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Fine-grained linings of leveed channels facilitate runout of granular flows

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ABSTRACT

Catastrophic dense granular flows, such as occur in rock avalanches, debris flows and pyroclastic flows, move as fully shearing mixtures that have approximately 60 vol.% solids and tend to segregate to form coarse-grained fronts and leveed channels. Levees restrict spreading of unconfined flows and form as coarse particles that become concentrated in the top of the flow are transported to the front and then advect to the sides in the flow head. Channels from which most material has drained away down slope are commonly lined with fine-grained deposit, widely thought to remain from the tail of the waning flow. We show how segregation in experimental dense flows of carborundum or sand (300–425 μm) mixed with spherical fine ballotini (150–250 μm), on rough slopes of 27–29°, produces fine-grained channel linings that are deposited with the levees, into which they grade laterally. Maximum runout distance is attained with mixtures containing 30–40% sand, just sufficient to segregate and form levees that are adequately robust to restrict the spreading attributable to the low-friction fines. Resin impregnation and serial sectioning of deliberately arrested experimental flows shows how fines-lined levees form from the flow head; the flows create their own stable 'conduit' entirely from the front, which in a geophysical context can play an important mechanistic role in facilitating runout. The flow self-organization ensures that low-friction fines at the base of the segregated channel flow shear over fine-grained substrate in the channel, thus reducing frictional energy losses. We propose that in pyroclastic flows and debris flows, which have considerable mobility attributable to pore-fluid pressures, such fine-grained flow-contact zones form similarly and not only reduce frictional energy losses but also reduce flow–substrate permeability so as to enhance pore-fluid pressure retention. Thus the granular flow self-organization that produces fine-grained channel linings can be an important factor in facilitating long runout of catastrophic geophysical flows on the low slopes (few degrees) of depositional fans and aprons around mountains and volcanoes.

1. Introduction

Pyroclastic flows, debris flows and rock avalanches commonly involve dense, shearing granular mixtures with solids concentrations of around 60 vol.%. Despite different origins, particle types and interstitial fluids, they are all prone to grain-size segregation and their deposits tend to be morphologically similar. Their mobility, or effective friction, however, can differ widely and has diverse controls. Gaseous and aqueous pore-fluid pressures are important in conferring mobility via fluidization and liquefaction to pyroclastic flows and debris flows respectively. Also, the relatively fine-grained components ('fines') of natural dense flows can reduce tendency to deposit and thus increase mobility, for example by constituting a medium interstitial to the coarser particles that hinders their packing and reduces inter-particle friction, or via ball-bearing-like effects (Branney and Kokelaar, 2002; Druitt et al., 2007; Hsu, 1975; Iverson, 1997; Iverson et al., 2010; Linares-Guerrero et al., 2007; Midi, 2004; Moro et al., 2010; Phillips et al., 2006; Roche, 2012; Roche et al., 2005).

In dry, cohesionless, dense granular flows, particles generally maintain contact in a continuous shearing framework so that the overall behaviour is influenced by contact friction. Such frictional flows (Vallance and Savage, 2000) are only slightly dilated relative to their loosely packed deposit; on steepening slopes they transition to strongly dilated 'rapid-collisional' flows in which particle collisions and saltation dominate the rheological behaviour (e.g. Savage, 1984). Deposits of dense granular flows on fans and aprons around mountains and volcanoes tend to have lobate fronts dominated by relatively coarse particles, behind which is less well sorted and finer deposit between coarser-grained levees (e.g.

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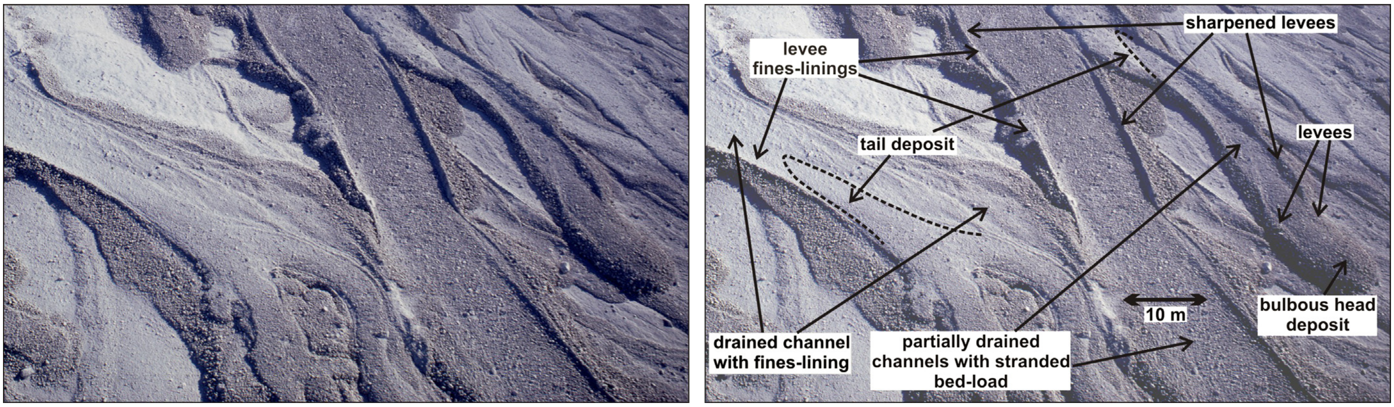

Fig. 1. Common features in deposits of natural dense granular flows. Pumiceous pyroclastic flow deposits at Mount St Helens, USA. The image shows virtually pristine deposits of the July 22nd 1980 eruption photographed on September 10th 1980. Deposit in the channels remained gas rich and deflated slowly during the weeks following emplacement (Hoblitt, 1985; Rowley et al., 1981). (Photo courtesy of Dan Miller and USGS.)

