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# 1 Evidence for deep gas loss in open volcanic systems

2

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4

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8

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10

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13

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19

## 20 Abstract

21 Previous studies of Vulcanian eruptive products have shown that the respective volcanic conduits were filled  
22 for the most part with low-porosity magma (i.e.  $< 10$  vol%) prior to eruption. Comparison with the  
23 theoretical porosity distribution expected from closed-system degassing suggests that gas loss must have  
24 taken place at depth within the magmatic column (between 3 and 5 km). At such high pressures (between 70  
25 and 110 MPa), however, porosities are low enough ( $< 20$  vol%) to rule out traditional gas loss mechanisms.  
26 We tested if channelling, an outgassing mechanism based on bubble connection due to high crystal content  
27 ( $>40$  vol%) proposed to occur in mushy magma reservoirs, could also happen in volcanic conduits. We  
28 reanalysed phenocryst, microlite, and porosity data from recent eruptions of Merapi volcano, Indonesia,  
29 Soufrière Hills volcano, Montserrat, and Tungurahua volcano, Ecuador. Overall, these magmas had crystal  
30 contents high enough for outgassing to occur by channelling. Gases could be channelled out of the magma  
31 columns at various levels during ascent to yield mostly gas-depleted magma columns prior to explosive  
32 behaviour. Such outgassing by channelling thus has the capacity to influence eruptive style. Depending on  
33 the phenocryst content, microlite growth during ascent can either foster, or impede gas escape by  
34 channelling. Considering the pervasive occurrence of microlites and ensuing high crystal contents in  
35 volcanic conduits (between 40 and 70 vol%), the high likelihood of channelling implies that other outgassing  
36 mechanisms might not be as dominant as previously envisioned.

37

38 **Keywords:** Silicic volcanoes, outgassing, crystal content, channelling, porosity

## 39 Introduction

40 The eruption of viscous magma at the Earth's surface often gives rise to abrupt regime changes, such as the  
41 transition from the gentle effusion of a lava dome to brief but powerful Vulcanian explosions. These eruptive  
42 regimes are controlled by outgassing, a process by which the gas contained in bubbles formed during ascent  
43 can escape from the magma. In the case of highly viscous magmas (viscosity  $>10^6$  Pa.s), individual bubbles  
44 are trapped within the melt and cannot migrate individually through the magmatic column, hindering the  
45 bubbly flow outgassing mechanism that is generally at play for low viscosity magmas (Parmigiani et al.  
46 2016; Cardoso and Woods, 1999). Gas loss within highly viscous magmas is mainly related to bubble

47 connectivity and to percolation, which controls the ability for the gas to travel through these bubble  
48 connections, making the magma permeable under specific physical conditions. Pavourable physical  
49 conditions for percolation to occur depend on the amount, size, and shape of the bubbles, deformation, which  
50 promotes bubble connectivity (e.g., Blower 2001; Rust and Cashman 2004; Burgisser et al. 2017; Kushnir et  
51 al. 2017), and the presence of crystals (Lindoo et al. 2017; deGraffenried et al. 2019; Degruyter et al. 2019;  
52 Colombier et al. 2020). In some cases, brittle failure and cracks can also appear (Shields et al. 2014). When  
53 quantified, permeabilities deduced from the combination of these parameters range between  $10^{-15}$  and  $10^{-12}$   
54  $\text{m}^2$  (e.g., Klug and Cashman, 1996; Farquharson et al. 2015; Kushnir et al. 2016; Burgisser et al. 2017).  
55 When integrated into numerical models, they contribute to reproduce effusive regimes that are compatible  
56 with field observations like bubble density distribution described on an eroded conduit, or extrusion rate  
57 during dome-forming activity (e.g., Melnik and Sparks, 2002; Collombet, 2009; Degruyter et al. 2012;  
58 Cassidy et al. 2018).

59  
60 However, these numerical models fail to reproduce the very low porosity values inferred to occur in the  
61 conduit prior to Vulcanian eruptions. Figure 1 shows the porosity distribution prior to the Vulcanian  
62 explosion on February 10, 2010 at Soufrière Hills volcano, Montserrat (Burgisser et al. 2019). Samples  
63 collected in the field provide porosity data down to approx. 70 MPa (~3 km depth) that are significantly  
64 below the theoretical porosities suggested for a closed system. The outgassing mechanisms, which are based  
65 on bubble connection relationships implemented in various numerical models, could explain low porosity  
66 values near the surface but fail to reproduce porosity values at depth (beyond a corresponding pressure of 10  
67 MPa). This implies that another outgassing mechanism is at play and/or that a large amount of gas has been  
68 evacuated from the deepest parts of the magma column (most likely above 70 MPa) during and/or before the  
69 ascent from the reservoir.

70  
71 We test the hypothesis that this mismatch is due to a missing physical mechanism that greatly enhances  
72 outgassing efficiency within the conduit, even at very low porosity values (<10 vol%). This mechanism,  
73 channelling, which involves a rigid crystal framework, was first described for the case of magma chambers  
74 by Parmigiani et al.(2017) and Degruyter et al. (2019). Channelling relies on the capacity of crystal-rich

75 magmas to build sustainable channels for gas percolation independently from magma movements. For  
76 crystal volume fractions between 40 and 70 vol%, this mechanism allows gas permeability to reach the order  
77 of  $10^{-10}$  m<sup>2</sup>, which is two to five orders of magnitude higher than permeability calculated for bubbles alone at  
78 an equivalent porosity (Klug and Cashman, 1996; Burgisser et al. 2017). Under such permeable conditions, it  
79 is much more plausible that magma succeeds to extensively degas and outgas, even at the high pressures and  
80 low gas volume fractions typical of the deepest parts of a volcanic conduit. In addition, the formation of such  
81 channel-like porous pathways reduces significantly the percolation threshold, which is the critical  
82 vesicularity at which system-spanning bubble connectivity and permeability occur (e.g., Lindoo et al. 2017;  
83 Colombier et al. 2020). As a consequence, provided that crystallinity is high enough, outgassing can occur  
84 before or early during ascent, resulting in a magma column severely depleted in gas.

85  
86 We revisited three data sets of the porosity distribution within volcanic conduits filled by andesitic magmas.  
87 They are from a Vulcanian explosion on February 11, 2010 at Soufrière Hills volcano, Montserrat (Burgisser  
88 et al. 2019), an explosive event on October 26, 2010 at Merapi volcano, Indonesia (Drignon et al. 2016), and  
89 a large Vulcanian event that occurred on July 14, 2013 at Tungurahua volcano, Ecuador (Gaunt et al. 2020).  
90 We show that the magmas feeding these Vulcanian events were crystal-rich enough to promote highly  
91 efficient outgassing by channelling.

92

## 93 Geological Context

94 The on-going eruption of Soufrière Hills is dominated by lava dome effusion with intermittent collapse. The  
95 magma emitted is andesitic in bulk composition with a rhyolitic melt. The fifth phase of lava extrusion since  
96 the beginning of the eruption was marked by a succession of dome growth as lava lobes and spines followed  
97 by partial dome collapse (Wadge et al. 2014b; Cole et al. 2014). The February 11, 2010 explosion was  
98 preceded by two small Vulcanian events on February 5 and 8 (Stinton et al. 2014b; Cole et al. 2015). The  
99 February 11 event was mostly likely triggered by a dome collapse that started 1 hour and 27 minutes prior to  
100 the onset of the Vulcanian explosion. Burgisser et al. (2019) analyzed twenty-three samples of the resulting  
101 pumice-rich, pyroclastic density current deposits and pumice fallout deposits. Phenocrysts are mostly

102 plagioclases that are up to 5 mm across (Higgins and Roberge, 2003). Large plagioclases have irregular  
103 shapes and smaller plagioclases are euhedral. Euhedral amphiboles up to 12 mm across are also present with  
104 a low number density. Microlites are mostly plagioclases with a concave up distribution in the 20-1000  $\mu\text{m}^2$   
105 range (Couch et al. 2003) and short/long axis ratios of  $\sim 0.5$  (Murch and Cole, 2019).

106  
107 Merapi volcano produced in 2010 the largest explosive eruption since 1872 (Surono et al. 2012). This  
108 unusual event, which emitted basaltic andesites with a rhyolitic melt (Costa et al. 2013), occurred in several  
109 stages between October 26 and November 23 (Komorowski et al. 2013; Jenkins et al. 2013). The first large  
110 explosion lasted for 2h on October 26, producing an ash plume and pyroclastic density currents. This  
111 explosion had a phreatomagmatic component and was interpreted as a laterally directed explosion from a  
112 newly formed cryptodome. Drignon et al. (2016) analyzed forty-one samples from a pumice levee of the  
113 valley-filling pyroclastic deposits produced by the October 26 event. Phenocrysts populations vary little  
114 between the recent eruptions (van der Zwan et al. 2013). Crystals that are 1.6–4 mm across make up one  
115 population with a size distribution that is approximately a straight line. The most common phenocrysts are  
116 plagioclases and pyroxenes that both have subhedral morphologies with evidences of resorption (Erdmann et  
117 al. 2016). Microlites are mostly plagioclases with a rectangular prism habit, areas of 10–15  $\mu\text{m}^2$ , and  
118 short/long axis ratios ranging from 0.35 to 0.67 (Costa et al. 2013).

119  
120 The latest activity (1999 – 2016) at Tungurahua volcano varied from small-scale gas and ash venting and  
121 Strombolian outbursts to rare sub-Plinian events (Eychenne et al. 2012; Hall et al. 2015; Battaglia et al.  
122 2019). The magma emitted is a low silica andesite with a high silica andesitic melt. The last six years of this  
123 eruptive phase was marked by two to three months of relative quiescence followed by Vulcanian events and  
124 ending with several weeks of low-explosivity Strombolian activity and ash venting (Hidalgo et al. 2015). On  
125 July 14, 2013, an unusually large Vulcanian event occurred at 06h46 (local time), producing a large ash  
126 column and pyroclastic density currents that travelled up to 7.5 km away from the vent. Gaunt et al. (2020)  
127 analyzed twenty-seven samples from three lithological groups (pyroclastic current deposits, fallout pumice,  
128 and ballistic ejecta) present in the ejecta. Plagioclase is the most abundant phenocryst phase, followed by  
129 pyroxene (Samaniego et al. 2011). Both exhibit mostly euhedral habits. Microlites are mostly plagioclase

130 with habits ranging from rectangular prisms to acicular crystals (Gaunt et al. 2020). Dense plug rocks have  
131 mean microlite areas of 4.2–26  $\mu\text{m}^2$  with mostly tabular morphologies. Juvenile vesicular clasts of the  
132 pyroclastic current deposits have mean microlite areas of 10–66  $\mu\text{m}^2$  with occasional swallow-tail and  
133 hopper morphologies.

