Instruments and Methods

Granulometric investigations of snow avalanches

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ABSTRACT. Avalanche deposits consist of rounded granules composed of aggregates of snow and ice particles. The size of the granules is related to vertical shear gradients within the flow; studying the granule-size distribution may be useful in understanding the flow and stopping of avalanches. We applied a sediment-size sampling method to measure snow granule-size distributions at different depositional environments on two dry and two wet avalanche deposits at three field sites. The granule-size distributions are approximately log-normal, similar to many natural sediment deposits. The median granule size in the wet and dry avalanches varies between 65 and 162 mm. Wet avalanches tend to produce more large granules than dry avalanches, indicating both smaller flow velocities and near-surface shear gradients. Granule size is similar in frontal lobes and levee deposits, suggesting that levee formation occurs independently of the size segregation at the avalanche front.

1. INTRODUCTION

Snow avalanche deposits are typically comprised of solid, rounded aggregates of ice particles (called granules in this paper) formed during the rapid shear flow within the dense avalanche core (Fig. 1). The size of the granules varies from large snow boulders or blocks (diameters $d > 200$ mm) to clumps and clods ($d \sim 100$ mm) to smaller particle aggregates ($d > 50$ mm). Immediately following deposition, if the air temperature is low enough, the differently sized granules sinter together, forming a hard snow deposit. The deposits vary in height, depending on the local topography, and contain large-scale flow features such as levees and frontal lobes.

An understanding of the relationship between snow granule size and the internal flow dynamics is a long-standing topic of interest in avalanche science. The ubiquitous presence of snow granules on avalanche deposits, and their variability from deposit to deposit, suggests there may be a relationship between the size of the granules and the properties of the avalanche in which they formed. Avalanche-flow models are based on granular mechanics (Salm and Gubler, 1985; Norem and others, 1987; Salm, 1993), and we therefore require some understanding of (1) how the granule size influences the evolution of shear rates within the avalanche core (Dent, 1993; Dent and others, 1998; Kern and others, 2009) and (2) the collisional energy dissipation (Gubler, 1987; Bartelt and others, 2006; Buser and Bartelt, 2006). The size distribution is critically important in the vertical sorting process, which is often invoked to describe the dynamics of the avalanche head and the formation of flow levees (Gray and Thornton, 2005). The granules can exert local instantaneous impact forces that are larger than would be expected from the mean flow (McClung and Schaerer, 1985; Sovilla and others, 2008) so an understanding of granule formation is relevant for civil-engineering and hazard-mapping guidelines that require the definition of the impact pressure produced by an avalanche. Jomelli and Bertran (2001), in their work to characterize the general sedimentology of wet snow avalanche deposits in the French Alps, reported snow granule-size data; however, they had no data on the properties of the flows and did not report the distribution of granule sizes in the deposits.

Here we describe the application of a surface grain-size sampling method that allows rapid characterization of the size distribution of granules in an avalanche run-out zone. Although the variation in granule size with depth is also of interest (e.g. Kern, 2000), there is rarely sufficient time to excavate large pits, which requires the use of construction machinery in frozen avalanche deposits under hazardous conditions. We therefore focus on characterizing the large-scale surface features of the deposit, such as the leading edge of the avalanche or the lateral levees. Thus, we measure the size of the coarse granules that have been created in the flow, and transported vertically to the surface as they flow downstream.