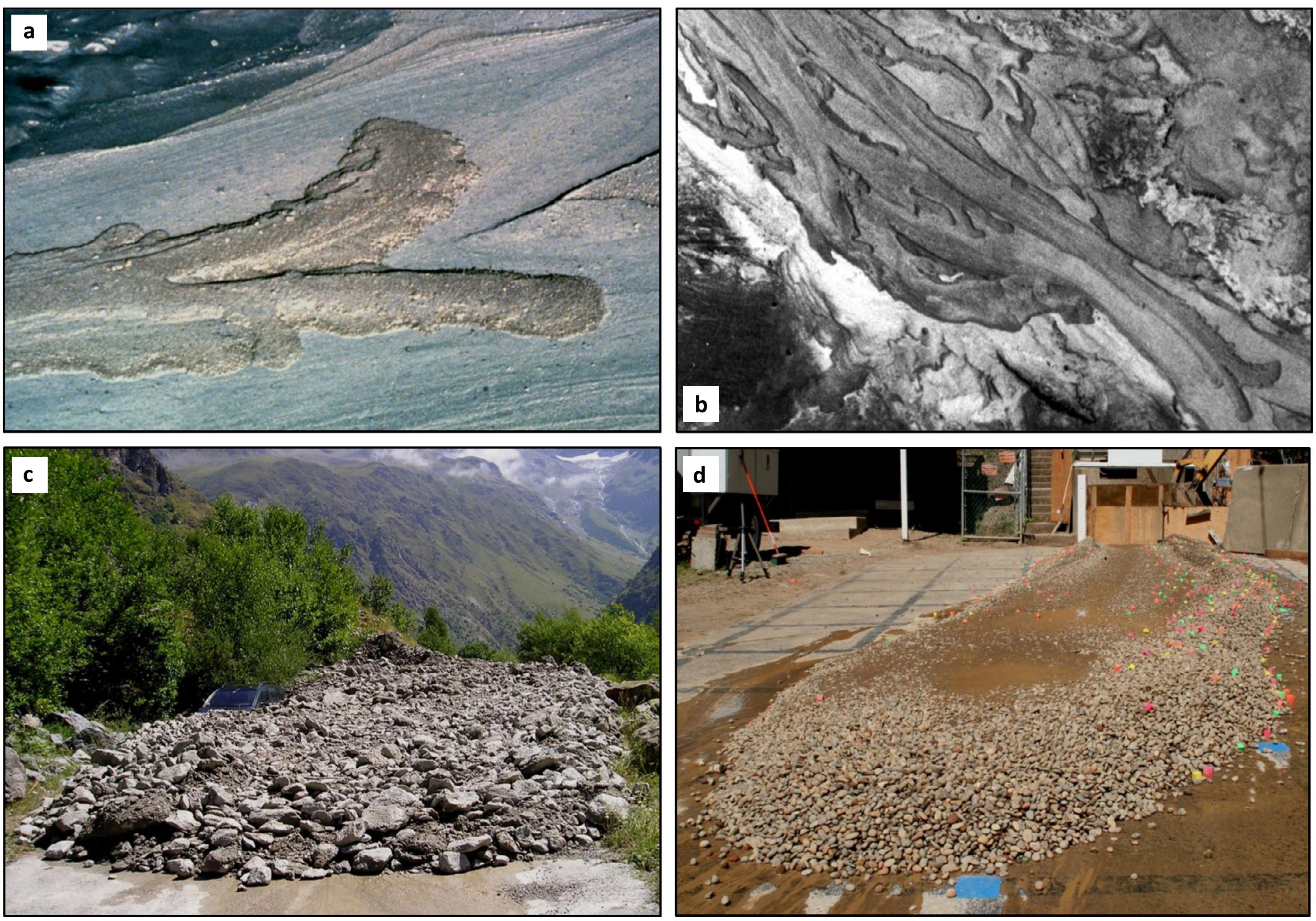

Fig. 2. Similarities in forms of diverse dense granular flow deposits. (a) and (b) Pumiceous pyroclastic flow deposits formed on July 22nd 1980 at Mount St Helens, USA (photos courtesy of USGS). The prominent bifurcating lobes rest upon thin channel fines linings of preceding flows. Less distinct beyond these features are pyroclastic flow deposits of earlier eruptions. Lengths of lobate deposits in the fields of view are respectively ∼50 m and ∼650 m. (c) Debris flow deposit at Rif du Sap, Réserve Naturelle Haute Vallée de la Séveraisse, French Alps. Water carrying some washed-out 'fines' has leaked from the deposit front; note the partly buried car. Deposit thickness ⩽1.3 m (photo courtesy of Christophe Ancey). (d) Experimental debris flow deposit, USGS flume, Oregon, USA (August 2009). Deposit runout is 12 m and maximum thickness ∼35 cm. Water carrying washed-out 'fines' has leaked from the deposit.

Figs. 1 and 2a–c). Thicknesses of unconfined deposits, typically 1–5 m, reflect dynamic flow-head thicknesses and levee (deposit) yield strengths (Jessop et al., 2012; Kokelaar and Branney, 1996). Closely analogous features are created in small- and large-scale experiments (Iverson et al., 2010; Iverson and Vallance, 2001; Johnson et al., 2012; Pouliquen and Vallance, 1999; Savage and Lun, 1988; Vallance and Savage, 2000) (Fig. 2d) and similar levee-forms arise from monodisperse dense flows, both experimentally (Felix and Thomas, 2004) and numerically (Mangeney et al., 2007).

Development of the characteristic sedimentary architecture of both natural and experimental polydisperse-flow deposits involves shear-related segregation of the particles, predominantly

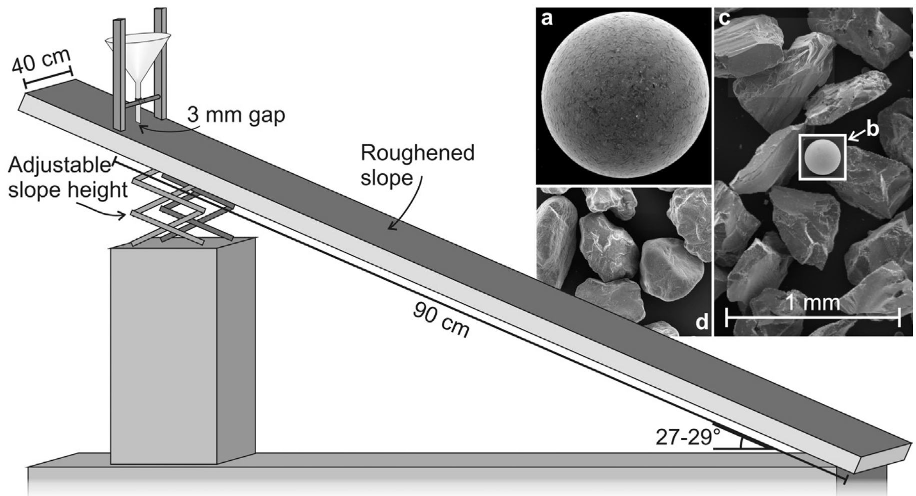

Fig. 3. Experimental rig and (inset) scanning electron microscope images of experimental particles shown at the same scale. (a) 0.75–1 mm ballotini, used to roughen the slope surface. (b) 150–250 μm ballotini used as fine particles in all experiments; ~2550 $kg\,m^{-3}$. (c) 300–425 μm angular carborundum; ~3210 $kg\,m^{-3}$. (d) 300–355 μm sub-angular and sub-rounded silicate (mostly quartz and feldspar) sand; ~2600 $kg\,m^{-3}$.

Table 1
Friction parameters. Angle of basal friction is that at which a light plastic ring (diameter 7 cm) containing a 0.5 cm layer of grains starts to slide. No account is taken of humidity, room temperature or static electrical charging, which were similar for these measurements, but unconstrained relative to the (normal room) conditions during the experimental flows. ± value is one standard deviation.

	Conical pile repose-slope angle (quasi-static internal friction); $n = 10$		Angle of Coulomb basal friction (initial slide angle); $n = 5$	
	Cone on substrate of 0.75–1 mm ballotini	Cone on substrate of 150–250 μm ballotini	Substrate of 0.75–1 mm ballotini	Substrate of 150–250 μm ballotini
Carborundum	$36.9 \pm 0.8°$	$35.3 \pm 1.2°$	$36.7 \pm 0.8°$	$33.3 \pm 0.7°$
Silicate sand	$33.3 \pm 0.8°$	$32.8 \pm 0.4°$	$35.6 \pm 1.3°$	$33.0 \pm 0.3°$
Fine ballotini	$22.8 \pm 0.9°$	$23.9 \pm 0.3°$	$24.5 \pm 0.2°$	$24.4 \pm 0.4°$

by 'kinetic sieving': downward percolation of the fines and consequent squeeze expulsion, or levering, upwards of the coarser particles (Vallance and Savage, 2000). This forms a flow-top layer dominated by relatively coarse particles, which pass over the front, where, on the ground, they frictionally interact to resist flow. The resistance causes slight bulbous elevation of the flow-head region, within which over-ridden coarse grains are re-segregated and advect sideways to form levees (Johnson et al., 2012). The fate of fine particles that reach the flow front has been considered only in simplified numerical treatments (Gray and Ancey, 2009; Johnson et al., 2012). Fine-grained deposit is common in channels from which material has largely drained away downstream (Figs. 1 and 2a, b) and it is usually interpreted as representing the fines-rich tail of a waning flow.

