Experiments on deaerating granular flows and implications for pyroclastic flow mobility

Olivier Roche, M Gilbertson, J C Phillips, R S J Sparks

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O. Roche,[1] M. Gilbertson,[2] J. C. Phillips,[1] and R. S. J. Sparks[1]

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[1] Granular flows were generated by the release of beds of particles in various fluidized states, which then deaerated in a horizontal channel. We describe characteristics of the flows and their deposits. Morphological similarities between deposits in experiments and in the field suggest that pyroclastic flow deposits form from a fluidized mixture. The experiments show that slightly expanded, fluidized flows are more mobile than non-fluidized flows of equivalent volume and material composition. They travel to a fixed distance from their source, which depends only weakly on their initial degree of fluidization. Flows of fine particles (<100 μm) deaerate slowly and are highly mobile. Pyroclastic flows commonly have large amounts of fine ash, which may have a controlling influence on their high mobility. *INDEX TERMS:* 8414 Volcanology: Eruption mechanisms; 8499 Volcanology: General or miscellaneous; *KEYWORDS:* Volcanology, pyroclastic flow, mobility, fluidization, deaeration

1. Introduction

[2] Pyroclastic flows are common products of explosive volcanic eruptions and result from the gravitational collapse of a dome or of an eruptive column. They consist of a mixture of particles and gas that commonly travels at high speed, and are thus very hazardous phenomena. Their deposits have volumes in a range of a few millions of m^3 to a few thousands of km^3, and their granulometry ranges from fine micrometric ashes to centimetric and decimetric-sized blocks [*Sparks*, 1976].

[3] Several observations suggest that pyroclastic flows are fluidized [*Sparks*, 1978; *Wilson*, 1980]. One of these features is that they are very mobile. A common measure of mobility is the ratio of the change in altitude (H) over the horizontal distance traveled by the flow (L). The coefficient of friction μ between the granular flow and the ground is equal to H/L and is commonly 0.6. Pyroclastic flow deposits commonly have low H/L of less than 0.2, which implies that friction is very much reduced. *Calder et al.* [1999] considered an alternative mobility coefficient $A/V^{2/3}$ where A is the area inundated by the deposits and V is their volume [*Vallance and Scott*, 1997; *Dade and Huppert*, 1998]. On this measure they showed that pyroclastic flows generated during the eruption of the Soufrière Hills Volcano, Monserrat, were more mobile than cold rock avalanches of similar volume, which are unlikely to be fluidized.

[4] Reduction of internal friction can be caused by fluidization in which a fluid passes through a bed of granular material and so support its weight [*Sparks*, 1976; *Wilson*, 1980]. For geophysical flows to be fluidized it is necessary for there to be a source for gas. In pyroclastic flows this source can be the magmatic gas supplied during the generation of the flow and its emplacement [*Sparks*, 1978]. Furthermore, once the gas has been generated, it does not necessarily pass instantly through the flow, but can be retained for a while. When there are sufficient fine particles sedimentation is retarded [*Geldart and Wong*, 1985].

[5] This paper presents the results of a laboratory investigation on the mobility of granular flows generated by the release of granular material in various fluidized states. The geometry of the resulting deposits is also studied. In particular, the study shows the increased mobility of a fluidized flow when it is composed of fine particles.

2. Principles of Fluidization

[6] Fluidization is used in a large number of engineering processes and has been extensively studied [see *Rhodes*, 1998]. When a fluid passes through a bed of particles, the drag force it exerts on them increases with the fluid velocity (U). At low values of U, the drag force is smaller than the buoyant weight of the particles, the bed is static, and it may be called aerated. Above a critical fluid velocity U_{mf}, the minimum fluidization velocity, the drag force equals the buoyant weight of the particles and the bed is then fluidized.

[7] *Geldart* [1973] classified particles according to their behavior when they are gas-fluidized. The observed behavior corresponded with the density difference between the particles and the fluid, and the particle size. When coarse particles (groups B and D) are fluidized, bubbles form in the bed and the expansion of the dense phase is limited to a few percent or less. Group D particles are larger than group B particles. When finer particles (group A) are fluidized, but the gas velocity is less than a second, larger critical velocity U_{mb} (the minimum bubbling velocity), bubbles do not form but the bed remains uniform, and the dense phase expands by about 10%. Above U_{mb} expansion ceases and the bed bubbles. Particles in pyroclastic flows have a density range of 500–2500 kgm^{-3}, and the size range for group A particles lies between ~20 and 100–200 μm and for group B between 100–200 and 600–1000 μm.

