Available online at www.sciencedirect.com
SCIENCE DIRECT
EPSL
Earth and Planetary Science Letters 214 (2003) 561–574
www.elsevier.com/locate/epsl

Vesicle connectivity in pyroclasts and implications for the fluidisation of fountain-collapse pyroclastic flows, Montserrat (West Indies)

Y. Formenti[a,b,*], T.H. Druitt[a]

[a] *Laboratoire Magmas et Volcans, Université Blaise Pascal-CNRS, 5 rue Kessler, 63038 Clermont-ferrand, France*
[b] *School of Earth Sciences, University of Leeds, Leeds LS2 9JT, UK*

Received 19 February 2003; received in revised form 18 June 2003; accepted 8 July 2003

Abstract

Pyroclastic flows are noted for their highly 'mobile' behaviour, being able to flow on slopes as low as a few degrees, and this has been attributed to fluidisation or partial fluidisation by escaping gases. The three types of pyroclastic flows generated during the eruption of Soufrière Hills Volcano on Montserrat (dome-collapse, fountain-collapse and surge-derived) differ in their apparent 'mobility', suggesting different degrees of fluidisation and friction reduction in the flowing granular materials. Several possible sources of fluidising gas operate in pyroclastic flows. The purpose of this paper is to assess the feasibility of one mechanism: the release during flow of pressurised gases trapped in the vesicles of juvenile clasts. Measurements with a helium pycnometer show that all vesicles in dense lava blocks from dome-collapse pyroclastic flows are connected, so that the mechanism is probably not viable for such flows. On the other hand, pumices from fountain-collapse pyroclastic flows from Soufrière Hills and other volcanoes contain up to 10 vol% of isolated vesicles. This is confirmed by SEM imagery, which shows that Soufrière Hills pumices contain two vesicle populations, with a bimodal size distribution. The large vesicles are mostly interconnected, whereas about two thirds of the smaller population (< 15 μm) are isolated. The small vesicles are located as strings, and in some cases as distinctive spheroidal clusters, in the walls between the large vesicles. Many small vesicles and spheroidal vesicle clusters inflated into the (connected) large vesicles as they grew, because they were isolated and had higher internal pressures. The populations probably record two bubble nucleation events in the ascending magma. The second nucleation event must have occurred before the pumices left the vent because the two populations are also preserved in fallout pumices ejected during the same 1997 Vulcanian explosions that generated the pyroclastic flows. One possibility supported by calculations is that the second event occurred in response to brutal decompression of the magmatic foam as it fragmented. Rupture of isolated vesicles provides a potential source of gas in fountain-collapse pyroclastic flows at Soufrière Hills and other volcanoes. Despite significant uncertainties of the relevant parameters, rough calculations show that abrasion of pumice clasts during flow transport could potentially liberate gas at a sufficient rate to fluidise or partially fluidise the material. However, this mechanism is not tenable in dome-collapse or surge-derived flows on Montserrat, the juvenile components of which lack isolated vesicles. Other gas sources, or other mechanisms of friction reduction, must be invoked for these flows.

* Corresponding author. Tel.: +44-113-343-6620; Fax: +44-113-343-52-59.
E-mail address: formenti@earth.leeds.ac.uk (Y. Formenti).

0012-821X/03/$ – see front matter
doi:10.1016/S0012-821X(03)00386-8

Keywords: isolated vesicles; fluidisation; helium pycnometer; pumice; pyroclastic flows; SEM; vesicularity

1. Introduction

Pyroclastic flows are concentrated, gravity-driven mixtures of hot gas and particles capable of travelling several kilometres or even tens of kilometres on slopes as small as a few degrees [1]; recent examples include those of Ngauruhoe Volcano, New Zealand, in 1975 [2], Mount Unzen, Japan, in 1991 [3], Lascar Volcano, Chile, in 1993 [4], and Merapi Volcano, Indonesia, in 1930 and 1994 [5–6]. The ongoing eruption of Soufrière Hills Volcano, Montserrat, has produced three types of pyroclastic flow: dome-collapse flows, generated by gravitational destabilisation of lava domes, fountain-collapse flows, generated by partial collapse of eruptive plumes, and surge-derived flows, generated by rapid sedimentation from pyroclastic surges [7–10]. The juvenile components in dome-collapse and surge-derived pyroclastic flows are dense, whereas in fountain-collapse flows they are pumiceous. Deposits from surge-derived and fountain-collapse pyroclastic flows on Montserrat have on average higher mobility indices than those of dome-collapse flows, irrespective of whether L/H (L: horizontal distance to distal limit of deposit; H: height dropped) or $A/V^{2/3}$ (A: surface area of deposit in plan view; V: deposit volume) is used as the mobility index [11]. Dome-collapse flows, on the other hand, have slightly higher L/H than cold-rock avalanches, but similar $A/V^{2/3}$ ratios [11].

The enhanced mobility and low apparent friction of some pyroclastic flows with respect to cold-rock avalanches has been attributed to fluidisation by escaping gases. Possible sources of gas include ingestion of air, vaporisation of surface water or vegetation, exsolution from juvenile clasts, and release by clast attrition of gas trapped in vesicles [12–15]. Surface water or vegetation do not seem to play important roles at Montserrat because mobility is independent of whether flows are emplaced onto virgin ground or onto recently emplaced flow deposits that are dry and non-vegetated [11]. Exsolution cannot be important owing to the low emplacement temperatures of the flows (dome-collapse 365–640°C; fountain-collapse 180–220°; surge-derived 120–400°C, all measured a few hours to a few days after emplacement [8]), since the diffusion rate of water in silicate glass is negligible at such temperatures. Calder et al. [11] noted that the most mobile pyroclastic flows on Montserrat (fountain-collapse and surge-derived) form by rapid sedimentation from dilute suspensions (respectively, collapsing eruption fountains and rapid settling from pyroclastic surges) and they suggested that this rapid settling generates concentrated granular flows with low frictional resistance. They also speculated that the relatively fine-grained character of the fountain-collapse and surge-derived flows may have played a role in their low frictional resistance.

In this paper we test the role of clast attrition as a fluidisation mechanism. The proportion of isolated vesicles capable of retaining exsolved gas is measured on juvenile clasts from pyroclastic flow deposits at Soufrière Hills and elsewhere. Observations of vesicle textures are also reported. Calculations suggest that clast attrition may have played a role in the fluidisation of the fountain-collapse flows, but not of the dome-collapse or surge-derived flows.

2. Vesicle connectivity

We determined the abundances of isolated vesicles in juvenile clasts from pyroclastic flow deposits using a helium pycnometer. This is well adapted for vesicularity measurements because the helium can enter even the smallest vesicles. Samples were cut into cubes of known total volume (solids+vesicles; V_{sam}). Measurement with the pycnometer gives the volume V_{meas} of the solid phases (glass+crystals) plus the volume of any