Here we show experimentally how self-organization of segregating cohesionless dry flows can facilitate runout, by creating, from the flow front, a stable leveed 'conduit' lined by low-friction fines. Such organization reduces frictional energy losses and in a geophysical context would also reduce flow–substrate permeability with potential to promote retention of gas and liquid pore pressures. We suggest that this is a factor in sustaining the fluidization and liquefaction that facilitate the considerable low-slope mobility of pyroclastic flows and debris flows.

2. Experimental method

The experiment rig is a plane surface 90 cm long and 40 cm wide, sloping at 27° or 29° (±0.1°) and roughened with close-packed, fixed, coarse (0.75–1 mm) spherical ballotini (Fig. 3). A glass funnel with (closable) outlet set to a uniform gap of 3 mm above the slope regulates steady discharge of mixtures of fine-grained spherical ballotini (150–250 μm; white or dyed blue or red) with either medium-grained angular carborundum (300–425 μm; natural brown SiC) or medium-grained sub-angular to sub-rounded silicate sand (300–355 μm; tan or dyed black). Measured frictional parameters show qualitatively the lower inter-particle friction of the fine grains relative to the carborundum and sand (Table 1); the experimental slope is steeper than the angle of repose of the fine ballotini and less steep than the repose angles of the coarser grains. Thin (~3–5 mm) and narrow (4–7 cm) flows advance at 3.0–4.4 $cm\,s^{-1}$ nearly steadily for up to 80 cm, limited only by the length of the rig or exhaustion of mixture at source. Particle tracking with high-speed digital photography (30 frames per second) shows channel-axial flow-top particles travel at twice the speed of the frontal advance. Slight mixture heterogeneity at the point of release, and minor flow surging, have no impact on the main outcomes. (Most experimental and natural flows tend spontaneously to develop surging; 'steady' as used in this paper acknowledges this and means absence of overall waxing (increasing) or waning (diminishing) flow.) All experiments are replicated; some measure of the actual variability of notionally identical experiments is given in Fig. 4, where plots of area inundated and distances of runout are given for repeated runs. Constant solids fraction and dense-frictional flow characterize all experiments. Carborundum particles form robust levees, but they tend to interlock such that small clusters of them cause unwanted branching and lateral fingering. Mixtures of ballotini and silicate sand flow more steadily. Instantaneous switching of the colour of the fines during steady discharge enables recognition of where and when fines deposit, and reveals shear profiles when the flow is arrested. To introduce an instantaneous flow-colour change of the fine particles, a transparent acetate-sheet cylinder resting upright and centrally

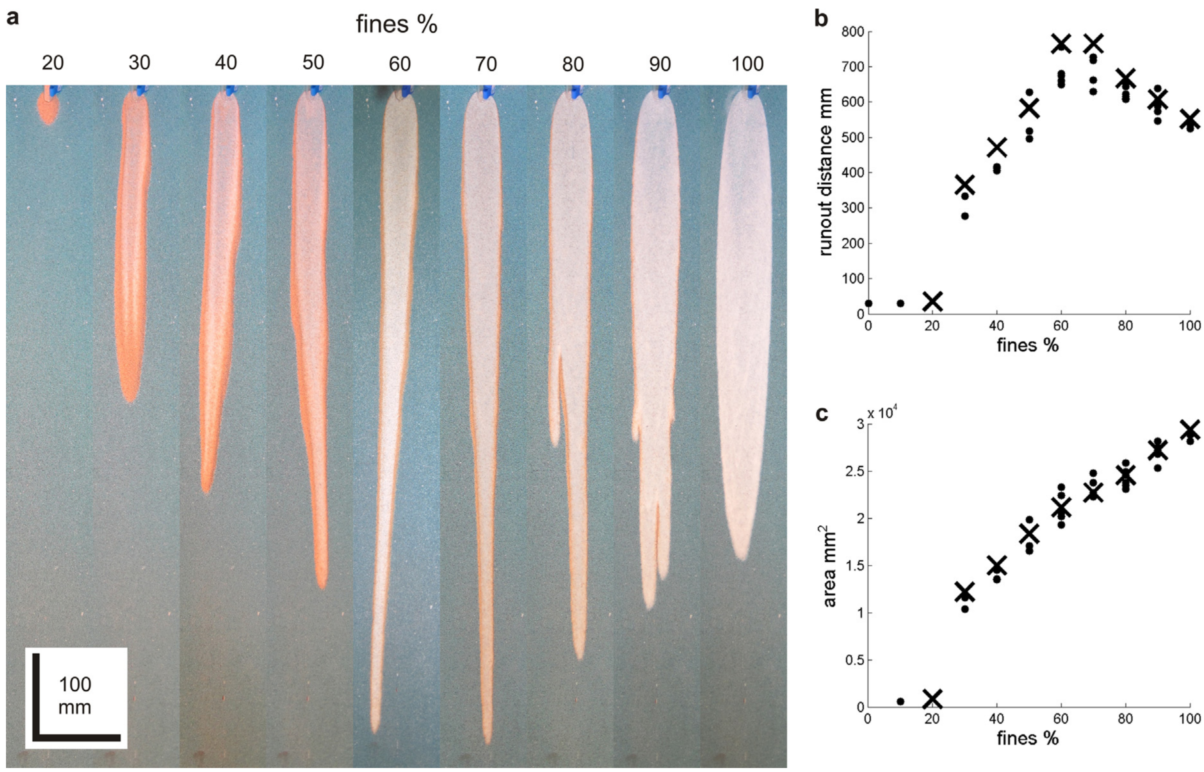

Fig. 4. Runout of frictional flows influenced by fine particles. (a) Orthogonal-to-slope views of the runout of 15 cm^3 charges of various mixtures of sand (tan/pink) and fine ballotini (white) steadily released from a glass funnel (top) 3 mm above a 29° roughened slope. (b) Runout distances of various sand–fine-ballotini mixtures. Plots as crosses are of the deposits shown in (a) and dots represent experimental runs not illustrated. (c) Runout areas ('footprint') of the various sand–fine-ballotini mixtures, measured using ImageJ processing.

in the funnel is used to form a compartment that contains the initial-colour charge and is surrounded by the second charge. The cylinder is removed to release the second charge as the first drains into the funnel neck; thus the colour change, which has no physical significance, is initially perpendicular to flow, sharp and released steadily. Flows are stopped instantaneously by raising the lower end of the runout board slightly to decrease the slope. Experiment documentation involves digital photographs, high-speed video at 300 frames per second, and impregnation of deposit with a low-viscosity acrylic resin followed by serial sectioning, polishing and high-resolution scanning.

