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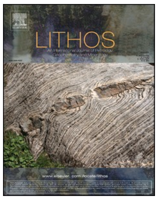

Discussion

Reply to the comment by Trua (2024) on Gennaro et al. (2023), Lithos 456–457, 107325, Large silicic magma chambers at the Moho depth characterize the multi-level plumbing system of back-arc spreading ridges

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1. Introduction

We thank Trua (2024) for her comments and criticisms on the study by Gennaro et al. (2023) published on Lithos (https://www.sciencedirect.com/science/article/pii/S0024493723003092). Our reply allows us to better clarify our methodological approach, discussion points, and, ultimately, the integrated petrological/geophysical model of the Marsili plumbing system we proposed. We are sincerely sorry for the minor typo error on the citation of Trua et al. (2018 and not 2017). In the following, we maintain the scheme proposed by Trua (2024), i.e., numbered sections with titles. We also stress that the used petrological data were obtained on the studies provided by Trua and co-workers in the last years, but also on two tephra (Iezzi et al., 2014; Tamburrino et al., 2015) that extend the previous geochemical SiO_2-rich end-member. Consequently, we take into account any possible previous studies on the Marsili Volcano (MV).

2. Materials and methods

We summarize in the Introduction of Gennaro et al. (2023) the main features of the Marsili plumbing system from previous studies. These include the occurrence of a heterogeneous mantle source (OIB and IAB basalts), mixing between different basaltic magmas, melt evolution by dominant fractional crystallization processes, the occurrence of crystal mush, and the time scale of the magma pre-eruptive processes, which are partly controlled by melt-crystal mush interactions. As concerns the comment on the use of '*trachyte*' instead of '*dacite*', we fully agree that most of the intermediate and less evolved lavas show a calc-alkaline affinity (Fig. 1d in Gennaro et al., 2023). Moreover, we remark that some lavas of Savelli and Gasparotto (1994), Maccarone (1970), Selli et al. (1977), a glass of Savelli and Gasparotto (1994), and most of the tephra of Iezzi et al. (2014) and Tamburrino et al. (2015) fall close to the sub-alkaline/alkaline transition (Fig. 1c in Gennaro et al., 2023). This also holds for some intermediate lavas of Trua et al. (2011). Therefore, the nomenclature of the reported rocks agree with the TAS diagram (Le Maitre, 2002; see also Fig. 1c in Gennaro et al., 2023).

About the robustness of the pre-eruptive conditions inferred by Gennaro et al. (2023), we remember that our conceptual model of the MV plumbing system is supported by (a) pressure and temperature estimated from geobarometry and geothermometry on clinopyroxenes following Putirka (2008), (b) independent simulations with MELTS (Ghiorso and Sack, 1995), (c) results from independent inverse and forward modelling of potential field (gravimetric and magnetic) data, and (d) sensitivity and back validation analysis of the results from the modelling. All these points will be discussed in the following reply to the comments/criticism raised by Trua (2024).

3. Results

In the maps of Marani et al. (1999) and Gamberi et al. (2006), most of the traces of dredging, i.e. the clamshell pathway, extend from the upper to the lower flanks of small cones placed on the axial portion of the Marsili or on the outer flanks of the main edifice. Therefore, we are uncertain if these samples are representative of the small cones or of the substratum on which they formed. In principle, these samples could also be lava fragments eroded from the conduit walls during the eruptions, i.e. xenoliths, as well as portions of debris of lavas accumulated far from the original substratum. The above considerations do not detract from the high quality of the sampling by Marani et al. (1999) and Gamberi et al. (2006), and their significance in the reconstruction of the volcanic activity at MV. In the absence of these samples, petrological features of MV would remain a mystery for the whole scientific community.

However, it is evident that single samples from a dredging may lack representativeness of broader landforms unless there are direct

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observations. Within this framework, a recent 5 m × 5 m digital bathymetric model of the top of MV between 550 m and 1650 m depth (Nicotra et al., 2024) shows that lava flows are a subordinated feature of the volcanic landforms of the Marsili axial zone. The majority of the cones appear to be associated to explosive activity and arranged along dikes. Maybe most of the misunderstanding by Trua (2024) is due to our use of the word 'volcano' instead of 'volcanoes'. Finally, we stress that, until now, the unique rocks from the MV sampled in a detailed geological framework are the tephra gravity-cored on its summit area and described in Iezzi et al. (2014); Iezzi et al. (2020) and Tamburrino et al. (2015).

