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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 Fani Maoré volcano, Mayotte)**

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27 **Abstract**

28

29 Selenium (Se) and tellurium (Te) are oxygen group elements that share chemical properties  
30 with sulfur, but also show subtle differences that are useful to constrain magmas genesis and  
31 source. Using high-precision isotope dilution measurements, this study characterizes the  
32 behavior of Se and Te, relatively to S, during the degassing and crystallization of cogenetic  
33 magmas from the southwest Indian Ocean. The study of subaerial and submarine lavas from  
34 La Réunion Island first shows that, unlike S and Te, Se is not significantly lost during the rapid,  
35 final ascent of less differentiated magmas (MgO > 6wt%). This is because Se is retained as  
36 selenide in primary melts despite relatively oxidized conditions. Conversely, selenium  
37 degassing occurs during magma crystallization below 6 wt% MgO, at a similar rate as sulfur,  
38 yielding small S/Se fractionation in the residual magma. Sulfide fractionation, which begins  
39 between 5 and 4 wt% MgO, has minor effect on Se compared to Cu. Tellurium is extensively  
40 outgassed from La Réunion subaerial lavas but shows a very specific behavior in submarine  
41 lavas where it is retained and even accumulate near 6 wt% MgO. The very different behaviors  
42 of Se and Te during magma degassing yields extremely large Se/Te variations between  
43 subaerial (up to 225) and submarine (down to 1) lavas from La Réunion.

44 The Fani Maoré eruption that occurred between 2018 and 2021 offshore the island of Mayotte  
45 (Comoros Archipelago) also provided the opportunity to study chalcogens degassing during  
46 the emplacement of submarine lavas. The study of a pillow lava showing a radial textural  
47 zonation typical of degassing-crystallization during cooling reveals that S, Se and other  
48 moderately volatile elements (Mo, W, Cs) are the most depleted at intermediate depth within  
49 the pillow where pipe vesicles occur, suggesting these elements escape with major volatiles.  
50 Conversely, Te is depleted in the whole interior of the pillow, suggesting Te is more efficiently  
51 lost due to a lower solubility in magma. Assessment of pillow degassing during emplacement  
52 yields a 6.5% loss of the initial S content, 7.2% for Te, but only 1.6% for Se confirming the lower  
53 volatility of Se during lava emplacement. Chalcogens degassing is accompanied with  
54 significant loss of W (8.9%), Mo (5.1%) and Cs (5.1%) from Fani Maoré lavas. Based on these  
55 values, the 6.5 km<sup>3</sup> Fani Maoré eruption released 1.1 – 1.5 x 10<sup>6</sup> tons of S, 2300 – 2700 tons  
56 of Mo, 970 – 1130 tons of W, 194 – 339 tons of Cs, 13.3 – 16 tons of Se and 4.5 – 11.8 tons of  
57 Te during emplacement.

58 The unusually elevated S/Se ratios (16929 – 22130) of Fani Maoré lavas requires a mantle  
59 source extensively fertilized by sulfide melts, whereas the reconstructed S – Se – Te  
60 composition of La Réunion plume source is consistent with the preservation of chondritic S/Se  
61 and Se/Te ratios.

62

63 Keywords : selenium, tellurium, magma degassing, magma differentiation, La Réunion,  
64 Mayotte, Fani Maoré eruption

## 65 1. Introduction

66

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

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

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

99

## 100 2. Geological setting

101

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

114 Mayotte is one of the four islands of the Comoros Archipelago located between Africa and  
115 Madagascar (Fig. 1a). The origin of Comoros volcanism is debated and could either be related  
116 to a mantle plume or to lithosphere deformation (Hajash and Armstrong, 1972; Emerick and  
117 Duncan, 1982; Class et al., 2005; Nougier et al., 1986; Famin et al., 2020; Feuillet et al., 2021;  
118 Thinon et al., 2022). The Fani Maoré submarine eruption occurred between 2018 and 2021,  
119 50 km east of Mayotte, along the East-Mayotte submarine Volcanic Chain, on a 3300 m-deep  
120 seafloor (Fig. 1c). The eruption produced 6.5 km<sup>3</sup> of homogeneous basanitic magmas during  
121 three main eruption phases related to different magma paths (Berthod et al., 2021, 2022;  
122 Chauvel et al. 2024).

123

## 124 3. Samples

125

126 La Réunion sample set, summarized in table 1 and displayed in figure 1b, is composed of: (1)  
127 twelve co-genetic samples from the Piton des Neiges differentiation suite, including three  
128 olivine-basalts, two hawaiites, two benmoreites and five trachytes. These samples cover all

