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# The effects of outgassing on the transition between effusive and explosive silicic eruptions

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## Abstract

The eruption style of silicic magmas is affected by the loss of gas (outgassing) during ascent. We investigate outgassing using a numerical model for one-dimensional, two-phase, steady flow in a volcanic conduit. By implementing Forchheimer's equation rather than Darcy's equation for outgassing we are able to investigate the relative influence of Darcian and inertial permeability on the transition between effusive and explosive eruptions. These permeabilities are defined by constitutive equations obtained from textural analysis of pyroclasts and determined by bubble number density, throat-bubble size ratio, tortuosity, and roughness. The efficiency of outgassing as a function of these parameters can be quantified by two dimensionless quantities: the Stokes number, the ratio of the response time of the magma and the characteristic time of gas flow, and the Forchheimer number, the ratio of the viscous and inertial forces inside the bubble network. A small Stokes number indicates strong coupling between gas and magma and thus promotes explosive eruption. A large Forchheimer number signifies that gas escape from the bubble network is dominated by inertial effects, which leads to explosive behaviour. To provide context we compare model predictions to the May 18, 1980 Mount St. Helens and the August-September 1997 Soufrière Hills eruptions. We show that inertial effects dominate outgassing during both effusive and explosive eruptions, and that in this case the eruptive regime is determined by a new dimensionless quantity defined by the ratio of Stokes and Forchheimer number. Of the considered textural parameters, the bubble number density has the strongest influence on this quantity.

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This result has implications for permeability studies and conduit modelling.

*Keywords:* effusive-explosive transition, conduit, textures, permeability, outgassing

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## 1. Introduction

The efficiency of gas escape during the ascent of silicic magma governs the transition between effusive and explosive eruptions (Slezin, 1983; Eichelberger et al., 1986; Jaupart and Allegre, 1991; Woods and Koyaguchi, 1994; Slezin, 2003; Gonnermann and Manga, 2007). If the gas can escape readily from the magma, an effusive outpouring of lava occurs. On the other hand, when the gas stays trapped within the ascending magma, it provides the potential energy needed to fragment the magma and produce an explosive eruption. Gas can separate from magma through a network of coalesced bubbles or fractures, both horizontally into the conduit walls and vertically to the surface (Stasiuk et al., 1996; Melnik and Sparks, 1999; Tuffen et al., 2003; Gonnermann and Manga, 2003). Here we study vertical gas segregation through a network of bubbles in order to quantify the effects of permeability on the outcome of an eruption.

Juvenile pyroclasts contain information on the pore-scale geometry of the magma at the time they are quenched. Pyroclasts ejected by Vulcanian eruption, for example, preserve some evidence for the effusive dome-forming phase prior to fragmentation. Formenti and Druitt (2003) found that syn-explosion bubble nucleation may occur, resulting in a uniformly distributed porosity change of  $< 15\%$ , which suggests that porosity trends with depth are approximately preserved in the pyroclasts. Giachetti et al. (2010) used such pyroclasts to determine pre-explosive conditions of the 1997 eruptions at Soufrière Hills Volcano, Montserrat. Products of Plinian eruptions on the other hand can record the state of the magma at fragmentation provided post-fragmentation deformation is limited. This is true for highly viscous magmas and relatively small pyroclasts. A snapshot of the outgassing history can thus be found in these pyroclasts, and measuring their permeability can provide insights into outgassing (Figure 1; Klug and Cashman, 1996; Melnik and Sparks, 2002a; Rust and Cashman, 2004; Bernard et al., 2007; Takeuchi et al., 2008; Wright et al., 2009; Bouvet de Maisonneuve et al., 2009; Yokoyama and Takeuchi, 2009).

27 It has been suggested that outgassing during magma ascent can be described by Forch-  
 28 heimer’s law (Forchheimer, 1901; Rust and Cashman, 2004), an extension to Darcy’s law,  
 29 which accounts for the effects of turbulence,

$$30 \quad \left| \frac{dP}{dz} \right| = \underbrace{\frac{\mu_g U}{k_1}}_{\text{viscous term}} + \underbrace{\frac{\rho_g U^2}{k_2}}_{\text{inertial term}}, \quad (1)$$

31 where  $z$  is the direction of flow,  $P$  is the pressure,  $U$  is the volume flux,  $\mu_g$  is the viscosity,  $\rho_g$  is  
 32 the density of the gas phase. The Darcian permeability,  $k_1$ , and the inertial permeability,  $k_2$ ,  
 33 account for the influence of the geometry of the network of bubbles preserved in the juvenile  
 34 pyroclasts. Figure 1 compiles permeability measurements as a function of the connected  
 35 porosity found in pyroclasts. In general, permeability increases with increasing porosity, but  
 36 there is large variability in the data sets. Effusive products are overall less porous than their  
 37 explosive counterparts, but have a similar range over 5 to 6 orders of magnitude in Darcian  
 38 and inertial permeability.

39 Textural studies have shown that the spread of permeability found in juvenile pyroclasts  
 40 is caused by the variation in size, shape, tortuosity, and roughness of connected channels  
 41 through the network of bubbles (Figure 1; Blower, 2001; Bernard et al., 2007; Wright et al.,  
 42 2006, 2009; Degruyter et al., 2010a,b). Several constitutive equations that link these pa-  
 43 rameters to the Darcian and inertial permeability have been proposed. In the present study  
 44 we use the Kozeny-Carman or equivalent channel equations as discussed by Degruyter et al.  
 45 (2010a)

$$46 \quad k_1 = \frac{r_t^2}{8} \phi_c^m, \quad (2)$$

$$48 \quad k_2 = \frac{r_t}{f_0} \phi_c^{\frac{1+3m}{2}}, \quad (3)$$

49 with  $\phi_c$  the connected porosity,  $r_t$  the throat radius (the minimum cross section between two  
 50 coalesced bubbles). The parameter  $m$  is the tortuosity or cementation factor connected to  
 51 the tortuosity  $\tau$  using Archie’s law,

$$52 \quad \tau^2 = \phi_c^{1-m}, \quad (4)$$

53 with the tortuosity defined as the length of the connected channels divided by the length  
 54 of the porous medium. The parameter  $f_0$  is a fitting constant that only appears in the

55 expression for  $k_2$ , which we refer to as the roughness factor. We adapt this formulation for  
56 outgassing in a conduit flow model and apply it to two well-studied eruptions: (i) the Plinian  
57 phase of the May 18, 1980 eruption of Mount St. Helens, USA (MSH 1980) and (ii) the dome-  
58 forming eruptions of August-September 1997 at Soufrière Hills Volcano, Montserrat (SHV  
59 1997). These case studies allow us to understand the implications of using Forchheimer’s  
60 equation rather than Darcy’s equation for outgassing during an eruption. We use scaling to  
61 quantify the relative importance of the textural parameters and show where further under-  
62 standing is needed.

## 63 **2. Model**

64 Conduit flow models have been successful in the past to demonstrate how gas loss de-  
65 termines eruption style (Woods and Koyaguchi, 1994; Melnik and Sparks, 1999; Yoshida  
66 and Koyaguchi, 1999; Slezin, 2003; Melnik et al., 2005; Kozono and Koyaguchi, 2009a,b,  
67 2010). We adapt the model from Yoshida and Koyaguchi (1999) and Kozono and Koyaguchi  
68 (2009a,b, 2010), which assumes a one-dimensional, steady, two-phase flow in a pipe with  
69 constant radius. Relative motion between the magma (melt + crystals) and gas phase is  
70 accounted for through interfacial drag forces. The exsolution of volatiles is in equilibrium  
71 and the magma fragments when the gas volume fraction reaches a critical value  $\phi_f$ . We con-  
72 sider fragmentation governed by a critical strain rate (Papale, 1999) and critical overpressure  
73 (Zhang, 1999); details are in Appendix B. This changes the flow from a permeable foam to  
74 a gas phase with pyroclasts in suspension at which point the magma-gas friction and wall  
75 friction forces are adjusted. The model of Kozono and Koyaguchi (2009a) is adapted for our  
76 purpose in two ways: (i) the description of the magma rheology, and (ii) the description of  
77 the interphase drag force.

