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TEXTURAL AND PETROLOGIC STUDY OF THE SUBVOLCANIC MAFIC AND ULTRAMAFIC EJECTA OF PITON DE LA FOURNAISE AS A KEY TO UNRAVEL THE SHALLOW MAGMATIC CRYSTALLIZATION PROCESSES AT LA RÈUNION ISLAND (INDIAN OCEAN)

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This study deals with subvolcanic ejecta within the Bellecombe Ash Member (BAM) an explosive eruption occurred ≈ 5.5-3.0 ka at Piton de la Fournaise (Réunion Island). Petrological investigations of more than one hundred ejecta led to recognize a wider spectrum (at least on textural point of view) of ultramafic and mafic lithotypes (dunites, wherlites, ophitic gabbros, sub-ophitic gabbros, poikilitic gabbros, doleritic gabbros, micro-monzogabbros and "porphyrogabbros", *i.e.*, gabbros *lato sensu* with interstitial micro-crypto crystalline groundmass) than already evidenced by the literature. These intrusive lithic suites highlighted subvolcanic processes of cumulate crystallization *vs*. slowly cooled equivalents counterparts of basaltic melts (*i.e.*, rocks with subvolcanic textures but retaining a liquid composition). Some of this ejecta also show silicate melts of basic-intermediate composition entrapped interstitially within the subvolcanic crystal framework and quenched as glass during the eruption. Alternatively, these interstitial melts could evolve and expelled from the crystal frameworks, forming separated small pockets of liquids of trachytic composition whose crystallization were temporarily prevented by the very high heat flux of the La Reunion mantle plume and occasionally erupted as trachytic pumices as occurred for the BAM or the 2007 major basaltic eruption. It is worth to note that also the micro-crypto crystalline groundmass of the so called porphyrogabbros can be considered very small fractions of entrapped trachytic melts as the presence of

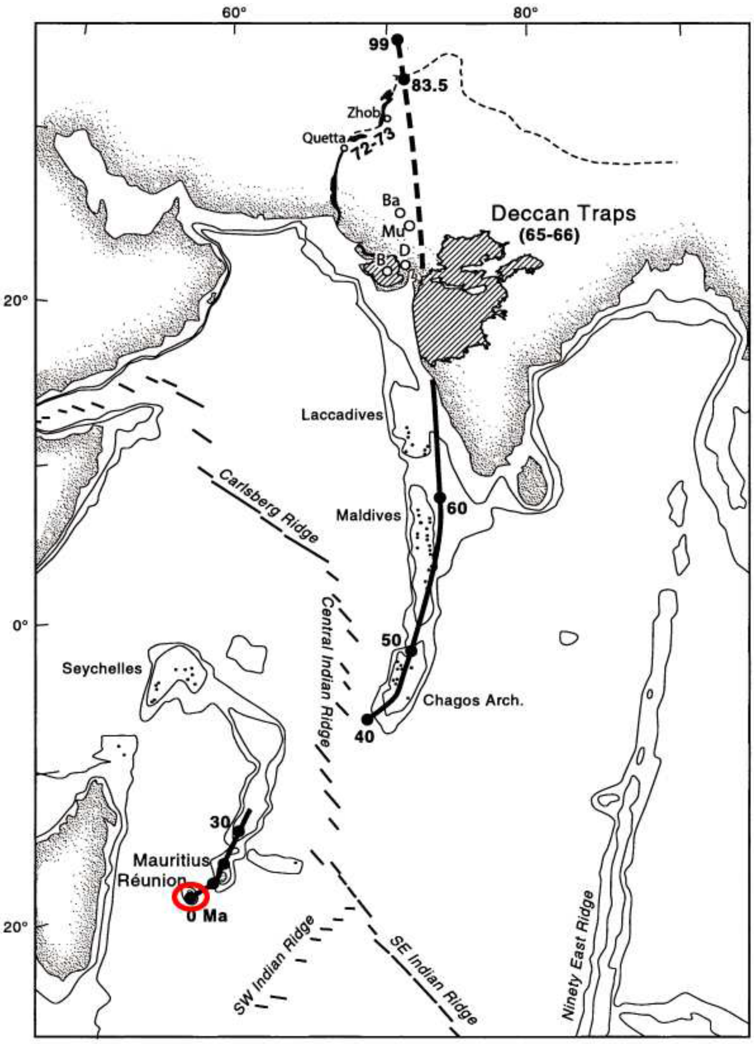

Fig. 1 - The model 0-99 Ma track of the Réunion hotspot (the heavy line in the map is assuming a stationary hotspot and that plate reconstructions are accurate; Kent *et al*., 2002; Duncan, 1990). The Réunion Island is indicated in the map with a red circle.

