Moho depth, add constraints for magma production and ascent pathways. Therefore, this study confirms that the scientific community must pay attention also to the inactive volcanoes, because they could be still hazardous systems notwithstanding the last volcanic activity occurred hundreds/thousands of years ago.

Data Availability Statement

The complete data set of minerochemical and micro-thermometric analyses of this study was uploaded to the Zenodo FAIR aligned repository (www.zenodo.org) and will be available for download at the required link: Carnevale et al. (2022). Micro-thermometry and minerochemical composition of ultramafic xenoliths and minerals from Mt. Vulture volcano (southern Italy) [Data set]. Zenodo. https://doi.org/10.5281/zenodo.6426785. Accessed 9 april 2022.

Acknowledgments

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References

Beccaluva, L., Coltorti, M., Di Girolamo, P., Melluso, L., Milani, L., Morra, V., & Siena, F. (2002). Petrogenesis and evolution of Mt. Vulture alkaline volcanism (Southern Italy).

Mineralogy and Petrology, *74*(2–4), 277–297. https://doi.org/10.1007/s007100200007

Blanks, D. E., Holwell, D. A., Fiorentini, M. L., Moroni, M., Giuliani, A., Tassara, S., et al. (2020). Fluxing of mantle carbon as a physical agent for metallogenic fertilization of the crust. *Nature Communications*, *11*(1). https://doi.org/10.1038/s41467-020-18157-6

Bouabdellah, M., Hoernle, K., Kchit, A., Duggen, S., Hauff, F., Klügel, A., et al. (2010). Petrogenesis of the Eocene Tamazert continental carbonatites (Central High Atlas, Morocco): Implications for a common source for the Tamazert and Canary and Cape Verde Island carbonatites. *Journal of Petrology*, *51*, 1655–1686. https://doi.org/10.1093/petrology/egq033

Bragagni, A., Mastroianni, F., Münker, C., Conticelli, S., & Avanzinelli, R. (2022). A carbon-rich lithospheric mantle as a source for the large CO_2 emissions of Etna volcano (Italy). *Geology*, *50*(4), 486–490. https://doi.org/10.1130/g49510.1

Brooker, R. A., & Kjarsgaard, B. A. (2011). Silicate-carbonate liquid immiscibility and phase relations in the system SiO_2-Na_2O-Al_2O_3-CaO-CO_2 at 0·1-2·5 GPa with applications to carbonatite genesis. *Journal of Petrology*, *52*, 1281−1305. https://doi.org/10.1093/petrology/egq081

Buettner, A., Principe, C., Villa, I. M., & Bocchini, D. (2006). Geocronologia ^{39}Ar-^{40}Ar del Monte Vulture. In C. Principe (Ed.), *La Geologia del Monte Vulture* (pp. 73–86). Lavello.

Caracausi, A., Nuccio, P. M., Favara, R., Nicolosi, M., & Paternoster, M. (2009). Gas hazard assessment at the Monticchio crater lakes of Mt. Vulture, a volcano in Southern Italy. *Terra Nova*, 21(2), 83–87. https://doi.org/10.1111/j.1365-3121.2008.00858.x

Caracausi, A., Martelli, M., Nuccio, P. M., Paternoster, M., & Stuart, F. M. (2013a). Active degassing of mantle-derived fluid: A geochemical study along the Vulture line, southern Apennines (Italy). *Journal of Volcanology and Geothermal Research*, *253*, 65–74.

https://doi.org/10.1016/j.jvolgeores.2012.12.005

Caracausi, A., Nicolosi, M., Nuccio, P. M., Favara, R., Paternoster, M., & Rosciglione, A. (2013b). Geochemical insight into differences in the physical structures and dynamics of two adjacent maar lakes at Mt. Vulture volcano (southern Italy). *Geochemistry, Geophysics, Geosystems*, *14*(5), 1411–1434. https://doi.org/10.1002/ggge.20111

Caracausi, A., Paternoster, M., & Nuccio, P. M. (2015). Mantle CO_2 degassing at Mt. Vulture volcano (Italy): Relationship between CO_2 outgassing of volcanoes and the time of their last eruption. *Earth and Planetary Science Letters*, *411*, 268–280. https://doi.org/10.1016/j.epsl.2014.11.049

Carnevale, G., Caracausi, A., Correale, A., Italiano, L., & Rotolo, S. G. (2021). An overview of the geochemical characteristics of oceanic carbonatites: New insights from fuerteventura carbonatites (Canary islands). *Minerals*, *11*(2). https://doi.org/10.3390/min11020203

