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# Sulfur, selenium and tellurium fractionation during magma crystallization and degassing: constraints from southwest Indian Ocean volcanism (La Réunion Island and Fani Maoré volcano, Mayotte)

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1 **Sulfur, selenium and tellurium fractionation during magma crystallization and**  
2 **degassing: constraints from Southwest Indian Ocean volcanism (La Réunion**  
3 **Island and Mayotte Fani Maoré eruption)**

4

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24 **Abstract**

25 Selenium (Se) and tellurium (Te) are oxygen group elements that share chemical properties  
26 with sulfur, but also show subtle differences that are useful to constrain magma genesis and  
27 source. Using high-precision isotope dilution measurements, this study characterizes the  
28 behavior of Se and Te, relatively to S, during the degassing and crystallization of cogenetic  
29 magmas from the southwest Indian Ocean. The study of subaerial and submarine lavas from  
30 La Réunion Island first shows that, unlike S and Te, Se is not significantly lost during the rapid,  
31 final ascent of less differentiated magmas (MgO > 6wt%). This is because Se is retained as  
32 selenide in primary melts despite relatively oxidized conditions. Conversely, selenium  
33 degassing occurs during magma crystallization below 6 wt% MgO, at a similar rate as sulfur,  
34 yielding small S/Se fractionation in the residual magma. Sulfide fractionation, which begins  
35 between 5 and 4 wt% MgO, has minor effect on Se compared to Cu. Tellurium is extensively  
36 outgassed from La Réunion subaerial lavas but shows a very specific behavior in submarine  
37 lavas where it is retained and even accumulate near 6 wt% MgO. The very different behaviors  
38 of Se and Te during magma degassing yields extremely large Se/Te variations between  
39 subaerial (up to 225) and submarine (down to 1) lavas from La Réunion. The Fani Maoré  
40 eruption that occurred between 2018 and 2021 offshore the island of Mayotte (Comoros  
41 Archipelago) also provided the opportunity to study chalcogens degassing during the  
42 emplacement of submarine lavas. The study of a pillow lava showing a radial textural zonation  
43 typical of degassing-crystallization during cooling reveals that S, Se and other moderately  
44 volatile elements (Mo, W, Cs) are the most depleted at intermediate depth within the pillow  
45 where pipe vesicles occur, suggesting these elements escape with major volatiles. Conversely,  
46 Te is depleted in the whole interior of the pillow, suggesting Te escapes through other means.  
47 Assessment of pillow degassing during emplacement yields a 6.5% loss of the initial S content,  
48 7.2% for Te, but only 1.6% for Se confirming the lower volatility of Se during lava  
49 emplacement. Chalcogens degassing is accompanied with significant loss of W (8.9%), Mo  
50 (5.1%) and Cs (5.1%) from Fani Maoré lavas. Based on these values, the 6.5 km<sup>3</sup> Fani Maoré  
51 eruption released 1.1 – 1.5 x 10<sup>6</sup> tons of S, 2300 – 2700 tons of Mo, 970 – 1130 tons of W, 194  
52 – 339 tons of Cs, 13.3 – 16 tons of Se and 4.5 – 11.8 tons of Te during emplacement. The  
53 unusually elevated S/Se ratios (16929 – 22130) of Fani Maoré lavas requires a mantle source  
54 extensively fertilized by sulfide melts, whereas the reconstructed S – Se – Te composition of

55 La Réunion plume source is consistent with the preservation of chondritic S/Se and Se/Te  
56 ratios.

57

58 Keywords : selenium, tellurium, magma degassing, magma differentiation, La Réunion,  
59 Mayotte, Fani Maoré eruption

## 60 1. Introduction

61

62 Selenium (Se) and tellurium (Te) are group 16 elements sharing chemical and physical  
63 properties with the element sulfur. In particular  $S^{2-}$ ,  $Se^{2-}$  and  $Te^{2-}$  have very similar ionic radii  
64 (Shannon et al., 1976) allowing extensive substitution in reducing conditions. These elements  
65 are the object of a growing interest because Se and Te are useful elements to constrain models  
66 of Earth accretion and differentiation (Wang and Becker, 2013), upper mantle processes such  
67 partial melting and refertilization of the lithosphere (Lorand and Allard, 2010; König et al.,  
68 2012), while Se plays an important role in biogeochemical cycle (Sharma et al., 2015).  
69 Selenium and tellurium are highly volatile elements but also tend to substitute for sulfur in  
70 immiscible sulfide liquids. This dual nature led to different views regarding the fate Se and Te  
71 during magma genesis an eruption. On the one hand, studies of mantle rocks, ultramafic  
72 cumulates and lavas show that Se and Te are trapped in dense sulfides that accumulate in the  
73 deep roots of volcanoes (Hertogen et al., 1980; Lissner et al., 2014; Collins et al., 2012; Yierpan  
74 et al., 2019). On the other hand, studies of more-or-less degassed lavas (Yierpan et al., 2021)  
75 and volcanic gas products (Greenland and Aruscavage; 1986; Zelenski et al., 2021; Rosca et al.,  
76 2021) show that Se and Te extensively partition into the vapor phase and are delivered to the  
77 outer layers of the Earth. At the heart of this debate is the timing of sulfide saturation relative  
78 to magma degassing, and the degree to which Se and Te partition into sulfide melts relative  
79 to the gas phase. Edmonds et al. (2018) suggest that sulfide saturation control the metal  
80 signature of volcanic gas, and its variations in arc and hotspot settings. Conversely, Zelenski et  
81 al. (2021) suggest that the trace element budget of volcanic gas is mainly determined by the  
82 near-surface partitioning of elements between gas and silicate melt.

83 This paper investigates the S – Se – Te signature of La Réunion hotspot magmatic system to  
84 constrain the nature of the hotspot source, and the role of sulfide saturation versus degassing  
85 on the composition of the erupted lavas. Our approach is based on the study of cogenetic  
86 rocks including plutonic rocks and lavas showing a wide range of degassing (submarine and  
87 subaerial) and crystallization (basalt to trachyte) extents, as well as contrasted cooling rates  
88 (lava flow and glassy tephra). We also compare the S-Se-Te signature of the low-pressure  
89 Réunion magmas to the signature of the high-pressure sulfide saturated magmas that were  
90 emitted during the 2018-2021 Fani Maoré eruption offshore the Mayotte Island (Berthod et  
91 al., 2021, 2022). The results show that the residual abundances of S, Se and Te in lavas are

92 dominantly controlled by degassing processes, unlike less volatile Cu, which records the  
93 deeper processes of sulfide saturation.

94

## 95 2. Geological setting

96

97 The island of La Réunion (Indian Ocean) is the present location of the hotspot that created the  
98 Deccan traps ca. 66 Ma ago (Fig. 1a). The oldest submarine activity is dated at 3.8 Ma  
99 (Smietana, 2011), but the edifice most likely started to grow ca. 5 Myr ago (Bonneville et.,  
100 1988). The emergent part of the island comprises a quiescent volcano (Piton des Neiges) in  
101 the NW and a basaltic shield volcano (Piton de la Fournaise) in the SE (Fig. 1b). Piton des Neiges  
102 produced olivine basalts between 2.1 and 0.43 Ma ago, and increasingly differentiated lavas  
103 (hawaiite, benmoreite, mugearite and trachyte) until its final activity ca. 27 ka ago (Upton and  
104 Wadsworth, 1972; Gillot and Nativel, 1982; Famin et al., 2022). Piton de la Fournaise has been  
105 regularly active since at least 400-450 ka (Gillot and Nativel, 1989; Merle et al., 2010) and is  
106 still presently in its shield building stage. This volcano, one of the most regularly active of the  
107 planet, is well known for producing olivine basalts with little compositional variability  
108 (Albarède et al., 1997; Vlastelic et al., 2018).

109 Mayotte is one of the four islands of the Comoros Archipelago located between Africa and  
110 Madagascar (Fig. 1a). The origin of Comoros volcanism is debated and could either be related  
111 to a mantle plume or to lithosphere deformation (Hajash and Armstrong, 1972; Emerick and  
112 Duncan, 1982; Class et al., 2005; Nougier et al., 1986; Famin et al., 2020; Feuillet et al., 2021;  
113 Thinon et al., 2022). The Fani Maoré submarine eruption occurred between 2018 and 2021,  
114 50 km east of Mayotte, along the East-Mayotte submarine Volcanic Chain, on a 3300 m-deep  
115 seafloor (Fig. 1c). The eruption produced 6.5 km<sup>3</sup> of homogeneous basanitic magmas during  
116 three main eruption phases related to different magma paths (Berthod et al., 2021, 2022;  
117 Chauvel et al. 2024).

118

## 119 3. Samples

120

121 La Réunion sample set, summarized in Table 1 and displayed in Figure 1b, is composed of: (1)  
122 twelve co-genetic samples from the Piton des Neiges differentiation suite, including three  
123 olivine-basalts, two hawaiites, two benmoreites and five trachytes. These samples covered all

124 four magmatic stages of Piton des Neiges (Upton and Wadsworth, 1972; Gillot and Nativel,  
125 1982) and were previously selected and studied by Famin et al. (2016), Nauret et al. (2019),  
126 and Berthod et al. (2020) to cover the four magmatic stages of Piton des Neiges volcano. All  
127 these samples were collected on land, some emplaced as lava flows and others as sheet  
128 intrusions; (2) three plutonic rocks with wehrlitic composition (33 – 41.5 wt% MgO)  
129 interpreted as magma chamber cumulates (Barrat and Bachèlery, 2019; Berthod et al., 2020);  
130 (3) nine lava samples from the recent (2007-2020) activity of Piton de la Fournaise volcano  
131 studied by Vlastelic et al. (2013), including eight basalts with a homogeneous MgO content  
132 (6.4 to 8 wt%), and one olivine-rich lava (29.2 wt% MgO). These samples were selected to  
133 cover a wide range of textures and cooling rates (crystallized lava, quenched lava, scoria,  
134 pumice, Pele’s hairs). (4) Ten submarine lavas, including four samples related to the early  
135 history of Piton des Neiges, and six lavas related to the submarine volcanism that occurred in  
136 the southeast of the island prior to Piton de la Fournaise. These samples have MgO content  
137 between 5.1 and 13 wt% (Smietana et al., 2010; Smietana, 2011).

138 The Fani Maoré samples selected for this study are all fresh submarine lavas studied by  
139 Berthod et al. (2021, 2022) and Chauvel et al. (2024). The samples were dredged during  
140 MAYOBS (Rinnert et al., 2019) and GEOFLAMME cruises (Rinnert et al., 2021). Dredge  
141 locations are reported in [Table 1](#) and displayed in [Figure 1c](#). Samples include: (1) eight evolved  
142 basanites covering the three main phases of the 2018-2020 submarine eruption ([Table 1](#)).  
143 Except for one sample with 9.9 wt% MgO, the eight samples display small compositional  
144 variations ( $3.8 \leq \text{MgO} \leq 4.8$  wt%) ascribed to magma differentiation in a large ( $\geq 10$  km<sup>3</sup>)  
145 reservoir located within the lithospheric mantle (Berthod et al., 2021). Bulk porosity decreases  
146 from 30 – 45% during phase 1 to 5 – 20% during phase 3 (Verdurme et al., 2024). Sulfides  
147 droplets occur in all these samples and are most abundant in the third phase samples (Berthod  
148 et al., 2022). (2) Nine samples regularly drilled from the glassy margin to the center of a pillow  
149 lava (Fig. 2) erupted during the third phase of the 2018-2021 eruption (sample GFL-DR20-0101  
150 in Berthod et al., 2022, with MgO of 4.45 wt%).

