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RESEARCH ARTICLE

Particle velocity fields and depositional processes in laboratory ash flows, with implications for the sedimentation of dense pyroclastic flows

L. Girolami · O. Roche · T. H. Druitt · T. Corpetti

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Abstract We conducted laboratory experiments on dam-break flows of sub-250-μm volcanic ash, generated by the release of gas-fluidized and variably non-expanded to expanded (up to 35%) beds, in order to gain insights into the internal kinematics of pyroclastic flows. The flows were typically several cm thick and had frontal speeds of up to ~2 m s^{-1}. High-speed videos taken through the transparent sidewall of the 3-m-long channel were analyzed with a particle-tracking algorithm, providing a spatial and temporal description of transport and sedimentation. The flows deposited progressively as they traveled down the flume, being consumed by sedimentation until they ran out of volume. Deposition commenced 5–20 cm rearward of the flow front and (for a given expansion) proceeded at a rate independent of distance from the lock gate. Deposit aggradation velocities were equal to those inferred beneath quasi-static bed collapse tests of the same ash at the same initial expansions, implying that shear rates of up to ~300 s^{-1} have no measurable effect on aggradation rate. The initially non-expanded (and just fluidized) flow deposited progressively at a rate indicative of an expansion of a few percent, perhaps due to shear-induced Reynolds dilation during initial slumping. The fronts of the flows slid across the flume floor on very thin basal shear layers, but once deposition commenced a no-slip condition was established at the depositional interface. Within the flows, the trajectory of the constituent particles was linear and sub-horizontal. The velocities of the particles increased with height above the depositional interface, reached a maximum, then declined slightly towards the flow surface, perhaps due to air drag. At a given location, the velocity profiles were translated upwards as the deposit aggraded. The results show that even cm-thin, poorly expanded flows of ash deposit progressively, as inferred for many pyroclastic flows. The change from (frontal) slip to (rearward) no-slip conditions at the bases of the laboratory flows are qualitatively consistent with some textural features of pyroclastic flow deposits.

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Introduction

Pyroclastic flows are dense granular avalanches of hot particles and gas generated by gravitational collapse from lava domes or fallback of eruption columns. They travel at high speeds and constitute one of the most important hazards around active volcanoes (e.g., Wilson 1986; Druitt 1998; Freundt and Bursik 2001). Their ability to travel large distances on slopes as gentle as a few degrees has been attributed to non-equilibrium gas pore pressure and associated fluidization effects generated either by gases released internally or by entrainment of air (Sparks 1976; Wilson 1980; Druitt et al. 2007). Development of quantitative models of pyroclastic flows is a priority for modern volcanology, and this requires better understanding of their physical properties. While the physics of gravitational dry granular flows (in which it is assumed that particle interactions dominate and that interstitial gas plays a negligible role), has been explored extensively (for reviews, see GDR MiDi 2004 and Forterre and Pouliquen 2008), research on dense gas-particle flows dominated by fluid-particle interactions is much less advanced (Roche et al. 2004, 2008, 2010; Girolami et al. 2008). Up to now the dynamics of pyroclastic flows has been largely based on field observations of active flows (e.g., Hoblitt 1986; Levine and Kieffer 1991), and in particular inferred from textural studies of flow deposits (Sparks 1976; Branney and Kokelaar 2002 and references therein). However in order to use deposits to infer flow dynamics, it is crucial to understand how such deposits form (Branney and Kokelaar 2002). Moreover, pyroclastic flows appear to be capable of a wide spectrum of behaviors, from depositional to strongly erosional, the physics of which are poorly understood.

The kinematics of gas-fluidized particulate flows can be investigated through quantitative analysis of laboratory experiments. Fluidization is the process whereby the drag exerted by an upward flow of gas through a granular bed counterbalances the weight of the particles and hence reduces interparticle stresses, the fluidization state being determined by the vertical superficial gas velocity U_g (gas volumetric flux divided by surface area at the temperature of operation) (Rhodes 1998). Once U_g exceeds a minimum fluidization value U_{mf}, gas drag balances particle weight, friction disappears, and the bed adopts a liquid-like behavior. Some fine-grained powders (group A of Geldart 1973) expand uniformly between U_{mf} and the minimum bubbling threshold, U_{mb} ($>U_{mf}$). If the gas supply to a uniformly expanded bed is cut, the bed re-sediments from the base upwards by hindered settling in what is called a bed-collapse test (Lettieri et al. 2000; Druitt et al. 2007).

Laboratory studies of dense gravitational gas-particle flows include those of both continuously fluidized flows (Eames and Gilbertson 2000; Takahashi and Tsujimoto 2000; Gilbertson et al. 2008), and dam-break (i.e., transient) flows of initially fluidized particles released from a reservoir and that defluidize progressively during propagation (Roche et al. 2004, 2008, 2010; Girolami et al. 2008). Roche et al. (2008) showed that dam-break flows of small (<100 µm) group-A glass beads initially fluidized at U_{mb} (with a corresponding bed expansion of 2–4%) propagate on a horizontal substrate in three distinct phases based on observations of the flow front: (1) a short initial acceleration phase as the reservoir empties, (2) a dominant phase in which the front has an approximately constant velocity $U \sim \sqrt{(2gh_0)}$, where g is gravitational acceleration and h_0 is the height of the initial material in the reservoir, and (3) a short stopping phase. Flow behavior during phases 1 and 2, which together account for ~80% of the flow runout (equal to ~5.5–6 h_0), strongly resembles that of inertial fluids such as water, probably because of strong gas-particle interactions and associated high pore fluid pressure. It is consequently inferred that inertia dominates flow motion during the first two phases of emplacement, while a granular-frictional regime may dominate the third phase (Roche et al. 2008).

Similar experiments were carried out by Girolami et al. (2008) with hot volcanic ash. Hot ash differs from glass beads in that it can be expanded considerably (up to ~40%) above loose packing when fluidized above U_{mf}, allowing the effect of initial expansion on flow kinematics to be investigated. Heating the ash to ~200°C was necessary to reduce interparticle cohesion due to atmospheric humidity, allowing the ash to behave as a group-A material (Druitt et al. 2007). The ash-flow experiments showed that the runout of initially expanded flows scaled with the initial expansion and were in the range of 5.5–10 h_0, the first emplacement phase being governed by gravitational acceleration, and the second and third phases being dominated by both gravity and hindered settling. Additional experiments with tracer particles revealed that deposition from initially expanded flows took place incrementally at the flow base. A major finding of this work was that the upper surface of the deposit aggraded at a mean velocity identical to that inferred to take place at the base of a collapsing quasi-static bed of the same ash, expanded by the same initial amount, in the flume reservoir with the lock gate closed. High rates of shear therefore appeared not to affect deposit aggradation rate under collapsing layers of initially expanded ash.

The aim of the present study is to investigate in more detail the internal kinematics and deposition behavior of experimental flows of volcanic ash similar to those described by Girolami et al. (2008). For this, we made high-speed videos of the experiments, which were subsequently treated with sophisticated techniques of motion field estimation. For a range of initial bed expansions, we analyzed the temporal and spatial development of both the deposit and the velocity profile in the overlying flowing ash. We first present the method of image sequence analysis and the results obtained, then discuss possible implications for the way in which pyroclastic flows deposit.

