The fluidization behaviour of ignimbrite at high temperature and with mechanical agitation

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[1]   Experiments were carried out to study the fluidization behaviour of ignimbrite at high temperature and while being mechanically agitated. Geldart group C behaviour occurs up to 565°C when the material is subjected to increasing gas flow (without agitation) from the loosely packed state. In contrast, even gentle mechanical agitation inhibits channelling and results in group-A type behaviour with homogeneous (non-bubbling) expansions of up to 30–40%. Bed collapse tests exhibit group-C behaviour at room temperature, group-A behaviour at 200–565°C, and transitional behaviour at 55°C. Both elevated temperature and mechanical agitation greatly increase the fluidizability of ignimbrite. It is inferred that a combination of high temperature and shear during transport will promote Geldart group A behaviour in pyroclastic flows.   *INDEX TERMS:* 5480 Planetology: Solid Surface Planets: Volcanism (8450); 8414 Volcanology: Eruption mechanisms; 8404 Volcanology: Ash deposits; 8499 Volcanology: General or miscellaneous. **Citation:** Druitt, T. H., G. Bruni, P. Lettieri, and J. G. Yates (2004), The fluidization behaviour of ignimbrite at high temperature and with mechanical agitation, *Geophys. Res. Lett.*, *31*, L02604, doi:10.1029/2003GL018593.

1.   Introduction

[2]   Pyroclastic flows are one of the most hazardous of volcanic phenomena. Their ability to flow on slopes as low as a few degrees implies low friction, which has been attributed in part to fluidization by escaping gases [*Sparks*, 1976]. Fluidization is believed to be an important particle-support mechanism particularly in slow, small-volume ($\ll$1 km^3) pyroclastic flows that travel as high-concentration granular avalanches of hot pyroclasts and gas [*Druitt*, 1998].

[3]   In the fluidization process a granular material is subjected to a vertical flow of gas [e.g., *Rhodes*, 1998]. The material is said to be fluidized when the gas velocity exceeds U_{mf} (minimum fluidization velocity) at which the dynamic pressure drop equals the bed weight per unit area. Interparticle friction is greatly reduced, and the material takes on a fluid-like behaviour. *Geldart* [1973] classified the gas fluidization behaviour of powders into four groups, according to particle size and density. In groups B and D (particles coarse and/or dense) bubbles form as soon as U_{mf} is exceeded, so that $U_{mf} = U_{mb}$ (minimum bubbling veloc-

ity). Group A materials (intermediate) expand uniformly over a certain velocity range above U_{mf} before bubbling, so that $U_{mb} > U_{mf}$. In group C (particles small and/or light) interparticle cohesion causes the gas to channel and full bed support is hard to achieve.

[4]   Ignimbrite (pyroclastic flow material containing abundant pumice) is very poorly sorted and contains fractions of all four Geldart groups, but it exhibits group-C behaviour in laboratory rigs at room temperature [*Wilson*, 1984]. This contrasts with the high fluidizability of pyroclastic flows evident from their ability to flow on low gradients. However, pyroclastic flows are typically emplaced at 200–700°C and elevated temperature can modify fluidization behaviour by increasing gas viscosity (approximately doubling between room temperature and 600°C), decreasing gas density, and changing particle surface properties [*Yates*, 1996]. Furthermore, pyroclastic flows are subject to strong gravity-driven shear during transport. Our fluidization experiments at elevated temperature and with mechanical agitation explore some effects of these parameters.

2.   Experimental Methods

[5]   We used sub-4 mm samples of chemically fresh, non-welded 0.58-Ma trachytic ignimbrite from Neschers in the French Massif Central. When fluidized at room temperature this segregates into two layers: (i) a normally graded lower layer enriched in dense components (lithics and crystals) and (ii) an essentially homogeneous upper layer enriched in pumiceous and fine components. To avoid segregation in our experiments we separated off the upper layer and used it as the starting material (Table 1). We refer to this as 'ignimbrite', but stress that it is depleted of dense components compared to the original material. It has *Inman* [1952] mean and sorting parameters of 63 μm and 2.3 phi respectively, a surface-volume mean [*Rhodes*, 1998] of 25 μm, and a loose-packed bulk density at room temperature of 780 kg m^{-3}. The material fluidizes without significant segregation, making quantitative interpretation of our results more straightforward, but it retains the essential features of the original ignimbrite such as poor sorting, low permeability, and irregular particle shape.