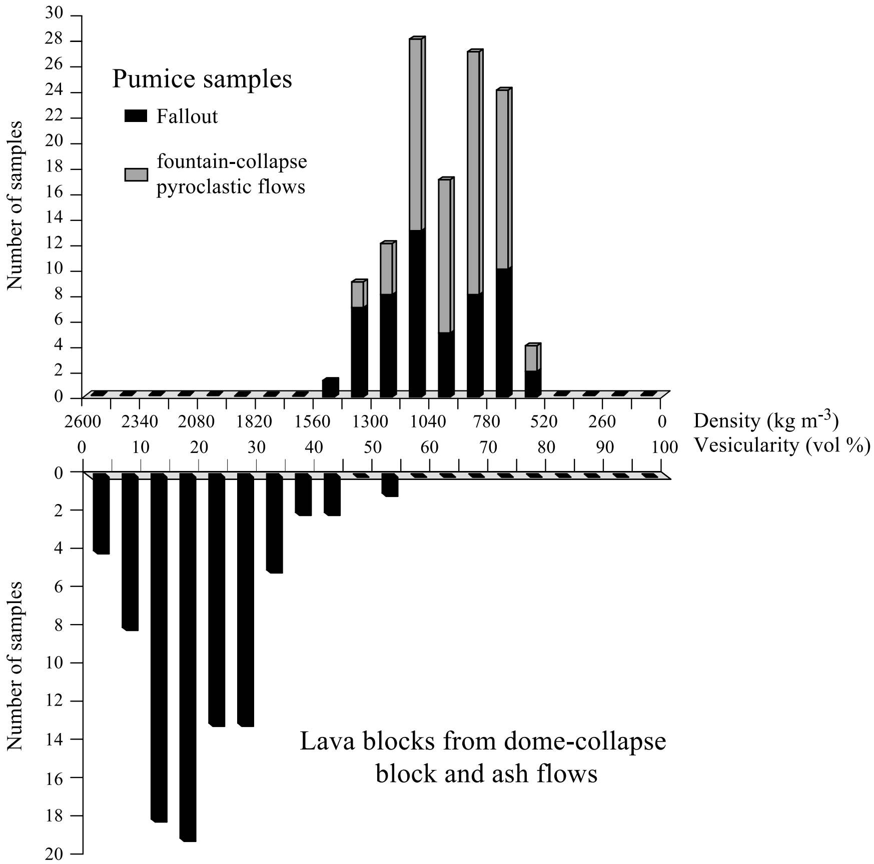


Fig. 1. Densities of pumices and lava blocks from Soufrière Hills Volcano: 85 lava blocks from the 21 September 1997 dome-collapse pyroclastic flows and 120 pumice blocks from the 1997 Vulcanian products (fountain-collapse pyroclastic flow deposits and associated fallout). Samples were dried and weighed, then placed into water to saturate the pores. They were then lightly dabbed to remove surface water and placed again in water to measure the external volume. Vesicularities were calculated using a mean density of 2600 kg m^{-3} for the solid phases.

isolated vesicles. The connected vesicularity (X_c) is given by:

$$X_c = 1 - \frac{V_{meas}}{V_{sam}} \tag{1}$$

The same cubes were then crushed (grain size of about 20–30 μm) and the volume again determined using the pycnometer. This then gives the mean density of the solid phases in each sample (ρ_s). The total vesicularity (X_t) is then given by:

$$X_t = 1 - \frac{m_{sam}}{\rho_s V_{sam}} \tag{2}$$

where m_{sam} is the mass of each cube. The fraction of isolated vesicles is given by $X_t - X_c$.

Measurements were carried out on 10 pumices from fountain-collapse pyroclastic flows (Vulcanian explosions of August–October 1997) and seven dense lava blocks from dome-collapse flows (21 September 1997) from Soufrière Hills. Vesicularities of 1997 pumices range from 45 to 80 vol% and those of dome lava blocks from 0 to 50 vol% (Fig. 1). For comparison we also included 22 pumices from Lascar Volcano, Chile (19–20 April 1993 fountain-collapse flows) and a total of nine dense lava blocks from Merapi Volcano, Indonesia (1930 and 1994 dome-collapse flows; 1993 and 1995 lava domes), Cayambe Volcano, Ecuador (Holocene dome-collapse flows), and Mount Saint Helens, USA (disrupted cryptodome, 18 May

Table 1
Values for the mass and the volume of the cube (m_{sample} and V_{sample}), the density of the solid phase (ρ_s), the volume of the solid phase plus the volume of the isolated vesicles ($V_{measured}$), the bulk vesiculrity (X_b) and the connected vesicularity (X_c) of the sample of pumices and lava blocks studied in this work

Samples	m_{sample} (g)	V_{sample} (cm^3)	ρ_s (g cm^{-3})	$V_{measured}$ (cm^3)	X_b (vol%)	X_c (vol%)
Lava blocks from Soufrière Hills Volcano						
YF 8	47.59 ± 0.01	21.26 ± 0.78	2.73 ± 0.01	17.44 ± 0.06	18.0 ± 3.0	18.0 ± 3.0
YF 9	67.85 ± 0.01	29.29 ± 1.20	2.71 ± 0.01	24.86 ± 0.08	14.5 ± 2.9	15.1 ± 2.8
YF 10	81.50 ± 0.01	37.67 ± 1.20	2.74 ± 0.01	29.45 ± 0.07	21.1 ± 2.5	21.8 ± 2.5
YF 13	45.57 ± 0.01	23.66 ± 1.05	2.69 ± 0.01	16.90 ± 0.08	28.3 ± 3.2	28.6 ± 3.2
YF 14	63.10 ± 0.01	33.02 ± 0.81	2.71 ± 0.01	23.10 ± 0.09	29.5 ± 1.8	30.1 ± 1.7
YF 15	35.51 ± 0.01	18.22 ± 0.81	2.68 ± 0.00	13.26 ± 0.07	27.2 ± 3.3	27.2 ± 3.3
YF 33	34.42 ± 0.01	24.04 ± 0.47	2.64 ± 0.01	13.11 ± 0.05	45.7 ± 1.1	45.5 ± 1.1
Pumice from Soufrière Hills Volcano						
YF 16-2	5.96 ± 0.01	8.25 ± 0.09	2.64 ± 0.01	3.11 ± 0.02	72.6 ± 0.3	62.3 ± 0.5
YF 17-1	33.94 ± 0.01	38.07 ± 0.13	2.66 ± 0.00	16.33 ± 0.10	66.4 ± 0.1	57.1 ± 0.3
YF 17-2	19.88 ± 0.01	23.66 ± 0.40	2.65 ± 0.06	9.83 ± 0.06	68.3 ± 0.9	58.5 ± 0.8
YF 18	29.83 ± 0.01	42.36 ± 0.45	2.63 ± 0.01	15.03 ± 0.07	73.3 ± 0.3	64.5 ± 0.4
YF 19-1	25.78 ± 0.01	27.67 ± 0.60	2.64 ± 0.01	11.02 ± 0.09	67.7 ± 0.8	62.3 ± 0.5
YF 19-2	27.85 ± 0.01	29.87 ± 0.82	2.70 ± 0.01	11.69 ± 0.10	65.5 ± 1.0	60.9 ± 1.1
YF 20-1	30.22 ± 0.01	23.73 ± 0.37	2.66 ± 0.01	11.92 ± 0.10	52.2 ± 0.8	49.8 ± 0.9
YF 20-2	29.51 ± 0.01	23.30 ± 0.29	2.70 ± 0.01	11.59 ± 0.10	53.1 ± 0.6	50.2 ± 0.8
YF 21-1	14.82 ± 0.01	22.51 ± 0.60	2.65 ± 0.01	6.93 ± 0.05	75.2 ± 0.1	69.2 ± 0.2
YF 21-2	18.64 ± 0.01	28.26 ± 0.96	2.67 ± 0.01	8.87 ± 0.09	75.3 ± 0.8	68.6 ± 1.1
Pumice from Lascar Volcano						
La 1	27.44 ± 0.01	38.31 ± 0.62	2.60 ± 0.01	11.37 ± 0.03	72.4 ± 0.5	70.3 ± 0.5
La 2	35.36 ± 0.01	41.06 ± 0.59	2.59 ± 0.00	15.00 ± 0.08	66.8 ± 0.4	63.5 ± 0.6
La 3	42.15 ± 0.01	47.01 ± 0.58	2.62 ± 0.01	17.86 ± 0.11	65.7 ± 0.4	62.0 ± 0.5
La 4	31.44 ± 0.01	33.95 ± 0.32	2.58 ± 0.01	13.35 ± 0.05	64.1 ± 0.4	60.7 ± 0.4
La 5	48.81 ± 0.01	53.48 ± 0.63	2.55 ± 0.01	21.02 ± 0.10	64.7 ± 0.4	60.7 ± 0.5
La 6	30.92 ± 0.01	36.68 ± 0.36	2.59 ± 0.01	13.52 ± 0.06	67.4 ± 0.3	63.2 ± 0.4
La 7	30.83 ± 0.01	36.88 ± 0.50	2.62 ± 0.00	13.46 ± 0.05	68.1 ± 0.4	63.5 ± 0.5
La 8	31.46 ± 0.01	38.90 ± 0.63	2.59 ± 0.01	13.87 ± 0.07	68.8 ± 0.5	64.3 ± 0.6
La 9	17.60 ± 0.01	23.25 ± 0.48	2.60 ± 0.01	7.79 ± 0.02	70.9 ± 0.6	66.5 ± 0.7
La 10	37.61 ± 0.01	43.08 ± 0.40	2.60 ± 0.01	15.39 ± 0.05	66.4 ± 0.3	64.3 ± 0.4
La 11	39.44 ± 0.01	41.24 ± 0.44	2.60 ± 0.00	16.31 ± 0.04	63.3 ± 0.4	60.5 ± 0.4
La 12	25.38 ± 0.01	38.72 ± 0.52	2.59 ± 0.01	11.05 ± 0.02	74.7 ± 0.4	71.5 ± 0.4
La 13	28.89 ± 0.01	35.18 ± 0.52	2.61 ± 0.01	13.38 ± 0.03	68.4 ± 0.5	62.0 ± 0.6
La 14	30.82 ± 0.01	46.83 ± 0.69	2.62 ± 0.00	12.99 ± 0.06	74.9 ± 0.4	72.3 ± 0.4
La 15	27.05 ± 0.01	33.72 ± 0.60	2.60 ± 0.01	11.27 ± 0.02	69.1 ± 0.6	66.6 ± 0.6
La 16	22.59 ± 0.01	29.29 ± 0.58	2.62 ± 0.01	9.73 ± 0.02	70.5 ± 0.6	66.8 ± 0.7
La 17	31.62 ± 0.01	39.59 ± 0.68	2.58 ± 0.01	12.93 ± 0.05	69.1 ± 0.6	67.4 ± 0.6
La 18a	31.16 ± 0.01	30.67 ± 0.31	2.56 ± 0.01	13.51 ± 0.02	60.2 ± 0.4	56.0 ± 0.5
La 18b	33.71 ± 0.01	31.54 ± 0.23	2.58 ± 0.01	14.21 ± 0.13	58.6 ± 0.3	55.0 ± 0.5
La 19	34.25 ± 0.01	34.73 ± 0.69	2.64 ± 0.00	14.66 ± 0.04	62.6 ± 0.7	57.8 ± 0.9
La 20	46.65 ± 0.01	45.89 ± 0.42	2.63 ± 0.01	20.06 ± 0.07	61.3 ± 0.4	56.3 ± 0.4
La 21	42.20 ± 0.01	43.39 ± 0.48	2.56 ± 0.01	17.36 ± 0.06	62.0 ± 0.4	60.0 ± 0.5
Lava blocks from Merapi Volcano						
Me 30	29.56 ± 0.01	11.47 ± 0.21	2.74 ± 0.01	10.50 ± 0.06	6.0 ± 1.8	8.5 ± 1.8
Me 93	64.88 ± 0.01	30.58 ± 0.31	2.72 ± 0.00	23.41 ± 0.09	21.9 ± 0.8	23.5 ± 0.8
Me 94	74.44 ± 0.01	32.10 ± 0.55	2.72 ± 0.01	26.89 ± 0.11	14.9 ± 1.5	16.2 ± 1.5
Me 95	35.37 ± 0.01	15.94 ± 0.53	2.73 ± 0.01	12.85 ± 0.05	18.8 ± 2.7	19.4 ± 2.7