129 four magmatic stages of Piton des Neiges (Upton and Wadsworth, 1972; Gillot and Nativel,  
130 1982) and were previously selected and studied by Famin et al. (2016), Nauret et al. (2019),  
131 and Berthod et al. (2020). All these samples were collected on land, some emplaced as lava  
132 flows and others as sheet intrusions; (2) three plutonic rocks with wehrlitic composition (33 –  
133 41.5 wt% MgO) interpreted as magma chamber cumulates (Barrat and Bachèlery, 2019;  
134 Berthod et al., 2020); (3) nine lava samples from the recent (2007-2020) activity of Piton de la  
135 Fournaise volcano studied by Vlastélic et al. (2013), including eight basalts with a  
136 homogeneous MgO content (6.4 to 8 wt%), and one olivine-rich lava (29.2 wt% MgO). These  
137 samples were selected to cover a wide range of textures and cooling rates (crystallized lava,  
138 quenched lava, scoria, pumice, Pele's hairs). (4) Ten submarine lavas, including four samples  
139 related to the early history of Piton des Neiges, and six lavas related to the submarine  
140 volcanism that occurred in the southeast of the island prior to Piton de la Fournaise. These  
141 samples have MgO content between 5.1 and 13 wt% (Smietana et al., 2010; Smietana, 2011).  
142 The Fani Maoré samples selected for this study are all fresh submarine lavas studied by  
143 Berthod et al. (2021, 2022) and Chauvel et al. (2024). The samples were dredged during  
144 MAYOBS (Rinnert et al., 2019) and GEOFLAMME cruises (Rinnert et al., 2021). Dredge  
145 locations are reported in [table 1](#) and displayed in [figure 1c](#). Samples include: (1) eight evolved  
146 basanites covering the three main phases of the 2018-2021 submarine eruption ([Table 1](#)).  
147 Except for one sample with 9.9 wt% MgO, the eight samples display small compositional  
148 variations ( $3.8 \leq \text{MgO} \leq 4.8$  wt%) ascribed to magma differentiation in a large ( $\geq 10$  km<sup>3</sup>)  
149 reservoir located within the lithospheric mantle (Berthod et al., 2021). Bulk porosity decreases  
150 from 30 – 45% during phase 1 to 5 – 20% during phase 3 (Verdurme et al., 2024). Sulfides  
151 droplets occur in all these samples and are most abundant in the third phase samples (Berthod  
152 et al., 2022). (2) Nine samples regularly drilled from the glassy margin to the core of a pillow  
153 lava ([Fig. 2](#)) erupted during the third phase of the 2018-2021 eruption (sample GFL-DR20-0101  
154 in Berthod et al., 2022, with MgO of 4.45 wt%).

155

#### 156 4. Analytical methods

157

158 Selenium and tellurium concentrations were analyzed by isotope dilution (ID) hydride  
159 generation (HG) quadrupole inductively coupled plasma mass spectrometry (ICP-MS)  
160 following a method modified from Yierpan et al. (2018). We first prepared <sup>77</sup>Se enriched

161 (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  
162 solutions from solid sources obtained from Oak Ridge National Laboratory, USA. The  
163 concentrations of the spike solutions were calibrated by isotope dilution against solutions  
164 prepared by diluting a 10 µg/g certified standards from Inorganic Venture. The spikes  
165 concentrations were obtained by averaging the measurements of three spike-standard  
166 mixtures prepared around the spike/standard optimal ratio. For sample analysis, 200 mg of  
167 rock powders were weighted in 15 ml Teflon vials. Immediately after, we added between 250  
168 and 500 mg of <sup>77</sup>Se enriched spike and between 150 and 300 mg of <sup>125</sup>Te enriched spike. The  
169 silicates were digested by adding successively 1 ml of 14M HNO<sub>3</sub> and 6 ml of 29M HF and  
170 placing the vials on a hotplate at 90°C for 24 hours. The samples were evaporated at 70°C to  
171 avoid major Se and Te volatilization (Vlastélic and Piro, 2022). The dry residues were taken in  
172 3 ml of 6M HCl, heated at 90°C for 24H, and evaporated at 70°C. This step of HCl conversion  
173 was repeated once. The two-step chemistry from Yierpan et al. (2018) was used to purify Se  
174 and Te. The column separation was calibrated by dissolving 320 mg of a La Réunion basalt  
175 doped with 500 ng of Se and Te. After HCl conversion, the sample residues were dissolved in  
176 3 ml of 4M HCl, centrifuged for 5 min, before being loaded on anionic columns (polypropylene  
177 Biorad filled with 5 ml of AG1-X8 100-200 mesh resin). Most elements and Se were eluted by  
178 adding successively 3 x 1 ml and 4 ml of 4M HCl, while Te was retained probably as chloro-  
179 complex. Iron was eluted with 2 x 5 ml of 2M HCl – 5M HF and 2 x 3 ml of 0.4M HCl. Tellurium,  
180 with minor amount of remaining Pb, was eluted with 6 ml of 0.4M HCl. After evaporation at  
181 65°C, the major element – Se fraction was dissolved in 4 ml of 0.1M HNO<sub>3</sub> and centrifugated  
182 before being loaded on cationic columns (polypropylene Biorad filled with 5 ml of AG50-X8  
183 200-400 mesh resin). Selenium was eluted by adding successively 2 x 1 and 3ml of 0.1M HNO<sub>3</sub>.  
184 The collected Se fraction is not highly pure but is sufficiently depleted in Fe and other  
185 transition metals for efficient hydride generation during subsequent ICPMS analysis.  
186 After evaporation at 85°C the fractions of Se (0.14 – 135 ng) and Te (0.04 – 24 ng) recovered  
187 from samples were taken in 6 and 3 ml of HNO<sub>3</sub> 1M, respectively. The resulting solutions with  
188 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  
189 hydride generation system (HGX-200 from Teledyne Cetac Technologies). The H<sub>2</sub>Te and H<sub>2</sub>Se  
190 vapors were entrained by two Ar flows (carrier flow of 0.42 L/min and make up flow of 0.82  
191 L/min) to an Agilent 7500 ICPMS. To improve ICPMS sensitivity, we used two primary pumps  
192 increasing the vacuum of the interface. <sup>78</sup>Se/<sup>77</sup>Se was measured using the reaction cell (He