78 The governing equations are:

$$79 \quad \frac{d(\rho_m u_m (1 - \phi))}{dz} = -\frac{dn}{dz} q, \quad (5)$$

$$80 \quad \frac{d(\rho_g u_g \phi)}{dz} = \frac{dn}{dz} q, \quad (6)$$

$$81 \quad \rho_m u_m (1 - \phi) \frac{du_m}{dz} = -(1 - \phi) \frac{dP}{dz} - \rho_m (1 - \phi) g + F_{mg} - F_{mw}, \quad (7)$$

$$82 \quad \rho_g u_g \phi \frac{du_g}{dz} = -\phi \frac{dP}{dz} - \rho_g \phi g - F_{mg} - F_{gw} \quad (8)$$

84 Equations (5)-(6) represent the conservation of mass and equations (7)-(8) the conservation  
 85 of momentum for the magma phase ( $m$ ) and the gas phase ( $g$ ), where  $z$  is the vertical  
 86 coordinate,  $u$  is the vertical velocity,  $\rho$  is the density,  $\phi$  is the gas volume fraction,  $n$  is the  
 87 gas mass flux fraction,  $q$  is the total mass flux,  $P$  is the pressure,  $F_{mg}$  is the magma-gas  
 88 friction, and  $F_{mw}$  and  $F_{gw}$  are the wall friction with the magma and gas phase respectively.  
 89 The magma is incompressible and the gas density follows the ideal gas law,

$$90 \quad \rho_g = \frac{P}{RT}, \quad (9)$$

91 where  $R$  is the specific gas constant of water and  $T$  is the temperature. Gas exsolution is  
 92 governed by Henry's law for water,

$$93 \quad n = \frac{c_0 - sP^{1/2}}{1 - sP^{1/2}} \quad (n \geq 0), \quad (10)$$

94 where  $s$  is the saturation constant for water, and  $c_0$  is the initial (dissolved) water content.

### 95 *2.1. Rheology*

96 The wall friction is governed by the magma phase below the fragmentation depth. As  
 97 viscosity exerts a first order control on eruption dynamics, we replace the constant viscosity  
 98 used in Kozono and Koyaguchi (2009a,b) by a viscosity  $\mu_m$  that depends on magma properties

99 by combining models of Hess and Dingwell (1996) and Costa (2005):

$$100 \quad F_{mw} = \begin{cases} \frac{8\mu_m u_m}{r_c^2} & \phi \leq \phi_f \\ 0 & \phi > \phi_f \end{cases}, \quad (11)$$

$$101 \quad \log(\mu) = -3.545 + 0.833 \ln(100c) + \frac{9601 - 2368 \ln(100c)}{T - (195.7 + 32.25 \ln(100c))} \quad (12)$$

$$102 \quad \theta = \left\{ 1 - c_1 \operatorname{erf} \left( \frac{\sqrt{\pi}}{2} \chi \left[ 1 + \frac{c_2}{(1 - \chi)^{c_3}} \right] \right) \right\}^{-B/c_1} \quad (13)$$

$$103 \quad \mu_m = \mu(c, T)\theta(\chi) \quad (14)$$

105  $r_c$  is the conduit radius,  $c = sP^{1/2}$  is the dissolved water mass fraction,  $\chi$  is crystal content,  
 106  $B$  is Einstein's coefficient, and  $c_1, c_2, c_3$  are fitting coefficients. Once magma fragments we  
 107 use turbulent gas-wall friction,

$$108 \quad F_{gw} = \begin{cases} 0 & \phi \leq \phi_f \\ \frac{\lambda_w}{4r_c} \rho_g |u_g| u_g & \phi > \phi_f \end{cases} \quad (15)$$

109 where  $\lambda_w$  is a drag coefficient.

## 110 2.2. Outgassing

111 Below the fragmentation depth equation (1) is implemented for the interphase drag force  
 112  $F_{mg}$ ; above the fragmentation depth we use the model in Yoshida and Koyaguchi (1999). To  
 113 ease calculations before and after fragmentation there is a gradual transition region between  
 114  $\phi_f$  and a slightly higher gas volume fraction that we define as  $\phi_t = \phi_f + 0.05$ .

$$115 \quad F_{mg} = \begin{cases} \left( \frac{\mu_g}{k_1} + \frac{\rho_g}{k_2} |u_g - u_m| \right) \phi (1 - \phi) (u_g - u_m) & \phi \leq \phi_f \\ \left( \frac{\mu_g}{k_1} + \frac{\rho_g}{k_2} |u_g - u_m| \right)^{1-t} \left( \frac{3C_D}{8r_a} \rho_g |u_g - u_m| \right)^t \phi (1 - \phi) (u_g - u_m) & \phi_f < \phi \leq \phi_t \\ \frac{3C_D}{8r_a} \rho_g \phi (1 - \phi) |u_g - u_m| (u_g - u_m) & \phi > \phi_t \end{cases}, \quad (16)$$

$$116 \quad t = \frac{\phi - \phi_t}{\phi_f - \phi_t},$$

117  
 118 where  $C_D$  is a drag coefficient and  $r_a$  is the average size of the fragmented magma particles.  
 119 To implement the Kozeny-Carman type equations (2) and (3) we have to make some further  
 120 assumptions about the network of bubbles:

- 121 1. Various critical porosity values for percolation have been cited in the literature (Blower,  
122 2001; Burgisser and Gardner, 2004; Okumura et al., 2006; Namiki and Manga, 2008;  
123 Takeuchi et al., 2009; Laumonier et al., 2011) ranging from 0.1 to 0.8 gas volume  
124 fraction. Here we assume continuous percolation, i.e. the percolation threshold is  
125 zero and the connected porosity is equal to the gas volume fraction ( $\phi_c = \phi$ ). Zero  
126 permeability has the same effect as very low permeability as the two phases remain  
127 coupled in both cases. We note that varying the tortuosity factor is therefore equivalent  
128 as varying the percolation threshold as it controls the rate at which the permeability  
129 increases. A high tortuosity factor leads to a longer delay in developing permeability  
130 as would a larger percolation threshold.
- 131 2. The average throat radius  $r_t = f_{tb}r_b$ , where  $f_{tb}$  is the throat-bubble size ratio and  $r_b$  is  
132 the average bubble size.
- 133 3. The average bubble size is determined from the bubble number density and the gas  
134 volume fraction as in Gonnermann and Manga (2005),

$$135 \quad r_b = \left( \frac{\phi}{\frac{4\pi}{3}N_d(1-\phi)} \right)^{1/3}. \quad (17)$$

136 These assumptions bring us to the following closure equations for the permeability

$$137 \quad k_1 = \frac{(f_{tb}r_b)^2}{8}\phi^m, \quad (18)$$

$$138 \quad k_2 = \frac{(f_{tb}r_b)}{f_0}\phi^{\frac{1+3m}{2}}. \quad (19)$$

140 Bounds on the four parameters can be found in the literature:  $N_d = 10^8-10^{16} \text{ m}^{-3}$  (Klug and  
141 Cashman, 1994; Polacci et al., 2006; Sable et al., 2006; Giachetti et al., 2010),  $f_{tb} = 0.1 - 1$   
142 (Saar and Manga, 1999; Degruyter et al., 2010a),  $m = 1 - 10$  (Le Pennec et al., 2001;  
143 Bernard et al., 2007; Wright et al., 2009; Degruyter et al., 2010a,b), and Degruyter et al.  
144 (2010a) estimated  $f_0$  between 10 and 100 for pumices. For comparison,  $f_0$  for permeameter  
145 standards used by Rust and Cashman (2004) is estimated to be around 0.025 and for packed  
146 beds a value of 1.75 is found (Ergun, 1952).