3. Influence of fine-grained constituents on runout behaviour

Investigation of the influence of fines on the runout of frictional granular flows involves steady release onto a 29° roughened slope of separate 15 cm^3 charges with systematically different proportions of the fine ballotini and medium-grained sand (Fig. 4). The proportion of fine ballotini, which have significantly lower interparticle friction than the medium-grained sand (Table 1), influences flow behaviour. Mixtures with $\leqslant$20% fines do not flow on the 29° slope. Those with 30–50% fines rapidly segregate their medium-sand fraction into progressively smaller frictional levees and flow increasing distances. Mixtures with 60% and 70% fines produce narrow, straight-leveed, strongly channelized flows with maximal runout distances (Fig. 4a, b). Mixtures with $\geqslant$80% fines produce flows that increasingly spread laterally and travel less far; the sparse sand forms variable weak levees prone to fingering. The low-friction fine ballotini with sand absent spread most readily, inundate the greatest area, and thus have the greatest mobility overall (Fig. 4c). In contrast, maximum downstream runout occurs when there is an optimal balance between fines-enhanced mobility and coarse-frictional limitation of spreading. Initial mixtures need abundant fines to minimize effective friction and just sufficient coarse material to segregate and form levees that are adequately robust to restrict lateral spreading (in this case, 30–40% of the coarser component, medium sand). In all of the cases of mixed-material runout, a thin layer of fines remains between the levees (Fig. 4a). To assess the mechanism behind this behaviour we examined the grain-size segregation and fate of the fines at the flow front.

4. Development of fines-lined levees and channel

Flow of 20 vol.% carborundum and 80 vol.% fine ballotini on a roughened 27° slope illustrates flow-head particle segregation and trajectories, formation and evolution of a leveed channel, and channel draining (Fig. 5a–d; Appendix A, Supplementary material, Video 1; see also Johnson et al., 2012). As the front advances, coarse-grained carborundum segregates to the flow top and then advects directly over the flow front, where the flow over-rides on-axis grains and advects off-axis grains outward. At the 'back' of the bulbous flow head, levees form and stabilize the deposit width (levee outer limits), and linings of fine ballotini become exposed on the inner faces of the levees. Upstream of the flow head, levees channelize the flow such that its top is slightly lower than both the head and the levees. As the flow head advances, the levees propagate downslope at the same rate and the fines-lined channel provides a stable conduit for continuing throughput from upslope (Fig. 5a, e). Once mixture supply at source is cut, flow levels in the channel subside and coarse-particle-rich bands appear inboard of levees along active flow margins (Fig. 5b; Video 1). The bands reflect the inability of coarse particles to lock amidst the fine particles as the waning-flow top surface drops down the lining. Draining away of the flow tail reveals a uniform channel lining of fine particles with a few stranded coarse grains (Fig. 5d, g).

Levees 'sharpen' from the inside outwards as the flow wanes. Initially, inner levee slopes are less steep than outer slopes

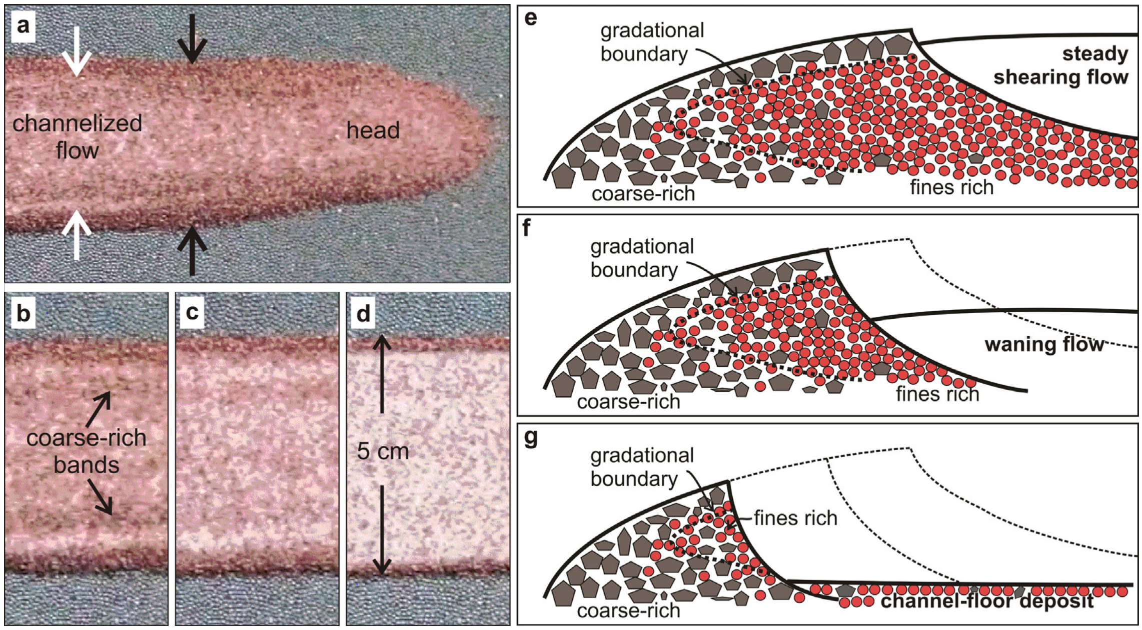

Fig. 5. Levee-forming flow and leveed-channel evolution. Images (a)–(d) are from 300 frames-per-second video (Video 1; blurred due to motion) of a flowing mixture of carborundum and fine ballotini (20:80 vol.%); slope 27° left to right; deposit width ~5 cm. (a) Levee fines linings have formed from the head simultaneously with the coarser-grained outer parts. The back of the flow head is located approximately between the black arrows; this is the position where (i) the flow top surface drops slightly in elevation from the bulbous head to the channelized flow, (ii) the white inner levee wall fines linings (white arrows) are first exposed, and (iii) the levee outer limits become parallel and essentially stable. (b) Early waning and draining of the channelized flow off the fines-lined levees; coarse-particle-rich bands form adjacent to the (white) exposed inner levee walls. At this stage, the visible fines inside the levee shear slowly downstream. (c) Further draining with levee sharpening. (d) Drained channel with remaining steep levee inner walls and thin channel-floor fines lining. (e)–(f) Schematic transverse cross sections illustrating fines lining persistently revealed in levee sharpening. (e) Behind the flow head the channel-flow top surface is slightly lower than the levees formed by the head. (f) During waning-stage draining flow the inner levee wall progressively collapses as fines shear down into the flow, making the levee narrower. (g) In a drained channel, further loss of inner levee material has rendered the wall steep and the levee thus sharpened. Throughout levee sharpening, a fines lining persists to reduce both flow-contact friction and deposition of large bed-load particles by locking.

(Fig. 5a, e). As the flow drains away the visible surface layer of the fines lining shears inwards and downstream, thus progressively cutting back the inner levee walls so that levees become narrower and more angular (Fig. 5c, d, f, g). Progressive levee 'sharpening' continuously exposes fine ballotini and shows that the levees have a fines-rich interior. The coarse-particle-rich bands that appear in the waning flow (Fig. 5b) derive from the upper parts of levees reworked in sharpening.

A flow arrested just as an abrupt fine-ballotini colour change reaches the front illustrates the architecture and evolution of levees and flow fronts (Fig. 6). Otherwise-identical fine ballotini switch abruptly at source from red to blue without perturbing the flow. As they flow downstream, the blue mixture shears over the red mixture. The arrested flow of Fig. 6 section 1, which is farthest from source, records the arrival of the second-colour mixture, with only a few blue particles on the top surface, and closer to source the second or blue mixture thickens progressively and exhibits a transverse concave colour-change boundary. The longitudinal profile of the colour change (compiled from serial sections) suggests an almost linear shear gradient that in the bulbous head becomes slightly convex upwards (Fig. 6b). The colour change remains sharp throughout, indicating little, if any, diffusive mixing during channelized flow.