Table 1 (*Continued*).

Samples	m_{sample} (g)	V_{sample} (cm^3)	ρ_s (g cm^{-3})	$V_{measured}$ (cm^3)	X_b (vol%)	X_c (vol%)
Lava blocks from Cayambe Volcano						
CAY 7	76.50 ± 0.01	33.43 ± 0.34	2.54 ± 0.01	29.91 ± 0.02	9.8 ± 0.9	10.6 ± 0.9
CAY 4b	71.17 ± 0.01	28.29 ± 0.55	2.57 ± 0.01	27.44 ± 0.06	2.2 ± 1.9	3.0 ± 1.9
CAY 4d	49.10 ± 0.01	22.55 ± 0.12	2.55 ± 0.01	19.18 ± 0.12	14.6 ± 0.5	15.0 ± 0.7
Lava blocks from Mount Saint Helens						
MS^{t}H 1	41.11 ± 0.01	31.89 ± 0.27	2.57 ± 0.01	17.60 ± 0.16	49.9 ± 0.5	44.8 ± 0.7
MS^{t}H 2	22.04 ± 0.01	17.27 ± 0.17	2.57 ± 0.01	9.56 ± 0.12	50.4 ± 0.5	44.7 ± 0.9

1980 blast deposit). The volumes of the cubes used for this study ranged from 10 to 50 cm^3. Pumice blocks from Soufrière Hills and Lascar pyroclastic flows have rounded shapes due to abrasion during transport (Fig. 2a).

Results are given in Table 1 and are shown in Fig. 3. For each sample, five measurements were made with the helium pycnometer in order to calculate the standard deviations of V_{meas} and ρ_s. The error bars in Fig. 3 reflect the standard deviations on V_{sam}, V_{meas} and ρ_s. Lava blocks (from the dome-collapse flows) have total and connected vesicularities that are within error of each other (2–30 vol%; one Soufrière Hills sample with 45 vol%), showing that no isolated vesicles exist in these materials. In contrast, all pumice samples from Soufrière Hills and Lascar have connected vesicularities lower than total vesicularities, the latter lying in the range 50–75 vol%. Thus in each case there exists a population of isolated vesicles, these accounting for 2–10 vol% (mean 6.5%) vesicularity at Soufrière Hills and for 2–7 vol% (mean 3.5%) at Lascar. The two cryptodome samples from Mount Saint Helens have vesicularities of about 50 vol%, of which about 5% represent isolated vesicles.

3. Scanning electron microscopy (SEM) investigation

In order to characterise the vesicle textures, six pumices (YF 16 to YF21; Table 1) from the Soufrière Hills fountain-collapse flows were examined by SEM. We also included three fallout pumices from the 1997 Vulcanian explosions (Fig. 2b). Fallout pumices could not be studied by pycnometry because they are in general too small; how-

