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Mobility of pyroclastic flows and surges at the Soufriere Hills Volcano, Montserrat

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Abstract. The Soufriere Hills Volcano on Montserrat has produced avalanche-like pyroclastic flows formed by collapse of the unstable lava dome or explosive activity. Pyroclastic flows associated with dome collapse generate overlying dilute surges which detach from and travel beyond their parent flows. The largest surges partially transform by rapid sedimentation into dense secondary pyroclastic flows that pose significant hazards to distal areas. Different kinds of pyroclastic density currents display contrasting mobilities indicated by ratios of total height of fall *H*, run-out distance *L*, area inundated *A* and volume transported *V*. Dome-collapse flow mobilities (characterised by either L/H or $A/V^{2/3}$) resemble those of terrestrial and extraterrestrial cold-rockfalls (Dade and Huppert, 1998). In contrast, fountain-fed pumice flows and fine-grained, secondary pyroclastic flows travel slower but, for comparable initial volumes and heights, can inundate greater areas.

Introduction

The 1995-1998 eruption of the Soufriere Hills Volcano involved the growth of an andesite lava dome and the generation of pyroclastic density currents by dome collapse and during explosive eruptions (*Young et al.*, 1998). About 0.3 km^3 of andesite has erupted (*Sparks et al.*, 1998) and the dome currently has a volume of 0.094 km^3. We distinguish four kinds of pyroclastic density current on Montserrat in order to differentiate their aerial coverage and potential destructiveness, which are important concerns for hazard mitigation. The types are: i) pyroclastic flows caused by the collapse and disintegration of unstable dome material; ii) pyroclastic surges associated with and generated above pyroclastic flows; iii) secondary pyroclastic flows derived from pyroclastic surges in late-stage runout; and iv) pumice-rich flows associated with fountain collapse. Herein, the term "flow" refers to a densely concentrated, avalanche-like stream of debris, and "surge" refers to the gravity-driven transport of ash in a relatively dilute and turbulent suspension.

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Deposit Dimensions and Mobility Parameters

We have documented the horizontal distance *L*, area inundated *A* and volume *V* transported by individual flows down from height *H* on the dome (Table 1). For pumice-rich flows, *H* is estimated from the top of fountain collapse as a maximum and from the top of the crater rim height as a minimum to give a range in values. For surge-derived secondary pyroclastic flows *H* is taken from the point of surge transformation. Theoretical approaches indicated that strictly *H* and *L* should be taken as that for the centre of mass of the moving debris (*Hayashi and Self*, 1992). Although initial conditions are well constrained, centre of mass measurements of the emplaced deposits are difficult to constrain. Conventionally-accepted field measurements of these data use maximum *H* and *L*. The volumes of material involved in the flows have been measured by mapping, direct estimates of thickness and analyses of digital elevation maps of the deposit topography (*Sparks et al.,* 1998).

We consider these observations in terms of the geometric mobility parameter $A/V^{2/3}$ suggested by a new analysis of avalanches of large volumes of rock (*Dade and Huppert*, 1998). In the analysis, a mass of debris of density ρ falls from a height *H* and is subjected to a constant, resisting shear stress τ during runout. The predicted relative area of runout $A/V^{2/3}$ is $\lambda^{1/3}(\rho g H/\tau)^{2/3}$, where the plan-shape parameter $\lambda = A/L^2$. The ratio $A/V^{2/3}$ should exhibit a characteristic value for relatively constant heights of fall (of the order of 1 km), a constant shape of the flow deposit in plan view, and constant values of the dynamic resisting stress τ. We also consider the ratio L/H which, from the new analysis, is predicted to be equivalent to $(\rho g V/\lambda H^2 \tau)^{1/3}$. The inverse of L/H is a measure of the coefficient of solid friction employed in previous models of mass transport (*Hayashi and Self*, 1992). Figures 1-2 illustrate the key mobility relationships, which we compare with flow-front velocities *U* and deposit temperatures *T* in Table 2. The data for surges on Montserrat and known from elsewhere are included in Figure 1a and b only as a point of reference. The *Dade and Huppert* (1998) model strictly applies only to dense avalanches, but parameters based on geometric and volumetric characteristics can be usefully compared without reference to a specific model.

On Montserrat, pyroclastic flows formed by dome collapse range in size from small rockfalls to avalanches involving many millions of cubic metres of material (*Cole et al.*, 1998) and travelling up to 6 km. Individual episodes of dome collapse were associated with pulses of magma extrusion and shallow earthquake swarms. They occurred as retrogressive failures of the dome which excavate into its interior over a

Table 1. Raw Data for Montserrat Flows.

