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1 Fast ascent rate during the 2017-2018 Plinian eruption of  
2 Ambae (Aoba) volcano; a petrological investigation.

3  
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14  
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16  
17 **ABSTRACT**

18 In September 2017, after more than a hundred years of quiescence, Ambae (Aoba), Vanuatu's  
19 largest volcano, entered a new phase of eruptive activity, triggering the evacuation of the  
20 island's 11,000 inhabitants resulting in the largest volcanic disaster in the country's history.

21 Three subsequent eruptive phases in November 2017, March 2018 and July 2018 expelled  
22 some of the largest tropospheric and stratospheric SO<sub>2</sub> clouds observed in the last decade.

23 Here, we investigate the mechanisms and dynamics of this eruption. We use major elements,  
24 trace elements, and volatiles in olivine and clinopyroxene hosted melt inclusions,  
25 embayments, crystals and matrix glasses together with clinopyroxene geobarometry and

26 olivine, plagioclase and clinopyroxene geothermometry to reconstruct the physical and  
27 chemical evolution of the magma as it ascends to the surface. Volatile elements in melt  
28 inclusions and geobarometry data suggest that the magma originated from depth of  $\sim 14$  km  
29 before residing at shallow ( $\sim 0.5$  to 3 km) levels. Magma ascent to the surface was likely  
30 facilitated by shallow phreatic eruptions that opened a pathway for magma to ascend.  
31 Succeeding eruptive phases are characterised by increasingly primitive compositions with  
32 evidence of small amounts of mixing having taken place. Mg-Fe exchange diffusion  
33 modelling yields olivine residence times in the magma chamber ranging from a few days to a  
34 year prior to eruption. Diffusion modelling of volatiles along embayments (melt channels)  
35 from the first two phases of activity and microlite number density suggest rapid magma  
36 ascent in the range of 15 to 270 km/h, 4 to 75 m/s (decompression rates of 0.1 to  $\sim 2$  MPa/s)  
37 corresponding to a short travel time between the top of the shallow reservoir and the surface  
38 of less than two minutes.

39

## 40 INTRODUCTION

41 Ambae (also known as Aoba;  $167^{\circ}50'E$ ,  $15^{\circ}23'S$ ), is an island volcano located in the central  
42 part of the Vanuatu archipelago. The volcano summit is located 3900 m above the sea floor  
43 and 1496 m above sea level (Fig. 1). The emerged part of the edifice is  $38 \times 16$  km and host a  
44 pre- 2017 eruption population of about 11,000 inhabitants. Although part of a particularly  
45 active volcanic arc, Ambae's magmatic system has been very little studied compared to its  
46 volcanic neighbour Ambrym (e.g., Firth et al. 2016; Allard et al. 2016; Sheehan and Barclay  
47 2016). Yet the volcano's magmatic activity together with the presence of large acid lakes at  
48 the volcano's summit, poses a particularly high risk to the island's population due to the  
49 potential for highly explosive phreato-magmatic eruptions and especially lahars. An  
50 understanding of Ambae's magmatic system is an essential first step towards a better

51 comprehension of its past and forecasting of its future activity. In this contribution, we aim to  
52 draw such an understanding by studying deposits from the 2017-2018 eruption of Ambae, the  
53 largest in recorded history.

54

55 Ambae is located in the central part of the Vanuatu arc, created by the north-eastward  
56 subduction of the Australian plate underneath the Pacific plate (e.g., Daniel et al. 1989). This  
57 central part of the arc is characterised by the collision of the D'Entrecasteaux ridge, a 100 km  
58 wide Eocene–Oligocene island arc complex on the Australian subducting plate, with the fore-  
59 arc (e.g., Collot et al. 1985). Ambae is a shield volcano composed of a pile of primitive  
60 basalts (Gorton 1977; Eggins 1993). At the summit is a 5 x 4 km caldera partially filled by 3  
61 lakes one of which was considered among the world's largest acid crater lakes (Voui lake)  
62 (Bani et al. 2009a). According to local knowledge, the last significant eruption occurred  
63 about 350 years ago, with lava flows reaching the sea near N'dui N'dui (Warden 1970).  
64 Volcanic activity at Ambae in the last hundred years has been limited to fumarolic  
65 manifestation (Wiart 1995; Bani et al. 2009b). However since the early 1990s Ambae  
66 resumed eruptive activity within lake Voui, first with a phreatic eruption in 1995, followed by  
67 a Surtseyan eruption in 2005 that formed a 500 m width and 50 m high islet in the centre of  
68 the lake (Nemeth et al. 2006). This latter eruption has disrupted the equilibrium within lake  
69 Voui leading to a spectacular colour change from blue to red in 2006 (Bani et al. 2009b).

70

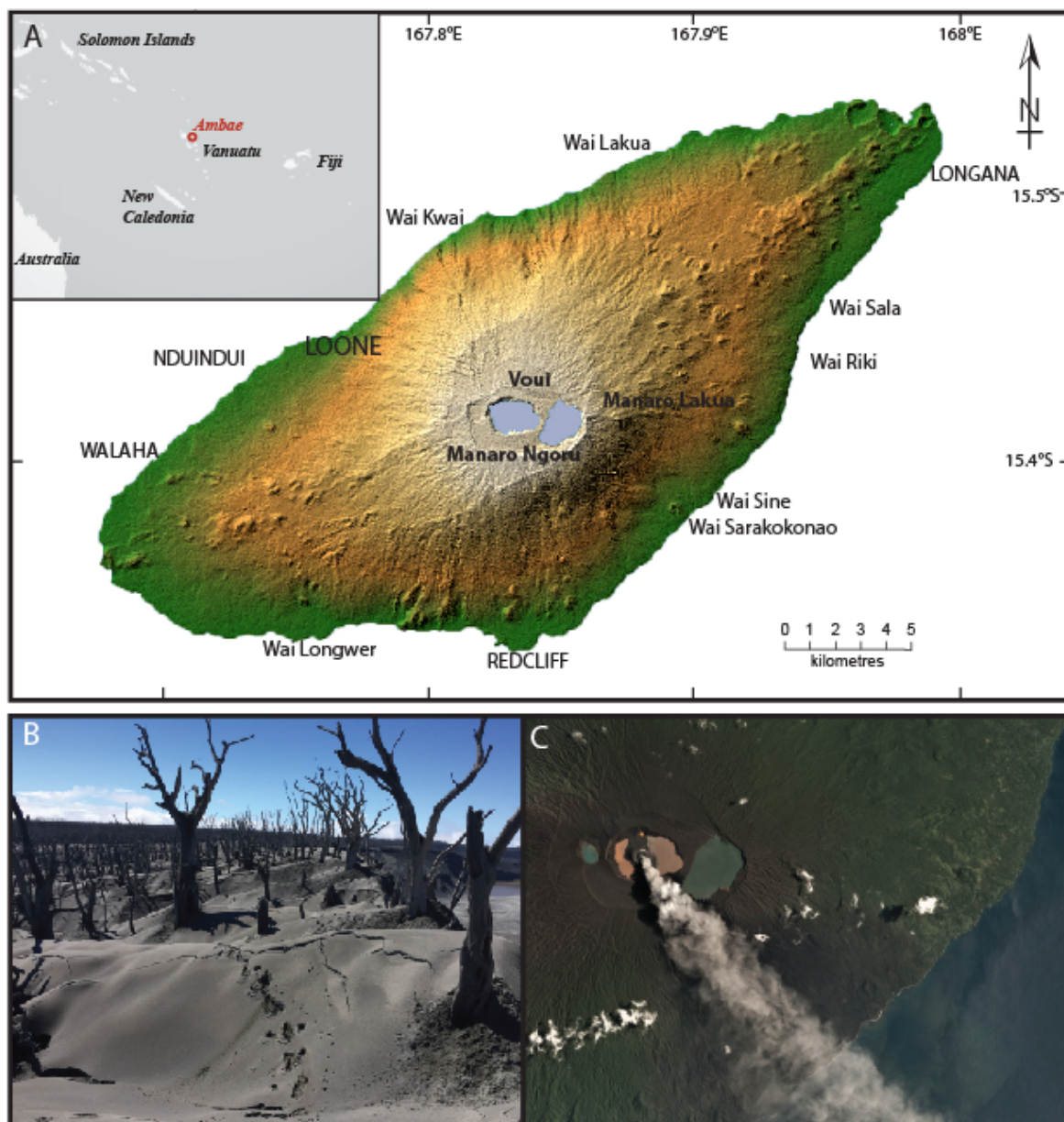
71 On 6 September 2017, a new eruptive period started with series of strong explosions (heard  
72 from neighbouring islands) that generated ash-laden plumes into the atmosphere. These first  
73 eruptions were likely phreatic, judging by the absence of juvenile material in the ejected  
74 products (Bani et al., in prep.), but injected large quantities (38,000 tons) of SO<sub>2</sub> into the  
75 atmosphere (OMI data, Bani et al., in prep.). On 22 September 2017, lava reached the surface

76 producing fire fountains, Strombolian eruptions and lava flows. In early October 2017 the  
77 surficial activity had subsided, the period from 22 September to 6 October 2017 is referred to  
78 here as phase 1 of activity. On 21 October 2017, a second phase of high-intensity eruptive  
79 activity started. Intense ash fall and acid rains were reported on coastal villages. 39,000 tons  
80 of SO<sub>2</sub> were injected on the first two days of activity alone (OMPS data, Bani et al., in prep.).  
81 By the end of November, the eruption intensity had subsided with ash and gas impacts  
82 limited only to the top of the island. The period from 21 October to 7 December 2017 is  
83 referred to here as phase 2 of activity. In mid-March 2018 a third intense eruptive phase  
84 started producing ash falls and acid rains with even more destructive impacts on the  
85 population and environment than during the prior phases. A night glow, presumably from fire  
86 fountains, could be seen from Maewo and Pantacost islands, 50 km away from the summit.  
87 Gas jetting was sustained for more than 20 days and clearly audible in a 15 km radius. The  
88 eruption intensity decreased around 15 April after significant release of volcanic gases to the  
89 atmosphere (123,000 tons released on April 6, 2018 alone; OMI data, Bani et al., in prep.).  
90 The period from mid-March to mid-April 2018 is referred to here as phase 3 of activity.  
91 Three months later, in mid-July 2018, the eruption intensity increased once again to its most  
92 violent and destructive eruptive period. Ash fall covered the entire island, momentarily  
93 plunging coastal villages in total darkness, causing houses to collapse. By early August 2018  
94 the eruption intensity had waned. The period of July 2018 is referred to here as phase 4 of  
95 activity. This July 2018 episode released an estimated 400,000 tons of sulfur dioxide into the  
96 upper troposphere and stratosphere at an altitude of 16.9 km (NASA Earth Observatory,  
97 2019). All together an estimated 3.2 Tg of SO<sub>2</sub> was released during the 2017-2018 Ambae  
98 eruption placing it among the top 6 largest eruption of the last 40 years in terms of SO<sub>2</sub>  
99 loading (Bani et al., in prep.). A detailed narrative of the eruption and its impacts in terms of  
100 ash fall, lahar and gas emissions will be presented elsewhere (Bani et al., in prep.).

101

102 In this contribution, we perform a petrological investigation of the magma expelled during  
103 the four phases of activity. We present major element, trace element, and volatile content in  
104 olivine and clinopyroxene hosted melt inclusions, embayments, matrix glasses and bulk rock  
105 together with clinopyroxene geobarometry, olivine, plagioclase, and clinopyroxene  
106 geothermometry and major element and volatile diffusion modelling. We find that the Ambae  
107 plumbing system extends from 0.5 to 14 km depth with most of the magma involved in the  
108 2017-2018 eruption sourced from a shallow reservoir at 0.5 to 3 km depth. Phreatic eruptions  
109 in early September 2017 likely served as trigger to or facilitated the subsequent magmatic  
110 activity but was itself likely triggered by magmatic gases. Olivine residence times in the  
111 magma chamber(s) range from a few days to a year prior to eruption. We constrain the ascent  
112 rate of the magma from the shallow reservoir to the surface at 4 to 75 m/s. This fast ascent  
113 rate suggests that large amounts of pre-eruptive volatiles must have been present in the  
114 reservoir, consistent with satellite observations of large SO<sub>2</sub> emissions and of eruptive clouds  
115 reaching the lower stratosphere.

116



117

118 **Figure 1:** *A. Topographic hill shaded Shuttle Radar Topography Mission (SRTM) image of*  
 119 *Ambae island (credit NASA). Location of all coastal settlements are marked together with the*  
 120 *location of Vouli lake. Upper left inset shows the location of Ambae/Aoba island within the*  
 121 *south Pacific. B. Ash deposit on the north-western part of Vouli crater (image take on 21 May*  
 122 *2018). C. Planetscope Ortho tile satellite image of the summit area taken 10 March 2018*  
 123 *showing the strong degassing at that time (image credit: ESA)*

124

## 125 **METHOD**

### 126 **Samples**

127 Tephra samples from phase one (September 2017), two (November 2017) and three (March  
128 2018) were collected in the summit area within a few days to weeks of deposition. Ash  
129 samples from phase four (July 2018) were collected 10 km west of the vent during  
130 deposition. Samples from phase 1, 2 and 3 consisted of lapilli-size scoria with fragments  
131 typically about 1 cm in diameter. Scoriae from eruptive phase 1, 2 and 3 and ash from  
132 eruptive phase 4 were embedded in epoxy resin and polished to investigate their texture and  
133 the composition of crystal phases and interstitial glasses. For eruptive phase 1, 2 and 3, part  
134 of the same samples was crushed and sieved, and melt-inclusion bearing, euhedral and  
135 unbroken olivine and pyroxene crystals were handpicked under a binocular microscope (in  
136 the 0.5- and 2-mm grain size fraction). Melt inclusions and embayments were exposed by  
137 polishing single crystals individually. Olivine crystals were oriented for polishing in order to  
138 expose a maximum length of the embayments, from the end to the mouth of the embayment.  
139 Polishing was performed without the use of diamond as to entirely avoid possible C  
140 contamination in subsequent ion probe analysis, instead silicon carbide mats for coarse  
141 polishing and corundum mats for final 3  $\mu\text{m}$ , 1  $\mu\text{m}$  and  $\frac{1}{4}$   $\mu\text{m}$  polishing were used. Single  
142 crystals were subsequently mounted in indium. Melt inclusions are entirely glassy, often  
143 contain a contraction bubble and are typically about 50 to 200  $\mu\text{m}$  in diameter (Fig. 2B).