Experimental procedures

The high-temperature flume

The experiments were carried out in a linear flume consisting of a fluidization reservoir and a horizontal channel built of aluminium and pyrex in order to withstand temperatures of up to 200°C (Fig. 1; see Girolami et al. 2008 for a detailed description). The high temperature was provided by external heating tapes regulated by thermostats and covering both the reservoir and an underlying windbox, and all experiments were carried out with the incoming gas and reservoir contents at the same temperature. The ash was fluidized and expanded in the rectangular reservoir (30-cm-long; 50-cm-high) and was subsequently released into the channel (3-m-long; 30-cm-high) by means of a lock gate. The width of both the reservoir and the channel was 15 cm. The ash rested on a porous plate of mean pore size of 17 µm that separated the windbox from the reservoir. The gas flux entering the windbox was controlled by flowmeters and was recalculated according to the operating temperature and the ideal gas law. The fluidization state of ash in the reservoir was given by the pressure drop across the bed measured by a pressure transducer. By means of a three-way valve, the incoming gas could be either directed into the windbox or vented outward during bed collapse tests as the gas supply was suddenly cut. The reservoir gate had a 20-kg counterweight allowing upward motion at a consistently high speed, and had a heat-resistant seal and a downward-tapering shape to prevent leakage and reduce resistance during opening. Releasing quasi-instantaneously the fluidized ash across the impermeable floor of the flume (i.e., dam-break condition) formed a fast-moving, short-lived, shear current that defluidized progressively during propagation until motion ceased.

Experimental material and procedure

The volcanic ash used in the experiments was the same as that used by Girolami et al. (2008). It contained a broad spectrum of particle sizes, from ~1 µm to 250 µm, and was obtained by disaggregating the matrix of a 0.58-Ma non-welded trachytic ignimbrite from Neschers (Massif Central, France) and removing particles >250 µm. The ash was then fluidized in the flume reservoir in the bubbling regime ($U_g > U_{mb}$) for 5 h, so that the finest particles were elutriated from the bed. The operation was stopped when the elutriation rate became negligible, and this resulted in a slightly fines-depleted material that was subsequently used in the experiments. We could use the same batch for all experiments since no subsequent elutriation occurred and the grain-size distribution remained constant (Girolami et al. 2008).

The ash was dried at 200°C for 24 h before each experiment, then transferred to the lock-gate reservoir where it was fluidized and expanded as required. The operating temperature of all experiments was fixed at 170°C, which was high enough to avoid humidity-related cohesive effects (Druitt et al. 2007). All experiments were

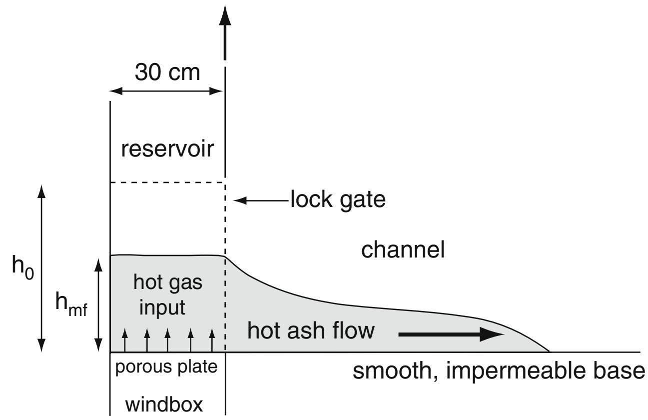

Fig. 1 Sketch of the experimental apparatus used in this study. The widths of both the reservoir and the channel are 15 cm. Heights h_{mf} and h_0 are those of the bed at the minimum fluidization velocity (U_{mf}) and of the expanded bed (at $U_g > U_{mf}$), respectively

limited to the non-bubbling state ($U_{mf} \leq U_g < U_{mb}$), and the bed expansion was defined as

$$E = h_0 / h_{mf}, \qquad (1)$$

where h_0 and h_{mf} are respectively the expanded and non-expanded (i.e., at U_{mf}) heights of initial bed of ash (Fig. 1). Under these conditions, the maximum value of E (at U_{mb}) was 1.45.

No detectable particle-size segregation occurred during expansion or re-sedimentation of the ash, either during quasi-static expansion and collapse in the reservoir, or during horizontal flow, as confirmed by sieving (Girolami et al. 2008). It is known that even strongly polydispersed suspensions of particles may settle without segregation, provided the initial concentration is high enough (Davies and Kaye 1971; Lockett and Al-Habbooby 1974; Druitt 1995). This enabled us to assign bulk properties to the ash (e.g., flow velocity, deposit aggradation velocity), and interpret the results quantitatively. In some experiments, tracer particles of 500-µm silicon carbide (SiC) were added to the ash in proportions up to 10 vol%. This was done to allow visualization of particle motions from videos for comparison with those calculated using the optical-flow algorithm. Results obtained with both methods were similar, and this is consistent with previous findings that low amounts of large particles are advected passively in flows of fluidized group-A particles (Roche et al. 2005).

We first studied the hindered settling behavior of the ash under quasi-static (non-shearing) conditions in bed-collapse tests in the reservoir of the device with the gate shut. The second part of our investigation involved the study of the flows in the channel. Once at working temperature, the fluidized bed in the reservoir was first stirred to avoid the channeling that typically occurs under static conditions in such fine-grained materials. Then mixing was stopped to allow homogeneous bed expansion to a known amount. In bed-collapse tests, we then cut the gas supply and measured the descent rate of the surface (Druitt et al. 2007). For flow experiments, the lock gate was opened and no channeling was observed in the shearing material. The experimental conditions were the same as in experiment series 2 of Girolami et al. (2008): h_{mf} was fixed at 16.5 cm in all experiments, so that h_0 increased proportionally with E and flows were generated at four different values of E: 1.00 (non-expanded), 1.09, 1.17 and 1.35.

Method of particle velocity-field estimation

Principle of the method

Particle velocity fields and vertical profiles were determined using the particle-tracking technique of Corpetti et al. (2006), which is based on the theory of optical flow. Among the existing approaches to estimate a velocity field from a pair of images, the "correlation" techniques are widely used in the physical community. These techniques are based on a spatio-temporal cross-correlation submitted to a consistency assumption of the flow within a local interrogation window. Even if they are very efficient in many applications, it is now admitted in the computer vision community that they are not optimal for the estimation of fluid-like flows. Indeed, the choice of the interrogation window is a very critical point that prevents us from estimating correctly both local and global motions. In addition, the estimated displacement vector is intrinsically discretized on the image grid, and this results in the well known "peak-locking" effect which reduces the accuracy of the velocity measurement.

In recent years, some optical-flow techniques have been proposed as alternatives for the estimation of fluid flows. Optical-flow techniques are commonly used in the computer-vision community, and were introduced by Horn and Schunck (1981) for the tracking of rigid objects (i.e. particles in the present context) in image sequences. They allow estimation of a dense motion field (i.e. the velocity at each point of the image) from the intensities (also called luminance) of a pair of consecutive images. The fundamental principle is to minimize an energy function based on two assumptions: 1) luminance conservation and 2) spatial consistency of the velocity-vector field. The first assumption is that all points of the first image conserve their intensities on the second image. This enables the use of an image pair to generate an estimate of the particle velocity field. However, in areas of the images where no spatial or temporal variations of luminance are apparent, this leads to an undetermined equation with an infinity of possible solutions. To solve this problem, Horn and Schunck (1981) introduced a spatial-smoothing term that roughly assumes that all neighboring points have a similar motion (assumption 2). This generates smooth flow fields where spatial gradients of motion are very low. The optical-flow method we used (Corpetti et al. 2006) is a modified version of the original (Horn and Schunck 1981), where instead of generating very smooth flow fields, we estimate velocity vectors where some properties of flows such as divergence and vorticity are conserved.