Our sentence *"Plagioclase is the most abundant phase followed by clinopyroxene and olivine"* (Gennaro et al., 2023) refers to the whole set of the Marsili rocks. In Trua et al. (2002), plagioclase is the most abundant phenocryst in 70% of the analyzed samples. In the same samples, the primary abundant phase of microlites within the mostly microcrystalline groundmass is constituted by plagioclase, with the exception of only one sample. In Trua et al. (2018), 12 samples out of 16 have phenocrysts of plagioclase as the most abundant phase. No details are provided on microlites, but given that the majority of the samples are the same of Trua et al. (2002), we can infer that plagioclase is the predominant phase in the groundmass. Hence, our sentence, which refers to the whole MV rock suite is not '*reductive*'. It addresses a general feature of the MV magmas. Also, Gennaro et al. (2023) specify that: "*The rocks depict a continuous and uninterrupted evolution trend (Fig. 1c) consistent with the dominant fractionation of early olivine, pyroxene, plagioclase, and later alkali-feldspar (*Iezzi et al., 2014*;* Trua et al., 2002*)*". Therefore, we recognize the role of olivine and clinopyroxene in the evolution of the MV basalts and basaltic andesites.

As concerns the role of amphibole in the evolution of the Marsili magmas, Trua et al. (2014) report that, among all the analyzed samples, amphibole has been detected in one sample (D2) alone and write: '*Rare (0.5 vol.%) and small ($<$ 0.5 mm) amphibole crystals were only found in the D2/1 basaltic andesite*'. In line, occasional amphibole minerals have been also detected in some tephra levels (Iezzi et al., 2014; Tamburrino et al., 2015; Gennaro et al., 2023); in turn, the role of amphibole in the overall evolution of the Marsili magmas is absolutely of second-order, if not practically negligible at a large scale according to the nowadays available data-set.

Concerning the comment by Trua (2024) on '*Indeed, the trachytes refer to the glassy component of the andesite tephra…*' indeed two out of three "trachytic" compositions plotted in the Fig. 2 of our paper are actually the glassy component of the tephra which the bulk rock composition is trachyandesite/trachyte (as reported in the Supplementary tables of Gennaro et al., 2023), and not '*andesitic tephra*' as reported by Trua (2024). This trachyandesite/trachytic tephra gives the *"maximum estimated P"* for the Marsili whole rocks (right plots on the Fig. 2 in Gennaro et al., 2023), justifying our statements unfairly commented by Trua (2024): '*The maximum estimated P values inferred by clinopyroxenes at equilibrium conditions follow a rough general increase from basalts to trachytes*'.The statement by Trua (2024) that '*It is thus surprising that* Gennaro et al. (2023) *provide thermobarometry results in Fig. 2 and the Supplementary Table 5 based on the complete set of these clinopyroxene data. This makes questionable the robustness of the thermobarometry results provided by* Gennaro et al. (2023)' does not mirror the truth. The SiO_2 vs. $Kd_{Fe\text{-}Mg}$ clinopyroxene-liquid plot in Fig. 2a of Gennaro et al. (2023) reports the *equilibrium* and *dis-equilibrium* values calculated for all the available rocks compositions of MV; even more, minerals described like resorbed or antecrysts from the literature were excluded from the data-set used to compute intensive variables. In the SiO_2 vs *T* and *P* diagram (on the right side of Fig. 2, Gennaro et al., 2023) plot only the *P* and *T* estimates from whole rock-cpx couples in which the $Kd_{Fe\text{-}Mg}$ values indicate *equilibrium* conditions according to Putirka (2008). This is also why Gennaro et al. (2023) delimit with horizontal stripped grey bar the field of the *equilibrium* conditions in the SiO_2 vs $KD_{Fe\text{-}Mg}$ plot (see their Fig. 2a). In the SiO_2 vs *T* and *P* plots, the reader can easily note that the samples used for these *P-T* estimates are less than half of the whole data set reported in the SiO_2 vs $KD_{Fe\text{-}Mg}$ plot. This is detailed in the legend of Fig. 2. It is obvious from the analysis of Fig. 2 of Gennaro et al. (2023) that many Marsili samples fall outside the *equilibrium* conditions. Consequently, these samples are not included in our *P-T* determinations, as further clarified above.