144

### 145 **Analyses of major elements**

146 Bulk tephra samples were powdered, mixed with  $\text{LiBO}_2$ , and melted in an induction oven at  
147 1050  $^\circ\text{C}$  for 4.5 min using graphite crucibles. Resulting glass beads were then dissolved in a  
148 solution of deionized water and nitric acid and finally diluted by a factor of 2000. The

149 solutions were analysed by ICP-AES at Laboratoire Magmas et Volcans in Clermont-  
150 Ferrand.

151 Individual melt inclusions, embayments, matrix glasses and crystals were analysed with a  
152 Cameca SX100 electron microprobe at the Laboratoire Magmas et Volcans in Clermont-  
153 Ferrand. For crystalline phases, beam conditions of 15 kV and 15 nA were employed,  
154 while for glass analyses, the beam current was 6-8 nA and the beam defocussed to 10  $\mu\text{m}$ .  
155 Sodium was analysed first as to limit the effects of Na loss. The instrument was calibrated on  
156 natural and synthetic mineral standards and glasses : wollastonite (Si, Ca),  $\text{MnTiO}_3$  (Ti, Mn),  
157  $\text{Al}_2\text{O}_3$  (Al in minerals), standard glass VG2 (Al in glasses, see Óladóttir et al. 2008),  $\text{Cr}_2\text{O}_3$   
158 (Cr), fayalite (Fe), forsterite (Mg), NiO (Ni), albite (Na), orthoclase (K) and apatite (P).  
159 Counting times were 10s minimum. Olivine core to rim transects were acquired by making  
160 measurements every 10  $\mu\text{m}$  from the crystal centre to the rim along a line perpendicular to  
161 the crystal face. In order to produce accurate analyses for minor elements, acceleration  
162 voltage was increased to 20 kV, beam current to 100 nA, and counting times to 20 s (Fe), 50 s  
163 (Mn, Ni), and 100 s (Al, P).

164

#### 165 **Ion Probe analyses of volatile elements**

166 Volatile ( $\text{H}_2\text{O}$ ,  $\text{CO}_2$ , Cl, F, S) content in melt inclusions, embayments, and matrix glasses  
167 were determined using a Cameca IMS 1280 ion microprobe at CRPG-CNRS-Nancy.  
168 Analytical conditions were similar to other volatile studies (e.g., Hauri et al. 2002; Bouvier et  
169 al. 2008; Shimizu et al. 2009; Rose-Koga et al. 2014; Moussallam et al. 2015). We used a  $\text{Cs}^+$   
170 primary beam with a current of 1 nA and an electron gun to compensate for charge build-up  
171 at the sample surface. A 3-minute pre-sputter with a  $30 \times 30 \mu\text{m}$  square raster was applied,  
172 then analyses were performed on the 15 to 20  $\mu\text{m}$  spot in the center of the rastered-clean area  
173 by a mechanical aperture placed at the secondary ion image plane. The mass resolving  $\approx 7000$

174 (with the contrast aperture at 400  $\mu\text{m}$ , the energy aperture at 40 eV, the entrance slit at 52  $\mu\text{m}$   
175 and the exit slit at 173  $\mu\text{m}$ ) meant that complete discrimination of mass interferences was  
176 achieved ( $^{34}\text{S}^1\text{H}$  on  $^{35}\text{Cl}$ ,  $^{17}\text{O}$  on  $^{16}\text{O}^1\text{H}$ ,  $^{29}\text{Si}^1\text{H}$  on  $^{30}\text{Si}$  and  $^{31}\text{P}^1\text{H}$  on  $^{32}\text{S}$ ). We collected signals  
177 for  $^{12}\text{C}$  (8 seconds),  $^{17}\text{O}$  (3 seconds),  $^{16}\text{O}^1\text{H}$  (6 seconds),  $^{18}\text{O}$  (3 seconds),  $^{19}\text{F}$  (4 seconds),  $^{27}\text{Al}$   
178 (3 seconds),  $^{30}\text{Si}$  (3 seconds),  $^{32}\text{S}$  (4 seconds) and  $^{35}\text{Cl}$  (6 seconds; counting times in  
179 parenthesis), with 2 seconds waiting time after each switch of the magnet. This cycle was  
180 repeated 10 times during one analysis. One measurement lasted 12 min per spot.

181 The concentrations were determined using calibration curves (see supplementary materials)  
182 obtained, at the beginning and at the end of each session, by measuring a set of natural  
183 basaltic glasses during the same session and under the same analytical conditions (KL2G,  
184 Jochum et al. 2006); KE12, Mosbah et al. 1991; VG2, Jarosewich et al. 1980; experimental  
185 glasses N72, M35, M40 and M48, Shishkina et al. 2010 and MacQuarie glasses 47963 and  
186 25603, Kamenetsky et al. 2000) with a large range of concentrations of volatile elements  
187 overlapping those of our samples. Maximum errors, based on reproducibility over 10 cycles  
188 of analyses, were less than 15% for  $\text{CO}_2$ , 3% for Cl, 4% for S, and 5% for F and  $\text{H}_2\text{O}$ .

189

#### 190 **LA-ICP-MS analyses of trace elements**

191 Trace element measurements on melt inclusions, embayments and glasses were carried out  
192 using a laser ablation system (193 nm Excimer Resonetics M-50E) associated with an  
193 inductively coupled plasma mass spectrometer (Agilent 7500 cs LA-ICPMS at the  
194 Laboratoire Magmas et Volcans, Clermont-Ferrand). Analysis were performed following  
195 classical procedures outlined in previous studies (e.g., Le Voyer et al. 2010; Rose-Koga et al.  
196 2012). We used a pulse energy of about 3 mJ, a spot diameter between 15 and 33  $\mu\text{m}$  and a  
197 laser pulse frequency of 2-3Hz, depending in the inclusion size to keep a fluence at sample  
198 surface of about 4  $\text{J}/\text{cm}^2$ . The background was measured for 30 to 40 seconds before ablation

199 and analysis time was approximately 100s. Data reduction was performed using the  
 200 GLITTER software ([www.es.mq.edu.au/GEMOC](http://www.es.mq.edu.au/GEMOC)). This technique uses CaO (measured by  
 201 EMP) as an internal standard. Reproducibility and accuracy of the analysis were constrained  
 202 by systematic analysis of 2 standards BCR2-G and 612 at the beginning, in the middle and at  
 203 the end of the session. Typical errors on the samples ( $1\sigma$  error of mean) is less than 10 % for  
 204 all trace elements, except for Lu (<20%) and B (<40%).

205

### 206 **Volatile diffusion modelling**

207 Concentration profiles recorded in the embayments were fitted by a diffusion model similar  
 208 to that of Ferguson et al. (2016). While the detail of the model and test results are explained  
 209 in the [Supplementary](#), a brief description is given here. An embayment profile was measured  
 210 in a tube-like pocket of melt found within an olivine crystal. Because of its shape and  
 211 incompatibility of volatile elements, such as H, C, S, Cl, and F, in olivine, diffusive exchange  
 212 of elements was considered only possible at the mouth of the embayment. This justifies the  
 213 use of diffusion solution in 1-D geometry. Naturally, the concentrations of volatile elements  
 214 are systematically lower at the mouth of embayment. Having these geometrical constraints,  
 215 we have developed a model with the following initial and boundary conditions for Fick's  
 216 Second Law:

$$217 \quad \frac{dC}{dt} = D(C_W) \frac{\partial^2 C}{\partial x^2}, \quad (1)$$

$$218 \quad C = c_{initial}, x > 0, t = 0; \quad C = c_{initial}, x = \infty, t > 0,$$

$$219 \quad C = f(t), x = 0,$$

220 where  $D(C_W)$  is the diffusion coefficient of water in melt as a function of total dissolved  
 221 water concentration;  $C$ , the concentration of diffusing species;  $t$ , time; and  $x$ , distance.  
 222 Concentrations of volatile elements were set at a constant value  $c_{initial}$ , in the embayment,  
 223 determined by the plateau concentration value inside the embayment. Concentration at the

224 interface was set by a function with respect to time, which determines H<sub>2</sub>O-CO<sub>2</sub> solubility in  
225 magma along the linear isothermal decompression. In a magma ascending for eruption, and  
226 for fast diffusing species such as H<sub>2</sub>O, a closed system degassing approximates the volatile  
227 element segregation better than an open system, as the latter requires complete segregation of  
228 magma from gas at every instant of degassing. We used SolEx (Witham et al. 2012) to  
229 determine the closed system, equilibrium degassing path for H<sub>2</sub>O, CO<sub>2</sub>, S, and Cl, and the  $f(t)$   
230 was determined from the SolEx result with a constant decompression rate ( $dP/dt$ ). The  
231 diffusion equation was solved by Crank-Nicolson finite difference method for the 1-D  
232 geometry.

233

234 This diffusion calculation had therefore four parameters: (1) diffusion coefficient, (2) initial  
235 concentration, (3) concentration of a volatile element at  $x=0$  which changes with time (*i.e.*  
236 decompression), (4) the mass of equilibrium bubble/fluid present at the moment of the  
237 magma ascent, and (5) the decompression rate. The first three parameters were independently  
238 determined with reasonable confidence from the experimental data, concentration profile, and  
239 magma temperature. The parameter (4) was unknowable, and it influenced the degassing path  
240 significantly (see the **Supplementary**). Here, we have tested its influence by varying from 0 to  
241 1 wt % of pre-ascent volatile mass. By setting four parameters, the decompression rate was  
242 determined by minimizing the least-square residuals. While the method of Ferguson et al.  
243 (2016) minimizes  $X$  simultaneously for three volatile species (H<sub>2</sub>O, CO<sub>2</sub>, and S), it was not  
244 possible in our case. Diffusion profile of each volatile species were hence solved separately.  
245 R-based script, together with an example profile is given in **Appendix B**.

246

247 **Olivine diffusion modelling**

248 Chemical gradients (Fe–Mg) in olivines were modelled in one dimension with the DIPRA  
249 software program (Girona and Costa 2013). DIPRA is a finite difference code that solves  
250 Fick's second law of diffusion in order to model the one-dimensional diffusion of Fe – Mg (as  
251 forsterite,  $Fo = Mg/(Mg + Fe)$ , in mole fraction), Mn, Ni, and Ca in olivine. Diffusion  
252 anisotropy was accounted for by determining the olivine crystallographic axes using EBSD  
253 and the angles between the electron microprobe traverse and the three crystallographic axes.  
254 Temperature and pressure calculations are detailed below, oxygen fugacity was fixed at the  
255 Nickel-Nickel-Oxide buffer in all calculations. Initial conditions for sample Ph1O12E\_P1 and  
256 Ph1O12E\_P2 used a step function while all other calculations were performed using a  
257 homogeneous profile (see Fig. S6). The use of a step function for Ph1O12E\_P1 and  
258 Ph1O12E\_P2 was justified by the high and non-random residual that would result from using  
259 a homogeneous profile. Note that the effect of water on the Fe-Mg interdiffusion (e.g., Wang  
260 et al. 2004; Hier  $\square$  Majumder et al. 2005) is not taken into consideration in the DIPRA  
261 calculations.

262

### 263 **Post-entrapment crystallisation modelling**

264 Corrections of major and trace element composition in olivine-hosted melt inclusions for post  
265 entrapment crystallisations (PEC) was performed. It consisted of dissolving increments of  
266 equilibrium olivine into the melt inclusion liquid until the Fe-Mg  $K_d$  reaches the equilibrium  
267 value. The equilibrium value for the Mg/Fe exchange coefficient between olivine and liquid,  
268  $K_d$ , was determined by a model accounting for the influence  $H_2O$  and alkalis (Toplis 2005  
269 with  $T = 1145$  °C and  $P = 1000$  bars), and the predicted  $K_d = 0.25 \pm 0.01$ . It should be noted  
270 that this value of  $K_d$  lower than the common value of 0.3 reflects that the Ambae melts were  
271 rich in  $Na_2O$  and  $K_2O$ . To test the effect of oxygen fugacity,  $Fe^{3+}/Fe_{tot}$  ratio was varied from  
272 0.14 to 0.32 for the PEC calculation, reflecting the range observed for subduction zone

273 magmas, from FMQ-1 to FMQ+2; (e.g., Kress and Carmichael 1991; Bénard et al. 2018).  
 274 With  $Fe^{3+}/Fe_{tot} = 0.14$ , we added successive increment of olivine back into the melt  
 275 recalculating an observed Kd after each step and the process stopped when observed Kd =  
 276 predicted Kd ( $0.25 \pm 0.01$  here). By doing this, the mean mass of olivine added was only of  
 277 1% (with a standard deviation of 0.2%,  $n=57$ ) suggesting that very little PEC took place. At  
 278 higher  $Fe^{3+}/Fe_{tot} = 0.32$  (FMQ+2) or  $Fe^{3+}/Fe_{tot} = 0.23$  (FMQ+1), the redox-corrected observed  
 279 Kd is already too high compared to the “Toplis-predicted” Kd so that no olivine can be added  
 280 to the melt. In the following, the corrected value reported are calculated for  $Fe^{3+}/Fe_{tot} = 0.14$ .