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

201 Sulfur concentration was measured by isotope dilution using a  $^{34}\text{S}$  enriched spike (262 ppm S,  
 202 with 99.79%  $^{34}\text{S}$ ). The spike, initially in the form of native sulfur, was dissolved in 14M  $\text{HNO}_3$   
 203 and calibrated against IAEA-S-1 sulfur isotope reference material. For sample analysis, 50 mg  
 204 of rock powders were weighted in 15 ml Teflon vials, spiked and digested with 1 ml of 14M  
 205  $\text{HNO}_3$  and 6 ml of 29M HF at 90°C for 24 hours. After evaporation, the fluoride residue was  
 206 reduced by addition and evaporation of a few drops of 14M  $\text{HNO}_3$ . Unlike Wang and Becker  
 207 (2013) procedure, sulfur was not separated because of important S release (>1  $\mu\text{g}$ ) from the  
 208 cationic resin. Instead, the residue was taken in 5 ml of  $\text{H}_2\text{O}$ , centrifugated, and the  $^{32}\text{S}/^{34}\text{S}$   
 209 ratio of the supernatant was directly analyzed on an Element XR ICP-MS in high mass-  
 210 resolution mode ( $m/\Delta m$  of 10 000). To check the accuracy of S isotope compositions, the  
 211  $^{32}\text{S}/^{34}\text{S}$  ratios of a subset of samples from Fani Maoré volcano were also measured as oxides  
 212 ( $^{32}\text{S}^{16}\text{O}/^{34}\text{S}^{16}\text{O}$ ), using the oxygen reactive mode of an Agilent 8900 triple quadrupole ICPMS.  
 213 Instrumental mass fractionation was corrected by running IAEA-S-1 sulfur isotope reference  
 214 material. Sample concentration ( $C_{\text{Sample}}$ ) was calculated according to Eq. 1 :

215

$$216 \quad C_{\text{Sample}} = C_{\text{Spike}} \times \frac{m_{\text{Spike}}}{m_{\text{Sample}}} \times \frac{Ab_{\text{Spike}}^B}{Ab_{\text{Sample}}^B} \times \frac{R_{\text{Spike}} - R_{\text{mes}}}{R_{\text{mes}} - R_{\text{Sample}}} \quad (1)$$

217

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

223 1-3 %. The precision of the concentrations obtained by isotope dilution is inferred from the  
224 error magnification (M), defined as (Eq. 2) :

225

$$226 \quad M = \frac{\Delta C_{Sample}}{C_{Sample}} / \frac{\Delta R_{mes}}{R_{mes}} = \frac{R_{mes} \cdot (R_{Spike} - R_{Sample})}{(R_{Spike} - R_{mes}) \cdot (R_{mes} - R_{Sample})} \quad (2)$$

227

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

239

## 240 5. Results

241

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

244

### 245 5.1. S – Se – Te budget of La Reunion plutonic rocks

246

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

254

## 255 5.2. Differentiation of La Réunion and Mayotte magmas

256

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

264

## 265 5.3. Evolution of S, Se and Te in La Réunion magmas

266

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

276

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

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

291

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

303

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

315

316 5.4. S – Se – Te signature of the 2018-2021 Fani Maoré submarine lavas

317

318 All Fani Maoré lavas are enriched in sulfur (1342 – 1711 ppm) compared to La Réunion lavas  
319 (Fig. 5a), in agreement with the occurrence of droplets of iron sulfide (Berthod et al., 2021).  
320 Within the narrow S range, we note a trend of increasing S concentration during the 2018-  
321 2021 eruption with 1342 – 1413 ppm during phase 1 (July 2018 - May 2019), 1386 – 1509 ppm  
322 during phase 2 (May 2019 - August 2019), and 1712 ppm during phase 3b (October 2020 -  
323 January 2021). The S content (1430 ppm) of the magnesian sample DR11-0704 is consistent  
324 with other samples produced during phase 2.

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

333

#### 334 5.5. S – Se – Te degassing within the Fani Maoré pillow lava

335

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

346 Variations of S, Se and Te concentrations, and S/Se and Se/Te ratios from pillow rim to pillow  
347 core are reported in figure 6. Sulfur and Se display similar variations, with the base of layer 2  
348 being depleted in S (1518 – 1593 ppm) and Se (76.8 – 77.0 ppb) compared to pillow core (1671  
349 – 1794 ppm S and 82.6 – 83.5 ppb Se) and external layers (1751 – 1881 ppm S and 82.1 – 83.6

350 ppb Se). Sulfur loss (13%) being more important than Se loss (7%), S/Se is lower in layer 2  
351 (19706 – 20738) compared to pillow core (20235 – 21496) and external layers (21243 –  
352 22641). Tellurium displays a different zonation pattern, with low and homogeneous  
353 concentrations (4.5 – 4.9 ppb) in the internal layers 1 and 2, and markedly higher  
354 concentrations (5.7 – 6.0 ppb) in the external layers 3-6. Consequently, the Se/Te ratio is lower  
355 in the external layers (13.8 – 14.7) compared to the internal layers (16.3 – 17.2). Concentration  
356 profiles are also reported for elements showing remarkable variations across the pillow. Like  
357 S and Se, Mo and W are markedly depleted (20 – 30%) in the intermediate layer 2 compared  
358 to pillow core and rim. Unlike lighter alkali, Cs is also depleted (12%) in the outer part of layer  
359 2. Antimony is enriched in the outermost layer of the pillow.

360

## 361 6. Discussion

362

### 363 6.1. Processes controlling selenium retention in and degassing from magmas

364

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

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

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

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

419

## 420 6.2. Tellurium specific behavior

421

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

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



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

462

463 6.3. Assessment of S – Se – Te degassing during the emplacement of Fani Maoré submarine  
464 lavas

465

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

478 structures in pillows. In the studied differentiated Fani Maoré sample (MgO of 4.45 wt%), pipe  
479 vesicles are not rooted deep in the pillow, which explains the degassing of the intermediate  
480 layer mainly. Unlike S and Se, Te is depleted in both layers 1 and 2, showing a zonation (Fig. 6)  
481 unrelated to the pipe vesicles. This suggests that Te does not behave as major volatile  
482 species. To explain Te degassing of layer 1 in the absence of degassing pipes, it is hypothesized  
483 that Te is less soluble than major volatile species in silicate melts and is lost earlier by diffusion.  
484 In support of this possibility, Te is less soluble than S and Se in silicate melts saturated in  
485 sulfide, selenide and telluride (Helmy et al., 2020).