sanidine + phlogopite may testify crystallization from more evolved liquids than basalt. A Raman analyses barometry of fluid inclusion and noble gases and CO_2 from fluid inclusion crushing extraction and mass spectrometer analyses indicate the dunites are the intrusive ejecta from the deepest levels (~13 km b.s.l., *i.e.* underplating level) and wherlites should have crystallized close to the submarine base of the edifice (~6 km b.s.l.), whereas the mafic subvolcanic samples are even shallower. Nevertheless, some composite intrusive ejecta emphasizes the coexistence of ultramafic-mafic portions (wherlite passing to plagioclase wherlite to troctolite and gabbro) at shallow-intermediate crustal levels of crystallization, indicating interactions between batches of basaltic magmas and wherlite cumulates, thus producing heterogeneous ultramafic-mafic patchy microdomains at the mesoscale. Original texture of some wherlites were also possibly modified through melt percolation, giving rise to plagioclase-bearing wherlites. Some of these modifications could however be occurred during decompression due to transport of the ejecta to the surface by the erupting host basalt.

INTRODUCTION

La Réunion is a huge volcanic oceanic system in the southernmost part of the Mascarene Basin, in the Indian Ocean (Fig. 1). The island is a large volcanic edifice, with an overall volume of about 51500 km^3, elliptical in shape (50×70 km) with a NW-SE orientation and rising on the ocean floor (about 4200 m below sea level) to 3070 m above sea level. The Réunion Island consists of three volcanic massifs, the oldest Piton des Neiges (north-west), the youngest, presently active Piton de la Fournaise (south-east) and a third, poorly known buried volcano, named Les Alizés, mainly defined through exploratory drilling and constituting the basement of the Piton de la Fournaise (Fig. 2; Lénat *et al.*, 2012). The construction of Piton de la Fournaise *sensu stricto* started at about 400-450 ka.

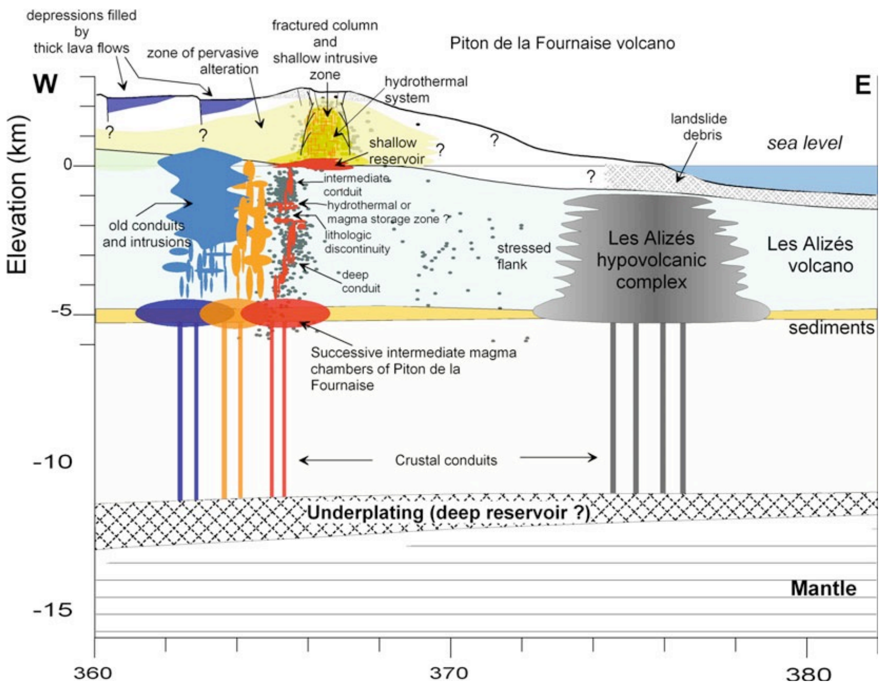

Fig. 2 - Interpreted W-E geological section of Piton de la Fournaise (Lénat *et al.*, 2012). Horizontal coordinates: UTM km WGS84.