281

### 282 **Estimation of microlite number density**

283 Toramaru et al. (2008) developed a model to link microlite number density (N) in pyroclastic  
 284 rocks to the rate of water exsolution which in turn can be linked to the rate of magma ascent.  
 285 Microlite crystallization can happen as a consequence of cooling or decompression-induced  
 286 degassing. In the case of decompression-induced degassing, a numerical simulation  
 287 performed by Toramaru (2008) shows that the microlite number density is directly linked to  
 288 the increase in liquidus temperature caused by degassing:

$$289 \quad \frac{\partial T_L}{\partial t} = \left(\frac{N}{a}\right)^{2/3} \quad (2)$$

290 With the constant  $a$  mostly a function of melt chemistry and water concentration:

$$291 \quad a = 3 \cdot 10^{15+0.345(C_{SiO_2}-50)-0.65C_{H_2O}} \quad (3)$$

292 where major element concentrations are in weight %.

293 The relationship between the increase in liquidus temperature  $T_L$  and the degassing rate is  
 294 given by the derivative of the liquidus depression curve:

$$295 \quad \frac{\partial T_L}{\partial t} = \frac{\partial T_L}{\partial C_{H_2O}} \cdot \frac{\partial C_{H_2O}}{\partial t} \quad (4)$$

296 The liquidus depression curve has been determined experimentally for olivine ( $\frac{\partial T_L}{\partial C_{H_2O}} =$   
 297  $40.4 - 5.94C_{H_2O} + 0.2283C_{H_2O}^2$ ; Médard and Grove 2008), and plagioclase ( $\frac{\partial T_L}{\partial C_{H_2O}} =$   
 298  $54.66e^{-0.29C_{H_2O}}$ ; Almeev et al. 2012) in basaltic melts. In the absence of an experimental  
 299 calibration for clinopyroxene, we calculated ( $\frac{\partial T_L}{\partial C_{H_2O}} \sim 26$ ) for the bulk scoria of phase 1 using  
 300 the pMelts software (Ghiorso et al. 2002).

301 The degassing can in turn be converted into a decompression rate using the derivative of the  
 302 water solubility curve:

$$303 \quad \frac{\partial P_{H_2O}}{\partial t} = \frac{\partial P_{H_2O}}{\partial C_{H_2O}} \cdot \frac{\partial C_{H_2O}}{\partial t} \quad (5)$$

304 For our trachybasaltic bulk composition, we fit a quadratic function to the solubility data  
 305 produced by the model of Moore et al. (1998) which gives  $\frac{\partial P_{H_2O}}{\partial C_{H_2O}} = 182.3C_{H_2O}$

306 In a steady state, the decompression rate at the microlite nucleation depth is linked to the  
 307 ascent velocity (Toramaru et al. 2008):

$$308 \quad V_N = \frac{1}{\rho g} \cdot \frac{\partial P_{H_2O}}{\partial t} \quad (6)$$

309 where  $\rho$  is the magma density at the microlite nucleation depth.

310

## 311 RESULTS

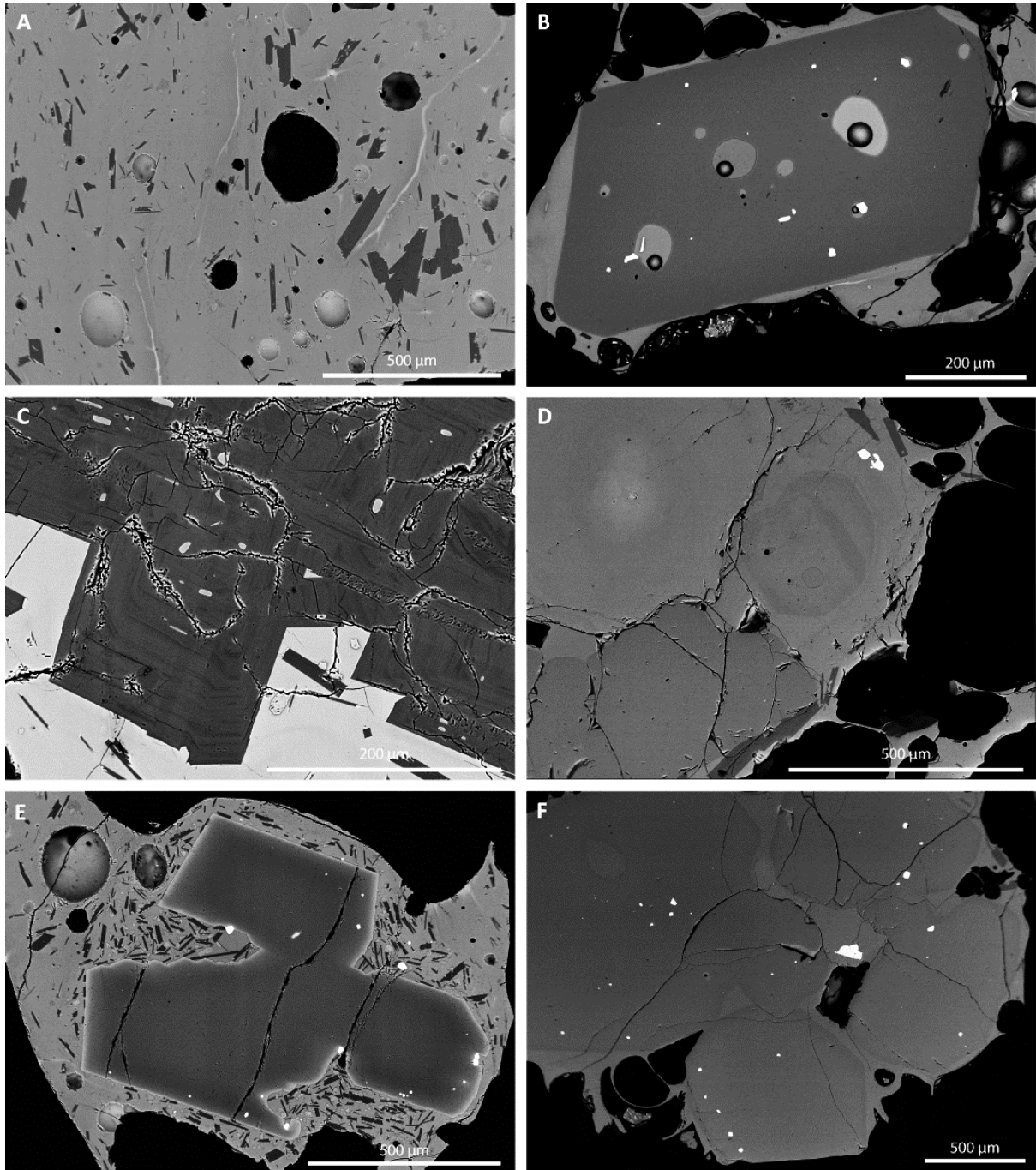
### 312 Mineralogy

313 The investigated scoriae are glassy, and typically have low crystallinity (Fig. 2A), with rare  
 314 phenocrysts of plagioclase, olivine, and clinopyroxene, and microlites of the same phases.  
 315 Small euhedral spinel microlites are also present, often associated with olivine phenocrysts  
 316 (Fig. 2B). Most olivine phenocrysts have compositions ranging from Fo<sub>85</sub> to Fo<sub>79</sub>, as expected  
 317 for equilibrium with the bulk rock compositions (Table S1, S2, S3, S4, Fig. 3 and 4). Four  
 318 types of zoning patterns can be identified in olivine phenocrysts (Fig. 3, 4B): (1) no zoning

319 (homogeneous crystals, Fig 3D, 4B); (2) normal zoning (Fig 3A, 3B, , 3C, 3F, 3G 4B); (3)  
320 reverse zoning (Fig 2B, 2F, 3H, 3I); and (4) complex zoning (Fig 2E). Homogeneous crystals  
321 are dominant in phase 1, and a few are still present in phase 2. Crystals with weak normal  
322 zoning (less than 1.5 Fo unit) are only present in phase 1 and again in phase 4. Reverse  
323 zoning is typical for most crystals from phase 2 and 3. Crystals with the stronger reverse  
324 zoning also show rounded edges indicative of dissolution. Reverse zoning can be interpreted  
325 as reflecting either magma mixing (Ruth et al. 2018) or reheating of a magma reservoir.  
326 Complex zoned phenocrysts have a weak internal reverse zoning very similar to the one  
327 observed in the previous type, followed by a strong normal zoning. These complex zoned  
328 phenocrysts are associated with a high microlite density, and present mostly in phase 1,  
329 although one crystal has been found in phase 2 and one in phase 3. These complex zoned  
330 phenocrysts are very similar to the olivine phenocrysts described from the April 2007  
331 eruption of Piton de la Fournaise (Reunion Island) where they have been interpreted as  
332 products of lateral magma transfer in the plumbing system (Albert et al. 2019). As for the  
333 Reunion samples, normal zoning patterns around melt inclusions are identical to normal  
334 zoning patterns near the crystal rims, indicating that the zoning is not due to magma mixing  
335 (Albert et al. 2019).

336 A significant fraction of the olivine phenocrysts (Fig. 4A) have core compositions more  
337 magnesian than Fo<sub>84</sub> and are thus not in equilibrium with any of the measured bulk rock  
338 compositions (Fig. 4). We interpret those crystals as antecrysts, formed from a batch of more  
339 primitive magma. A few small olivine microlites have compositions ranging from Fo<sub>82</sub> to  
340 Fo<sub>74</sub> (Table S3). Clinopyroxene phenocrysts are normally zoned, with Mg# ranging from 85  
341 to 78 (Table S5, calculated assuming all Fe as FeO). Oscillatory zoning is occasionally  
342 observed (Fig. 2D). Clinopyroxene microlites are small and difficult to analyse but have Mg#  
343 in the range 80-72. Plagioclase phenocrysts are euhedral, normally zoned and commonly

344 show oscillatory zoning (Fig.2C). Their composition varies from An<sub>81</sub> in the core to An<sub>70</sub>  
345 near the rims (Table S6). Euhedral plagioclase microlites have compositions varying from  
346 An<sub>80</sub> to An<sub>58</sub>. Spinel compositions are highly variable: spinel included in olivine phenocrysts  
347 are chromites (41 wt% Cr<sub>2</sub>O<sub>3</sub>), whereas the rare spinel microlites tend to be richer in iron (58  
348 wt% FeO+Fe<sub>2</sub>O<sub>3</sub> on average, up to 76 wt%).



349

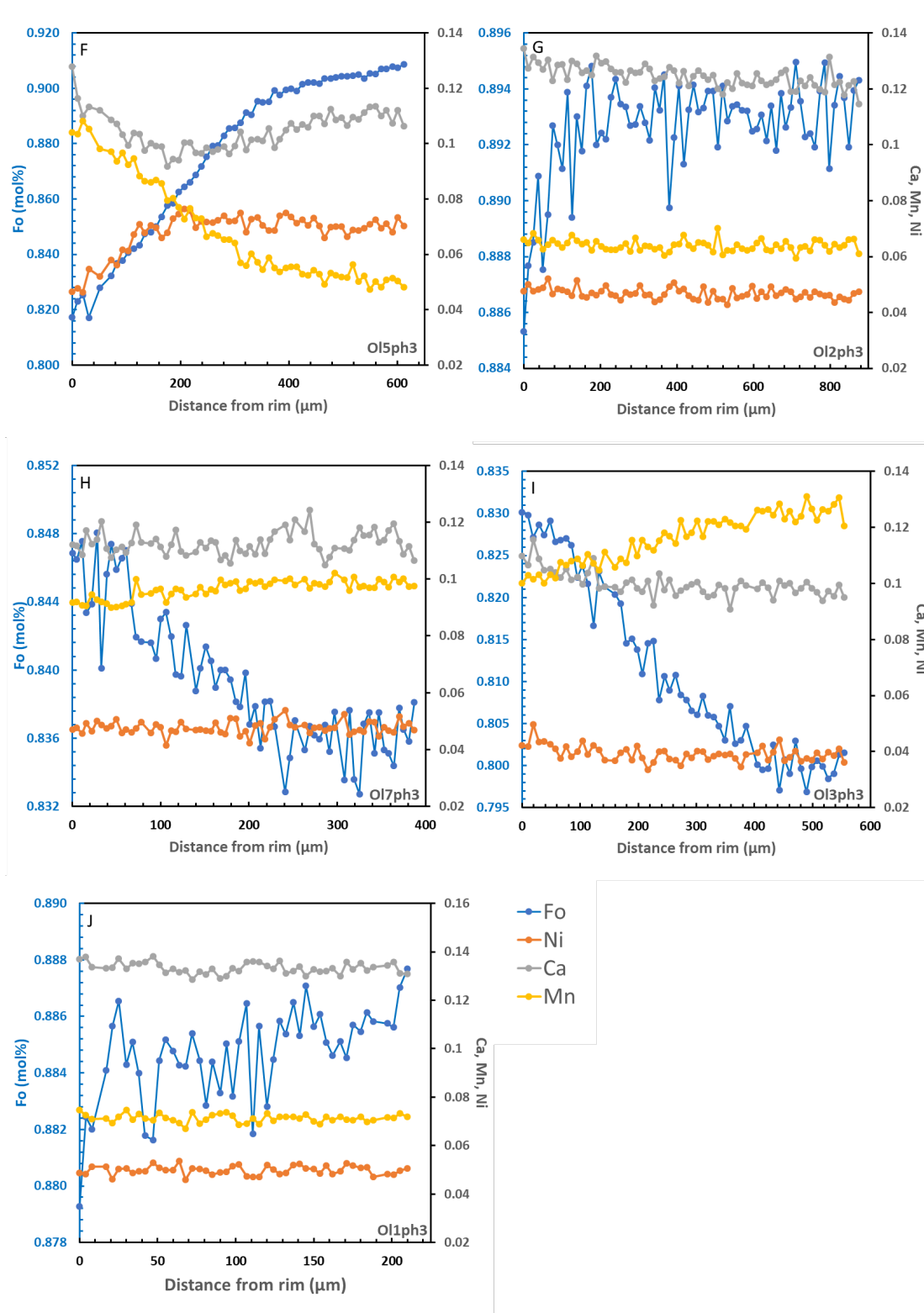
350 **Figure 2:** *A. BSE microphotograph of the typical glassy texture of the pyroclasts (phase 1),*  
351 *with plagioclase (micro-)phenocrysts and microlites and a few olivine and clinopyroxene*  
352 *microlites. B. BSE microphotograph of a normally zoned olivine phenocryst with large glassy*  
353 *melt inclusions associated with spinel crystals and retraction bubbles (phase 2). C. Enhanced*  
354 *BSE microphotograph of oscillatory zoning in a plagioclase phenocryst that contain small*  
355 *melt-inclusions (phase 1). D. BSE microphotograph of clinopyroxene phenocrysts with*  
356 *complex oscillatory zoning and melt inclusions (phase 2). E. BSE microphotograph of an*  
357 *olivine phenocryst showing complex zoning: slight inverse zoning around the core, followed*  
358 *by clean normal zoning on the edges (phase 1). The phenocryst also contains spinel*  
359 *inclusions and is surrounded by an increased microlite density. F. Enhanced BSE*  
360 *microphotograph of a group of olivine phenocrysts with a slight reverse zoning around the*  
361 *edges (phase 2). The phenocrysts contain spinel and melt inclusions.*

362



363

364 **Figure 3:** Rim to core electron microprobe %Fo (mol%) ( $= 100 \times \text{Mg} / [\text{Fe} + \text{Mg}]$ ), Ca, Mn,  
 365 and Ni traverses in olivine crystals from phase 1 (A to E) and phase 3 (F to J). AO10, AO11,  
 366 AO22 and AO18 show predominantly normal zoning with AO10 showing an alternation from  
 367 normal to reverse zoning close to the rim. AO12 shows no resolvable zoning pattern. Ol5ph3,  
 368 Ol2ph3 and Ol1ph3 show normal zoning while Ol7ph3 and Ol3ph3 shows reverse zoning.