A transverse section of the arrested flow just upstream of the flow head illustrates the formation of levees and fine-grained channel lining. In section 6 of Fig. 6a and c, the (blue) channel-flow top surface is slightly lower than the levee top (red). Furthermore, levees have fines-rich interiors with the coarser particles (brown) concentrated towards the outer margins and along the upper surfaces, as interpreted from the fines linings revealed during levee sharpening (Fig. 5b–g). Viewed from the outside levees appear coarse-grained, but levee interiors actually contain large proportions of fine-grained ballotini. Towards outer levee margins, coarse particles are sufficiently abundant to form a 3-dimensional framework, but on the inside they are few and no coarse framework exists. Levee sharpening reflects such absence of a coarse framework, where low-friction fines are unsupported and prone to shearing downstream. Red fine ballotini fill spaces between grains of the roughened bed and partially smooth the channel floor (Fig. 6cii). This basal lining of fine ballotini reduces basal friction and reduces potential for entrapment and deposition of large particles. To summarize, fines-lined leveed channels form from the flow head with an internal structure that places low-friction fine-grained deposit at the contacts of the flow.

5. Channel stability

To assess the stability of fines-lined leveed channels formed from the flow head, we arrested runout of the red-to-blue mixture experiment (Section 4) when the second-colour (blue) mixture had passed steadily along a channel formed of the first-colour mixture (red) and reached the flow front (Fig. 7a). Despite the transport of blue flow between early-formed red levees, there is practically no contamination of the blue with the red ballotini (Fig. 7e). Furthermore, as the flow surface subsides during waning-stage draining flow, blue tail mixtures remain sharply delimited by red fine-ballotini-lined levees (Fig. 7b, c, d). On the basis of this evidence, we conclude that levees with fines linings can endure and form stable efficient conduits beneath steady channel flows.

6. Flow and accretion of granular flow deposit: a new model

Our experiments illustrate a previously poorly known process in which large and small particles segregate and advect within the flow head to deposit relatively coarse-grained levees with fine-grained channel linings that together govern the motion and

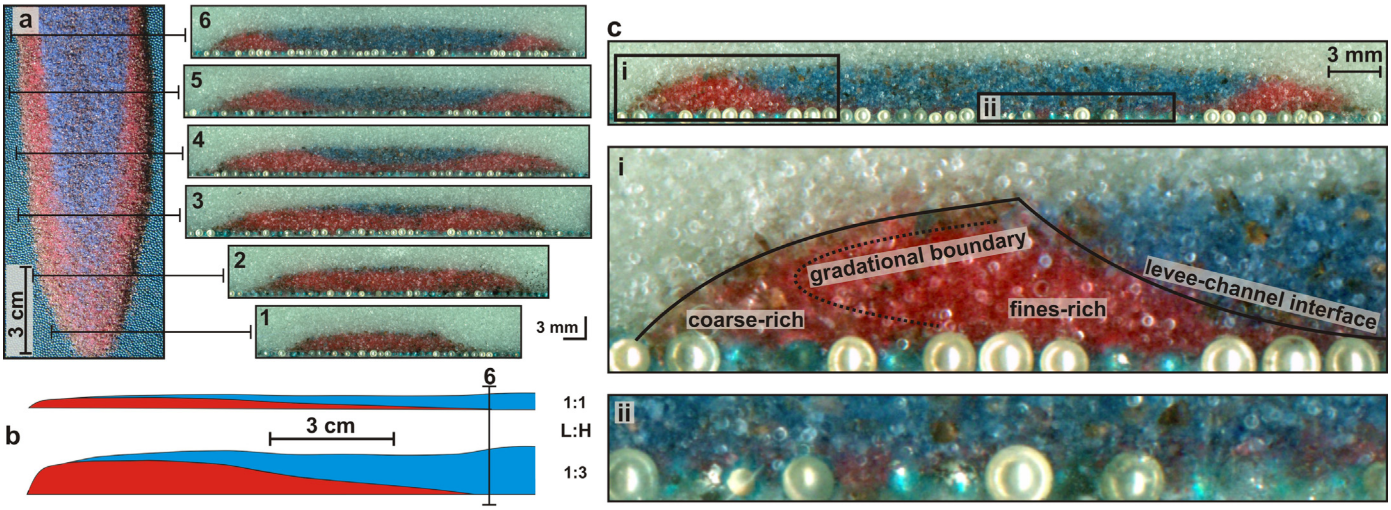

Fig. 6. Arrested flow of carborundum and fine ballotini (30:70 vol.%; slope 27°) with colour-change boundary and serial sections of the resin-impregnated deposit. (a) Deposit with serial sections. The transition from head to channelized flow, where the levees stabilize and the flow top surface drops slightly, is in the vicinity of section 5. (b) Longitudinal profiles of arrested flow, to scale and vertically exaggerated (×3), showing the colour-change boundary according to section measurements. The profile records a linear channel-flow shear gradient, with the colour change slightly deflected upwards within the (slightly) bulbous head. Also shown is a surge-wave arrested near the location of section 6. (c) Details of section 6 showing slight lowering of the channel flow (blue) relative to the just-formed levees (mainly red); the colour-change boundary here has become the stable levee–channel-flow contact. Carborundum grains are brown and also appear as fuzzy brown patches where they are out of focus just behind the scanned cut face of the section; the large substrate ballotini are green, or pearl where cut. Red fine ballotini infill and partially smooth-out the substrate roughness of the channel floor; they form a lining more or less continuous with the just-formed red levees.