Its lavas are mainly transitional basalts defining a differentiation trend towards mugearites, intermediate in character between the alkaline and the tholeiitic series, both aphyric ("cotectic basalts" or Steady State Basalts, SSB) and olivine-rich ("oceanites"). They slightly differ from Les Alizés aphyric basalts ("abnormal group") that belong to the more alkalic (K_2O-rich) series, with higher MgO and lower CaO and SiO_2 contents. The moderate chemical heterogeneity has been since long attributed to a combination of slight mantle source heterogeneity and influence of clinopyroxene fractionation at mantle/underplating depth. Magmas stored at crustal depths and erupted at the summit area are quite homogeneous and result from the hybridization process of "tholeiitic" and "alkaline" end members (Di Muro *et al.*, 2014; Boudoire *et al.*, 2018; Vlastélic *et al.*, 2018).

The present work deals with a petrological study of mafic and ultramafic ejecta of the "Bellecombe Ash Member" (BAM, ≈ 5.5-3.0 ka), to unravel the pre-eruptive conditions of basalt crystallization and tentatively match the various recognized petrographic groups of the subvolcanic igneous rocks with the whole extrusives (Piton de la Fournaise, Piton des Neiges, Les Alizés) combining mineralogy, petrographic texture and geochemistry. Large caldera forming events such as that of the BAM, the largest Holocene explosive eruption produced by Piton de la Fournaise involve, as ejecta, a large fraction of the crustal magmatic plumbing system and may thus allow to i) access to a rare snapshot of the magmatic processes (cumulate *vs*. liquid composition; volatile exsolution and percolation; melt and rock assimilation) occurring below one of the most active basaltic volcanoes of the world, and ii) study the magmas driving these rare but very hazardous eruptions.

RESULTS

The petrological study of more than one hundred samples, representative of the ejecta found within the BAM, emphasizes the presence of many subvolcanic mafic and ultramafic igneous rocks: dunites, wherlites, ophitic gabbros, sub-ophitic gabbros, poikilitic gabbros, doleritic gabbros, micro-monzogabbros and porphyrogabbros (*i.e*. gabbros *lato sensu* with interstitial micro-crypto crystalline groundmass; Fig. 3).

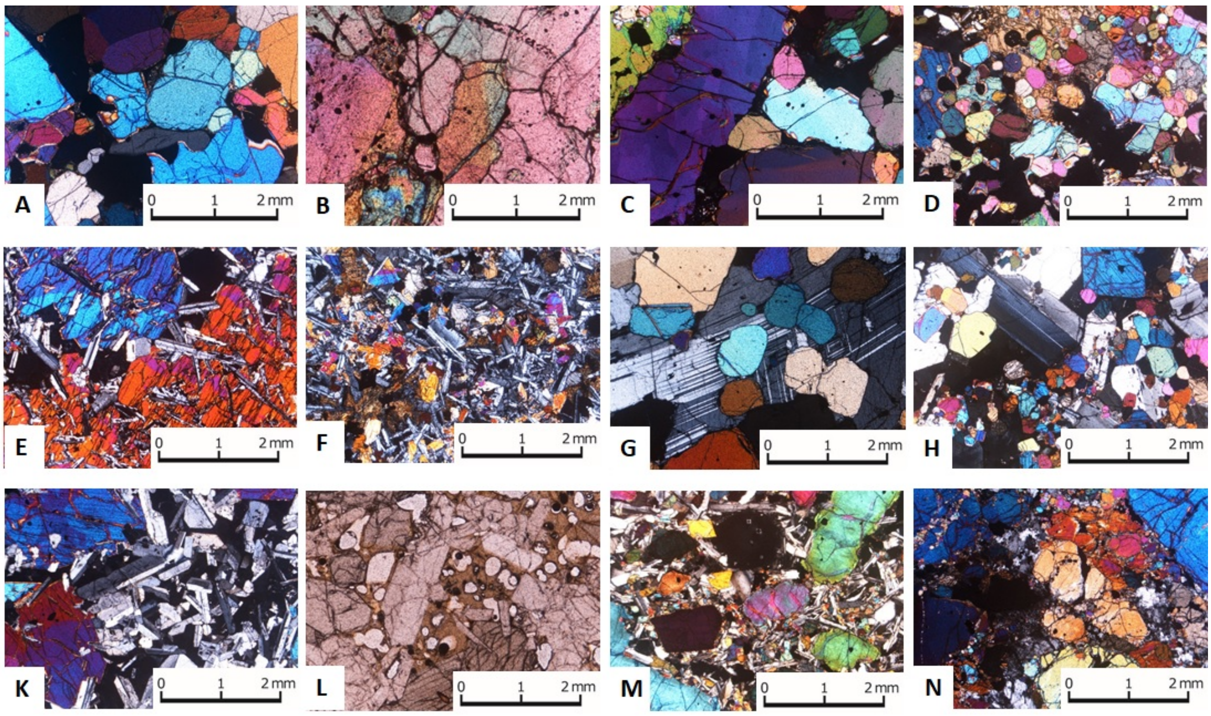

Fig. 3 - Thin section microphotos of dunites (A, B), wherlites (C, D), ophitic gabbro (E), doleritic gabbro (F), poikilitic gabbros (G, H), sub-ophitic gabbro (K) and porphyrogabbros (M, N) at crossed nicols and sub-ophitic gabbro with interstitial glass (L) at normal plane polarized light.