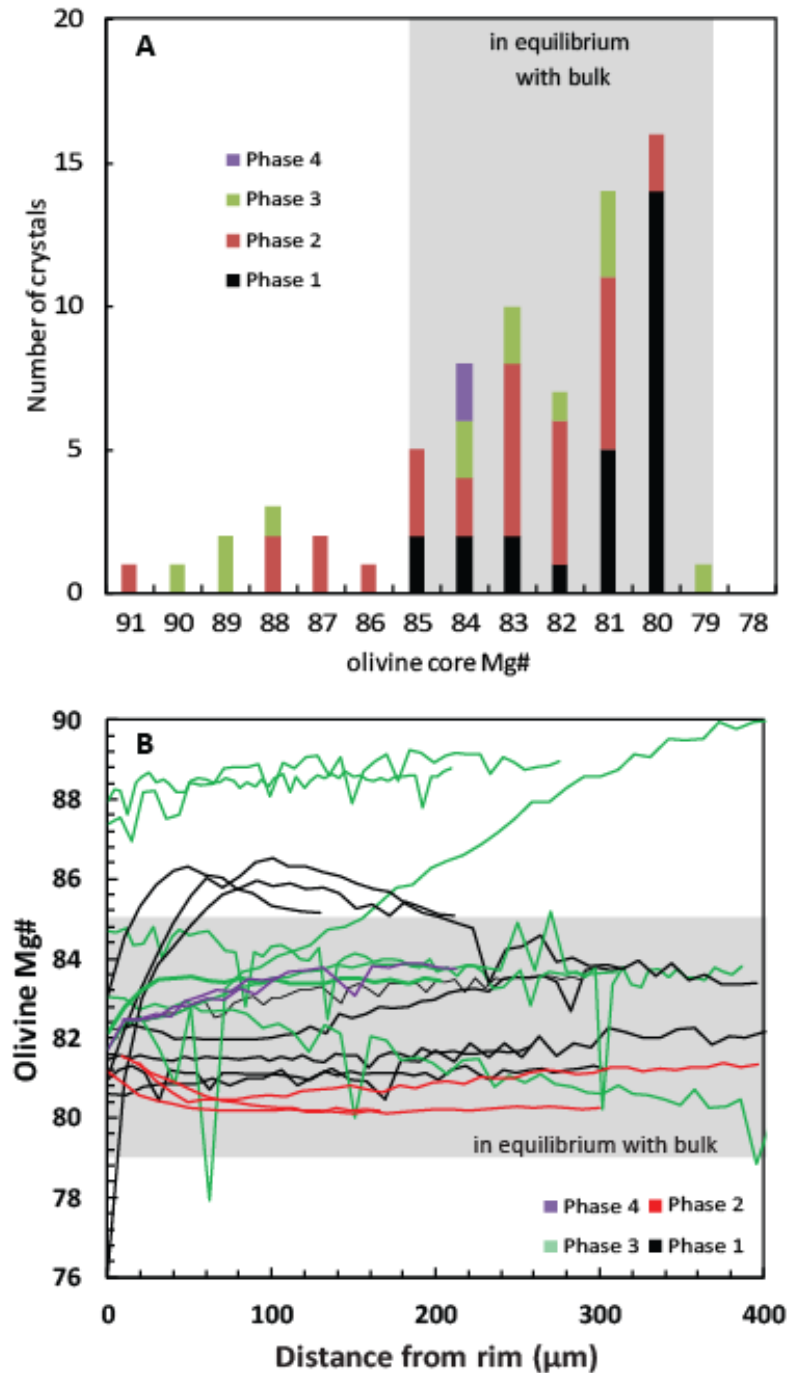


369

370

**Figure 3con:** Rim to core electron microprobe %Fo (mol%) ( $= 100 \times \text{Mg} / [\text{Fe} + \text{Mg}]$ ), Ca, Mn, and Ni traverses in olivine crystals from phase 1 (A to E) and phase 3 (F to J). AO10, AO11, AO22 and AO18 show predominantly normal zoning with AO10 showing an alternation from normal to reverse zoning close to the rim. AO12 shows no resolvable zoning pattern. Ol5ph3, Ol2ph3 and Ol1ph3 show normal zoning while Ol7ph3 and Ol3ph3 shows reverse zoning.

375



376

377 **Figure 4:** A. Frequency diagram of the Fo content in olivine cores from phase one, two and  
 378 three. The range of Fo composition in equilibrium with bulk is calculated using measured  
 379 bulk rock compositions and a  $K_d$  of 0.3. Note that a significant fraction of phase 2 and 3  
 380 olivines have core composition more magnesian-rich than expected for equilibrium with the  
 381 bulk. B. Fo profiles of olivine phenocrysts from phases 1,2,3 and 4.

382

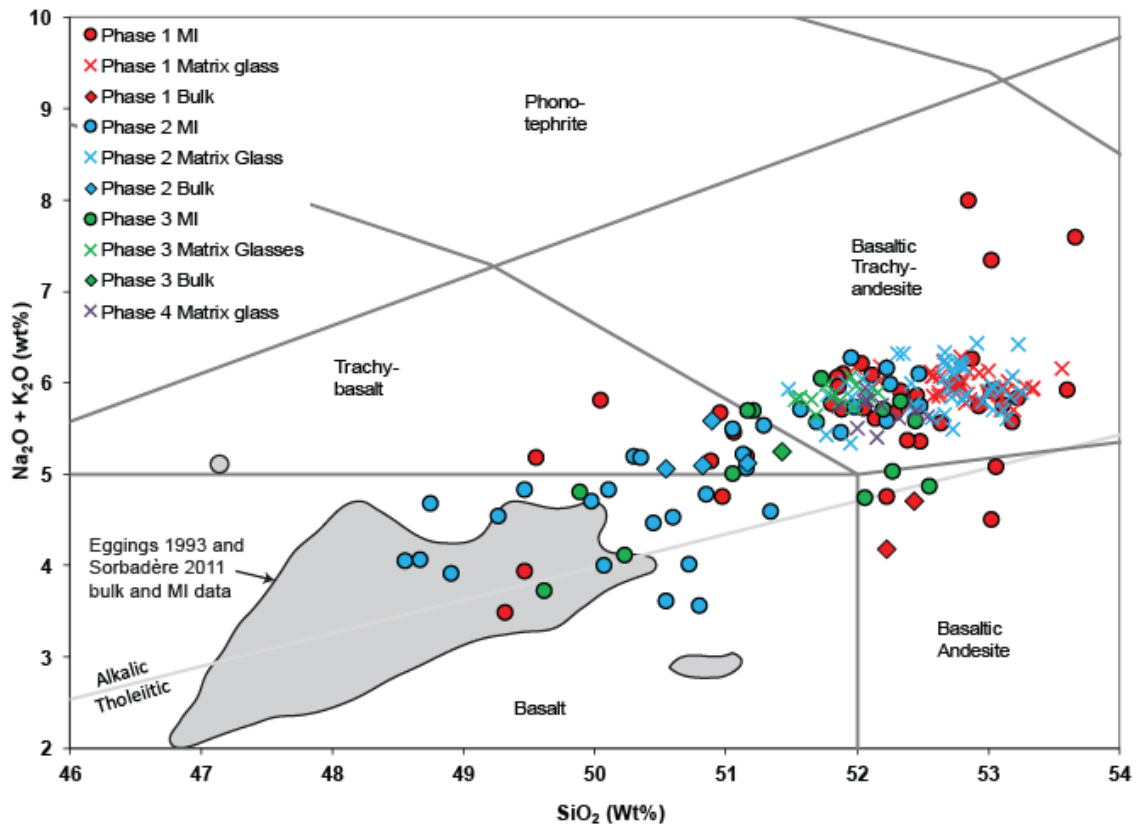
383 **Major elements**

384 The PEC corrected composition of melt inclusions, embayments and matrix glasses in major  
385 and trace element is given in **Tables S1 and S7**. Uncorrected compositions are given in **Tables**  
386 **S2 and S8**.

387

388 Samples for the 2017-2018 eruption are the most differentiated volcanic rocks on the island,  
389 with the exception of one trachyandesite analysis reported by Eggins (1993). The bulk rock  
390 compositions (**Table S1**) plot in the trachybasalt and basaltic trachyandesite fields of the TAS  
391 diagram (**Fig. 5**), as an extension of previously published analyses for Ambae island (Warden  
392 1970; Gorton 1977; Eggins 1993). Previously reported whole rocks (and melt inclusion)  
393 compositions from older (undated) deposits on Ambae are more primitive, mostly tholeiitic  
394 and alkali basalts. The younger rocks of Ambae belong to the low-Ti suite of Eggins (1993).  
395 This suite starts with voluminous magnesian olivine- and clinopyroxene-phyric basalts  
396 (“ankaramites”) that form the largest part of the island. More differentiated plagioclase-  
397 phyric basalts are confined to stream courses and represent the youngest eruptive products of  
398 the volcano, including lava flows from the latest significant eruption of the volcano that  
399 produced the N’dui N’dui flow about 350 years ago (Warden 1970). Products of the 2017-  
400 2018 eruptive phase are slightly more differentiated than these plagioclase-phyric basalts, and  
401 likely represent further evolution along a fractional crystallization trend (**Fig. 5**). In total  
402 alkali-silica space, most inclusions plot as alkali basalt, trachy-basalt or basaltic trachy-  
403 andesite while matrix glasses are basaltic trachy-andesite in composition. In details, melt  
404 inclusions, matrix glasses and bulk rock compositions from phase 1 tend to be slightly more  
405 evolved than the ones of phase 2, 3 and 4.

406



407

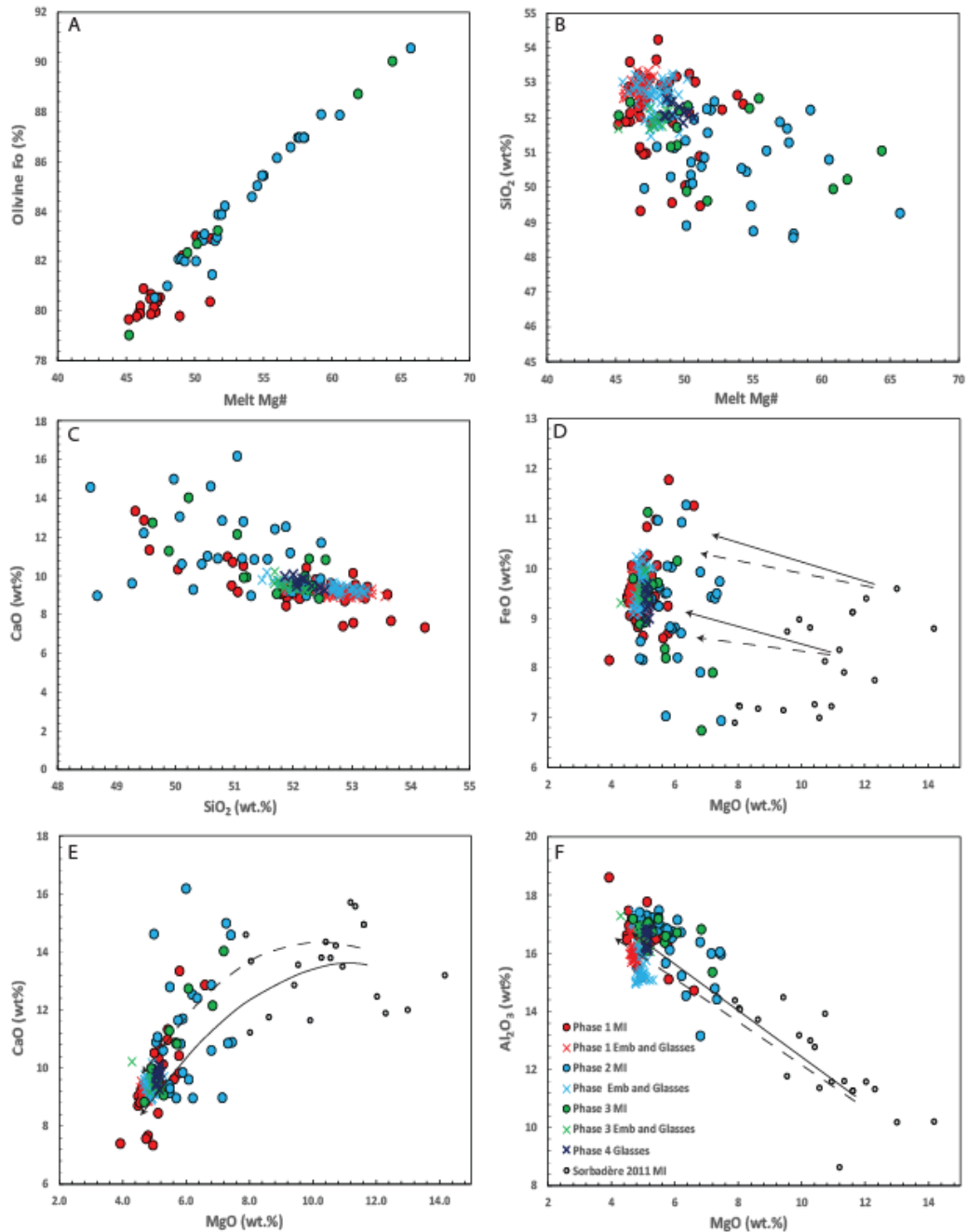
408 **Figure 5:** Total alkalis versus silica. Melt inclusions, matrix glasses and bulk rock  
 409 compositions (all normalized) are reported for the first three phases of eruptive activity  
 410 between 2017 and 2018 and matrix glass compositions are reported for phase 4. Bulk rock  
 411 and melt inclusion composition data from older (undated) deposits are from Eggings (1993)  
 412 and Sorbadere et al. (2011).