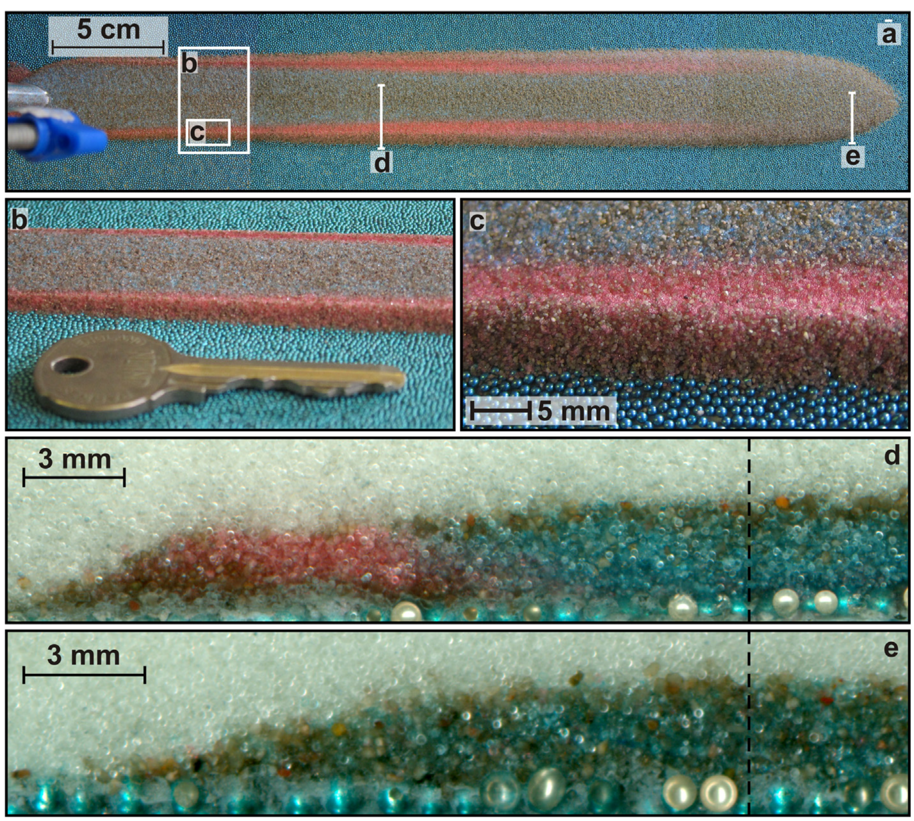

Fig. 7. Arrested flow of sand and ballotini (30:70; slope 29°) with colour change of the fines. (a) The coarser material, concentrated towards the flow front, is black-dyed sand (mostly 'dirty' browns in section with a few cream or orange). The mixture, steadily released, initially had red fines and then blue. Details in (b)–(e) are located in (a). (b) and (c) Partly drained channel with blue flow-tail deposit resting sharply delimited upon red fines-lining deposit. (d) Coarse grains segregated to the top in the channel flow. Early (red) fines are absent in the middle of the channel floor. Dashed line marks central axis. (e) At the front coarse particles occur throughout the flow thickness, having been over-run and here arrested as they re-segregated ultimately to concentrate in the levees. Close examination reveals no more than 2 or 3 red fine ballotini, confirming the stability of the red-lined channel upstream.

distribution of the subsequent channelized flow (Fig. 8a). Importantly, this process involves not only deposition of low-frictional fine grains from the flow head to form a lining deposit between the levees, but it also involves advection of fines to the lowermost part of the channel flow, thereby ensuring that the less-frictional fine-grained component shears across itself. Notionally the channel

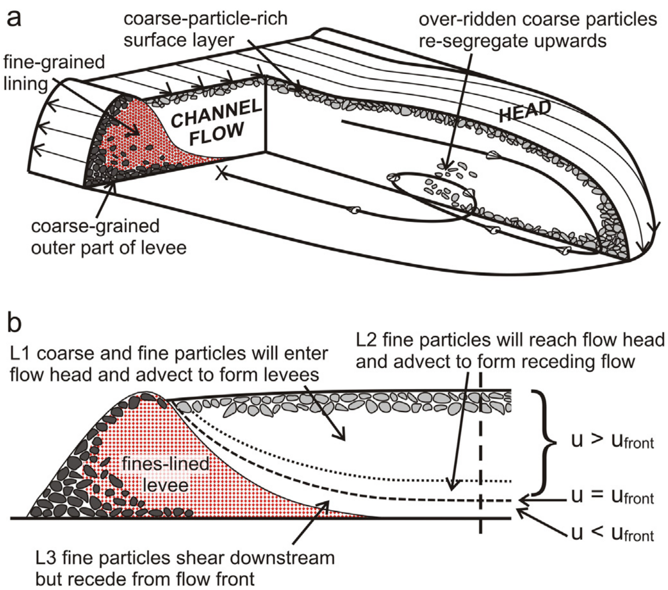

Fig. 8. Particle segregation and deposition of levees with fines linings related to channel flow. (a) Simultaneous segregation and deposition of coarse and fine particles from the back of the flow head, in the vicinity of X, with formation of a leveed channel with fine-grained lining. Arrows indicate coarse-particle trajectories in the reference frame of the advancing flow front (after Johnson et al., 2012). A schematic helical trajectory of an off-axis coarse particle within the segregating head cell is shown. As the coarse particle arrives at the front it is over-ridden and then, at the base of the head, moves back relative to the advancing front. As the flow shears over it, the coarse particle is re-segregated upwards and eventually reaches a level where the streamwise shear is faster than the front so that it advances towards the front again. Since material is continuously supplied to the head predominantly along the flow axis, the re-segregated coarse particle is forced to advect laterally. (In the reference frame of the ground, no particles shear upstream.) (b) Section of levee and channel flow behind the flow head, showing three notional channel-flow layers, L1–L3, within which particles have different destinies; the relative thicknesses of the three layers will vary according to vertical and horizontal shear profiles and are not necessarily to scale. The dashed vertical line represents the flow central axis. In steady flow there is a flux balance wherein the coarse and fine particles of layer L1 will form the leveed channel with fines lining, and flow layer L2 will reach the head and advect to form the basal layer L3, which comprises particles receding from the advancing front. This flow self-organization ensures that the flow-against-deposit contact is within the finest particles, thus reducing frictional energy loss.

flow has three layers, L1–L3 in Fig. 8b. The top layer, L1, includes segregated coarse particles in its upper part and advects towards the flow front and then laterally to form the leveed channel with fines linings. The basal flow layer, L3, comprises fine-grained particles that shear downstream in the channel more slowly than the advance of the flow front, thus receding from the front. This layer, L3, must be fed by another layer, L2, which comprises mainly fine-grained particles that advect towards the front and then, from the back of the head, into the underlying receding layer; the notional surface between L2 and L3 is where all grains shear downstream at the same rate as the frontal advance. Thus the granular mixture supplied to the flow head continually builds a stable flow conduit bounded by levees and maintains a low-frictional shearing layer of fine-grained particles moving across fine-grained deposit. This flow self-organization reduces frictional dissipation of momentum and acts to prevent deposition of large particles, thus facilitating flow and enhancing runout.

Formerly steady slow-frictional flows wane and thin as the supply of the granular mixture is exhausted. As the channel-flow top initially subsides, the exposed fines that line the levees tend to shear downstream, causing levee sharpening and adding coarse particles to the flow top. As waning proceeds, the lowermost part of the channel flow, layer L3 of Fig. 8b, begins to deposit from the bottom upwards while material above shears downstream. Next, as the channel flow continues to thin, what had been layer L2 accretes farther downstream and finally layer L1, carrying the coarse grains, accretes farther yet downstream. The surface layer consisting largely of coarse grains freezes progressively sourcewards; it tends to jam up as it accretes upstream from the arrested front, so that surface motion ceases like an upslope-migrating shock feature. Thus the original vertically inverse-graded flow smears into longitudinally graded medial deposit that has greater proportions of coarse grains downstream than upstream. Hence, fines-lined channels that acted as stable conduits for protracted phases of nearly steady flow are likely to contain waning-flow, fine-grained tail deposits that grade longitudinally downstream into closely packed coarse material. This sedimentary architecture occurs in nature (e.g. Fig. 1) and general applicability of the self-organization and channel fines-lining process is considered next.