151

#### 152 4. Analytical methods

153

154 Selenium and tellurium concentrations were analyzed by isotope dilution (ID) hydride  
155 generation (HG) quadrupole inductively coupled plasma mass spectrometry (ICP-MS)

156 following a method modified from Yierpan et al. (2018). We first prepared <sup>77</sup>Se enriched  
157 (44.773 ppb Se with 94.38% <sup>77</sup>Se) and <sup>125</sup>Te enriched (5.214 ppb Te with 95.52% <sup>125</sup>Te) spike  
158 solutions from solid sources obtained from Oak Ridge National Laboratory, USA. The  
159 concentrations of the spike solutions were calibrated by isotope dilution against solutions  
160 prepared by diluting a 10 µg/g certified standards from Inorganic Venture. The spikes  
161 concentrations were obtained by averaging the measurements of three spike-standard  
162 mixtures prepared around the spike/standard optimal ratio. For sample analysis, 200 mg of  
163 rock powders were weighted in 15 ml Teflon vials. Immediately after, we added between 250  
164 and 500 mg of <sup>77</sup>Se enriched spike and between 150 and 300 mg of <sup>125</sup>Te enriched spike. The  
165 silicates were digested by adding successively 1 ml of 14M HNO<sub>3</sub> and 6 ml of 29M HF and  
166 placing the vials on a hotplate at 90°C for 24 hours. The samples were evaporated at 70°C to  
167 avoid major Se and Te volatilization (Vlastélic and Piro, 2022). The dry residues were taken in  
168 3 ml of 6M HCl, heated at 90°C for 24H, and evaporated at 70°C. This step of HCl conversion  
169 was repeated once. The two-step chemistry from Yierpan et al. (2018) was used to purify Se  
170 and Te. The column separation was calibrated by dissolving 320 mg of a La Réunion basalt  
171 doped with 500 ng of Se and Te. After HCl conversion, the sample residues were dissolved in  
172 3 ml of 4M HCl, centrifuged for 5 min, before being loaded on anionic columns (polypropylene  
173 Biorad filled with 5 ml AG1-X8 100-200 mesh). Most elements and Se were eluted by adding  
174 successively 3 x 1 ml and 4 ml of 4M HCl, while Te was retained probably as chloro-complex.  
175 Iron was eluted with 2 x 5 ml of 2M HCl – 5M HF and 2 x 3 ml of 0.4M HCl. Tellurium, with  
176 minor amount of remaining Pb, was eluted with 6 ml of 0.4M HCl. After evaporation at 65°C,  
177 the major element – Se fraction was dissolved in 4 ml of 0.1M HNO<sub>3</sub> and centrifugated before  
178 being loaded on cationic columns (polypropylene Biorad filled with 5 ml AG50-X8 200-400  
179 mesh). Selenium was eluted by adding successively 2 x 1 and 3ml of 0.1M HNO<sub>3</sub>. The collected  
180 Se fraction is not highly pure but is sufficiently depleted in Fe and other transition metals for  
181 efficient hydride generation during subsequent ICPMS analysis.

182 After evaporation at 85°C the fractions of Se (0.14 – 135 ng) and Te (0.04 – 24 ng) recovered  
183 from samples were taken in 6 and 3 ml of HNO<sub>3</sub> 1M, respectively. The resulting solutions with  
184 0.02- 23 ppb Se and 0.013 – 8 ppb Te were mixed online with 0.3 M NaBH<sub>4</sub>–0.1 M NaOH in a  
185 hydride generation system (HGX-200 from Teledyne Cetac Technologies). The H<sub>2</sub>Te and H<sub>2</sub>Se  
186 vapors were entrained by two Ar flows (carrier flow of 0.42 L/min and make up flow of 0.82  
187 L/min) to an Agilent 7500 ICPMS. To improve ICPMS sensitivity, we used two primary pumps



188 increasing the vacuum of the interface.  $^{78}\text{Se}/^{77}\text{Se}$  was measured using the reaction cell (He  
 189 mode) to lower polyatomic interferences from the Ar carrier gas (e.g.,  $^{40}\text{Ar}^{38}\text{Ar}^+$ ,  $^{36}\text{Ar}^{40}\text{Ar}^1\text{H}^+$ ,  
 190  $^{38}\text{Ar}_2^1\text{H}^+$ ), while  $^{126}\text{Te}/^{125}\text{Te}$  was measured in “no-gas” mode. Each measurement included  
 191 typically 100 scans, with 200 ms acquisition on each mass, and lasted 1 minute. The  $\text{HNO}_3$  1M  
 192 solution used to dissolve samples was repeatedly measured for background correction.  
 193 Instrumental mass fractionation was corrected by measuring a 5 ppb Se isotopic standard  
 194 (NIST SRM 3149) and a 1 ppb Te isotopic standard (NIST SRM 3156) at the beginning and/or  
 195 at the end of each measurement session. Signals of ca. 130 000 CPS/ppb  $^{78}\text{Se}$  and 500 000  
 196 CPS/ppb  $^{126}\text{Te}$  were measured on the NISTs.

197 Sulfur concentration was measured by isotope dilution using a  $^{34}\text{S}$  enriched spike (262 ppm S,  
 198 with 99.79%  $^{34}\text{S}$ ). The spike, initially in the form of native sulfur, was dissolved in 14M  $\text{HNO}_3$   
 199 and calibrated against IAEA-S-1 sulfur isotope reference material. For sample analysis, 50 mg  
 200 of rock powders were weighted in 15 ml Teflon vials, spiked and digested with 1 ml of 14M  
 201  $\text{HNO}_3$  and 6 ml of 29M HF at 90°C for 24 hours. After evaporation, the fluoride residue was  
 202 reduced by addition and evaporation of a few drops of 14M  $\text{HNO}_3$ . Unlike in the procedure  
 203 applied by Wang and Becker (2013), sulfur was not separated because of important S release  
 204 (>1  $\mu\text{g}$ ) from the cationic resin. Instead, the residue was taken in 5 ml of  $\text{H}_2\text{O}$ , centrifugated,  
 205 and  $^{32}\text{S}/^{34}\text{S}$  of the supernatant was directly analyzed on an Element XR ICP-MS in high mass-  
 206 resolution mode ( $m/\Delta m$  of 10 000). To check the accuracy of S isotope compositions, the  
 207  $^{32}\text{S}/^{34}\text{S}$  ratios of a subset of samples from Fani Maoré were also measured as oxides  
 208 ( $^{32}\text{S}^{16}\text{O}/^{34}\text{S}^{16}\text{O}$ ), using the oxygen reactive mode of an Agilent 8900 triple quadrupole ICPMS.  
 209 Instrumental mass fractionation was corrected by running IAEA-S-1 sulfur isotope reference  
 210 material. Sample concentration ( $C_{\text{Sample}}$ ) was calculated according to Eq. 1 :

211

$$212 \quad C_{\text{Sample}} = C_{\text{Spike}} \times \frac{m_{\text{Spike}}}{m_{\text{Sample}}} \times \frac{Ab_{\text{Spike}}^B}{Ab_{\text{Sample}}^B} \times \frac{R_{\text{Spike}} - R_{\text{mes}}}{R_{\text{mes}} - R_{\text{Sample}}} \quad (1)$$

213

214 Where  $C_{\text{Spike}}$  is the spike concentration,  $m_{\text{Spike}}$  and  $m_{\text{Sample}}$  are the spike and sample masses,  
 215  $R_{\text{Spike}}$ ,  $R_{\text{Sample}}$  and  $R_{\text{mes}}$  are the isotopic ratios of the spike, the sample and the measured  
 216 sample-spike mixture, respectively.  $R_{\text{Sample}}$  being not measured, we use the natural  
 217 abundances of Se and Te isotopes of the NIST standards.  $Ab^B$  is the isotopic abundance of the  
 218 denominator isotope. The precision of isotopic ratios measured by ICPMS are on the order of

219 1-3 %. The precision of the concentrations obtained by isotope dilution is inferred from the  
220 error magnification (M), defined as (Eq. 2) :

221

$$222 \quad M = \frac{\Delta C_{Sample}}{C_{Sample}} / \frac{\Delta R_{mes}}{R_{mes}} = \frac{R_{mes} \cdot (R_{Spike} - R_{Sample})}{(R_{Spike} - R_{mes}) \cdot (R_{mes} - R_{Sample})} \quad (2)$$

223

224 Error magnification ranges between 1.03 and 1.3 for most samples and reaches 2-3 for the  
225 most depleted (olivine-rich basalt) or enriched (Réunion pumice and Pele's hairs) samples.  
226 Average procedural blanks are 0.8 ng S, 0.2 ng Se and 0.05 ng Te. The concentrations of the  
227 four reference basalts measured during this study (BHVO-2, BCR-2, BEN and BIR-1, Table 2)  
228 fall within the range of the recommended values reported in the GeoRem database (Jochum  
229 et al. 2005). However, our S value of BIR-1 (4.4 ppm) is much lower than the information value  
230 of 70 ppm. Réunion samples that were not previously analyzed for major and trace elements  
231 were analyzed conventionally at LMV by ICP-AES (major elements) and ICPMS (trace  
232 elements) using the methods described in Gurioli et al. (2018) and Vlastélic et al. (2013),  
233 respectively. The only difference is that the plutonic rocks were dissolved using NH<sub>4</sub>-HF<sub>2</sub>  
234 instead of HF-HNO<sub>3</sub> for ICPMS analysis to ensure complete dissolution.

235

## 236 5. Results

237

238 The concentrations of S, Se and Te of La Réunion and Fani Maoré samples are reported in  
239 Table 2. Major element and trace element data are reported in supplementary Table S1.

240

### 241 5.1. S – Se – Te budget of La Reunion plutonic rocks

242

243 The Piton des Neiges wehrlites (SAL206 and CB150914) have 264-358 ppm S, 19-36 ppb Se  
244 and 2.7-3.1 ppb Te. They show S/Se ratios (9985-16966) higher than La Réunion lavas and  
245 mantle peridotites (S/Se < 8000) but preserve similar Se/Te ratios (6.1 - 13.2) (Fig. 3). The Piton  
246 de la Fournaise wehrlite (CHI-7) has 12.7 ppm S, 9.96 ppb Se and 2.56 ppb Te and plot within  
247 the compositional field of mantle peridotites (Fig. 3) (Lorand and Alard, 2010; Wang and  
248 Becker, 2013). The S/Se (1275) and Se/Te (3.9) ratios of this sample are significantly lower  
249 than in carbonaceous chondrites.

250

## 251 5.2. Differentiation of La Réunion and Mayotte magmas

252

253 Major element and trace element variations during the differentiation of La Réunion and  
254 Mayotte magmas are shown in [Figure 4](#). The Réunion samples show four evolution steps,  
255 described in [Fig. 4](#) caption, which are consistent with the sequence of low-pressure  
256 crystallization of La Réunion magmas (e.g., Villemant et al. 2009; Pichavant et al. 2016).  
257 Compared to La Réunion lavas, Fani Maoré lavas are characterized by lower Sc and V, in  
258 keeping with high-pressure fractionation of clinopyroxene (Berthod et al., 2021) ([Fig. 4e,f](#)).  
259 Fani Maoré lavas also have higher Th at given MgO ([Fig. 4h](#)).

260

## 261 5.3. Evolution of S, Se and Te in La Réunion magmas

262

263 La Réunion lavas are extensively depleted in sulfur (5 - 884 ppm S) compared to primitive  
264 melts with up to 1800 ppm S (Bureau et al., 1998; Vigouroux et al., 2009; Di Muro et al., 2016)  
265 ([Fig. 5a](#)). The least degassed submarine lavas from step 1 with 416 – 632 ppm S have already  
266 lost between 65 and 77% S, while submarine lava from step 2 (119 – 146 ppm) have lost 92 %  
267 of S mostly through degassing because the magmas are not yet sulfide saturated ([Fig. 5a](#)). In  
268 subaerial conditions, lavas from step 1 (30 – 266 ppm S) have 36 to 95% less S than their  
269 submarine counterpart, while lavas from steps 3 and 4 are even more depleted with 5 – 168  
270 ppm S. Generally, sulfur concentration shows some scattering in subaerial lavas, and there is  
271 only a rough trend of decreasing S with decreasing MgO.