Cumulate cognates *sensu stricto* are present, often with quenched basaltic glass entrapped interstitially and in minerals (melt inclusions), with no disequilibrium textures recognized in the subvolcanic crystal frameworks. Other subvolcanic clasts (*e.g*. doleritic gabbros) may simply represent slowly-cooled equivalents (with no crystal-

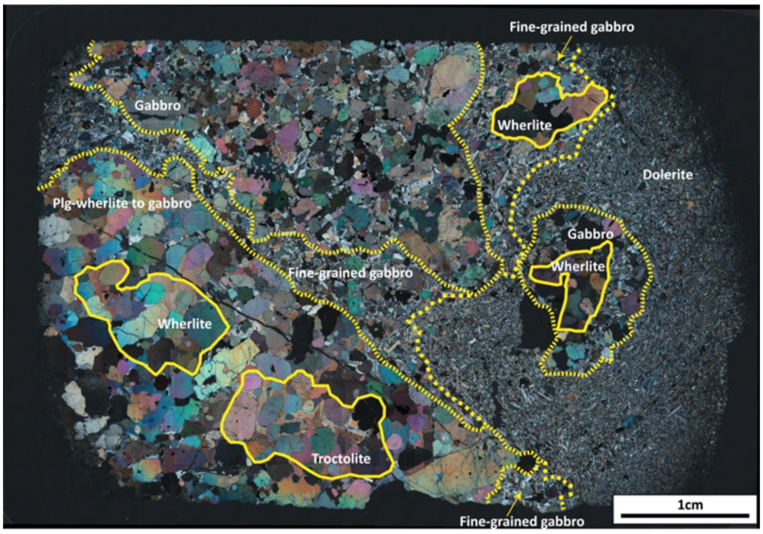

Fig. 4 - Large (3.5×5 cm) thin section microphoto (crossed nicols) of the sample B108. Ultramafic and mafic portions are present in the whole sample, with different modal mineralogy and texture. Troctolite portion coexist with wherlite to plagioclase wherlite to gabbro.

liquid fractionation) of the erupted cotectic basalts. Chemistry of both minerals (olivine, clinopyroxene, feldspar, oxides and phlogopite) and interstitial glass from the subvolcanic ejecta has been performed by EMPA.

It is worth to note that porphyrogabbros emphasize a wide range of feldspars, as interstitial crystals between the large olivine phenocrysts, represented by plagioclase, anorthoclase and sanidine, defining a complete miscibility feldspar curve. Olivines of each mafic and ultramafic lithotypes ejecta show different forsterite contents and the whole composition ranges from Fo_{68} (sub-ophitic gabbros) to Fo_{90} (dunite), with CaO contents varying from 0.05 to 0.4 wt.% in the whole ejecta. Clinopyroxene of mafic and ultramafic subvolcanic ejecta ranges from Fs_{14} (mafic lithotypes) to Fs_8 (wherlites). Mg# content of clinopyroxene show three range of composition: evolved samples (pumices of BAM and Piton des Neiges, Mg# 55-68), mafic ejecta (Mg# 73-85) and wherlite + dunite samples (Mg# 86-88). Opaque minerals were also found. Dunite and wherlite show Cr-spinels (also present in the porphyrogabbros) whereas magnetite and/or ilmenites are mostly found in the remaining ejecta.