413

414 Melt inclusions have Mg# ranging from 31.7 to 59.6 (assuming all iron is FeO). Host olivine  
 415 crystals have compositions ranging from Fo<sub>79</sub> to Fo<sub>91</sub>. As expected for near equilibrium melt  
 416 inclusion-host pairs, there is a clear correlation between the olivine and melt inclusions  
 417 compositions (Fig. 6A). Interestingly, olivine erupted during the first phase of activity  
 418 (September 2017) tend to have lower Forsterite content (Fo < 84%) and to contain inclusions  
 419 with low Mg# (Mg# < 50) while olivine erupted during the subsequent two phases of activity  
 420 (November 2017 and March 2018) have a larger range of Forsterite content (Fo up to 91%)  
 421 and contain inclusions with a larger range of Mg# (Mg# up to 60). In addition, melt  
 422 inclusions from the first phase tend to be richer in Si, Al, Fe, Mn and K, and poorer in Ca and  
 423 Mg compared to melt inclusions from the second and third phases (Fig. 6). This is also seen

424 with the interstitial glasses which show a small increase in MgO, Mg# and CaO/Al<sub>2</sub>O<sub>3</sub>, and a  
 425 small decrease in Na<sub>2</sub>O and K<sub>2</sub>O between phases 1, 2, 3 and 4.

426



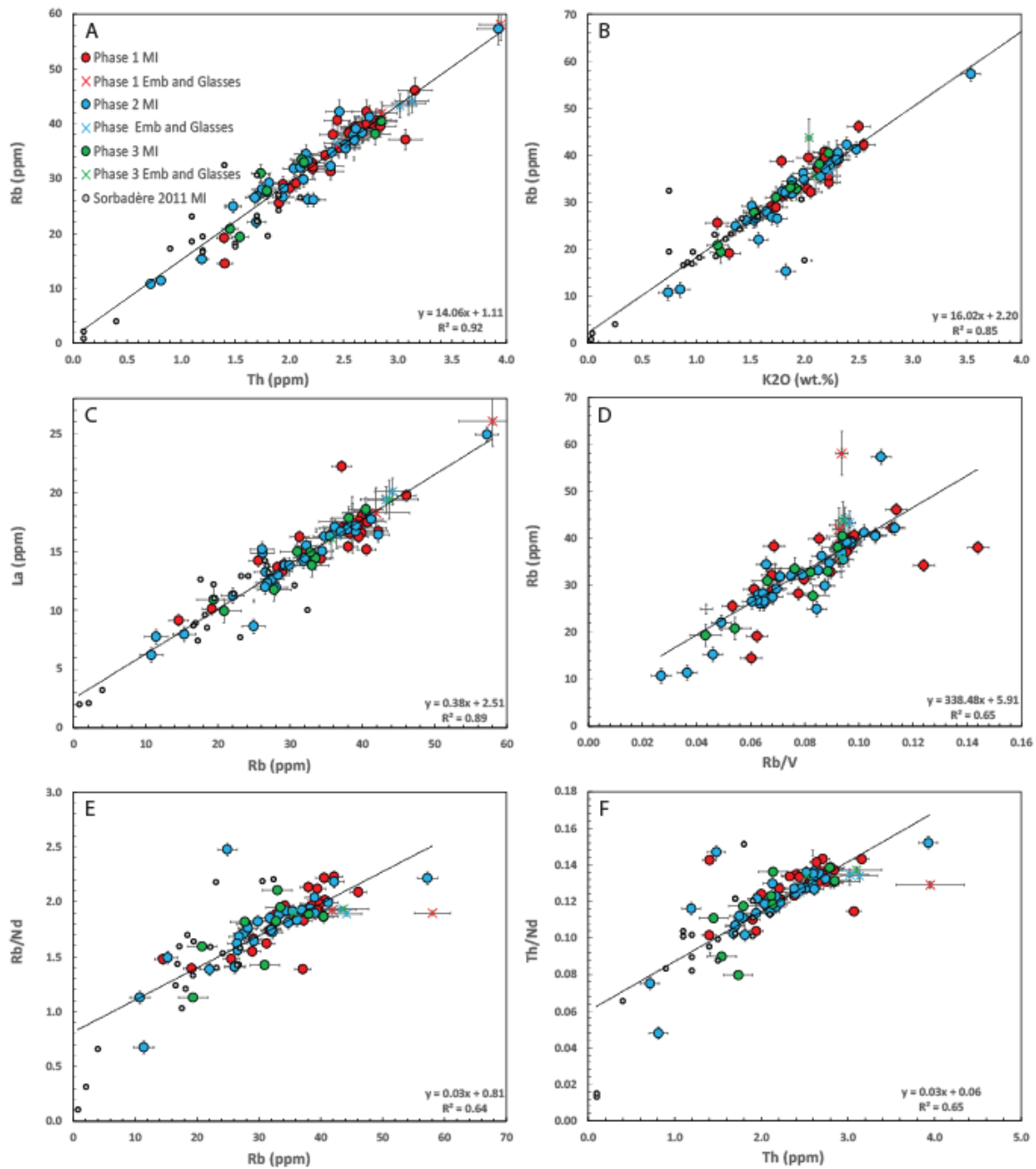
427

428 **Figure 6:** Major element compositions of olivine and pyroxene-hosted melt inclusions  
 429 (olivine-hosted inclusions are PEC-corrected). **A.** Olivine Forsterite content vs melt inclusion  
 430 Mg#. **B.** SiO<sub>2</sub> vs melt Mg#. **C.** CaO vs SiO<sub>2</sub>. **D.** FeO<sub>t</sub> vs MgO. **E.** CaO vs MgO. **F.** Al<sub>2</sub>O<sub>3</sub> vs  
 431 MgO. More primitive melt inclusions data from Ambae are also shown, together with  
 432 MELTS-calculated liquid lines of descent at 200 MPa (dotted arrow) and 500 MPa (solid  
 433 arrow) (Sorbadere et al. 2011).  
 434

435 **Trace elements**

436 Trace and rare earth elements concentrations in melt inclusions and matrix glasses show no  
437 systematic differences between the first three eruptive phases (Fig. S4 and 7). The rare earth  
438 element distribution, normalised to chondrite (Sun and McDonough 1989), is typical of arc  
439 magmas, being depleted in heavy rare earth elements. The positive correlations, passing close  
440 to the origin, between incompatible element pairs (Fig. 7A and 7B) show that melt inclusion  
441 compositions of the three eruption phases plot on a single trend of magma differentiation,  
442 suggesting they belong to a co-genetic magmatic series.

443



444

445 **Figure 7:** Trace element variation diagrams from melt inclusions and matrix glasses from the  
 446 2017-2018 eruption (this study; note that olivine-hosted MI are PEC-corrected) and from  
 447 older deposits (Sorbadere et al. 2011). **A.** Plot of Rb versus Th. **B.** Plot of Rb versus K<sub>2</sub>O. **C.**  
 448 Plot of La versus Rb. **D.** Plot of Rb versus Rb/V. **E.** Plot of Rb/Nd versus Rb. **F.** Plot of Th/Nd  
 449 versus Th. Linear regression lines through all data are presented on each plot. The data from  
 450 **A** and **B** define linear trends that passes through the origin as expected for fractional  
 451 crystallization while data from **C** define a linear correlation that does not pass through the  
 452 origin, potentially indicative of mixing between two components. Data from **D** is not well  
 453 explained by a linear relationship ( $R^2=0.65$ ) as expected for melts related by either mixing or  
 454 fractional crystallisation. Data from **E** and **F** are not well explained by linear relationships  
 455 ( $R^2=0.64$  and  $0.65$  respectively), potentially indicating mixing between two components. On  
 456 diagram **E** and **F** fractional crystallisation should result in no variations in Rb/Nd and Th/Nd  
 457 as a function of Rb and Th concentrations respectively.

458 **Volatiles**

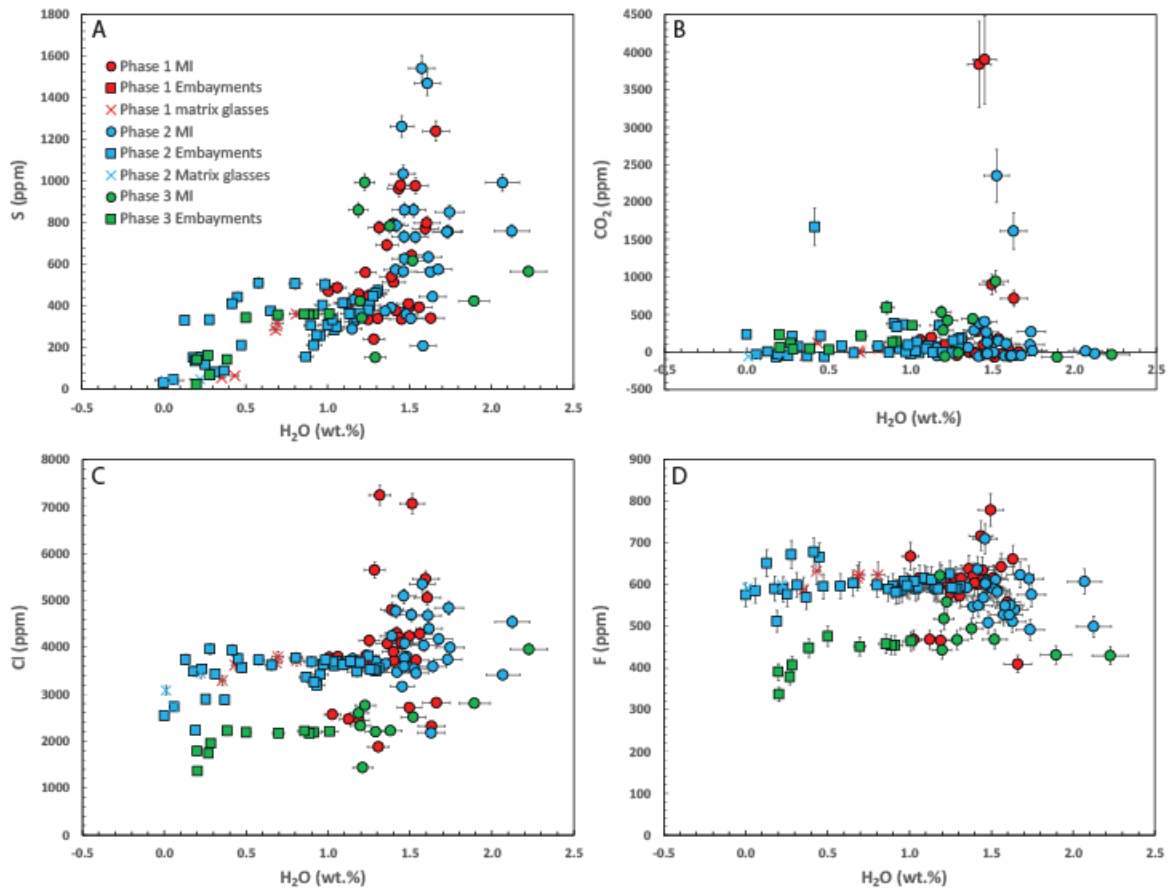
459 In melt inclusions and matrix glasses, chlorine ranges from 1435 to 7243 ppm, fluorine from  
460 410 to 779 ppm, water from 0 to 2.2 wt.%, CO<sub>2</sub> from 0 to 3899 ppm and sulfur from 30 to  
461 1541 ppm. Both H<sub>2</sub>O and CO<sub>2</sub> in melt inclusions have the potential to be altered during post-  
462 entrapment processes such as diffusive H<sup>+</sup> exchanges between the MI and the melt through  
463 the olivine (e.g., Massare et al. 2002; Danyushevsky et al. 2002; Chen et al. 2011; Gaetani et  
464 al. 2012; Bucholz et al. 2013; Portnyagin et al. 2019) or CO<sub>2</sub> diffusion between the MI and its  
465 shrinkage bubble (e.g., Anderson and Brown, 1993; Steele-Macinnis *et al.*, 2011; Wallace *et*  
466 *al.*, 2015). While there is no evidence for either process in the investigated sample set, neither  
467 can be discarded. A conservative approach is hence to consider the measured H<sub>2</sub>O and CO<sub>2</sub>  
468 values as minima. Melt inclusions from phase one tend to be richer in chlorine and fluorine  
469 and poorer in water than melt inclusions from phase two and three, with phase three being the  
470 poorest in chlorine and fluorine. No systematic differences are observed in the CO<sub>2</sub> and sulfur  
471 content of the melt inclusions between the three phases.