147 The set of equations (5)-(19) can be converted into two ordinary differential equations  
148 for  $P$  and  $\phi$ . We set the differential velocity between the two phases to be initially zero.



149 In combination with two boundary conditions: (i) initial pressure  $P_0$ , and (ii) atmospheric  
 150 pressure or the choking condition at the vent, this 2-point boundary value problem is solved  
 151 using the ordinary differential equation solver *ode23s* built in Matlab (Shampine and Re-  
 152 ichelt, 1997) in combination with a shooting method. Table 1 summarizes model parameters  
 153 used in this study.

154 The behaviour of this model allows us to distinguish between explosive and effusive  
 155 eruptions. Figure 2 shows profiles of pressure, gas volume fraction, velocity, and permeability  
 156 for a representative explosive and effusive case. In the explosive case the pressure rapidly  
 157 decreases just prior to fragmentation, while in the effusive case the pressure remains close  
 158 to magmastatic (Figure 2a). The gas volume fraction reaches high values in the case of an  
 159 explosive eruption, while in the effusive case it reaches a maximum and decreases at low  
 160 pressures (Figure 2b). The velocity of the gas phase starts to differ from that of the magma  
 161 phase at depth in the case of an effusive eruption, while in the explosive case velocities of  
 162 both phases are nearly equal until fragmentation after which they start to differ (Figure  
 163 2c). Both Darcian and inertial permeability are larger at similar pressures in the case of an  
 164 effusive eruption compared to the explosive case (Figure 2d).

### 165 3. Stokes and Forchheimer number

166 We focus on the influence of the textural parameters  $N_d$ ,  $f_{tb}$ ,  $m$ , and  $f_0$  on the eruption  
 167 style. We therefore non-dimensionalize the equations (5)-(19) using initial and boundary  
 168 conditions as reference values to extract dimensionless quantities that depend on textures  
 169 (see Appendix A for details). These are found to be the Stokes number,  $St$ , and the  
 170 Forchheimer number,  $Fo$ .  $St$  is the ratio of the response time scale of the magma and the  
 171 characteristic flow time of the gas phase

$$172 \quad St = \frac{\tau_V}{\tau_F} = \frac{\rho_m k_{10}}{\frac{\mu_g}{U_0}} \quad (20)$$

173 with  $U_0$  and  $k_{10}$  the reference velocity and Darcian permeability respectively (Appendix A).  
 174 When  $St$  is small the magma and gas phase are closely coupled and ascend at the same  
 175 speed, while for a large  $St$  the gas decouples from the magma and can ascend more rapidly

176 than the magma. Fo is the ratio of the inertial term and the viscous term in Forchheimer's  
177 equation

$$178 \quad \text{Fo} = \frac{\rho_{g0} k_{10} U_0}{k_{20} \mu_g}. \quad (21)$$

179 with  $\rho_{g0}$  and  $k_{20}$  the reference gas density and inertial permeability respectively (Appendix  
180 A). For a low Fo the outgassing is controlled by the Darcian permeability, while for a high  
181 Fo the inertial permeability is dominant. We are now able to explore the effusive-explosive  
182 transition in terms of St and Fo when conduit geometry and magma properties are held  
183 constant. In other words, by looking at specific eruptions we can single out the influence of  
184 textures from other parameters. This strategy is used in the following section. Monte Carlo  
185 simulations are used to explore the texture parameter space defined by  $N_d$ ,  $f_{tb}$ ,  $m$ , and  $f_0$ .  
186 We determine if the eruption is explosive or effusive for each combination of parameters and  
187 then map the results on the (St,Fo)-space.

## 188 4. Results

### 189 4.1. Mount St. Helens May 18, 1980 eruption

190 The MSH 1980 eruption is a good case study of an explosive eruption as extensive data has  
191 been collected on magma properties, conduit geometry, and textures. We use the magma  
192 properties as obtained by Blundy and Cashman (2005) and listed in Table 1. Following  
193 Dobran (1992) the conduit length was estimated from lithostatic pressure  $P_0/\rho g = 5291$  m  
194 for a wall rock density of  $2700 \text{ kg/m}^3$ . The fragmentation criterion is set by a critical gas  
195 volume fraction  $\phi_f$  at 0.8 as found in the white pumice produced by this eruption (Klug  
196 and Cashman, 1994). We use a conduit radius of  $r_c = 30$  m to match the mass flow rates  
197 estimated by Carey et al. (1990). Figure 2 shows the typical behaviour of an explosive  
198 eruption for these conditions.

199 The results of the Monte Carlo simulations over the texture parameter space are divided  
200 into explosive and effusive eruptions and projected on a (St,Fo)-map (Figure 3). Parameters  
201 leading to explosive eruptions occupy a region of the (St,Fo)-space separated from the ones of  
202 leading to effusive eruptions. The separation between these two regions can be approximated  
203 by a linear relationship defined by a critical Stokes number  $\text{St}_c$  and critical Forchheimer

204 number  $Fo_c$ ,

$$205 \quad Fo = \frac{Fo_c}{St_c}(St - St_c). \quad (22)$$

206 Such a relationship can be expected when inspecting equation (A.14) that shows that the  
207 dimensionless drag is inversely correlated with  $St$  and linearly with  $Fo$ . For MSH 1980  
208 conditions we found  $St_c \approx 10^{-3}$  and  $Fo_c \approx 50$ .

209 The definition of  $St$  and  $Fo$  in combination with the effusive-explosive map can now be  
210 used to interpret the influence of each of the textural parameters individually (Figure 3a).  
211 Starting from an arbitrarily chosen point on the  $(St, Fo)$  map, we increase the value of one of  
212 the textural parameters, while keeping the others constant. Increasing the bubble number  
213 density  $N_d$  leads to higher coupling between gas and magma, while turbulent outgassing  
214 becomes less dominant. This results in conditions favorable for explosive eruptions. The  
215 opposite effect is noted for the throat-bubble ratio  $f_{tb}$ . An increase of the tortuosity factor  
216  $m$  leads to increased coupling between the gas and magma as well as increased dominance of  
217 turbulent outgassing, which makes explosive eruptions more likely. Increasing the roughness  
218 factor  $f_0$  increases  $Fo$  and leaves  $St$  constant. This brings conditions closer to the explosive  
219 regime where outgassing is governed by the inertial term in equation (1). The size of the  
220 arrows is based on the variability of each of the parameters found in the literature. The  
221 large range in measurements of bubble number density implies that this is the main textural  
222 feature that controls outgassing. The influence of other parameters is smaller, but we note  
223 that uncertainty can be large, especially in the case of the roughness factor  $f_0$  for which data  
224 are sparse.

225 The textural studies by Klug and Cashman (1994, 1996) provide constraints on where  
226 the MSH 1980 eruption falls on this regime diagram (Figure 3b). A bubble number density  
227 of  $N_d = 10^{15} \text{ m}^{-3}$  and tortuosity factor of  $m = 3.5$  was measured. The  $St$  and  $Fo$  number  
228 range for the MSH 1980 eruption (Figure 3b) predict a permeability between  $5 \times 10^{-14} \text{ m}^2$   
229 and  $5 \times 10^{-12} \text{ m}^2$  near fragmentation in agreement with the data of Klug and Cashman  
230 (1996). The failure of the bubbles to form larger connected channels does not allow for  
231 the gas to decouple from the magma and an explosive eruption results ( $St < St_c$ ). The  
232 spread for the roughness factor  $f_0$  puts the MSH 1980 eruption in the turbulent outgassing

233 regime ( $Fo > Fo_c$ ), implying that the outgassing was dominated by the inertial permeability.  
234 Measurements of inertial permeability on MSH 1980 pyroclasts could test this hypothesis.