Flow type	*Date*	*H* (km)	*L* (km)	*V* (x 10^6 m^3)	*A* (x 10^6 m^2)
i) dome-collapse flows	3-Apr-96	0.59 ± 0.03	1.60 ± 0.04	0.152	0.101
	12-May-96	0.91 ± 0.03	2.90 ± 0.04	0.331	0.175
	31-Mar-97	0.86 ± 0.03	2.50 ± 0.04	0.163	0.109
	5-Jun-97	0.86 ± 0.03	3.10 ± 0.04	0.375	0.192
	17-June-97	0.86 ± 0.03	3.90 ± 0.04	0.766	0.300
	25-Jun-97	1.01 ± 0.03	6.70 ± 0.04	5.538	0.784
	30-Mar-97	0.83 ± 0.03	3.60 ± 0.04	2.600	0.160
	11-Apr-97	0.90 ± 0.03	4.05 ± 0.04	2.900	0.430
	3-Aug-97	0.90 ± 0.03	5.60 ± 0.04	8.750	1.784
	21-Sep-97	0.92 ± 0.03	6.00 ± 0.04	13.563	2.357
ii) surges	25-Jun-97	1.01 ± 0.03	6.70 ± 0.05	0.791	3.954
	26-Dec-97	1.20 ± 0.03	5.00 ± 0.05	2.500	9.794
iii) derived flows	25-Jun-97	0.26 ± 0.1	4.00 ± 0.15	0.087	0.262
	26-Dec-97	0.51 ± 0.1	3.00 ± 0.15	0.053	0.511
iv) pumice-rich flows	18-Oct-97	1.22 ± 0.1	4.60 ± 0.15	0.141	0.471
	18-Oct-97	1.27 ± 0.1	4.40 ± 0.15	0.082	0.272
	18-Oct-97	1.05 ± 0.1	3.00 ± 0.15	0.020	0.066
	18-Oct-97	1.11 ± 0.1	3.30 ± 0.15	0.063	0.209

The pumice flow data is the product of a single explosion where the flows in different directions are considered as 4 individual events.

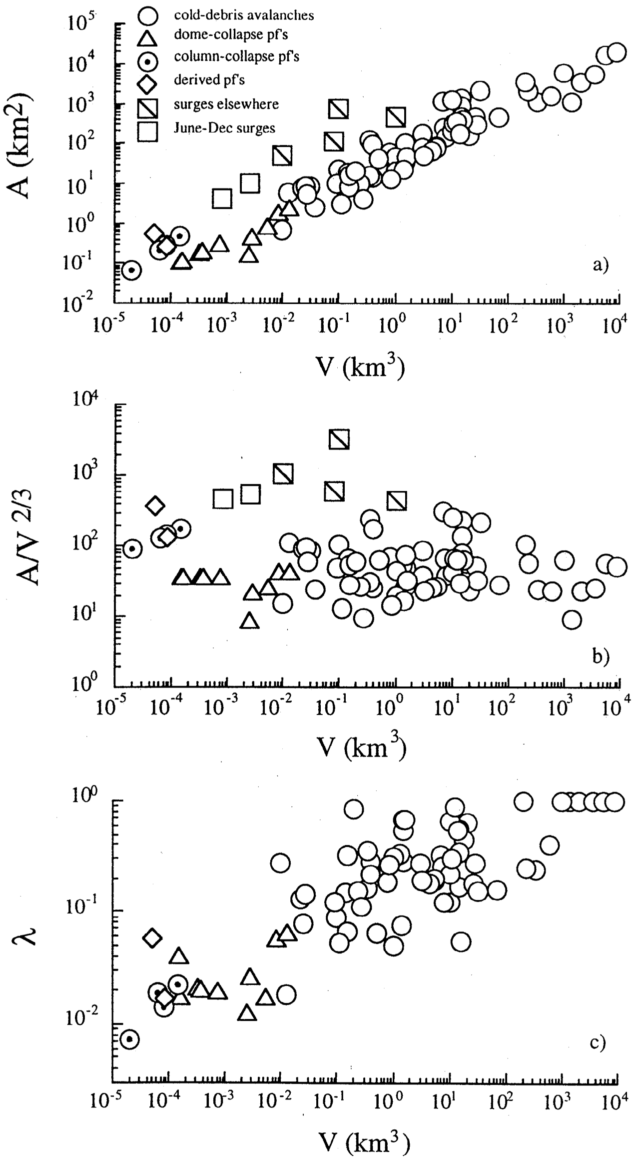

Figure 1. Plots of (a) the area inundated A, (b) the mobility ratio $A/V^{2/3}$ and (c) the plan aspect ratio λ as functions of flow volume V for the different kinds of pyroclastic density currents on Montserrat and cold rock avalanches and pyroclastic surges known from elsewhere. Data compiled from: *Howard* (1973), *Voight* (1978), *Lucchitta* (1978, 1979), *Crandell et al.* (1984), *Francis et al.* (1985), *Siebert et al.* (1987), *McEwen* (1989) and *Stoopes and Sheridan* (1992). Uncertainties in values for Montserrat data are generally smaller that the size of the symbol.

