Inferences on flow mechanisms from snow avalanche deposits

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ABSTRACT. In the winters 2004–2006, the deposit structure of 20 avalanches that occurred in the Davos area (eastern Swiss Alps) and whose size ranged from very small to large was investigated. Snow-cover entrainment was significant in the majority of all events and likely to have occurred in all cases. Evidence was found both for plough-like frontal entrainment (especially in wet-snow avalanches) and more gradual erosion along the base of dry-snow avalanches. Several but not all of the dry-snow avalanches, both small and large, showed a fairly abrupt decrease of the deposit thickness in the distal direction, often accompanied by changes in the granulometry and the deposit density. Combined with other observations (snow plastered onto tree trunks, deposit-less flow marks in bends, etc.) and measurements at instrumented test sites, this phenomenon is best explained as being due to a fluidised, low-density flow regime that formed mostly in the head of some dry-snow avalanches. The mass fraction of the fluidised deposits ranged from less than 1 to about 25 percent of the total deposit mass. Fluidisation appears to depend rather sensitively on snow conditions and path properties.

INTRODUCTION

For over 30 years, evidence has been accumulating from full-scale experiments in the USSR (see Bozhinskiy and Losev, 1998, Ch. 5.4 for a summary and references), Canada (Schaerer and Salway, 1980), Japan (Nishimura and others, 1987) and Europe (Schaer and Issler, 2001; Gauer and others, 2007) that a third flow regime, intermediate between the well-known dense and suspension regimes, occurs in dry-snow avalanches. Field observations report extensive and relatively thin distal deposits with interspersed snow clods that are far too large to be carried in suspension (Issler and others, 1996). They are responsible for the intermittent strong, short-duration pressure peaks recorded on small load cells (Schaer and Issler, 2001). Both the concept of three distinct flow regimes (dense, fluidised[1] and suspension) and the estimated range of densities (100–500, 10–100 and 1–10 $\mathrm{kg\,m^{-3}}$, respectively) correspond closely to the quasi-static/collisional, grain-inertia and macroviscous regimes identified in granular flows. Astonishingly, adoption of these concepts has been slow, both in the scientific community and in practice, despite the significant consequences that the high mobility of the fluidised layer may have for hazard mapping, as exemplified in (Issler and Gauer, 2008).

Entrainment of snow by the moving avalanche is another important process that has been slow to achieve due recognition, even though it had been included in early models (Briukhanov and others, 1967). Thanks to the convincing field measurements of Sovilla and others (2001) and confirmation from observations and other measurements (Issler and others, 1996; Vallet and others, 2001; Sovilla, 2004), research on the mechanisms underlying this phenomenon has been intensified recently. Figure 1 schematically indicates the structure and the relevant mass exchanges between the different layers as suggested by the experimental data. Typically, both the dense core and the fluidised head entrain snow from the snowcover.

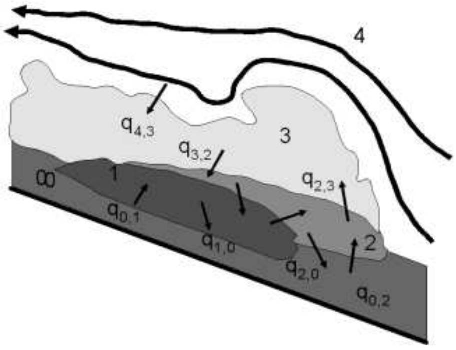

Fig. 1. Schematic representation of the structure of fully developed dry-snow avalanches with (1) the dense, (2) fluidised and (3) suspension flow regimes occurring simultaneously. Arrows indicate mass exchange between the layers, including the snowcover (0) and the ambient air (4).

Data from instrumented test sites are extremely valuable, but they do not readily allow conclusions as to how frequently and under which conditions specific features like entrainment or fluidisation occur. Investigating a large number of different avalanches, both natural and artificially released, can help to close this gap: With the guidance of the insights from the test sites, it is possible to obtain at least semi-quantitative data from avalanche deposits, using simple methods and instruments. In the winters 2004–2006, we monitored the western and southern area of Davos (eastern Swiss Alps), particularly the Parsenn-Klosters skiing area. The interactive map at http://www.tur.ch/nfp/kampagnen.html links to brief re-

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[1] The layer in the fluidised regime was called saltation layer in earlier work (Norem, 1995; Issler, 1998), in analogy with blowing snow.

