The potential of sedimentology and stratigraphy in avalanche-hazard research

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ABSTRACT.. Detailed sedimentology studies in cross sections and studies of recent processes on avalanche-dominated colluvial fans have been combined in order to evaluate the characteristic sedimentary facies of avalanche processes. These include rock avalanches, rockfalls, debrisflows and snow avalanches. Moreover, the sedimentary facies provides important data on the mechanics of the depositional processes involved. Avalanche deposits are commonly separated by soil or peat beds, which can be dated by the radiocarbon method. In many cases it is thus in many cases possible to estimate the frequency of different avalanche events through time. Geological data can also be used in combination with other methods to evaluate potential impact or run-out zones. Debrisflow and snowflow events can be recognised in excavations, and the run-out distances for older events can thus be mapped. Snow avalanches commonly transport considerable amounts of debris, and far-reaching snow avalanches can be recognised from the occurrence of scattered clasts in peat or soil successions. Such data can be important in testing statistical and dynamic run-out models. A register of historic and prehistoric rock avalanches is currently being compiled, a database which will be of fundamental importance in the future in evaluating run-out distance for potential bedrock failures. This research as a whole suggests that detailed geological studies involving sedimentology and stratigraphy can be of interest and importance in projects concerned with avalanche hazard.

INTRODUCTION

Geological studies involving sedimentology and stratigraphy have hitherto attracted relatively little attention in avalanche-hazard research. Recently, projects at the Geological Survey of Norway and the Icelandic Meteorological Office have focused on evaluating the potential of different geological methods in avalanche-hazard work as a supplement to other methods (Blikra 1994; Blikra and Aa 1996; Blikra and Anda 1997). This includes geomorphic mapping, geophysical studies (seismics and ground penetrating radar), sedimentological and stratigraphical investigations in cross sections and studies of lacustrine cores. This paper consentrates on sedimentology and stratigraphy in evaluating avalanche hazard, and discuss the contribution of such data to different topics of avalanche-related work. The term avalanche is here used as a synonym for rapid mass movements on steep slopes, involving wet or dry rock, debris, snow, or a mixture of these media. These avalances include rockfalls, debrisfalls, debrisflows, snowflows, and possibly some slides of snow, rock or debris.

SEDIMENTARY FACIES AND AVALANCHE MECHANICS

The studies of sedimentary facies in cross sections and analyses of modern processes on avalanche-dominated colluvial fans have formed the basis for the classification of the main depositional processes operating on colluvial slopes (Fig. 1). Some few main diagnostic characteristics of these features are given here, but these are described and discussed in detail in Blikra and Nemec (1998) and Nemec and Kazanci (1998). These features are important in order to understand the depositional processes and mechanics involved in a specific event.

The deposits of *rockfalls* range from scattered or randomly clustered boulders and cobbles, to distinct, tongue-shaped beds of highly immature gravel characterised by a mainly openwork texture (Fig. 1). The openwork texture is well preserved in many cases, but often shows some infill due to sheetwash or an overriding, watery debrisflow. The clast fabric of rock fall deposits is varied, with parts showing a "rolling" fabric of *a*(t) or *a*(t)*b*(i) type. However, due to secondary sliding and reorientation by subsequent avalanches, many such clasts show an *a*(p) or intermediate orientation. The deposits of large *rockfall avalanches* (commonly termed rockslides) generally have a well-defined tongue shape