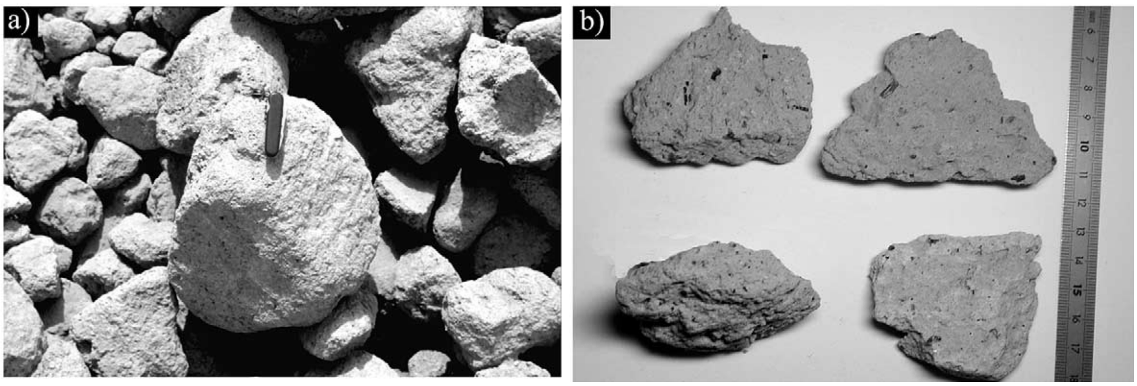
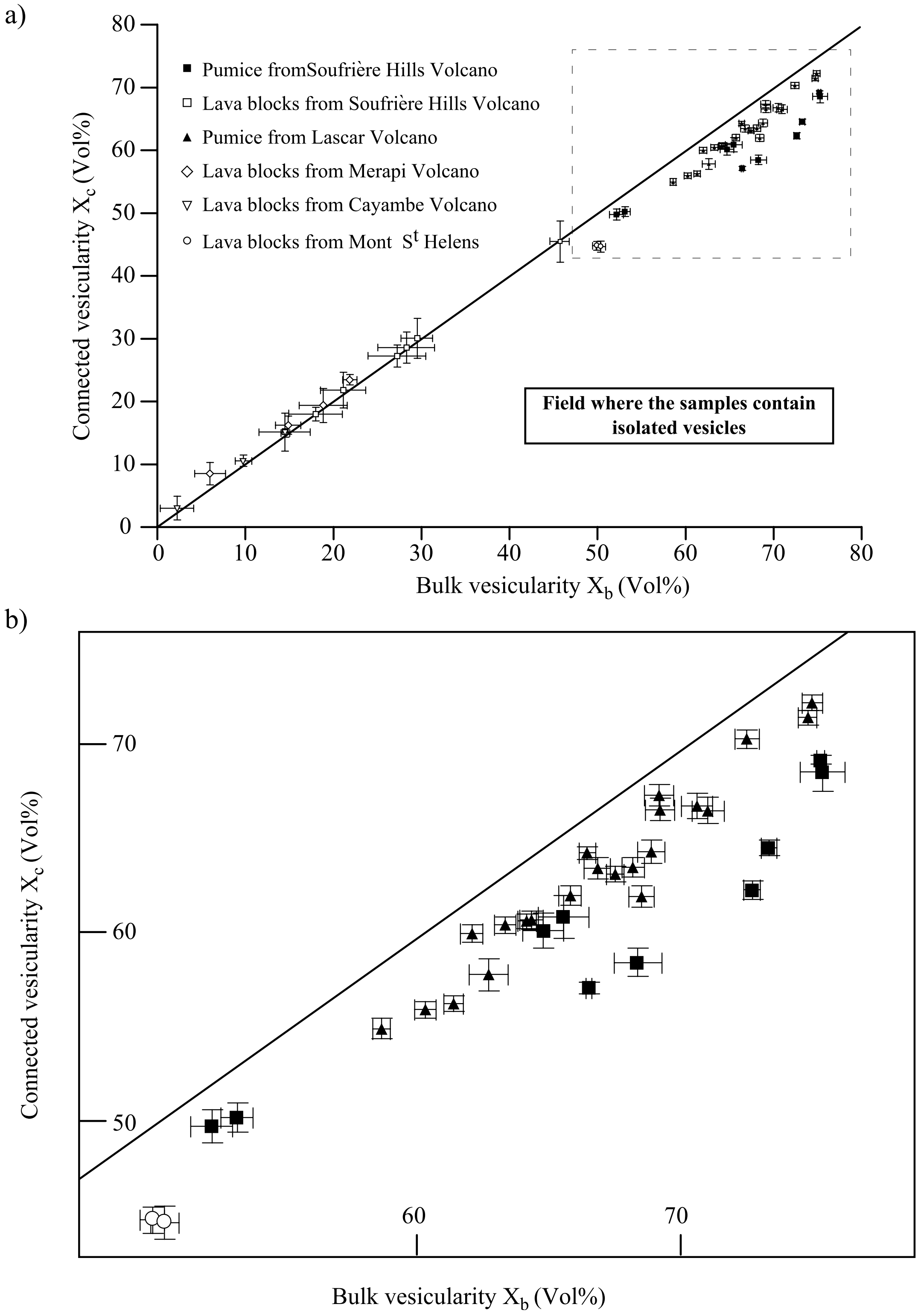


Fig. 2. (a) Typical pumice block in a fountain-collapse pyroclastic flow deposit from the 1997 Vulcanian explosions on Montserrat. The block is rounded due to attrition in the flow. (b) Fallout pumices generated by the same Vulcanian explosions in 1997. The angular, tabular shapes show that fragmentation in the conduit occurred by brittle spallation of a gas-pressurised magmatic foam [9].


a)
Pumice fromSoufrière Hills Volcano
Lava blocks from Soufrière Hills Volcano
Pumice from Lascar Volcano
Lava blocks from Merapi Volcano
Lava blocks from Cayambe Volcano
Lava blocks from Mont S^t Helens
Field where the samples contain isolated vesicles
Connected vesicularity X_c (Vol%)
Bulk vesicularity X_b (Vol%)
0
10
20
30
40
50
60
70
80
b)
Connected vesicularity X_c (Vol%)
Bulk vesicularity X_b (Vol%)
50
60
70

ever they were examined by SEM in order to contrast them texturally with the pyroclastic flow pumices, which, although generated by the same set of explosions, had different thermal histories after leaving the vent. Two Lascar pumices (La 1 and La 2) and two samples from Soufrière Hills dome-collapse flows (YF 14 and YF 33) were also examined.

3.1. *Vesicle textures in pumices from Soufrière Hills fountain-collapse pyroclastic flows*

All six pumices from Soufrière Hills fountain-collapse flows have two populations of vesicles of different sizes. The relatively large vesicles have diameters of 15–50 μm and are characterised by textures of ductile connectivity, such as the presence of ovoid holes between adjacent vesicles. These holes are surrounded by the remains of retracted liquid films (arrows on Fig. 4a–c,f), showing that most of the connectivity did not occur by brittle fracture. The relatively large sizes of these vesicles partly result from ductile coalescence of pre-existing vesicles, probably prior to fragmentation of the magma. The large vesicles are interpreted to form a connected network and to account for most of the connected vesicularity of the pumice.

Vesicles of the relatively small population have diameters in the range 1–15 μm and are commonly located in the walls between the large ones, forming groups or strings of bubbles (Fig. 4a,d), as also described from pumices elsewhere [16]. Some of the small vesicles are grouped into spheroidal clusters several tens of μm in diameter (Fig. 4b,c). Many of the small vesicles show evidence of inflation into adjacent, larger vesicles (Fig. 4f). During inflation, the walls of the small vesicles were thinned, but in many cases were quenched before they could rupture. The spherical clusters (Fig. 4c) as a whole also show evidence of inflation. They commonly protrude with bulbous, cauliform shapes into adjacent large vesicles (Fig. 4c). Individual vesicles within the clusters show numerous signs of ductile connectivity (Fig. 4b,c); it therefore seems that many of the small vesicles within the spheroidal clusters are mutually interconnected, while being isolated from the larger vesicles.