2. FIELD OBSERVATIONS

Field investigations require working on avalanche-endangered slopes, so it is necessary to use a method that can rapidly characterize granule-size distribution under adverse conditions, such as poor lighting or deposition of snow from the powder cloud on top of the deposit. To measure granule size, Jomelli and Bertran (2001) measured the three orthogonal axes on 40 granules. This method is time-consuming, so we applied a similar method introduced by Wolman (1954), which has been extensively used to rapidly characterize the grain size on the surface of similar coarse sedimentary deposits in gravel-bed rivers (e.g. Church and others, 1987). In this method, a grid is established on the deposit surface and the sediment granules directly beneath the gridpoints are measured. Granule diameters are typically grouped into size-class bins in a geometric progression as $2^{1/2}$ with the diameter d (mm) taken, by convention, to be the intermediate length of the three orthogonal axes or by using an aluminum template with square holes machined into it (Fig. 1a). Using the template, the granule is rotated and compared to the size of the openings in the template, and the
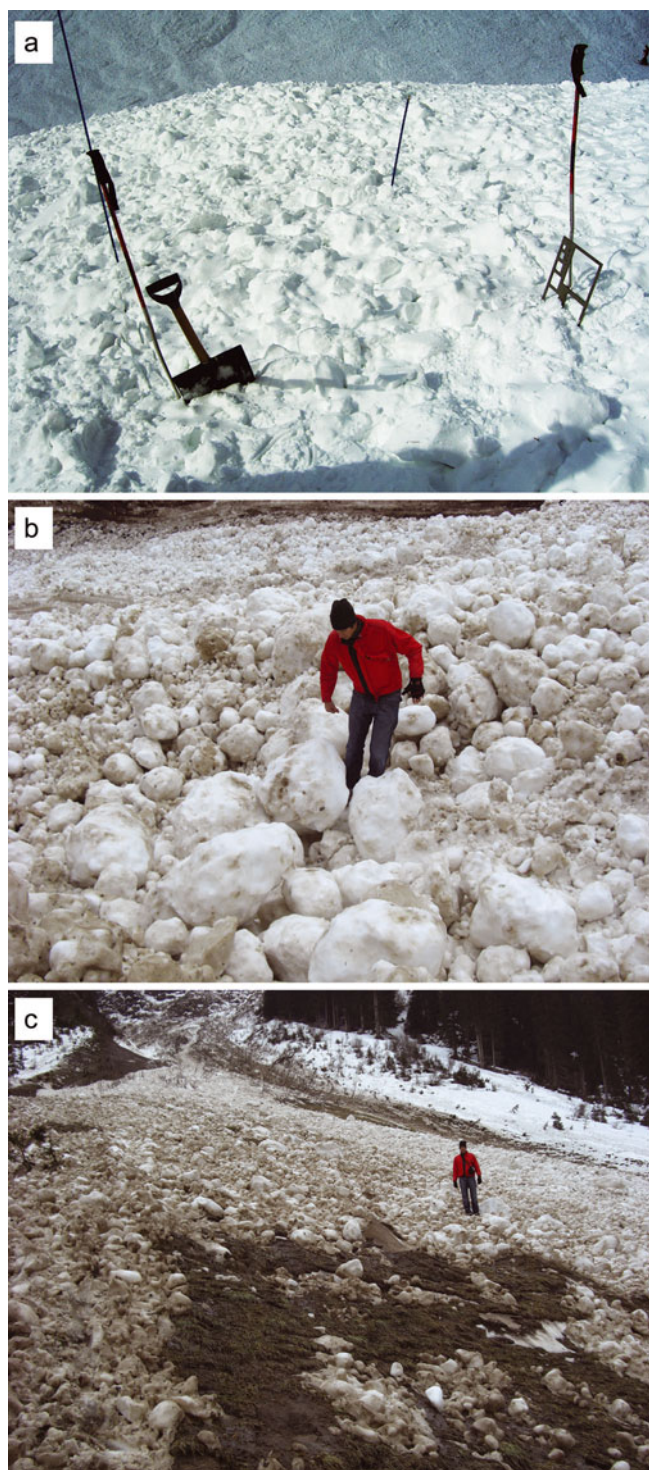
Fig. 1. Examples of snow avalanche deposits. (a) Depositional lobe front from Vallée de la Sionne avalanche No. 816, sample S1; the template for measurement is on the right-hand side. (b) Levee deposit from Gatschiefer, sample S10. (c) Channel deposit in the tail region of the Grünbödeli deposit, sample S7.

size category is defined as between the smallest opening through which the granule may pass and the next size of opening. Care is taken to avoid abrading the granule. Due to time constraints, we generally did not lay out a grid using a tape measure, using instead an approximate spacing by pacing and selecting the point lying underneath the toe or finger of the person collecting the samples. This is commonly done in sampling river-bed gravel sediments. We measured at least 100 points for each sample, which is considered

sufficient to characterize the median size of the deposits. The individual granules were generally sintered together at the grain contacts with others, but it was easy to separate individual granules from their neighbors. The granules can be manually removed even when a matrix of much smaller particles (arising from the deposition of the powder cloud) is present in the surface layer.