Image acquisition and algorithm validation

For each experiment, the whole channel flow was filmed with a standard video camera (25 frames per second) to determine the flow front velocity. Parts of the flows were filmed in detail with a high-speed video camera (1,000 frames per second) placed at a distance that was adjusted depending on flow runout, in order to focus the analysis on flow phase 2 (i.e. constant front velocity). The camera was thus located at various distances (20-30 cm; 50-60 cm; 80-90 cm; 110-120 cm) from the lock gate. This was done using a single camera and by repeating each experiment multiple times, assuming a good reproducibility of the experiments. Girolami et al. (2008) showed that the flows slipped along the pyrex wall of the channel, so that particle movements observed through the wall were inferred to be representative of the flow interior.

The video sequences were analyzed using the optical-flow algorithm; in each case, a series of velocity fields were determined from motion estimation between two images at a time interval of 1/500 s, which was sufficient for detectable motion. The high-speed video camera was placed at a distance of 30 cm from the transparent channel wall, so that the algorithm determined particle motion in vertical strips of 10-cm-wide. Velocity profiles were then extracted from strips of 1-cm-wide perpendicular to the upper surface of the aggrading deposit. Inconsistent velocity fields at flow boundaries due to sidewall-reflection or perspective-related-shadow effects were avoided using a masking technique (Corpetti et al. 2006). Mask generation consisted of grouping pixels outside the flow and associating them with a color that contrasted markedly with that of the flow, so that the algorithm encountered no ambiguity.

In order to test the validity of the algorithm, we used it to measure the thickness of the basal deposit as a function of time from videos of the ash flows. For comparison, we also measured the deposit thickness simply by visual inspection of videos. Both methods gave similar results (Fig. 2), showing that the algorithm was suitable for the aim of our study.

Results

Bed collapse tests and general flow behavior

The results of the quasi-static bed collapse tests in the reservoir are presented in Fig. 3 for initial expansions from 1.06 to 1.43. The hindered settling velocity (V, in cm s^{-1}) of the ash given by the descent rate of the upper surface increases with E, the best-fit relationship in the present case being

$$V = 2.44E - 2.15. \quad (2)$$

Note that the value of V for a given E is higher than for the ash of Girolami et al. (2008) (grey region of Fig. 3), owing to the presence of the SiC particles.

The general behavior of the flows was described by Girolami et al. (2008). When released, the ash flowed along the channel until defluidization was complete and frontal motion ceased. Propagation took place in the three main phases typical of dam-break granular flows: the first, brief initial acceleration phase (1) lasted 0.1–0.2 s; the second, dominant phase (2) during which the front had an approximately constant velocity lasted 0.6–0.8 s and accounted for about two thirds of the flow duration and 70–80% of the flow runout; and the third, brief stopping phase (3) lasted 0.1–0.4 s. The non-expanded flow (E= 1.00) had a phase-2 velocity of ~1.1 m s^{-1}, a runout distance of 0.6 m (~3.5 h_0) and a runout duration of 0.8 s, whereas the most expanded flow (E=1.35) had a phase-2 velocity of ~2.1 m s^{-1}, a runout distance of 2.2 m (~9.6 h_0) and a runout duration of 1.4 s.

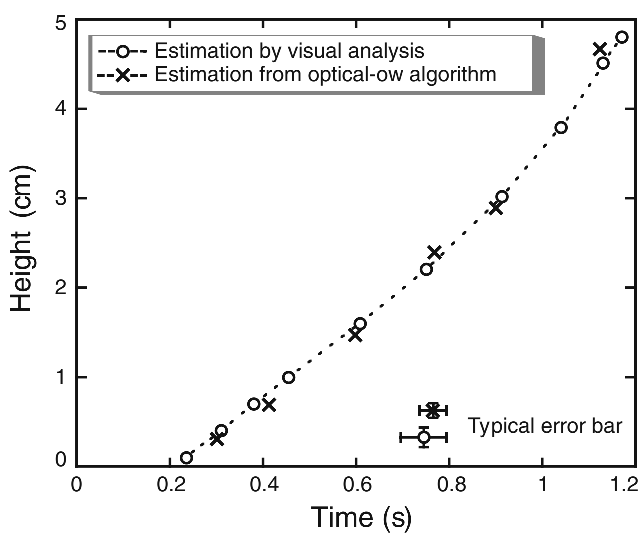

Fig. 2 Thickness of the basal deposit as a function of time in an initially moderately expanded flow (E=1.17) at a distance of 20 cm from the lock gate. Comparison of data determined by visual analysis and by using the optical-flow algorithm. The good agreement validates the results of the algorithm

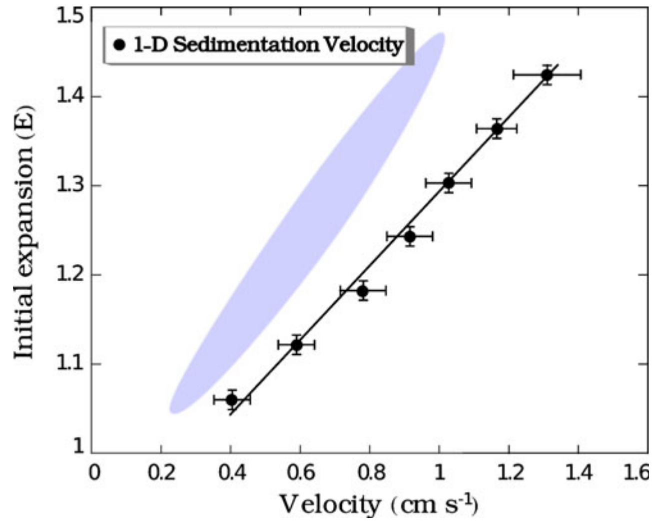

Fig. 3 Quasi-static hindered settling velocities of the SiC-laden ash as a function of initial expansion. Measurements were carried out in the flume reservoir with the lock gate closed. The data are approximated by a linear best fit V=2.44E–2.15 cm s^{-1} (black line). The grey zone shows the equivalent data on the raw ash (lacking SiC particles) used by Girolami et al. (2008). The effect of the SiC particles is to increase hindered settling velocity at a given expansion

Characteristics of particle velocity fields and profiles

The particle velocity fields revealed a basal (static) deposit beneath the overriding flow for the whole range of initial bed expansions investigated (Figs. 4, 5, 6 and 7). Sedimentation commenced approximately 0.05-0.10 s (at ~5-20 cm) behind the flow front at all distances from the lock gate, and the deposit took the form of a wedge that thickened with time at the expense of the flow until the latter was entirely consumed. The upper surface of the deposit was steeply inclined (up to 20–25°) and remained approximately constant with time beneath the initially non-expanded flow (E=1.00). In contrast, it was much more gently inclined beneath the initially expanded flows (E>1.00), and decreased from 2° to 0.8° as E increased from 1.09 to 1.35. The flow fronts were typically rounded in cross section near the lock gate, but became progressively more triangular in form with increasing distance downstream. Immediately behind the front, the flowing region thickened to a maximum of 3 cm to 4 cm, before then decreasing in thickness, both temporally at a given location as the deposit aggraded, and longitudinally down the flume. In the initially expanded flows, the angle of the flow surface was slightly greater than that of the underlying deposit, whereas the reverse was true in the non-expanded flow.