272

273 In submarine environment, selenium displays a similar behavior as sulfur with relatively  
274 uniform concentrations (74 – 131 ppb Se) in lavas from step 1 and lower concentrations (34 –  
275 51 ppb Se) in lavas from step 2 ([Fig. 5b](#)). Unlike sulfur, the selenium contents of subaerial (121  
276  $\pm$  21 ppb, n=10) and submarine lavas (104  $\pm$  16 ppb, n=8) from step 1 are similar. The absence  
277 of subaerial degassing of Se results in a smooth trend of decreasing Se with decreasing MgO  
278 in subaerial samples from Piton des Neiges, with less than 3 ppb Se in the most differentiated  
279 samples ([Fig. 5b](#)). Most lavas plot within a narrow range of S/Se (2300 – 5000), close to the  
280 chondritic value (2750  $\pm$  200), except for subaerial lavas with 4 – 8 wt% MgO where S/Se  
281 decreases down to 400 due to degassing loss of S ([Fig. 5d](#)). The Cu/Se ratio is relatively uniform

282 (605 – 1234) in subaerial and submarine lavas from step 1, but markedly increases up to 3010  
283 in the submarine lavas from stage 2 (Fig. 5e). This increase must reflect Se degassing because  
284 Cu remains elevated during step 2 (Fig. 4d). The Cu/Se ratio then drops to 89 during step 3  
285 and early step 4 due to sulfide saturation. During late step 4 (<2.5 wt% MgO), Cu/Se increases  
286 again up to 9029 due to extensive Se degassing.

287

288 Tellurium shows more complex variations (Fig. 5c). The tellurium concentrations of submarine  
289 lavas first decrease from 12.4 to 3.7 ppb as MgO decreases from 13 to 7.6 wt%, before  
290 increasing abruptly until the end of step 1 (6 wt% MgO) where Te reaches 62 ppb. Then, Te  
291 concentrations decrease again during stage 2, while remaining elevated (23 – 33 ppb).  
292 Samples collected on land show a very different behavior, with a marked decrease of Te at  
293 the end of step 1, from 2.95 to 0.38 ppb. Only sample SAL 51 seems to plot on the submarine  
294 trends, possibly because this dyke sample emplaced under elevated pressure. An event of Te  
295 increase above 1 ppb occurs during step 3, or early step 4, before the final decrease of Te  
296 down to 0.2 ppb. The large variations of Se/Te (1 – 225) between 5 and 8 wt% MgO (Fig. 5f)  
297 are mostly due to the large variations of Te between Te-depleted subaerial and Te-enriched  
298 submarine lavas (Fig. 5c), while Se remains relatively uniform (Fig. 5b).

299

300 Noteworthy, a few samples with biased compositions plot outside the frame of Fig. 5 or are  
301 highlighted: (1) The picritic sample (070408-1b) with 29.2% wt% MgO has low S (24 ppm), Se  
302 (59 ppb) and Te (0.69 ppb) contents due to the occurrence of olivine crystals highly depleted  
303 in S, Se and Te. Yet this sample has Se/Te (86) within the range of subaerial basalts. (2)  
304 Compared to other subaerial samples with identical MgO content, the Pele's hairs sample  
305 (200409-6) has 80 times more Te (120 ppb) and 5 times more Se (677 ppb), but similar S  
306 concentration (196 ppm), yielding very low S/Se (290) and low Se/Te (5.7) ratios (Fig. 5 d, f).  
307 (3) Some of the trachytes from Piton des Neiges (SAL 201 and SAL 203) hosting hydrothermal  
308 pyrite have anomalously elevated S (730 – 884 ppm), and to a lesser extent Se (76 – 206 ppb)  
309 and Te (1.3 – 2.5 ppb) contents. The occurrence of pyrite increases S/Se up to 9600 (Fig. 5d)  
310 but does not seem to drastically fractionate the Se/Te ratios of these samples (58 – 83).

311

312 5.4. S – Se – Te signature of 2018-2021 Fani Maoré submarine lavas

313

314 All Fani Maoré lavas are enriched in sulfur (1342 – 1711 ppm) compared to La Réunion lavas  
315 (Fig. 5a), consistently with the occurrence of droplets of iron sulfide (Berthod et al., 2021).  
316 Within the narrow S range, we note a trend of increasing S concentration during the 2018-  
317 2021 eruption with 1342 – 1413 ppm during phase 1 (July 2018 - May 2019), 1386 – 1509 ppm  
318 during phase 2 (May 2019 - August 2019), and 1712 ppm during phase 3b (October 2020 -  
319 January 2021). The S content (1430 ppm) of the magnesian sample DR11-0704 is consistent  
320 with other samples produced during phase 2.

321 Unlike sulfur, the selenium concentration of Fani Maoré lavas (66 – 81 ppb) is only slightly  
322 higher than La Réunion subaerial and submarine lavas (38 – 51 ppb) with similar MgO  
323 content, excluding samples hosting pyrite (Fig. 5 b). Consequently, Fani Maoré lavas display  
324 very elevated S/Se ratios (16929 – 22130) (Fig. 5 d), which increase slightly with decreasing  
325 MgO. The tellurium concentrations (4.4 – 13.6 ppb) (Fig. 5 c), and Se/Te ratios (5.1 – 15.6)  
326 (Fig. 5 f) of Fani Maoré lavas are within the range of La Réunion submarine lavas. The two  
327 most evolved Fani Maoré samples (MgO <3.9 wt%) have distinctly higher Te contents (9.5 –  
328 13.6 ppb) and lower Se/Te ratios (5.1 – 7.2).

329

#### 330 5.5. S – Se – Te degassing within the Fani Maoré pillow lava

331

332 The studied GFL-DR20-0101 pillow lava presents five concentric layers with distinctive  
333 textures (Fig. 2): In the core of the pillow (layer 1), only rare small rounded (<1 mm) vesicles  
334 occur. The overlying thick layer 2 shows the occurrence of 1-3 cm pipe vesicles with radial  
335 distribution. The number of pipes markedly increases in layer 3. However, closer to the surface  
336 where the extent of crystallization decreases, neither vesicles nor degassing pipes occur in the  
337 layers 4, 5 and 6. Layer 5 stands out from layer 4 due to the occurrence of glass, while the  
338 pillow rim (layer 6) is fully glassy. This textural structure is very similar to that described by  
339 Berthod et al. (2022) for a pillow lava erupted earlier during the eruption. More generally, this  
340 degassing-crystallization structure is typical of pillows lavas (e.g., Philpotts and Lewis, 1987;  
341 Merle et al., 2005).

342 Variations of S, Se and Te concentrations, and S/Se and Se/Te ratios from pillow rim to pillow  
343 core are reported in Figure 6. Sulfur and Se display similar variations, with the base of layer 2  
344 being depleted in S (1518 – 1593 ppm) and Se (76.8 – 77.0 ppb) compared to pillow core (1671  
345 – 1794 ppm S and 82.6-83.5 ppb Se) and external layers (1751– 1881 ppm S and 82.1-83.6 ppb

346 Se). Sulfur loss (13%) being more important than Se loss (7%), S/Se is lower in layer 2 (19706  
347 – 20738) compared to pillow core (20235 – 21496) and external layers (21243 – 22641).  
348 Tellurium displays a different zonation pattern, with low and homogeneous concentrations  
349 (4.5 – 4.9 ppb) in the internal layers 1 and 2, and markedly higher concentrations (5.7 – 6.0  
350 ppb) in the external layers 3-6. Consequently, the Se/Te ratio is lower in the external layers  
351 (13.8 – 14.7) compared to the internal layers (16.3 – 17.2).

352 Concentration profiles are also reported for elements showing remarkable variations across  
353 the pillow. Like S and Se, Mo and W are markedly depleted (20 – 30%) in the intermediate  
354 layer 2 compared to pillow core and rim. Unlike lighter alkali, Cs is also depleted (12%) in the  
355 outer part of layer 2. Antimony is enriched in the outermost layer of the pillow.

356

## 357 6. Discussion

358

### 359 6.1. Processes controlling selenium retention in and degassing from magmas

360

361 The drop of sulfur solubility in oxidized melts below 100 MPa (Lesne et al., 2011; Di Muro et  
362 al., 2016) explains why sulfur outgassing from submarine lavas increases with decreasing  
363 water depth and is extensive in shallow or subaerial lavas. No experimental work has  
364 characterized selenium degassing during magma decompression, but several studies of  
365 oceanic basalts noted that, unlike sulfur, selenium is retained in seafloor lavas emplaced over  
366 a wide depth range (Jenner et al., 2010; Lissner et al., 2014; Yierpan et al. 2019, 2021; Kurzawa  
367 et al., 2019). This work shows that moderately differentiated ( $\text{MgO} > 6\%$ ) subaerial lavas from  
368 La Réunion Island also preserve the same Se content as their submarine counterpart (Fig. 5b),  
369 while S is extensively lost (Fig. 5a). Jenner et al. (2010) suggested that selenium must be  
370 stabilized in silicate melts as  $\text{Se}^{2-}$ , in the same manner as sulfur is stabilized as  $\text{S}^{2-}$ . The  
371 stabilization mechanism involves substitution of  $\text{S}^{2-}$  and  $\text{Se}^{2-}$  for  $\text{O}^{2-}$  in the silicate liquid (Wykes  
372 et al., 2015). The low volatility of Se during final magma ascent and decompression may be  
373 related to the selenide-selenate transition occurring at an oxygen activity  $> 10^3$  higher than  
374 the sulfide-sulfate transition. In the relatively oxidized redox conditions of undegassed basaltic  
375 magmas (near the nickel nickel-oxide buffer, Moussallam et al. 2016; Pichavant et al., 2016) a  
376 large fraction of sulfur occurs as sulfate not stabilized in the silicate melt and thus available  
377 for degassing, while selenium still occurs as selenides retained in the silicate melt structure.

378 During magma differentiation, Se loss starts during step 2, where clinopyroxene and  
379 plagioclase join olivine as major fractionating phases, and is extensive during step 4 where  
380 sulfide is stable (Fig. 5). This can be explained either by (1) Se degassing and/or (2) the  
381 fractionation of a sulfide phase in which Se partition. Note that selenide saturation has hardly  
382 any chance to form because Selenium Content at Selenide Saturation ( $\text{SeCSes} > 1000$  ppm) is  
383 much higher than the total Se budget of magmas ( $\text{Se} < 0.5$  ppm) (Wykes et al., 2015). The drop  
384 of Se concentration in the most differentiated subaerial lavas from La Réunion Island ( $\text{Se} < 5$   
385 ppb for  $\text{MgO} < 2$  wt%) contrasts with the subtle Se decrease reported for evolved submarine  
386 lavas from convergent margins (Jenner et al., 2015; Kurzawa et al. 2019), where Se remains  
387 above 70 ppb even in the most evolved samples. For La Réunion samples, the drop of Se below  
388 4 wt% MgO correlates with a factor of 100 increase of Cu/Se (Fig. 5), from 89 to 9020. Selenium  
389 being more volatile than Cu, but less compatible in sulfide, the Cu/Se ratio reflects the  
390 contribution of Se degassing (high Cu/Se) relative to sulfide saturation (low Cu/Se). This  
391 observation indicates that Se exhaustion in the most evolved Réunion lavas results from  
392 extensive degassing, either during shallow magma storage or during eruption.