Other granule-size sampling methods, such as bulk sampling and sieving (e.g. Church and others, 1987) involve mechanical separation of the granules (and many more granules would be needed). Also, the mechanical sieving commonly used needs to be performed manually to avoid abrasive wear and fracture of the quite brittle granules. However, once an appropriate method is available, it can be used as a basis for calibrating even more rapid methods such as photographic analysis of the deposits (Butler and others, 2001), perhaps using near-infrared images to make the granules more distinct (Matzl and Schneebeli, 2006) for avalanche deposits that are not covered with fine snow deposited from the powder cloud.

We performed ten measurements on four different avalanche deposits. Two of the avalanches (VdlS No. 816, samples S1–S3 and VdlS No. 9167, samples S4–S6) were released artificially using explosives at the instrumented Vallée de la Sionne (VdlS) test site (Sovilla and others, 2006). Both these avalanches can be considered dry flowing avalanches that generated a turbulent powder cloud, which obstructed the view of the granular core in motion. However, data regarding size and extent, flow velocities and heights (Sovilla and others, 2006, 2008), as well as internal-shear deformations (Kern and others, 2009), are available (Table 1). The other two avalanches, Grünbödeli (samples S7 and S8) and Gatschiefer (samples S9 and S10), were large wet snow avalanches that occurred during late April 2008 in the Davos–Klosters region, Switzerland. Aerial laser scanning was performed to measure the extent, height distribution and other deposition features of these immense avalanches (Table 1). The Gatschiefer avalanche (Fig. 1b) was filmed by a passing bus driver using a mobile telephone, allowing us to approximate flow velocities over the 750 m long run-out distance (Table 1). This avalanche occurred on the same day as the Grünbödeli avalanche. Before each series of measurements at a given deposit we selected morphologically distinct areas, such as levees, channels and flow fronts in the deposit, from the opposite valley wall, because these features are easier to recognize from outside and above the deposit. Each sample generally required 20–30 min to process in the field.