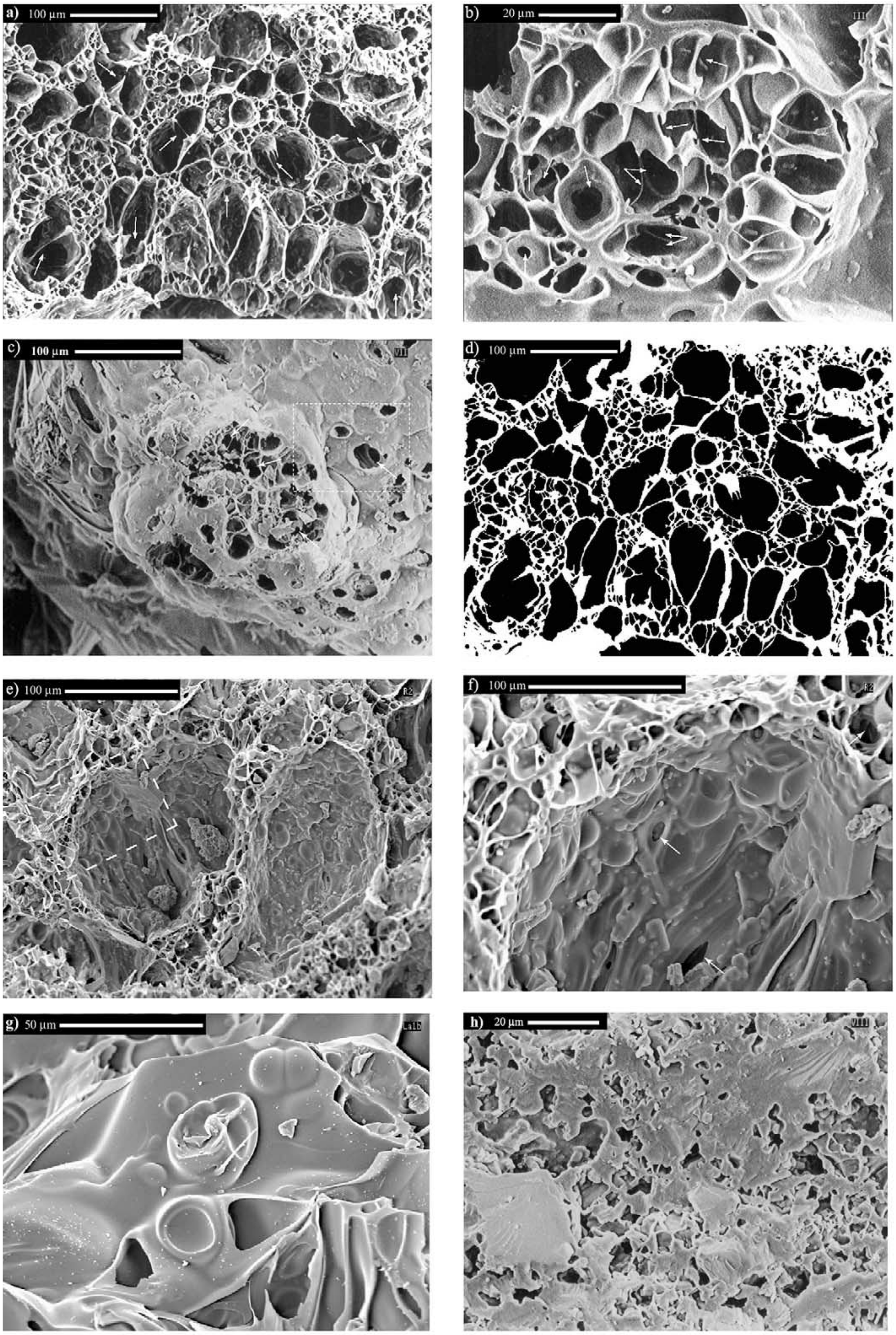
The vesicle-size distribution shown in Fig. 5 confirms the existence of two distinct vesicle populations. It was obtained from the photograph in Fig. 4d in the manner described in the caption of Fig. 5. The small vesicle population represents about 20% of the area of Fig. 4d, whereas that of the large vesicles represents about 40%. Transforming the 2D distribution into a 3D one using the method of Saltikov [17] (and assuming that the vesicles are spherical) suggests that in volumetric terms the small vesicles represent about 15% of the pumice and the large ones about 45%. If we compare this with the proportion of isolated vesicles yielded by pycnometry (up to 10 vol%), we infer that about two thirds of the small vesicles are isolated.

3.2. *Vesicle textures in pumices from Soufrière Hills fallout*

Fallout pumices from the 1997 Soufrière Hills explosions are more variable texturally than those from the pyroclastic flows. Of the three clasts studied, two have textures resembling those of pumices from the pyroclastic flows, with two populations of vesicles and with small vesicles forming strings located in the walls of larger vesicles (Fig. 4e). Many of the small vesicles in these clasts also preserve evidence of late-stage inflation into larger vesicles (Fig. 4f). The third fallout clast studied is less vesicular, the vesicles are subangular to angular in shape and the vesicle-size distribution appears by visual inspection to be unimodal. This clast appears to be texturally transitional to the dome samples described below and possibly

←

Fig. 3. (a) Graph of connected vesicularity versus total vesicularity in samples of pumices and dense lava blocks from Soufrière Hills and other volcanoes. The diagonal line represents equality between the two, $X_b = X_c$. Beneath this line the samples have isolated vesicles. (b) Enlargement of the area marked in a.


a) 100 μm
b) 20 μm
c) 100 μm
d) 100 μm
e) 100 μm
f) 100 μm
g) 50 μm
h) 20 μm

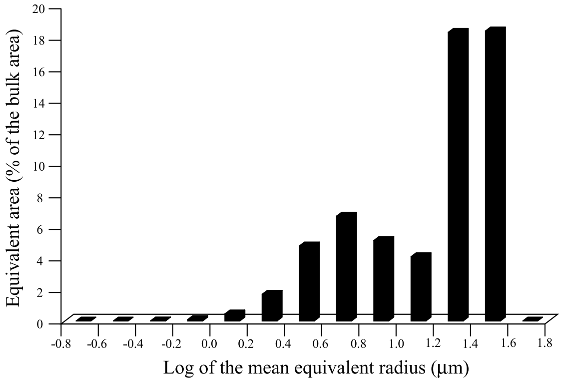


Fig. 5. 2D vesicle-size distribution of a typical pumice from 1997 fountain-collapse pyroclastic flow on Montserrat, measured from the image in Fig. 4d. 'Equivalent area' is the number of vesicles of a size class (radius between x_i and x_{i+1}) multiplied by the area S of a vesicle with the mean radius of the class size: $S=\pi[x_i+((x_i+x_{i+1})/2]^2$. Note that the horizontal scale is logarithmic.

represents a fragment of the dome ejected by the explosions, rather than fresh, gas-rich magma from the conduit.

3.3. Vesicle textures in dense clasts from Soufrière Hills dome-collapse pyroclastic flows

Lava blocks from the 21 September 1997 Soufrière Hills dome-collapse flow are poorly vesicular, with subangular to angular vesicles typically less than 10 μm in size (Fig. 4h). The paucity of spherical vesicles in these samples is due to the high percentage of microlites, which limit vesicle growth and impose angular shapes. Although some vesicles visibly form a network (Fig. 4h), the complete interconnectivity revealed by pycnometry is not evident from SEM images.

3.4. Vesicle textures in pumices from Lascar fountain-collapse pyroclastic flows

For comparison, we include here some SEM observations made on pumices from the 1993 Lascar pyroclastic flows. As for those from the Montserrat fountain-collapse flows, Lascar pumices have numerous vesicles that have inflated. However, some small vesicles that have inflated show signs of connectivity with large vesicles. Indeed some of these vesicles deflated after their inflation, as shown in Fig. 4g. The deflation of the inflated vesicles has not been observed in Montserrat pumices; it has only been observed in the Lascar pumices. The film of liquid of these vesicles retracts and adopts a concave curvature whereas the film of liquid of the inflated vesicles adopts a convex curvature. The deflation of the vesicles occurred before the viscous quench of the pumice. The deflation of the isolated vesicles can be explained by two phenomena: first, it may be due to the loss of gas when these vesicles coalesced with a large vesicle connected to the atmospheric environment, or, secondly, it may be due to the thermal contraction of the gas inside the vesicles during the cooling of the pumice. But the coexistence of inflated vesicles near the deflated vesicles in Fig. 4g suggests that this is not the cooling of the pumice which is responsible for the deflation of the vesicles. This idea is confirmed by the shrivelled shapes of some deflated vesicles (Fig. 4g), which suggests that the deflation is brutal.