[6]   The high-temperature INCONEL (Ni-Cr alloy) fluidization rig at University College London is 1000 mm high and 140 mm in diameter, with a stainless steel distributor plate of 20 μm pore diameter [*Lettieri et al.*, 1999; 2000]. Gas flux, bed pressure drop, and bed temperature were measured using rotameters, pressure transducers, and thermocouples, respectively. The bed was filmed at 25 frames per second using a pulsed, high-energy X-ray beam to measure bed heights and to image bubbles and channels. Heights were corrected for perspective and slight camera

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Table 1. Particle Size Distribution of the Ignimbrite-Derived Material Used in the Experiments[a]

Particle size (μm)	2000	1000	500	250	125	63	32	16	8	4	2	1
Size distribution (wt%)	1.9	2.7	5.1	9.8	13.7	16.3	20.2	11.6	11.9	5.4	1.2	0.2

[a]Size fractions from 2000 to 63 μm by sieving and from 32 to 1 μm by Coulter Multisizer.

distortion. Bottled nitrogen of negligible humidity was used as the fluidizing medium. Elutriated particles were partly recycled back into the bed from an upward-flaring disengaging section, and the finest were trapped in an exit filter. Fines loss by elutriation was never great enough to significantly change bed grain-size characteristics and fluidization behaviour during the experiments reported here.

[7] As conventional, gas velocities are quoted as superficial velocity (volumetric flux per unit area of the empty rig) at the temperature of the bed.

3. Effects of Temperature

[8] Two types of experiment were carried out to investigate the effects of temperature in the absence of any agitation: (1) progressive fluidization from the loosely packed state, and (2) rapid defluidization from initial high velocity (bed collapse test). Five temperatures were employed: 17 (room temperature), 55, 200, 405 and 565°C (all ±5°C). Particle sintering did not occur, even at the highest temperature.

[9] A fresh ignimbrite batch of 2.5 kg was used at each temperature. It was first dried at 200°C for >12 hours. For the 200, 405 and 565°C runs, the material was then transferred as quickly as possible (~5 min) to the rig and

Figure 1. Variation of (a) bed pressure drop and (b) height as gas velocity is increased from the loosely packed state, then decreased again, at 565°C. There was no agitation of the bed in these experiments.

brought to temperature in 2−4 hours. The 55°C sample was transferred quickly to the rig, then cooled in a gentle flow of nitrogen. The room-temperature sample was first cooled in laboratory air for ~10 min, which in retrospect was enough for it to adsorb some atmospheric water and become cohesive.

3.1. Progressive Fluidization From the Packed State

[10] Starting from the loosely packed state the gas velocity was increased incrementally from 0 to ~8 cm s^{-1}, then decreased back to zero, over about 30 min. The results at 565°C are shown in Figure 1.

[11] The ignimbrite exhibited group-C behaviour at all five temperatures. At each temperature the pressure drop increased up to a maximum (~0.1 cm s^{-1}), where the full bed weight was supported (Figure 1a). We follow *Wilson* [1984] in referring to this velocity as U$_{mp}$ (maximum pressure); it is broadly equivalent to U$_{mf}$, but the conventional definition of U$_{mf}$ cannot be applied in group-C materials. Above U$_{mp}$, the pressure then declined rapidly to 20−40% of bed support as channelling set in. With further increase in velocity: (i) channels became larger, and (ii) bubbling set in and became progressively more vigorous. At the highest velocities investigated the beds bubbled turbulently at all temperatures, with a pressure drop corresponding to 75−85 % of full bed support. As the gas velocity was then decreased the pressure stayed initially above the up-curve, then fell below it, reflecting a strong hysteresis in the behaviour.

[12] Hysteresis also characterised the bed expansion plots (Figure 1b). Gas velocities of 15−50 times U$_{mp}$ were required before significant expansion occurred as velocity was increased (Figure 1b). As velocity was decreased the bed first remained expanded, then deflated abruptly once the velocity fell below a critical value. It is inferred that high velocities the strong buoyancy forces generated by bubbling kept the bed expanded, but as velocity decreased there came a point when cohesive forces dominated, channels formed, and the bed suddenly deflated.

[13] Elutriation of fine (<100 μm) components took place at all temperatures at velocities above U$_{mp}$, typical elutriation rates being about 0.5 wt% of the bed per minute.