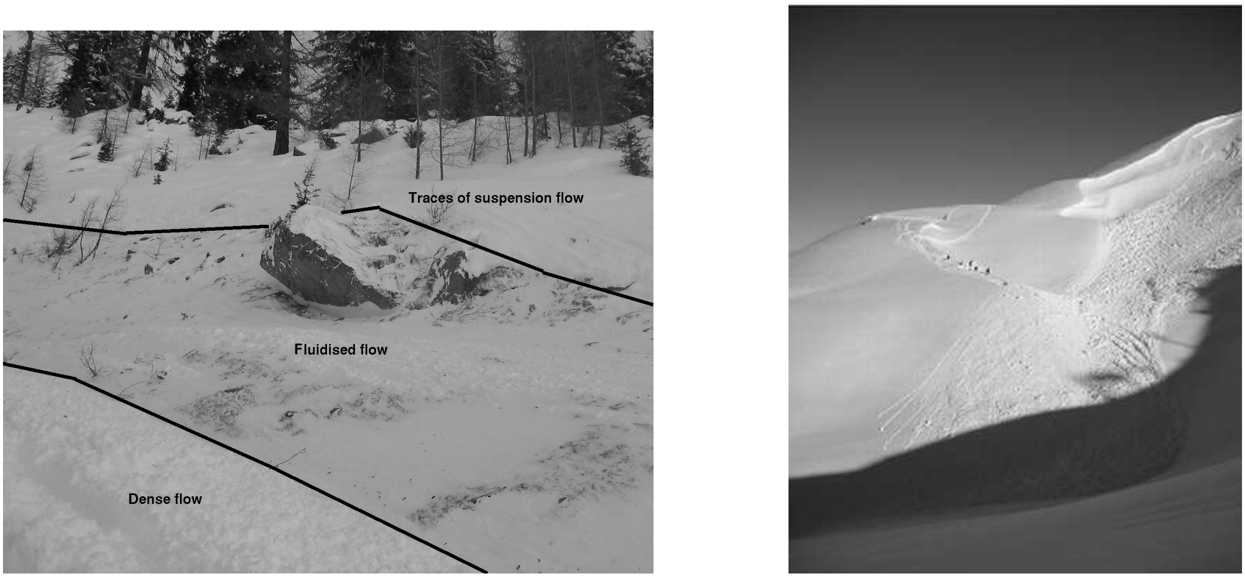

Fig. 2. View of the side of the gully of the January 18 2006 Rüchitobel avalanche (left panel) and of the track and deposit area of the January 22 2006 Kreuzweg avalanche (right panel), showing that the fluidised head and the dense body of these avalanches took different paths at bends due to their widely different velocities.

ports on the investigated avalanches, whose sizes ranged from very small ($\mathcal{O}(10^2\,\mathrm{m}^3)$) to large ($\mathcal{O}(10^5\,\mathrm{m}^3)$). Here we discuss our observations with regard to fluidisation and entrainment, but our data also lend themselves to other types of analysis that we intend to report elsewhere.

METHODS USED IN FIELD WORK

During the daily monitoring in 2006, we recorded the positions, altitudes and aspects of newly fallen avalanches, their geomorphological features (vertical drop and channelization of the tracks), the weather conditions, and snowcover features (strength, depth of new snow and snowcover). Where possible, the outlines of the avalanches were recorded by GPS. For six among these avalanches, we collected additional data from single snow pits, and in 14 cases investigated the deposit structure in detail, estimated the mass balance, and recorded damage to the vegetation. In three cases the velocity at a bend could be estimated thanks to flow marks. Unfortunately, we could access the starting zones only in very few instances due to safety considerations.

Detailed analysis of avalanche deposits comprised pits or extended trenches in locations selected either for representativity or for special phenomena such as long humps aligned with the flow direction. In one case (avalanche in the Sertig valley) we used a logging-grade chain saw to cut trenches because the deposits were too hard for steel shovels. In the pits and trenches we identified and recorded the different layers, measured their density and hardness, and tested manually or with a brush for the presence of snow clods embedded in a matrix of fine-grained snow. We estimated the depth of entrained snow by comparing the layering with the undisturbed snow cover to the side of the deposit.