472

473 Neither chlorine, fluorine nor CO<sub>2</sub> correlates with Nb despite being theoretically similarly  
474 incompatible (Fig. S5A, B and D). Likewise, water does not correlate with Ce despite being  
475 theoretically similarly incompatible (Fig. S5C). Finally, the sulfur content does not correlate  
476 with FeO content suggesting that sulphide saturation did not take place during the magmatic  
477 evolution recorded by melt inclusions. Together all these observations suggest that the  
478 volatiles contents of melt inclusions and matrix glasses are not determined by differentiation  
479 and must be more reflective of degassing processes even though no clear open- nor closed-  
480 system degassing trend is shown by the data. Little correlations are observed between volatile  
481 element excepted for water and sulfur (Fig. 8). The majority of the sixty-eight melt inclusions

482 analysed have low CO<sub>2</sub> content, between detection limit (<50) and 500 ppm, while only five  
 483 inclusions have CO<sub>2</sub> content above 1000 ppm.

484



485

486 **Figure 8:** Volatile elements abundance in melt inclusions, embayments and matrix glasses  
 487 from Ambae.

488

#### 489 **Geothermobarometry and volatile saturation pressure**

490 The presence of euhedral microlites of plagioclase, clinopyroxene, and olivine indicates that  
491 interstitial glasses are saturated with all three phases. Interstitial glasses are in equilibrium  
492 with olivine microlite rims ( $\text{Fe/Mg } K_d = 0.27\text{-}0.29$ ; Roeder and Emslie 1970), clinopyroxene  
493 microlite rims ( $\text{Fe/Mg } K_d = 0.19\text{-}0.33$ ; Putirka 2008), and plagioclase microlite rims ( $\text{Ab/An}$   
494  $K_d = 0.17\text{-}0.32$ , Putirka 2008). Pre-eruptive temperatures were thus calculated using a variety  
495 of mineral-saturation models (Table 1). At least 15 glass compositions were analysed for each  
496 phase; for a given phase, all analyses are within analytical error of each other, so only the  
497 average value was used for thermobarometry calculations. All these estimates are within  
498 error of each other and are consistent with a pre-eruptive temperature of  $1145 \pm 15 \text{ }^\circ\text{C}$ , with  
499 possibly a small increase of  $8 \text{ }^\circ\text{C}$  between phase 1 and phase 4. These calculations were  
500 performed without taking into account the influence of water on mineral-saturation  
501 temperatures. Water concentrations in matrix glasses vary between 0.01 and 0.81 wt% (Table  
502 S9). Addition of a maximum of 0.81 wt%  $\text{H}_2\text{O}$  results in a  $30 \text{ }^\circ\text{C}$  decrease (Médard and  
503 Grove 2008), i.e. a minimum pre-eruptive temperature of  $1115 \pm 15 \text{ }^\circ\text{C}$ .

504

505 Since interstitial glasses are saturated with olivine, plagioclase and clinopyroxene, it is  
506 possible to estimate the equilibration pressure from the pressure-dependence of the olivine-  
507 plagioclase-clinopyroxene cotectic (Yang et al. 1996). The calibration of Yang et al. (1996)  
508 as implemented by Kelley and Barton (2008) gives pressure estimates of  $50 \pm 110 \text{ MPa}$ , ,  
509 indicating that the latest stages of crystallization occurred in the upper 6 km of the crust.  
510 Given that the bulk rock compositions are also saturated with olivine, plagioclase and  
511 clinopyroxene, it is possible to estimate a pressure where the melt equivalent to the bulk rock  
512 was extracted using the same method. The average pressure at which fractional crystallization  
513 from a more mafic magma produces the bulk rock composition is  $133 \pm 110 \text{ MPa}$ . The model

514 of Kelley and Barton (2008) has been developed for water-poor Icelandic basalts. Addition of  
515 water stabilizes clinopyroxene, resulting in pressure estimates that are too high (Husen et al.  
516 2016). If interstitial glasses contained water when they last equilibrated with the phenocrysts,  
517 the equilibration pressure would be lower, i.e. within error of the surface.

518

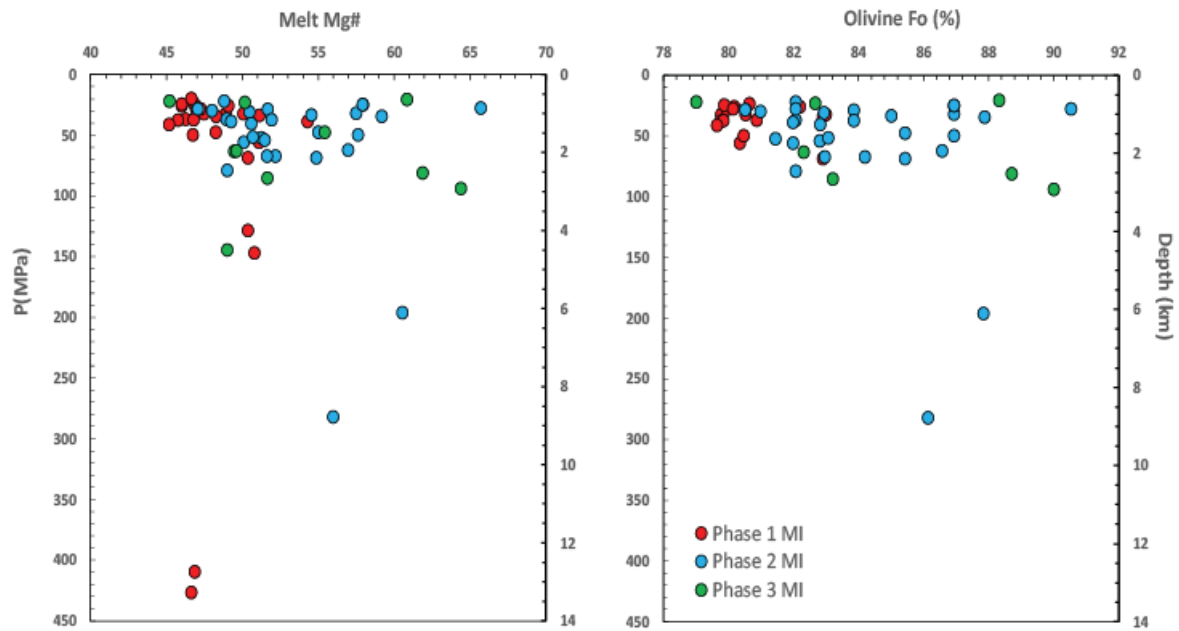
519 Crystallization pressures can also be estimated using the pressure-sensitive incorporation of  
520 the jadeite component in clinopyroxene (e.g., Putirka, 2008). Barometers have been  
521 calibrated either purely from the jadeite component of the clinopyroxene, or from jadeite  
522 partitioning between clinopyroxene and melt. This equation is very sensitive to temperature  
523 and water concentration in melts, but less sensitive to the exact melt composition. We  
524 simultaneously solved for pressure and temperature using equation (30) and (33) of Putirka  
525 (2008) to minimize temperature effects. We initially paired microlite and phenocryst rims  
526 compositions with matrix glass compositions, phenocryst core compositions with bulk rock  
527 compositions, and melt inclusion compositions with their host phenocrysts, and only kept  
528 clinopyroxene analyses for which  $Fe/Mg K_d = 0.28 \pm 0.08$  (Putirka 2008). Phenocrysts cores  
529 are, however, rarely in equilibrium with the bulk composition, and more commonly in near-  
530 equilibrium with the matrix glass, so we paired phenocryst core compositions with matrix  
531 glasses. This approximation could produce a  $\sim 30$  MPa error on pressure, much smaller than  
532 the accuracy of the barometer. Water concentration in glasses was assumed to be 1.5 wt%,  
533 the average water content in melt inclusions, except for melt inclusions in which water  
534 concentrations have been analysed. Equilibrium between 11 melt inclusions and their host  
535 clinopyroxenes gives pressures between 43 and 326 MPa, with an average pressure of  $184 \pm$   
536  $75$  MPa at an average temperature of  $1089 \pm 11$  °C. The temperature is lower than the  
537 temperature estimated from glass thermometry, since it is calculated with a higher water  
538 content. Identical pressures and temperatures were obtained from 26 analyses of phenocryst

539 cores ( $170 \pm 86$  MPa at  $1091 \pm 13$  °C) and 28 analyses of phenocryst and microlite rims (188  
540  $\pm 73$  MPa at  $1093 \pm 12$  °C), with a global average of all pressure calculations of  $181 \pm 78$   
541 MPa. Individual pressures vary between 13 and 328 MPa. Interestingly, the use of a  
542 clinopyroxene-only barometer (equation 32b of Putirka et al. 2008) produces similar results,  
543 with an average of  $155 \pm 65$  MPa. Uncertainties due to barometer calibrations are quite large,  
544 with a standard error of estimate of 160 MPa for equation (30) of Putirka (2008). The final  
545 pressure estimates of  $180 \pm 160$  MPa indicates that crystallization happened between 1 and  
546 12 km, assuming a  $2900 \text{ kg.m}^{-3}$  density for the basaltic crust. These values are consistent with  
547 estimates from melt inclusion volatile elements concentrations, and within error of estimates  
548 based on cotectic melt compositions using bulk rock compositions. Pressure estimated from  
549 cotectic melt compositions of interstitial glasses are lower and register the latest stages of  
550 crystallization, whereas mineral compositions can register earlier, possibly deeper, stages.

551

552 Melt inclusions entrapment pressures were calculated using the model of Iacono-Marziano et  
553 al., (2012) for  $\text{H}_2\text{O-CO}_2$  saturation pressure. They yield entrapment pressures between 20 and  
554 427 MPa (Fig. 9), consistent with pressures of 43 to 326 MPa estimated from  
555 clinopyroxene/melt barometry. Given the above-reported error on the volatile content  
556 determination and the error on the model, the results can conservatively be taken to be  
557 accurate at  $\pm 20\%$ . Yet, as discussed previously,  $\text{H}_2\text{O}$  and  $\text{CO}_2$  values are to be considered as  
558 minimum values due to possible diffusion of both species out of the MI. The entrapment  
559 pressures are therefore also to be taken as minimum pressure estimates. The two deepest  
560 inclusions are hosted in pyroxenes and their entrapment pressure estimates from volatile  
561 saturation (410 and 427 MPa) is fairly consistent, although higher, than their host pyroxene  
562 calculated crystallisation pressure ( $277$  and  $302 \pm 160$  MPa). Most other pyroxene-hosted  
563 inclusions record volatile saturation pressure lower than their host pyroxene calculated

564 crystallisation pressure yet within the standard error. Saturation pressures are also consistent  
 565 with the calculated cotectic pressures, and point to a shallow magma storage system  
 566 somewhere between 0.5 and 3 km depth for most of the crystals.

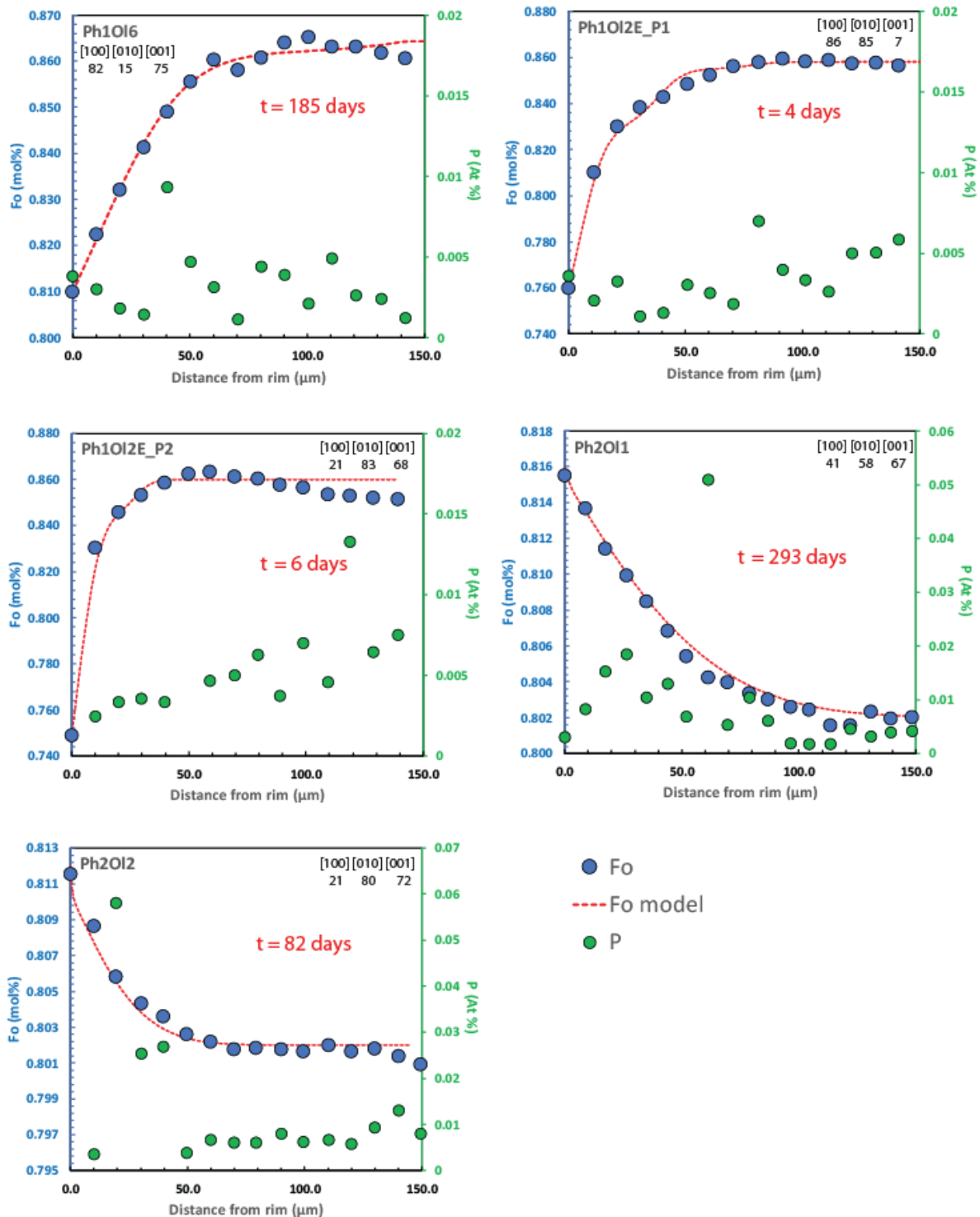


567

568 **Figure 9:** Melt inclusions entrapment pressure calculated from  $H_2O-CO_2$  saturation  
 569 pressure, compared to melt Mg# and host olivine forsterite content. Note that some of the MI  
 570 are hosted in pyroxenes, hence not plotted on the right-hand side diagram.  
 571

572 **Residence time**

573 We modelled the %Fo concentrations of five profiles obtained from two olivine from phase 1  
574 and two olivine from phase 2 (Fig. 10). The diffusion model parameters and results are  
575 provided in Table 2. For normally zoned phase 1 olivine we determined diffusion timescales  
576 ranging from 4 to 185 days. For reversely zoned olivine from phase 2 we determined  
577 diffusion timescales ranging from 82 to 293 days (keeping in mind that phase 2 occurred  
578 about two months after phase 1). While our dataset is limited, it does already highlight a  
579 variety of diffusion timescales recorded by olivine phenocryst/antecryst. These results  
580 suggest that the shallow magma chamber has been periodically recharged over the days to  
581 year preceding the eruption. The latest recorded recharge event potentially occurred only a  
582 few days prior to the eruption while the oldest recorded event occurred about a year before  
583 the eruption.