3.2. Bed Collapse

[14] In these experiments the gas velocity was raised to ~8 cm s^{-1}, at which the beds were in a state of turbulent fluidization at all temperatures. The gas supply was then cut abruptly by remote closure of the rig entry valve, allowing the bed to defluidize and settle under its own weight while being X-rayed. At the same instant gas was allowed to escape from the windbox, so that collapse took place in the dual-drainage configuration.

[15] The collapse curves at 200, 405 and 565°C each exhibit the three segments typical of group-A materials (Figure 2a): (i) rapid decrease of bed height as bubbles are evacuated (segment BE on the 565°C curve on Figure 2a), (ii) slower hindered settling of the bed in the
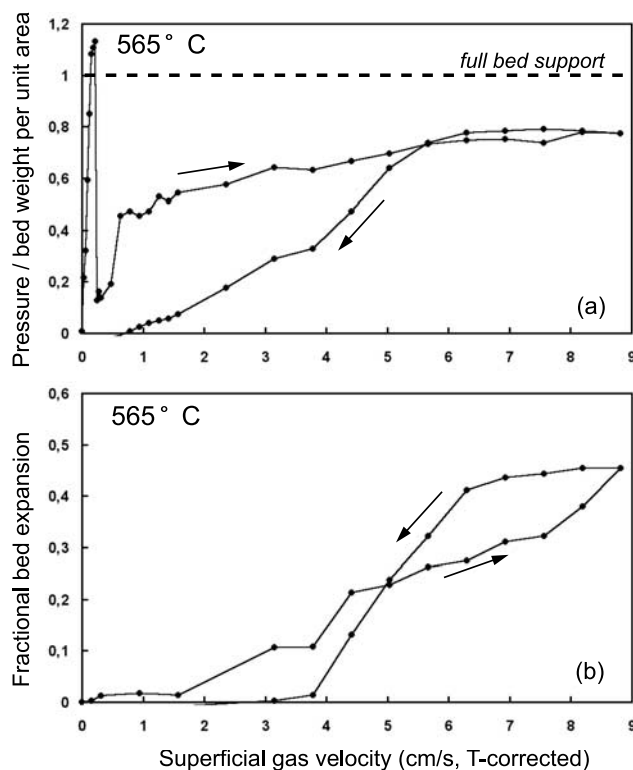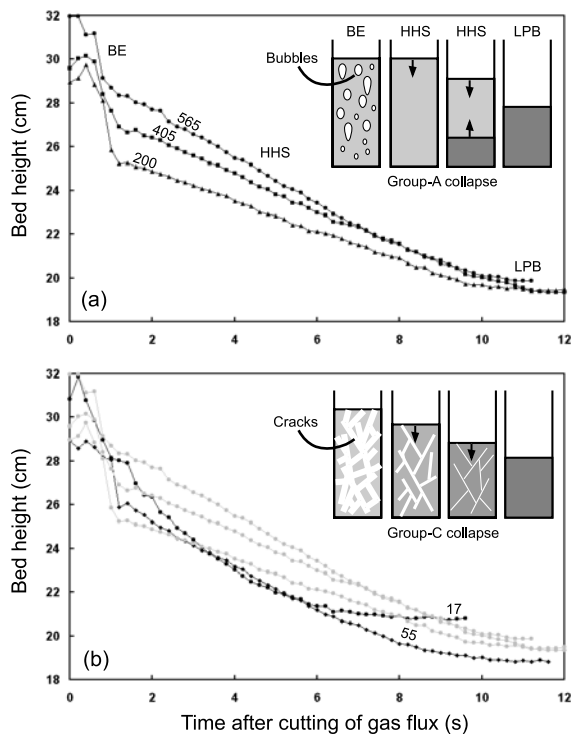
Figure 2. Collapse curves for ignimbrite. (a) Data at 200, 405 and 565°C showing group-A behaviour. The following segments are marked on the 565°C curve: BE: bubble evacuation, HHS, homogeneous hindered settling, and LPB: loosely packed bed. (b) Data at 17°C and 55°C showing group-C and transitional A-C behaviours, respectively. The group-A collapse curves from (a) are shown in grey for comparative purposes. Insets show group-A and group-C collapse behaviours described in the text.

homogeneous state, with no bubbles large enough to see (HHS on Figure 2a), and (iii) fully sedimented, and loosely packed, bed (LPB on Figure 2a). During hindered settling of a group-A material a layer of loosely packed sediment is inferred to accumulate progressively from the base upwards across an interface until settling is complete [*Lettieri et al.*, 1999]. The sharp transition between segments HHS and LPB on Figure 2a suggests that this interface is well defined in our ignimbrite.