In many cases we visualized the texture of the snow layers with a technique developed by one of us (HG) in the 1980s: We sprayed a solution of 2-propanol alcohol and blue Pelikan writing ink (which exhibits little flocculation at low temperatures) thinly on a vertical wall of the pit, which had been carefully smoothed with a shovel avoiding pressure normal to the surface. The ink/alcohol solution infiltrates the snow cover along the free grain surfaces within a few minutes and highlights areas of higher density or different structure quite clearly. If the snow is very cold and fine-grained, careful heating by means of a gas burner as used for ski waxing may improve the results.

Many of the investigated avalanches occurred above timberline and the gliding layer was well within the snowcover. However, the largest events in our sample reached the valley floor at elevations between 1400 and 1900 m a. s. l. and either produced light to considerable damage on the trees flanking the gully, or eroded to the ground at some locations. We recorded such traces and also snow plastered on tree trunks in order to obtain rough estimates of the pressure exerted by the flow or an indication of the flow height.

Under specific conditions it was possible to estimate the flow velocity v at bends in the flow path from scour marks or deposits (see Fig. 2). If we may assume the avalanching snow to behave similar to a low-viscosity fluid, the surface of a cross-sectional profile is superelevated by an angle

$$\tan\gamma \approx \frac{v^2}{Rg\cos\theta}, \tag{1}$$

where R is the mean curvature radius of the bend, g is the gravitational acceleration and θ the slope angle (Fig. 3a). In another case, most of the mass was deflected by a low moraine ridge of height h protruding into the path, but some went over the moraine in an almost straight line, with little residual momentum at the crest. Its velocity at the base of the moraine (see Fig. 3b), v_0, can be estimated from a simple energy balance, taking into account friction on the way upslope with an effective friction parameter μ_{eff}:

$$v_0 \gtrsim \sqrt{2gh(1+\mu_{\mathrm{eff}}\cot\theta)}. \tag{2}$$

As a first approximation to the effective friction, one may take the runout ratio of the avalanche under consideration, $\mu_{\mathrm{eff}} \approx H/L$, where H is the drop height and L the horizontally measured runout distance; typical values are in the range 0.5–0.7. Obviously, such calculations can only give rough esti-

Table 1. Main characteristics of the avalanches that were investigated during the project and are mentioned in this paper. Size is classified according to the Canadian avalanche size scale (see McClung and Schaerer, 2006, App. D). H and L are the drop height and the horizontally measured travel distance, respectively (measured from crown to toe). The runout angle is given by $\tan\alpha = H/L$. The mass estimates refer to the deposit (including avalanching snow stopped in the track) and are affected by large uncertainties, as is the degree of fluidisation.

Name	Date	Size	H [m]	L [m]	α[°]	Mass [t]	Type	Fluidisation	Entrainment [m]
Breitzug	2004-01-13	3–4	900	1400	32.5	20 000	wet	no	0.5–1 (soil)
Dorfbachtobel	2005-12-18	2	250	550	24.5	200	dry	yes	very likely
Rüchitobel	2006-01-18	3	665	1185	29	4 000	dry	1–3 %	0.1–0.7
Gotschnawang	2006-01-20	3	460	750	31.5	3 000	dry	3–5 %	0.1–0.4
Kreuzweg	2006-01-22	2	130	240	28.5	250	dry	< 1 %	very likely
Drusatscha	2006-02-14	3	460	710	33	4 000	dry	25–30 %	0.2–0.7
Sertig Dörfli	2006-02-21	3	470	800	30.5	7 000	dry	< 1 %	0.1–0.8 (soil)
Dischma	2006-03-10	4	900	1550	30	70 000	dry	5–10 %	0.3–1

mates because dense-snow avalanches are less fluid-like than e. g. a hyperconcentrated stream flow. Furthermore, the scour marks on the inside and outside of the bend may not correspond to the same surge because marks of a slower surge overtop those of a fast surge on the inside but not on the outside. Variations of the flow height might also influence the interpretation of the scour marks.

In the case of the Sertig Dörfli avalanche of 21 February 2006 we cut snow blocks mixed with eroded top soil of about 8 kg from various locations (see Fig. 6), and later weighed and melted them in the laboratory. The slurries were passed through coffee filters, which were then dried and weighed to determine the soil concentrations.