393

394 The question then arises as to how and why Se volatilizes during magma differentiation, while  
395 it does not during magma decompression. The critical decrease of Se between 6.0 and 0.5%wt  
396 MgO (Fig. 5b) despite the important decrease of the melt fraction (a factor of 6 based on Th  
397 increase, Fig. 4h) requires a major drop of Se solubility. Selenium must remain in the form of  
398  $\text{Se}^{2-}$  in a differentiating melt that becomes increasingly reduced due to  $\text{SO}_2$  degassing  
399 (Moussallam et al. 2016). If  $\text{Se}^{2-}$  substitutes for  $\text{O}^{2-}$  in the melt, it is hypothesized that the Se—  
400 (Si, Al) bonds are weaker than the original O—(Si, Al) bonds and are preferentially broken  
401 during crystal nucleation and growth, releasing Se. Kinetic might also play a major role  
402 because magma storage and differentiation occur over long timescales compared to magma  
403 ascent, which inevitably facilitates the diffusion and loss of volatile elements. For instance, it  
404 took about 300 ka for Piton des Neiges olivine basalts to evolve into trachyte (Upton and  
405 Wadsworth, 1972; Gillot and Nativel, 1982), whereas Piton de la Fournaise magmas can  
406 ascend from crustal reservoirs to the surface in a matter of days (Battaglia et al., 2005).  
407 [Between these two end-member cases, variable Se loss is expected in the current steady-state](#)  
408 [regime of Piton de la Fournaise, where magma undergo static degassing during its storage at](#)  
409 [different depths before being by rapidly extruded.](#) Interestingly, S/Se is little fractionated in

410 the most differentiated subaerial lavas ( $\text{MgO} < 4 \text{ wt}\%$ ). This suggests that in the reducing  
411 conditions of differentiated magmas, sulfur dominantly occurs as  $\text{S}^{2-}$  and follows the same  
412 degassing processes as Se. However, detailed inspection of the data (Fig. 5) reveals a slight  
413 decrease of S/Se in the most differentiated samples (step 4), in keeping with the high S/Se of  
414 cumulative rocks (Fig. 3) where sulfides accumulate (Upton et al., 2000).

415

## 416 6.2. Tellurium specific behavior

417

418 As for sulfur, tellurium is extensively lost from subaerial lava, with nearly no overlap between  
419 Te-depleted subaerial lavas and Te-enriched submarine enriched lavas: in the Réunion-  
420 Mayotte data set, 18 out of the 20 subaerial samples have less than 3.5 ppb Te, whereas all  
421 the submarine lavas (20) have more than 3.5 ppb Te. This feature is also generally seen in the  
422 global OIB data set (Yi, 2000; Forrest et al., 2017, Yierpan et al., 2021), although some well-  
423 documented subaerial basalts from Hawaii (BHVO2 from Kilauea with 14.2 ppb Te) or Iceland  
424 (BIR-1 from Iceland with 5.8 ppb Te) have similar Te content as their submarine counterparts  
425 (Yierpan et al., 2018). Like S and Se,  $\text{Te}^{2-}$  solubilizes in silicate melt by replacing  $\text{O}^{2-}$  (Renggli et  
426 al, 2022). The telluride – tellurate transition being close to the sulfide – sulfate transition along  
427 the oxygen fugacity scale (McPhail et al., 1995), only a fraction of Te occurs as soluble  $\text{Te}^{2-}$  in  
428 the redox conditions of basaltic magmas. Thus, Te exsolution and volatilization at atmospheric  
429 pressure might thus result from partial oxidation, as for sulfur.

430 During the crystallization sequence of La Réunion magmas, major degassing-induced loss of  
431 Te (from 2.9 to 0.38 ppb) occurs in subaerial lavas between MgO of 8.2 and 5 wt%.  
432 Remarkably, over the same MgO range where Te is extensively lost from subaerial lavas, the  
433 Te content of submarine lavas rises from 3.7 to 62 ppb Te, exceeding the highest  
434 concentrations reported so far in submarine basalts (29.2 ppb Te in one sample from Loihi  
435 seamount, Hawaii, Yi et al., 2000)). Such enrichment cannot be explained by crystallization  
436 alone because the concentration of highly incompatible elements, like Th, increases by no  
437 more than 50%. Another possibility is that the most elevated Te concentrations of submarine  
438 basalts result from sample contamination with seawater derived Fe-Mn oxides, in which Te is  
439 enriched more than any other elements relative to Earth crust (Hein et al., 2003). However,  
440 we consider this possibility as unlikely because (i) the whole rock powders analyzed were  
441 made from the interior of the pillow lavas (Smietana, 2011), and (ii) elements highly enriched



442 in Fe-Mn crusts, such as Mn and Co, do not show anomalous concentrations in the Te-enriched  
443 sampled. Instead, the anomalous Te increase correlates with a marked increases of the  
444 metalloids As (from 1 to 13.8 ppm) and Sb (from 0.1 to 1 ppm), suggesting that Te is mobilized  
445 and enriched by degassing processes. We also note that, despite very different volcanic and  
446 petrologic contexts, Te concentration also anomalously increase in the most differentiated  
447 lavas from the Fani Maoré eruption (Fig. 5c), hence pointing to a general process. We  
448 hypothesize that Te enrichment at some steps of magma evolution could result from Te  
449 exsolution from deep melts, transfer and accumulation in magmas stored at shallower depth,  
450 in a similar manner as CO<sub>2</sub> fluxing (Blundy et al., 2010). Such process is supported by the lower  
451 solubility of Te in silicate melts compared to S and Se (Helmy et al., 2020). Alternatively, Te  
452 accumulation could occur after eruption at the surface of thick lavas flows that undergo  
453 internal differentiation and degassing. Such process has been shown to occur for Li, B and Cs  
454 (Kuritani and Nakamura, 2006), and is not inconsistent with the fact that the surface of  
455 submarine lavas flow is preferentially sampled during dredging. In both cases, extensive  
456 degassing of Te in subaerial setting is expected to prevent Te accumulation in the lavas.

457

458 6.3. Assessment of S – Se – Te degassing during the emplacement of Fani Maoré submarine  
459 lavas

460

461 Pillow lava degassing is a complex process due to the opposite effects of rim quenching and  
462 progressive crystallization of its interior. Previous studies reported differences in S, Se and Te  
463 concentrations between pillow interiors and glassy rims (Lissner 2014; Forrest et al. 2017).  
464 They noted that sulfur concentration is generally lower in pillow interiors, and that the  
465 difference between rim and interior is less systematic for Se, and especially for Te. The  
466 compositional profile reported here for a sample from the Fani Maoré eruption provides a  
467 more detailed view on pillow degassing, revealing that only the intermediate layer of the  
468 pillow hosting pipes vesicles is extensively outgassed in S and Se. Pipes vesicles are the textural  
469 remnants of the internal degassing of pillow lavas. They are thought to form by exsolution of  
470 gas from crystallizing magma onto bubbles attached to the advancing solidification front  
471 (Philpotts and Lewis, 1987). Merle et al. (2005) estimated that at least 25 vol% crystallization  
472 is necessary to produce a crystal framework required for generating the segregation  
473 structures in pillows. In the studied differentiated Fani Maoré sample (MgO of 4.45 wt%), pipe

474 vesicles are not rooted deep in the pillow, which explains the degassing of the intermediate  
475 layer mainly. Unlike S and Se, Te is depleted in both layers 1 and 2, showing a zonation (Fig. 6)  
476 unrelated to the pipe vesicles. This suggests that Te does not behave as major volatile  
477 species. To explain Te degassing of layer 1 in the absence of degassing pipes, it is hypothesized  
478 that Te is less soluble than major volatile species in silicate melts and is lost earlier by diffusion.  
479 In support of this possibility, Te is less soluble than S and Se in silicate melts saturated in  
480 sulfide, selenide and telluride (Helmy et al., 2020).

481 The compositional profile reported on Fig. 6 allows an assessment of pillow degassing during  
482 emplacement and cooling. The sample was divided into nine shells (s) corresponding to the  
483 nine analyzes. The boundary between each shell was set at equal distance between  
484 neighboring drill holes (Fig. 2). The volume of each shell ( $V_s$ ) was calculated assuming a  
485 spherical geometry. The density ( $\rho$ ) of the pillow was assumed to be uniform ( $\rho_s = \rho_{tot}$ ). At the  
486 scale of the pillow, the mass fraction of element lost by degassing ( $\varepsilon$ ) is calculated according  
487 to (Eq. 3):

488

$$489 \quad \varepsilon_x = 1 - \frac{\sum_{s=1}^{s=9} [X]_s \times V_s \times \rho_s}{[X]_{max} \times V_{tot} \times \rho_{tot}}$$

490

491 Where  $[X]_s$  is the element concentration in shell s, and  $[X]_{max}$  is the highest concentration  
492 measured in the pillow thought to be close to the pre-eruptive value. Values of  $\varepsilon$  are 6.5% for  
493 S, 7.2% for Te, but only 1.6% for Se confirming the lower volatility of Se during lava  
494 emplacement. Chalcogens degassing is accompanied with significant loss of W ( $\varepsilon = 8.9\%$ ), Mo  
495 ( $\varepsilon = 5.1\%$ ) and Cs ( $\varepsilon = 5.1\%$ ), which appear to be much more volatile than during subaerial  
496 eruptions where  $\varepsilon$  is lower than 0.15% for those elements (Rubin et al., 1997). W and Mo are  
497 highly refractory elements, but their oxides are known to volatilize readily at 1000°C and 1  
498 atmosphere pressure in the presence of water vapor (Millner and Neugebauer, 1949), and this  
499 effect is expected to increase with pressure. Thus, water exsolution from the pillow seems to  
500 have played a role in mobilizing refractory elements. Between 2018 and 2020, the Fani Maoré  
501 submarine eruption produced 6.5 km<sup>3</sup> of lava with an average vesicularity of 27% (i.e., 4.8 km<sup>3</sup>  
502 of dense rock) (Berthod et al., 2021). Using a dense rock density of 2500 kg/m<sup>3</sup> (Verdurme et  
503 al., 2024) and the highest element concentrations of the three eruptive phases as reference,  
504 it is estimated from the  $\varepsilon$  values that the Fani Maoré eruption released 1.1 – 1.5 x 10<sup>6</sup> tons of

505 S, 2300 – 2700 tons of Mo, 970 – 1130 tons of W, 194 – 339 tons of Cs, 13.3 – 16 tons of Se  
506 and 4.5 – 11.8 tons of Te. By comparison the Se amount released in the ocean by the Fani  
507 Maoré eruption between 2018 and 2021 corresponds to 1% of the degassing fluxes of mid-  
508 ocean ridges (Rubin et al., 1997).

509

#### 510 6.4. Brief constraints on magma sources

511

512 The elevated S/Se ratios of the two Piton des Neiges wehrlites confirm previous field and  
513 petrological evidences (Berthod et al., 2020) that the samples formed at the bottom of a  
514 magma chamber where they accumulated dense sulfides (Fig. 3). Conversely, the S – Se – Te  
515 signature of Piton de la Fournaise wehrlite (CHI-7) is consistent with a mantle origin. Its low  
516 S/Se and Se/Te ratios relative to the Bulk Silicate Earth (BSE) (Fig. 3), together with its  
517 depletion in incompatible elements (Table S1), indicate that this sample is a mantle residue  
518 after melt extraction. To reconstruct the possible composition of the parental fertile  
519 peridotite, the CHI-7 melting residue is mixed with the extracted melts, best represented by  
520 the erupted lavas. The resulting mixing curve intercept the BSE composition (Fig. 3), raising  
521 the possibility that the La Réunion plume source preserved the same S/Se and Se/Te ratios as  
522 the BSE and CI chondrites. This agrees with previous inferences from Highly Siderophile  
523 Elements (Peters et al., 2016) and U-Th-Pb isotope systematics (Vlastélic et al., 2006) that the  
524 Réunion plume samples a less differentiated mantle domain.

525 All Fani Maoré lavas including the magnesian sample (MAY04-DR11-0704) display S/Se ratios  
526 (16929 – 22130) that are much higher than in worldwide MORB and OIB ( $S/Se < 10000$ ). The  
527 S/Se ratios of Fani Maoré lavas are also higher than the most fertile mantle peridotites  
528 ( $S/Se \sim 8000$ ) (Wang and Becker, 2013) and the two cumulative rocks from La Réunion ( $10000 < S/Se < 14000$ ), which are known to be enriched in sinking sulfur liquids (Upton et al.,  
529 2000). Fani Maoré's S – Se signature is hardly explained by magma generation processes and  
530 must reflect a source property. The most likely explanation is that the Fani Maoré lavas derive  
531 from the melting of a lithospheric mantle extensively refertilized by sulfide melts. This is not  
532 inconsistent with previous inferences that the Fani Maoré volcano, like the island of Mayotte,  
533 formed by melting of a carbonated mantle source enriched in Ba and volatiles (Chauvel et al.  
534 2024; Pelleter et al. 2014). Lithosphere refertilization is a common process driven by repeated

536 melt intrusions, but in the case of the Fani Maoré volcano, it might have reached an unusual  
537 extent and caused this exceptionally large-volume eruption.