584

585 **Figure 10:** Results of diffusion modelling compared to %Fo concentrations profiles  
 586 (measured by EMPA) in two olivine crystals from phase 1 and two olivine crystals from  
 587 phase 2 of the 2017-2018 Ambae eruptions. Modelling was performed using the DIPRA  
 588 software (Girona and Costa 2013). Phosphorus profiles are shown and do not correlate with  
 589 %Fo content as expected for Fe-Mg zoning resulting from diffusion although the error on  
 590 phosphorus measurement ( $3\sigma = \pm 0.002$ ) could partly mask any correlation. Initial conditions  
 591 are shown in Fig. S6.  
 592

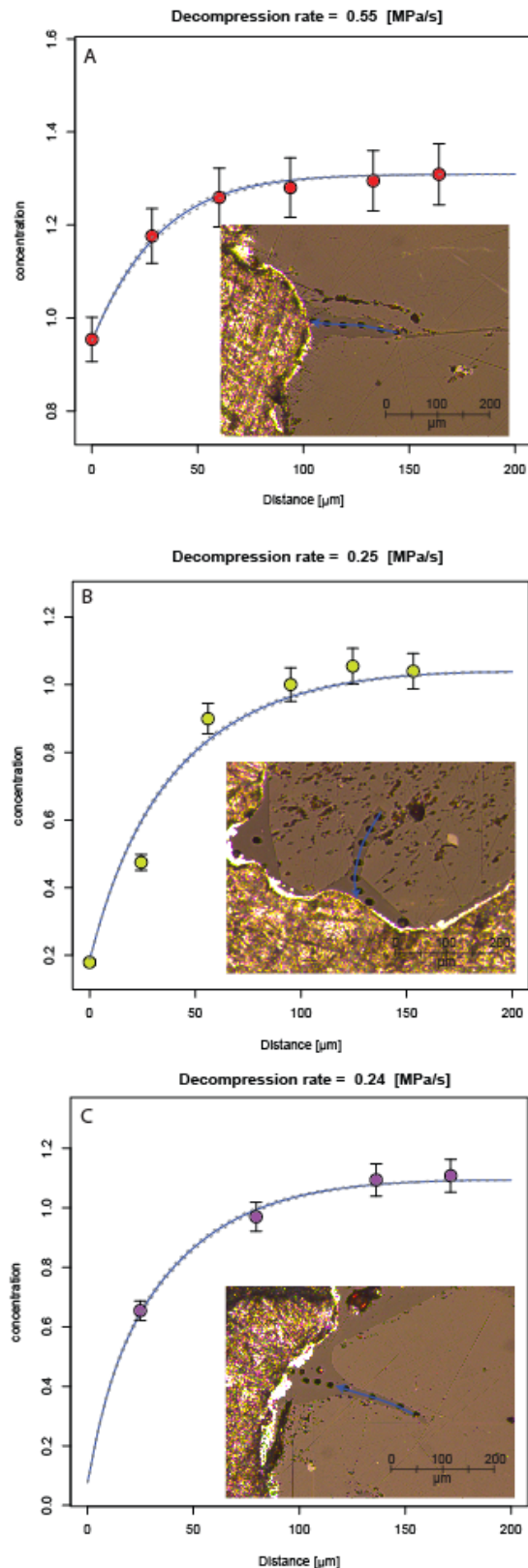
### 593 Ascent rates

594 Volatile diffusion modelling was performed to match the measured H<sub>2</sub>O concentration  
595 profiles (obtained by SIMS) along three melt embayments from phase two of the 2017-2018  
596 eruption (note that the olivine used here are different from the ones used for Fe-Mg diffusion  
597 modelling in the previous section). Best fit solutions of the diffusion models are shown in  
598 **Fig. 11** with initial conditions and model parameters given in **Table 3**. These results give  
599 decompression rates of  $0.24 \pm 0.04$ ,  $0.25 \pm 0.06$  and  $0.55 \pm 0.20$  MPa/s which corresponds to  
600 ascent rates in the order of 33-75 km/h, assuming a unique melt/rock density of  $2665 \text{ kg.m}^{-3}$   
601 for the trachybasaltic magma (Lange and Carmichael 1990). Concentrations of H<sub>2</sub>O at the  
602 edge of the profiles are 0.06, 0.18, and 0.95 wt% indicating the degassing process can be  
603 quenched at about 4 MPa.

604

605 Diffusion modelling was also performed to reproduce S and Cl concentration profiles  
606 (obtained by SIMS). However, the measured profiles showed S and Cl concentrations at the  
607 edge of the embayments and in the surrounding matrix glass, that are much higher than  
608 expected for equilibrium at 0.1 MPa (i.e., ~50 to 200 ppm S and > 3400 ppm Cl remaining).  
609 This suggests that decompression rates were too high for S and Cl to maintain equilibrium  
610 during degassing, resulting in oversaturation of these species in the melt, as shown  
611 experimentally for CO<sub>2</sub> (Pichavant et al. 2013).

612



613

614 **Figure 11:** Results of diffusion modelling compared to  $H_2O$  concentration (measured by  
 615 SIMS) in three melt embayments from phase two of the 2017-2018 Ambae eruptions. Insets  
 616 show microphotograph of each embayment with blue arrows marking the location of the  
 617 SIMS analyses.

618  
619 Ascent rates can also be estimated from the microlite density (Toramaru et al. 2008). The  
620 number and nature of microlites is extremely similar between samples of phases 1, 2 and 3  
621 (Fig. S7). A higher number of microlites is observed in ashes from phase 4, but this is mainly  
622 due to the abundance of very small microlites that are not observed in other phases. These  
623 microlites might have crystallized during eruption. 2D microlite number densities and phase  
624 proportions were estimated using BSE images. This allowed us to compute average microlite  
625 sizes using the method of Hammer et al. (1999). To calculate 3D microlite number densities,  
626 we then divided the 2D microlite number densities by the average microlite size. For samples  
627 from phase 1, average microlite number densities averaged on seven BSE images are  $3.8 \cdot 10^{13}$   
628  $\text{m}^{-3}$  for plagioclase,  $9.7 \cdot 10^{12} \text{ m}^{-3}$  for clinopyroxene, and  $1.8 \cdot 10^{12} \text{ m}^{-3}$  for olivine. Given the  
629 small number of crystals (2 to 10 per image), the olivine MND has a very large uncertainty,  
630 and will not be taken into account. Using a maximum volatile content at microlite nucleation  
631 of 2.23 wt%  $\text{H}_2\text{O}$  (highest measurement in melt inclusions) results in decompression rates of  
632  $1.6 \cdot 10^5 \text{ Pa} \cdot \text{s}^{-1}$  and  $1.1 \cdot 10^5 \text{ Pa} \cdot \text{s}^{-1}$  calculated from plagioclase and clinopyroxene, respectively.  
633 The density of the trachybasaltic magma is  $2665 \text{ kg} \cdot \text{m}^{-3}$  (Lange and Carmichael 1990),  
634 producing ascent rates of  $4\text{-}6 \text{ m} \cdot \text{s}^{-1}$ , or  $15\text{-}23 \text{ km} \cdot \text{h}^{-1}$ , consistent with values determined from  
635 volatile diffusion.

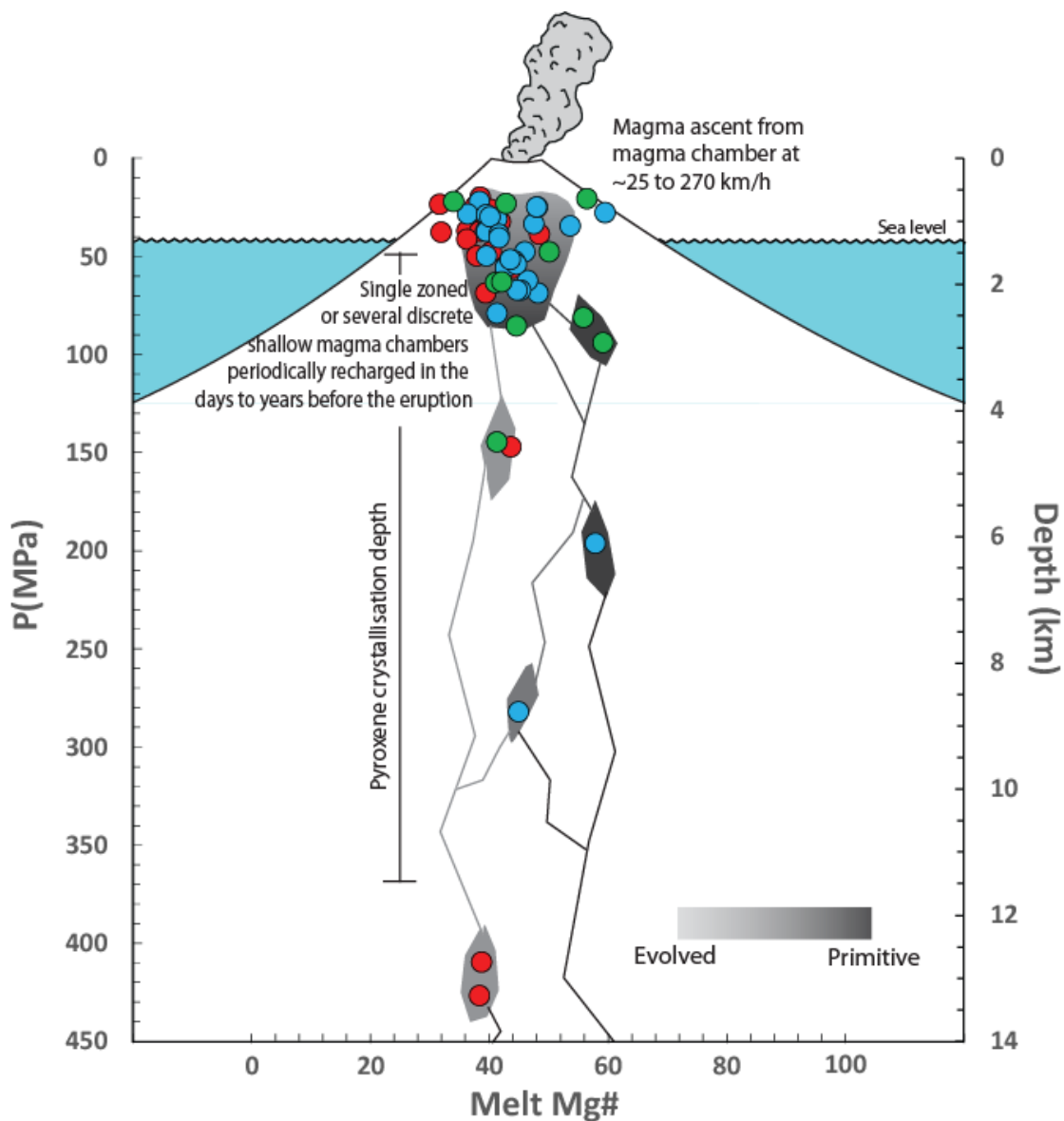
636

## 637 **DISCUSSION**

### 638 **The Ambae plumbing system**

639 Clinopyroxene crystallisation pressures and melt inclusions entrapment pressures both  
640 suggest that the magma involved in the 2017-2018 Ambae eruption had been crystallising  
641 pyroxene and olivine at depths of 0.5 to 14 km minimum. Most melt inclusions, however,  
642 record low entrapment pressures corresponding to depth of 0.5 to 3 km. This suggest that  
643 most of the erupted magma originated from a shallow magma chamber located at sea level

644 (Fig. 12). There is no relationship between the melt inclusions entrapment pressures and  
 645 markers of magmatic differentiation (Fig. 9), suggesting that the plumbing system is not  
 646 arranged in a succession of progressively shallower and more evolved magma chambers.  
 647 Instead, multiple chambers of variously differentiated magma must occupy similar depth  
 648 levels, following horizontally separated pathways (Fig. 12).  
 649



650

651 **Figure 12:** Schematic representation of the Ambae plumbing system on which melt inclusions  
 652 entrapment pressure and Mg# are overlaid. Magmas at different stages of differentiation  
 653 migrate through the crust and mix via episodic recharge events in a shallow magma chamber  
 654 located at sea level. During the eruption, evolved magma is emptied preferentially towards

655 *the beginning while more primitive magma is erupted during later phases. Note that there is*  
656 *no relationship between Mg# and horizontal coordinates of the melts.*  
657

### 658 **The 2017-2018 emptying of Ambae's plumbing system**

659 The 2017-2018 eruption started with phreatic activity and the creation of a small pyroclastic  
660 cone at the lake centre several days before the first appearance of phase one lava at the  
661 surface (Bani et al., in prep). A phreatic or phreatomagmatic start to a magmatic eruption is a  
662 commonly observed occurrence at volcanoes with previously-closed conduits, examples  
663 include the 1955 Bezymianny (Gorshkov 1959), 1980 Mt St Helens (Lipman and Mullineaux  
664 1981), 1990 Kelut (Bourdier et al. 1997), 1990–1995 Unzen (Nakada et al. 1999) and 2017-  
665 ongoing Nevados de Chillan (Moussallam et al. 2018) eruptions. Even if they do not  
666 necessarily lead to edifice destruction (e.g., 1888 Bandai eruption, Yamamoto et al. 1999),  
667 phreatic events can vaporize and expel water in shallow aquifers, unloading the upper crust  
668 hence changing the stress field around, and the magmatic pressure within, a magma reservoir  
669 (Pinel and Jaupart 2005). As such, phreatic events can act as trigger or facilitate magmatic  
670 eruptions. Given the delay observed between the phreatic eruptions (6 September 2017) and  
671 magma arrival at the surface (22 September 2017), it is conceivable that the phreatic  
672 eruptions played a role in favouring the magmatic ones, although it is likely that the phreatic  
673 eruptions themselves were driven by magmatic gases given the large quantities of SO<sub>2</sub> they  
674 released (Bani et al., in prep.).