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

493

$$494 \quad \epsilon_x = 1 - \frac{\sum_{s=1}^{s=9} [X]_s \times V_s \times \rho_s}{[X]_{max} \times V_{tot} \times \rho_{tot}}$$

495

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

509 as reference, it is estimated from the  $\varepsilon$  values that the Fani Maoré eruption released 1.1 – 1.5  
510  $\times 10^6$  tons of S, 2300 – 2700 tons of Mo, 970 – 1130 tons of W, 194 – 339 tons of Cs, 13.3 – 16  
511 tons of Se and 4.5 – 11.8 tons of Te. By comparison the Se amount released in the ocean by  
512 the Fani Maoré eruption corresponds to 1% of the annual degassing flux of mid-ocean ridges  
513 (Rubin et al., 1997).

514

#### 515 6.4. Brief constraints on magma sources

516

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

530 All Fani Maoré lavas including the magnesian sample (MAY04-DR11-0704) display S/Se ratios  
531 (16929 – 22130) that are much higher than in worldwide MORB and OIB (S/Se < 10000). The  
532 S/Se ratios of Fani Maoré lavas are also higher than the most fertile mantle peridotites  
533 (S/Se~8000) (Wang and Becker, 2013) and the cumulative rocks from La Réunion (10000  
534 <S/Se< 14000, Fig. 3), which are known to be enriched in sinking sulfur liquids (Upton et al.,  
535 2000). Fani Maoré's S – Se signature is hardly explained by magma generation processes and  
536 must reflect a source property. The most likely explanation is that the Fani Maoré lavas derive  
537 from the melting of a lithospheric mantle extensively refertilized by sulfide melts. This is  
538 consistent with previous inferences that the Fani Maoré volcano, like the island of Mayotte,  
539 formed by melting of a carbonated mantle source enriched in Ba and volatiles (Chauvel et al.  
540 2024; Pelleter et al. 2014). Lithosphere refertilization is a common process driven by melt or

541 fluid infiltrations, but in the case of the Fani Maoré volcano, it might have reached an unusual  
542 extent and caused this exceptionally large-volume eruption.

543

## 544 7. Conclusions

545

546 This work obtained the following results:

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

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

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

563 (4) A pillow lava emplaced during the Fani Maoré eruption offshore Mayotte shows degassing-  
564 driven radial compositional zonation. Degassing of S, Se and other moderately volatile  
565 elements (Mo, W, Cs) is the most important at intermediate depth within the pillow where  
566 pipe vesicle occur, suggesting they escape with major volatiles. Conversely, Te is depleted in  
567 the whole interior of the pillow, suggesting Te is more efficiently lost due to a lower solubility  
568 in magma.

569 (5) Assessment of pillow degassing during emplacement yields losses of 6.5% for S, 7.2% for  
570 Te, but only 1.6% for Se confirming the lower volatility of Se during lava emplacement.  
571 Chalcogens degassing is accompanied with significant loss of W (8.9%), Mo (5.1%) and Cs  
572 (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

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

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

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

580

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582

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588 study and provided dredged samples.

589

590 **Figure captions**

591

592 Figure 1. Location maps. (a) Relief map of the southwest Indian Ocean showing the locations  
593 of La Réunion and Mayotte islands. (b) Relief map of La Réunion Island showing the location  
594 of the Piton des Neiges and Piton de la Fournaise volcanoes, and the location of subaerial and  
595 submarine samples analyzed in this study. Closed triangles: Piton des Neiges lavas; closed  
596 circles: Piton de la Fournaise lavas; closed hexagons: cumulates ; closed diamond: peridotite,  
597 open circles: submarine lavas. (c) Relief map of Mayotte Island, showing the locations of the  
598 samples from the Fani Maoré submarine eruption (open diamonds) that occurred between  
599 2018 and 2021 50 km east of Mayotte island, along the East-Mayotte submarine Volcanic  
600 Chain. All maps were made using GeoMapApp (<https://www.geomapapp.org/>).

601

602 Figure 2. Cross section of GFL-DR20-0101 pillow lava emplaced during phase 3 of the Fani  
603 Maoré eruption. Drill holes are shown and numbered from pillow interior (DR20-1) to pillow  
604 rim (DR20-12). Sample DR20-Sp is a chip taken from the thin glassy layer at the surface of the  
605 pillow. The five main textural unit (1-5) and the surface glassy layer (layer 6) described in text  
606 are indicated. Because the external layers 4 and 5 are thinner than other layers, between 3  
607 and 4 smaller drill holes were made and mixed within each layer.

608

609 Figure 3. Composition of La Réunion plutonic rocks reported in (a) S/Se and (b) Se/Te versus  
610  $Al_2O_3$  plots. The compositional field of mantle peridotites, and the composition of  
611 carbonaceous chondrites (CI) and Bulk Silicate Earth (BSE) are shown (Lorand and Alard, 2010;  
612 König et al., 2012; Wang and Becker, 2013). Closed hexagons: cumulates; closed diamond:  
613 peridotite. Analytical error is smaller than symbols size. Data are from [table 2](#) (S, Se and Te  
614 concentrations) and supplementary [table S1](#) ( $Al_2O_3$  concentrations). The dashed line is a  
615 mixing curve calculated by mixing CHI-7 peridotite with the less degassed submarine DR6-2  
616 lava sample.