[8] An important property is the deaeration rate of the bed, or bed collapse velocity U_{de}, when the gas supply is stopped [*Geldart and Wong*, 1985]. U_{de} is much smaller

[1]Department of Earth Sciences, Center for Environmental and Geophysical Flows, University of Bristol, UK.
[2]Department of Mechanical Engineering, Center for Environmental and Geophysical Flows, University of Bristol, UK.

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Table 1. Characteristics of the Particles Used in Experiments

Group [a]	Grain size range (μm)	U_{mf} [b] (cm s^{-1})	U_{mb} [b] (cm s^{-1})	U_{de} [b] (cm s^{-1})	U_t [c] (cm s^{-1})	Dense phase expansion [b] (%)
A	45–90	0.83	1.60	0.62	43	∼10
B	106–212	2.15	2.15	1.35	130	<5
D	600–800	27.0	27.0	–	595	∼0

[a] *Geldart* [1973].
[b] Measured.
[c] Calculated, assuming mean grain size of 67 μm (group A), 159 μm (group B), and 700 μm (group D), [*Rhodes*, 1998].

than the terminal fall velocity of the particles, U_t. It is larger for coarse particles of groups B and D than for fine particles of group A (Table 1).

3. Experimental Procedure

[9] A series of experiments investigated the influence of the initial degree of fluidization and of the grain size of the particles involved on the flow mobility. We used nearly spherical glass beads (Ballotini) of density ρ_p = 2500 kg m^{-3}. Three different sizes were used to study flows of group A, B, and D particles (Table 1). The experimental apparatus consists of a fluidization reservoir and a horizontal channel whose base is smooth (Figure 1). A bed of particles, 10–20 cm high, is fluidized by introducing an air flux through a porous plate at ambient laboratory temperature. The fluidized bed is released by means of a sliding gate, and the flow progressively deaerates as it propagates into the channel. We made videos recordings and measurements of the distance traveled by the flows and of the morphology of the deposits.

4. Results

4.1. Flow Emplacement

[10] With non-fluidized beds (U = 0), on opening the gate, part of the top, front portion of the bed slumps forward and the base and rear parts remain static. This contrasts with fluidized beds where all the particles are all involved in motion. The bed in the reservoir collapses maintaining an approximately horizontal upper surface and feeds a flow propagating into the channel (Figure 2). In flows of group A particles, the flows first accelerate and then exhibit approximately constant flow speed and flow thickness. Deceleration takes place when the bed height in the reservoir has decreased to the thickness of the flow. For groups B and D particles, the flows accelerate and decelerate with no intermediate constant velocity stage. Emplacement times are typically less than one second, and peak speeds are in the range 0.9 to 1.6 m s^{-1}. A more detailed analysis of flow motion will be presented elsewhere.

4.2. Morphology of the Deposits

[11] The effects of particle size and gas flow rate on the morphology of the deposits is shown in Figure 3. For non-fluidized beds (U = 0), a tapering wedge is formed with a surface upper slope equal to or slightly smaller than the angle of internal friction of the material (∼28°). The slope decreases beyond this region to about 2–5° at the end. When the beds are initially aerated (U/U_{mf} <1), the deposits of group A particles have a greater horizontal extent than those of groups B and D. The group B and D deposits form a tapering wedge with an upper slope below the static friction angle, and they slightly extend beyond the non-fluidized case. Group A deposits have a flat region of nearly constant thickness at the rear, behind a wedge, and extend further. Initially fluidized ($U/U_{mf} \geq 1$) bed deposits are characterized by a front wedge with a small and near constant downstream slope, and their morphology shows little variation as a function of the degree of fluidization. For incipiently fluidized beds (U/U_{mf} = 1), the morphology of group A deposits contrasts markedly with that of group B and D: group A deposits have a well developed front wedge with a slope of 1–2°, and their upstream slope is either horizontal or can dip gently upstream (1–2°); group B and D deposits have a front wedge with a slope of 3–5° and their upstream slope is steeper (5–10°). The thickness of the