235 The use of a critical gas volume fraction as a criterion for fragmentation has been shown  
236 to be oversimplified and a stress-based criterion either by critical strain rate or gas overpres-  
237 sure is now favored (Dingwell, 1996; Papale, 1999; Zhang, 1999). However, using different  
238 fragmentation mechanisms in a one-dimensional conduit model leads to qualitatively similar  
239 results as the runaway effect that leads to increased acceleration will ensure all fragmenta-  
240 tion criteria will be met over the same narrow depth interval (Melnik and Sparks, 2002b;  
241 Massol and Koyaguchi, 2005). In other words, a critical gas volume fraction has similar  
242 consequences as a critical strain rate or overpressure in this type of model. This effect is  
243 demonstrated here using a criterion based on strain rate and one on overpressure (Appendix  
244 B). The strain rate criterion leads to explosive eruptions at a gas volume fraction of about  
245 0.85, while the overpressure criterion was equivalent to a gas volume fraction near 0.6. This  
246 leads to a shift in the critical Stokes number defining the transition curve, while its shape  
247 is preserved (Figure 3b). We have chosen the critical gas volume fraction that matches the  
248 observations in the pyroclasts of the MSH 1980 and note that this is equivalent to the choice  
249 of a critical stress criterion.

250 The calculated mass flow rates vary little within each of the eruption regimes, showing  
251 that textural parameters have little influence on it. Rather, mass flow rate appears domi-  
252 nantly controlled by the magma properties and conduit geometry in combination with the  
253 imposed boundary conditions at the top and bottom of the conduit. In the explosive regime  
254 the mass flow rate is limited by the choked flow condition at the vent and the conduit ra-  
255 dius. For the MSH 1980 conditions we obtain  $2 \times 10^7$  kg/s by setting the conduit radius  
256 to match the mass flow rate estimates of Carey et al. (1990). In the effusive regime the  
257 top boundary condition becomes the ambient pressure and mass flow rates are controlled  
258 mostly by magma viscosity and conduit radius (Melnik et al., 2005; Kozono and Koyaguchi,  
259 2009a,b). For the MSH 1980 conditions we find a mass flow rate around  $2 \times 10^6$  kg/s, an  
260 order of magnitude smaller than in the explosive case. The lava dome growth that followed  
261 the MSH 1980 eruption had mass flow rates around  $1 - 5 \times 10^4$  kg/s (Moore et al., 1981).

262 This large mismatch implies that the rheology and/or geometry during the dome-forming  
 263 eruption significantly changed from the explosive MSH 1980 eruption. These issues could  
 264 be addressed by incorporating improved rheology laws (Cordonnier et al., 2009) as well as  
 265 crystallization kinetics (Blundy and Cashman, 2005; Melnik et al., 2011) into the model.  
 266 However, we can conclude that bubble number density, throat-bubble size ratio, tortuosity,  
 267 and roughness factor play a secondary role in controlling the mass flow rate.

#### 268 *4.2. August-September 1997 Soufrière Hills Volcano dome-forming eruptions*

269 The SHV 1997 dome-forming eruptions provide a well-defined case study for an effusive  
 270 eruption. Note that we use our model only for the dome-forming phase and not for the  
 271 Vulcanian eruptions, which require a model that contains transient dynamics (Melnik and  
 272 Sparks, 2002b; de' Michieli Vitturi et al., 2010; Fowler et al., 2010). We used the eruption  
 273 conditions summarized by Melnik and Sparks (1999) and Clarke et al. (2007): a temperature  
 274 of 1123 K, conduit length of 5 km, initial pressure of 120 MPa, volatile content of 4.6 wt.%  
 275 water, and magma density of 2450 kg/m<sup>3</sup>. As was evident from the simulations under MSH  
 276 1980 eruption conditions, in the case of effusive eruptions crystallization due to decompres-  
 277 sion needs to be taken into account in order to capture the lower mass flow rates. We adopt  
 278 the parametrization as formulated by de' Michieli Vitturi et al. (2010) based on the work of  
 279 Couch et al. (2003) for the relationship between  $\chi$  and  $P$

$$280 \quad \chi = \min \left[ \chi_{\max}, \chi_0 + 0.55 \left( 0.58815 \left( \frac{P}{10^6} \right)^{-0.5226} \right) \right] \quad (23)$$

281 where  $\chi_{\max} = 0.6$  and the initial crystal volume fraction is 0.45. Setting the conduit radius  
 282 at  $r_c = 22.5$  m gives a mass flow rate of  $3.5 \times 10^4$  kg/s in the effusive regime, in agreement  
 283 with Druitt et al. (2002). Figure 2 shows example (effusive) profiles produced for these  
 284 conditions. The mass flow rate in the explosive regime under SHV 1997 conditions is higher  
 285 by nearly two orders of magnitude,  $2.2 \times 10^6$  kg/s. We stress that this is not related to  
 286 the mass flow rate associated to the Vulcanian explosions at Soufrière Hills Volcano as we  
 287 only model steady state eruptions, which are dynamically very different from the Vulcanian  
 288 eruptions (Melnik and Sparks, 2002b; de' Michieli Vitturi et al., 2010; Fowler et al., 2010).

289 Using again the strategy of Monte Carlo simulations over the textural parameter space,  
 290 we obtain a new (St,Fo)-map for SHV 1997 conditions that is split into an effusive and  
 291 explosive region by a transition curve approximated by equation (22) with  $St_c = 2.5 \times 10^{-5}$   
 292 and  $Fo_c = 100$ . There is a strong shift of the transition curve compared to MSH 1980 with  
 293  $St_c$  about two orders of magnitude smaller. This is due to the two orders of magnitude  
 294 increase of the effective viscosity controlled by the increase in crystal content during ascent.  
 295 A parameter that is highly uncertain is the critical condition for explosive eruption, as we  
 296 cannot interpret pyroclast vesicularity of the SHV 1997 eruption in the same fashion as the  
 297 quenched samples from MSH 1980 eruption. We have chosen  $\phi_f = 0.8$ .

298 The bubble number density of the SHV 1997 eruptions during the dome-forming stage is  
 299 between  $10^9$  and  $10^{10} \text{ m}^{-3}$ , based on the large-bubble population in the pyroclasts produced  
 300 by the Vulcanian eruptions (Giachetti et al., 2010). The St-Fo region defined by this number  
 301 is indicated in black on Figure 4a. This region can be refined by using the relationship  
 302 between pressure and gas volume fraction in the conduit as reconstructed by Clarke et al.  
 303 (2007) and Burgisser et al. (2010). Using Monte Carlo simulations we can search for the  
 304 St-Fo values that best fit this profile. There is a large spread of the data near the top of the  
 305 conduit ( $< 10 \text{ MPa}$ ) indicating a complex and non-unique behaviour in the conduit plug in  
 306 between Vulcanian eruptions (de' Michieli Vitturi et al., 2010). Therefore we fit the model to  
 307 the data at greater depth ( $> 10 \text{ MPa}$ ). The best fit as determined by the lowest chi-square  
 308 value was  $St = 2.6 \times 10^{-1}$ ,  $Fo = 3.7 \times 10^4$ , which can be formed by e.g.  $N_d = 10^{9.5} \text{ m}^{-3}$ ,  
 309  $f_{tb} = 10^{-0.5}$ ,  $m = 2.1$ , and  $f_0 = 10$  (Figure 4b). Below the conduit plug, bubbles create  
 310 large enough pathways through the magma to allow gas escape at low gas volume fraction,  
 311 thereby hindering magma acceleration ( $St > St_c$ ). Figure 4b indicates, as in the case of MSH  
 312 1980, that outgassing is turbulent ( $Fo > Fo_c$ ) and dominated by inertial permeability.