617

618 Figure 4. Major-trace elements versus MgO plot showing the composition of La Réunion and  
619 Fani Maoré lavas. Vertical thin lines indicate major changes in the crystallization assemblage.  
620 The crystallization sequences of La Réunion magma involves four steps (Villemant et al. 2009;  
621 Pichavant et al. 2016) : (1) primary melts ( $MgO \geq 9\%$ ) first crystallize olivine and spinel causing

622 an important decrease of Ni and Cr; (2) Clinopyroxene and plagioclase appear at the liquidus  
623 at MgO~6 wt% as recorded by the onset of Sc, V and Ca/Al decrease. (3) Between ~5 and ~4  
624 wt% MgO, the increase of Fe and Ti indicate that olivine is no longer a liquidus phase, while  
625 Ti-magnetite has not yet appeared. The abrupt drop of Cu (from 97 to 18 ppm) indicates that  
626 the onset of sulfide saturation occurs at this step. This corresponds to the first phase of sulfide  
627 formation which is triggered by S becoming saturated in magmas (Collins et al. 2012). (4)  
628 Below ~4 wt% MgO, the decrease of Fe, Ti, Ca/Al, Sc and Cu, and the increase of Th are  
629 consistent with precipitation of clinopyroxene, plagioclase, magnetite and sulfides. This  
630 second phase of sulfide saturation is related to the crystallization of titanomagnetite which  
631 reduces the sulfur content at sulfide melt saturation (Jenner et al., 2010; Collins et al. 2012).  
632 The crystallization assemblage of Fani Maoré samples (80% Cpx – 20 % Ol) is from Berthod et  
633 al. (2021). Symbols are as in previous figures. Data are from [table 2](#) (S, Se and Te  
634 concentrations) and supplementary [table S1](#) (major and trace element concentrations from  
635 La Réunion samples). Fani Maoré data are from Berthod et al. (2022) (major elements) and  
636 Chauvel et al. (2024) (trace elements). Fani Maoré trace element data not given in Chauvel et  
637 al. (2024) were taken from Berthod et al. (2022).

638  
639 Figure 5. Chalcogen contents (S, Se, Te) and ratios (S/Se, Cu/Se, Se/Te) plotted against MgO  
640 content of lavas. Vertical thin lines indicate major changes in the mineral assemblage  
641 crystallizing (see figure 4). The composition of La Réunion and Fani Maoré lavas are reported  
642 using the same symbols as in previous figures. Analytical error is smaller than symbols size.  
643 Data are from [table 2](#) (S, Se and Te concentrations) and supplementary [table S1](#) (MgO and Cu  
644 concentrations from La Réunion samples). Fani Maoré data are from Chauvel et al. (2024) (Cu)  
645 and Berthod et al. (2022) (MgO and Cu).

646  
647 Figure 6.  
648 Radial compositional zonation of GFL-DR20-0101 pillow lava emplaced during the third and  
649 last phase (October 2020 - January 2021) of the Fani Maoré eruption (Berthod et al., 2020).  
650 Vertical dashed lines separate the major textural units shown in [figure 2](#) and described in text.  
651 Error bars are indicated or smaller than symbols size. Data are from [table 2](#) and supplementary  
652 [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 reference materials and rock samples from La Réunion island and Fani Maoré volcano, Mayotte.

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 ±
	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	4.45	1711		81.5		5.23		
	drilling	distance to pillow rim							
	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)

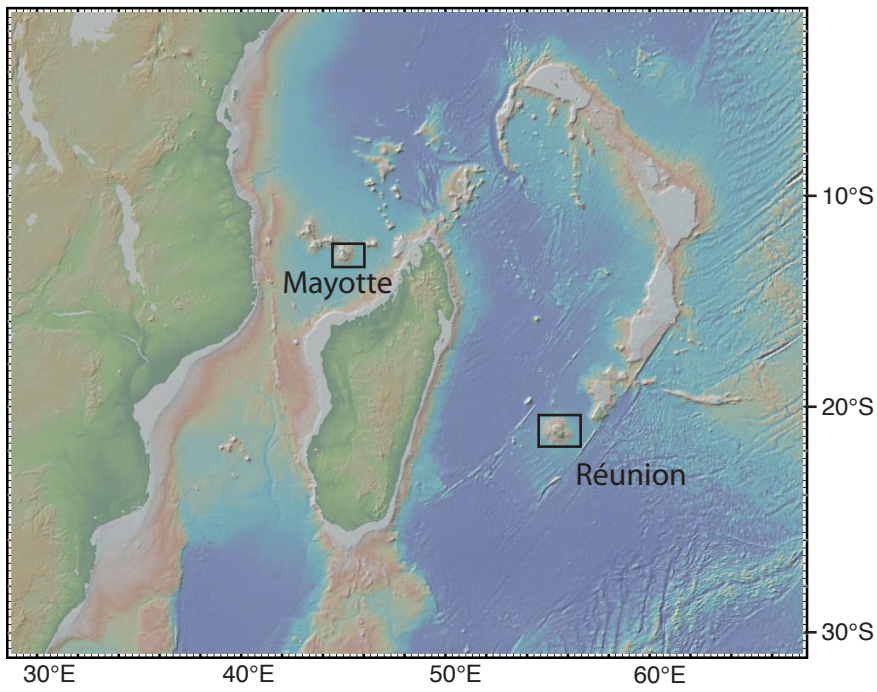
SD: sample SD is calculated by propagating errors on isotopic ratios (see text)