The same texture with two vesicle populations

←

Fig. 4. Typical textures of pumice samples examined by SEM. (a–d) Pumices from 1997 Soufrière Hills fountain-collapse pyroclastic flow deposits. (a) Typical texture (YF 16) with two populations of vesicles: a population of large, interconnected vesicles and a population of small vesicles forming groups or strings in the walls between larger vesicles. (b) Small vesicles grouped in a spheroidal cluster (pumice YF 16). (c) Cauliflower external form of a spheroidal vesicle cluster (comparable to that of b) due to inflation into a neighbouring large vesicle (pumice YF 21). (d) Threshold image of the photo of a, used for measuring the vesicle-size distribution in Fig. 5. Vesicles appear in black and solid phases in white. (e) Strings of small vesicles nucleated in the walls of larger vesicles in a 1997 Vulcanian fallout pumice from Soufrière Hills Volcano. (f) Detail of small vesicles that have inflated into a large neighbouring vesicle (enlargement of area in e). Some of these vesicles have thinned walls indicating that they were approaching ductile rupture when they were quenched. (g) Small vesicles in a Vulcanian pumice from Lascar Volcano, showing evidence of initial inflation, followed by deflation. The deflation is evident from the shrivelled appearance of the vesicle walls. (h) Typical texture of a lava block from the 21 September 1997 dome-collapse pyroclastic flow deposit on Montserrat.

has been clearly observed in all the samples from fountain-collapse pyroclastic flows, in two of the three samples from fallout deposits and in the two samples of the Lascar pumice.

4. Discussion

4.1. Vesicle bimodality and growth

Our observations show that dense blocks derived from lava domes are commonly not able to retain gas because essentially all the vesicles are interconnected, as also found by Le Pennec et al. [18] in an electrical conductivity study of samples of Merapi lava dome. On the other hand, typically a few volume percent of vesicles in pumices from fountain-collapse pyroclastic flows at Soufrière Hills and Lascar are isolated, showing that gas can be retained in isolated vesicles of pumices even after cooling and deposition. The results are consistent with vesicularity studies of pyroclasts from other volcanoes using the same or other techniques. Helium pycnometry studies on pumices from Mount Saint Helens and Crater Lake have revealed a percentage of isolated vesicles comparable ($<10\%$) to that measured in this study [19,20]. With the same technique, Rust et al. [21] have shown that dacitic lavas and pumices from Mount Meager Volcano have up to 17% of isolated vesicles when the bulk vesicularity exceeds 50%. Pinti et al. [22] have estimated from isotopic data that the percentage of isolated vesicles in pumice samples from Hokkaïdo (Japan) and Lipari (Aeolian Islands, Italy) is less than 10 vol%.

Our SEM observations show that pumices from Soufrière Hills fountain-collapse pyroclastic flows contain two populations of vesicles: a large population of vesicles that are largely interconnected, and a small population of vesicles, most of which are isolated. Preliminary observations on pumices from Lascar 1993 pyroclastic flows also reveal two vesicle populations. Vesicle bimodality has also been observed in pumices from other volcanoes, and has been attributed to two distinct nucleation events [23–25]. At Soufrière Hills, the large vesicles nucleated relatively early during magma ascent, whereas the small vesicle population nucleated at a later stage within the walls of the large vesicles. Evidence as to the timing of the second nucleation event is provided by the fallout pumices erupted during the same Vulcanian explosions, most of which also contain two vesicle populations. Fallout and pyroclastic flow pumices therefore followed similar thermal and decompression histories up to the moment they left the vent; thereafter their histories must have diverged. It follows that the second nucleation event must have taken place in the magmatic foam prior to leaving the vent. One possibility is that the second event took place during conduit ascent but before fragmentation, perhaps due to microlite growth [26–28]; another possibility is that it occurred in response to fragmentation, but that growth was arrested due to either thermal or viscous quench before the material left the vent [28–29].

The second mechanism can be tested by an approximate calculation. The radius of a growing vesicle is given by:

$$R = R_0 \exp\left(\frac{\Delta P}{4\eta}t\right) \tag{3}$$

[29,30], where R_0 is the radius of the nucleus, taken as 0.1 μm [29], ΔP is the decompression of the magma during and following fragmentation (estimated at 10–16 MPa [31]), η is the viscosity of the melt phase and t is the growth duration. Considering the size of the small vesicle population (<15 μm), which is of the same order as that of the microlites (Fig. 4e), the relevant viscosity 'seen' by the growing vesicles would be that of the rhyolitic melt phase alone. The viscosity of rhyolitic melt (η_0) is given by [32]:

$$\mathrm{Log}(\eta_0) = -3.545 + 0.833 \times \mathrm{Ln}(w) + \frac{9601 - 2368 \times \mathrm{Ln}(w)}{T - [195.7 + 32.25 \times \mathrm{Ln}(w)]} \tag{4}$$

where T is the temperature and w is the water percentage of the magma. So for the conditions at fragmentation, $T = 1150$ K [33–34] and $w = 0.6$ wt% [31], the melt viscosity would be about 10^7 Pa s. Under these conditions, the time necessary for a vesicle to reach 15 μm diameter is of the order of 10 s; this is comparable to the time taken by a pumice travelling from the fragmentation level to the surface assuming an ascent speed (100 m s^{-1}) and fragmentation depth (1 km) typical of the 1997 Vulcanian explosions [9]. We conclude that sudden decompression of the magma at the moment of fragmentation may have triggered a second nucleation event within the walls of large, pre-existing vesicles. Growth of the second vesicle population must have essentially ceased, either due to thermal or viscous [35] quenching, by the time the material left the vent, since the vesicle bimodality is preserved both in pumices emplaced as fallout and in those that entered the pyroclastic flows.

Irrespective of the exact timing of the second nucleation event, once fragmentation occurred, the large network-forming vesicles would have rapidly lost their gas and their pressure would have fallen to atmospheric. Many of the small vesicles, on the other hand, would have retained overpressures and inflated into the larger ones, as seen on the SEM images. As the small vesicles grew, some of the liquid walls would have ruptured in a ductile fashion, allowing them to release their gas. The walls of other small vesicles ruptured in a brittle mode, either in the eruptive column or during the emplacement of pyroclastic flows. A few percent of small vesicles in pyroclastic flow pumices failed to rupture and remained isolated.

4.2. Role of exsolved gas in the emplacement of pyroclastic flows

The presence of isolated vesicles provides a potential source of gas in pyroclastic flows by the abrasion and breakage of clasts during flow transport. We now evaluate approximately the amount of gas that could have been released in the Soufrière Hills fountain-collapse flows and the role that this could have played in their fluidisation.

Let us as consider that at inception the flow consists entirely of pumice blocks without any fines. The volume abraded during flow emplacement may be estimated by XV_t, where X is the percentage of attrition and V_t is the bulk volume of the flow. In this volume there is a fraction Y of isolated vesicles that release their gas (at pressure P) by attrition. The gas then expands to atmospheric pressure (P_a). The volume of gas thus released is:

$$V_{\text{gas released}} = \frac{P}{P_a} XYV_t \qquad (5)$$

The value of Y, as constrained by this study, ranges from 0.01 to 0.1. However, the presence of brittle fractures in some vesicle walls suggests that some connectivity could have taken place by microfracturing during cooling [36] or by collisions of pumice clasts during flow transport. Thus the value of Y during emplacement of the pyroclastic flows may have been higher. We have therefore used values of Y from 0.01 to 0.15.

The value of X is difficult to estimate. Attrition is known to be an important process in pyroclastic flows [37–40], as shown by the rounded shapes of the pumice clasts (Fig. 2a). Fragmentation during the Vulcanian explosions occurred by brittle spallation of magmatic foam, generating angular fragments of pumice that were then rounded by abrasion in the flows [9]. Assuming that the pumices initially had cubic shapes and were abraded to spheres, then X would be 0.48. Power-law fits of pyroclastic flow grain-size distributions also imply a degree of particle abrasion during flow generation and transport [39], although this is hard to quantify. Given the considerable uncertainties involved we have used a range of values of X from 0.1 to 0.75.