675

676 Bulk rocks, matrix glasses and melt inclusions from phase one are compositionally more  
677 evolved than those of phase two and three (Fig. 5 and 6). Melt inclusions from phase two and  
678 three have higher Mg#, MgO, CaO content, lower Si and Al content and tend to be hosted in  
679 more forsteritic olivine (Fig. 6). An overlap in composition exist however between the three  
680 phases such that phase two and three, whilst dominated by more primitive melt inclusions, do

681 also contain inclusions that have similar compositions as the ones from phase one. Normal  
682 zoning of olivine and pyroxene phenocrysts is most commonly observed in the early and late  
683 phases of the eruption, yet reverse zoning is common also shown by a number of crystals,  
684 particularly in phase 2 and 3 (Fig. 2, 3 and 10). The observed compositional continuity (as  
685 opposed to a bimodal distribution) shown by the melt inclusions, from primitive to evolved  
686 end members (Fig. 5,6) suggest a simple magmatic evolution with all erupted melts related by  
687 simple liquid line of descent from the same primitive parental magma (potentially similar to  
688 the 8 to 14 wt.% MgO melts described by Sorbadère et al. 2011) (Fig. 6). Trace element  
689 variation diagrams from melt inclusions and matrix glasses (Fig. 7) show a strong linear  
690 correlation between Rb, Th and K<sub>2</sub>O (highly incompatible elements) that points towards the  
691 origin as expected for melts related by fractional crystallisation. This again suggests that all  
692 melt inclusion compositions (including from older lavas) are consistent with simple fractional  
693 crystallisation evolution from a single parental magma.

694

695 Some trace element systematic do hint at mixing processes having taken place. A strong  
696 linear correlation is evident between La and Rb (Fig. 7C) but a regression through the data  
697 does not pass through the origin potentially indicative of mixing between two components  
698 (e.g., Schiano et al. 2010). Plots of Rb/Nd versus Rb and Th/Nd vs Th (Fig. 7E and F) define  
699 trends that are not well described by linear relationships suggesting again mixing between  
700 two components. On these diagrams, simple fractional crystallisation would result in no  
701 variations in Rb/Nd and Th/Nd as a function of Rb and Th concentrations respectively (e.g.,  
702 Schiano et al. 2010). In addition, the fact that numerous olivine crystals exhibit reverse  
703 zoning and the bi-modal distribution observed in olivine forsterite content with a significant  
704 proportion of phase 2 and 3 olivine recording core Fo content higher in magnesium than

705 expected for equilibrium with the bulk rock (Fig. 4), both suggest that some of the olivine are  
706 antecrystic and that some amount of mixing has taken place.

707

708 Diffusion timescales from olivine zoning show multiple recharge events occurring a few days  
709 to a year prior to the 2017-2018 eruption (exact timescale depending on initial conditions). It  
710 is possible therefore that the latest recharge event played a role in triggering (via magmatic  
711 gas release) the initial phreatic and subsequent magmatic activity as the timing (a few days  
712 before phase 1 eruption) is consistent with the onset of phreatic and seismic activity.

713

714 Based on all these observations we suggest that:

715 1. The Ambae plumbing system was periodically recharged by co-genetic magmatic  
716 batches in the days to year prior to eruption.

717 2. The initial phreatic activity, propelled by magmatic gases, likely opened a pathway or  
718 modified the local stress field allowing pressurized magma to travel to the surface.

719 3. The eruption first tapped into the most evolved magma chamber(s) erupting phase one  
720 magma. As the eruption progresses from phase one to four, the most evolved  
721 chamber(s) got progressively exhausted opening the way to more primitive (and yet  
722 not necessarily deeper) magma from other chambers.

723 4. During or prior to the eruption some small amount of mixing between co-genetic  
724 magmas from different chambers occurred.

725

## 726 **Magma ascent rate**

727 Modelling of volatile diffusion profiles in melt embayments suggest magma decompression  
728 rates in the order of 0.24 to 0.55 MPa/s, corresponding to ascent rates of 9 to 21 m/s (33 to 75  
729 km/h) while calculated decompression rates based on microlite number densities are in the

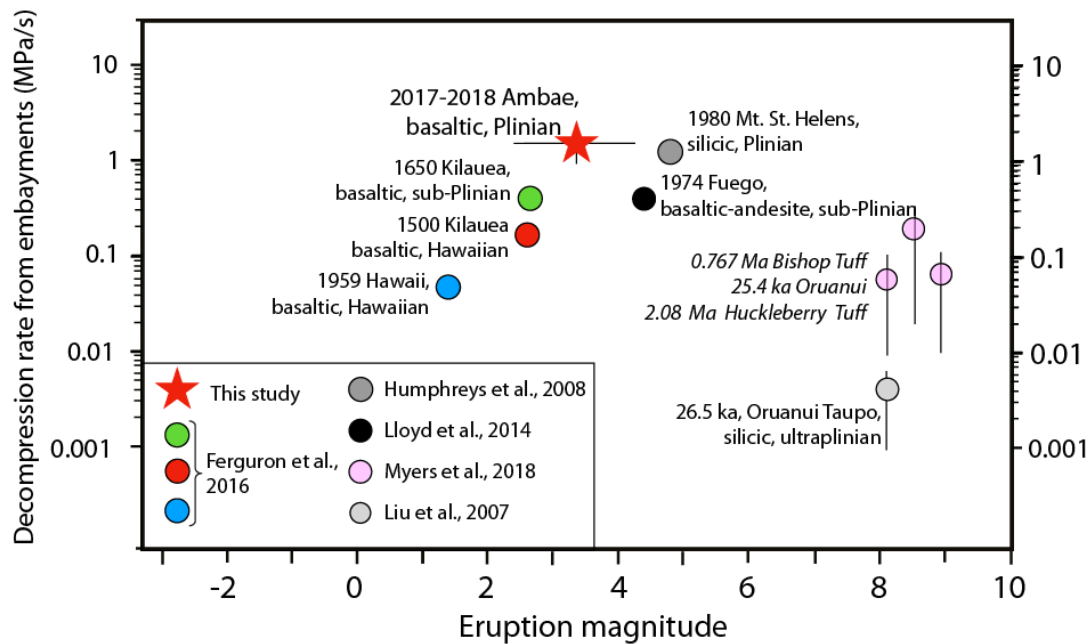
730 order 0.11 to 0.16 MPa/s corresponding to ascent rates of 4 to 6 m/s (15 to 23 km/h).  
731 Considering that the two methods are entirely independent their broad agreement is worth  
732 highlighting and brings confidence in the determined values. Given a shallow magma  
733 chamber at 0.5 to 3 km depth, it must hence have taken 24 to 122 seconds for the magma to  
734 travel from the top of the magma chamber to the surface. The decompression and ascent rates  
735 we calculate are comparable to other volcanoes using the same embayment volatile diffusion  
736 modelling method. Liu et al., (2007) investigated the 26.5 ka phreatomagmatic Oruanui  
737 eruption of Taupo (New Zealand) and found a decompression rate of 0.001 to 0.007 MPa/s.  
738 Myers et al., (2018) investigated the 25.4 ka Oruanui eruption of Taupo, 0.767 Ma Bishop  
739 Tuff and 2.08 Ma Huckleberry Tuff and found decompression rates in the order of  $10^{-3}$  to  $10^{-1}$   
740 MPa/s. Humphreys et al., (2008) found decompression rates of 0.9-1.6 MPa/s for the 1980  
741 Plinian eruption of Mount St Helens, (Washington, USA). Lloyd et al., (2014) found  
742 decompression rate of 0.3 to 0.5 MPa/s for the basaltic andesite sub-Plinian eruption of  
743 Volcán de Fuego (Guatemala) while Ferguson et al., (2016) found decompression rates  
744 between 0.05 and 0.45 MPa/s during fire fountain to sub-Plinian basaltic eruptions at Kīlauea  
745 volcano (Hawaii, USA). **Figure 13** shows a compilation of currently available magmatic  
746 decompression rate estimated using the embayment volatile diffusion method and compares it  
747 to eruption magnitude. For basaltic eruptions a trend seems to emerge of increasing  
748 decompression rate (i.e. ascent rate) with increasing eruption magnitude. The trend however  
749 does not extend to more silicic and higher magnitude eruptions with the largest, ultraplinian,  
750 eruptions yielding comparatively slow decompression rates.

751

752

753

754



755  
 756 **Figure 13:** *Compilation of decompression rate estimates using the embayment volatile*  
 757 *diffusion method and comparison with eruption magnitude. For basaltic eruptions a trend of*  
 758 *increasing decompression rate (i.e. ascent rate) with increasing eruption magnitude can be*  
 759 *observed. The trend however does not extend to more silicic and higher magnitude eruptions.*  
 760

761 Calculated magma ascent rate is strongly influenced by a parameter that is difficult to assess:  
 762 the amount of pre-existing fluid/bubble before the onset of the final eruptive ascent (Ferguson  
 763 et al., 2016). This is because the curve of the H<sub>2</sub>O depletion with respect to pressure varies  
 764 towards deeper degassing with more pre-existing fluid (see Fig. S1). While Ferguson et al.  
 765 (2016) used H<sub>2</sub>O-CO<sub>2</sub>-S profiles to simultaneously constrain this parameter, it was not  
 766 possible for the case here as CO<sub>2</sub>, S and Cl show significant disequilibrium (super-saturation  
 767 compared to H<sub>2</sub>O). The values reported here are minimum ascent rate with pre-existing fluid  
 768 mass of 0 %. Supposing a value of fluid mass of 1 %, the ascent rate increases by  
 769 approximately a factor of 2.5. As the volatile element abundances in the melt inclusions are  
 770 somewhat higher than the highest value of the embayments, an estimated pre-existing fluid  
 771 mass of 0.5 to 1.5 % could be close to reality. A faster magma ascent rate is furthermore  
 772 consistent with the strong disequilibrium recorded in slower diffusing elements (CO<sub>2</sub>, S, Cl).  
 773 The magma ascent rate can hence be estimated to be in the order of 1-2 MPa/s.

774

775 Considering pre-eruptive volatiles in our calculations, magma ascent rate during the 2017-  
776 2018 Ambae eruption therefore appears as one of the fastest among other eruptions where the  
777 same methodology has been applied (Liu et al. 2007; Humphreys et al. 2008; Lloyd et al.  
778 2014; Ferguson et al. 2016). This fast ascent was likely propelled by pre-eruptive volatiles,  
779 consistent with observations that the eruption reached the lower stratosphere (NASA Earth  
780 Observatory 2019) and released extremely large amounts of gases into the atmosphere (2.08  
781 Tg of SO<sub>2</sub> in the first nine months, equivalent to a third of the atmospheric loading from the  
782 1982 El Chichon eruption) while expelling relatively minor amounts of solid materials during  
783 the same period (Bani et al., in prep).

784

## 785 **CONCLUSIONS**

786 The 2017-2018 eruption of Ambae (Aoba) volcano was the largest recorded event in Vanuatu  
787 since the 1929 eruption of Ambrym. It expelled large quantities of gases to the atmosphere  
788 and prompted local authorities to evacuate the 11,000 inhabitants of the islands making it the  
789 largest volcanic disaster in the country's recorded history. In this contribution we used major,  
790 trace and volatile elements in bulk rocks, matrix glasses, melt inclusions, embayments and  
791 minerals to shed light on the magmatic processes operating during this eruption. We found  
792 that (i) The Ambae plumbing system was periodically recharged by magmatic batches in the  
793 year prior to eruption with the latest recharge event occurring only a few days before  
794 eruption. (ii) the eruption was likely facilitated by an initial phase of phreatic activity, itself  
795 triggered by magmatic gases potentially associated with the latest magmatic recharge event.  
796 (iii) The magma released during the eruption started crystallising at 14 to 5 km depth before  
797 residing in a shallow magma chamber, located at ~0.5 to 3 km depth. (iv) From the shallow  
798 magma chamber to the surface, minimum magma decompression rate ranges from 0.11 to

799 0.55 MPa/s, with a possible actual rate of 1-2 MPa/s, corresponding to average ascent rates in  
800 the order of 15 to 270 km/h and a travel time between the top of the shallow reservoir and the  
801 surface of 9 seconds to 2 minutes. Such a fast ascent rate, together with the high eruptive  
802 plume heights (reaching the lower stratosphere) and the large quantities of SO<sub>2</sub> released,  
803 suggest that a large amount of pre-eruptive volatiles must have been present in the reservoir.

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