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

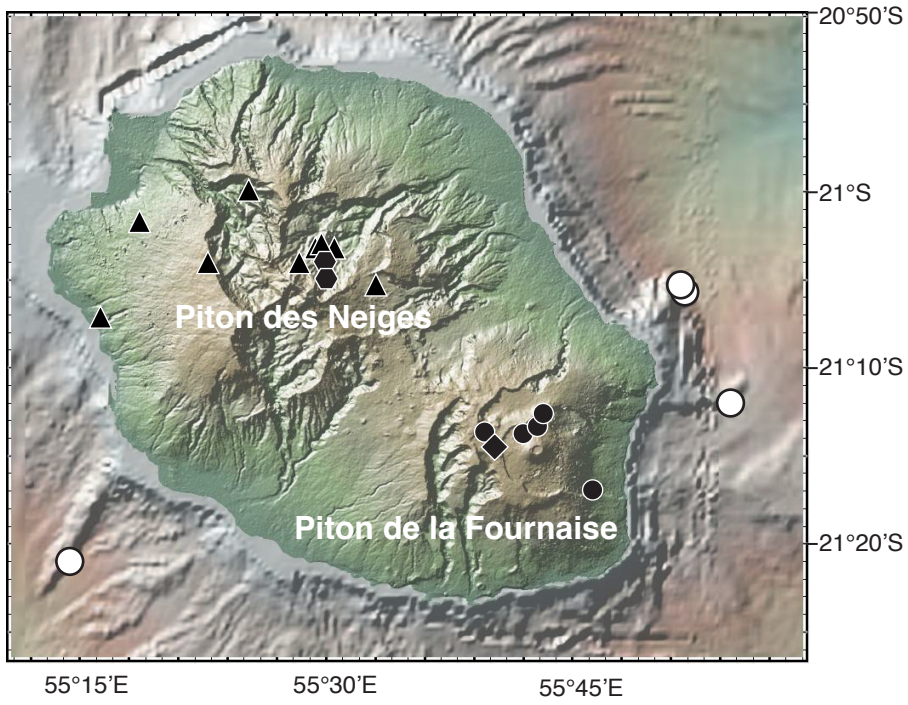
PdN: Piton des Neiges. PdF: Piton de la Fournaise.

F1

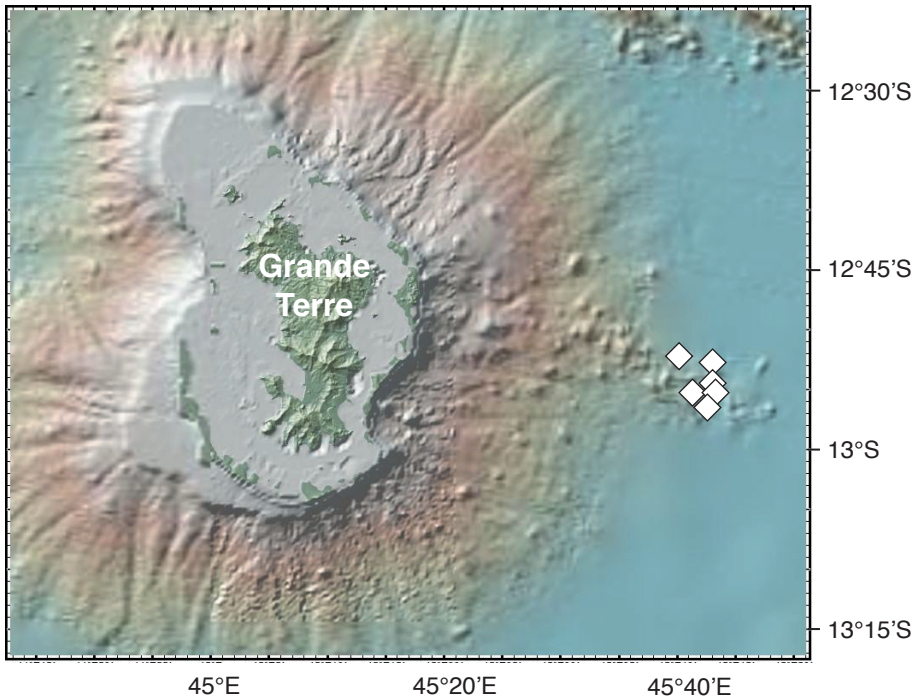
A)



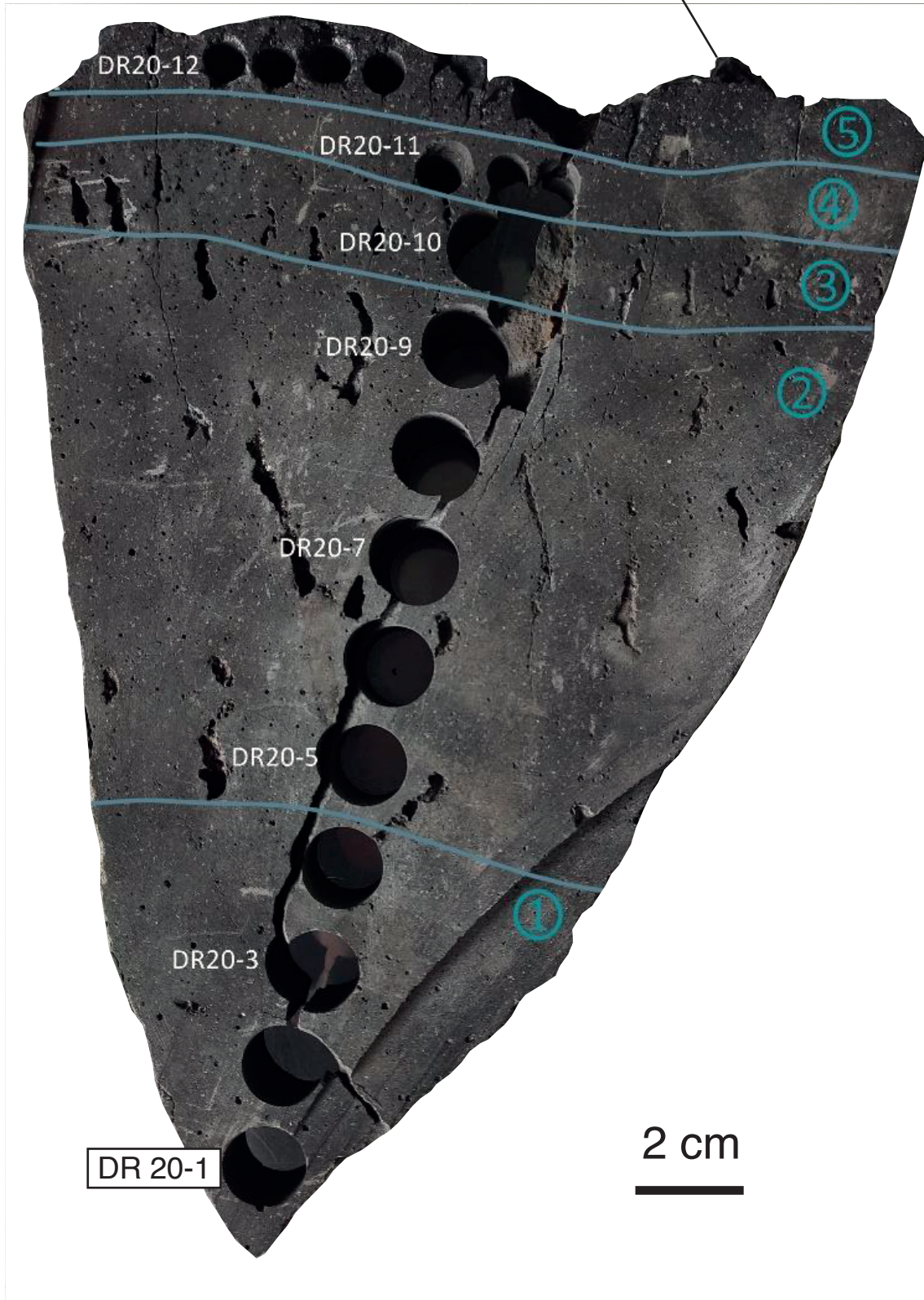
B)