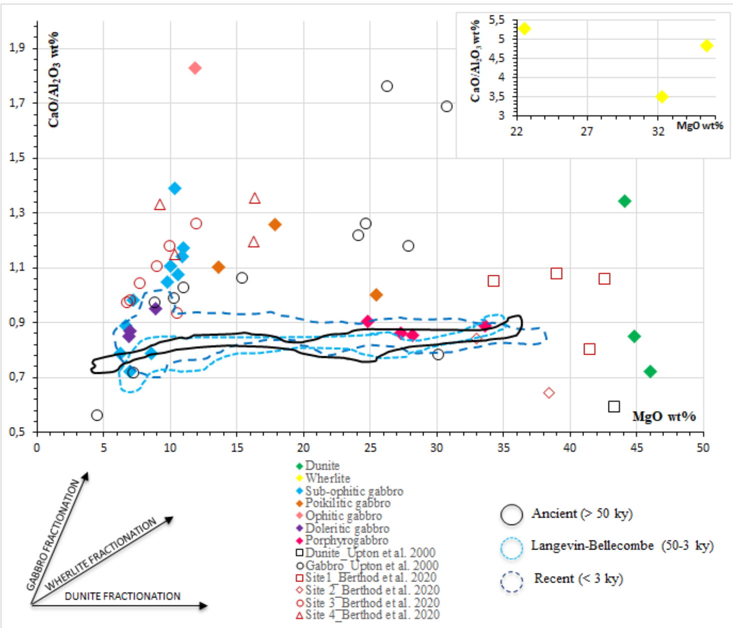

Fig. 5 - CaO/Al_2O_3 *vs*. MgO diagram compared with literature data (Upton *et al*., 2000; Berthod *et al*., 2020; OVPF data from Ancient, Langevin-Bellecombe and Recent extrusives).

In addition, some large composite intrusive ejecta (*e.g.*, B108) emphasizes the coexistence at the mesoscale of ultramafic-mafic patchy microdomains (wherlite to plagioclase-wherlite to troctolite to gabbro; Fig. 4).

A comprehensive geochemical comparison among the analysed mafic and ultramafic ejecta (bulk-rock major and trace elements by ICP-OES-MS) and the whole compositional spectrum of the Piton de la Fournaise and Les Alizés volcanic rocks available from literature was also carried out. Major and trace elements geochemistry allowed to confirm the three fractional crystallization trends already defined by the literature, namely gabbro- wherlite- and dunite-fractionations which well agree with the erupted basalts in the Réunion Island in the last 500 ka (Fig. 5).

Major elements characterization by EMPA of the quenched interstitial glass and few pumice samples are also reported in the TAS diagram along with the bulk-rock composition (Fig. 6).

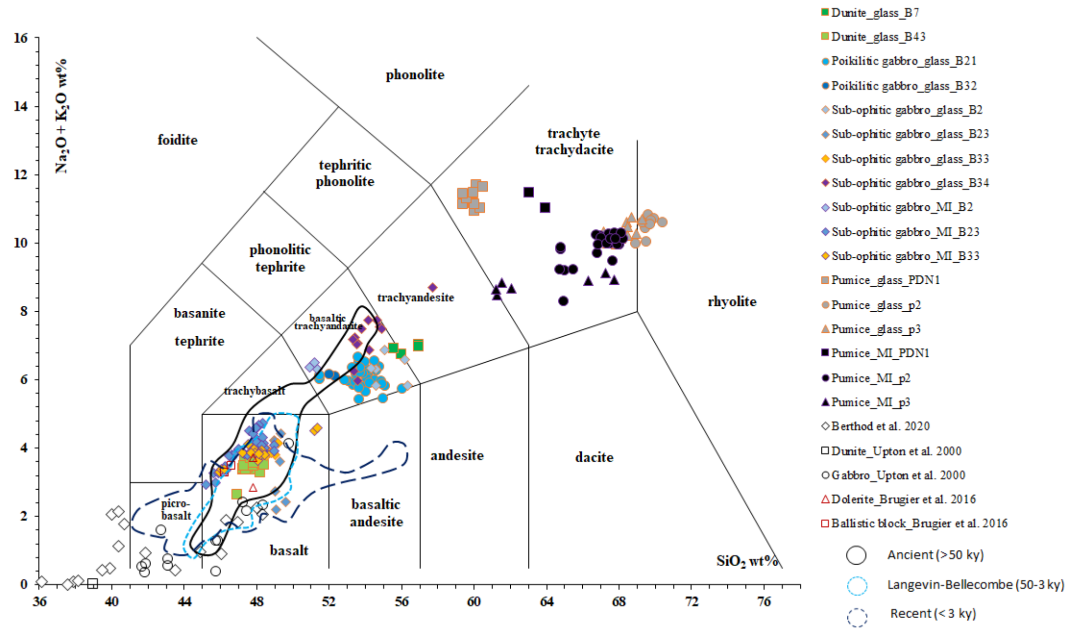

Fig. 6 - Total alkali *vs.* silica diagram of interstitial glass and melt inclusions of analysed representative subvolcanic samples of Bellecombe Ash Member (dunites, poikilitic gabbros and sub-ophitic gabbros) and some trachyte pumice samples (p2, p3: Bellecombe Ash Member; PDN1: Piton de Neiges) compared with whole rock literature data, from OVPF database, Berthod *et al.* (2020), Upton *et al.* (2000) and Brugier (thesis, 2016).