538

## 539 7. Conclusions

540

541 This work obtained the following results:

542 (1) Unlike sulfur, selenium degassing is not significant during the final (30 – 0.1 MPa),  
543 presumably rapid ascent of moderately differentiated (MgO > 6wt%) magmas from La  
544 Réunion. Conversely, selenium degassing occurs during magma differentiation below 6 wt%  
545 MgO, at a similar rate as sulfur, yielding small S/Se fractionation in the residual magma. The  
546 long timescales require to markedly differentiate La Réunion magmas certainly facilitates the  
547 diffusion and loss of less volatile selenium. Variable Se loss is expected in the intermediate  
548 situations involving both static degassing during more or less prolonged magma storage  
549 followed by rapid extrusion of magma.

550 (2) During the evolution of La Réunion magma reservoir, the onset of sulfide saturation occurs  
551 between ~5 and ~4 wt% MgO, while olivine just left the liquidus, and Ti-magnetite has not yet  
552 appeared. Sulfide fractionation controls Cu/Se variations over this narrow MgO range, while  
553 degassing dominates outside.

554 (3) As sulfur, tellurium is extensively lost from La Réunion subaerial lavas, whereas submarine  
555 lavas tend to retain Te and possibility accumulate Te near 6% MgO. The contrasted behavior  
556 of Se and Te yields extremely large Se/Te variations between subaerial (up to 225) and  
557 submarine (down to 1.0) lavas.

558 (4) A pillow lava emplaced during the Fani Maoré eruption offshore Mayotte shows degassing-  
559 driven radial compositional zonation. Degassing of S, Se and other moderately volatile  
560 elements (Mo, W, Cs) is the most important at intermediate depth within the pillow where  
561 pipe vesicle occur, suggesting they escape with major volatiles. Conversely, Te is depleted in  
562 the whole interior of the pillow, suggesting Te degassing through other means.

563 (5) Assessment of pillow degassing during emplacement yields losses of 6.5% for S, 7.2% for  
564 Te, but only 1.6% for Se confirming the lower volatility of Se during lava emplacement.  
565 Chalcogens degassing is accompanied with significant loss of W (8.9%), Mo (5.1%) and Cs  
566 (5.1%). Based on these values, the 6.5 km<sup>3</sup> Fani Maoré eruption released 1.1 – 1.5 x 10<sup>6</sup> tons

567 of S, 2300 – 2700 tons of Mo, 970 – 1130 tons of W, 194 – 339 tons of Cs, 13.3 – 16 tons of Se  
568 and 4.5 – 11.8 tons of Te during emplacement.

569 (6) The reconstructed S – Se – Te composition of La Réunion plume source is consistent with  
570 the preservation of chondritic S/Se and Se/Te ratios, in agreement with previous suggestions  
571 that the Réunion plume samples a less differentiated mantle domain.

572 (7) The unusually elevated S/Se ratios (16929 – 22130) of Fani Maoré lavas suggests that the  
573 mantle source of this exceptional eruption has been extensively fertilized by sulfide melts.

574

575 **Figure captions**

576

577 Figure 1. Location maps. (a) Relief map of the southwest Indian Ocean showing the locations  
578 of La Réunion and Mayotte islands. (b) Relief map of La Réunion Island showing the location  
579 of the Piton des Neiges and Piton de la Fournaise volcanoes, and the location of subaerial and  
580 submarine samples analyzed in this study. Closed triangles: Piton des Neiges lavas; closed  
581 circles: Piton de la Fournaise lavas; closed hexagons: cumulates ; closed diamond: peridotite,  
582 open circles: submarine lavas. (c) Relief map of Mayotte Island, showing the locations of the  
583 samples from the Fani Maoré submarine eruption (open diamonds) that occurred between  
584 2018 and 2021 50 km east of Mayotte island, along the East-Mayotte submarine Volcanic  
585 Chain. All maps done with GeoMapApp (<https://www.geomapapp.org/>).

586

587 Figure 2. Cross section of GFL-DR20-0101 pillow lava emplaced during phase 3 of the Fani  
588 Maoré eruption. Drill holes are shown and numbered from pillow interior (DR20-1) to pillow  
589 rim (DR20-12). Pillow surface (DR20-Sp) is the thin external glassy layer not shown here  
590 (layer 6). The five main textural unit (1-5) described in text are shown. Because the external  
591 layers 4 and 5 are thinner than other layers, between 3 and 4 smaller drill holes were made  
592 and mixed within each layer.

593

594 Figure 3. Composition of La Réunion plutonic rocks reported in (a) S/Se and (b) Se/Te versus  
595  $Al_2O_3$  plots. The compositional field of mantle peridotites, and the composition of  
596 carbonaceous chondrites (CI) and Bulk Silicate Earth (BSE) are shown (Lorand and Alard, 2010;  
597 König et al., 2012; Wang and Becker, 2013). Closed hexagons: cumulates; closed diamond:  
598 peridotite. Analytical error is smaller than symbols size. Data are from **Table 2** (S, Se and Te  
599 concentrations) and supplementary **Table S1** ( $Al_2O_3$  concentrations). **The dashed line is a**  
600 **mixing curve calculated by mixing CHI-7 peridotite with the less degassed submarine DR6-2**  
601 **lava sample, which is representative of the most common composition of La Réunion**  
602 **volcanism.**

603

604 Figure 4. Major-trace elements versus MgO plot showing the composition of La Réunion and  
605 Fani Maoré lavas. Vertical thin lines indicate major changes in the crystallization assemblage.  
606 The crystallization sequences of La Réunion magma involves four steps (Villemant et al. 2009;

607 Pichavant et al. 2016) : (1) primary melts ( $\text{MgO} \geq 9\%$ ) first crystallize olivine and spinel causing  
608 an important decrease of Ni and Cr; (2) Clinopyroxene and plagioclase appear at the liquidus  
609 at  $\text{MgO} \sim 6$  wt% as recorded by the onset of Sc, V and Ca/Al decrease. (3) Between  $\sim 5$  and  $\sim 4$   
610 wt% MgO, the increase of Fe and Ti indicate that olivine is no longer a liquidus phase, while  
611 Ti-magnetite has not yet appeared. The abrupt drop of Cu (from 97 to 18 ppm) indicates that  
612 the onset of sulfide saturation occurs at this step. This corresponds to the first phase of sulfide  
613 formation which is triggered by S becoming saturated in magmas (Collins et al. 2012). (4)  
614 Below  $\sim 4$  wt% MgO, the decrease of Fe, Ti, Ca/Al, Sc and Cu, and the increase of Th are  
615 consistent with precipitation of clinopyroxene, plagioclase, magnetite and sulfides. This  
616 second phase of sulfide saturation is related to the crystallization of titanomagnetite which  
617 reduces the sulfur content at sulfide melt saturation (Jenner et al., 2010; Collins et al. 2012).  
618 The crystallization assemblage of Fani Maoré samples (80% Cpx – 20 % Ol) is from Berthod et  
619 al. (2021). Symbols are as in previous figures. Data are from [Table 2](#) (S, Se and Te  
620 concentrations) and supplementary [Table S1](#) (major and trace element concentrations from  
621 La Réunion samples). Fani Maoré data are from Berthod et al. (2022) (major elements) and  
622 Chauvel et al. (2024) (trace elements). Fani Maoré trace element data not given in Chauvel et  
623 al. (2024) were taken from Berthod et al. (2022).

624

625 Figure 5. Chalcogen contents (S, Se, Te) and ratios (S/Se, Cu/Se, Se/Te) plotted against MgO  
626 content of lavas. Vertical thin lines indicate major changes in the mineral assemblage  
627 crystallizing (see figure 4). The composition of La Réunion and Fani Maoré lavas are reported  
628 using the same symbols as in previous figures. Analytical error is smaller than symbols size.  
629 Data are from [Table 2](#) (S, Se and Te concentrations) and supplementary [Table S1](#) (MgO and Cu  
630 concentrations from La Réunion samples). Fani Maoré data are from Chauvel et al. (2024) (Cu)  
631 and Berthod et al. (2022) (MgO and Cu).

632

633 Figure 6.

634 Radial compositional zonation of GFL-DR20-0101 pillow lava emplaced during the third and  
635 last phase (October 2020 - January 2021) of the Fani Maoré eruption (Berthod et al., 2020).  
636 Vertical dashed lines separate the major textural units shown in figure 2 and described in text.  
637 Error bars are indicated or smaller than symbols size. Data are from [Table 2](#) and  
638 supplementary [Table S1](#).

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Table 1: Samples type and location

Site	Volcano	Sample	Composition	Sample type	Location / eruption phase	Lat. °S	Long. °E	Elevation (m)
Reunion	PdN subaerial	CB2150914	Wehrlite	Cumulate	LM	-21.07	55.50	876
		SAL 206	Wehrlite	Cumulate	Phase I	-21.08	55.50	1077
		BSUZ 2	SSB	Lava flow	Phase I	-21.00	55.42	500
		SAL 51	SSB	Dyke in breccia	Phase I	-21.06	55.49	830
		SAL 48	SSB	Dyke in breccia	Phase I	-21.06	55.49	830
		RUN 008-2006	Hawaiite	Lava flow	Phase III	-21.12	55.27	220
		RUN 038-2006	Benmoreite	Lava flow	Phase IV	-21.09	55.55	1505
		RUN 048-2006	Benmoreite	Lava flow	Phase IV	-21.07	55.38	2020
		SAB 1	Trachyte	Dyke	Phase IV	-21.07	55.47	1710
		SAL 88	Trachyte	Sill in breccia	Phase IV	-21.06	55.51	858
		SAL 200	Trachyte	Sill in breccia	Phase IV	-21.07	55.50	820
		SAL 203	Trachyte*	Sill in breccia	Phase IV	-21.06	55.49	880
		SAL 201	Trachyte*	Sill in breccia	Phase IV	-21.07	55.50	890
		PdF subaerial	CHI-7	Wehrlite	Peridotite	Piton Chisny	-21.24	55.67
	REU 070402-1b		SSB	Lava flow	April 2007 eruption	-21.28	55.77	580
	REU 070403-b		SSB	Lava flow	April 2007 eruption	-21.28	55.77	580
	REU 070404-b		SSB	Lava flow	April 2007 eruption	-21.28	55.77	580
	REU 070408-1b		Olivine-rich basalt	Lava flow	April 2007 eruption	-21.28	55.77	580
	REU 150731-7		SSB	Golden pumice	July 2015 eruption	-21.22	55.71	2139
	REU 180413-1		SSB	Lava crust	April 2018 eruption	-21.21	55.72	1920
	REU 180403		SSB	Scoria	April 2018 eruption	-21.21	55.72	1920
	REU 180713-1		SSB	Lava, water quenched	July 2018 eruption	-21.23	55.70	2230
	REU 200409-6		SSB	Pele hairs	April 2020 eruption	-21.23	55.66	2269
	PdN submarine	ERO2 DR6-2	SSB	Pillow lava	Etang Salé Ridge, 2.48 Ma	-21.35	55.24	-2000
		ERO2 DR7-4B	SSB	Pillow lava	Etang Salé Ridge	-21.35	55.24	-1780
		ERO2 DR7-3	SSB	Pillow lava	Etang Salé Ridge	-21.35	55.24	-1780
		ERO2 DR7-5	SSB	Pillow lava	Etang Salé Ridge	-21.35	55.24	-1780
	PdF submarine	ERO2 DR2-6	SSB	Pillow lava	North of PdF NE Rift Zone, 3.34 Ma	-21.09	55.86	-1700
		GSR2-DR11-47	Mg-rich basalt	Pillow lava	North of PdF NE Rift Zone, 3.77 Ma	-21.09	55.86	-1850
		ERO2 DR8-7	Mg-rich basalt	Pillow lava	South of PdF NE Rift Zone, 0.439 Ma	-21.20	55.91	-1443
		ERO2 DR8-1	Mg-rich basalt	Pillow lava	South of PdF NE Rift Zone, 0.439 Ma	-21.20	55.91	-1443
		ERO2 DR8-6	Mg-rich basalt	Pillow lava	South of PdF NE Rift Zone, 0.439 Ma	-21.20	55.91	-1443
		ERO2 DR8-8	Mg-rich basalt	Pillow lava	South of PdF NE Rift Zone, 0.439 Ma	-21.20	55.91	-1443
	Mayotte	Fani Maoré	MAY01-DR01-05	Evolved basanite	Pillow lava	Phase 1 (July 2018 - May 2019)	-12.91	45.72
MAY02-DR08-01ALF			Evolved basanite	Pillow lava	Phase 2 (May 2019 - August 2019)	-12.94	45.71	-3061
MAY02-DR08-0102MB			Evolved basanite	Pillow lava	Phase 2 (May 2019 - August 2019)	-12.94	45.71	-3061
MAY04-DR10-07			Evolved basanite	Pillow lava	Phase 1 (July 2018 - May 2019)	-12.92	45.72	-3035
MAY04-DR11-0704-2			Evolved basanite	Pillow lava	Phase 2 (May 2019 - August 2019)	-12.92	45.69	-3239
MAY04-DR12-0301			Evolved basanite	Pillow lava	Phase 1 (July 2018 - May 2019)	-12.88	45.72	-3222
MAY04-DR11-0704			Evolved basanite	Pillow lava	Phase 2 (May 2019 - August 2019)	-12.92	45.69	-3239
GFL-DR20-0101			Evolved basanite	Pillow lava	Phase 3b (October 2020 - January 2021)	-12.87	45.67	-3179