Carnevale, G., Caracausi, A., Rotolo, S. G., Paternoster, M., & Zanon, V. (2022). Micro-thermometry and minerochemical composition of ultramafic xenoliths and minerals from Mt. Vulture volcano (southern Italy) [Data set]. Zenodo. https://doi.org/10.5281/zenodo.6426785

D'Orazio, M., Innocenti, F., Tonarini, S., & Doglioni, C. (2007). Carbonatites in a subduction system: The Pleistocene alvikites from Mt. Vulture (southern Italy). *Lithos*, *98*(1–4), 313–334. https://doi.org/10.1016/j.lithos.2007.05.004

Dalton, J. A., & Wood, B. J. (1993). The compositions of primary carbonate melts and their evolution through wallrock reaction in the mantle. *Earth and Planetary Science Letters*, *119*, 511–525. https://doi.org/10.1016/0012-821X(93)90059-I

Doucelance, R., Hammouda, T., Moreira, M., & Martins, J. C. (2010). Geochemical constraints on depth of origin of oceanic carbonatites: The Cape Verde case. *Geochimica et*

Cosmochimica Acta, *74*, 7261–7282. https://doi.org/10.1016/j.gca.2010.09.024

Downes, H., Kostoula, T., Jones, A. P., Beard, A. D., Thirlwall, M. F., & Bodinier, J. L. (2002). Geochemistry and Sr-Nd isotopic compositions of mantle xenoliths from the Monte Vulture carbonatite-melilitite volcano, central southern Italy. *Contributions to Mineralogy and Petrology*, *144*(1), 78–92. https://doi.org/10.1007/s00410-002-0383-4

Gautheron, C., & Moreira, M. (2002). Helium signature of the subcontinental lithospheric mantle. *Earth and Planetary Science Letters*, *199*, 39–47. https://doi.org/10.1016/S0012-821X(02)00563-0

Giannandrea, P., La Volpe, L., Principe, C., & Schiattarella, M. (2006). Unità stratigrafiche a limiti inconformi e storia evolutiva del vulcano medio-pleistocenico di Monte Vulture (Appennino meridionale, Italia). *Bollettino Della Societa Geologica Italiana*, *125*(1), 67–92.

Hansteen, T. H., & Klügel, A. (2008). Fluid inclusion thermobarometry as a tracer for magmatic processes. *Reviews in Mineralogy and Geochemistry*, *69*(Roedder 1984), 143–177. https://doi.org/10.2138/rmg.2008.69.5

Harangi, S., Lukács, R., Schmitt, A. K., Dunkl, I., Molnár, K., Kiss, B., et al. (2015). Constraints on the timing of Quaternary volcanism and duration of magma residence at Ciomadul volcano, east-central Europe, from combined U-Th/He and U-Th zircon geochronology. *Journal of Volcanology and Geothermal Research*, *301*, 66–80. https://doi.org/10.1016/j.jvolgeores.2015.05.002

Horton, F. (2021). Rapid recycling of subducted sedimentary carbon revealed by Afghanistan carbonatite volcano. *Nature Geoscience*, *14*(7), 508–512. https://doi.org/10.1038/s41561-021-00764-7

Improta, L., De Gori, P., & Chiarabba, C. (2014). New insights into crustal structure, Cenozoic magmatism, CO_2 degassing, and seismogenesis in the southern Apennines and Irpinia region from local earthquake tomography. *Journal of Geophysical Research: Solid Earth*, *119*(11), 8283–8311. https://doi.org/10.1002/2013JB010890

Jones, A. P., Kostoula, T., Stoppa, F., & Woolley, A. R. (2000). Petrography and mineral chemistry of mantle xenoliths in a carbonate-rich melilititic tuff from Mt. Vulture volcano, southern Italy. *Mineralogical Magazine*, *64*(4), 593–613. https://doi.org/10.1180/002646100549634

Jones, A. P., Genge, M., & Carmody, L. (2013). Carbonate melts and carbonatites. *Reviews in Mineralogy and Geochemistry*, *75*, 289–322. https://doi.org/10.2138/rmg.2013.75.10

Kelemework, Y., Milano, M., La Manna, M., de Alteriis, G., Iorio, M., & Fedi, M. (2021). Crustal structure in the Campanian region (Southern Apennines, Italy) from potential field modelling. *Scientific Reports*, *11*(1), 1–18. https://doi.org/10.1038/s41598-021-93945-8

Laurenzi, M.A., Brocchini, D., Principe, C., & Ferrara, G. (1993). Mt. Vulture volcano chronostratigraphy and the effectiveness of dating young phlogopites. Abstracts EUG 7, Strasburgo, 572‑573.