A fluid inclusion chemical and thermobarometric study (CO_2, H_2O and noble gases) was made on selected olivine, clinopyroxene, and feldspar crystals. Noble gases and CO_2 content in fluid inclusions of the studied ejecta reveal variable concentrations and elemental ratios (*e.g.* He/Ar*), indicating, for the whole mafic and ultramafic suite of the Piton de la Fournaise magmatic plumbing system a wide range of depths, from the underplating zone to the submarine base of the edifice and various extent of magmatic degassing. The above barometric data have been also confirmed by fluid inclusion study by Raman spectroscopy analyses. The CO_2-H_2O fluid inclusion and thermobarometric studies carried out by Raman spectroscopy on selected single crystals (olivine and clinopyroxene) permitted to better understand the depths of crystallization of the samples (Fig. 7).

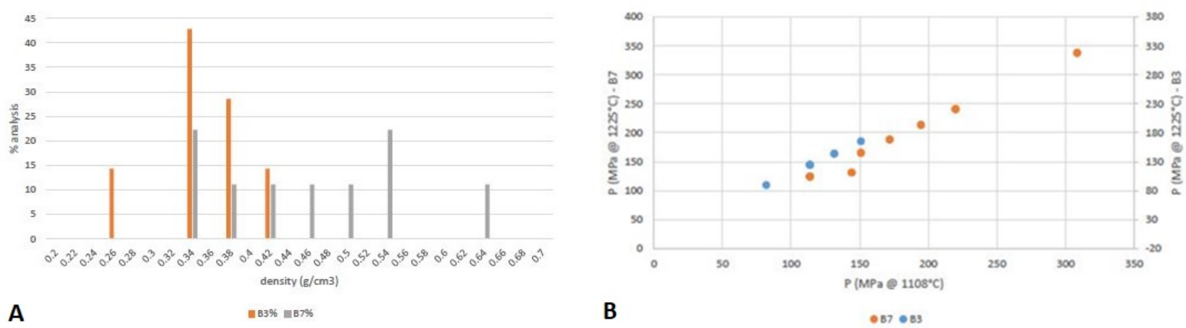

Fig. 7 - A) Density content of CO_2 in the fluid inclusions of olivine crystals of sample B7 (dunite) and clinopyroxene of sample B3 (wherlite); B) P *vs.* T°C diagram for samples B7 and B3. Assuming a temperature of formation range of 1108-1225°C, dunite show a pressure of 309-338 MPa, corresponding to 13 km depth, ~ underplating level; wherlite pressure is about 151-166 MPa, and it corresponds to 6 km depth, rather close to the submarine base of the edifice.

DISCUSSION AND CONCLUSIONS

Textural and petrologic studies of the subvolcanic ejecta within the BAM provides new insights into the magmatic plumbing system and the subvolcanic crystallization processes at La Réunion Island, also allowing to target the transcrustal plumbing system still active during large caldera forming events. With respect to the available literature data, a wider spectrum of mafic and ultramafic subvolcanic lithotypes, at least in terms of variety of textures, was emphasized. Mafic ejecta can be grouped into doleritic gabbros, poikilitic gabbros, sub-ophitic gabbros, ophitic gabbros, micro-monzogabbros and porphyrogabbros. Ultramafic samples consist of dunites and wherlites, these latter being also represented by composite samples making transition to plagioclase wherlite, troctolite and gabbro patchy microdomains. Fluid inclusion barometry and noble gases and CO_2 from fluid inclusion crushing extraction and mass spectrometer analyses indicate the dunites are the intrusive ejecta from the deepest levels, approximately at the underplating levels of formation (~13 km b.s.l.). Wherlites should have crystallized close to the submarine base of the edifice (~6 km b.s.l.), whereas the mafic subvolcanic samples are even shallower.

A wide spectrum of crystallization processes can be envisaged in this mafic-ultramafic subvolcanic suite: (i) dunites, wherlites, poikilitic to ophitic and sub-ophitic gabbros are cumulates *stricto sensu* whereas (ii) doleritic gabbros and some sub-ophitic gabbros represent *in situ* crystallization of cotectic basalt (SSB) in subvolcanic environment and thus retaining a liquid composition (*i.e.* slowly cooled equivalents of basalts). However, the overall textural and geochemical data of the investigated mafic-ultramafic ejecta do not only reflect different mode of subvolcanic crystallization but also (a) the possibility that small pockets of liquids may also evolve to trachytic compositions and (b) the interaction between basaltic liquids and cumulates already formed at crustal level of the Piton de la Fournaise plumbing system.