SSB : Steady State Basalts. Most common basalts at La Réunion Island, with composition transitionnal between tholeiites and alkali basalts

PdN : Piton des Neiges. PdF : Piton de la Fournaise.

\* With hydrothermal pyrite



Table 2: S, Se and Te concentrations of La Réunion and Mayotte samples

Site	Volcano	Sample	MgO (wt%)	[S] ppm	SD	[Se] ppb	SD	[Te] ppb	SD
		BHVO-2		185 ±	7 (n=10)	170 ±	11 (n=20)	14.52 ±	0.77 (n=14)
		BCR-2		341 ±	1 (n=2)	79.6 ±	0.8 (r=3)	2.84 ±	0.07 (r=3)
		BE-N		336 ±	5 (r=1)	71.7 ±	0.9 (r=1)	1.06 ±	0.01 (r=2)
		BIR-1		4.43 ±	0.04 (r=3)	16.1 ±	0.04 (r=2)	5.90 ±	0.06 (r=1)
La Réunion	PdN subaerial	CB2150914	33.0	358 ±	1.9	35.9 ±	1.2	2.72 ±	0.04
		SAL 206	41.5	264 ±	2.8	18.9 ±	0.6	3.11 ±	0.05
		BSUZ 2	6.5	30 ±	0.2	71.0 ±	2.4	0.38 ±	0.02
		SAL 51	6.7	257 ±	2.5	132 ±	4.2	8.76 ±	0.07
		SAL 48	8.2	141 ±	1.1	93.4 ±	3.3	2.95 ±	0.04
		RUN 008-2006	4.4	28 ±	0.3	37.9 ±	1.3	0.25 ±	0.02
		RUN 038-2006	1.4	10 ±	0.2	3.0 ±	0.2	0.46 ±	0.02
		RUN 048-2006	2.4	40 ±	0.3	11.6 ±	0.4	1.00 ±	0.03
		SAB 1	0.4	4.9 ±	0.1	2.0 ±	0.2	0.27 ±	0.01
		SAL 88	0.6	-		0.7 ±	0.1	0.19 ±	0.02
		SAL 200	2.3	168 ±	1.2	23.0 ±	0.9	0.64 ±	0.03
		SAL 203	2.8	730 ±	5.4	75.8 ±	2.5	1.30 ±	0.02
		SAL 201	4.4	884 ±	11	206 ±	5.0	2.47 ±	0.03
	PdF subaerial	CHI-7	33.4	13 ±	0.1	10.0 ±	0.4	2.56 ±	0.12
		070402-1b	7.3	101 ±	1.6	124 ±	2.7	2.16 ±	0.21
		070403-b	7.5	266 ±	1.8	130 ±	2.9	1.54 ±	0.15
		070404-b	7.3	102 ±	1.2	134 ±	2.7	1.07 ±	0.11
		070408-1b	29.2	24 ±	0.3	59.3 ±	1.0	0.69 ±	0.09
		150731-7	6.4	245 ±	3.1	131 ±	2.7	0.74 ±	0.01
		180413-1	6.9	199 ±	2.5	134 ±	2.9	0.87 ±	0.09
		180403	6.9	210 ±	2.8	133 ±	2.2	1.53 ±	0.17
		180713-1	6.9	147 ±	0.6	127 ±	2.7	0.56 ±	0.05
		200409-6	8.0	196 ±	0.8	677 ±	10	120 ±	6
		PdN submarine	DR6-2	7.6	416 ±	1.7	96.7 ±	2.4	3.73 ±
	DR7-4B		5.1	119 ±	0.7	51.0 ±	2.1	22.8 ±	0.79
	DR7-3		6.2	437 ±	4.3	112 ±	2.9	61.6 ±	4.88
	DR7-5		5.5	146 ±	0.8	33.8 ±	1.1	33.0 ±	0.63
	PdF submarine	DR2-6	6.7	165 ±	1.0	74.3 ±	1.8	9.54 ±	0.52
		GSR2-DR11-47	10.5	564 ±	3.0	116 ±	5.4	4.47 ±	0.21
		DR8-7	10.9	632 ±	7.5	125 ±	2.6	6.95 ±	0.07
DR8-1		13.1	551 ±	5.8	112 ±	2.4	12.4 ±	0.55	
DR8-6		9.6	502 ±	4.0	109 ±	3.1	3.71 ±	0.02	
DR8-8		12.0	435 ±	4.9	89.9 ±	1.8	6.04 ±	0.26	
Mayotte	Fani Maoré	MAY01-DR01-05	4.77	1342 ±	32	76.7 ±	1.1	6.15 ±	0.06
		MAY02-DR08-01ALF	3.77	1509 ±	40	68.2 ±	1.1	9.53 ±	0.07
		MAY02-DR08-0102MB	3.79	1454 ±	32	69.4 ±	1.0	13.6 ±	0.10
		MAY04-DR10-07	4.18	1413 ±	41	72.8 ±	1.0	6.26 ±	0.05
		MAY04-DR11-0704-2	3.97	1386 ±	32	66.5 ±	1.2	4.43 ±	0.06
		MAY04-DR12-0301	4.52	1367 ±	39	80.7 ±	1.3	5.71 ±	0.06
		MAY04-DR11-0704	9.89	1430 ±	25	67.3 ±	1.1	5.48 ±	0.06
	GFL-DR20-0101 Bulk	drilling distance to pillow rim	4.45	1711		81.5		5.23	
		DR20-1 21.3 cm		1794 ±	30	83.5 ±	2.1	4.89 ±	0.05
		DR20-3 17.5 cm		1671 ±	26	82.6 ±	2.0	4.79 ±	0.06
		DR20-5 13.5 cm		1593 ±	47	76.8 ±	1.7	4.70 ±	0.06
		DR20-7 9.5 cm		1518 ±	37	77.0 ±	2.0	4.47 ±	0.05
		DR20-9 5.5 cm		1625 ±	34	81.4 ±	1.6	4.87 ±	0.05
		DR20-10 3.5 cm		1768 ±	49	83.2 ±	1.7	5.75 ±	0.06
		DR20-11 2 cm		1751 ±	35	82.1 ±	1.4	5.94 ±	0.06
		DR20-12 1 cm		1801 ±	35	83.6 ±	1.6	6.04 ±	0.08
		DR20-SP 0 cm		1881 ±	30	83.1 ±	1.8	5.65 ±	0.07

n: dissolution &amp; chemistry duplicate

r: analysis replicate (same solution)

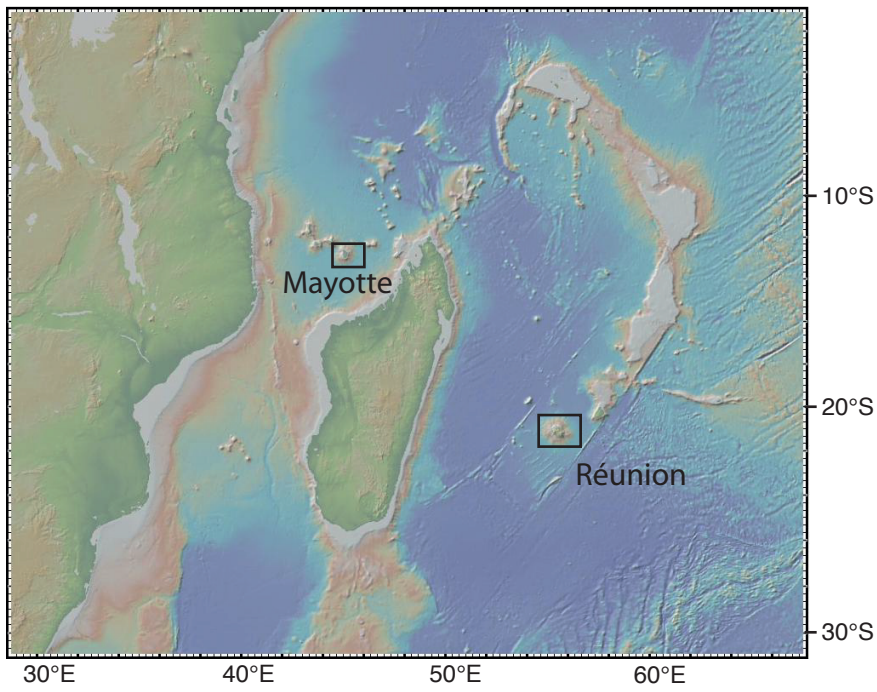
SD: sample SD is calculated by propagating errors on isotopic ratios (see text)

MgO data are from the supplementary table S1 (La Reunion) and from Berthod et al. (2022)

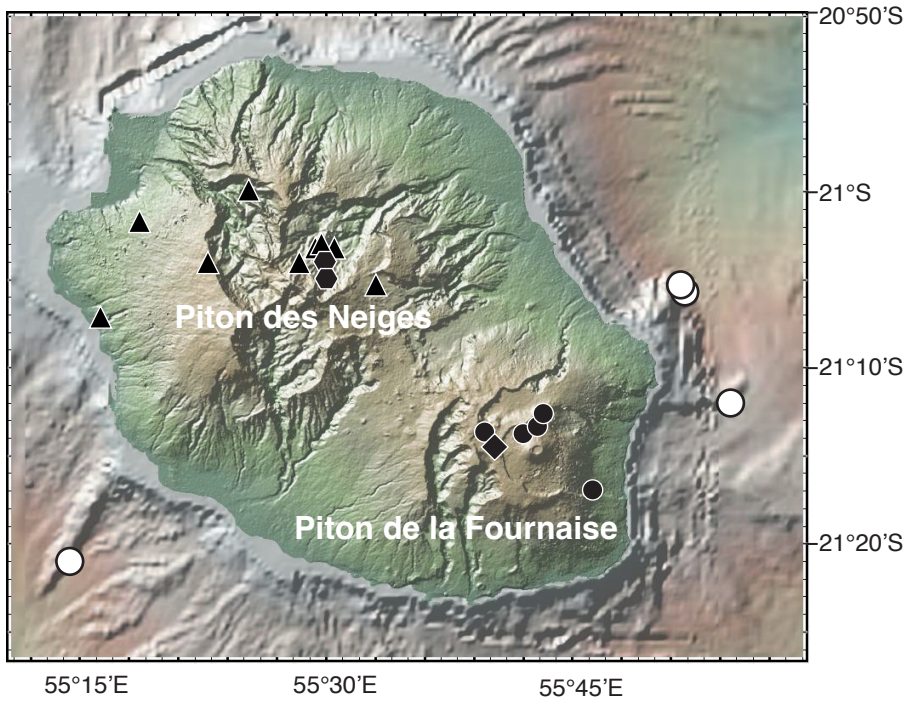
PdN: Piton des Neiges. PdF: Piton de la Fournaise.