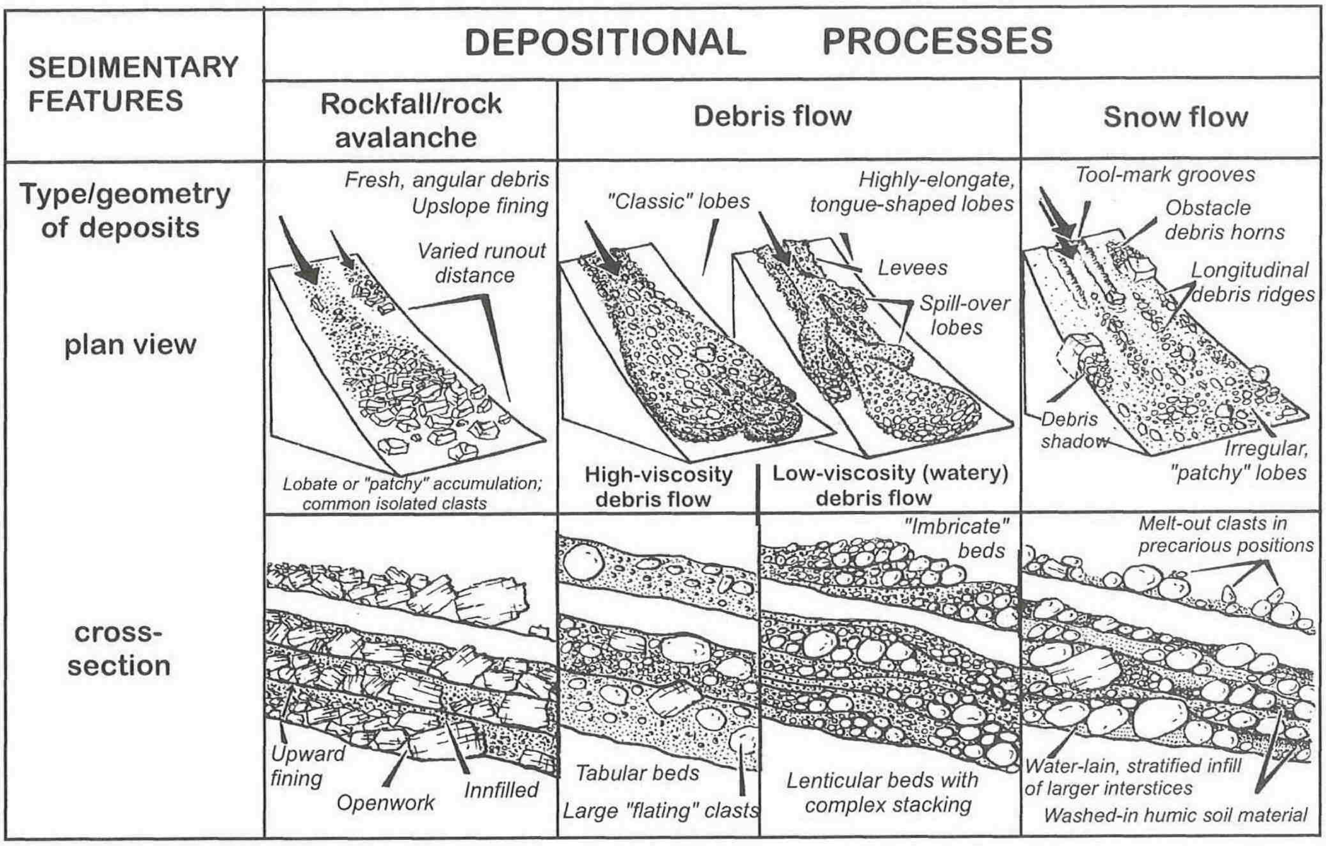

Fig. 1. Summary of the main depositional processes of colluvium in western Norway (modified from Blikra and Nemec, 1998)