# 3. GRANULE SIZE AND INTERNAL DEFORMATION RATES

The granule-size distribution was found to be log-normal (Fig. 2), similar to other sedimentary deposits (Rogers, 1959). The median granule size, d_{50}, for both the dry and wet snow avalanche deposits is ~80 mm with one outlier (162 mm) for wet snow avalanche S8 (Fig. 3; Table 1). Snow 'boulders' ($d > 500$ mm) are present on the surface of both wet snow avalanches. The smallest granule size is ~20 mm on both the wet and dry snow avalanches. This may be a consequence of sorting, as small granules fall through the flow, the smaller granules (generated during breakage of other granules) becoming agglomerated onto the surface of the larger granules. The ratio between d_{84} and d_{16} (the granule size for which 84% and 16% of the material is smaller in size,
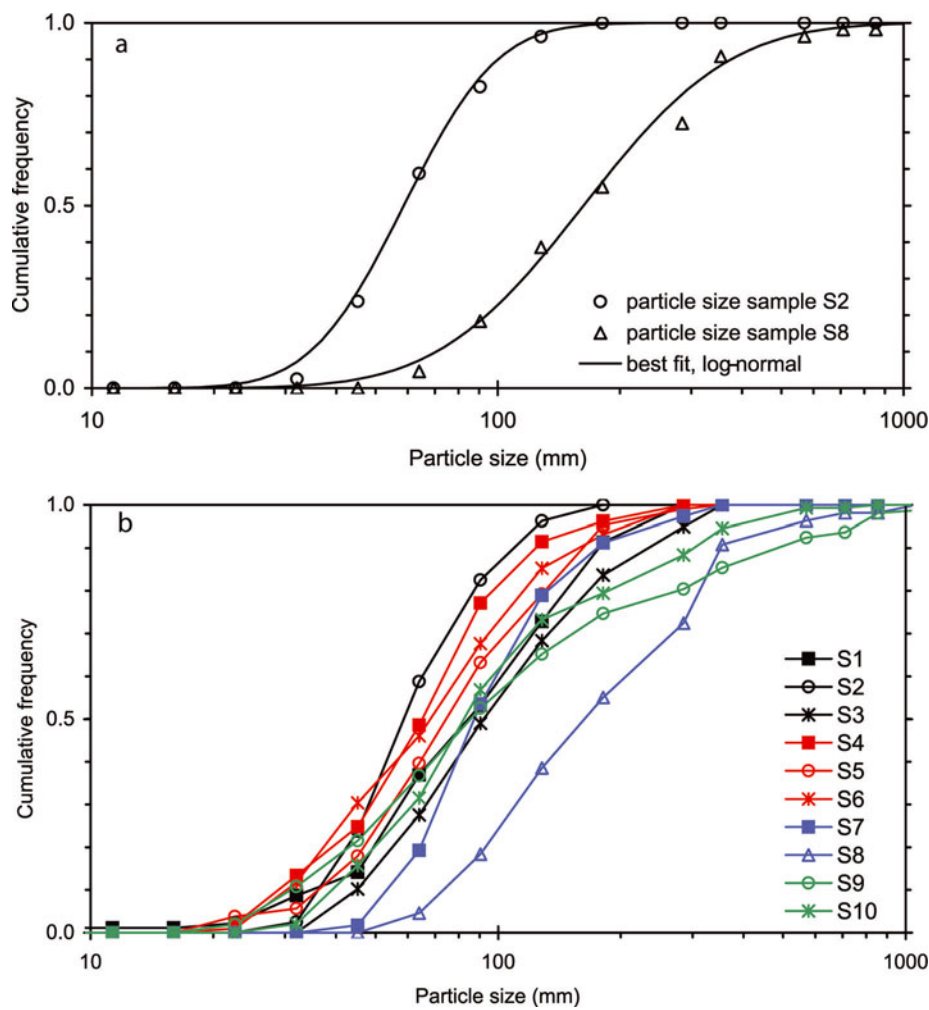
Fig. 2. Granule-size distributions for (a) the finest and coarsest snow deposits, with a log-normal cumulative curve fitted to the data and (b) for all granule-size samples.

Table 1. Properties of the avalanches and their deposits

	Avalanche			
	VdlS No. 816	VdlS No. 917	Grünbödeli	Gatschiefer
Date	6 Mar 2006	26 Mar 2008	24 Apr 2008	24 Apr 2008
Flow type	Dry	Dry	Wet	Wet
Release volume (m^3)	53 400	82 600	35 000	322 000
Deposit volume (m^3)	320 000	128 000	81 200	323 000
Fall height (m)	900	900	600	1000
Distance travelled (m)	1900	1900	1000	2200
Mean slope angle (°)	25	25	31	24
Mean deposition height (m)	~2.0	–	2.8	2.5
Max. deposition height (m)	~5.0	–	15.0	9.0
Flow velocity ($m\,s^{-1}$)	35–40	25–30	–	20
Max. shear rate (s^{-1})	25–40	20–30	–	–
Shear rate tail (s^{-1})	5	5	–	–