(a) The compositional range from basalt to basaltic trachyandesite of the interstitial glass found in the intrusive clasts indicate that the melt was entrapped within the crystal frameworks and quenched during the eruption. This likely suggests the clast were disrupted from the wall rocks and transported very fast to the surface, mostly as cognates. If not entrapped interstitially during *in situ* crystallization, silicate liquid could be also expelled from the crystal frameworks, forming small, separated melt pockets. Rare trachytic pumices from the BAM show a more evolved composition than the quenched interstitial glass in the subvolcanic ejecta, therefore suggesting the liquid may really evolve and escape if not entrapped in the crystal framework of some crystallization front of the magma plumbing system. It is worth to note that the so called porphyrogabbro ejecta could represent oceanite magmas stored at crustal levels where sanidine- and phlogopite-bearing micro-cryptocrystalline groundmass crystallized from the residual melt and interstitially entrapped within the abundant olivine crystals. This groundmass in the porphyrogabbros (Fig. 8 e, f) could be approached to a trachytic liquid, which might be erupted as glassy pumice if groundmass crystallization is precluded. It is worth to note that in April 2007, Piton de la Fournaise emitted a very small volume of trachytic pumice during its largest historical eruption. The trachyte, genetically related to the evolution of basic magmas of the La Réunion mantle plume, was interpreted by Vlastélic *et al*. (2021) as a liquid remnant of an extinct volcano, such as Piton des Neiges or Les Alizés or partial melting of old syenite intrusions or remobilization of interstitial melts not fully crystallized. The few trachitic pumices in the BAM and the sanidine- and phlogopite-bearing micro-cryptocrystalline groundmass in the porphyrogabbro ejecta indicate the hypothesis that small pockets of trachyte melt could form also in the Piton de la Fournaise plumbing systems. Solidification and trapping of these very small volumes of trachytic melts in the subvolcanic crystallization processes could be locally and temporarily prevented by very high heat flux which is not unlikely for La Reunion mantle plume.

(b) Some textures and modal mineralogy of composite ultramafic-mafic ejecta (*e.g.*, B108) or plagioclase-bearing wherlites (*e.g.*, B28) can be the result of complex processes of modification of the pristine ultramafic cumulates by the interactions with high-temperature basalts persistently rising in the plumbing system of the Piton de la Fournaise. Textures shown in the composite ultramafic-mafic ejecta can be the result of basaltic melts interacting with wherlite cumulates, leading to the instability (dissolution) of clinopyroxene and highly rounded olivine crystals even with fritted margins, in cotectic relationship with plagioclase (Fig. 8 a, b). In this way at the same pressure, but higher temperature, only olivine + plagioclase are on the liquidus, successively associated to gabbro patchy microdomains at the mesoscale when temperature decrease after troctolite crystallization.

The presence of highly rounded olivines surrounded by clinopyroxene, in the wherlite sample B28 (Fig. 8 c, d) can be also explained by processes of interaction with rising basaltic magmas and phase relations in the system forsterite-diopside-SiO_2 (Kushiro, 1969, 1972), where the ferromagnesian minerals (olivine, clinopyroxene) are not sensitive to water pressure. The peritectic between forsterite, diopside and enstatite in the anhydrous system at atmospheric pressure changes composition only slightly in the water-saturated system up to 2 GPa (whereas silica strongly reduce its stability). The texture characterizing the wherlite sample B28 should reflect processes occurring in the Forsterite-Diopside-Quartz system along the upper part of the cotectic line Fo-Di whose behaviour can be as reaction curve rather than cotectic. As a matter of fact, it can be predicted that at 0.3 GPa (pressure inferred for the wherlite lithotypes by fluid inclusions) textural and modal modifications of ultramafic cumulate assemblages may occur during percolation and rising of basaltic melts. It is worth to note that at this pressure (about 0.3 GPa) clinopyroxene can be out of its stability curve whereas plagioclase is on the liquidus (Fisk *et al*., 1988; Albarède *et al*., 1997). B28 wherlite has got, in fact, a plagioclase modal content of about 8 vol%.