7. Application to natural granular mass flows

Despite notable differences, natural granular mass flows such as debris flows and pyroclastic flows appear to segregate their coarsest material into levees and their finer fractions into less-frictional channel linings by processes kinematically similar to those we delineate in our experiments. Such self-organization in natural flows requires two key conditions to be met. First, the flows must contain sufficient coarse grains and be moving sufficiently slowly so that segregation processes can predominate. Flows on slopes too steep or too close to a rapid-inertial reach will be too energetic, such that collisional, diffusive-mixing processes will predominate rather than frictional-flow processes. In chute-flow experiments with bidisperse granular mixtures Vallance and Savage (2000) show that slow-frictional flow optimizes size segregation, which is critical to the flow self-organization envisioned in this work. Second, the fine-grained fraction of the flow must be less resistant to flow than coarser-grained fractions. In our experiments the fine-grained fraction has less resistance to flow than the coarse-grained fraction primarily because the fine ballotini are round. In contrast, fines-rich fractions in natural flows can have less resistance to flow because they act as lubricants. Lubrication requires fluid to be dynamically over-pressured, that is, effective fluid pressure p is greater than $\rho_{fluid}gh$ and perhaps approaching total load $\rho_{bulk}gh$, where ρ is density, g is gravitational acceleration, and h is depth from the surface (Iverson, 1997). Such non-equilibrium pore-fluid pressure in interiors of debris flows and pyroclastic flows can spread diffusively and reduce net energy dissipation by reducing grain-contact stresses and transferring shear stress to the fluid phase (Druitt et al., 2007; Iverson, 1997; Iverson and Vallance, 2001). As p approaches $\rho_{bulk}gh$ the mixture will flow freely on very low slopes. Fluid overpressure is likely to be most strongly developed in fines-rich fractions, because neither the liquefying agent in the case of debris flow (water with suspended silt and/or mud) nor the gaseous fluidizing agent in the case of pyroclastic flow ('dusty' gas) can readily escape the sediment–fluid mixture owing to its low permeability. In uniform-size close-packed frameworks permeability diminishes as a function of particle diameter squared; in polydisperse frameworks permeability also diminishes as small particles fill spaces between larger grains. Once over-pressured, fines-rich parts of flows and channel linings are apt to remain so for as long as, or longer than, it takes the catastrophic flow to come to rest, because their permeability (and hence hydraulic diffusivity) is very small (Beard and Weyl, 1973; Major, 2000; Major and Iverson, 1999; Roche et al., 2004). Thus we suggest that lubrication in flow-contact zones of debris flows and pyroclastic flows can be enhanced by flow-head segregation and formation of fines-lined, leveed channels kinematically similar to our experiments, and that this promotes low-slope runout in nature.

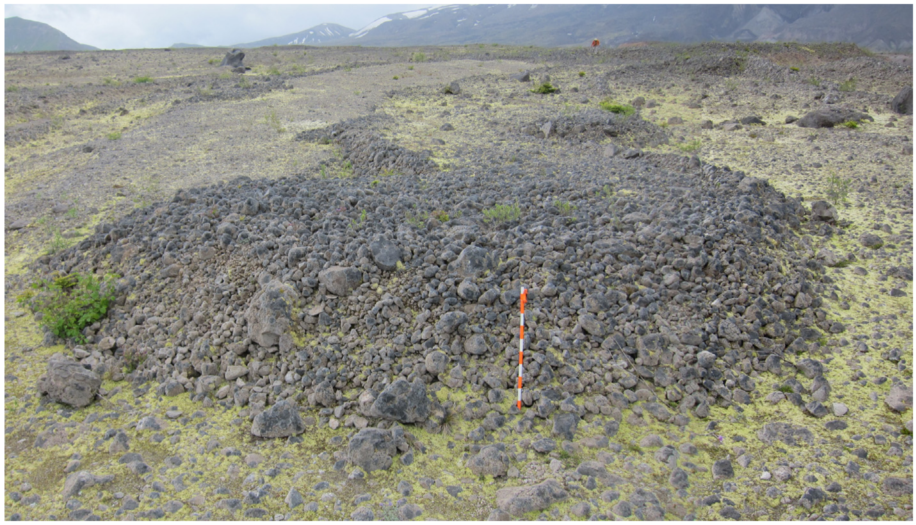

Fig. 9. Lobe of July 1980 pumiceous pyroclastic flow deposit on the Pumice Plain at Mount St Helens (photographed in 2010). The flow-head deposit shows characteristic bulbous form, about 1 m thick (pole is 1 m), while the levees behind maintain the same form and grain-size characteristics as they bound channel-flow deposit for >250 m into the distance. Sparse metre-scale boulders between the levees (middle distance) are a stranded 'bed-load' of relatively dense rock presumed to have rolled and/or slid along the channel driven and partially supported by the channel-flow mixture. The substrate slope is approximately 4°.

8. Distinctive sedimentary architecture

The granular flow self-organization revealed in our experiments leads to distinctive deposit features. Steady frictional polydisperse flows form stable deposit from the flow head and if the material supply to the head is compositionally unchanging they produce lined levees without longitudinal grain-size grading. Small changes of slope cause variation of frontal advance of frictional flows, entailing slight changes only in the developed lobe and levee size and shape (Jessop et al., 2012).

Levees formed from dense polydisperse flows are not simply 'coarse-grained', but have internal particle-distribution grading, coarsening outwards and upwards. This condition is recorded in large-scale debris-flow experiments (Johnson et al., 2012, Figs. 14 and 15) and in nature (Wilson and Head, 1981, Fig. 30; Kim and Lowe, 2004, Figs. 6 and 12). Because the segregation places coarse material in the outermost parts of levees, with finer particles on the inside, flows with a small proportion of coarse material will tend to produce weak levees prone to sharpening by collapse during channel draining. Large proportions of coarse particles will produce more robust levees with relatively extensive frictionally locked frameworks (see Fig. 4).

The longitudinal deposit uniformity that distinguishes flow self-organization with 'conduit' formation from the flow head occurs in small-volume pyroclastic flow deposits emplaced after May 18th, 1980, at Mount St Helens (Fig. 9). Lobes and levees there showed no significant change of pumice-block size with distances across the depositional plain measured in kilometres (Rowley et al., 1981), largely on slopes of 5°–2°. Similarly, 450 m-long levees of the 1984 debris flow on the South Dolomite alluvial fan, California (Kim and Lowe, 2004), show streamwise-uniform granulometry on slopes diminishing to 3°, as do distal pumiceous levees of the Lascar 1993 pyroclastic flow deposits (Chile) on slopes down to 6° (Jessop et al., 2012). Natural conduit-forming flows of the type explained here evidently can have considerable runout on the low slopes of depositional fans and aprons around volcanoes and mountains.

The longitudinal deposit uniformity that results from steadily segregating conduit-forming flows contrasts with deposits known to result from highly unsteady rapid-collisional flows that quickly deposit in depletive reaches (lower slopes). These segregate grain sizes longitudinally to cause pronounced downstream changes of the flow and deposit composition (e.g. Lube et al., 2007), as do the waning-phase draining flows trapped in leveed channels (see Section 6). The latter highly unsteady flow types are analogous to lock-release and collapsing-pile experimental flows and their deposits (e.g. Iverson et al., 2004; Lube et al., 2011; Moro et al., 2010; Phillips et al., 2006; Roche, 2012; Roche et al., 2005), which differ considerably from our experiments.

9. Conclusions

Flowing dense mixtures of granular materials spread differently according to differing proportions of the components. In experiments, maximum runout distance is attained with mixtures containing 30–40% of the coarser and more frictional component (sand), just sufficient to segregate and form levees that are adequately robust to restrict the spreading attributable to the low-friction fines. Maximum area of inundation, the flow footprint, is attained when coarse frictional grains are absent. Not only is coarse-particle segregation an important control on flow behaviour, but also fines segregation and advection to channel linings affects flow mobility. Critical particle segregation occurs in the flow head. Flows create their own stable 'conduit' entirely from the front and flow self-organization ensures that low-friction fines at the base of the segregated channel flow shear over fine-grained substrate in the channel, thus reducing frictional energy losses.

Levees formed from dense polydisperse flows are not simply 'coarse-grained', but are internally graded, coarsening outwards and upwards. Flows with a small proportion of coarse material cannot produce robust levees and will be prone to sharpening by collapse during channel draining. Provided the material supply is unchanging, steady frictional flows produce leveed channels that have no longitudinal grain-size variation. This is in contrast to rapid-collisional flows, the deposits of which tend to be longitudinally graded.