Measurement	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
Median granule size, d_{50} (mm)	84	59	92	65	75	68	87	162	86	82
Granule size d_{84} (mm)	158	94	183	107	142	125	148	327	334	228
Granule size d_{16} (mm)	47	40	51	35	43	35	60	85	38	46
Sorting index, s (d_{84}/d_{16})	3.4	2.4	3.6	3.1	3.3	3.6	2.5	3.8	8.8	5.0
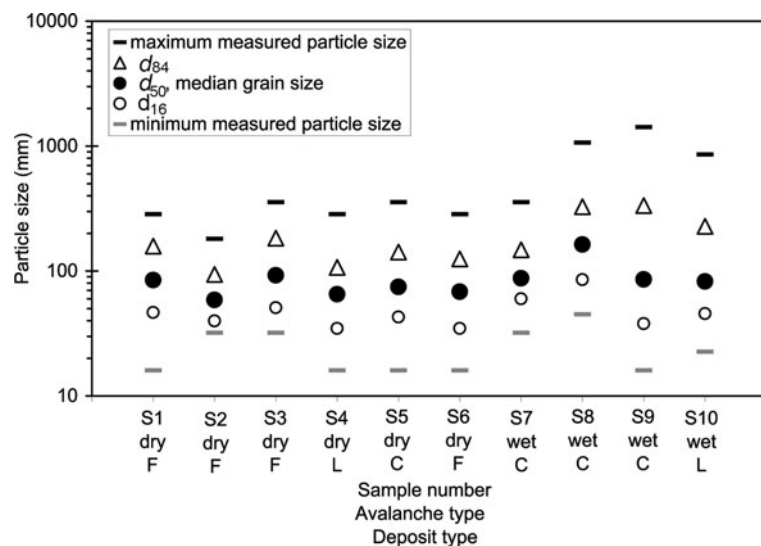
Fig. 3. Comparison of granule-size measurements for both wet (S1–S6) and dry (S7–S10) avalanche deposits, including the largest and smallest measured granule sizes, the median granule size and metrics for the coarse and fine tails of the distributions, d_{84} and d_{16}, respectively. Deposit type: F – flow front, L – levee, C – channel.

respectively) can be taken as an indication of the degree of grain-size sorting (Table 1; Fig. 3). The dry snow avalanche deposits are generally well sorted, with values of the sorting $s = d_{84}/d_{16} < 3.8$, for all investigated dry snow avalanche deposits. The channel deposits of the wet snow avalanches contain large snow blocks (S9, S10; Fig. 1c) and the corresponding $s \geq 3.8$ for most of the samples.

The dry snow avalanches have larger velocities, larger internal-shear rates and smaller median granule size than wet snow avalanches, indicating either that the smaller granules are created by the shearing processes or that the higher velocities and larger internal-shear deformations are the result of the smaller granule size. Both explanations are consistent with our observations, but we cannot establish the causality with any certainty. The causality triangle between shear rate, granule size and granule strength is made even more complex by the changing collisional properties of the granules. Dry (cold) snow is brittle with little cohesive strength; wet snow is weaker, depending on the moisture content (Bozhinskiy and Losev, 1987), but, under compression, will densify and strengthen (Voytkovskiy, 1977). The churning motion of the avalanche will sculpt the snow into hard, rounded granules, similar to the formation of a snowball. In the end, the viscous and collisional interactions between the wet snow granules dissipate more kinetic energy than their colder (more brittle and elastic) counterparts. This highly dissipative mechanism would cause the wet snow avalanches to move slower and, therefore, reduce the internal-shear deformations within the avalanche, with the net effect that the flow would contain larger granule sizes, in agreement with our observations. The basal shear planes commonly observed in regions not covered by deposits (typically at the tail; Fig. 1c) indicate considerable basal slipping and therefore cohesive, block-like movements, with little or no bulk-shear deformation.

However, the fact that wet snow avalanche deposits can contain similar median granule sizes to dry snow avalanches (e.g. S7 cf. S1; Table 1; Fig. 2) is an indication that the upper granule size is not limited by the strength of the granules. If clod strength alone were controlling granule size, we would not find the larger granules in wet snow avalanches. In

regions where the highly sheared layers are exposed, for example at the tail of the avalanche (Fig. 1c, a channel deposit at the tail of the avalanche, S7), we found fewer large granules on the surface than elsewhere. Therefore, both dry and wet snow clumps can be easily formed and re-sized by the internal-shear gradients, but the shear gradients are controlled by the dissipative properties of the granules, which are, in turn, influenced by granule size. There appears to be some limit state where the granule-size distribution and shear gradient reach equilibrium (Gubler, 1987).