In order to characterize the flow behavior, we use by analogy with pure fluid flows the terms “turbulent” and “non-turbulent” for convenience hereafter. The term “non-turbulent” means that paths of neighboring particles were

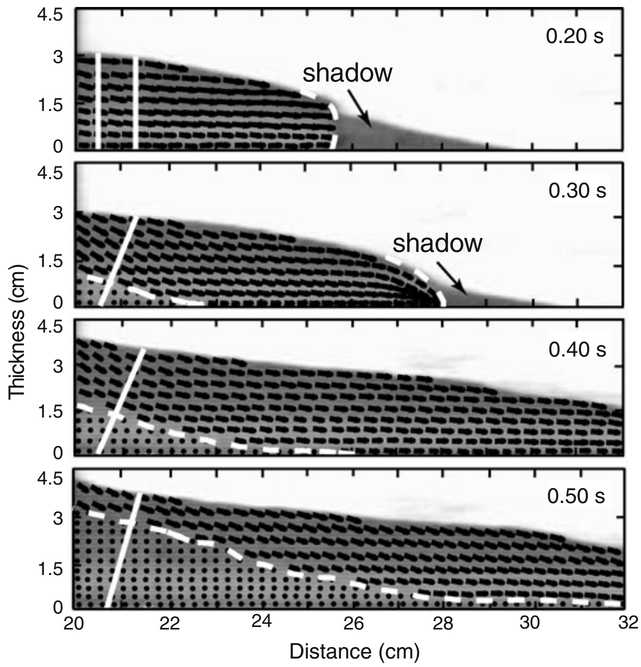

Fig. 4 Velocity fields at 20–30 cm from the reservoir gate and at different times after release of the initially non-expanded flow (E=1.00). The dashed white line represents the interface between the flow and the aggrading deposit. White lines show where the flow velocity was extracted to build the profiles of Fig. 8

linear and parallel to each other on scales larger than a few individual grains. Particle velocity vectors in the initially expanded flows had significant downward components within 20–25 cm of the lock gate inherited from the initial phase-1 collapse, but beyond this the vectors became sub-horizontal. A downward flow component was maintained to the distal limit in the initially non-expanded flow, owing to the steep surface of the aggrading deposit.

Particle velocity profiles revealed different flow behaviors before and after the onset of deposition (Fig. 8). The fronts of both expanded and non-expanded flows slid along the channel floor on a basal slip zone <1 mm thick with only a weak vertical velocity gradient in the over-riding flow. Once deposition had commenced, however, shear was distributed more uniformly throughout the flow height, and velocity increased more progressively towards the deposit surface. In the initially non-expanded flow, velocity increased rapidly upwards over a few mm above the deposit surface, then increased more slowly towards the flow surface and reached a maximum of about 1.2 m s^{-1}. In contrast, in the initially expanded flows, velocity increased upwards in a quasi-linear manner (through velocity profiles were slightly concave upward), but then decreased again near the flow surface. Maximum velocity increased with E, from 1.6 m s^{-1} (E=1.09) to 2.0 m s^{-1} (E=1.35), these being similar to the phase-2 frontal velocity in each case. As the deposit aggraded at a given site, the velocity profile was translated upwards while maintaining approximately the same shape. Velocity gradients increased as the flows thinned progressively downstream. Consequently, the highest shear rate estimated at a distance of 25 cm from the lock gate was ~125–150 s^{-1}, while that at 85 cm was ~275–300 s^{-1}.

Aggradation of the basal deposit

Figure 9 shows the evolution of deposit thickness with time for the different flows, t=0 marking the passage of the flow front at various distances from the reservoir gate. The

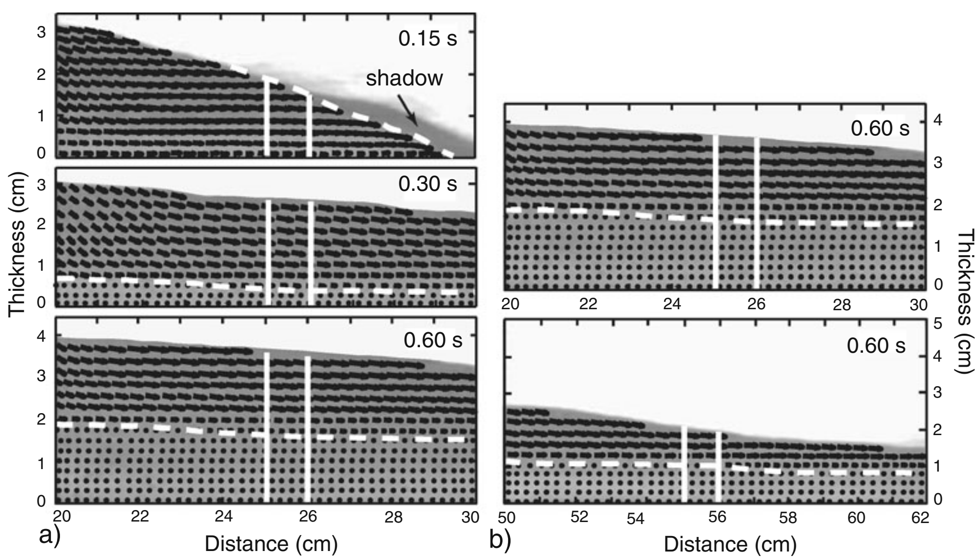

Fig. 5 Velocity fields at 20–30 cm from the reservoir gate and at different times after release of an initially expanded flow with E=1.09. The dashed white line represents the interface between the flow and the aggrading deposit. White lines show where the flow velocity was extracted to build the profiles of Fig. 8