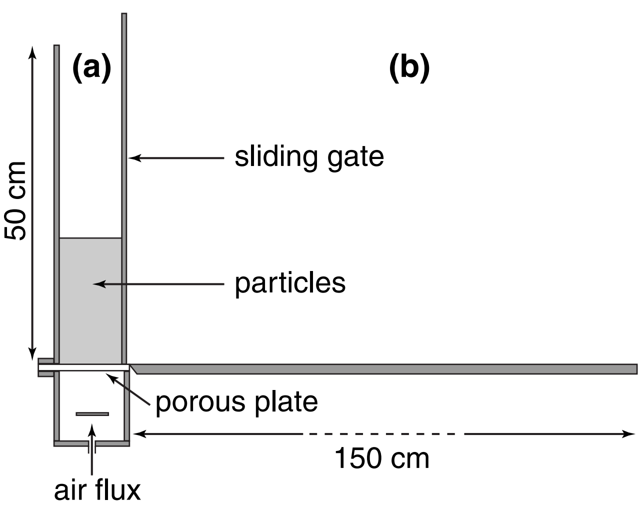

Figure 1. Experimental apparatus (8 cm wide). (a) Fluidization reservoir. (b) Channel.

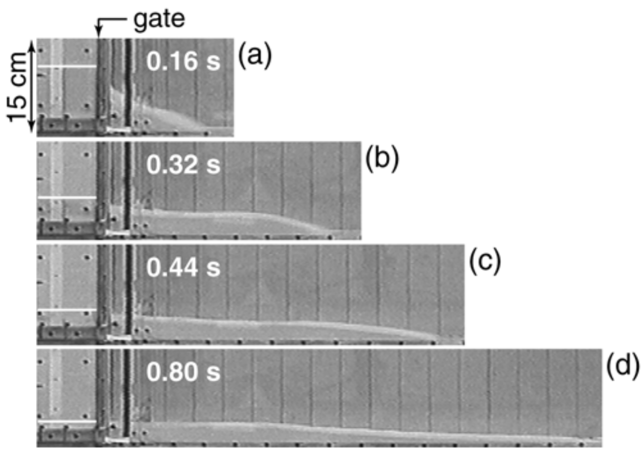

Figure 2. Flow of particles of group A generated from a bed 15 cm high. The white bold line is the level of the top of the bed in the reservoir. Vertical thin black lines each 5-cm. (a) Acceleration. (b) Constant velocity. (c) Deceleration. (d) Deposit.

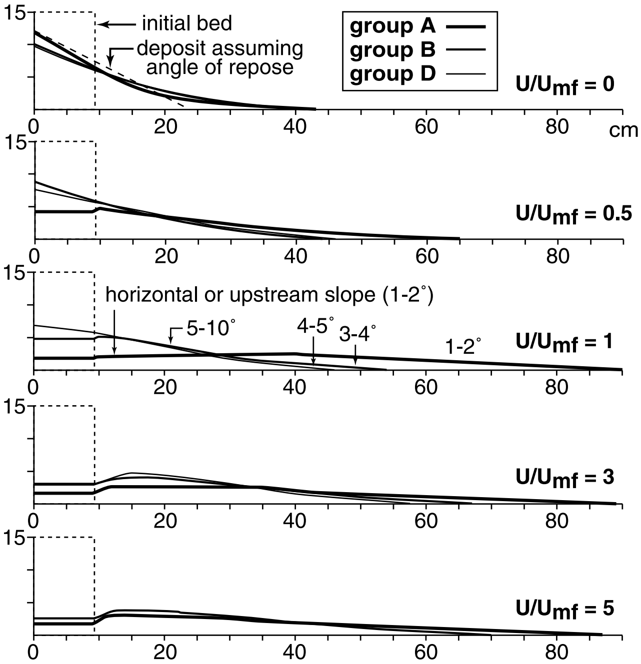

Figure 3. Deposits formed in experiments as a function of the degree of fluidization of the bed in the reservoir (U/U_{mf}). Distance in cm.

proximal deposits is about 10–15 % less than the thickness of the flows, showing that these travel as concentrated dispersions.