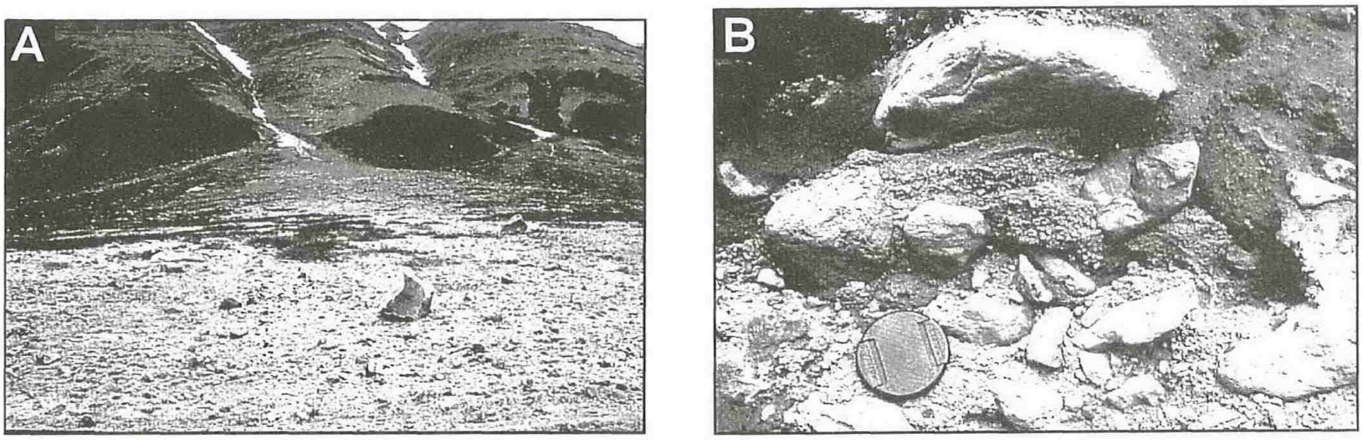

Fig. 2. Snow-avalanche deposits. (A) Snow-avalanche debris on the surface of a colluvial fan in Fnjoskadalur, northwestern Iceland; (B) Sedimentary facies of snow-avalanche deposits. Note the secondary sandy infill. Lens-cap for scale.

with steep frontal lobes, at least those connected with moderate fall heights. Rock avalanches with large fall heights often distribute the sediments over a more extensive area, and usually characterised by a chaotic morphology with ridges, mounds and intervening basins/pounds. Detailed geological studies have provided evidence that some of these events initiate secondary debris flows which have very large run-out potential (Blikra and Anda, 1997). Some of the avalanches have deformed underlying deltaic sediments, with distinct folds down to 15-20 m depth. The importance of clast collisions in a rockfall increases with the volumetric concentration, and the avalanching mass of debris evolves into a cohesionless debrisflow or the shear-flow regime of an avalanching grainflow (Campbell, 1989; Nemec, 1990). This is one of the explanations for the observed long run-out distances. Another important reason for a dramatic increase in the run-out distance is the initiation of secondary debris flows due to destabilised finer-grained valley sediments. In these cases, dynamic models have to take into account the transformation from collisional-dominated grainflow to possibly cohesive debris flows to estimate potential run-out distances.

The *debrisflow* deposits are gravel beds ranging from matrix- to clast-supported, and from pebbly to bouldery (Fig. 1). Likewise, their matrix varies from muddy, poorly-sorted sand to sandy granule gravel. Debrisflow beds are normally 0.4 to 1.7 m thick, and some of them show two types of inverse grading. The inverse grading in some matrix-supported beds is of a 'coarse-tail' type, with only the coarse fraction of clasts being distinctly finer in the lower part of a bed. This type of grading is thought to be formed due to a 'rigid-plug' effect (Johnson, 1970), where the lower, shearing part of the debrisflow becomes depleted of large clasts as these settle through the liquidised matrix and tend to be dropped from the flow (Naylor, 1980). The inverse grading in clast-supported beds is more of a 'distribution' type, involving a wider range of clast sizes. It is attributed to clast collisions, with the upward displacement of larger clasts as a result of dispersive pressure (Bagnold, 1954; Lowe, 1976; Walton, 1983) combined with kinematic sieving (Middleton, 1970; Scott and Bridgwater, 1975; Jullien *et al.*, 1992). The clast fabric varies according to the type of flow, but it may also vary internally in individual debrisflow beds. Some are characterized by «shear fabric» of *a*(p) or *a*(p)a(i), while others might also have a «rolling» *a*(t) fabric. The relationship between the bed thicknesses (BTh) and maximum clast sizes (MCS) indicates that the matrix-rich debrisflows can generally be classified as cohesive and the matrix-poor ones as cohesionless (Blikra and Nemec, 1998). The sedimentary facies of debrisflows thus provide a clue to the mechanics of the flow, which might include regimes characterised by simple shear (plug flow), collisional forces, or by turbulence.