134

## 135 Methods

136 We modified data treatment of the recompression model of Burgisser et al. (2010) used by Drignon et al.  
137 (2016), Burgisser et al. (2019), and Gaunt et al. (2020). We briefly outline the data acquisition and the data  
138 treatment done in these three studies before describing our modification. The petrological and textural  
139 analysis of the samples was carried out in the three studies according to the procedures outlined in Burgisser  
140 et al. (2010) and Drignon et al. (2016). Polished sections were imaged by Scanning Electron Microscopy  
141 (SEM) or by element mapping based on Energy Dispersive Spectroscopy (EDS). Images were taken at  
142 several magnifications depending on the average size of the vesicles and crystals. Images were used to  
143 quantify the amounts of vesicles, glass, phenocrysts, and microlites in the samples by manually tracing each  
144 of the elements (SEM) or by automatic thresholding and by successive subtractions of Boolean combinations  
145 of the binary images of the analyzed elements (EDS). The segmented images were then used to measure the  
146 proportions of phenocrysts, microlites, and vesicles. In this study, we use “vesicles” and “vesicularity” to  
147 characterize voids regardless of genesis. We use “bubbles” and “porosity” to characterize voids resulting  
148 from the exsolution of magmatic volatiles.

149

150 Imaged vesicles were subdivided in four types (Fig. 2, Burgisser et al. 2010; Giachetti et al. 2010). The  
151 first type was composed of large, deformed vesicles of equivalent diameter  $>300 \mu\text{m}$  and circularity  $<0.2$ .  
152 The second type was composed of small, rounded vesicles of equivalent diameter  $<40 \mu\text{m}$  and circularity  
153  $>0.65$ . The third type was composed of large angular voids between crystal fragments and of irregular voids  
154 delimited by crystal faces that are found in dense, diktytaxitic samples. The last type was composed of the  
155 remaining vesicles, which are of intermediate sizes and often composed of coalesced bubbles. Type 1  
156 vesicles were caused by degassing during magma ascent from the reservoir. The sudden decompression

157 linked to the explosion nucleated new, syn-explosive bubbles. The first syn-explosive bubbles are of Type 4  
158 because they had enough time to grow and coalesce before quenching. The latest syn-explosive bubbles are  
159 of Type 2 because they were quenched as small, isolated vesicles. Finally, Type 3 vesicles that are gaps  
160 between crystal fragments result from crystal failure caused by the decompression accompanying conduit  
161 evacuation. The remaining Type 3 vesicles found in diktytaxitic samples are likely due to reorganization of  
162 voids under shear (Laumonier et al. 2011).

163  
164 The recompression model of Burgisser et al. (2010) assumes that, prior to explosion, the piece of magma to be  
165 ejected is at a pressure  $P_i$  and porosity,  $\phi$ , with water weight fraction distributed as exsolved,  $x_i$ , and  
166 dissolved,  $s_i$ . The clast is quenched at pressure  $P_q$ , porosity  $\phi_q$ , and dissolved water content,  $s_q$ . Quench  
167 porosity,  $\phi_q$ , is the sum of volume fractions of the four vesicle types. Only Type 1 vesicles were present in the  
168 conduit prior to the explosion. Type 2 vesicles nucleate during the explosion but were not affected by  
169 outgassing. Type 3 and 4 vesicles both appeared during the explosion and could participate to outgassing  
170 because they feature various degrees of interconnection. The weight fraction of the exsolved water content at  
171 quench time is thus composed of an outgassed part,  $x_{out}$ , and a part remaining within the clast that is divided  
172 into three weight fractions:  $x_{q1}$  (Type 1 vesicles),  $x_{d1}$  (Type 2 vesicles), and  $x_{q2}$  (Type 3 and 4 vesicles).  
173 Similarly, quench pressures differ from pre-explosive pressures. The conversion from quench to pre-  
174 explosive conditions (Fig. 2) was done by a mass balance linking the state of the magma just before the  
175 explosive event (pre-explosive state characterized by  $P_i$ ,  $\phi$ ,  $s_i$  and  $x_i$ ) to that once the magma has quenched  
176 (quench state characterized by  $P_q$ ,  $\phi_q$ ,  $s_q$ ,  $x_{q1}$ ,  $x_{d1}$ , and  $x_{q2}$ ).

177  
178 Model input data are the magma temperature, the densities of melt and crystals at that temperature,  $\phi_q$ ,  
179 and, to obtain  $P_i$ , one of plagioclase microlite content, or glass water content. In Gaunt et al. (2020),  $P_i$  was  
180 obtained by converting the glass-referenced volume proportions of plagioclase microlites of each sample into  
181 pressure. In Drignon et al. (2016) and Burgisser et al. (2019),  $P_i$  was calculated by using the glass water  
182 content determined by elemental analyzer and converting successively glass water content into dissolved  
183 water content and into pressure with a solubility relationship. The original recompression model has four free  
184 parameters (Burgisser et al. 2010). The first one,  $O = x_{out}/(x_{q1} + x_{q2} + x_{d1} + x_{out})$ , quantifies the gas fraction



185 outgassed during the explosion to propel the ejecta. This poorly constrained parameter, which has a modest  
186 effect on pre-explosive values (Burgisser et al. 2010), is assumed to lie between 10% and 70–82% with a  
187 reference value of 50%. The second parameter,  $H$ , estimates the maximum, near-instant pressure drop that  
188 clasts can sustain before breaking (Mueller et al. 2008) as a proxy for quench pressure. In other words,  $P_q$  is  
189 the smallest of  $P_i$  and  $P_{atm} + H P_{Mueller}$ , where  $P_{atm}$  is the atmospheric pressure,  $P_{Mueller}$  is the value of the  
190 pressure drop, and  $H$  is a multiplicative factor that was assumed to lie between 0.5 and 2 with a typical value  
191 of 1. The upper limits of  $O$  and  $H$  were chosen so that the maximum total water content of every clast lies  
192 below that inferred in the reservoir and that all clasts undergo syn-explosive inflation so as to match textural  
193 observations. The upper values of  $O$  were 70, 76, and 82% for Tungurahua, Soufrière Hills, and Merapi,  
194 respectively. The two last parameters of the model quantify the proportions of vesicles:  $E=(x_{d1}+x_{q2})/x_{q1}$  and  
195  $F=x_{d1}/x_{q1}$ . As vesicle types occur in similar proportions in the products of a given explosion, Burgisser et al.  
196 (2010) and the authors of the three data set studied herein (Drignon et al. 2016; Burgisser et al. 2019; Gaunt  
197 et al. 2020) used a lumped approach; they averaged vesicle proportions in all samples of a given explosion.  
198 They then calculated  $E$  and  $F$  using the median proportions and standard deviations of each vesicle type.  
199  
200 In this study, we attempted to gain precision in the pre-explosive porosities by considering for each clast the  
201 respective proportions of the vesicle types. These proportions were published in the original studies. Using  
202 individual vesicle proportions means that  $E$  and  $F$  were no longer considered as free parameters with a  
203 median value and a standard deviation. Instead, they were considered as input parameters with an assumed  
204 negligible uncertainty, which reduced the number of degrees of freedom of the recompression procedure  
205 from four to two. In the Drignon et al. (2016) study of the October 26 event at Merapi, for instance, the  
206 vesicles of Types 1, 2, and 3–4 were present in respective median proportions of 28.4:2.5:70, which yields  
207  $E=2.7$  and  $F=0.14$ . We replaced these median proportions by the individual values of each sample (AME 10  
208 A1: 33.5:3.1:63.4, etc.) to obtain  $E$  and  $F$  values for each sample. Beyond reducing the number of sources of  
209 uncertainties, this modification evidenced a shortcoming of the vesicle size distribution analysis, which led  
210 us to discard data from Drignon et al. (2016) (Supplementary Text S1).

211

212 The recompression model has two types of uncertainty. Analytical uncertainties result from error propagation  
213 of the uncertainties on quench vesicularities, glass water contents, and plagioclase microlite proportions.  
214 Analytical uncertainties for each sample were calculated with four sets of model outputs that used the  
215 reference values of  $H$  and  $O$  and the respective minimum and maximum values of  $\phi$ , microlite content and/or  
216 glass water content. Analytical errors on pre-explosive porosity are small in absolute value ( $<1$  vol%). Our  
217 new procedure with fewer free parameters does not significantly affect these absolute errors ( $<15\%$ ).  
218 Similarly, errors on pre-explosive pressure are modified by  $<10\%$  and typically by  $<2\%$ . These changes will  
219 not be discussed further as they are smaller than those stemming from model uncertainties. This second type  
220 of uncertainty results from propagation of the uncertainties on  $H$  and  $O$ . The reference values and bounds of  
221 these two parameters were combined to yield five sets of pre-explosive pressures and porosities. The set with  
222 the reference values was kept as the average set and the two sets with the largest and smallest porosity values  
223 at any pressure were kept as extrema to characterize model uncertainty. Only these three sets are reported in  
224 the Results section.

225  
226 In the case of a rigid crystal network with crystal volume fraction  $\phi_x$  between 0.4 and 0.7, the minimum  
227 porosity required to make percolation possible (i.e. the percolation threshold),  $\phi_{cr}$  (Fig. 2), follows a third-  
228 degree polynomial equation-:

$$229 \quad \phi_{cr} = a\phi_x^3 - b\phi_x^2 + c\phi_x + d \quad (1)$$

230 where the constants are  $a=0.7495$ ,  $b=0.4268$ ,  $c=-0.1626$ , and  $d=0.1478$  for Degruyter et al. (2019) or  $a=2.75$ ,  
231  $b=2.79$ ,  $c=0.6345$ , and  $d=0.0997$  for Parmigiani et al. (2017). The difference between these two sets of  
232 constants is due to the initial conditions chosen for the bubbles. In the case of Parmigiani et al. (2017), the  
233 initial positions of the bubbles and their respective size was set randomly, whereas these parameters followed  
234 a spinodal distribution in the case of Degruyter et al. (2019). A spinodal distribution means that the size and  
235 the position of bubbles satisfy the principle of mass conservation and capillary stresses, which leads to more  
236 consistent and more accurate initial conditions. This higher level of physical verisimilitude led us to use the  
237 set of parameters of Degruyter et al. (2019).

238  
239 The vesicle-free crystal content,  $\phi_{xvf}$ , is related to  $\phi_x$  by (Fig. 2):

240  $\phi_x = (1 - \phi)\phi_{xvf}$  (2)

241 Drignon et al. (2016) reported bulk volume fractions of vesicles, phenocrysts and microlite, from which  $\phi_{xvf}$   
242 (Table 1) was calculated using Eq (2). Burgisser et al. (2019) reported  $\phi_q$  and  $\phi_{xvf}$ . We used their original  
243 unpublished quantifications of microlites to obtain vesicle-free volume fractions of phenocrysts. Gaunt et al.  
244 (2020) reported bulk volume fractions of vesicles, of plagioclase and pyroxene phenocrysts, and of  
245 plagioclase and pyroxene microlite. We used their original unpublished quantifications of oxide phenocrysts  
246 and microlites to calculate  $\phi_{xvf}$ .

247  
248 For a given vesicle-free crystal content, there is one critical porosity such that  $\phi = \phi_{cr}$ :

249  $a(1 - \phi)^3 \phi_{xvf}^3 - b(1 - \phi)^2 \phi_{xvf}^2 + c(1 - \phi)\phi_{xvf} + d - \phi = 0$  (3)

250 For each  $\phi_{xvf}$  within the 40–70% interval, we solve equation (3) to obtain a solution  $\phi_{cr} = f(\phi_{xvf})$ . The associated  
251 uncertainties,  $d\phi_{xvf}$ , were obtained by error propagation and mostly reflect natural variability. Uncertainties  
252 on the critical porosity,  $d\phi_{cr}$ , were calculated using the variation of the  $f$  function:  $d\phi_{cr} = df(d\phi_{xvf})$ .