The vertical gas velocity generated in a pyroclastic flow by pumice abrasion also depends on the pressure in isolated vesicles at the moment of rupture. This might in turn depend on the timing of the nucleation event that formed the small vesicle population. If the small vesicles grew almost entirely before fragmentation, then they could theoretically retain pre-fragmentation pressures (10–16 MPa [31,41,42]). Cooling from 1150 to $\sim$500 K (the approximate emplacement temperature of the fountain-collapse flows) would have lowered this by a factor of more than two, to a few MPa. If, on the other hand, the small vesicles grew following fragmentation, expansion during growth could have resulted in pressures very much lower than this. Furthermore, experi-

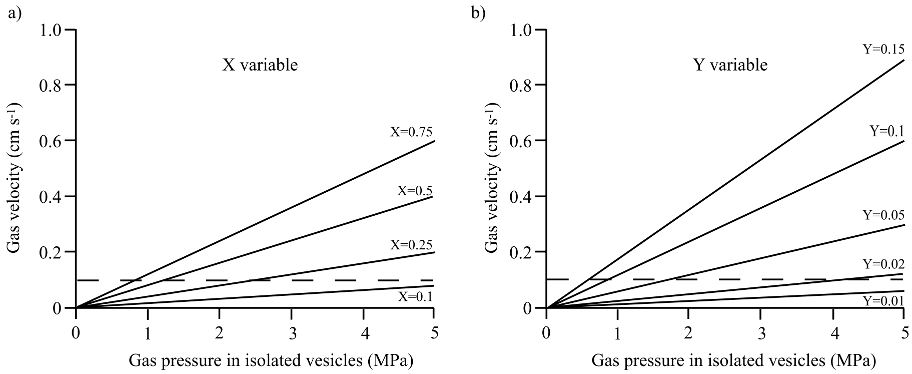


Fig. 6. Vertical gas velocities generated by attrition of pumices in a pyroclastic flow, as a function of gas pressure in isolated vesicles. (a) $Y = 0.065$ and X is variable. (b) $X = 0.48$ and Y is variable. The dotted line corresponds to a gas velocity of 0.1 cm s^{-1}, at which some fine-grained pyroclastic flow materials are fully fluidised. The gas velocity is calculated as the gas volume flux per unit surface area, as is the standard fluidisation practice. See text for discussion.

mental studies of magmatic foams have shown that vesicles cannot retain excess pressures higher than 1–5 MPa without bursting [43–44]. For these reasons it is unrealistic to envisage pressures higher than 5 MPa, and possibly as little as 1 MPa, within isolated vesicles in the Montserrat pyroclastic flows.

Fig. 6 shows vertical gas velocities generated by pumice attrition in an average 1997 Montserrat fountain-collapse pyroclastic flow using the above assumptions. These are obtained by dividing the total volume of gas released (Eq. 5) by the mean transport duration of the pyroclastic flow ($\sim$500 s [9]) and the area of the resulting deposit (1.8×10^5 m^2 [11]). In fact this underestimates gas velocity because the mean surface of the flow during emplacement is half that of the final deposit. Moreover, it assumes that attrition occurred progressively over the transport duration of the pyroclastic flow; however, if most of the attrition took place during fountain collapse or during the early stages of flow transport [37,38,40], then we may significantly underestimate the gas release during the early stages and overestimate it during later stages.

Despite these reservations, Fig. 6 provides at least an indication of the feasibility of the process. The minimum gas velocity necessary to fluidise typical ignimbrite has been determined experimentally as about 0.5–1 cm s^{-1} [45]. Moreover recent studies have shown that full fluidisation can occur at gas velocities as low as 0.1 cm s^{-1} in fine-grained ignimbrite at high temperature (T.H. Druitt, unpublished data). If we take 5 MPa for the vesicle pressure, then a velocity of 0.1 cm s^{-1} can be achieved for very low values of X (about 10%) if Y is fixed at 6.5 vol% or low values of Y if $X \sim 50\%$ (Fig. 6).

We infer that gas release by rupture of isolated vesicles may have played a role in the fluidisation of the Montserrat fountain-collapse pyroclastic flows, in particular during the early stages of flow transport. This is in contrast to gas release by exsolution, which does not appear to have been important because the flows cooled too rapidly for diffusive release to be significant [11]. Vesicle rupture is less likely to have been important in the dome-collapse and surge-derived flows, as the poorly vesicular lava fragments that constitute them contain few or no isolated vesicles, or at least did not once the flows had come to rest. The fact that, of the three pyroclastic flow types on at Soufrière Hills, it is the surge-derived flows that are the most ‘mobile’ shows that other factors such as fine-grain size or elevated gas pore pressures generated during flow formation [11] must be important.

Acknowledgements

We thank Didier Laporte for his guidance in using the SEM and for fruitful discussions, and Marc Leblanc to let us use the helium pycnometer of the 'Laboratoire des fluorures' of Le Mans University. We are also grateful to Steve Self and Steve Sparks for reviewing this paper.*[BW]*

References

[1] T.H. Druitt, Pyroclastic density currents, in: J.S. Gilbert, R.S.J. Sparks (Eds.), The Physics of Explosive Volcanic Eruptions, Geol. Soc. Spec. Publ. 145, The Geological Society, London, 1998, pp. 145–182.

[2] I.A. Nairn, S. Self, Explosive eruptions and pyroclastic avalanches from Ngauruhoe in February 1975, J. Volcanol. Geotherm. Res. 3 (1978) 39–60.

[3] T. Yamamoto, S. Takarada, S. Suto, Pyroclastic flows from the 1991 eruption of Unzen Volcano, Japan, Bull. Volcanol. 55 (1993) 166–175.

[4] R.S.J. Sparks, M.C. Gardeweg, E.S. Calder, S.J. Matthews, Erosion by pyroclastic flows on Lascar Volcano, Chile, Bull. Volcanol. 58 (1997) 557–565.

[5] G. Boudon, G. Camus, A. Gourgaud, J. Lajoie, The 1984 nuées-ardente deposits of Merapi Volcano, Central Java, Indonesia: Stratigraphy, textural characteristics, and transport mechanisms, Bull. Volcanol. 55 (1993) 327–342.

[6] K. Kelfoun, F. Legros, A. Gourgaud, A statistical study of trees damaged by the November 22, 1994 eruption of Merapi Volcano (Java, Indonesia): relationship between ash-cloud surges and block-and-ash flows, J. Volcanol. Geotherm. Res. 100 (2000) 379–394.

[7] E.S. Calder, R. Luckett, R.S.J. Sparks, B. Voight, Mechanisms of lava dome instability and generation of rockfalls and pyroclastic flows at Soufrière Hills Volcano, Montserrat, in: T.H. Druitt, B.P. Kokelaar (Eds.), The Eruption of Soufrière Hills Volcano, Montserrat, from 1995 to 1999, Geol. Soc. Lond. Mem. 21, 2002.

[8] P.D. Cole, E.S. Calder, R.S.J. Sparks, A.B. Clarke, T.H. Druitt, S.R. Young, R.A. Herd, C.L. Harford, G.E. Norton, Deposits from dome-collapse and fountain-collapse pyroclastic flows at Soufrière Hills Volcano, Montserrat, in: T.H. Druitt, B.P. Kokelaar (Eds.), The Eruption of Soufrière Hills Volcano, Montserrat, from 1995 to 1999, Geol. Soc. Lond. Mem. 21, 2002.

[9] T. Druitt, S. Young, B. Baptie, C. Bonadonna, E. Calder, A. Clarke, P. Cole, C. Harford, R. Herd, R. Luckett, G. Ryan, B. Voight, Periodic Vulcanian explosions and fountain collapse at Soufrière Hills Volcano, Montserrat, 1997, in: T.H. Druitt, B.P. Kokelaar (Eds.), The Eruption of Soufrière Hills Volcano, Montserrat, from 1995 to 1999, Geol. Soc. Lond. Mem. 21, 2002.

[10] T. Druitt, S. Young, B. Baptie, C. Bonadonna, E. Calder, A. Clarke, P. Cole, C. Harford, R. Herd, R. Luckett, G. Ryan, R.S.J. Sparks, B. Voight, Small volume, highly mobile pyroclastic flows formed by rapid sedimentation from pyroclastic surges at Soufrière Hills Volcano, Montserrat: an important volcanic hazard, in: T.H. Druitt, B.P. Kokelaar (Eds.), The Eruption of Soufrière Hills Volcano, Montserrat, from 1995 to 1999, Geol. Soc. Lond. Mem. 21, 2002.