### 313 4.3. Influence of turbulent outgassing on the effusive-explosive transition

314 The transition curve separating the effusive and explosive eruption regimes in terms of  
 315 textures is determined by a critical Stokes and Forchheimer number, the values of which will

316 depend on magma properties and conduit geometry, i.e.

$$317 \quad \text{St}_c = \Phi_1 (\text{Re}, \text{Fr}, \text{Ma}, c_0, \chi_0, \phi_f, \delta, \sigma, a_r), \quad (24)$$

$$318 \quad \text{Fo}_c = \Phi_2 (\text{Re}, \text{Fr}, \text{Ma}, c_0, \chi_0, \phi_f, \delta, \sigma, a_r). \quad (25)$$

319

320 Regardless of the exact forms of these equations, the results show a change in the eruption  
 321 dynamics when changing from laminar ( $\text{Fo} \ll \text{Fo}_c$ ) to turbulent outgassing ( $\text{Fo} \gg \text{Fo}_c$ ). This  
 322 becomes more clear when we inspect equation (22) and rewrite it as

$$323 \quad \text{St} = \text{St}_c \left( 1 + \frac{\text{Fo}}{\text{Fo}_c} \right). \quad (26)$$

324 We see that in the case of laminar outgassing ( $\text{Fo} \ll \text{Fo}_c$ ) the transition is simply described  
 325 by  $\text{St} \approx \text{St}_c$ . In the case of turbulent outgassing ( $\text{Fo} \gg \text{Fo}_c$ ) the transition occurs when

$$326 \quad \Pi = \frac{\text{St}}{\text{Fo}} = \frac{\rho_m k_{20}}{\rho_{g0} r_c} \approx \Pi_c = \frac{\text{St}_c}{\text{Fo}_c}, \quad (27)$$

327 with  $\Pi$  a new dimensionless quantity defined as the ratio of the  $\text{St}$  and  $\text{Fo}$ . Textural mea-  
 328 surements on juvenile pyroclasts in combination with our numerical results suggest that  $\text{Fo}$   
 329  $\gg \text{Fo}_c$  (Figures 3b and 4b) and thus that  $\Pi$  is the relevant quantity for the effusive-explosive  
 330 transition rather than  $\text{St}$ . Equation (27) reveals that the variation of  $\Pi$  is mostly due to  
 331 the ratio of the characteristic inertial permeability with respect to the conduit radius as  
 332 the density ratio between the magma and the gas will not vary much over a wide range of  
 333 parameters. Hence, in order to have an effusive eruption the inertial permeability that has  
 334 to develop during a volcanic eruption needs to be higher in a conduit with a large radius  
 335 than one with a small radius. In other words, a conduit with a large radius is more likely to  
 336 produce an explosive eruption.

## 337 5. Concluding remarks

338 We developed a model to study the effect of outgassing on eruption style with a specific  
 339 focus on the effect of using Forchheimer's equation instead of Darcy's equation. We suggest  
 340 that the inertial term in Forchheimer's equation is dominant during both explosive and ef-  
 341 fusive eruptions. In terms of textural parameters, the radius of connected channels through

342 the bubble network dominates the outgassing dynamics. The channel radii are controlled  
343 by bubble number density and throat-bubble size ratio, and can vary over many orders of  
344 magnitude. Higher tortuosity and roughness factor increase the chances for an explosive  
345 eruption, but are less important. However, attention needs to be drawn towards the rough-  
346 ness factor as it is the least constrained parameter. Even if the roughness factor would be  
347 lowered by several orders of magnitude, the estimated  $Fo$  for MSH 1980 and SHV 1997 would  
348 still be above  $Fo_c$ . In terms of dimensionless parameters this means that the shift in erup-  
349 tion style is not governed by  $St$  as previously assumed (e.g., Melnik et al., 2005; Kozono and  
350 Koyaguchi, 2009a,b) but by  $\Pi$  as defined in equation (27). This result has implications for  
351 (i) permeability studies on juvenile pyroclasts that need to quantify the controls on inertial  
352 permeability (Rust and Cashman, 2004; Mueller et al., 2005; Takeuchi et al., 2008; Bouvet de  
353 Maisonneuve et al., 2009; Yokoyama and Takeuchi, 2009; Degruyter et al., 2010a) and (ii)  
354 conduit models that need to include the inertial term in the closure equation for outgassing  
355 (Fowler et al., 2010).

356 Products from effusive eruptions tend to have a lower porosity than their explosive coun-  
357 terparts, while their permeability can reach similar high values (Figure 1). Although pyro-  
358 clasts of effusive eruptions can be altered by bubble expansion after dome collapse or bubble  
359 collapse during emplacement, the porosity-permeability measurements in combination with  
360 the conduit model show that high permeability at low porosity can be explained by a larger  
361 radius of permeable channels. Such channels can develop due to low bubble number density  
362 (Giachetti et al., 2010) and early coalescence due to pre-eruptive magma heating (Ruprecht  
363 and Bachmann, 2010) or deformation (Okumura et al., 2006; Laumonier et al., 2011). Hys-  
364 teresis, whereby high permeability is preserved and porosity is decreased by bubble collapse,  
365 can further enhance the difference between effusive and explosive products (Saar and Manga,  
366 1999; Rust and Cashman, 2004; Michaut et al., 2009).

367 Several additions to the model can be made to improve quantification of the effusive-  
368 explosive transition. The most important include adding spatial (Dufek and Bergantz, 2005)  
369 and temporal variations (Melnik and Sparks, 2002b; de' Michieli Vitturi et al., 2010; Fowler  
370 et al., 2010) as well as non-equilibrium growth of bubbles (Burgisser and Gardner, 2004;



371 Gonnermann and Manga, 2005) and crystals (Melnik et al., 2011). In explosive eruptions,  
372 delayed bubble growth will reduce development of permeability and crystals will not be  
373 able to grow fast enough to increase viscosity and reduce the ascent speed. On the other  
374 hand, in effusive eruptions both bubble and crystal growth will be closer to equilibrium.  
375 Including spatial and temporal variation will help identify the development of heterogeneity  
376 of permeability inside the conduit.

377 By treating the textural properties independent from magma properties and conduit ge-  
378 ometry we were able to distill the relative importance of these properties on outgassing.  
379 However, textures are intimately tied to the magma properties as they control nucleation,  
380 growth, deformation and coalescence of bubbles. For example, bubble number density will in-  
381 crease with increasing decompression rate (Toramaru, 2006) and decrease due to coalescence  
382 (Burgisser and Gardner, 2004), while tortuosity can be lowered by deformation (Degruyter  
383 et al., 2010a). Incorporating the coupling between the textures and the magma properties  
384 is worthy of future study.