253

## 254 Results

255 Considering the vesicle proportions of each sample instead of an average value does not change much  
256 (<17%) the final values of pre-explosive pressures (Fig. S1). When using microlites (Gaunt et al. 2020), no  
257 pressure change occurs because the power-law relationship linking microlite proportion to pressure does not  
258 depend on vesicle content. Pre-explosive porosities are more influenced by this reduction of free parameters.  
259 Samples located at pressures >10 MPa change by <10% from the original value. Shallower samples undergo  
260 porosity changes of up to 25% with one outlier at 40% (Fig. S2), but the general trend with pressure remains  
261 (Fig. S1). Changes in model uncertainties compared to the ones from the original studies are small but  
262 uneven between data points, varying by <15% from the original value except for a couple of samples with  
263 vanishing porosity. As a result, the overall respective envelopes of model uncertainties are similar for each  
264 volcano.

265

266 Two conditions need to be met for outgassing to occur by channelling (Parmigiani et al. 2017; Degruyter et  
267 al. 2019). The first condition is that total crystal content must be between 40 and 70 vol%. Provided the  
268 germane amount of crystals, the second condition is that a critical porosity is reached. Channelling allows  
269 gas escape at very low gas volume fraction with a percolation threshold below 10 vol%. We used the critical  
270 values given by the empirical relationship of Degruyter et al. (2019) because they correspond to more  
271 realistic initial conditions, but similar results are found when using the Parmigiani et al. (2017) values. To  
272 take the empirical nature of these fits into account, we also considered the maximum and minimum  
273 percolation values they yield within the validity bounds of crystal content (5 and 12 vol% porosity,  
274 respectively). Once channelling is established, outgassing rate is controlled by a balance between magma  
275 permeability, driving pressure, and the collapse rate of the medium. As a result, outgassing could evacuate  
276 more gas than the critical porosity. Such hysteresis has been proposed to occur at low (Rust and Cashman,  
277 2004; Michaut et al. 2009; Gonnermann et al. 2017) and high crystal contents (Colombier et al. 2020), albeit  
278 not by channelling. In the absence of more specific evidence, we considered that non-vanishing porosities  
279 lower than the percolation threshold could result from channel collapse.

280

281 To test if channelling could explain low porosity distributions within volcanic conduits before explosion, we  
282 assessed to which extent these two conditions of crystallinity and porosity were met in three sets of data on  
283 andesitic products from different volcanoes. These datasets are composed of the pressures associated with  
284 the corresponding pre-eruptive porosities and of the amounts of phenocrysts (which are generally already  
285 present in the magmatic chamber) and microlites (which develop during magma ascent). It is important to  
286 consider these two populations of crystals since they could, depending on how their amounts change during  
287 ascent, prevent or enhance channelling.

288

## 289 Montserrat

290 The amounts of “phenocrysts” and “phenocrysts plus microlites” in the Soufrière Hills samples from 2010  
291 are plotted in Fig. 3a. Microlite crystallization during ascent increased the total amount of crystals from 30  
292 vol% to approximately 55 vol% on average, thereby helping channelling to develop. Figure 3b shows pre-

293 explosive porosities of the samples, of closed-system degassing, and of the channelling threshold. All  
294 threshold porosities are within a narrow range smaller than 5 vol%. Considering that all samples have a  
295 porosity well below that of closed-system degassing, it means that most of the gas present in the conduit has  
296 been lost. Physical conditions propitious to channelling were thus probably met during ascent. However, it  
297 appears that most measured porosities are slightly below the threshold values, except two points among the  
298 shallowest samples and one point around 57 MPa that are slightly above threshold. This situation indicates  
299 that, if channelling occurred, a little more than the gas in excess of the threshold value has been lost,  
300 deflating the magma back below the critical porosity.

## 301 Merapi

302 Data from the October 26, 2010 Merapi eruption are particularly interesting because they provide  
303 information down to ~10 km (270 MPa), which is close to the pure water exsolution level for that eruption  
304 (Erdmann et al. 2016; Drignon et al. 2016). Estimating the exsolution level at Merapi is a complex task  
305 because 1) a significant amount of CO<sub>2</sub> coexisted with H<sub>2</sub>O in the gas phase and 2) the magmas feeding the  
306 2010 eruption were stored at multiple levels and mixed prior to their final ascent towards the surface (Costa  
307 et al. 2013; Nadeau et al. 2013; Preece et al. 2014; Erdmann et al. 2016; Widiyantoro et al. 2018). The  
308 mixing process started by magma assembly at depth and continued during ascent. This induced complexities  
309 in the crystal cargo that hinders straightforward interpretations of porosity and crystal contents  
310 (Supplementary Text S2). Here, we framed the likely conduit conditions according to the experimental  
311 results of Erdmann et al. (2016) by performing two closed-system, multicomponent decompressions.  
312 Following Drignon et al. (2016), we used the model D-Compress (Burgisser et al. 2015) to simulate the  
313 porosity evolution of rhyolitic melts undergoing isothermal, equilibrium decompression at NNO+1. The first  
314 decompression represents the hotter recharge magma at 975 °C. It starts from 250 MPa with 5 wt% melt H<sub>2</sub>O  
315 content and 400 ppm melt CO<sub>2</sub> content, which yields a CO<sub>2</sub>/H<sub>2</sub>O molar ratio of 0.2. The second represents  
316 the colder resident magma at 925 °C. It starts from 175 MPa with 3 wt% melt H<sub>2</sub>O content and 500 ppm melt  
317 CO<sub>2</sub> content, which yields a CO<sub>2</sub>/H<sub>2</sub>O molar ratio of 0.66. The resident and recharge magmas were mixed in  
318 a way that we expect to fall within these two end members. The initial porosity is mostly unconstrained, so  
319 we considered a small (<< 1 vol%) and a large (10 vol%) value for each magma.

320

321 Figure 4a shows the phenocrysts and total crystal content for Merapi conduit prior to the October 26  
322 explosion. Unlike at Soufrière Hills, phenocrysts alone are already within the range for which channelling is  
323 possible. The amount of crystals already present in reservoir(s) was thus sufficient to foster outgassing at  
324 depth without magma ascent if sufficient gas was present. There was also enough time for the awakened  
325 reservoir to degas during the weeks to months prior to eruption (Budi-Santoso et al. 2013). If microlites are  
326 taken into account, however, the total crystal content clearly rises above 70 vol% in most of the magmatic  
327 column. Thus, if outgassing occurred by channelling, this outgassing mechanism took place earlier or during  
328 the first phase of microlite crystallization. Once 70 vol% of crystals was reached, channelling mostly likely  
329 stopped.

330

331 Pre-eruptive porosities, percolation thresholds, and associated uncertainties are shown in Fig. 4b. Above ~70  
332 MPa, samples suggest that the conduit was filled with nearly gas-free magma, well below percolation  
333 threshold. This observation makes the two scenarios starting with high initial porosities unlikely, so they  
334 were not given further consideration. Assuming that the porosity evolution was controlled by an initially gas-  
335 poor recharge magma, no bubbles are expected at pressures higher than 250 MPa, which is consistent with  
336 the very small values (<1 vol%) of the samples located around that pressure. At ~150 MPa, the gas available  
337 by closed-system degassing matches that needed for channelling (black line on Fig. 4b) although measured  
338 porosities are well below percolation. Assuming instead that the eruptive products sampled the resident  
339 magma brings the pressure at which closed-system porosities are within the threshold range from 150 to 70  
340 MPa (green line on Fig. 4b). This situation is compatible with the vanishing measured porosities at higher  
341 pressure and the fact that porosities increase below 70 MPa while remaining below the threshold porosities.

342

343 The combined data of Figs. 4a and 4b suggest that deeper than 3 km (70 MPa), there was not enough gas  
344 available in the reservoir to be outgassed despite the favourable phenocryst content for channelling. Between  
345 3 km and the surface, however, gas contents stemming from closed-system degassing would have been high  
346 enough for outgassing to occur. Shallower than 3 km, crystal contents vary from 40–50 vol% before  
347 microlite crystallization, to more than 70 vol % post-crystallization. If the shallow magma column stagnated

348 while (or before) microlite crystallization occurred, channelling could have started before microlite  
349 crystallization and continued until 70 vol% of crystals was reached. If the magma still contained substantial  
350 gas volume fraction once this high limit of crystallinity reached, other mechanisms, such as cracks due to  
351 brittle failure of the melt, should be evoked to explain further outgassing. In any case, the degassing trends  
352 suggest that the analysed clasts sampled the colder resident magma. As in the case of Soufrière Hills, pre-  
353 eruptive shallow samples display porosities below the critical threshold, possibly suggesting outgassing  
354 accompanied by deflating.

## 355 Tungurahua

356 Storage conditions at Tungurahua were more H<sub>2</sub>O-rich than at Merapi, with a molar fraction of H<sub>2</sub>O in the  
357 gas phase of 0.8 (Andújar et al. 2017). As a result, D-Compress runs with mixed H<sub>2</sub>O-CO<sub>2</sub> fluids do not  
358 differ much from pure H<sub>2</sub>O ones, and closed-system decompressions with pure water were assumed instead  
359 for simplicity. Porosities and crystal contents from Tungurahua give information from the surface down to ~7  
360 km depth (170 MPa), which, like at Merapi, is deep enough to constrain the point at which gas loss starts.  
361 Similarly to Soufrière Hills, phenocrysts in the Tungurahua magma cannot trigger channelling alone (Fig.  
362 5a). The total amount of crystals, however, approaches the lower limit of 40% around 100 MPa, and exceeds  
363 it for pressures lower than 50 MPa. This implies that microlites were required for channelling to occur  
364 possibly around 100 MPa, and more certainly around 50 MPa. Near the surface, the upper limit of 70% is  
365 overcome, stopping channelling and potentially fostering a shallow gas-rich area that appears clearly on the  
366 porosity data with values spanning from 25% to 50 vol% (Fig. 5b). Closed-system porosities suggest that gas  
367 was available for channelling at ~150 MPa, although the amount of crystals was not sufficient at this depth to  
368 foster channelling (Fig. 5a). The first calculated pre-eruptive porosity approaching the channelling threshold  
369 is located around 110 MPa and the first pre-eruptive porosity which effectively coincides with that threshold  
370 appears at ~50 MPa (Fig. 5b). As a result, gas loss by channelling may have started between 110 and 50 MPa  
371 and was no longer possible below 10 MPa.

372

## 373 Discussion

374 Our data show that, to first order, channelling is a process that is consistent with the low porosities inferred  
375 in volcanic conduits prior to Vulcanian explosions. That channelling can occur during ascent due to an  
376 increase in crystal content brings a partial answer to the long-standing issue of gas transfer across the entire  
377 depth of magmatic systems (e.g., Oppenheimer et al. 2009) despite sometimes very high magma viscosity  
378 and no obvious physical mechanism of transfer (Edmonds et al. 2010). Gas percolation in magmas has long  
379 been studied in decompression experiments, which have notably shown that the presence of >20 vol%  
380 crystals lowers percolation thresholds compared to crystal-poor melts (Lindoo et al. 2017; deGraffenried et  
381 al. 2019). Such type of viscous percolation occurs when bubbles can expand spherically while pushing  
382 crystals apart (Colombier et al. 2020).