As concerns the weight of the water column above the Marsili seamount, which vertically extends from 500 m to 3200 m below the sea level, we remark that, in accordance with the Stevin's law, the related pressure for this depth interval ranges from 4.9 MPa to 31 MPa. These values are one to two orders of magnitude lower than the standard error (170 MPa, i.e. ± 85 MPa) estimated for our *P* determinations (see section 2.1 of Gennaro et al., 2023). Therefore, the pressure exerted by the water column is irrelevant, at least between 500 m to 3200 m depth. We agree that our geobarometric estimates have the significance of '*order of magnitude determinations*'; in our opinion, these petrological outcomes are here corroborated and substantiated by totally independent geophysical data and models (see below and in our study Gennaro et al., 2023). This is rarely observed in the petrological and geophysical fields.

We use the MELTS simulations (Ghiorso and Sack, 1995) to test the role of *P*, *T* and H_2O in the crystallization path of magmas with different compositions (basalt, basaltic andesite, trachyandesite, andesite) and compare the results with the real mineral assemblages and the *P-T* conditions inferred from independent geobarometric and geothermometric determinations. In other words, we use simulations to answer the question: are our *P-T* determinations and observed mineral assemblages compatible with theoretical liquid line of descent? This is why Gennaro et al. (2023) concentrate their simulations on samples representative of magmas with a different degree of evolution. The aim of Gennaro et al. (2023) is not to reproduce the full crystallization history of a selected sample, but to focus especially on a magma with a given degree of evolution. Therefore, we select sample D19 because of its degree of evolution, i.e. because this sample is representative of a basaltic andesite, and check if the mineral assemblage from simulations is compatible with that observed in the rocks.

The observation by Trua (2024) about the more hydrous conditions than the ones so far documented by olivine hosted melt inclusions (Rose-Koga et al., 2012; Trua et al., 2010) is certainly true but does not add anything to the configuration and geometry of the MV plumbing system. The rare occurrence of amphibole in few samples is representative of a highly localized fractionation process and cannot be considered indicative of a major, water-rich reservoir.

4. Discussion

In the sentence of Gennaro et al. (2023) *"early basalt/trachybasalts up to later trachytic magmas originated by fractional crystallization processes"*, we simply summarize the evolution trend depicted by the MV magmatic suite, without any reference to the eruptive history of the seamount, i.e. *the reiterate eruptions of basaltic magma* of Trua (2024). The adjective '*later*' in the above sentence of Gennaro et al. (2023) refers to the younger pyroclastic and more evolved rocks of Marsili from gravity cores (Iezzi et al., 2014, 2020; Tamburrino et al., 2015). These rocks have ages of 2–3 ka. The lava flows from previous studies are older (when dated) and never reach the degree of evolution of trachytes. Therefore, based on the few present-day geochronological and geochemical data, these trachytic pyroclastics represent the younger and more evolved products of MV.

Trua (2024) criticizes the conceptual model of the Marsili seamount by Gennaro et al. (2023). This model localizes the trachytes at the crust/mantle interface, the intermediate compositions in the middle crust and overlying edifice, and the less evolved magmas upraising from the mantle and eventually stopping for short times within the crust, at any depth. The model by Gennaro et al. (2023) is constrained not only from the above discussed *P-T* determinations, but also from potential field data. Importantly, the re-scrutinization of this updated and enlarged rock data-set from MV prompted the re-analysis of geophysical data; it is also relevant to state that petrological results can "observe" *P-T* conditions in a poorly defined time, while potential field data "image" the current situation.

The Marsili seamount shows an "inverted" gravimetric and magnetic structure suggesting that the more evolved (lower density) magmas occur in the lower crust or at the crust/mantle interface. The direct modelling of combined gravimetric and magnetic data in Gennaro et al. (2023), which has the *P-T* values from petrology as input data, fully explains the geophysical"inverted" configuration of the MV plumbing system. Also, the results of the inverse modelling (Fig. 5 of Gennaro et al., 2023), which are fully independent from a priori assumptions, are also fully compatible with the results from petrology. In addition, Gennaro et al. (2023) performed sensitivity and back-validation analyses of the results by testing the effect of other crustal configurations. These include, as reported in Gennaro et al. (2023): *"(a) varying the density and magnetic susceptibility values and trying to exclude the deep and/or shallow magmatic reservoirs, (b) inverting the depth of the SiO_2-rich and SiO_2-poor magma reservoirs, and (c) excluding the presence of the hydrothermal alteration at the summit of MAV."* The results of such back and validation analyses on alternative geologic models are summarized in the Figs. S14a,b,c,d,e of Gennaro et al. (2023) and show that the fits are not compatible with such alternative geological models including that proposed by Trua et al. (2014, 2018). This latter implies a "normal" density/magnetic structure of the Marsili plumbing system.