[16] In contrast, the collapse curve at 17°C lacks a well defined bubble evacuation segment and has the overall exponential shape typical of group-C materials (Figure 2b). In group C expansion is due to cracks and irregular voids, rather than bubbles. On cutting the gas supply the bed settles exponentially as gas is expelled through progressively smaller and smaller channelways, and densification takes place simultaneously at all levels of the bed [*Geldart and Wong*, 1985]. The collapse at 55°C is transitional between A and C types.

[17] Hindered settling velocities for the three group-A collapses increase with increasing temperature (Figure 3a). Bed expansion at the onset of hindered settling (Figure 3b) shows a similar trend. This is the expansion of the bed immediately following bubble evacuation and provides a measure of the density of the particulate phase between the

bubbles at high velocity before the gas supply is cut. Considered in reverse, it is approximately the bed expansion at the onset of bubbling were the material inflating, rather than deflating. Reproducibility of the results were tested by doing multiple runs (i) in succession, to test for effects of progressive fines loss through elutriation, (ii) at different durations of heating of the ignimbrite in the rig prior to fluidization, and (iii) with collapse from different initial gas velocities. The results from all runs are included in the error bars on Figure 3, showing that the trends with temperature are real.

4. Effects of Mechanical Agitation

[18] The effects of mechanical agitation were explored at 200°C by increasing the gas velocity incrementally from the loosely packed state while gently stirring the bed with a metal rod (Figure 4). As the gas velocity was increased from zero the pressure drop first rose, but there was no measurable expansion; stirring was not possible in this state because the frictional resistance was too great. However once U_{mp} was reached the material lost strength and acquired the consistency of runny mud. As velocity was further raised, stirring broke down the cohesive structure of the bed and prevented channelling. Consequently full bed support was maintained (Figure 4a) and the bed expanded homogeneously in the manner of a group-A material. The inflexion on the pressure plot provides a true measure of U_{mf} in this agitated state. Homogeneous expansion then persisted to approximately $0.8-1.0$ cm s^{-1} when bubbling set in ($U_{mb}/U_{mf} \sim 5-8$). Only very gentle stirring on the order of a revolution per second was required to generate this behaviour. Homogeneous expansion of at least 30% prior to U_{mb} agrees with the result of the collapse test at the same temperature (Figure 4b).

[19] If the agitation was suddenly stopped during homogeneous expansion ($U_{mb} > U > U_{mf}$), the pressure decreased over a few tens of seconds ($25-60$ s) to about half the full value as channels formed spontaneously throughout the bed.
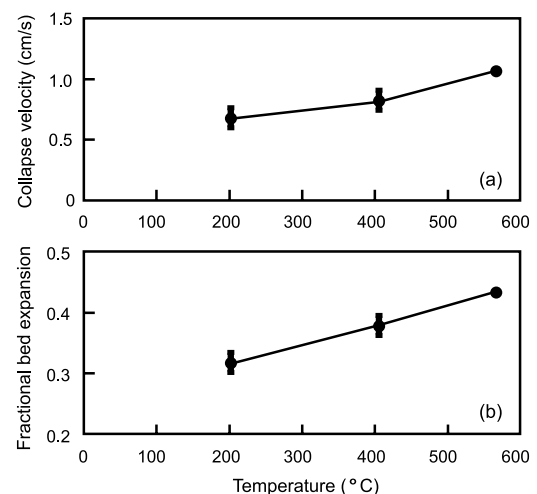

Figure 3. Variation of (a) hindered settling velocity and (b) bed expansion at the onset of hindered settling (BE-HHS transition in Figure 2), with temperature for group-A collapses.
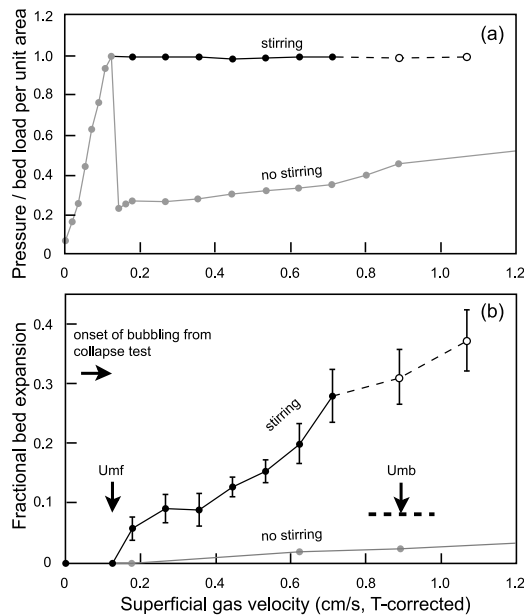
Figure 4. Effect of gentle mechanical agitation on (a) bed pressure drop and (b) bed expansion at 200°C. Dots: no bubbling. Circles: possible bubbling.