383  
384 The percolation associated with channelling, on the other hand, is fostered by buoyancy-driven deformation  
385 of the bubbles in the constricted space between crystals and subsequent coalescence at moderate to low Bond  
386 numbers. Additional processes can also form similar channel-like interconnected porous pathways at low  
387 critical porosity in crystal-rich magmas. For instance, Colombier et al. (2020) showed that brittle-viscous  
388 coalescence is favoured at melt viscosities higher than  $10^6$  Pa.s and relatively high gas overpressure. Because  
389 of such alternatives, conditions adverse to channelling do not imply the absence of outgassing. Figure 7  
390 shows a literature compilation of vesiculation experiments on crystal-free to crystal-rich magmas and magma  
391 analogues (Gardner et al. 2000; Larsen and Gardner 2000; Mangan and Sisson 2000; Gardner 2007;  
392 Takeuchi et al. 2009; Shea et al. 2010; Okumura et al. 2012; Martel and Iacono-Marziano 2015;  
393 Oppenheimer et al. 2015; Preuss et al. 2016; Colombier et al. 2020). Data is tallied in crystal-poor (<10  
394 vol%), moderately crystal-rich (10-40 vol%), and crystal-rich (>50 vol%) categories, as well as whether  
395 samples underwent closed-system degassing, or bore connected bubbles networks able to outgas. Figure 7  
396 suggests that experimental magma outgassing has only been explored in low-pressure, shallow conditions,  
397 which contrasts with our deep-seated determination of channelling during magma ascent. This compilation  
398 also confirms that high crystal contents promote outgassing at low percolation thresholds.

399  
400 The conditions leading to channelling are based on several key assumptions (Parmigiani et al. 2017;  
401 Degruyter et al. 2019), the validity of which must be assessed in the case of conduit flow. One is that



402 capillary forces dominates buoyancy forces so that the Bond number is 0.1-1. The Bond number depends on  
403 gravity, the density difference between melt and gas, the surface tension, and the radius of the gas bubbles. A  
404 reasonable estimate for the melt density of the three studied volcanoes is  $2300 \text{ kg/m}^3$ . According to  
405 Lyakhovsky et al. (1996), surface tension can be taken as  $0.05 \text{ N/m}$ . The most variable quantity is bubble size  
406 because it depends highly on the pressure and bubble number density. A Bond number between 0.1 and 1  
407 implies a bubble radius between 0.2 and 0.8 mm. At depth, bubbles that size and smaller were likely, and the  
408 assumption of dominating capillary forces holds. The possibility that bubbles adhere to crystal surfaces was  
409 also left aside. This is a reasonable assumption in conduit conditions because microlites are mostly composed  
410 of non-wetting phases like plagioclase in arc magmas. We note, however, that wetting phases like Fe-Mg  
411 silicates or Fe-Ti oxides are also present, which suggests that investigating how crystal adherence affects  
412 bubble channelling is a worthy pursuit.

413  
414 Two other assumptions of Parmigiani et al. (2017) and Degruyter et al. (2019) are that the ambient pressure  
415 is hydrostatic and that the crystal framework remains static during the onset of channelling. The lower  
416 crystallinity limit of 40 vol% stems from the assumption that crystalline matrix resists frictional sliding,  
417 which corresponds to a random loose packing. Their synthetic crystal size and shape distributions aim to  
418 represent a scaled version of phenocrysts prevailing in storage conditions. Microlite crystallization during  
419 ascent yielded in our three studied cases linear to concave-up crystal size distributions with a significant  
420 proportion of highly elongated microlites. Random loose packing and frictional effects in such distributions  
421 occur at volume fraction lower than 40 vol%, possibility as low as 8 vol% (Saar et al. 2001; Guo et al. 2013).  
422 The bubble coalescence leading to channelling, however, is controlled by how much interstitial space occurs  
423 between crystals, which is inversely proportional to the cubic root of crystal volume fraction. It is thus  
424 unlikely that the onset of channelling occurs at crystallinities much lower than that proposed by Parmigiani  
425 et al. (2017), depending on crystal shapes and sizes. Similarly, the transition from channelling to bubble  
426 trapping could also occur at a different (yet probably close to) volume fraction than the 70 vol% determined  
427 numerically.

428

429 Bubble trapping assumes a static solid matrix. It is no longer static when either local overpressure occurs, or  
430 a far-field stress is applied to the medium, which are two likely processes in ascending magmas. Different  
431 regimes of matrix deformation by local gas overpressure exist. Analogue experiments (Holtzman et al. 2012;  
432 Oppenheimer et al. 2015) show that a regime of slow solid matrix rearrangement occurs at the random loose  
433 packing, when gas bubbles begin to deform. This change is insensitive to liquid viscosity in the range 10-  
434 1000 Pa s. Another regime of rapid deformation of the immersed granular medium by gas-induced  
435 overpressure has been described as “venting” (Varas et al. 2015) or “capillary fracturing” (Holtzman et al.  
436 2012). It occurs near the random close packing (Oppenheimer et al. 2015), and it is characterized by gas  
437 migration in a fracture-like manner. These regimes have recently been proposed to play a role in Strombolian  
438 dynamics when gas proportions are large and melt viscosities low ( $<5$  Pa s; Barth et al. 2019; Oppenheimer  
439 et al. 2020). It is unclear yet probable that outgassing by channelling leads to limited grain displacement in  
440 melts of much higher viscosity. The two values of crystal content framing channelling are thus reasonable  
441 estimates that will be refined when reproduced experimentally with the assumption of static solid matrix  
442 relaxed. As the same reasoning holds for the critical porosity (Eq. (3)), the shaded regions in Fig. 3b, 4b, and  
443 5b indicate the two extreme values ever reached by numerical simulations of channelling (Degruyter et al.  
444 2019). Considering only these extreme values does not change the conclusion that conditions for channelling  
445 were met in the three studied cases.

446  
447 Once channelling is established, gas evacuation can proceed to the point of fracture healing if large-scale  
448 stresses are applied (Caricchi et al. 2011; Laumonier et al. 2011; Heap et al. 2015). Such gas expulsion is  
449 thus expected in a crystal-rich magma sheared along a volcanic conduit (e.g., Thomas et al. 2019). Provided  
450 that Eq. (3) is accurate, this is the most probable explanation of the porosities close to but lower than the  
451 critical porosity at Soufrière Hills and Merapi (Figs. 3b and 4b). We reiterate that channelling in deforming  
452 suspension remains to be quantified to add weight to our inferences.

453  
454 At Tungurahua, conditions for channelling were met between 110 MPa and a gas-rich region located at 1-10  
455 MPa. Outgassing, however, could have happened through other mechanisms such as viscous percolation in  
456 the main part of the conduit owing to the low melt viscosity ( $10^{3.7}$  Pa s at the reservoir level, Chevrel et al.

457 2015), or brittle-viscous coalescence shallowly, where much higher melt viscosities are expected. Figure 6  
458 shows closed-system degassing paths for three starting points: at 200 MPa (reservoir level, Andújar et al.  
459 2017), at 108 MPa, and at 34 MPa. These intermediate pressures correspond to the samples closest to the  
460 points where total crystal contents reach and exceed the lower bound for channelling, respectively. The  
461 decompression starting at 108 MPa overestimates shallower porosities, whereas that starting at 34 MPa  
462 closely follows the trend of the most porous samples. That the measured shallow porosities can be explained  
463 by decompressing the residual porosity around 40 MPa suggests that gas loss by channelling was enabled by  
464 microlite crystallization between 100 and 40 MPa (1.6-2.9 km depth). The gas-rich region at 1-10 MPa (40-  
465 400 m depth) could be due to the ascent of material immediately below that was fast enough to minimize  
466 outgassing, or to gas accumulation. Accumulation implies that outgassing was inefficient close to the surface.  
467 This could be caused by a combination of hindered channelling at high crystal content, hindered brittle-  
468 viscous coalescence because of insufficient gas overpressure, and impermeable plug and conduit walls. Gas  
469 accumulation is supported by the near-surface observation that measured porosities decrease to very low  
470 values (<1 vol%), revealing the presence of a low permeability, rigid plug (Gaunt et al. 2020). Since the  
471 amount of crystals is very high in this plug, cracks or bubble connections (e.g., Heap et al. 2014) were not  
472 efficient enough to evacuate the residual gas, thereby allowing the gas-rich region to form.

473  
474 Our results suggest that outgassing by channelling could have occurred down to (and probably deeper than)  
475 2.7 km at Soufrière Hills, shallower than 3 km depth at Merapi, and between 1.5 and 3 km at Tungurahua.  
476 One implication of such widespread channelling depths is that, besides rapidly changing magma rheology to  
477 possibly trigger more explosive eruptions (Arzilli et al. 2019), microlite could also spur gas escape. Another  
478 implication is that outgassing by channelling could occur regardless of near-surface conditions such as the  
479 presence of a dome, a plug, or a permeable wallrock. Finally, the permeabilities reached by channelling are  
480 high for magmas in general, and several orders of magnitude higher than commonly admitted permeabilities  
481 at low porosity (e.g., Farquharson et al. 2015; Kushnir et al. 2016). Such high permeabilities would affect  
482 transitions in eruptive style (Cassidy et al. 2018), and the corresponding permeability relationships given by  
483 Parmigiani et al. (2017) and Degruyter et al. (2019) can readily be tested in conduit flow models.

## 484 Conclusions

485 We revisited three reconstructions of porosity and crystal distributions prior to Vulcanian events that  
486 occurred respectively on February 10, 2010 at Soufrière Hills volcano, Montserrat (Burgisser et al. 2019), on  
487 October 26, 2010 at Merapi volcano, Indonesia (Drignon et al. 2016) and on July 14, 2013 at Tungurahua  
488 volcano, Ecuador (Gaunt et al. 2020). They all feature porosities too low to be explained by common shallow  
489 processes such as connected bubble pathways or cracks. Our data show that these magmas have high enough  
490 crystal contents for outgassing to occur by a process named channelling. When the amount of crystals in a  
491 three-phase magma lies within the 40-70 vol% range, the interstitial space is narrow enough to force bubbles  
492 to form channels in which the gas buoyantly moves upwards but not so constricted that channel connections  
493 are ruptured (Parmigiani et al. 2017). Channelling creates gas permeability of the order of  $10^{-10}$  m<sup>2</sup>, which is  
494 two to five orders of magnitude higher than the other permeability processes at the equivalent bubble  
495 content.

496  
497 At Soufrière Hills, microlite crystallization during ascent yielded conditions propitious to channelling from  
498 near surface down to a depth greater than 2.7 km. If confidence is given in the critical porosity  
499 quantification, outgassing deflated the magma slightly below the critical porosity, which suggests that large-  
500 scale stresses such as those related to conduit wall shearing were also at play in controlling the evolution of  
501 porosity during ascent.

502  
503 At Merapi, the phenocrysts in the reservoirs could have fostered outgassing at depth without magma ascent.  
504 Closed-system degassing in response to ascent, however, only yielded enough gas for channelling at mid-  
505 conduit depths. The part of the conduit where both gas contents were large enough and calculated porosities  
506 fall within the percolation range is located around 3 km depth. In this region and in the shallower parts of the  
507 conduit, outgassing by channelling could have taken place during (and possibly before) microlite  
508 crystallization but before the 70% crystal content was reached. This suggests that the strong gas depletion in  
509 the magma column could have resulted from weak exsolution at the beginning of the ascent followed by  
510 channelling at depths shallower than 3 km. Of the two end-member magmas involved in the eruption that we

511 considered in our analysis, this degassing behaviour is best explained if the conduit was filled by the colder  
512 resident magma.