F1

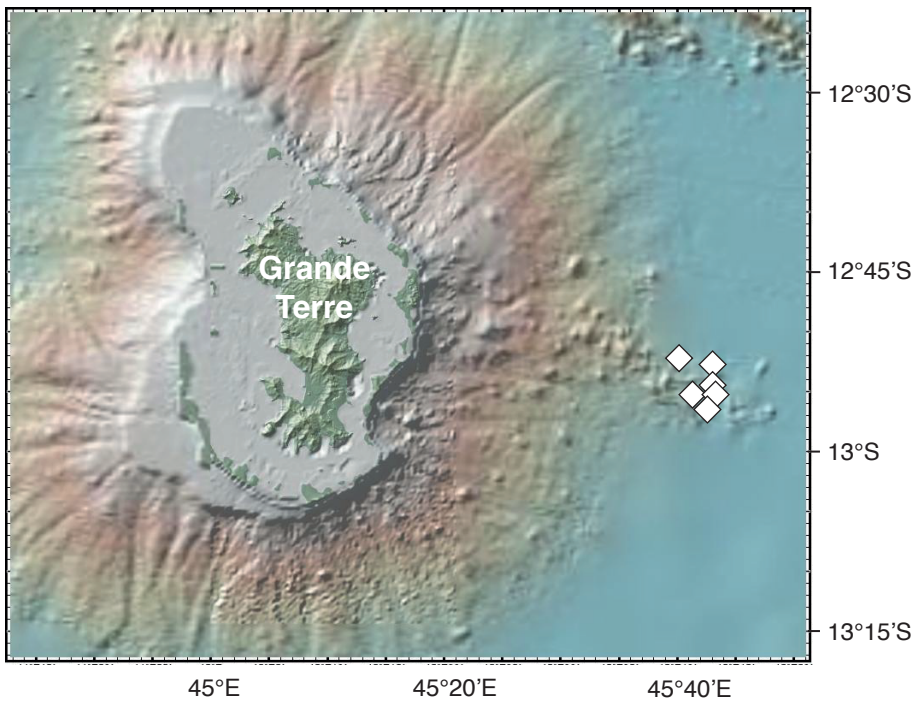
A)



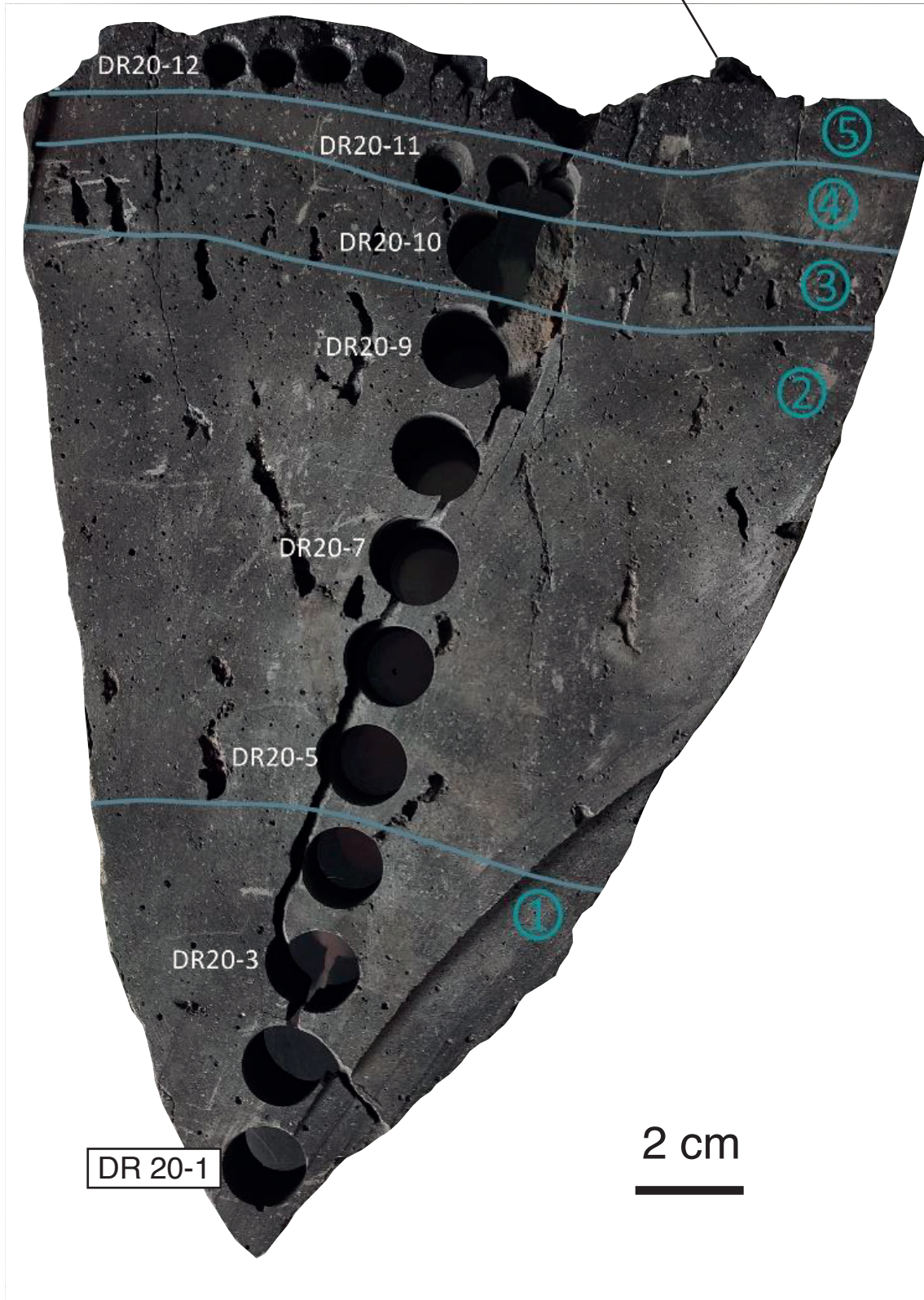
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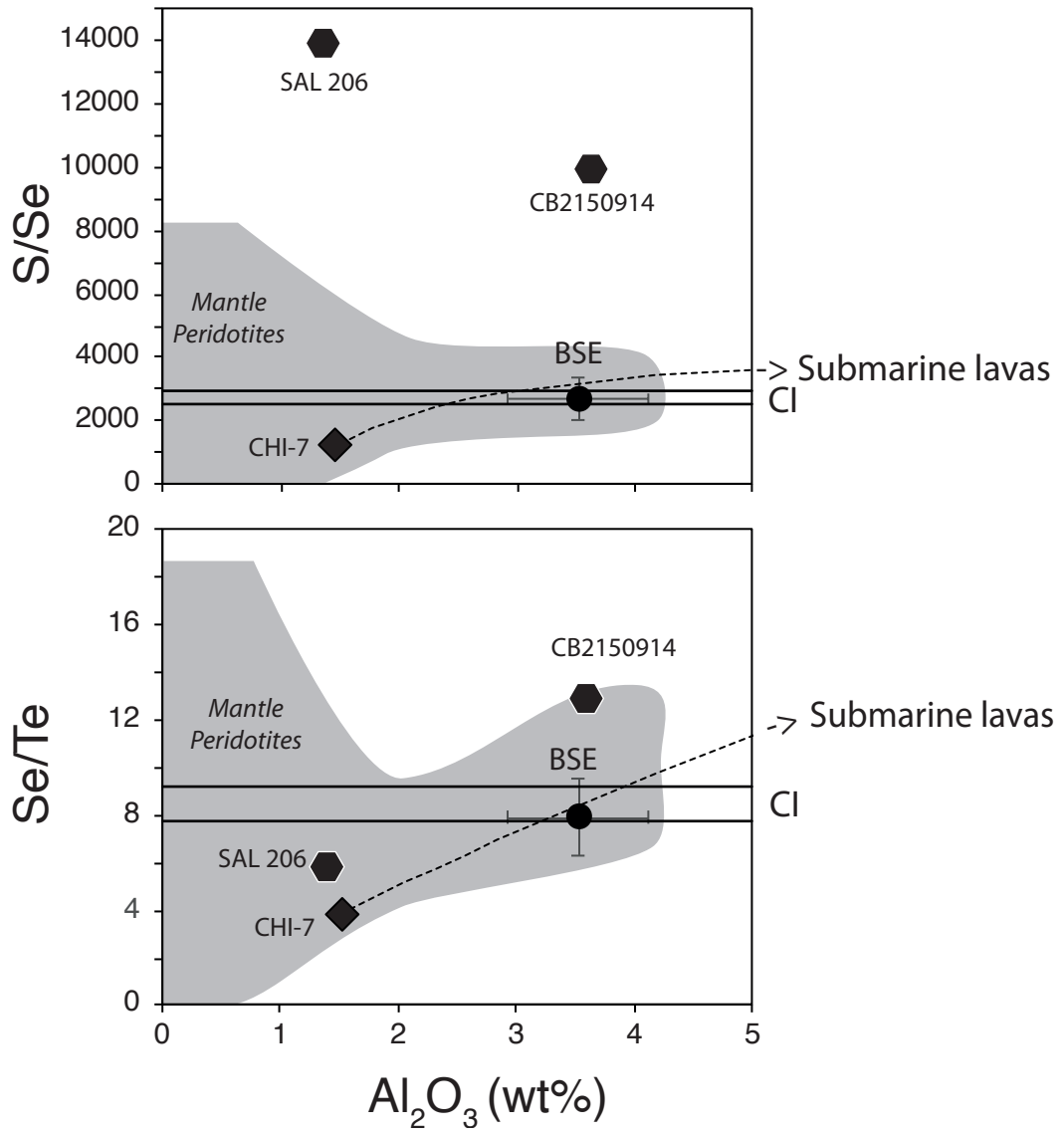


C)



DR20-Sp  
(Layer 6 : thin glassy crust)