Snowflows (snow avalanches) are capable of transporting large amounts of rock debris (Fig 2A). Some snowflows carry little or no debris, whereas others are very rich in clastic material. The content of debris within a single flow is often extremely variable (Luckman, 1971). Snowflows transport debris that has accumulated on the snowpack due to rockfall processes; debris that has been removed from the mountain slope/ravine and incorporated *en route* by the flow; and debris that has been swept by the flow from the apex and upper slope of a colluvial fan. Dense snowflows have a high shear strength, and their 'rigid plugs' can support clasts as large as boulders. The same pertains to the non-turbulent powder snowflows, which can carry cobbles. Relatively dense, turbulent snowflows carry fine debris in suspension, while dragging coarser debris along the base due to the high tractional stresses developed on a steep slope. These denser snowflows thus transport rock debris in much the same way as colluvial debrisflow avalanches, with the important difference that the snow 'matrix' here melts out shortly after the deposition and all the debris thus settles to the ground. The turbulent powder snowflows, in turn, are carrying debris in a manner analogous to rapid turbidity currents: sand and finer fractions are carried in turbulent suspension, and the coarser debris is carried in bedload traction. The sedimentary deposits of snowflows (Fig. 1), as observed on modern colluvial slopes, range from blankets of scattered and unsegregated debris to irregular, 'patchy' lobes of unsorted debris, no more than one-cobble or one-boulder thick (Fig. 2A). The debris is commonly surrounded by waterlain sand, usually rich in granules and small pebbles (Fig. 2B). The clast fabric of snowflow deposits varies on a local scale, and is disorderly when measured more systematically.

A review of snow rheology and snowflow types important for the understanding of snow-avalanche deposits is given in Blikra and Nemec (1998) and Nemec and Kazanci (1998).

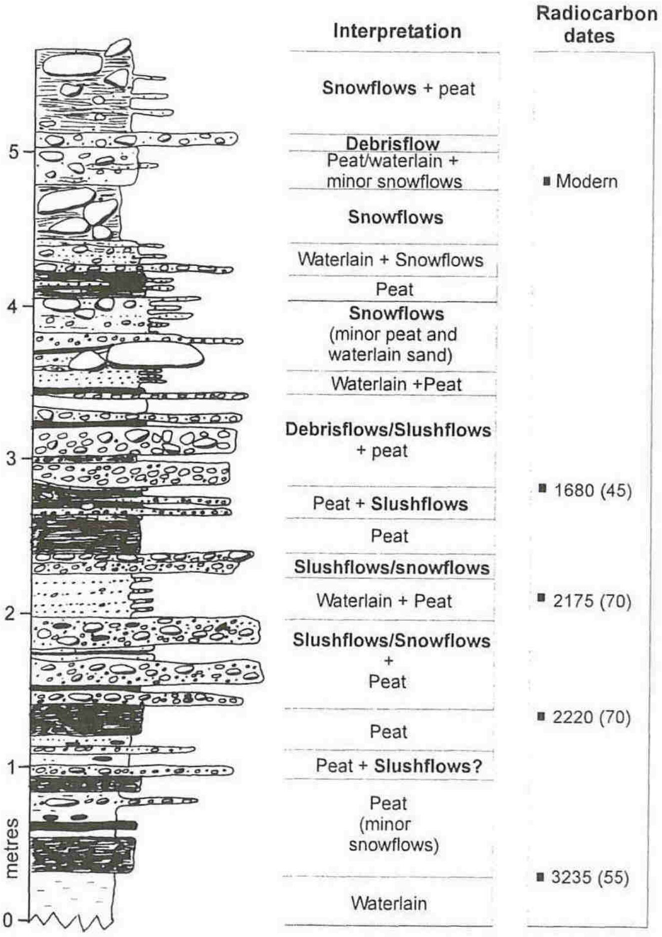

Fig. 3. Sedimentary succession from a colluvial fan in Flateyri, Iceland. The radiocarbon dates are uncalibrated with one standard deviation. The section shows a high snow-avalanche activity around 2200 years BP and from 1700 years BP. However, the occurrence of a high number of scattered clasts and blocks in peat units in the upper part indicate that the snow-avalanche frequency has increased during the last 1000 years.