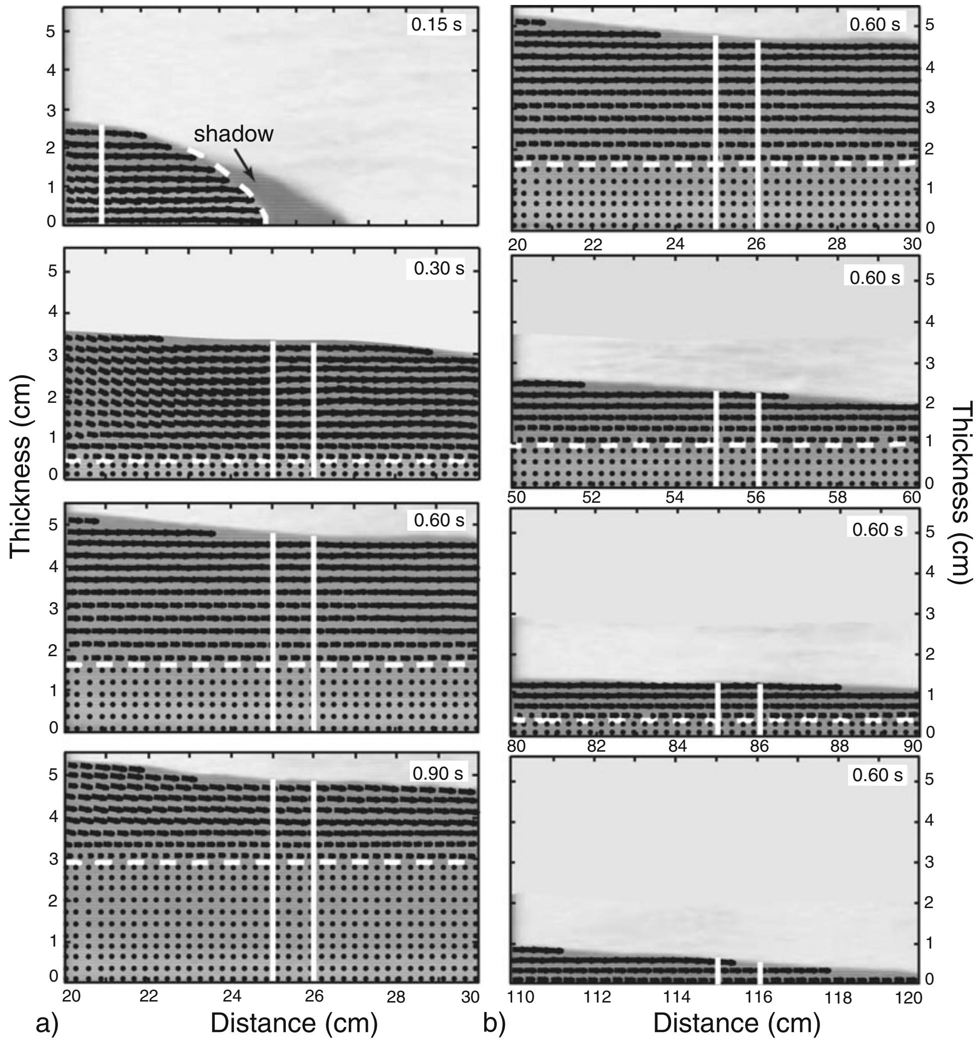

Fig. 6 Velocity fields at 20–30 cm from the reservoir gate and at different times after release of an initially expanded flow with E=1.17. The dashed white line represents the interface between the flow and the aggrading deposit. White lines show where the flow velocity was extracted to build the profiles of Fig. 8

formation of the basal deposit started after the passage of the front, and the time interval was about 0.05 s for the initially non-expanded (E=1) flow, and increased slightly from 0.05 s to 0.10 s as E increased from 1.09 to 1.35. Regarding aggradation of the deposit, the data reveal three main features. First, the mean aggradation velocity was dependent on E. Second, aggradation velocity at each value of E was almost independent of distance down the channel, showing that it was sufficient to measure this parameter at a single location down the flume to obtain representative values. Third, the aggradation velocity (at a given E) was approximately constant with time at each location. Initial aggradation occurred at ~4.9 cm s^{-1} at E=1.09, ~4.1 cm s^{-1} at E=1.17, and ~2.4 cm s^{-1} at E=1.35. In the E=1.00 flow, this rate remained constant until sedimentation was complete. In the initially expanded flows, however, there is an indication that aggradation speeded up during the final increments (0.7–0.9 s) of sedimentation, although this behavior is defined by only a few data points for measurements at a distance of 20–30 cm from the gate. We note, however, that this increase in aggradation rate occurred at a time corresponding approximately to the transition between the second (constant-velocity) and third (stopping) phases of the flows. In the initially moderately expanded flows (E=1.09 and 1.17) this late-stage aggradation velocity is close to that of the non-expanded flow, whereas in the most expanded flow (E=1.35), it is not. We stress, however, that to a first approximation the aggradation rates at each value of E are constant throughout most of the duration of sedimentation.

The deposit aggradation rates of the flows are here compared to those inferred from the quasi-static bed-collapse tests carried out in the flume reservoir with the lock gate closed. For an initially expanded bed collapsing at a velocity V, the deposit aggradation velocity S given by mass flux balance is S=V/(E−1) (Druitt et al. 2007). Hence

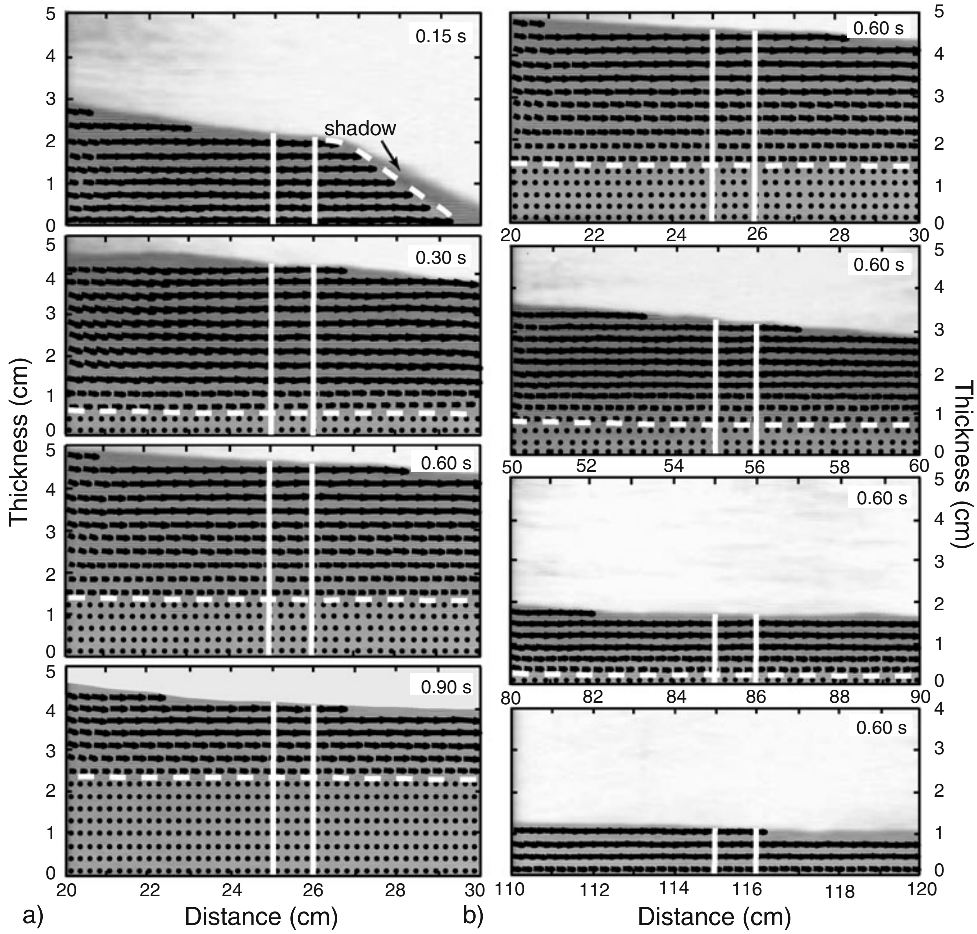

Fig. 7 Velocity fields at 20–30 cm from the reservoir gate and at different times after release of an initially expanded flow with E=1.35. The dashed white line represents the interface between the flow and the aggrading deposit. White lines show where the flow velocity was extracted to build the profiles of Fig. 8

from Eq. 2 the quasi-static aggradation velocity for the ash is S=(2.44E−2.15)/(E−1) cm s^{-1}. In Fig. 10, deposit aggradation rates beneath the expanded flows are compared with values calculated from the settling rates measured in the collapse tests and reported earlier. Values are plotted both for the rate of initial aggradation and for a mean value for the entire duration of deposition. Irrespective of which value is used, aggradation rates beneath the E>1 flows agree to within measurement error with those inferred beneath quasi-static collapsing beds of the same initial expansion.