OCCURRENCE AND CHARACTERISTICS OF THE FLUIDISED LAYER

Distinguishing between the deposits of the dense and fluidised parts of an avalanche is to some degree a subjective and uncertain task. The main criteria that have emerged in our previous work (Issler and others, 1996) are (i) rapid decrease (over distances of 2 m or less) of the deposit thickness in the distal or lateral direction, (ii) snowballs of various sizes (typically 0.01–0.1 m) embedded in a matrix of compacted fine-grained snow, (iii) large snowballs (0.1–1 m, depending on avalanche size) lying on top of the deposit, and (iv) fewer snowballs per unit area on the deposit surface than on the dense deposit. These criteria are consistent with our present knowledge of the fluidised and dense flow regimes. Deposits from fluidised flow are typically less dense than those from dense flows, but more than $500\,\mathrm{kg\,m^{-3}}$ were measured in a giant avalanche in 1995 (Issler and others, 1996). Our criteria depend somewhat on the avalanche size and there may be gradual transitions instead of clear boundaries, but we believe that there are few misinterpretations if the observations are checked carefully for mutual consistency. As a typical example, Figure 4 shows the boundary between the deposits of the dense and fluidised parts of the 20 January 2006 Gotschnawang avalanche.

Fig. 4. Distal part of the Gotschnawang avalanche of 20 January 2006, showing clear differences in surface texture between deposits from dense (D) and fluidised (F) flow, which ran up to 50 m farther than the dense flow.

Fluidisation did not occur in any of the wet-snow avalanches in our sample while all but one of the medium-size ($10,000\,\mathrm{m}^3$) to large ($100,000\,\mathrm{m}^3$) dry-snow avalanches showed clear signs of a developed fluidised part, albeit of widely varying importance. The exception was the fairly large avalanche at Sertig Dörfli on 21 February 2006, whose deposits were gradually diminishing in the distal direction but nevertheless sharp-edged. We have not been able to identify a convincing reason for the apparent absence of fluidisation in this case, nor are there obvious reasons why the degree of fluidisation (defined as the mass ratio of the “fluidised” and “dense” deposits) varies so strongly between avalanches of similar size, topographical setting and snow conditions. The Drusatscha avalanche of 14 February 2006 reached the highest degree of fluidisation, estimated at 25 %. This may be due to the high velocities in an intermediate steep passage. We have to caution, however, that our mass estimates have large uncertainties because the boundaries could not always be drawn with high precision and the deposit depths could only be sampled in a few locations.

Where a fluidised part could be recognised, the length of its deposit beyond the dense part ranged from about 10 m in some small avalanches to 100 m in the medium-sized Drusatscha avalanche (2006-02-14) and the large Dischma avalanche (2006-03-10). Much longer fluidised deposit lenghts have, however, been reported in the literature for very large avalanches Issler and others (1996).

The most important finding from the small dry-snow ava-

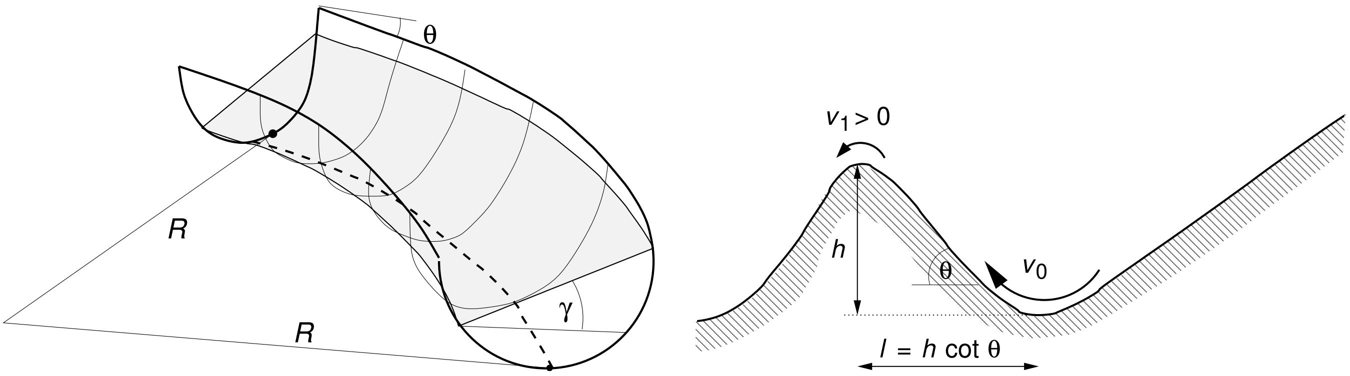

Fig. 3. a) Superelevation in a bent gully. The curvature radius of the centreline is R, its inclination θ. The idealised flow surface is inclined by the angle γrelative to the horizontal. b) Schematic drawing of moraine overflowed by the fluidised head of the 2006-01-22 Kreuzweg avalanche.

lanches in our sample is that they may also reach the fluidised flow regime in some cases. For example, the Kreuzweg avalanche of 22 January 2006 (Fig. 2) with a length of 240 m and a drop height of 130 m developed a fluidised head with very little mass that nevertheless overtopped a moraine ridge that deflected the dense part. As in the case of the larger events, it remains unclear why apparently similar paths along the same ridge that were released simultaneously showed so different behaviour.