Li, Y., Zhang, J., Mostofa, K. M. G., Wang, Y., Yu, S., Cai, Z., et al. (2018). Petrogenesis of carbonatites in the Luliangshan region, North Qaidam, northern Tibet, China: Evidence for recycling of sedimentary carbonate and mantle metasomatism within a subduction zone. *Lithos*, *322*, 148–165. https://doi.org/10.1016/j.lithos.2018.10.010

Lister, J. R., & Kerr, R. C. (1991). Fluid-mechanical models of crack propagation and their application to magma transport in dykes. *Journal of Geophysical Research*, *96*(B6), 49–77. https://doi.org/10.1029/91jb00600

Lloyd, F. E., & Stoppa, F. (2003). Pelletal Lapilli in Diatremes – Some Inspiration from the Old Masters. *GeoLines*, *15*, 65–71.

Mata, J., Moreira, M., Doucelance, R., Ader, M., & Silva, L. C. (2010). Noble gas and carbon isotopic signatures of Cape Verde oceanic carbonatites: Implications for carbon provenance. *Earth and Planetary Science Letters*, *291*, 70–83. https://doi.org/10.1016/j.epsl.2009.12.052

Molnár, K., Harangi, S., Lukács, R., Dunkl, I., Schmitt, A. K., Kiss, B., et al. (2018). The onset of the volcanism in the Ciomadul Volcanic Dome Complex (Eastern Carpathians): Eruption chronology and magma type variation. *Journal of Volcanology and Geothermal Research*, *354*, 39–56. https://doi.org/10.1016/j.jvolgeores.2018.01.025

Molnár, K., Lukács, R., Dunkl, I., Schmitt, A. K., Kiss, B., Seghedi, I., et al. (2019). Episodes of dormancy and eruption of the Late Pleistocene Ciomadul volcanic complex (Eastern Carpathians, Romania) constrained by zircon geochronology. *Journal of Volcanology and Geothermal Research*, *373*, 133–147. https://doi.org/10.1016/j.jvolgeores.2019.01.025

Moussallam, Y., Morizet, Y., & Gaillard, F. (2016). H_2O–CO_2 solubility in low SiO_2-melts and the unique mode of kimberlite degassing and emplacement. *Earth and Planetary Science Letters*, *447*, 151–160. https://doi.org/10.1016/j.epsl.2016.04.037

Ochs, F. A., & Lange, R. A. (1999). The density of hydrous magmatic liquids. *Science*, *283*(5406), 1314–1317. https://doi.org/10.1126/science.283.5406.1314

Peccerillo, A., & Frezzotti, M. L. (2015). Magmatism, mantle evolution and geodynamics at the converging plate margins of Italy. *Journal of the Geological Society*, *172*(4), 407–427. https://doi.org/10.1144/jgs2014-085

Peccerillo, A.. (2017). The Apulian Province (Mount Vulture). *Advances in Volcanology*, 203–216. https://doi.org/10.1007/978-3-319-42491-0_8

Rosatelli, G., Wall, F., & Stoppa, F. (2007). Calcio-carbonatite melts and metasomatism in the mantle beneath Mt. Vulture (Southern Italy). *Lithos*, *99*(3–4), 229–248.

https://doi.org/10.1016/j.lithos.2007.05.011

Rosenbaum, G., Gasparon, M., Lucente, F. P., Peccerillo, A., & Miller, M. S. (2008). Kinematics of slab tear faults during subduction segmentation and implications for Italian magmatism. *Tectonics*, *27*(2), 1–16. https://doi.org/10.1029/2007TC002143

Russell, J. K., Porritt, L. A., Lavallé, Y., & Dingwell, D. B. (2012). Kimberlite ascent by assimilation-fuelled buoyancy. *Nature*, *481*(7381), 352–356. https://doi.org/10.1038/nature10740

Schmidt, M. W., & Weidendorfer, D. (2018). Carbonatites in oceanic hotspots. *Geology*, *46*, 435–438. https://doi.org/10.1130/G39621.1

Solovova, I. P., Girnis, A. V., Kogarko, L. N., Kononkova, N. N., Stoppa, F., & Rosatelli, G. (2005). Compositions of magmas and carbonate-silicate liquid immiscibility in the Vulture alkaline igneous complex, Italy. *Lithos*, *85*(1-4 SPEC. ISS.), 113–128. https://doi.org/10.1016/j.lithos.2005.03.022

Sparks, R. S. J., Baker, L., Brown, R. J., Field, M., Schumacher, J., Stripp, G., & Walters, A. (2006). Dynamical constraints on kimberlite volcanism. *Journal of Volcanology and Geothermal Research*, *155*(1–2), 18–48. https://doi.org/10.1016/j.jvolgeores.2006.02.010