period of a few minutes to hours. Seismic evidence suggests that the largest flows are generated in a few tens of seconds. Maximum velocities are in the range 15 to 30 ms^{-1}. Such flows produced thick (1-15 m), coarse-grained deposits, confined to valleys with blocks of up to several metres in diameter. Large pyroclastic flows generated overlying pyroclastic surges (*Fisher*, 1979). On Montserrat, surges detached from their parent flows at valley bends to spread well beyond the ravines in which the flows remained. The largest event took place on 26 December 1997 when failure of the dome and south-western flank of the volcano produced a debris avalanche and a pyroclastic flow with a volume of at least 55 x 10^6 m^3. The flow with its accompanying surge devastated 10 km^2 of the island.

During the largest flows of 25 June 1997 and 26 December 1997 energetic surges separated from their parent flows and then transformed into dense secondary flows which travelled well beyond the limits of the surges (Figure 3). The surge of 25 June ran 70 m up a hillside and was deflected into the upper reaches of a distal valley. A dense derivative pyroclastic flow then travelled a further 3 km in a direction opposite to the main 25 June pyroclastic flow. The surge of 26 December climbed 200 m to surmount a topographic barrier and then transformed into a dense secondary flow which moved a further 2 km outside the area effected by the surge at estimated velocities of 5 to 7 ms^{-1}. Trees and shrubs inundated by the derivative flows burned but remained standing. The singe lines

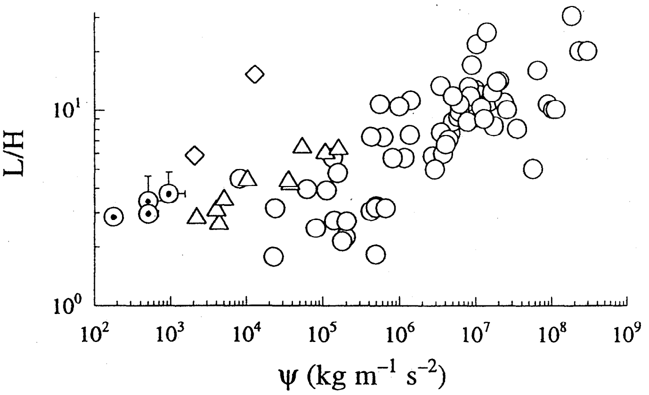

Figure 2. The ratio L/H as a function of the parameter $\psi = \rho g V/H^2$ for the avalanches and pyroclastic flows represented in Figure 1. Symbols as in Figure 1.

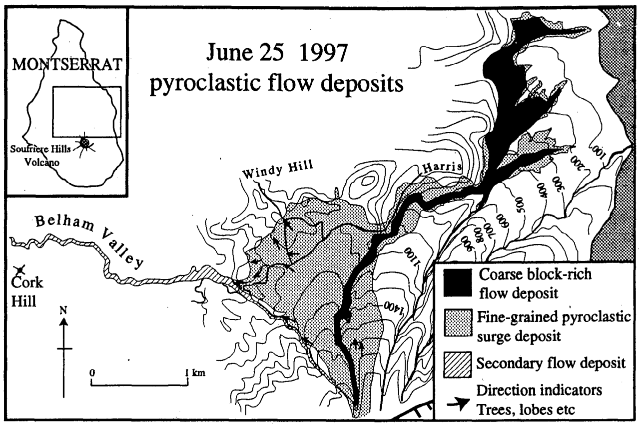

Figure 3. Map of the northern sector of Soufriere Hills Volcano, Montserrat, showing the routes of the main pyroclastic flow, surge and derivative pyroclastic flow of 25 June 1997.

generated by these flows, typically < 10 m high, decreased in height with distance downstream. The deposits of the derivative flows, typically 0.3-1 m thick, are confined to the valley bases with well-defined upper surfaces. Like those of the parent surges, they comprise coarse to very fine sand-sized material.

During the periods August 4 to 12 and September 22 to October 22, 1997, 85 vulcanian explosive eruptions occurred, each typically lasting a few tens of seconds. Many of the explosions generated fountains with heights of up to 350 m above the 950-m high crater rim. The fountains fed pyroclastic flows which travelled down the major valleys around the volcano decelerating rapidly from initial speeds of 30 to 60 m s^{-1} to speeds of 10 m s^{-1} or less. The individual flow deposits are thin (typically 0.3 to 0.6 m), lobate and display central channels, levees and abrupt terminations. The deposits are pumice-rich and coarse-grained, with rounded clasts of up to 30 cm in diameter.