Discussion

Processes in the laboratory flows

The velocity fields and profiles of Figs. 4–8 are to our knowledge the first measurements of particle motion in fluidized flows of hot natural ash. High-speed images show that the laboratory flows behaved to a first approximation as sheared-out collapsing beds, with a fast-moving flow below which a deposit aggraded progressively until the flow ran out of volume. The flows propagated in three distinct phases, and the measured phase-2 velocities were about $\sqrt{(2gh_0)}$, typical of inviscid dam-break flows (Roche et al. 2008), provided the mixture was initially expanded. Flow at all expansions was "non-turbulent", as we defined earlier. It cannot be ruled out that this was in part a boundary-layer effect against the flume wall, but it is consistent with the absence of surface vorticity reported by Girolami et al. (2008). An important observation is that at all expansions the frontal region of each flow, up to 5–20 cm (0.05–0.10 s) behind the leading edge, slipped across the channel floor with only weak internal velocity gradients, whereas, once deposition had begun, a no-slip basal condition was established and shear was accommodated more uniformly throughout the flow height. The origin of this effect is unclear and requires further study, but it could relate to differences in fluidization state between the flow head and body. Note that a frontal slipping region and a basal aggrading deposit were also observed in similar dam-

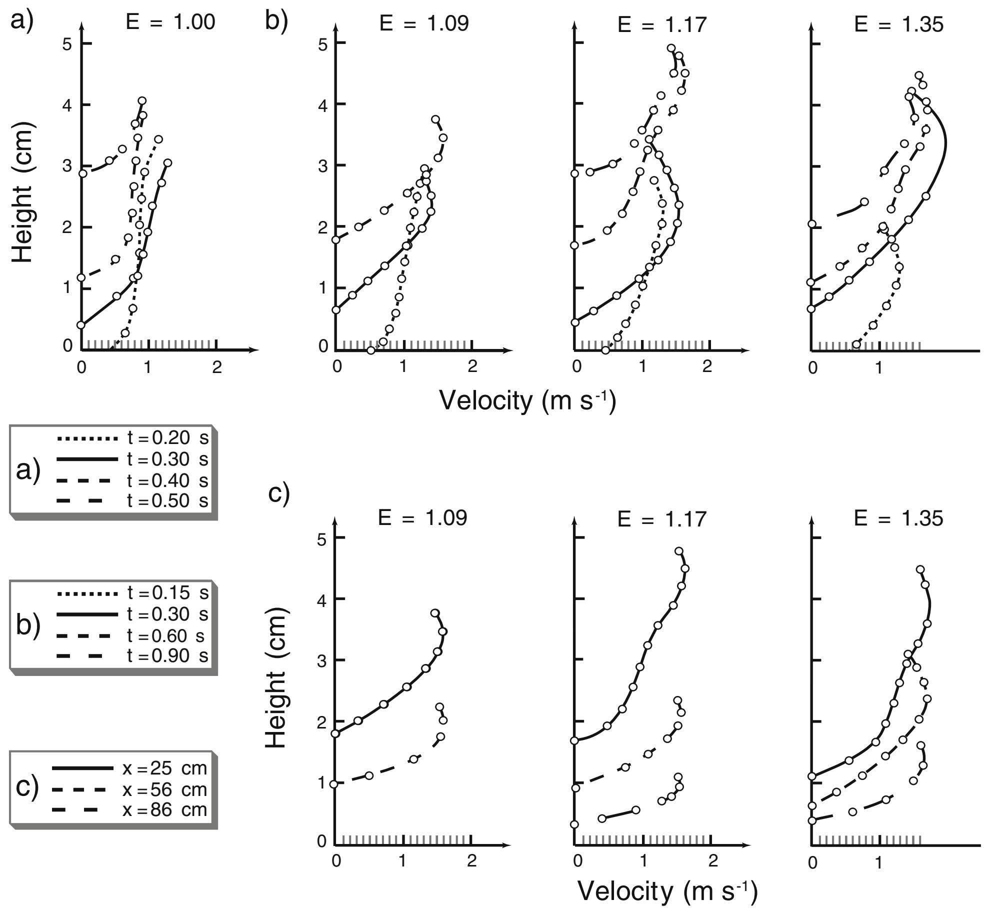

Fig. 8 Velocity profiles determined from the velocity fields in Figs. 4–7 for different initial expansions (E). **a**, **b** At a distance of 25 cm from the lock gate and at different times after release, and **c** at a time of 0.6 s and different distances. Heights and velocities in the flows were measured perpendicular and parallel to the depositional surface, respectively

break experiments of Roche et al. (2010) involving fine (~80 microns) glass beads, thus suggesting that these features are typical of such types of flows. In initially expanded flows, the data also revealed the existence of a superficial layer of decreasing velocity, possibly due to air drag since surface flow-velocity decrease is correlated positively with initial bed expansion. In flows of all initial expansions, the dynamics were probably constant over time at a given distance from the lock gate, as suggested by the simple upward translation of velocity profiles. As the flows traveled along the channel, the internal shear rate increased because the maximum internal velocity, about equal to the frontal velocity, was approximately constant, whereas the flow thickness decreased.

Girolami et al. (2008) estimated time-averaged deposit aggradation rates from initially expanded ash flows assuming (1) that deposition began immediately behind the flow front, and (2) that aggradation rate depended only on E and was independent of time or distance within a given flow; they then divided the final deposit thickness by the total deposition time. The new data confirm these assumptions to a first approximation. In detail, however, sedimentation began 5–20 cm (0.05–0.10 s) after passage of the flow front. The dependence of aggradation rate on initial bed expansion can be explained by comparing the flow values with those of our quasi-static bed-collapse tests. As shown in Fig. 10, the rates of deposit aggradation beneath the initially expanded (E>1.00) flows were similar to those inferred from the bed-collapse tests. Hence, despite rates of shear of up to 300 s^{-1} in the flows, shear had little effect on deposit aggradation rate, as also concluded by Girolami et al. (2008) based on their less accurate approach. While aggradation rate was almost independent of distance from the lock gate, there were some indications that it increased slightly with time at a given location in initially expanded flows. This could not be due to segregation of the dense SiC tracer particles (when present) towards the base of the flow, since this would result in higher initial deposition rates, which is the inverse of what is observed. As the aggradation rate increased approximately when the flows entered the stopping phase after about two thirds of the flow duration, this suggests a relationship between the internal dynamics of the flow and the kinematics of the front. Furthermore, the late-stage aggradation rates of the moderately expanded flows (E=1.09 and 1.17) were similar to those of the non-expanded flows, which could suggest that these initially expanded flows were then no longer expanded. This may be consistent with the observed evolution of flow-front