4.3. Flow Mobility

[12] The deposits are approximated as a wedge with a constant slope α (Figures 3 and 4a). As the bed in the reservoir and the deposit have the same cross-sectional area, then comparing the initial volume of the bed with the volume of the final triangular wedge of particles $Hd = (L^2 \tan\alpha)/2$, so that

$$L/H^{1/2} = (2d/\tan\alpha)^{1/2}, \qquad (1)$$

where L is the distance traveled by the flow, H is the initial bed height, and d is the reservoir length. As d and α are constant, therefore L is proportional to $H^{1/2}$ and we use the coefficient $L/H^{1/2}$ to quantify mobility. We show the results in the form $L/H^{1/2}$ as a function of U/U_{mf}, for different bed heights and particle types, and normalize data on the behavior of non-fluidized beds (U = 0). Two graphs are shown: in Figure 4b, H is taken to be the initial, compacted bed height (H_0) when there is no gas flow; in Figure 4c, it is taken to be the actual initial bed height which includes the expansion of the dense phase and the presence of bubbles. In the latter case, the bed expansion is about that of the dense phase (~10%) for group A particles, but is up to 35–40% for group B and D particles, owing to the presence of large bubbles, particularly at high gas velocities. The distance traveled by the flows increases with the initial volume (i.e., the bed height) and decreases with grain size. The flow mobility increases as the bed is increasingly aerated ($U/U_{mf} < 1$), consistent with reduction of the internal friction due to air flow [*Eames and Gilbertson*, 2000]. When the bed is fluidized ($U/U_{mf} \geq 1$), the flow mobility of group A particles is distinct from that of groups B and D. There is a good collapse of the data for group B and D and the flow mobility increases only slightly with the initial degree of fluidization. Compared to the non-fluidized state, the flow mobility is increased by a factor of ~1.7–2 (group B) and ~1.2–1.4 (group D) at the highest degree of fluidization studied. In contrast, the data for group A do not collapse. For a given value of U/U_{mf} (>1), the flow mobility increases with the initial bed height and is maximum when the bed is just fluidized (U/U_{mf} = 1.25) and slightly expanded. The mobility decreases from about incipient fluidization (U/U_{mf} = 1) until $U/U_{mf} \sim 6$, above which it is approximately constant and larger than ~1.7–1.8 times that of the non-fluidized state.

5. Discussion

[13] The experiments have shown that the flow mobility of an initially fluidized bed of particles depends on the fluidization behavior and deaeration rate of the particles involved. Flows of group A and B particles behave distinctly, although the grain size contrast is small. Flows of group B and D particles have a similar behavior even though the grain size contrast is large (Figures 3 and 4). Static beds of group B and D particles deaerate rapidly, as the initial dense phase expansion is small and deaeration rate is high (Table 1), and the time required for this to take place is less than half the duration of the flows. The propagating and thinning flows rapidly collapse to the concentration of a non-fluidized bed, and at this stage particle interactions become dominant and the flow ceases motion. In contrast, static beds of group A particles have a large initial dense phase expansion and the deaeration rate is low, with the result that the time taken for this is 2–3 times the duration of the flows. This suggests that flows of these fine particles are fluidized for the duration of the flow. Also, bed expansion is proportional to the original bed height, so at a given time, the deeper the bed, the more it is expanded and the more mobile it is, and this might explain why the data do not collapse in Figures 4b and 4c.

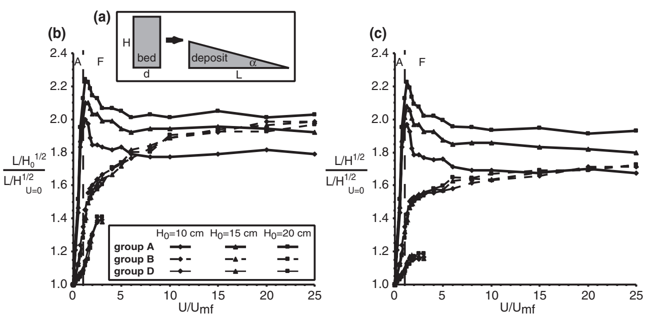

Figure 4. (a) Determination of the mobility coefficient $L/H^{1/2}$, see text for details. (b) Normalized mobility of flows as a function of the initial degree of fluidization (U/U_{mf}), taking into account the compacted bed height (H_0). A: aerated bed, F: fluidized bed. (c) shows the same as (b) but the normalized mobility is based on the actual bed height H including dense phase expansion and the presence of bubbles.