FREQUENCY

Estimates of frequency through time can principally be supplied by stratigraphic and sedimentological studies from all types of avalanches. Avalanche deposits are usually separated by peat or soil horizons, and some of them have an organic-rich matrix. The organic material can be dated by the radiocarbon method, and a time scale can thus be established. The frequency of debrisflow events can be estimated relatively exactly. The present discussion will focus on snow-avalanche deposits, and an example is shown from northwestern Iceland (Fig.3). The deposits of successive snowflows, when emplaced shortly after one another, are amalgamated. The indistinct boundaries render the individual avalanche events difficult to distinguish in an outcrop section. Although the discontinuous horizons of large clasts within a thicker blanket of waterlain sand almost certainly represent separate avalanches, the actual number of snowflow events represented by such a composite unit is likely to be larger, simply because not every snowflow must necessarily carry coarse debris or the large clasts may be few and unexposed. A sedimentary unit little more than one-cobble thick may well represent at least 10 consecutive snowflows. However, stratigraphic sections in the distal part of the colluvial fans can provide estimates of low-frequency and far-reaching avalanches. The section from Iceland demonstrates a typical section in a snow-avalanche dominated area (Fig. 3). Based on the section, a snow-avalanche frequency at this point is estimated to be about 1 event in 25 to 75 years.

RUN-OUT DISTANCE

Stratigraphical sections located at various distances from the avalanche source area will reveal the avalanche frequency at different zones, and also show the potential run-out distances. This is highly relevant data in projects concerning avalanche-hazard zoning. Such work has been done with some success several places in Norway (e.g. Blikra and Aa, 1996). Figure 4 shows an example from western Norway, where a snow avalanche reached a farm in 1994. An excavation in the far distal part of this event demonstrated that this was probably the only avalanche to have reached this point during the last 10 000 years. A section in a more proximal position (ca. 150 m towards the avalanche source area) showed that at least two additional snow avalanches had reached this point over the last 5000 years (Fig. 4). This gives an avalanche frequency of about 1 in 1500 years.

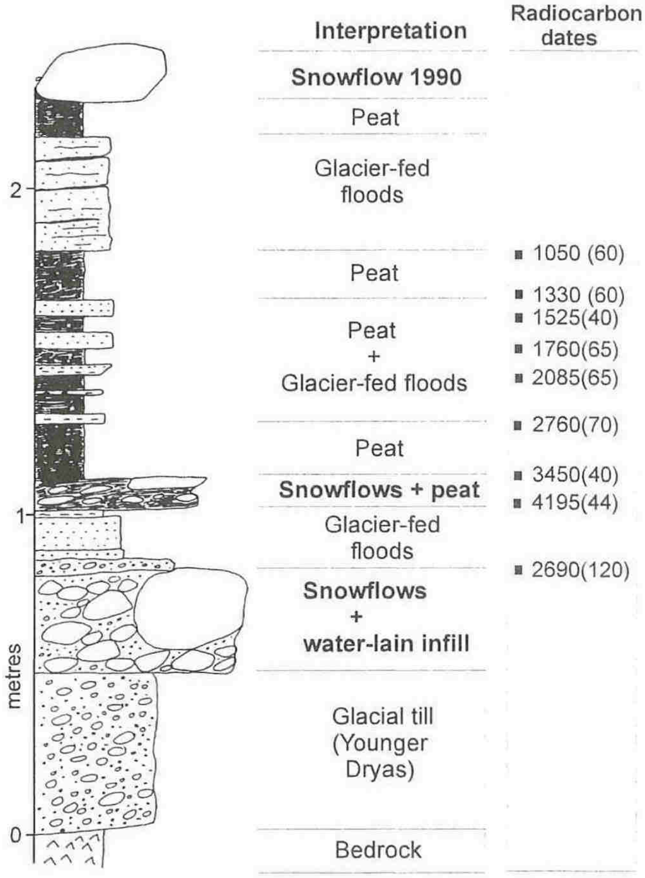

Fig. 4 Sedimentary succession in peat deposits in western Norway, showing some few debris beds demonstrating deposition by far-reaching snow avalanches. The radiocarbon dates are uncalibrated with one standard deviation

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