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Table 1: Parameter space explored with the conduit model.

parameter	symbol	value	unit
<b>constants</b>			
specific gas constant of water	$R$	461.4	$\text{J kg}^{-1} \text{K}^{-1}$
Einstein constant	$B$	2.5	
constants equation (13)	$c_1$	0.9995	
	$c_2$	0.4	
	$c_3$	1	
ash particle size	$r_a$	$1 \times 10^{-3}$	m
gas-wall drag coefficient	$\lambda_w$	0.03	
gas-ash particle drag coefficient	$C_D$	0.8	
<b>textures</b>			
bubble number density	$N_d$	$10^8$ – $10^{16}$	$\text{m}^{-3}$
tortuosity factor	$m$	1–10	
friction coefficient	$f_0$	$10^{-4}$ – $10^2$	
throat-bubble ratio	$f_{tb}$	0.05 – 0.5	
<b>conduit geometry</b>		MSH 1980	SHV 1997
length	$L$	5291	5000
radius	$r_c$	30	22.5
<b>magma properties</b>		MSH 1980	SHV 1997
density	$\rho_m$	2500	2450
temperature	$T$	1159	1123
volatile content	$c_0$	4.6	4.6
crystal content	$\chi_0$	0.4	0.45
pressure	$P_0$	140	120

Table 2: Values and range of dimensionless parameters.

parameter	symbol	value	
<b>fixed parameters</b>			
Reynolds number	Re	MSH 1980 6.69	SHV 1997 0.27
Froude number	Fr	0.15	0.026
Mach number	Ma	0.0193	0.0033
water content	$c_0$	0.046	0.046
crystal content	$\chi_0$	0.4	0.45
fragmentation gas volume fraction	$\phi_f$	0.8	0.8
density ratio	$\delta$	0.1	0.1
saturation water content at $P_0$	$\sigma$	0.049	0.045
ash/conduit size ratio	$a_r$	$3.33 \times 10^{-5}$	$4.44 \times 10^{-5}$
<b>outgassing parameters</b>			
Stokes number	St	$10^{-6} - 10^1$	
Forchheimer number	Fo	$10^{-3} - 10^7$	

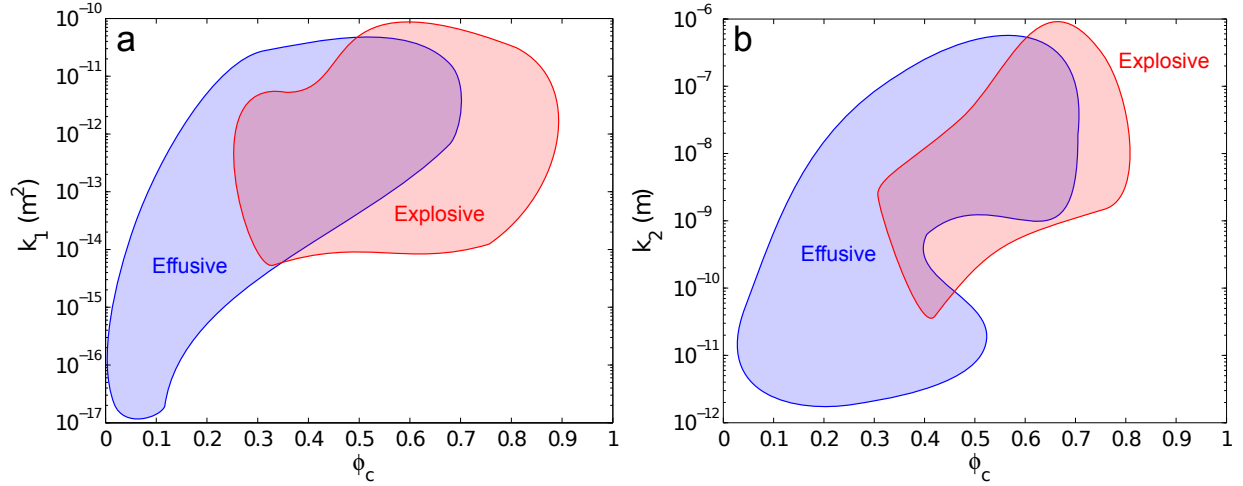


Figure 1: Summary of the relationship between of connected porosity  $\phi_c$  and permeability. The blue area represents the spread in data collected on pyroclasts from effusive eruptions, the red area represents the data spread on pyroclasts from explosive eruptions for (a) Darcian permeability  $k_1$  (Wright et al., 2009), and (b) inertial permeability  $k_2$  (Rust and Cashman, 2004; Mueller et al., 2005; Takeuchi et al., 2008; Bouvet de Maisonneuve et al., 2009; Yokoyama and Takeuchi, 2009). Data from pyroclasts ejected by Vulcanian explosions are treated as effusive. Data are mostly from silica-rich pyroclasts, but also includes mafic products as porosity-permeability data does not appear to depend on composition.

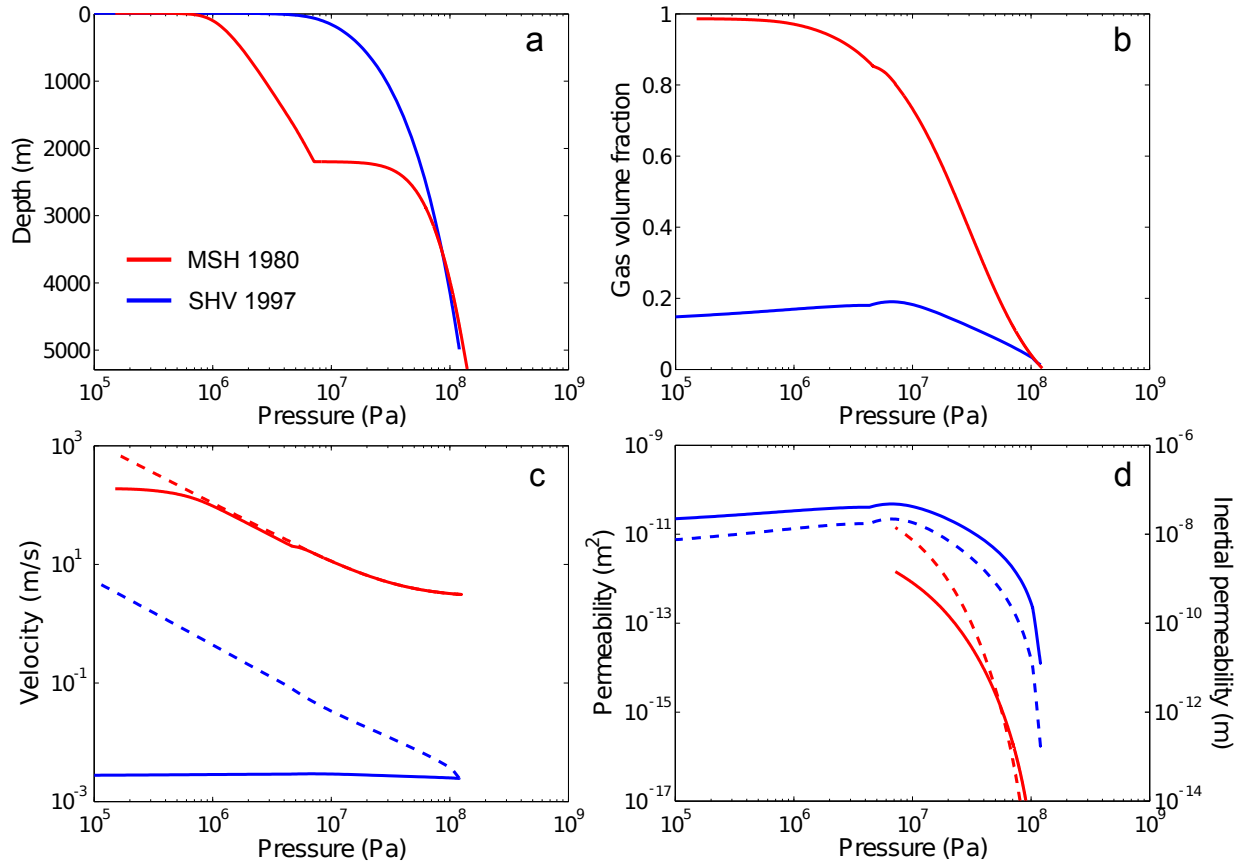


Figure 2: Illustrative solutions to the conduit model for MSH 1980 conditions with  $N_d = 10^{15} \text{ m}^{-3}$ ,  $m = 3.5$ ,  $f_{tb} = 0.1$ ,  $f_0 = 10$  (red) and SHV 1997 conditions with  $N_d = 10^9 \text{ m}^{-3}$ ,  $m = 2.2$ ,  $f_{tb} = 0.3$ ,  $f_0 = 10$  (blue) using a fragmentation criterion based on volume fraction. (a) depth versus pressure, (b) porosity versus pressure, (c) velocity versus pressure with the dashed curves indicating the gas velocity and the solid curves showing the magma velocity, and (d) the Darcian (solid curves) and the inertial permeability (dashed curves).