[14] The larger mobility for group A particles just above the point of minimum fluidization, compared with higher gas speeds, may be because of the absence of bubbles when $U/U_{mf} < 1.9$ (Table 1) and the low permeability of the barely fluidized bed, which allows more of the gas to be retained for longer within the bed. At the low air flux considered here, the particle Reynold's number Re_p is much less than 10, and the speed of a gas passing through the porous bed of these fine particles can be described by the first laminar term of the Ergun equation [*Rhodes,* 1998],

$$U_e = \frac{\Delta P}{H} \frac{dp^2 \varepsilon^3}{150\mu(1-\varepsilon)^2}, \quad (2)$$

where d_p is the particle diameter, μ is the gas viscosity, ε is the bed porosity. Equation 2 strictly applies to a static bed but here we use it for a slow flow. When the bed is fluidized, the pressure drop over the bed per unit depth $\Delta P/H$ is constant. With d_p and μ constant, the permeability (second right hand term in equation 2), and hence the air escape velocity from the dense phase U_e depends only on ε. For an expansion of 10% of a bed with an initial porosity $\varepsilon = 0.4$, U_e increases by a factor of 1.5. Therefore it would be expected that the deaeration rate increases with the initial bed expansion.

6. Implications for Pyroclastic Flow Mobility

[15] Distal pyroclastic flow deposits commonly have gentle surface inclination where emplaced on a sub-horizontal topography. Examples of small surface slopes of <4° for pumice rich deposits at Lascar Volcano [*Calder et al.*, 2000], <3° for the Ito and Minoan ignimbrites [*Yokoyama* 1974; *Bond and Sparks*, 1976], 1–2° for the Valley of Ten Thousands Smokes ignimbrite [*Walker et al.*, 1980 and references herein], and 4–6° for block ash flow deposits at Montserrat [*Cole et al.*, 1998] are reported. Here experiments were carried out with a highly simplified system involving monodisperse beds of spherical particles. However, the morphological similarities between deposits observed in the field and those obtained in experiments suggest that experimental gas-fluidized granular flows are suitable analogues for the study of pyroclastic flows.

[16] Our experiments demonstrate that a flow in a fluidized state can have a much greater run-out than a non-fluidized flow of equivalent volume and material. Fine particles of group A are particularly important because they only require very small gas velocities to be fluidized [*Sparks*, 1976] and they deaerate slowly. Pyroclastic deposits typically contain 10–20% of particles with a diameter less than 100 μm [*Sparks*, 1976], and this might be underestimated because of elutriation. Fluidized fines may be a critical factor in explaining mobility. For example, *Calder et al.* [1999] observed that fines-rich pumice flows were significantly more mobile than coarse-grained block-and-flows.

[17] Our experiments are most relevant to the flow of a slightly expanded (a few percent) gas-particle mixture. In experiments, such a mixture is generated as a static fluidized bed, while in nature it can be generated by rapid sedimentation from a more dilute mixture, agitation and dilatation of a fast moving granular flow, as well as by gas fluidization from either internal or external sources. This study has revealed that even a slightly expanded and deaerating mixture can be highly mobile. In our experiments, no additional gas source is provided as the flow moves along the channel, but the behavior of these actively fluidized flows of particles is described and modeled by *Eames and Gilbertson* [2000]. Our results therefore best apply to cases where fluidizing sources during the flow are very limited. In this context, irrespective of their initial degree of fluidization, pyroclastic flows propagating over a sub-horizontal surface could travel a fixed, maximum distance from their source with the mobility increased compared to the non-fluidized state.

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O. Roche, Department of Earth Sciences, Center for Environmental and Geophysical Flows, University of Bristol, Wills Memorial Building, Bristol BS8 1RJ UK. (olivier.roche@bristol.ac.uk)

J. C. Phillips and R. S. J. Sparks, Department of Earth Sciences, Center for Environmental and Geophysical Flows, University of Bristol, UK.

M. Gilbertson, Department of Mechanical Engineering, Center for Environmental and Geophysical Flows, University of Bristol, UK.