Crystallization assemblage**La Réunion**

(1) Ol + Spl

(2) Ol + Cpx + Plg + Spl

(3) Cpx + Plg + Sulf

(4) Cpx + Plg + Mnt + Sulf

**Fani Maoré eruption (Mayotte)**

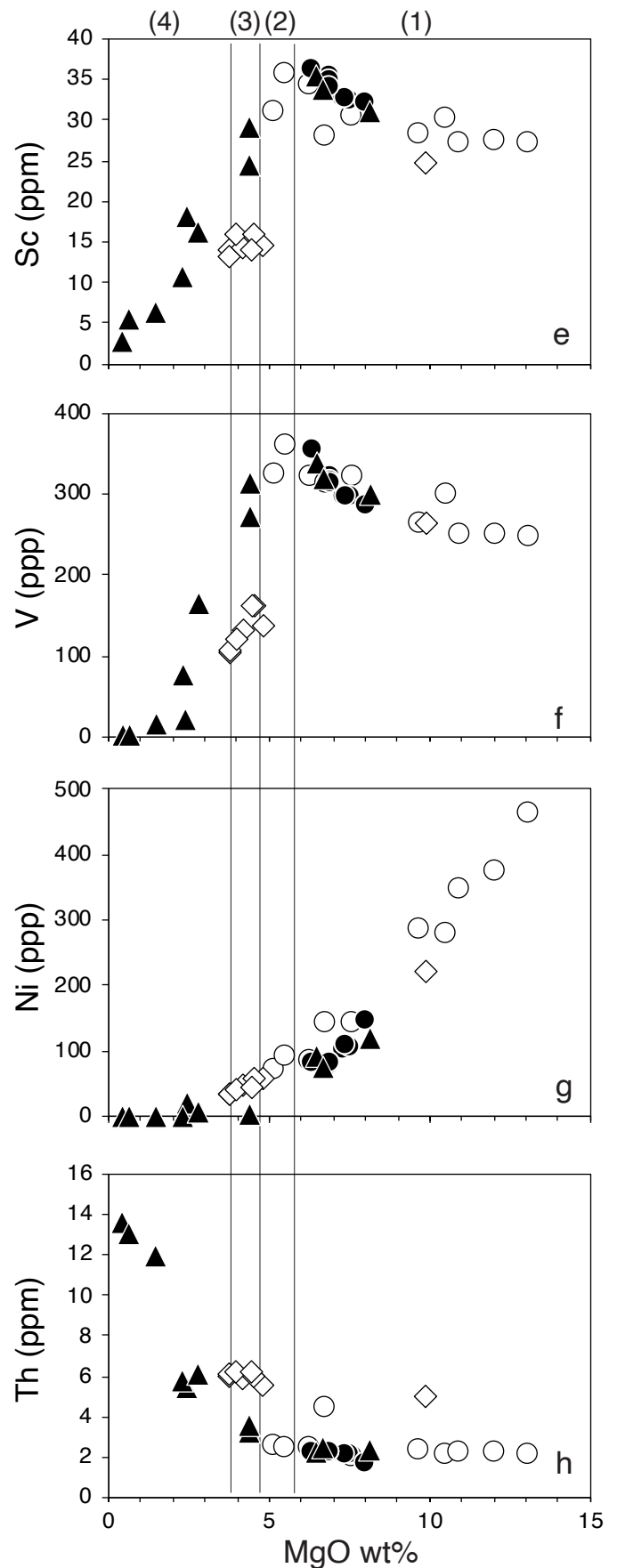
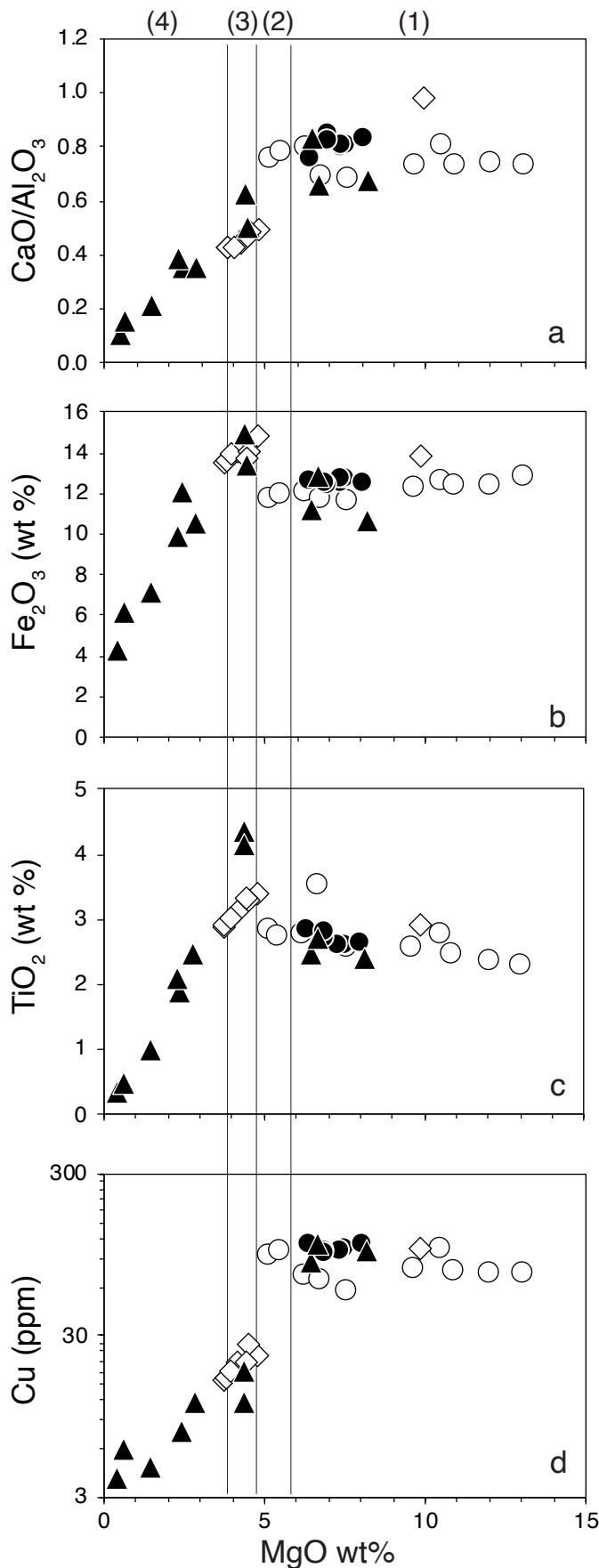
(2-3) 80% Cpx + 20% Ol + Sulf

○ La Réunion submarine lavas

● Piton de la Fournaise lavas

▲ Piton des Neiges lavas

◇ Fani Maoré submarine eruption



*Crystallization assemblage*

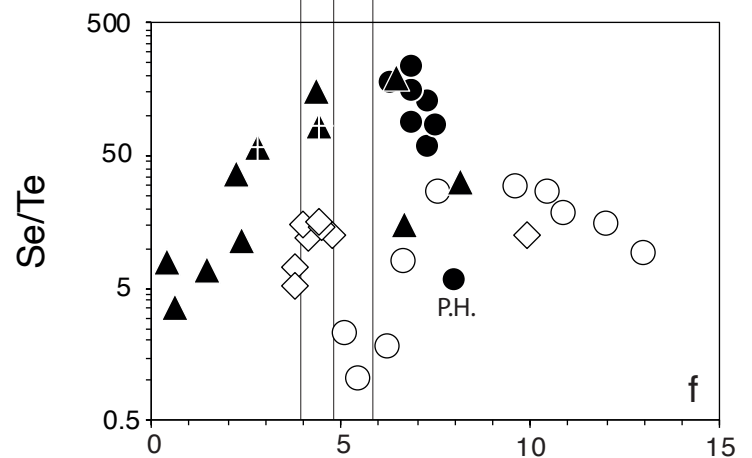
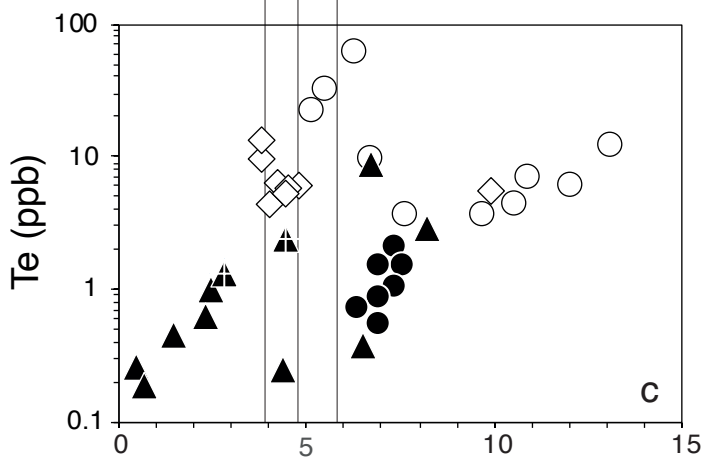
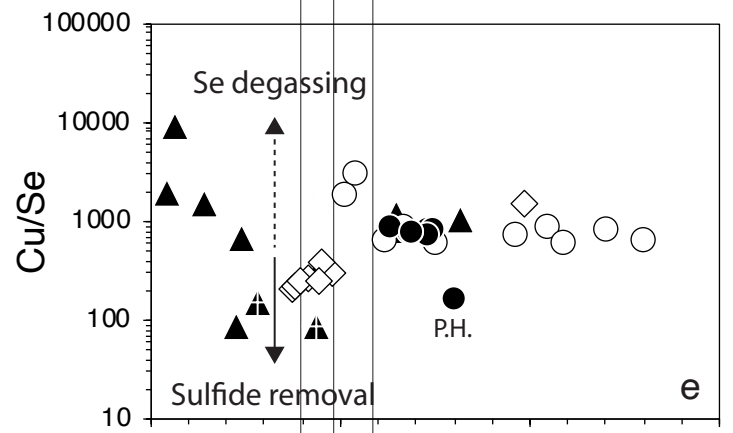
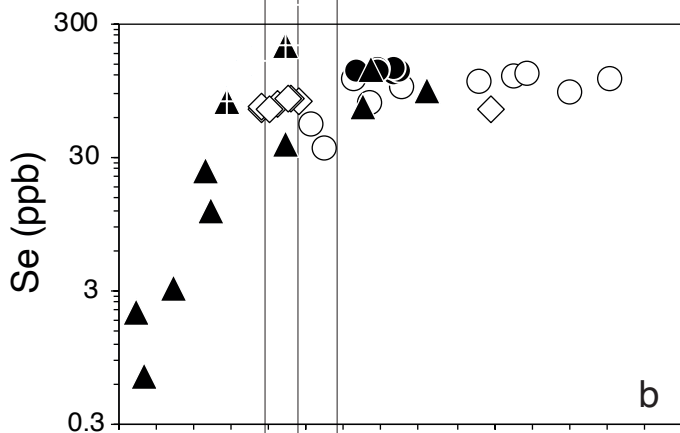
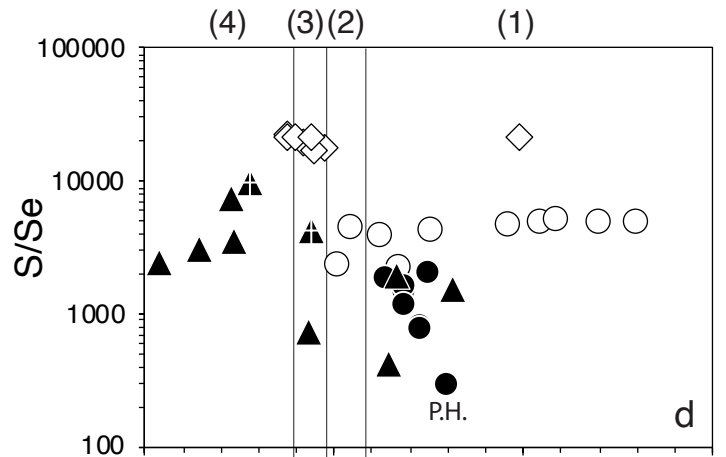
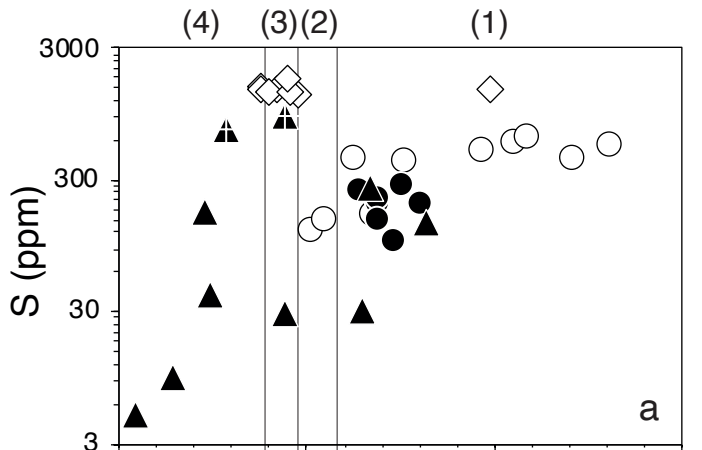
**La Réunion**

- (1) Ol + Spl
- (2) Ol + Cpx + Plg + Spl
- (3) Cpx + Plg + Sulf
- (4) Cpx + Plg + Mnt + Sulf

**Fani Maoré eruption (Mayotte)**

- (2-3) 80% Cpx + 20% Ol + Sulf

- La Reunion submarine lavas
- Piton de la Fournaise lavas
- P.H. PdF Pele's Hairs
- ▲ Piton des Neiges lavas
- ▲ Piton des Neiges lavas with pyrite
- ◇ Mayotte submarine lavas



MgO wt%

MgO wt%