513

514 At Tungurahua, outgassing by channelling was enabled by microlite crystallization at 1.6–2.9 km depth.  
515 Near the surface, a low permeability plug trapped a gas-rich region between 40 and 400 m depth. Inefficient  
516 outgassing between 1.6 km and the gas accumulation region was probably caused by a combination of  
517 hindered channelling at high crystal content, hindered brittle-viscous coalescence because of insufficient gas  
518 overpressure, and impermeable plug and conduit walls. This suggests that the triggering of the paroxysmal  
519 explosion was controlled by near-surface gas trapping.

520

521 We presented lines of evidence for deep gas loss prior to sudden explosive emissions of three basaltic  
522 andesitic to andesitic magmas. They suggest that channelling is a viable mechanism for gas to be removed  
523 from the magma column at various levels during ascent, yielding mostly gas-depleted magma columns prior  
524 to eruption. Such outgassing by channelling could thus influence eruptive style. Depending on the  
525 phenocryst content, microlite growth during ascent can either foster, or impede gas escape by channelling.  
526 Considering the pervasive occurrence of microlites and ensuing high crystal contents in volcanic conduits,  
527 the high likelihood of outgassing by channelling implies that other outgassing mechanisms might not be as  
528 dominant as previously envisioned.

529

## 530 Tables

531 **Table 1:** Pre-explosive volatile proportions, vesicle-free crystal proportions, and pressures. Values in  
 532 parenthesis are relative uncertainties in % except for the pressure, where they indicate lower and upper  
 533 bounds of uncertainties in MPa. Uncertainties on phenocryst content are sometimes very low (<1%), which  
 534 reflects that few SEM images were imaged to characterize phenocrysts. Uncertainties on the total crystal  
 535 fraction include those due to microlite, which are obtained from a larger number of images. They thus reflect  
 536 more accurately the natural spatial variability.

	Pressure (MPa)	Porosity <sup>a</sup> (vol%)	Gas <sup>b</sup> (ppmw)	Phenocrysts (vol%)	Crystals (vol%)
Soufrière Hills					
AMO 210 A	40 (-9,+10)	1.9 (1)	0.6	34 (2)	54 (10)
AMO 210 C	51 (-25,+31)	2.3 (2)	0.92	34 (12)	55 (22)
AMO 210 D	14 (-3,+3)	1.9 (1)	0.2	31 (6)	39 (11)
AMO 210 E	54 (-19,+22)	3.5 (0)	1.54	48 (0.3)	69 (9)
AMO 210 F	33 (-8,+9)	1.6 (1)	0.41	50 (2)	66 (13)
AMO 210 G	42 (-13,+15)	1.2 (3)	0.39	40 (12)	63 (11)
AMO 210 H	12 (-5,+6)	8.5 (1)	0.89	39 (8)	65 (12)
AMO 210 L	46 (-13,+14)	1.4 (2)	0.52	59 (3)	77 (6)
AMO 210 Q	41 (-7,+7)	3.4 (1)	1.14	32 (1.3)	40 (14)
WP1.095A	24 (-5,+5)	4.3 (0)	0.86	24 (0.4)	52 (3)
WP1.095B	16 (-6,+7)	7.2 (0)	0.95	32 (0.2)	59 (9)
WP1.108A	31 (-5,+5)	2.8 (0)	0.72	32 (0.3)	52 (10)
WP1.108B	56 (-5,+5)	7.8 (1)	3.68	36 (1.1)	48 (3)
WP2.200A	36 (-8,+9)	2.8 (0)	0.81	42 (0.3)	63 (19)
WP2.200B	31 (-2,+2)	3 (0)	0.76	31 (0.7)	42 (3)
WP2.201A	35 (-8,+9)	4.6 (0)	1.33	45 (0.2)	59 (10)
WP2.201B	69 (-14,+15)	2.4 (0)	1.36	31 (0.2)	51 (8)
WP2.329A	7 (-1,+1)	23.6 (0)	1.62	11 (1.2)	27 (15)
WP2.329B	41 (-4,+4)	2.7 (1)	0.89	51 (2)	65 (3)
Merapi Oct. 26					
AME 10 A1	75 (-22,+25)	2.3 (4)	1.27	33 (7)	70 (11)
AME 10 A2	100 (-34,+38)	1.5 (4)	1.12	44 (8)	79 (8)
AME 10 A3	150 (-123,+174)	1.2 (3)	1.32	40 (3)	82 (11)
AME 10 A4	100 (-22,+24)	1.6 (5)	1.16	45 (8)	80 (8)
AME 10 A5	73 (-25,+29)	2.4 (3)	1.32	47 (5)	76 (6)
AME 10 A6	58 (-12,+13)	3.1 (2)	1.32	46 (3)	72 (5)
AME 10 B1	158 (-48,+53)	0.9 (4)	1.03	41 (9)	80 (10)
AME 10 B2	63 (-11,+12)	2.3 (3)	1.05	50 (5)	72 (8)
AME 10 B4	268 (-106,+118)	0.6 (4)	1.14	36 (6)	87 (6)

AME 10 B5	260 (-153,+184)	0.4 (5)	0.73	44 (13)	87 (12)
AME 10 C1	159 (-57,+64)	1 (1)	1.13	38 (1)	80 (14)
AME 10 C2	141 (-31,+33)	0.7 (2)	0.69	38 (5)	81 (6)
AME 10 C3	55 (-17,+20)	2.8 (2)	1.16	46 (3)	70 (10)
AME 10 C4	77 (-24,+27)	1.4 (3)	0.78	44 (7)	77 (7)
AME 10 D1	107 (-25,+27)	1.1 (3)	0.88	44 (4)	79 (9)
AME 10 D2	85 (-37,+43)	1.4 (5)	0.88	42 (11)	79 (11)
AME 10 D3	64 (-37,+47)	2 (8)	0.96	34 (20)	69 (27)
AME 10 D4	63 (-14,+15)	2.8 (5)	1.34	42 (12)	71 (10)
AME 10 E1	75 (-23,+26)	1.2 (2)	0.67	42 (6)	74 (11)
AME 10 E2	202 (-67,+74)	0.9 (4)	1.26	57 (4)	88 (4)
AME 10 E3	59 (-11,+12)	2 (3)	0.86	43 (9)	74 (8)
AME 10 E4	77 (-15,+16)	1.9 (5)	1.1	45 (10)	72 (8)
AME 10 E5	227 (-78,+87)	0.5 (4)	0.85	45 (12)	86 (11)
AME 10 F1	12 (-5,+5)	2.3 (20)	0.2	21 (23)	54 (17)
AME 10 G1	42 (-16,+18)	2.3 (2)	0.76	52 (5)	75 (7)
AME 10 G2	75 (-54,+75)	1.1 (2)	0.78	51 (6)	82 (11)
AME 10 G3	44 (-21,+25)	0.3 (15)	0.48	41 (9)	70 (12)
AME 10 GA	94 (-25,+28)	2.8 (1)	0.89	48 (10)	81 (9)
AME 10 GB	196 (-80,+92)	1.6 (1)	0.86	47 (8)	88 (8)
Tungurahua					
1	0.8 (-0.2,+0.4)	36.8 (3)	0.33	15 (21)	55 (12)
2	0.5 (-0.1,+0.1)	0 (8)	0	46 (10)	73 (9)
4	0.9 (-0.2,+0.3)	0.9 (11)	0.01	42 (14)	67 (13)
6	0.5 (-0.1,+0.2)	0.3 (30)	0.001	39 (36)	70 (32)
7.5	0.6 (-0.2,+0.3)	0.8 (9)	0.004	30 (12)	62 (12)
11	3 (-1,+1)	0 (1)	0	25 (1.4)	44 (5)
12	109 (-63,+91)	0.3 (1)	0.24	34 (0.8)	38 (5)
13	5 (-2,+9)	44.2 (1)	2.53	32 (2)	48 (14)
14	31 (-17,+68)	8.5 (4)	2.07	38 (4)	45 (6)
16	1.6 (-0.4,+0.5)	15.7 (4)	0.21	31 (3)	55 (5)
17	24 (-8,+16)	1.7 (2)	0.29	36 (6)	43 (6)
18	34 (-15,+41)	6.1 (1)	1.57	34 (2)	43 (6)
20	66 (-14,+20)	1.5 (2)	0.69	31 (3)	36 (4)
21	5 (-3,+8)	3.2 (2)	0.12	36 (3)	51 (10)
22	2 (-1,+5)	0 (4)	0	26 (3)	48 (15)
26	51 (-36,+149)	8 (3)	3.14	32 (2)	39 (9)
27	15 (-5,+10)	8.5 (3)	1.01	34 (5)	42 (8)
28	5 (-2,+9)	36.5 (3)	1.86	29 (6)	45 (12)
29	30 (-17,+82)	7.7 (1)	1.77	30 (0.8)	36 (6)
30	4 (-1,+2)	51.7 (1)	3.14	23 (4)	41 (8)
34	1.2 (-0.3,+0.4)	45 (3)	0.69	25 (2)	53 (6)
35	4 (-1,+2)	11.5 (3)	0.4	28 (3)	46 (5)
36	5 (-1,+2)	8.1 (1)	0.33	30 (2)	47 (7)
38	31 (-14,+38)	10.6 (1)	2.62	39 (2)	45 (4)

39	31 (-17,+67)	1.5 (2)	0.33	34 (5)	40 (7)
40	10 (-0.1,+0.1)	25.7 (2)	2.43	38 (2)	49 (2)
41	174 (-79,+26)	0.3 (2)	0.4	26 (3)	32 (4)

537

## 538 Figure captions

539

540 **Fig.1:** Porosity as a function of pre-explosive pressure for the February 10, 2010 Vulcanian explosion at  
541 Soufrière Hills. Data are from Burgisser et al. (2019) and the «equilibrium» curve corresponds to  
542 closed-system degassing. Other curves are from the open-system degassing conduit flow models of  
543 Clarke et al. (2007), Melnik and Sparks (2002), the MAMMA code (La Spina et al. 2017; Degruyter et  
544 al. 2012), and Collombet (2009)

545 **Fig. 2:** Schematic depiction of the textural elements considered. Clasts represent the magma in “Quench  
546 state”, which is composed of melt (blue), crystals (red), and vesicles (white). Vesicles are pre-  
547 explosive (Type 1), syn-explosive and isolated (Type 2), syn-explosive gaps between broken crystals  
548 (Type 3), and syn-explosive and coalesced (Type 4). Prior to ejection, the magma is in a “Pre-  
549 explosive state”. It is composed of Type 1 vesicles that occupy a smaller volume than in the quench  
550 state because they are stored a high pressure in the conduit. The “ascent from the reservoir” allows the  
551 magma to reach the pre-explosive state in the conduit. If the critical porosity ( $\phi_{cr}$ ) is reached during  
552 ascent, channelling could cause vesicles to form channels that enable outgassing. The far-right panel is  
553 a visual depiction of the definitions of porosity,  $\phi$ , vesicle-free crystal volume fraction,  $\phi_{xvf}$ , and bulk  
554 crystal volume fraction,  $\phi_x$