Flow Mobilities

Our observations indicate contrasting mobilities of the different types of flow. Pyroclastic flows associated with dome collapse exhibit values of $A/V^{2/3}$ similar to cold rock avalanches known from elsewhere on the Earth, Moon and Mars (Table 2). In contrast, mobility ratios for the two largest surges are an order of magnitude larger than pyroclastic flows of similar volume but are less than those of volumetrically larger surges known from elsewhere (Rabaul, Taal, Mount St. Helens and El Chichon) (Figure 1a). Secondary pyroclastic flows and pumice-rich flows associated with fountain collapse exhibit intermediate mobilities. The aspect ratio $A/V^{2/3}$ of the different types of density current are relatively independent of volume (Figure 1b), although there is considerable scatter which we attribute to local geologic and topographic factors. Pyroclastic flows on Montserrat, for example, show smaller values of the plan-aspect ratio λ than larger avalanches known from elsewhere (Figure 1c). This reflects, in part, the channelization of small-volume flows. Values of L/H for pyroclastic flows and cold-rock avalanches shows comparable dependence on the variable $\psi = \rho g V/H^2$ (Figure 2), which is a measure of the magnitude of the event in terms of potential energy. In addition to the influence of potential energy, we now consider other factors contributing to flow mobility.

The pyroclastic surges are dilute, turbulent suspensions and thus highly mobile. The energetic character of the largest surges is related to large pore pressures within the collapsing

Table 2. Summary of observations of mass flows on Montserrat and elsewhere

Flow type	*# obs*	*V* (km^3)	*A/V* $^{2/3}$	*L/H*	*U* (m s^{-1})	*T* (°C)
on Montserrat:						
i) dome-collapse flows	10	(3.5 ± 1.4) x 10^{-3}	34 ± 4	4.5 ± 0.5	10-60	200-650
ii) surges	2	(0.8 and 2.5) x 10^{-3}	430-460	–	40-90	–
iii) derived flows	2	(0.5 and 0.9) x 10^{-5}	130-360	6 and 15	5-7	130-420
iv) pumice-rich flows	4	(8 ± 0.3) x 10^{-5}	135 ± 18	3.3 ± 0.2	10-25	140-220
from elsewhere:						
cold-rockfalls	67	362 ± 166	66 ± 8	9.2 ± 1	–	–
surges	4	0.3 ± 0.2	1356 ± 656	–	–	–

Values of flow volume V, $A/V^{2/3}$ and L/H are reported as mean ± one standard deviation or, in the case of surges and derived flows, as the two values. Parent flow speeds U and deposit temperatures T are reported as ranges of observed maximum values. Estimates of U are based on energetic constraints or observations from film recordings. For pumice flows data refer to observations beyond the influence of the collapsing fountain where initial velocities reach 60 ms^{-1}. T was measured within 72 hr of deposit emplacement. A dash indicates that data are not available.

dome (*Sato et al.*, 1992; *Fink and Kieffer*, 1993) The other three types of pyroclastic density current are all dense, high concentration flows of granular material. Various processes that might explain the greater mobility of the pumice flows and the secondary surge-derived flows can be ruled out on the following grounds: Temperature (Table 2) varies greatly and there is no evidence that hot flows are more mobile than cold flows. The pumice flows moved over surfaces made of earlier flow deposits so vaporisation of vegetation and surface waters cannot be invoked. The secondary flows are fine-grained and derived from decompressed surge clouds so release of magmatic gas to cause fluidisation seems unlikely. In fact, the dome-collapse flows partially form the overlying surge cloud by expansion and escape of ash-laden gas, yet the mobility of these flows is not significantly enhanced by escaping gases. The main differences between the flows are their origins and their physical composition. The dome-collapse flows result from the disintegration of dense lava into coarse-grained flows of blocks and ash. In contrast, the pumice flows and secondary flows form by rapid sedimentation from the dilute suspensions and, in comparison to the dome-collapse flows, are finer grained. Their enhanced mobility can be explained by rapid sedimentation from the dilute suspensions, which forms mobile concentrated underflows with low frictional resistance. Momentum can be inherited from the collapsing dilute suspensions. The finer-grained character of the pumice flows and secondary flows may also play a role in their enhanced mobility.

Implications

Our results have two broad implications. First, dense pyroclastic flows can have high mobilities in terms of area inundated in relation to volume, generating deposits with relatively low aspect ratios. Second, hazards assessments of areas threatened by pyroclastic flows need to incorporate the exceptional mobility of some kinds of flow. One newly-reported type of density current that is mobile yet highly topographically constrained are those derived from transformation of ash-laden surges. These can travel for significant distances in unexpected directions.

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