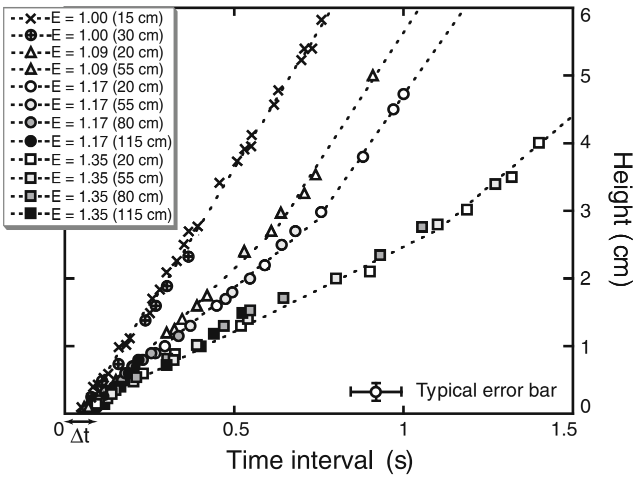

Fig. 9 Deposit thickness as a function of time for different initial bed expansions (E) and distances from the gate. Δt is the time delay between the passage of the flow front and the onset of deposition

shape from rounded to progressively triangular, the latter being typical of non-expanded flows.

The initially non-expanded flows behaved in a similar manner to the expanded ones: shearing throughout and depositing progressively. Particle sedimentation is theoretically not possible from an initially non-expanded fluid-particle mixture. A one-dimensional non-expanded granular bed initially just fluidized at U_{mf} defluidizes by pore-pressure diffusion, and no particle settling occurs. Either defluidization of the E=1.00 flow took place by pore-pressure diffusion, from the base upwards at a rate we cannot quantify, or the ash was slightly expanded by a combination of Reynolds dilation and particle agitation during shear, and then underwent re-sedimentation like the other flows. If the latter is true, then an expansion of a few % is implied by extrapolation of the quasi-static curve (Fig. 10), which agrees well with values reported for Reynolds dilation of sheared granular masses (Hutter et al. 2005). One implication of this observation could be that even a flow generated from initially non-expanded (but just fluidized) ash may deposit by settling because the shear generated by flow will always slightly expand the gas-particle mixture above loose-packing. Further investigation of this possibility is required.

Implications for pyroclastic flows

The experimental results provide information on the possible flow and deposition behavior of dense pyroclastic flows propagating on a sub-horizontal slope. Fluidization in pyroclastic flows is believed to affect only the sub-mm size fractions, so that lapilli and blocks are transported passively, in suspension or as bedload, within a matrix of partially or fully fluidized ash (Sparks 1976). As our experimental ash is representative of that matrix, the behavior of the laboratory flows is likely to resemble that of natural flows containing particles of a larger size range, and this idea is supported by laboratory experiments (Roche et al. 2005). The presence of very large and/or dense clasts may, however, complicate this simple picture.

Understanding the manner in which a pyroclastic flow deposits its load is fundamental to using deposits to reconstruct eruptive processes. The modes of deposition of pyroclastic flows have been widely debated, possible endmember mechanisms including frictional freezing or progressive aggradation (Sparks 1976; Branney and Kokelaar 1992, 2002, and references therein). The conceptual difference between these mechanisms is that freezing is envisaged to occur only at a late-stage following long transport, whereas progressive aggradation takes place throughout flow runout. Textural studies have been used to infer that the individual flow units and thick massive layers that constitute large ignimbrite sheets were laid down by progressive aggradation, not freezing (Branney and Kokelaar 1992, 2002). However, such flows may travel as turbulent suspensions at various degrees of expansion, so it is less clear to what extent progressive aggradation also takes place in pyroclastic flows of small volume in which whole-body turbulence is less likely (e.g., Sparks et al. 1997). However, the experiments of Girolami et al. (2008) and this paper now show that even "non-turbulent" weakly expanded dam-break flows of ash as thin as a few cm deposit progressively. Moreover, this behavior also charac-

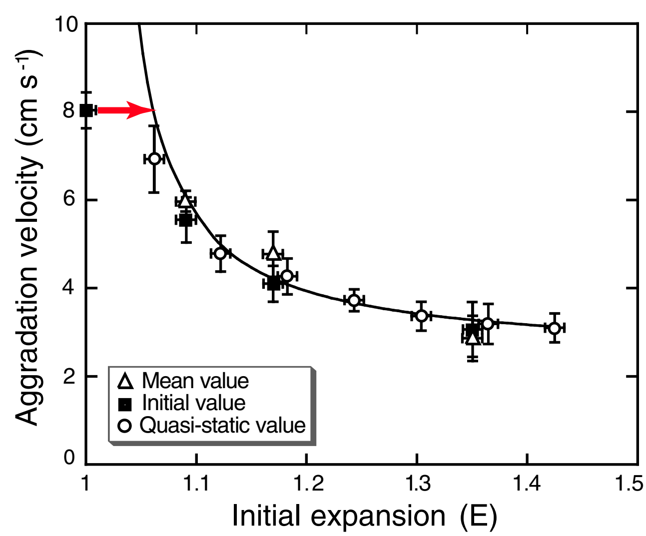

Fig. 10 Deposit aggradation velocity in the flows as a function of E. Black squares are the initial aggradation velocity; white triangles are the mean aggradation velocity including the slightly faster late-stage phase (cf. Fig. 9). White circles are aggradation velocity inferred by mass-flux balance calculation from the quasi-static bed-collapse values of Fig. 3. The curve is the best-fit function S=(2.44E−2.15)/(E−1) cm s^{-1} to the quasi-static data (see text for details). The horizontal arrow shows that deposit aggradation beneath the initially non-expanded (E=1.00) flow took place at a rate expected for an expansion of a few percent

terizes even the initially non-expanded ash flows, so it seems to be a general feature of gas-particle flows, irrespective of thickness, expansion or degree of turbulence.

The apparent insensitivity of deposit aggradation rate to shear may offer a means of parameterizing these rates in flow models by using sedimentation rates measured in quasi-static rigs. Mathematical models taking into account progressive deposition have been developed for granular flows, but only for dry (i.e., non-fluidized) flows and assuming empirical aggradation rates (Doyle et al. 2007). On the other hand, some numerical models simulate (partially) fluidized geophysical flows, but do not yet include progressive deposition (Iverson and Denlinger 2001; Denlinger and Iverson 2004). In this context, the results presented in this paper could serve as a guide for including deposit aggradation in models of fluidized flows. Such an approach would be limited to the modelling of relatively dense non-turbulent fluidized flows propagating on a sub-horizontal slope.