555 **Fig. S2:** Pre-explosive porosities and associated model uncertainties of this study (Table 1) and those of  
556 Burgisser et al. (2019) (A), Gaunt et al. (2020) (B), and Drignon et al. (2016) (C)

557 **Fig.3:** a) Amount of phenocrysts (red) and phenocrysts plus microliths (blue) relative to pressure for  
558 Soufrière Hills according to Burgisser et al. (2019). The shaded region covers the validity domain for  
559 the development of channelling according to Parmigiani et al. (2017). b) Porosity thresholds calculated  
560 from Degruyter et al. (2019) and associated uncertainties (blue) for Soufrière Hills. Samples with  
561 crystal contents outside the validity range were discarded. Red dots are observed porosities. The



562 associated uncertainties are smaller than the symbols. The green line gives theoretical porosities for a  
563 closed system. The shaded region covers the extreme porosity threshold values

564 **Fig.4:** a) Contents of phenocrysts (red) and phenocrysts plus microlite (blue) as a function of pressure for  
565 Merapi according to Drignon et al. (2016). The shaded region covers the validity domain for the  
566 development of channelling according to Parmigiani et al. (2017). b) Porosity thresholds calculated  
567 from Degruyter et al. (2019) and associated uncertainties (blue) for Merapi. Red dots are observed  
568 porosities and the associated uncertainties are smaller than the symbols. Green and black lines give  
569 theoretical porosities for a closed system with 5 wt% H<sub>2</sub>O and 400 ppm CO<sub>2</sub> in the melt (resident  
570 magma) and with 3 wt% H<sub>2</sub>O and 500 ppm CO<sub>2</sub> in the melt (recharge magma) respectively. The  
571 shaded region covers the extreme porosity threshold values

572 **Fig.5:** a) Contents of phenocrysts (red) and phenocrysts plus microlites (blue) as a function of pressure for  
573 Tungurahua according to Gaunt et al. (2020). The shaded region covers the validity domain for the  
574 development of channelling according to Parmigiani et al. (2017). b) Porosity thresholds calculated  
575 from Degruyter et al. (2019) and associated uncertainties (blue) for Tungurahua. Samples with crystal  
576 contents outside the validity range were discarded. Red dots are observed porosities and the associated  
577 uncertainties are smaller than the symbols. Green line gives the theoretical porosities for a closed  
578 system. The shaded region covers the extreme porosity threshold values

579 **Fig.6:** Comparison at Tungurahua between pre-eruptive porosities (red circles), and theoretical porosities for  
580 closed systems starting decompressing at the reservoir level of 200 MPa (green line), at 108 MPa  
581 (cyan line), and at 34 MPa (magenta line)

582 **Fig.7:** Porosity profile as a function of depth for vesiculation experiments on crystal-free to crystal-rich  
583 magmas and magma analogues. The coloured areas respectively overlap samples with connected  
584 bubbles networks capable of outgassing. All other samples featured closed system degassing. Data are  
585 from Gardner et al. (2000), Larsen and Gardner (2000), Mangan and Sisson (2000), Gardner (2007);  
586 Takeuchi et al. (2009), Shea et al. (2010), Okumura et al. (2012), Martel and Iacono-Marziano (2015),  
587 Oppenheimer et al. (2015), Preuss et al. (2016), and Colombier et al. (2020)

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Table

	Pressure (MPa)	Porosity <sup>a</sup> (vol%)	Gas <sup>b</sup> (ppmw)	Phenocrysts (vol%)	Crystals (vol%)
Soufrière Hills					
AMO 210 A	40 (-9,+10)	1.9 (1)	0.6	34 (2)	54 (10)
AMO 210 C	51 (-25,+31)	2.3 (2)	0.92	34 (12)	55 (22)
AMO 210 D	14 (-3,+3)	1.9 (1)	0.2	31 (6)	39 (11)
AMO 210 E	54 (-19,+22)	3.5 (0)	1.54	48 (0.3)	69 (9)
AMO 210 F	33 (-8,+9)	1.6 (1)	0.41	50 (2)	66 (13)
AMO 210 G	42 (-13,+15)	1.2 (3)	0.39	40 (12)	63 (11)
AMO 210 H	12 (-5,+6)	8.5 (1)	0.89	39 (8)	65 (12)
AMO 210 L	46 (-13,+14)	1.4 (2)	0.52	59 (3)	77 (6)
AMO 210 Q	41 (-7,+7)	3.4 (1)	1.14	32 (1.3)	40 (14)
WP1.095A	24 (-5,+5)	4.3 (0)	0.86	24 (0.4)	52 (3)
WP1.095B	16 (-6,+7)	7.2 (0)	0.95	32 (0.2)	59 (9)
WP1.108A	31 (-5,+5)	2.8 (0)	0.72	32 (0.3)	52 (10)
WP1.108B	56 (-5,+5)	7.8 (1)	3.68	36 (1.1)	48 (3)
WP2.200A	36 (-8,+9)	2.8 (0)	0.81	42 (0.3)	63 (19)
WP2.200B	31 (-2,+2)	3 (0)	0.76	31 (0.7)	42 (3)
WP2.201A	35 (-8,+9)	4.6 (0)	1.33	45 (0.2)	59 (10)
WP2.201B	69 (-14,+15)	2.4 (0)	1.36	31 (0.2)	51 (8)
WP2.329A	7 (-1,+1)	23.6 (0)	1.62	11 (1.2)	27 (15)
WP2.329B	41 (-4,+4)	2.7 (1)	0.89	51 (2)	65 (3)
Merapi Oct. 26					
AME 10 A1	75 (-22,+25)	2.3 (4)	1.27	33 (7)	70 (11)
AME 10 A2	100 (-34,+38)	1.5 (4)	1.12	44 (8)	79 (8)
AME 10 A3	150 (-123,+174)	1.2 (3)	1.32	40 (3)	82 (11)
AME 10 A4	100 (-22,+24)	1.6 (5)	1.16	45 (8)	80 (8)
AME 10 A5	73 (-25,+29)	2.4 (3)	1.32	47 (5)	76 (6)
AME 10 A6	58 (-12,+13)	3.1 (2)	1.32	46 (3)	72 (5)
AME 10 B1	158 (-48,+53)	0.9 (4)	1.03	41 (9)	80 (10)
AME 10 B2	63 (-11,+12)	2.3 (3)	1.05	50 (5)	72 (8)
AME 10 B4	268 (-106,+118)	0.6 (4)	1.14	36 (6)	87 (6)
AME 10 B5	260 (-153,+184)	0.4 (5)	0.73	44 (13)	87 (12)
AME 10 C1	159 (-57,+64)	1 (1)	1.13	38 (1)	80 (14)
AME 10 C2	141 (-31,+33)	0.7 (2)	0.69	38 (5)	81 (6)
AME 10 C3	55 (-17,+20)	2.8 (2)	1.16	46 (3)	70 (10)
AME 10 C4	77 (-24,+27)	1.4 (3)	0.78	44 (7)	77 (7)
AME 10 D1	107 (-25,+27)	1.1 (3)	0.88	44 (4)	79 (9)
AME 10 D2	85 (-37,+43)	1.4 (5)	0.88	42 (11)	79 (11)
AME 10 D3	64 (-37,+47)	2 (8)	0.96	34 (20)	69 (27)
AME 10 D4	63 (-14,+15)	2.8 (5)	1.34	42 (12)	71 (10)
AME 10 E1	75 (-23,+26)	1.2 (2)	0.67	42 (6)	74 (11)
AME 10 E2	202 (-67,+74)	0.9 (4)	1.26	57 (4)	88 (4)
AME 10 E3	59 (-11,+12)	2 (3)	0.86	43 (9)	74 (8)
AME 10 E4	77 (-15,+16)	1.9 (5)	1.1	45 (10)	72 (8)
AME 10 E5	227 (-78,+87)	0.5 (4)	0.85	45 (12)	86 (11)

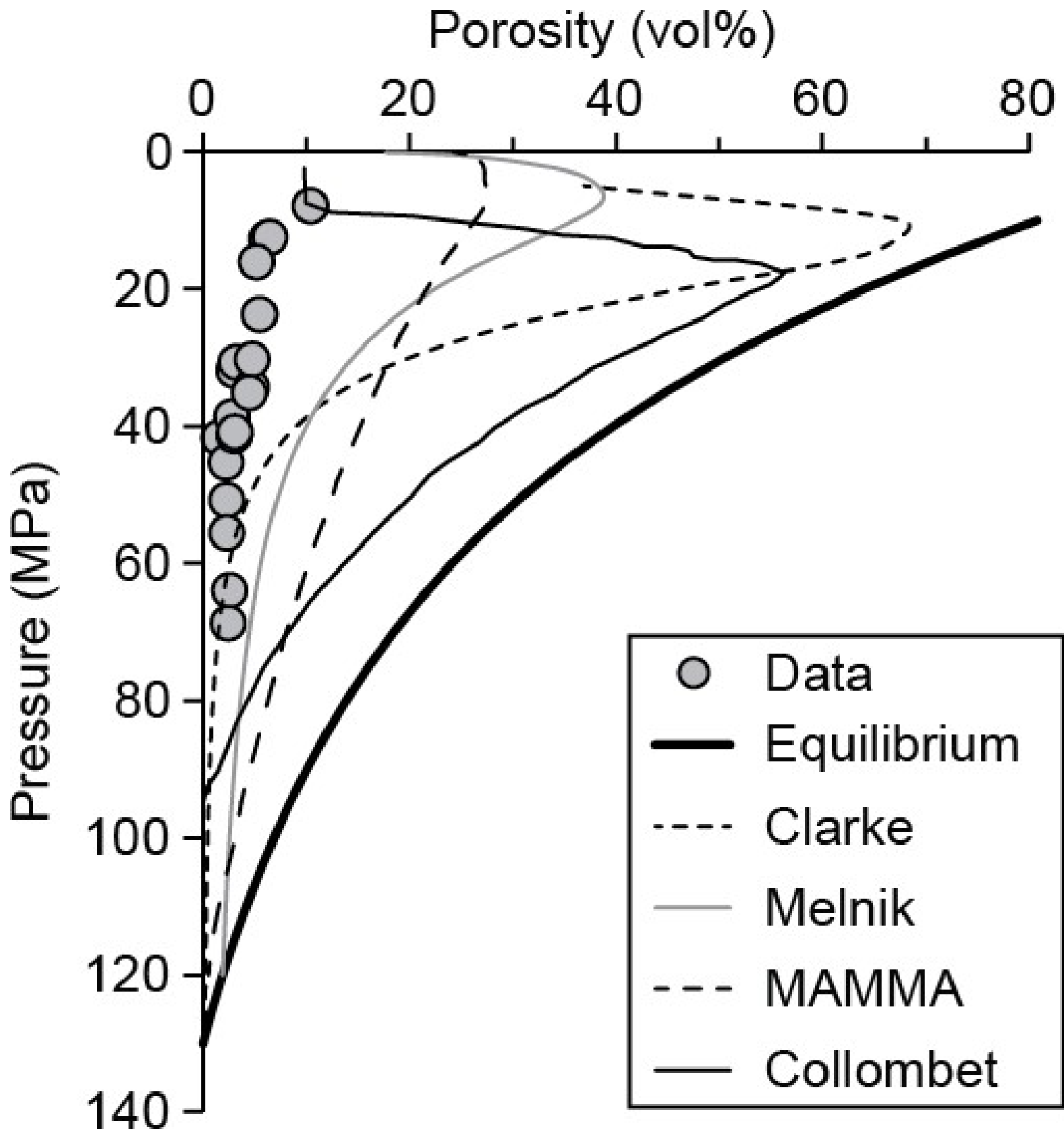
AME 10 F1	12 (-5,+5)	2.3 (20)	0.2	21 (23)	54 (17)
AME 10 G1	42 (-16,+18)	2.3 (2)	0.76	52 (5)	75 (7)
AME 10 G2	75 (-54,+75)	1.1 (2)	0.78	51 (6)	82 (11)
AME 10 G3	44 (-21,+25)	0.3 (15)	0.48	41 (9)	70 (12)
AME 10 GA	94 (-25,+28)	2.8 (1)	0.89	48 (10)	81 (9)
AME 10 GB	196 (-80,+92)	1.6 (1)	0.86	47 (8)	88 (8)
Tungurahua					
1	0.8 (-0.2,+0.4)	36.8 (3)	0.33	15 (21)	55 (12)
2	0.5 (-0.1,+0.1)	0 (8)	0	46 (10)	73 (9)
4	0.9 (-0.2,+0.3)	0.9 (11)	0.01	42 (14)	67 (13)
6	0.5 (-0.1,+0.2)	0.3 (30)	0.001	39 (36)	70 (32)
7.5	0.6 (-0.2,+0.3)	0.8 (9)	0.004	30 (12)	62 (12)
11	3 (-1,+1)	0 (1)	0	25 (1.4)	44 (5)
12	109 (-63,+91)	0.3 (1)	0.24	34 (0.8)	38 (5)
13	5 (-2,+9)	44.2 (1)	2.53	32 (2)	48 (14)
14	31 (-17,+68)	8.5 (4)	2.07	38 (4)	45 (6)
16	1.6 (-0.4,+0.5)	15.7 (4)	0.21	31 (3)	55 (5)
17	24 (-8,+16)	1.7 (2)	0.29	36 (6)	43 (6)
18	34 (-15,+41)	6.1 (1)	1.57	34 (2)	43 (6)
20	66 (-14,+20)	1.5 (2)	0.69	31 (3)	36 (4)
21	5 (-3,+8)	3.2 (2)	0.12	36 (3)	51 (10)
22	2 (-1,+5)	0 (4)	0	26 (3)	48 (15)
26	51 (-36,+149)	8 (3)	3.14	32 (2)	39 (9)
27	15 (-5,+10)	8.5 (3)	1.01	34 (5)	42 (8)
28	5 (-2,+9)	36.5 (3)	1.86	29 (6)	45 (12)
29	30 (-17,+82)	7.7 (1)	1.77	30 (0.8)	36 (6)
30	4 (-1,+2)	51.7 (1)	3.14	23 (4)	41 (8)
34	1.2 (-0.3,+0.4)	45 (3)	0.69	25 (2)	53 (6)
35	4 (-1,+2)	11.5 (3)	0.4	28 (3)	46 (5)
36	5 (-1,+2)	8.1 (1)	0.33	30 (2)	47 (7)
38	31 (-14,+38)	10.6 (1)	2.62	39 (2)	45 (4)
39	31 (-17,+67)	1.5 (2)	0.33	34 (5)	40 (7)
40	10 (-0.1,+0.1)	25.7 (2)	2.43	38 (2)	49 (2)
41	174 (-79,+26)	0.3 (2)	0.4	26 (3)	32 (4)