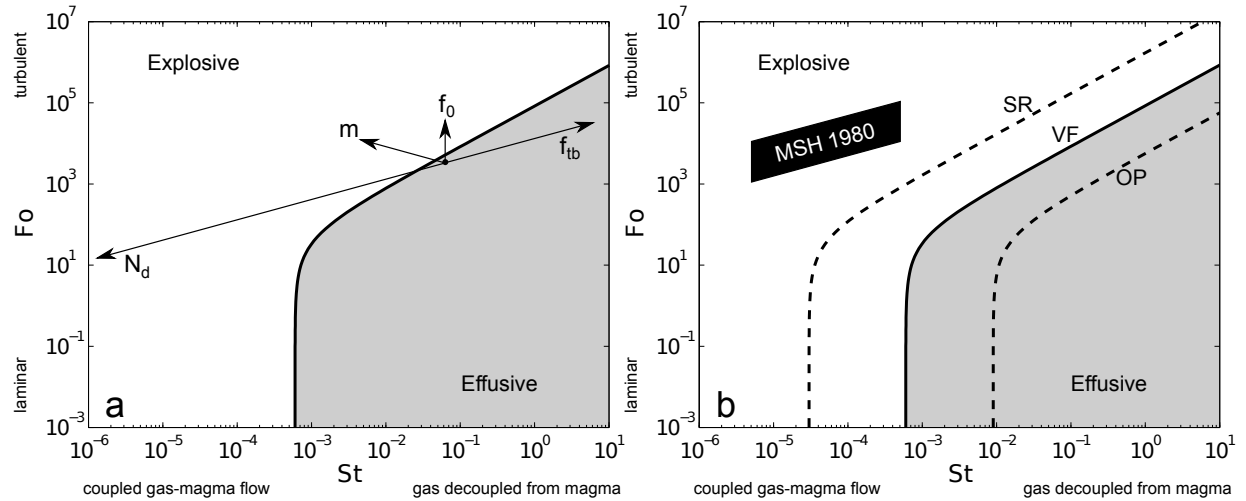


Figure 3: St-Fo map for the MSH 1980 magma properties and conduit geometry. The white area represents the explosive regime, and the grey area the effusive regime. (a) The arrows indicate how one travels on the map by increasing one of the textural properties starting from a randomly chosen point. The relative lengths of the arrows are determined by the range defined in Table 1. (b) The black area is defined by the textural properties found in the pyroclasts of the MSH 1980 eruption. It lies in the low St and high Fo region showing that the gas-magma flow was coupled and outgassing was turbulent. The dashed curves indicate the transition between effusive and explosive regimes for strain-rate fragmentation (SR) and overpressure fragmentation (OP), while the solid curve indicates fragmentation at a critical gas volume fraction (VF). See Appendix B for details on fragmentation criteria.

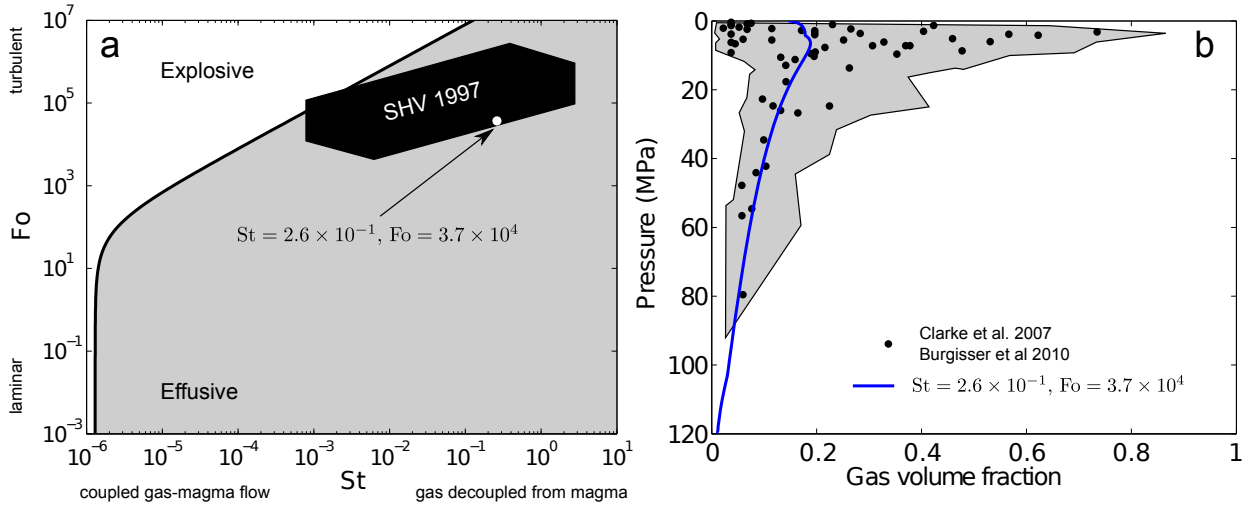


Figure 4: (a) St-Fo map for the SHV 1997 eruption conditions as determined from Monte Carlo simulations. The black area is defined by the textural properties found in the pyroclasts produced by the SHV 1997 eruptions. We can refine the black region to the white point by using the data points of pressure and gas volume fraction collected by Clarke et al. (2007) and Burgisser et al. (2010) in figure (b). The gray area in figure (b) represents the uncertainty in the model used by Burgisser et al. (2010) to obtain pre-explosive gas volume fraction. The blue line is the best fit of the model to this data for  $P > 10$  MPa:  $St = 2.6 \times 10^{-1}$ ,  $Fo = 3.7 \times 10^4$ , e.g.  $N_d = 10^{9.5} \text{ m}^{-3}$ ,  $f_{tb} = 10^{-0.5}$ ,  $m = 2.1$ , and  $f_0 = 10$ .

580 **Appendix A. Non-dimensionalization**

581 We scale the equations of the conduit model to permit better interpretation of the results.  
 582 The model parameters can be divided into three main groups: (i) conduit geometry  $L, r_c$ ,  
 583 (ii) magma properties  $P_0, T, c_0, \phi_f, \rho_m, \chi_0$ , and (iii) magma textures  $f_{tb}, f_0, N_d, m$ . From  
 584 these parameters we define all other characteristic scales: a reference gas density

$$585 \quad \rho_{g0} = \frac{P_0}{RT}, \quad (\text{A.1})$$

586 a reference viscosity

$$587 \quad \log \mu_0 = -3.545 + 0.833 \ln 100c_0 + \frac{9601 - 2368 \ln 100c_0}{T - (195.7 + 32.25 \ln 100c_0)} \quad (\text{A.2})$$

$$588 \quad \theta_0 = \left\{ 1 - c_1 \operatorname{erf} \left( \frac{\sqrt{\pi}}{2} \chi_0 \left[ 1 + \frac{c_2}{(1 - \chi_0)^{c_3}} \right] \right) \right\}^{-B/c_1} \quad (\text{A.3})$$

$$589 \quad \mu_{l0} = \mu_0 \theta_0 \quad (\text{A.4})$$

591 a reference mass and volume flux

$$592 \quad q_0 = \frac{P_0 \rho_m r_c^2}{L 8 \mu_{l0}}, \quad U_0 = \frac{q_0}{\rho_m}, \quad (\text{A.5})$$