In some cases, we could make rough velocity estimates: In the gully bend at 1750 m a. s. l. with a curvature radius of about 400 m, the superelevation of the scour marks from the fluidised part of the Rüchitobel avalanche of 18 January 2006 indicates a speed in the range 28–38 $\mathrm{m\,s^{-1}}$ whereas the deposits of the dense part remained at the bottom of the gully with a speed of approximately 15 $\mathrm{m\,s^{-1}}$. From Eq. (2) we estimate the speed of the fluidised part of the small Kreuzweg avalanche of 22 January 2006 at the foot of the moraine ridge at 13–16 $\mathrm{m\,s^{-1}}$, to be compared with 5–10 $\mathrm{m\,s^{-1}}$ from Eq. (1) for the dense part. The very large dry-snow avalanche of 10 March 2006 in the Dischma valley also demonstrated the high mobility of fluidised flow: The dense part of the southernmost branch stopped where the slope leveled to an angle of approximately 15°, forming an almost 2 m deep deposit. The fluidised part crossed the 15 m deep, narrow river gorge and climbed some 20 m on the steep opposite slope. Assuming an effective friction coefficient between 0.4 and 0.6, we estimate the front velocity at the bottom of the gorge in the range 24–29 $\mathrm{m\,s^{-1}}$. It was presumably somewhat higher still at the stopping point of the dense part because a significant fraction of the energy was dissipated in the gorge.

Two avalanches with clear signs of fluidisation (Dorfbachtobel on or before 19 January 2006 and Rüchitobel on 18 January 2006) reached forested areas and we found snow plastered onto tree trunks to heights of about 2 m in the runout zone. This suggests flow heights around 1 m, but detailed interpretation is difficult because the patches may be due to fluidised or suspension flow, whose run-up characteristics on narrow obstacles are not well known. The big avalanche of 10 March 2006 in the Dischma valley produced a suspension cloud with a 10 m high front and 30–40 m high body that exerted pressures in the range 1–2 kPa after traversing the 200 m wide valley floor.

INFERENCES ON THE ENTRAINMENT MECHANISMS

The interfacial shear stress exerted by the body of an avalanche in the track is of the order of $\tau_b \sim \rho g h \sin\theta \sim 0.2$–5 kPa. The average shear strength of freshly fallen snow is rarely more than 1–2 kPa in situations when dry-snow avalanches occur naturally (see e. g. McClung and Schaerer, 2006, Table 4.1 or Fig. 4.20). If the fresh snow has relatively high strength, this is often due to an extensive snowfall and correlates with larger avalanches and correspondingly higher shear stresses. In consideration of these relations, it is to be expected that the majority of dry-snow avalanches should entrain snow at least in the track and in the beginning of the runout phase when the velocity is still high. Analogous arguments can be put forward for wet-snow avalanches.

These considerations were confirmed by our observations, which can be summarized as follows: (i) Wherever we could access a path, we found that entrainment had indeed occurred. (ii) In all wet-snow avalanches, at least the most recent layer was deeply disturbed all the way to the distal end of the deposit. In dry-snow avalanches, entrainment often appeared less pronounced in the runout zone, in response probably to reduced flow velocity and/or reduced flow depth. (iii) Erosion was often limited to the new-snow layer, but in some cases (several wet-snow and one dry-snow avalanche) involved the topsoil as well. (iv) Most observed avalanches of all sizes deposited snow along the entire path, the deposited mass often being similar to the eroded one. (v) In areas only overflowed by the fluidised part of an avalanche, deposition was absent or significantly less than erosion as long as the terrain was sufficiently steep. However, only very few such instances were observed.