[11] E.S. Calder, P.D. Cole, W.B. Dade, T.H. Druitt, R.P. Hoblitt, H.E. Huppert, L. Ritchie, R.S.J. Sparks, S.R. Young, Mobility of pyroclastic flows at the Soufrière Hills Volcano, Montserrat, Geophys. Res. Lett. 26 (1999) 537–540.

[12] M.C. Brown, Nuées ardentes and fluidization: discussion, Am. J. Sci. 260 (1962) 467–470.

[13] R.S.J. Sparks, Grain size variations in ignimbrites and applications for the transport of pyroclastic flows, Sedimentology 23 (1976) 147–188.

[14] C.J.N. Wilson, The role of fluidization in the emplacement of pyroclastic flows: an experimental approach, J. Volcanol. Geotherm. Res. 8 (1980) 231–249.

[15] R.S.J. Sparks, Gas release rates from pyroclastic flows: an assessment of the role of fluidisation in their emplacement, Bull. Volcanol. 41 (1978) 1–9.

[16] G. Heiken, K. Wohletz, in: D.H. Sharp, L.M.J. Simmons (Eds.), Volcanic Ash, University of California Press, Berkley, CA, 1985, pp. 246.

[17] S.A. Saltikov, The Determination of the Size Distribution of Particles in an Opaque Material from a Measurement of the Size Distribution of their Section, Spinger, New York, 1967, pp. 163–173.

[18] J.-L. LePennec, D. Hermitte, I. Dana, P. Pezard, C. Coulon, J.-J. Cochemé, E. Mulyadi, F. Ollagnier, C. Revest, Electrical conductivity and pore-space topology of Merapi lavas: implications for the degassing of porphyritic andesite magmas, Geophys. Res. Lett. 28 (2001) 4283–4287.

[19] C. Klug, K.V. Cashman, Vesiculation of may 18, 1980, Mount St. Helens magma, Geology 22 (1994) 468–472.

[20] C. Klug, K.V. Cashman, C.R. Bacon, Structure and physical characteristics of pumice from the climactic eruption of Mount Mazama (Cater Lake), Oregon, Bull. Volcanol. 64 (2002) 486–801.

[21] A.C. Rust, J.K. Russell, R.J. Knight, Dielectric constant as a predictor of porosity in dry volcanic rocks, J. Volcanol. Geotherm. Res. 91 (2000) 79–96.

[22] D.L. Pinti, N. Wada, J.-I. Matsuda, Neon excess in pumice: volcanological implications, J. Volcanol. Geotherm. Res. 88 (1999) 279–289.

[23] R.S.J. Sparks, S. Brazier, New evidence for degassing processes during explosive eruptions, Nature 295 (1982) 218–220.

[24] A.G. Whitham, R.S.J. Sparks, Pumice, Bull. Volcanol. 48 (1986) 209–223.

[25] J.F. Larsen, J.E. Gardner, Experimental constraints on bubble interactions in rhyolitic melts; implications for vesicle size distributions, Earth Planet. Sci. Lett. 180 (2000) 201–214.

[26] R.S.J. Sparks, The dynamics of bubble formation and growth in magmas: a review and analysis, J. Volcanol. Geotherm. Res. 3 (1978) 1–37.

[27] S. Tait, C. Jaupart, S. Vergniolle, Pressure, Gas content and eruption periodicity of a shallow crystallizing magma chamber, Earth Planet. Sci. Lett. 92 (1989) 107–123.
[28] A. Toramaru, Vesiculation processes and bubble size distribution in ascending magmas with constant velocities, J. Geophys. Res. 94 (1989) 17523–17542.
[29] O. Navon, A. Chekmir, V. Lyakhovsky, Bubble growth in highly viscous melts, theory, experiments, and autoexplosivity of dome lavas, Earth Planet. Sci. Lett. 160 (1998) 763–776.
[30] A. Toramaru, Numerical study of nucleation and growth of bubbles in viscous magma, J. Geophys. Res. 100 (1995) 1913–1931.
[31] Y. Formenti, T.H. Druitt, Characterisation of the 1997 Vulcanian explosions of Soufrière Hills Volcano, Montserrat, by video analysis, Bull. Volcanol., in press.
[32] K.U. Hess, D.B. Dingwell, Viscosities of hydrous leucogranitic melts: a non-Arrenian model, Am. Mineral. 81 (1996) 1297–1300.
[33] J. Barclay, M.J. Rutherford, M.R. Carroll, M.D. Murphy, J.D. Devine, J. Gardner, R.S.J. Sparks, Experimental phase equilibria constraints on preeruptive storage conditions of the Soufrière Hills magma, Geophys. Res. Lett. 25 (1998) 3437–3440.
[34] J.D. Devine, M.D. Murphy, M.J. Rutherford, J. Barclay, R.S.J. Sparks, M.R. Carroll, S.R. Young, R. Simon, J.E. Gardner, Petrologic evidence for pre-eruptive pressure-temperature conditions, and recent reheating of andesitic magma erupting at the Soufrière Hills Volcano, Montserrat, W.I, Geophys. Res. Lett. 25 (1998) 3669–3672.
[35] N. Thomas, C. Jaupart, S. Vergniolle, On the vesicularity of pumice, J. Geophys. Res. 99 (1994) 15633–15644.
[36] J.E. Mungal, N.S. Bagdassarov, C. Romano, D.B. Dingwell, Numerical modelling of stress generation and microfracturing of vesicles walls in glassy rocks, J. Volcanol. Geotherm. Res. 73 (1996) 33–46.
[37] G.P.L. Walker, Grain size characteristics of pyroclastic deposit, J. Geol. 79 (1971) 696–714.
[38] A. Freundt, K. Schmincke, Abrasion in pyroclastic flows, Geol. Rundsch. 81 (1992) 383–389.
[39] E. Kaminski, C. Jaupart, The size distribution of pyroclasts and the fragmentation sequence in explosive volcanic eruptions, J. Geophys. Res. 103 (1998) 29759–29779.
[40] C.J. Horwell, L.P. Braña, R.S.J. Sparks, M.D. Murphy, V.L. Hards, A geochemical investigation of fragmentation and physical fraction in pyroclastic flows from the Soufrière Hills Volcano, Montserrat, J. Volcanol. Geotherm. Res. 109 (2001) 247–262.
[41] O. Melnik, R.S.J. Sparks, Dynamics of magma ascent at the Soufrière Hills Volcano, Montserrat: modelling explosive eruptions, in: T.H. Druitt, B.P. Kokelaar (Eds.), The Eruption of Soufrière Hills Volcano, Montserrat, from 1995 to 1999, Geol. Soc. Lond. Mem. 21, 2002.
[42] A.B. Clarke, A. Neri, B. Voight, G. Macedonio, T.H. Druitt, Multi-phase thermofluid axisymmetric transient dynamic modelling of the august 1997 Vulcanian explosions at Soufrière Hills Volcano, Montserrat: initial conduit conditions and profiles and their influence on near-vent model results, in: T.H. Druitt, B.P. Kokelaar (Eds.), The Eruption of Soufrière Hills Volcano, Montserrat, from 1995 to 1999, Geol. Soc. Lond. Mem. 21, 2002.
[43] C. Romano, J.E. Mungall, T. Sharp, D.B. Dingwell, Tensile strengths of hydrous vesicular glasses: An experimental study, Amer. Mineral. 81 (1996) 1148–1154.
[44] Y. Zhang, A criterion for the fragmentation of bubbly magma based on brittle failure theory, Nature 402 (1999) 648–650.
[45] C.J.N. Wilson, The role of fluidization in the emplacement of pyroclastic flows, 2: experimental results and their interpretation, J. Volcanol. Geotherm. Res. 20 (1984) 55–84.