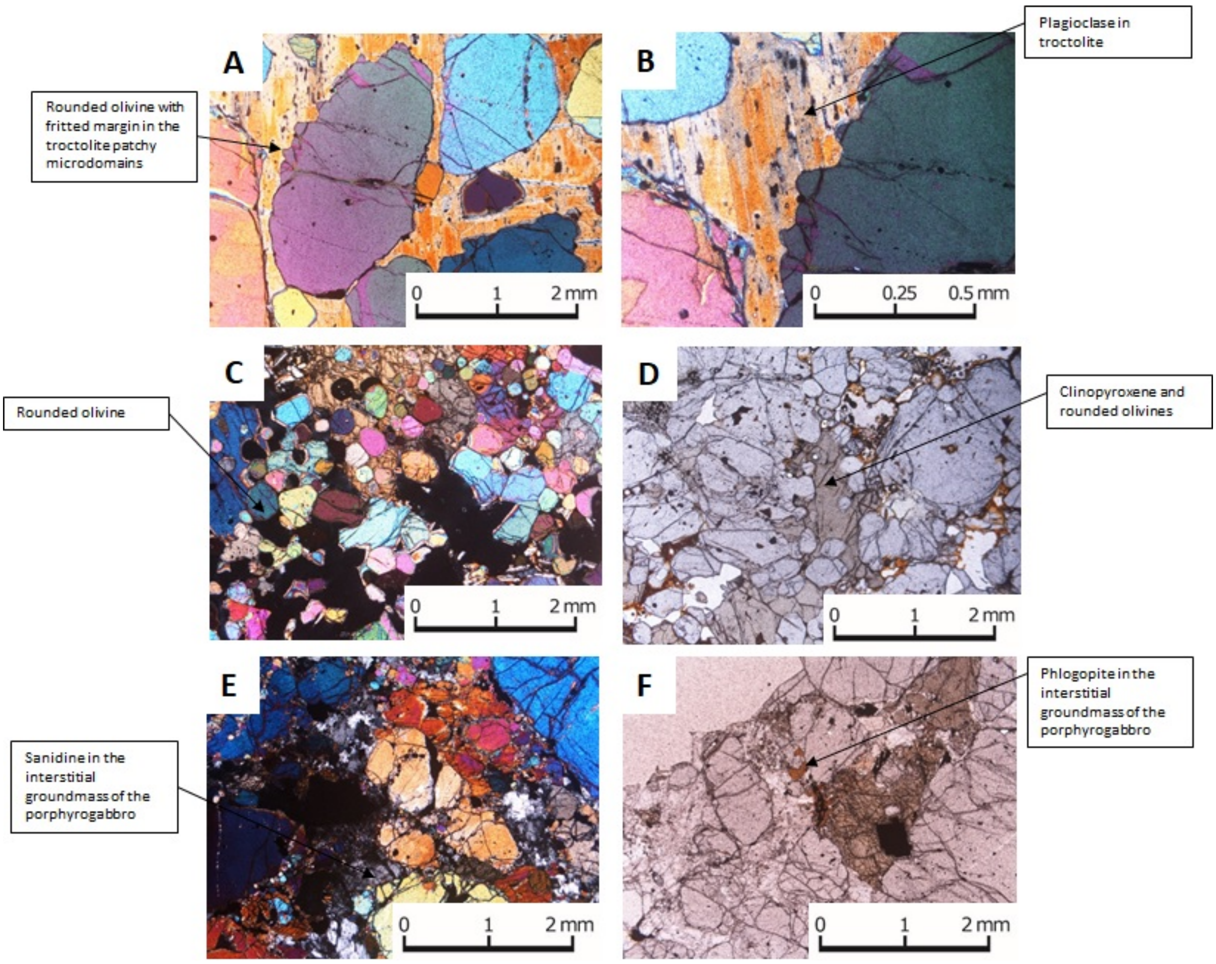

Fig. 8 - Thin section microphotos of some key-samples of the investigated subvolcanic ejecta. A-B: troctolite portions in the composite wherlite to plagioclase wherlite to troctolite and gabbro sample (B108); B is a close up of A. C-D: plagioclase wherlite sample (B28); E-F: porphyrogabbro sample (B20).

These destabilization/disequilibrium processes of cumulate assemblages should have occurred at shallow-intermediate crustal levels where the liquidus curves of plagioclase + clinopyroxene intersect the stability-out of clinopyroxene.

It is worth to note that similar processes of basaltic percolation into peridotites, although within mantle environments, give rise to an end-member process of "dunitization" (Renna & Tribuzio, 2011; Drouin *et al*., 2009, 2010; Basch *et al*., 2018).

Anyway, as the studied ejecta represent cognates disrupted from the subvolcanic magmatic plumbing system of the Piton de la Fournaise (or the older volcano edifices of the Réunion Island), some of the above-mentioned textural modification of ultramafic intrusive clasts could be also the result from the reactions with the host basalt rising to the surface and erupted.

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