Gauer and Issler (2004) argued that a variety of mechanisms, both intermittent and gradual, localized and distributed should be expected to occur, sometimes sequentially at different stages of an event, sometimes even simultaneously in different parts of the flow. Using the 2000–2004 data from Vallée de la Sionne, Sovilla (2004), emphasized the dominant role of frontal entrainment due to the ploughing mechanism whereas the 1999 profiling radar data from the same path used by Gauer and Issler (2004) indicate gradual erosion—very rapid at the fluidised front and diminishing further into the avalanche body as increasingly harder layers become exposed. Some of our observations also allow inferences on the

Fig. 5. Distal part of one branch of the 13 January 2004 Breitzug avalanche. The sharp boundary between recently eroded snow and snow mixed with eroded topsoil can be faintly seen along the deposit edge. Note the unbent trees inside the deposit.

erosion and entrainment mechanisms, but cannot be generalized because of their so far singular character.

The wet-snow avalanches that we observed eroded in a plough-like fashion at least in the last stages of the flow. The 13 January 2004 event in the Breitzug path (see description on the website) eroded the entire snowcover (apporximately 0.5–0.7 m near the distal end) as well as some topsoil at the beginning of the runout zone. At 5–10 m from the distal end of the 2–4 m thick deposit, we found a sharp, approximately vertical boundary separating clean snow from snow mixed with soil (Fig. 5). Taking into account compression during erosion, the piled-up clean snow corresponds to the mass eroded over a distance of (40 ± 20) m. This is at the same time the distance over which eroded material is mixed into the flow to a substantial degree. Since it is much larger than the flow depth and the boundary was quite sharp, we may conclude that the mixing was not turbulent but similar to the mixing of dough and that the shear layer at the bottom of the flow was rather thin and/or there was slip. (Shearing throughout the flow depth would mix in the eroded snow over shorter distances due to the conveyor-belt effect.) The most likely picture of our observations is that of erosion proceeding along an inclined surface of similar length as the flow height. The eroded snow is compressed, piled up at the leading edge and pushed forward. Despite limited shear in the body of the flow, some mixing eventually takes place due to the formation of localized shear bands. In this process snow clods grow by coalescing with other clods that consist themselves of a multitude of smaller clods. We observed these clods in each of the major wet-snow avalanches we investigated.

Topsoil erosion from a single area of less than $100\,\mathrm{m}^2$ also gave us insight into the processes occurring in the avalanche at Sertig Dörfli of 21 February 2006; Figure 6 schematically summarizes the relevant observations. The most likely interpretation is in terms of gradual erosion (at least for the bottom layers) because the distal part of the deposits, which clearly corresponds to the head of the avalanche, did not contain soil particles. The erosion front reached the soil only well after the head had passed the location, and apparently the shear stresses were sufficient to erode the soil only during a short interval, diminishing towards the tail. The highest soil concentrations—essentially uniform in the vertical direction—were found in the deepest and hardest deposits close to the bottom of the slope; they diminished gradually both in the upstream and downstream directions over distances of 10–20 m. The mixing was strong across the entire flow depth and resembled diffusion in the longitudinal direction. Our data do not allow more than a very crude estimate of the corresponding diffusion coefficient D. Taking a mean diffusion distance of $s \approx 10\,\mathrm{m}$ within a flow time of $t \approx 10\,\mathrm{s}$ from the source to stop, the well-known formula $s = \sqrt{Dt}$ leads to $D \sim 10\,\mathrm{m}^2\,\mathrm{s}^{-1}$. Such strong diffusion suggests "turbulent" granular flow in the dense part of this scarcely fluidised avalanche. D would then be due to coherent motion of particle swarms (analogous to eddies in turbulent fluids) over a mean 'mixing length' l_{mix} with a mean 'mixing velocity' u_{mix}. According to Prandtl's mixing-length approach (see e. g. Lesieur, 1993, p. 120), a granular diffusivity $D_t \sim l_{\mathrm{mix}} u_{\mathrm{mix}} \sim 7.5\,\mathrm{m}^2\,\mathrm{s}^{-1}$ results if we identify the mixing length with the flowdepth, $l_{\mathrm{mix}} \sim 0.5\,\mathrm{m}$, and the mixing velocity with the mean flow velocity in the body, $u_{\mathrm{mix}} \sim 15\,\mathrm{m\,s}^{-1}$. While D_t is reasonbably predicted, the shear stresses in the avalanche are overestimated by an order of magnitude. Thus a more detailed consideration of mixing effects in avalanche flows and more precise data are required to settle this question.