Stagno, V., Stopponi, V., Kono, Y., D'arco, A., Lupi, S., Romano, C., et al. (2020). The viscosity and atomic structure of volatile-bearing melilititic melts at high pressure and temperature and the transport of deep carbon. *Minerals*, *10*(3), 1–13. https://doi.org/10.3390/min10030267

Stoppa, F., & Principe, C. (1997). Eruption style and petrology of a new carbonatitic suite from the Mt. Vulture Southern Italy /: The Monticchio Lakes Formation. *Journal of Volcanology and Geothermal Research*, *78*(3–4), 251–265. https://doi.org/10.1016/S0377-0273(97)00004-8

Tumanian, M., Frezzotti, M. L., Peccerillo, A., Brandmayr, E., & Panza, G. F. (2012). Thermal structure of the shallow upper mantle beneath Italy and neighbouring areas: Correlation with magmatic activity and geodynamic significance. *Earth-Science Reviews*, *114*(3–4), 369–385. https://doi.org/10.1016/j.earscirev.2012.07.002

Verplanck, P. L., Mariano, A. N., & Mariano, A. (2019). Rare Earth Element Ore Geology of Carbonatites. *Rare Earth and Critical Elements in Ore Deposits*, 5–32. https://doi.org/10.5382/rev.18.01

Villa, I. M., & Buettner, A. (2009). Chronostratigraphy of Monte Vulture volcano (southern Italy): Secondary mineral microtextures and ^{39}Ar-^{40}Ar systematics. *Bulletin of Volcanology*, *71*(10), 1195–1208. https://doi.org/10.1007/s00445-009-0294-6

Woolley, A. R., & Kjarsgaard, B. A. (2008). Carbonatite occurrences of the world: map and database. *Geological Survey of Canada*, *5796*, 1–28. https://doi.org/https://doi.org/10.4095/225115

Zanon, V., Frezzotti, M.-L., & Peccerillo, A. (2003). Magmatic feeding system and crustal magma accumulation beneath Vulcano Island (Italy): Evidence from CO_2 fluid inclusions in quartz xenoliths . *Journal of Geophysical Research: Solid Earth*, *108*(B6). https://doi.org/10.1029/2002jb002140

Zong, K., & Liu, Y. (2018). Carbonate metasomatism in the lithospheric mantle: Implications for cratonic destruction in North China. *Science China Earth Sciences*, *61*(6), 711–729. https://doi.org/10.1007/s11430-017-9185-2

References From the Supporting Information

Bakker, R. J. (2003). Package FLUIDS 1. Computer programs for analysis of fluid inclusion data and for modelling bulk fluid properties. *Chemical Geology*, 194(1–3), 3–23. https://doi.org/10.1016/S0009-2541(02)00268-1

D'Orazio, M., Innocenti, F., Tonarini, S., & Doglioni, C. (2008). Reply to the discussion of: "Carbonatites in a subduction system: The Pleistocene alvikites from Mt. Vulture (Southern Italy)" by M. D'Orazio, F. Innocenti, S. Tonarini and C. Doglioni (Lithos 98, 313-334) by F. Stoppa, C. Principe and P. Giannandrea. *Lithos*, 103(3–4), 557–561. https://doi.org/10.1016/j.lithos.2007.10.010

Gernon, T. M., Brown, R. J., Tait, M. A., & Hincks, T. K. (2012). The origin of pelletal lapilli in explosive kimberlite eruptions. *Nature Communications*, 3, 832–837. https://doi.org/10.1038/ncomms1842

Scrocca, D., Sciamanna, S., Di Luzio, E., Tozzi, M., Nicolai, C., & Gambini, R. (2007). Structural setting along the CROP-04 deep seismic profile (Southern Apennines - Italy). *Bollettino Della Società Geologica Italiana*, Supplemento, 7, 283–296.

Sterner, S. M., & Bodnar, R. J. (1991). Synthetic fluid inclusions. X: Experimental determination of P-V-T-X properties in the CO_2-H_2O system to 6 kb and 700 °C. *American Journal of Science*, 291, 1–54. https://doi.org/https://doi.org/10.2475/ajs.291.1.1

Stoppa, F., Principe, C., & Giannandrea, P. (2008). Comments on: Carbonatites in a subduction system: The Pleistocene alvikites from Mt. Vulture (southern Italy) by d'Orazio et al., (2007). *Lithos*, 103(3–4), 550–556. https://doi.org/10.1016/j.lithos.2007.10.012