Once the ignimbrite had acquired some friction, prolonged and vigorous stirring was necessary to break down particle clusters and re-achieve full bed support.

5. Discussion

[20] Our results show that if gas velocity is raised incrementally from the loosely packed state in the absence of any agitation, then group-C behaviour is observed in ignimbrite at all temperatures up to and including 565°C. Full bed support is never achieved at $U > U_{mp}$ under these conditions. Indeed even at the highest velocities studied ($\sim$8 cm s^{-1}), in which the beds were in a state of turbulent fluidization, the pressure drop did not exceed 85% of the bed weight per unit area, probably due to persistent particle clustering. Temperature therefore has no significant effect under these conditions.

[21] The bed-collapse behaviour is influenced by temperature in two ways. First, adsorption of atmospheric moisture is sufficiently important and rapid at low temperatures (17 and 55°C) that cohesive forces dominate, despite (55°C case) the preventative measures described earlier. At and above 200°C, however, cohesion is sufficiently low that collapse proceeds in a group A manner. It is inferred that these collapses take place so rapidly that there is insufficient time for channelling to set in before settling is almost complete. Homogeneous expansions up to 40% over loose packing are observed in these tests (Figure 3a). The second effect of increasing temperature is the increases in homogeneous bed expansion and hindered settling velocity in the group-A collapses.

[22] The effect of mechanical agitation is very marked. By continuously breaking down cohesive bonds and particle clusters, even gentle agitation prevents the formation of channels and results in group-A expansion, as also observed in synthetic cohesive powders [*Nezzal et al.*, 1998]. If the

agitation is stopped, channeling sets in rapidly and bed support is lost.

[23] Geldart group A behaviour has not been previously reported in ignimbrite. Three fluidization states were observed in our experiments. (i) **Bubbling** $U > U_{mb}$. The material is expanded due to both (i) expansion of the particulate phase and (ii) the presence of bubbles. (ii) **Homogeneously fluidized** $U_{mf} < U < U_{mb}$. The material consists of a homogeneous particle-gas suspension with a macroviscosity comparable to that of runny mud. Expansions of up to 40% (bulk densities $\sim$560 kg m^{-3}) above those at loose packing are possible. (iii) **Aerated** $U < U_{mf}$. The material is at near-loose packing.

[24] Defluidization from the initially bubbling state, as observed in the high-temperature collapse tests, takes place first by bubble evacuation, then by homogeneous hindered settling with progressive aggradation of an aerated sediment layer. Once settling is complete, friction increases progressively by pressure diffusion in the loosely packed state until degassing is complete.

[25] The experiments may have implications for the fluidization behaviour of some small-volume pyroclastic flows. We envisage that gravity-driven shear in a pyroclastic flow would have a similar effect as stirring in our experiments, resulting in Geldart group-A properties. Slowly shearing, highly concentrated pyroclastic flows might be expected to exhibit the three fluidization states and defluidization behaviour described above. The existence of a defluidization regime in which the ignimbrite-gas suspension sediments homogeneously across a well-defined interface is especially intriguing. Such behaviour is typical of liquid-solid suspensions, but also occurs in gas-solid systems exhibiting group-A characteristics. We stress that these concepts cannot probably be applied to fast-moving pyroclastic flows in which Reynolds-Number turbulence could be important. In the light of our results, experiments on the dynamics of fluidized granular flows using group-A particles are of particular interest [*Roche et al.*, 2002].

[26] Finally, we emphasise that our ignimbrite-derived experimental material was specifically chosen so that it did not segregate during fluidization. However, segregation occurs in the raw ignimbrite at $U > U_{mp}$ (U_{mf}), both with or without agitation, and this will modify the above behaviour.

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