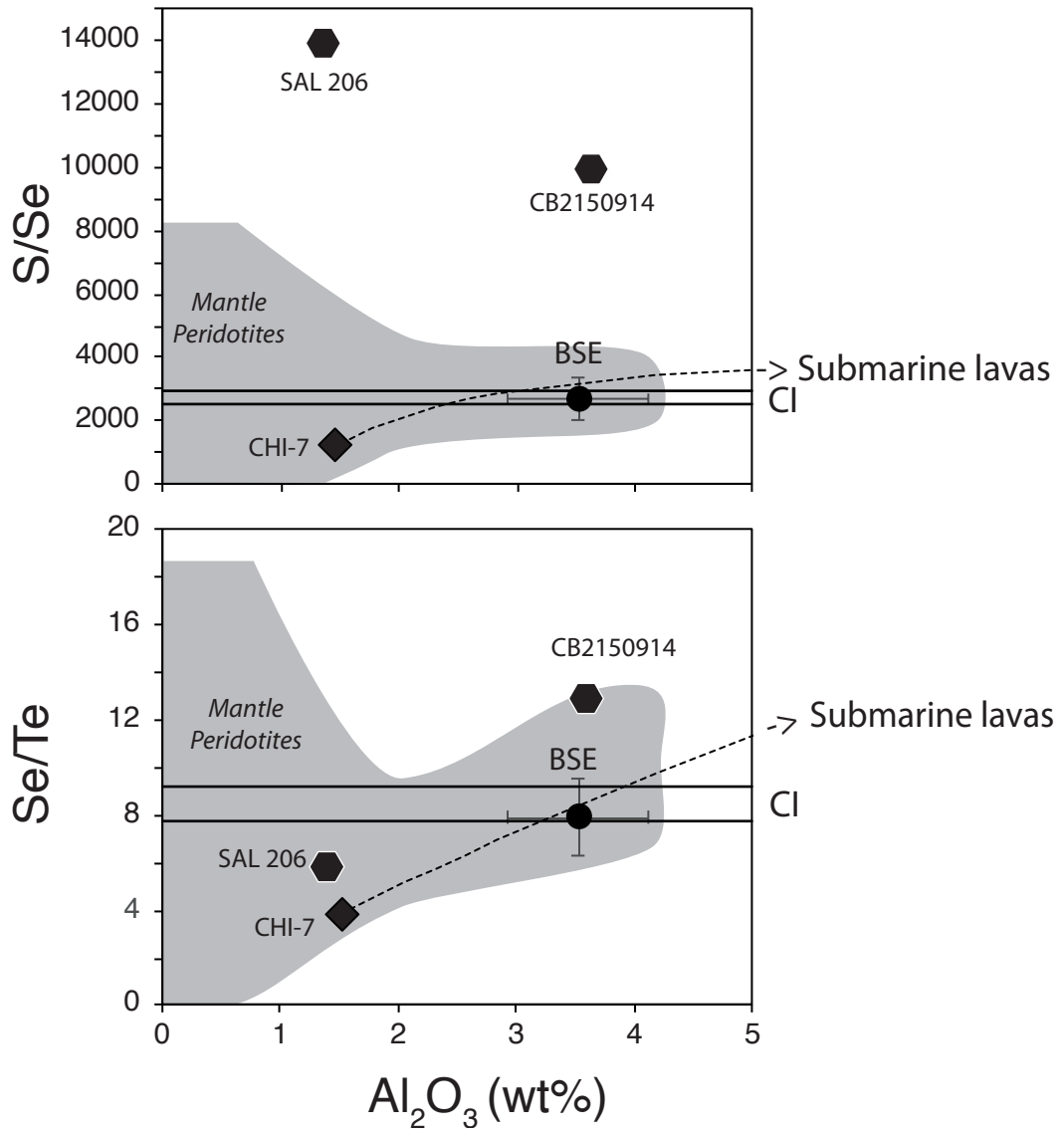


C)