The experiments also provide insight into the way in which shear may be accommodated vertically in different parts of a pyroclastic flow. Erosion features on the underlying substrate, such as deep channels, striations, furrows and percussion marks, have been reported at the bases of many pyroclastic flow deposits, especially on steep slopes (Rowley et al. 1982; Sparks et al. 1997; Cole et al. 2002; Pittari and Cas 2004). These features show that pyroclastic flow deposits (Fig. 11a) can exert high shear stresses on the ground over which they travel (Fig. 11b). The incorporation of substrate lithic clasts, as well as the shear-laminations and kinetic sieving common in some ignimbrite basal layers may be also indicative of high basal shear (Buesch 1992; Suzuki-Kamata 1988; Branney and Kokelaar 2002). Erosional features at Lascar Volcano were interpreted to form when highly concentrated flows slid over bedrock (Sparks et al. 1997). Similar conclusions have been reached for the Abrigo Ignimbrite on Tenerife, where impact and sole marks are interpreted as the consequence of the passage of a highly energetic flow head enriched in pebble- to cobble-sized lithic clasts (Pittari and Cas 2004). In contrast, the typically massive interiors of flow units preserve evidence only for lower levels of shear at the aggrading depositional surface, such as magnetic fabrics, clast imbrication and flow-parallel orientation of elongated particles, crystals and

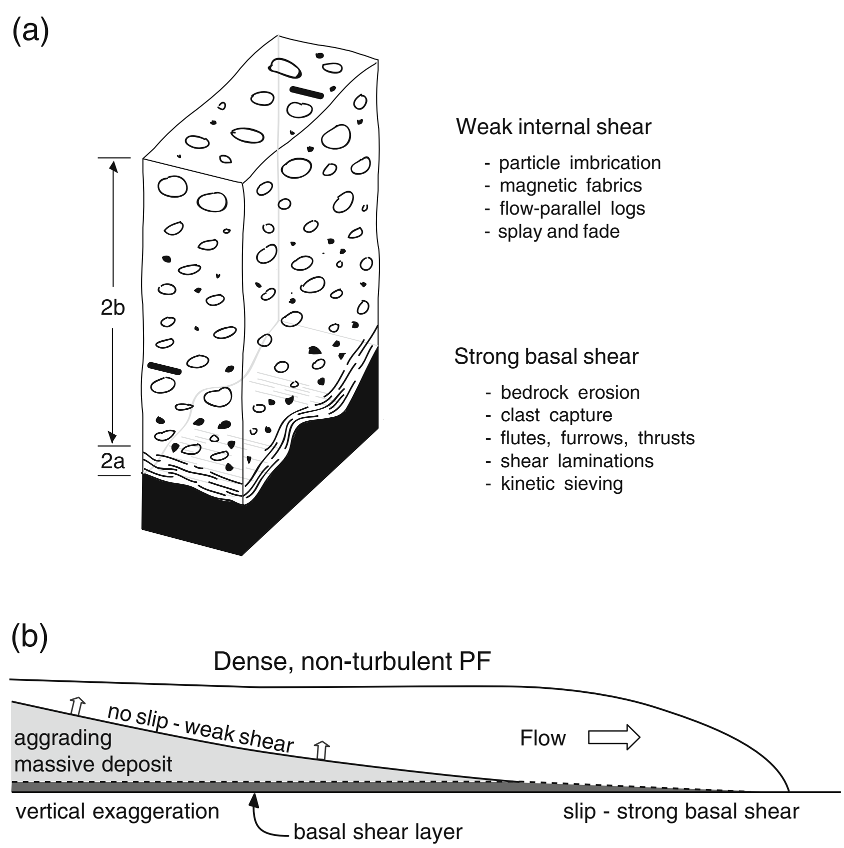

Fig. 11 **a** Selected textural features of a typical pyroclastic flow unit (Sparks 1976; Branney and Kokelaar 2002). Evidence for strong shear occurs at the base of the flow unit (layer 2a), whereas shear indicators are less common within the massive layer 2b. **b** The experiments provide a conceptual basis for explaining these relationships. The front of the pyroclastic flow slides on a thin basal layer, and exerts strong shear on the substrate and incipient deposit (layer 2a). However once the front has passed, a no-slip condition is established at the depositional interface, and aggradation of the rest of the deposit (layer 2b) takes place under conditions of less intense shear

logs (e.g., Suzuki and Ui 1982; Knight et al. 1986; Potter and Oberthal 1987; Hughes and Druitt 1998 and references therein) (Fig. 11a). Possible features indicative of intense shear, such as shear laminations and truncated clasts are generally absent within the massive interiors of flow units. This suggests that high basal shear stresses are limited to the frontal regions of pyroclastic flows and that, once the deposit starts to aggrade, shear stress at the base of the moving flow (i.e., the depositional surface) falls to lower values (Fig. 11b).

The field observations reported above are consistent with our experimental results. Velocity profiles showed that the flow head slid over the flume floor, which is likely to generate a strong shear stress (at the scale of the flow). although the effects of this basal shear were not visually evident because the floor was rigid. In a natural pyroclastic flow such a process might give rise to strong substrate erosion, as commonly observed. Frontal sliding has been proposed previously for highly concentrated pyroclastic flows with poorly-fluidized bouldery snouts (Iverson and Vallance 2001 and references therein), but our experiments show that it can occur even in the absence of coarse segregated particles. We acknowledge, however, that many pyroclastic flows are non-erosional, which poses limitations to our interpretations and in turn suggests that further investigations on that issue are required. The experiments also showed that as the flow front passed by and sedimentation commenced, the flow developed a no-slip boundary with its aggrading deposit, and shear was accommodated more pervasively throughout the flow. Textural evidence for shear may therefore be expected to be less common in the interiors of flow deposits, as is indeed the case.

Conclusions

We carried out experiments on dam-break flows of initially fluidized volcanic ash in order to better understand the transport and sedimentation processes in dense pyroclastic flows propagating on sub-horizontal slopes. The ash was representative of the matrices of natural flows and was expanded to amounts of up to 35% before release. The internal kinematics of the flows was documented by measuring the velocity fields of the constituent particles as well as their spatial and temporal variations. High-speed videos were acquired at 1,000 frames per second, and subsequently analyzed using a particle-tracking algorithm.

The results revealed that the experimental flows behaved to a first approximation as sheared-out collapsing beds, with a fast-moving flow overriding a basal deposit that aggraded progressively until the flow was consumed. The overriding flow was “non-turbulent” and pervasively sheared, with a slightly concave-upward velocity profile. In initially expanded flows, the maximum internal velocity was close to that of the flow front, with shear rates up to ~300 s^{-1}. Some decrease in velocity was observed near the flow surface, possibly due to air drag. Flows of all initial expansions were characterized by a frontal region that slid across the floor of the flume on a thin (less than ~1 mm), highly sheared basal layer. Deposit aggradation commenced ~0.05–0.10 s (~5–20 cm) behind the flow front, and took place at a rate of a few cm per second that was similar to that inferred for quasi-static bed collapse tests at the same values of initial expansion. Once deposition had begun, a no-slip condition was established at the base of the flow. At a given distance from the lock gate, the velocity profile of the flow was translated upward as the deposit aggraded, suggesting time-invariant flow dynamics. The aggradation rate decreased as the initial bed expansion increased, and it was independent of the distance travelled within a flow of given expansion. It was approximately constant with time at a given location, though it apparently increased when the flows entered their last, decelerating phase of emplacement. Initially non-expanded (just fluidized at U_{mf}) flows deposited progressively in a manner similar to initially expanded ones, even though particle sedimentation is theoretically not possible from the packed state. This suggests that the non-expanded flows may have undergone shear-induced dilation of a few percent during initial slumping.

Our study has some implications for our understanding of the kinematics of dense pyroclastic flows in nature. First, it shows that progressive aggradation of a basal deposit and pervasive shear of the overlying flow are likely mechanisms. Second, substratum erosion (and possibly lithics incorporation) observed in the field could be the consequence of intense shear stresses at the base of a sliding flow head. Third, the deposit aggradation rates essential for the modeling of pyroclastic flows may in principle be determined from simple quasi-static bed-collapse tests.

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