<sup>a</sup> Values at 0 are <0.1 vol% and errors at 0 are <1%.

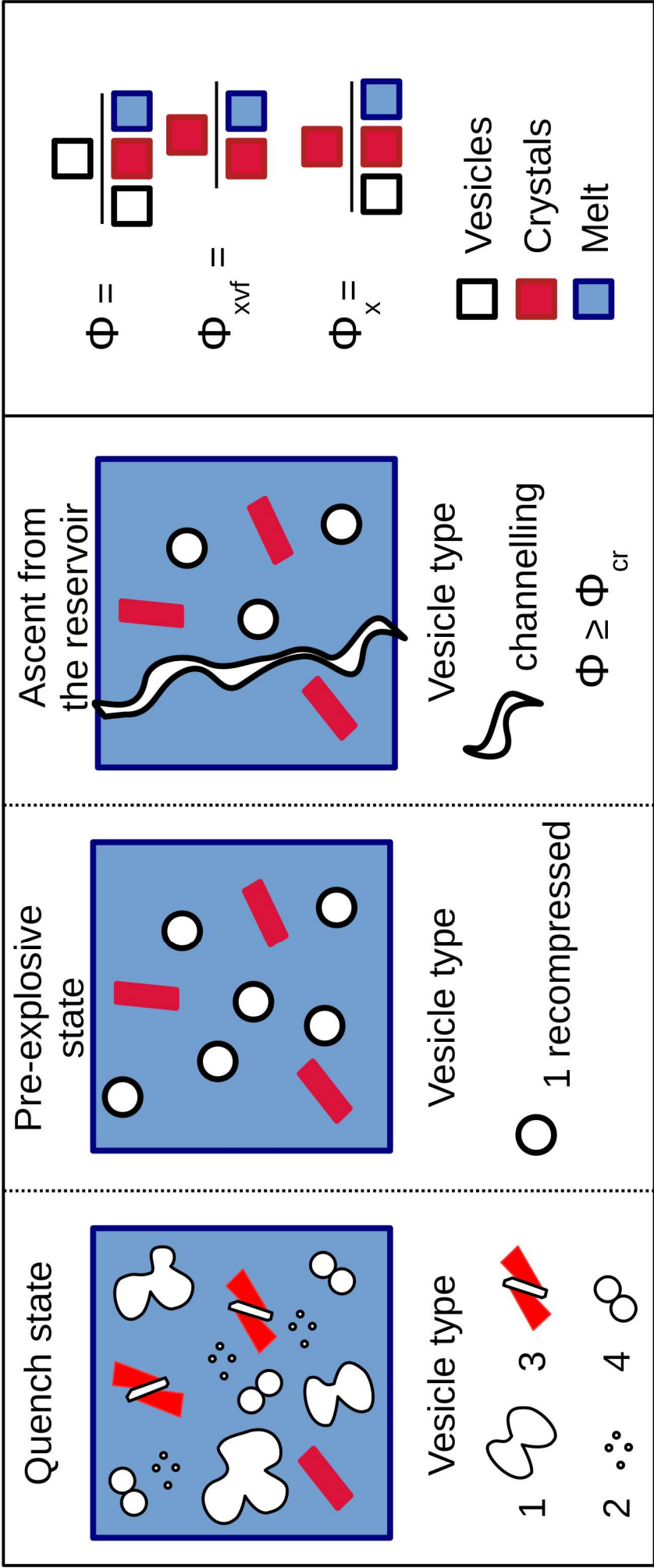
<sup>b</sup> Values at 0 are <0.001 ppm per weight.



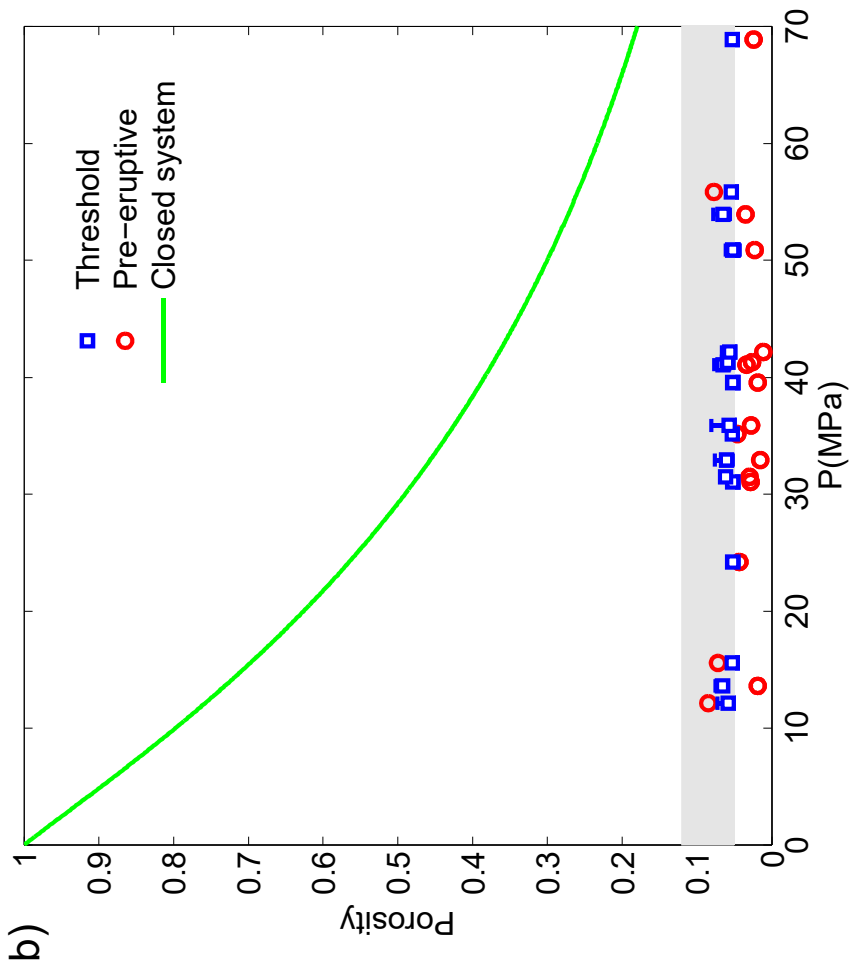
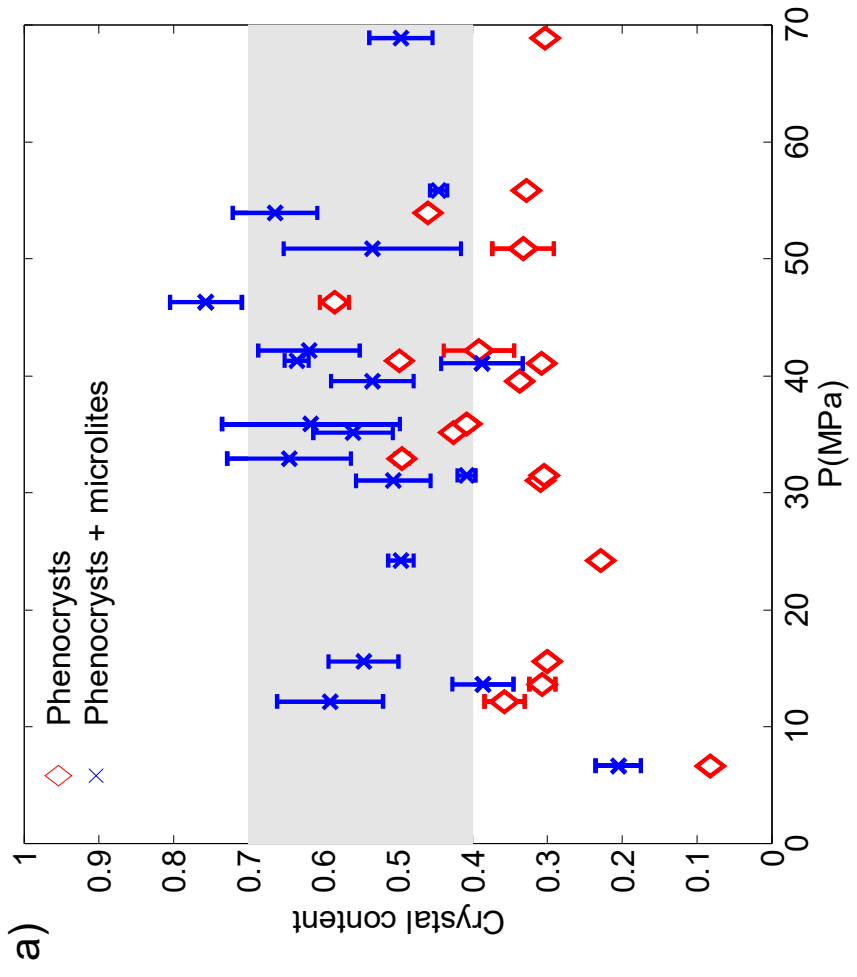
Figure