As concerns the hypothesis raised by Trua (2024) about the possibility that '*the deep crustal magma storage zone geophysically detected by* Gennaro et al. (2023) *is likely made of clinopyroxene- to amphibole-bearing mafic mush lithologies*', we remember that the density of pyroxenes is about 3189–3550 kg/m^3 and that of amphibole is 2900–3500 kg/m^3 (Deer et al., 2013; Robie and Bethke, 1962). These values of density are too high and the results of the geophysical modelling by Gennaro et al. (2023) require densities $\leq$2700 kg/m^3. From a critical perspective, it is well-established that the inversion of potential field data lacks uniqueness, particularly when it is unconstrained.

In Gennaro et al. (2023), the petrological data suggest a primary base to guide the inversion process reducing then the ambiguities. Assuming magma storage mostly made of *"clinopyroxene- to amphibole-bearing mafic mush lithologies"* would increase of about 30% the gravity signal along the axial zone of MV. This means that the best fitting of gravity and magnetic data would be achieved shifting downward the causative body within the upper mantle. In this context, from both density and magnetic point of view, the crustal mush proposed by Trua (2024) would be practically indistinguishable from the surrounding mantle. Nevertheless, this (hypothetic) configuration has already been accounted in the back-validation analyses (Fig. S14, case 2). Therefore, we exclude the hypothesis of Trua (2024) about the possible existence of significant clinopyroxene and/or amphibole crystal-mush in the deep crust below MV.

As concerns the comments by Trua (2024) about the sentences in Gennaro et al. (2023) (a) '*transition from an early, prevailing fissural basaltic volcanism to a later trachyandesitic to trachytic volcanism*' and (b) '*associated with a decrease in the spreading rate*', we remember that the Marsili trachytes are, at the present, the more recent products with a geochronological constraint (Iezzi et al., 2014; Tamburrino et al., 2015). Again, these trachytes come from gravity cores collected on a small volcanic cone located in a landform where, based on geomorphological data, the younger activity of MV developed (Nicotra et al., 2024).

Referring to the role of the spreading rate in the evolution of the MV, Gennaro et al. (2023) suggest that the storage of evolved magmas at depth may be favored by the observed decrease in the spreading rate of the Marsili back-arc basin (Cocchi et al., 2009) possibly associated with a compressive stress field related to the present-day closure of the Tyrrhenian Sea (Zitellini et al., 2019). A similar evolution is also observed in the Vavilov basin (central Tyrrhenian Sea) as proposed by Cocchi et al. (2023). Obviously, other hypotheses may be proposed. However, the relationships between the MV magmatic evolution and the geodynamic processes proposed by Gennaro et al. (2023) are based on the present-day available data. The alternative hypothesis by Trua (2024) about the role of a thinned crust at the northern edge of MV, which is suggested to favor a more rapid ascent of the basaltic magmas, is not consistent with the available tomographic data. Recent seismic attenuation and tomography studies (Magrini et al., 2022; Nardoni et al., 2021) clearly show that moving from the MV seamount northward, a thickening, and not a thinning, of the crust occurs. In addition, we remark that seismic data and, as consequence, tomography models at the scale of the Marsili seamount are still lacking.

5. Concluding remarks

We thank Trua (2024) for her criticisms of Gennaro et al. (2023). These critiques have given us the opportunity to (a) better clarify our approach to the study of the MV and (b) discuss "in-depth" how the merging of geochemical and geophysical data may allow us to propose comprehensive conceptual models of volcanoes. We want to close our reply with a sentence from a seminal paper by Magee et al. (2018): *"We show that approaching problems concerning magma plumbing systems from an integrated petrological, geochemical, and geophysical perspective will undoubtedly yield important scientific advances, providing exciting future opportunities."*

CRediT authorship contribution statement

Emanuela Gennaro: Data curation, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Gianluca Iezzi:** Conceptualization, Funding acquisition, Investigation, Supervision, Validation, Writing – original draft, Writing – review & editing. **Luca Cocchi:** Conceptualization, Data curation, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. **Guido Ventura:** Conceptualization, Investigation, Supervision, Validation, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that she has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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