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)**

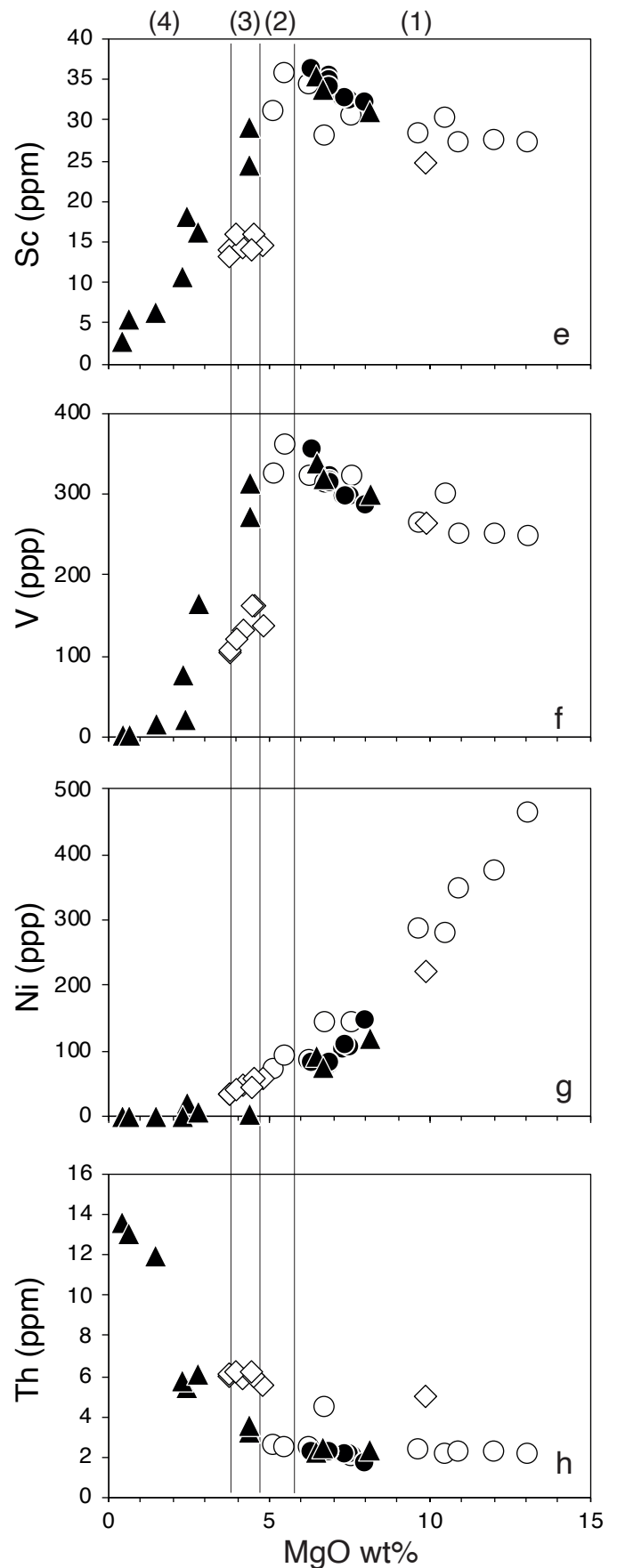
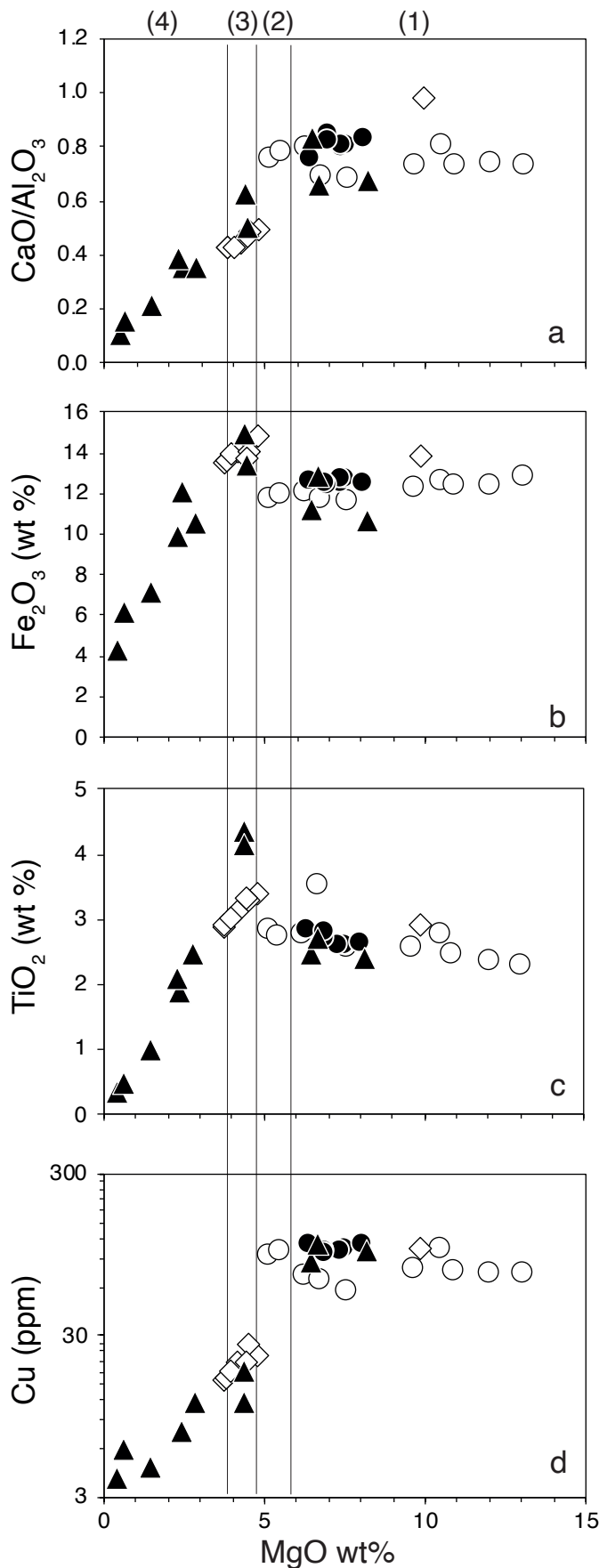
(2-3) 80% Cpx + 20% Ol + Sulf

○ 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