593 and the reference Darcian and inertial permeability

$$594 \quad k_{10} = \frac{\phi_f^m (f_{tb} r_{b0})^2}{8}, \quad (\text{A.6})$$

$$595 \quad k_{20} = \frac{(f_{tb} r_{b0}) \phi_f^{\frac{1+3m}{2}}}{f_0}, \quad (\text{A.7})$$

597 with

$$598 \quad r_{b0} = \left( \frac{\phi_f}{\frac{4\pi}{3} N_d (1 - \phi_f)} \right)^{1/3}. \quad (\text{A.8})$$

600 We then define the dimensionless quantities

$$601 \quad u'_m = \frac{u_m}{U_0}, \quad u'_g = \frac{u_g}{U_0}, \quad \rho'_g = \frac{\rho_g}{\rho_{g0}}, \quad \mu'_m = \frac{\mu_{l0}}{\mu_0}, \quad k'_1 = \frac{k_1}{k_{10}}, \quad k'_2 = \frac{k_2}{k_{20}}, \quad q' = \frac{q}{q_0} \quad (\text{A.9})$$



602 Substituting these in the conservation equations gives

$$603 \quad u'_m = \frac{1-n}{1-\phi} q' \quad (\text{A.10})$$

$$604 \quad \rho'_g u'_g = \frac{1-n}{\delta \phi} q' \quad (\text{A.11})$$

$$605 \quad u'_m \frac{du'_m}{dz'} = -\frac{3}{4} \delta \frac{1}{\text{Ma}^2} \frac{dP'}{dz'} - \frac{1}{\text{Fr}^2} + \frac{F'_{mg}}{1-\phi} - \frac{F'_{mw}}{1-\phi} \quad (\text{A.12})$$

$$606 \quad \rho'_g u'_g \frac{du'_g}{dz'} = -\frac{3}{4} \frac{1}{\text{Ma}^2} \frac{dP'}{dz'} - \frac{1}{\text{Fr}^2} \rho'_g - \frac{1}{\delta} \frac{F'_{mg}}{\phi} - \frac{F'_{gw}}{\phi} \quad (\text{A.13})$$

$$607 \quad F'_{mg} = \begin{cases} \frac{1}{\text{St}} \left( 1 + \text{Fo} \frac{k'_1}{k'_2} \rho'_g |u'_g - u'_m| \right) \frac{\phi(1-\phi)}{k'_1} (u'_g - u'_m) & \phi \leq \phi_t \\ \left( \frac{1}{k'_1 \text{St}} \left( 1 + \text{Fo} \frac{k'_1}{k'_2} \rho'_g |u'_g - u'_m| \right) \right)^{1-t} \left( \frac{3}{8} \frac{1}{a_r} C_D \rho'_g |u'_g - u'_m| \right)^t \phi(1-\phi)(u'_g - u'_m) & \phi_t < \phi \leq \phi_f \\ \frac{3}{8} \frac{1}{a_r} C_D \rho'_g \phi(1-\phi) |u'_g - u'_m| (u'_g - u'_m) & \phi > \phi_f \end{cases} \quad (\text{A.14})$$

$$608 \quad F'_{mw} = \begin{cases} \frac{8\mu'_m u'_m}{\text{Re}} & \phi \leq \phi_f \\ 0 & \phi > \phi_f \end{cases} \quad (\text{A.15})$$

$$609 \quad F'_{gw} = \begin{cases} 0 & \phi \leq \phi_f \\ \frac{\lambda_w}{4} \rho'_g u'^2_g & \phi > \phi_f \end{cases} \quad (\text{A.16})$$

$$610 \quad n = \frac{c_0 - \sigma P^{1/2}}{1 - \sigma P^{1/2}} \quad (n \geq 0), \quad (\text{A.17})$$

612 with Re the Reynolds number of the magma phase,

$$613 \quad \text{Re} = \frac{\rho_m r_c U_0}{\mu_{l0}}, \quad (\text{A.18})$$

614 Ma the Mach number of the gas phase (water),

$$615 \quad \text{Ma} = \frac{U_0}{\sqrt{\frac{4}{3} RT}}, \quad (\text{A.19})$$

616 Fr the Froude number,

$$617 \quad \text{Fr} = \frac{U_0}{\sqrt{g r_c}}, \quad (\text{A.20})$$

618  $\delta$  the density ratio between the gas and the magma phase,

$$619 \quad \delta = \frac{\rho_{g0}}{\rho_m}, \quad (\text{A.21})$$

620  $\sigma$  the saturation water content at initial pressure  $P_0$ ,

$$621 \quad \sigma = sP_0^{1/2}, \quad (\text{A.22})$$

622 and  $a_r$  the ratio between the ash size and the conduit radius,

$$623 \quad a_r = \frac{r_a}{r_c}. \quad (\text{A.23})$$

624 St is the Stokes number, the ratio of the response time scale of the magma and the charac-  
625 teristic flow time of the gas

$$626 \quad \text{St} = \frac{\tau_V}{\tau_F} = \frac{\frac{\rho_m k_{10}}{\mu_g}}{\frac{r_c}{U_0}} \quad (\text{A.24})$$

627 and Fo is the Forchheimer number the ratio of the inertial term and the viscous term in  
628 Forchheimer's equation

$$629 \quad \text{Fo} = \frac{\rho_{g0} k_{10} U_0}{k_{20} \mu_g}. \quad (\text{A.25})$$

630 From this scaling analysis we find two parameters that are influenced by textures, St and  
631 Fo. When keeping the conduit geometry and magma properties constant only St and Fo will  
632 vary, while others remain constant (Table 2). Therefore, the textural control on the effusive-  
633 explosive transition can be projected onto a St-Fo plane. We create such a St-Fo map for two  
634 case studies by doing Monte Carlo simulations within the defined texture parameter space  
635 (Table 1).

## 636 **Appendix B. Fragmentation mechanisms**

637 We investigate the effect of different fragmentation mechanisms on the results, using  
638 either a criterion based on (i) critical strain-rate, (ii) overpressure or (iii) volume fraction.  
639 The strain-rate criterion was defined by Dingwell (1996) and Papale (1999) as

$$640 \quad \frac{du_m}{dz} > 0.01 \frac{G}{\mu_m}, \quad (\text{B.1})$$

641 with  $G = 10$  GPa. Note that we use the elongational strain-rate and not the shear-strain  
642 rate, which cannot be assessed by a one-dimensional model (Gonnermann and Manga, 2003).  
643 Overpressure cannot be directly calculated in our model as the pressure between both phases

644 is at equilibrium. However, we assume the overpressure can be quantified by the dynamic  
645 pressure induced by the interphase drag between the two phases

$$646 \quad \frac{dP_{\Delta}}{dz} = F_{mg} \quad (\text{B.2})$$

647 Integrating this equation along with the governing conservation equations gives us an esti-  
648 mate of the overpressure  $P_{\Delta}$  in the bubble network. Following Zhang (1999), fragmentation  
649 occurs when

$$650 \quad P_{\Delta} > \frac{2(1-\phi)}{(1+2\phi)} P_c \quad (\text{B.3})$$

651 where we used  $P_c = 100$  MPa (Webb and Dingwell, 1990). Our results show a shift in  
652 the transition curve (Figure 3b), but do not produce any qualitative difference in the re-  
653 sults. These findings are in agreement with other studies comparing different fragmentation  
654 mechanisms (Melnik and Sparks, 2002b; Massol and Koyaguchi, 2005).