3.1. Large-scale deposition features: frontal lobes, tails and levees

Levee deposits formed in both dry and wet snow avalanches (VdlS No. 917 and Gatschiefer, respectively). We measured the granule-size distribution along the lateral levees as well as across the frontal lobes and found no significant difference in granule-size distribution (Fig. 3). This suggests that levee formation is not primarily a segregation process; the sorting appears to have taken place before the granules reach the front of the flow.

In the fast-moving dry snow avalanches, the larger granules quickly reach the top of the flow where they are transported (via the higher velocity at the surface) to the front. The well-sorted granule mixtures found at the front of the dry avalanches are thus an indication of vertical segregation and large vertical shearing rates. The levees are formed as the leading edge of the avalanche decelerates and some material is pushed to the side by the advancing avalanche core. This process requires longitudinal velocity gradients between the leading edge of the flow and the mass following the front.

Levee formation in the wet snow avalanches appears to be controlled by the same process (velocity gradients in the flow direction), but the speed and therefore gross vertical velocity gradients are, in general, smaller than in the dry snow avalanches, leading to more diverse granule sizes (larger sorting index, d_{84}/d_{16}) at the front of the wet snow avalanches. In the Grünbödeli avalanche the granule size increased from tail to front, suggesting again the existence of vertical shear gradients, as the larger granules are transported

to the front, leaving the smaller granules exposed at the tail. In the Gatschiefer avalanche, the channel and levee deposits have the same median granule size, but the channel deposits were not well sorted, having the highest sorting index of all measurements. These observations indicate that shear gradients exist in wet snow avalanches, but are probably concentrated near the bottom and are only apparent in the granule-size distributions when mass depletion at the tail exposes them. The large snow boulders found in the channel in the Gatschiefer avalanche indicate that the near-surface shear gradients are small. As the granules slowly move to the front, some size degradation occurs, but much less than in the dry snow avalanches.

We were unable to discern a relationship between the size of the granules and the angle of the deposit slope, suggesting that it is not the granule size alone that is responsible for the stopping behavior at the avalanche tail (Bartelt and others, 2007).

4. CONCLUSIONS

Using a surface granule-size sampling method on avalanche deposits, we find that the granule-size distribution for both dry and wet snow avalanches tends to a log-normal distribution, similar to other sedimentary systems. Dry avalanches contain smaller median granule sizes and are better sorted (narrower granule-size distributions) than wet snow avalanches. The broader granule-size distributions found in wet snow avalanches are related to lower flow velocities and smaller vertical shear gradients, especially near the upper surface of the flow.

We found no difference in granule-size distributions between the levees and front, implying that levee and front formation are closely related since they appear to be controlled by the same vertical segregation process. However, the formation of levees is often described as originating from the sorting process occurring near the avalanche front. While it is clear that sorting rapidly takes place in mixed-size granular flows, we suggest that granule sorting in snow avalanches occurs before the avalanche reaches the run-out zone. The sorted material accumulates at the front where it is deposited and pushed to the side by the flow to form levees. The deposition of levees necessarily requires strong longitudinal variations in velocity between the leading edge and the core of the avalanche. Central to understanding how levees are formed is knowledge of how granule interactions control the variation of shear stress at the leading flow edge, especially as the avalanche is decelerating in the run-out zone. At present, no model of avalanche flow is capable of representing this process.

The information contained in surface granule-size measurements reflects the flow properties of snow avalanches, such as mean velocity and shear rate. Since the information can be gathered rapidly and requires no expensive post-processing, we show that point-count measurements are a valuable on-site field procedure to assess flow behavior in avalanche run-out zones, where post-event analysis is often required. As it is often difficult to identify granule sizes without some light manual disaggregation of the clumps, surface granule-size measurements will be useful to calibrate more rapid photogrammetric measurements, when possible, in the future.

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