The granular flow self-organization that produces fine-grained channel linings can be important in facilitating long runout of geophysical flows on the low slopes (few degrees) of depositional fans and aprons around volcanoes and mountains. Fine-grained flow-contact zones not only reduce frictional energy losses but also can reduce flow–substrate permeability so as to enhance retention of the pore-fluid pressure that confers considerable low-slope mobility on pyroclastic flows and debris flows.

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Appendix A. Supplementary material

Video 1 related to this article can be found online at http://dx.doi.org/10.1016/j.epsl.2013.10.043.

References

Beard, D.C., Weyl, P.K., 1973. Influence of texture on porosity and permeability of unconsolidated sand. Am. Assoc. Pet. Geol. Bull. 57, 349–369.

Branney, M.J., Kokelaar, P., 2002. Pyroclastic density currents and the sedimentation of ignimbrites. Mem. Geol. Soc. Lond. 27.

Druitt, T.H., Avard, G., Bruni, G., Lettieri, P., Maez, F., 2007. Gas retention in fine-grained pyroclastic flow materials at high temperatures. Bull. Volcanol. 69, 881–901.

Felix, G., Thomas, N., 2004. Relation between dry granular flow regimes and morphology of deposits: formation of levees in pyroclastic deposits. Earth Planet. Sci. Lett. 221, 197–213.

Gray, J.M.N.T., Ancey, C., 2009. Segregation, recirculation and deposition of coarse particles near two-dimensional avalanche fronts. J. Fluid Mech. 629, 387–423.

Hoblitt, R.P., 1985. Observations of the eruptions of July 22 and August 7, 1980, at Mount St. Helens, Washington. Geological Survey Professional Paper 1335.

Hsu, K.J., 1975. Catastrophic debris streams (sturzstroms) generated by rockfalls. Geol. Soc. Am. Bull. 86, 129–140.

Iverson, R.M., 1997. The physics of debris flows. Rev. Geophys. 35, 245–296.

Iverson, R.M., Vallance, J.W., 2001. New views of granular mass flows. Geology 29, 115–118.

Iverson, R.M., Logan, M., Denlinger, R.P., 2004. Granular avalanches across irregular three-dimensional terrain: 2. Experimental tests. J. Geophys. Res., Earth Surf. 109. F01015.

Iverson, R.M., Logan, M., LaHusen, R.G., Berti, M., 2010. The perfect debris flow? Aggregated results from 28 large-scale experiments. J. Geophys. Res., Earth Surf. 115. F03005.

Jessop, D.E., Kelfoun, K., Labazuy, P., Mangeney, A., Roche, O., Tillier, J.L., Trouillet, M., Thibault, G., 2012. LiDAR derived morphology of the 1993 Lascar pyroclastic flow deposits, and implication for flow dynamics and rheology. J. Volcanol. Geotherm. Res. 245, 81–97.

Johnson, C.G., Kokelaar, B.P., Iverson, R.M., Logan, M., LaHusen, R.G., Gray, J.M.N.T., 2012. Grain-size segregation and levee formation in geophysical mass flows. J. Geophys. Res., Earth Surf. 117. F01032.

Kim, B.C., Lowe, D.R., 2004. Depositional processes of the gravelly debris flow deposits, South Dolomite alluvial fan, Owens Valley, California. Geosci. J. 8, 153–170.

Kokelaar, P., Branney, M.J., 1996. On pyroclastic flow emplacement – Comment. J. Geophys. Res., Solid Earth 101, 5653–5655.

Linares-Guerrero, E., Goujon, C., Zenit, R., 2007. Increased mobility of bidisperse granular avalanches. J. Fluid Mech. 593, 475–504.

Lube, G., Cronin, S.J., Platz, T., Freundt, A., Procter, J.N., Henderson, C., Sheridan, M.F., 2007. Flow and deposition of pyroclastic granular flows: A type example from the 1975 Ngauruhoe eruption, New Zealand. J. Volcanol. Geotherm. Res. 161, 165–186.

Lube, G., Huppert, H.E., Sparks, R.S.J., Freundt, A., 2011. Granular column collapses down rough, inclined channels. J. Fluid Mech. 675, 347–368.

Major, J.J., 2000. Gravity-driven consolidation of granular slurries – Implications for debris-flow deposition and deposit characteristics. J. Sediment. Res. 70, 64–83.

Major, J.J., Iverson, R.M., 1999. Debris-flow deposition: Effects of pore-fluid pressure and friction concentrated at flow margins. Geol. Soc. Am. Bull. 111, 1424–1434.

Mangeney, A., Bouchut, F., Thomas, N., Vilotte, J.P., Bristeau, M.O., 2007. Numerical modeling of self-channeling granular flows and of their levee-channel deposits. J. Geophys. Res., Earth Surf. 112. F02017.

Midi, G.D.R., 2004. On dense granular flows. Eur. Phys. J. E, Soft Matter 14, 341–365.

Moro, F., Faug, T., Bellot, H., Ousset, F., 2010. Large mobility of dry snow avalanches: Insights from small-scale laboratory tests on granular avalanches of bidisperse materials. Cold Reg. Sci. Technol. 62, 55–66.

Phillips, J.C., Hogg, A.J., Kerswell, R.R., Thomas, N.H., 2006. Enhanced mobility of granular mixtures of fine and coarse particles. Earth Planet. Sci. Lett. 246, 466–480.

Pouliquen, O., Vallance, J.W., 1999. Segregation induced instabilities of granular fronts. Chaos 9, 621–630.

Roche, O., 2012. Depositional processes and gas pore pressure in pyroclastic flows: an experimental perspective. Bull. Volcanol. 74, 1807–1820.

Roche, O., Gilbertson, M.A., Phillips, J.C., Sparks, R.S.J., 2004. Experimental study of gas-fluidized granular flows with implications for pyroclastic flow emplacement. J. Geophys. Res., Solid Earth 109, 1–14. B10201.

Roche, O., Gilbertson, M.A., Phillips, J.C., Sparks, R.S.J., 2005. Inviscid behaviour of fines-rich pyroclastic flows inferred from experiments on gas–particle mixtures. Earth Planet. Sci. Lett. 240, 401–414.

Rowley, P.D., Kuntz, M.A., McLeod, N.S., 1981. Pyroclastic flow deposits. In: Lipman, P.W., Mullineaux, D.R. (Eds.), The 1980 Eruption of Mount St. Helens, Washington. University of Washington Press, pp. 489–512. U.S. Geological Survey, Professional Paper 1250.

Savage, S.B., 1984. The mechanics of rapid granular flows. Adv. Appl. Mech. 24, 289–366.

Savage, S.B., Lun, C.K.K., 1988. Particle-size segregation in inclined chute flow of dry cohesionless granular solids. J. Fluid Mech. 189, 311–335.

Vallance, J.W., Savage, S.B., 2000. Particle segregation in granular flows down chutes. In: Rosato, A.D., Blackmore, D.L. (Eds.), IUATM Symposium on Segregation in Granular Flows. Kluwer Academic Publishers, Boston, MA, pp. 31–52.

Wilson, L., Head, J.W., 1981. Morphology and rheology of pyroclastic flows and their deposits, and guidelines for future observation. In: Lipman, P.W., Mullineaux, D.R. (Eds.), The 1980 Eruption of Mount St. Helens, Washington. University of Washington Press, pp. 513–524. U.S. Geological Survey, Professional Paper 1250.