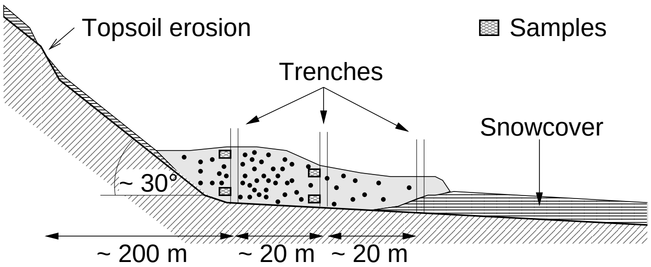

Fig. 6. Schematic longitudinal section of the deposit of the 21 February 2006 avalanche at Sertig Dörfli, indicating the location where soil was eroded, the placement of trenches and the soil concentration in the deposits.

DISCUSSION AND CONCLUSIONS

An important result of our work is that even small dry avalanches can partially fluidise, while we have never observed fluidisation in wet-snow avalanches. On physical grounds, we expect the occurrence of fluidisation to depend mainly on avalanche velocity, terrain roughness, snow density and cohesion, and possiby flow depth. However, it does not seem possible to extract fluidisation threshold conditions for these variables from our observations. One reason is that, among avalanches of very similar characteristics with regard to topography, size, and snow conditions, fluidisation occurred in some but not in others, i. e., our observations were either not accurate or not comprehensive enough to differentiate among them. Another reason is that our sample of dry-snow avalanches is quite homogeneous with respect to topographical and snow conditions, and contains only few large avalanches, thus it probes only a small region of the multi-dimensional parameter space. It appears likely on physical grounds that dry-snow avalanches in very steep terrain or of very large size will fluidise to a much higher degree, but our limited data set is not conclusive. From the strong variability of the degree of fluidisation under similar conditions in our sample, we may conjecture, however, that the snow conditions in January and February 2006 in the area of Davos were near the critical properties for fluidisation under the given topographical characteristics. This hypothesis can be tested by analogous investigations in different areas, either with similar snow climate and generally steeper slopes, or with similar topography but different snow climate.

We found evidence from both small and medium-sized avalanches that the fluidised head moves at close to double the speed of the dense body. This is fully consistent with inferences from earlier observations (Issler and others, 1996) and recent analyses of experimental data from Vallée de la Sionne and Ryggfonn.

Snow entrainment is not an exceptional but an ubiquitous phenomenon in avalanche flow and ploughing is probably the dominant mechanism in wet-snow avalanches. In the one dry-snow avalanche that allowed inferences on the entrainment mechanism, we found evidence for gradual erosion beneath the avalanche body in connection with strong mixing. Tracers like twigs from bushes or soil particles are highly useful in interpreting deposit structures. This suggests a dedicated experiment where different types of tracers are deployed at various locations in a small path before an artificial release in order to study the mixing and entrainment processes in more detail.

Field work with simple techniques can provide valuable complementary information to full-scale and laboratory experiments if it focuses on deposit properties linked to the dynamical processes during avalanche flow. However, more efficient methods for measuring the deposit distribution in the terrain should be developed to better determine the degree of fluidisation and the mass balance. Safer access to the starting zones would add important aspects that our study is largely lacking. Finally, having several teams working on the terrain after periods of high avalanche activity would increase both the quantity and quality of data.

Errera (2007) reports and discusses exploratory statistical analyses of our data, e. g. concerning the dependence of the runout angle α (Table 1) on the avalanche size or the slope angle in the track. If such analyses were applied to a larger data set of similar or better quality, extending over several years and areas with different topographical and climatic conditions, highly valuable information on the behaviour of small avalanches and practical tools for hazard mapping, such as an adapted statistical-topographical runout model, could be obtained.

ACKNOWLEDGEMENTS

The Swiss National Science Foundation supported the field work leading to this paper under grant no. 200021-101911, NGI supported the writing of the paper. The authors thank M. Christen, M. Kern, C. Pielmeier, B. Sovilla, T. Stucki and T. Wiesinger from SLF for information on avalanche events, logistic support and discussions. D.I. also fondly remembers animated discussions with P. Gauer, F. Hermann, M. Kern, K. Lied, M. Naaim, H. Norem, F. Sandersen and M. Schaer on the topics discussed here. Thanks go to an anonymous referee for carefully reading the manuscript and suggesting a number of clarifications and extensions.

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