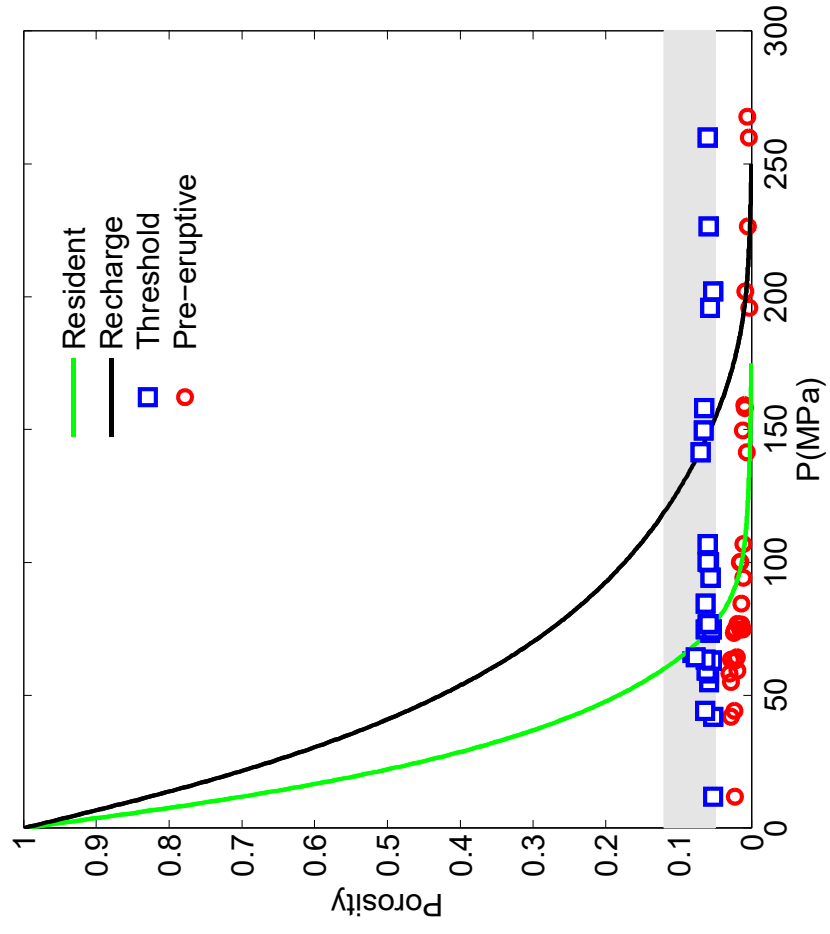


Figure

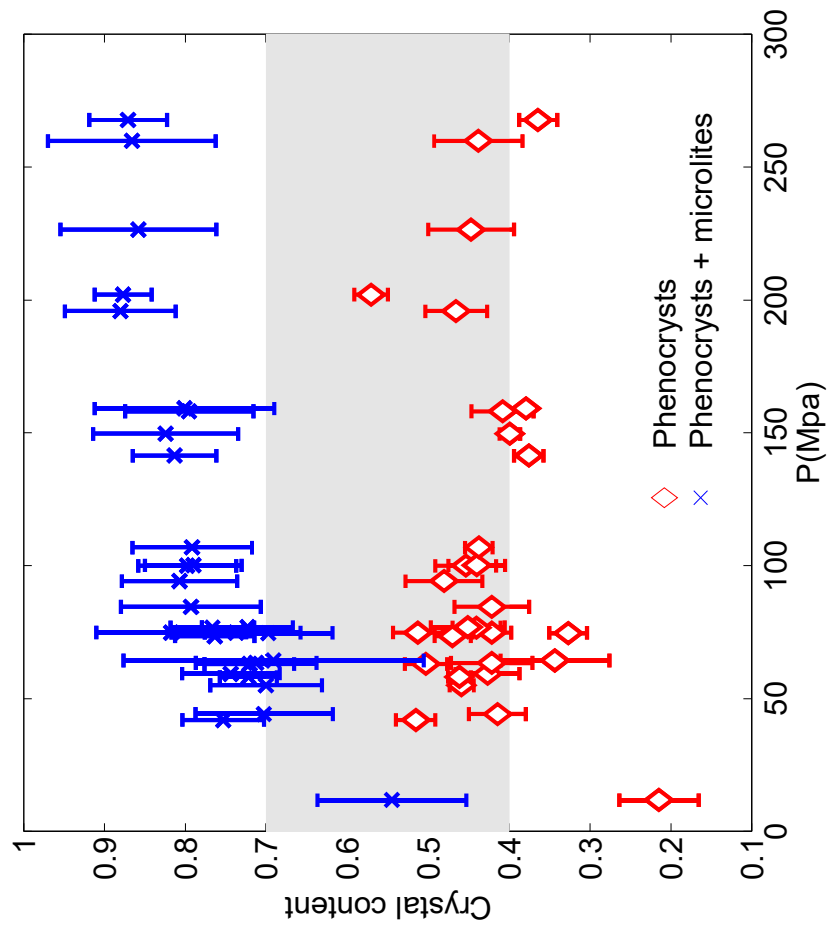


Figure

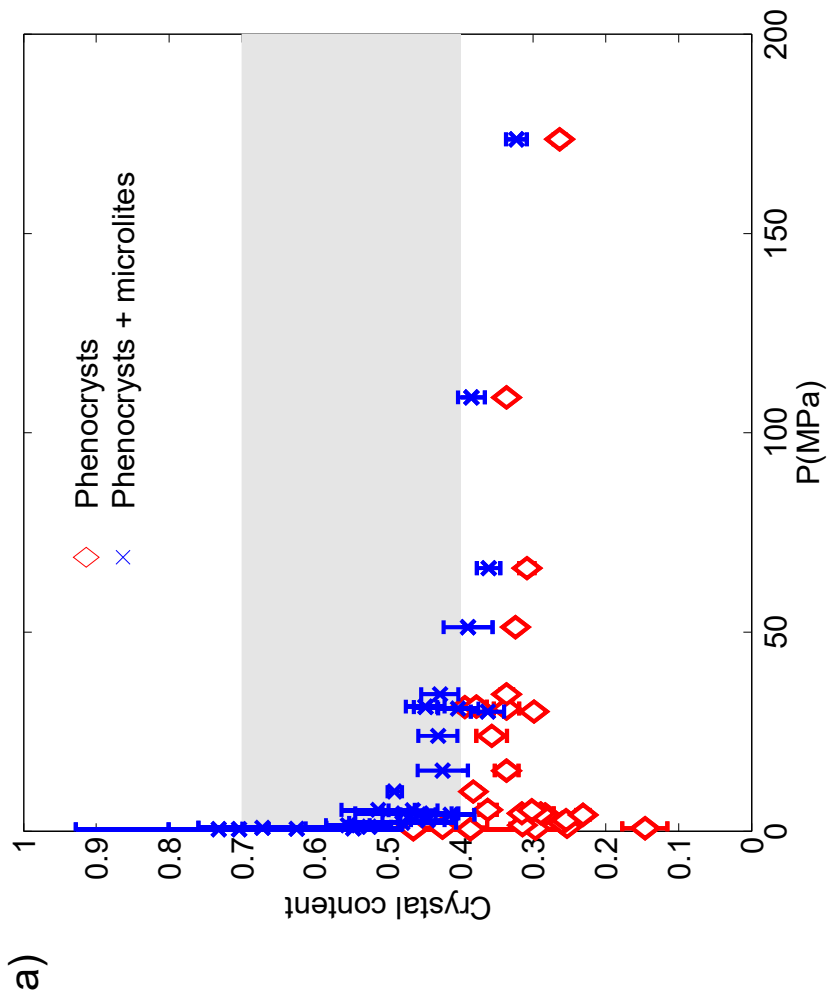
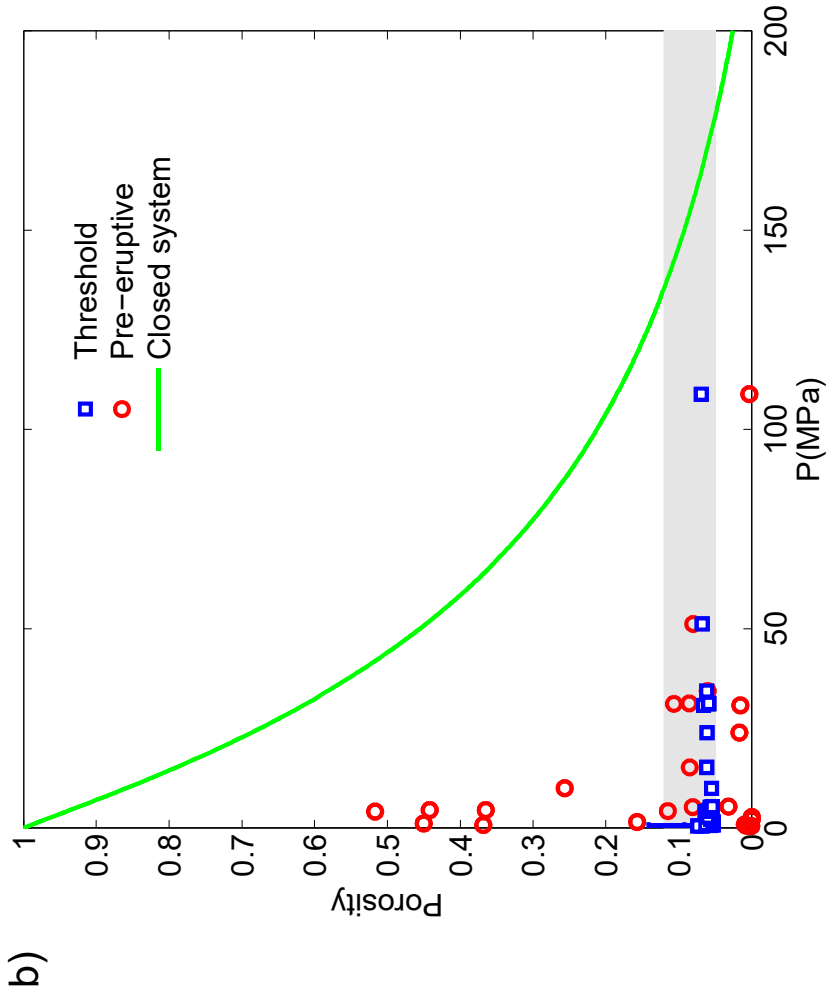




b)



a)



Figure

Figure

