Rock-avalanche hazard in Møre & Romsdal, western Norway

Einar Anda
The County Council of Møre & Romsdal, Fylkeshuset, N-6400 Molde, Norway

Lars Harald Blikra
Geological Survey of Norway, P.O. Box 3006-Lade, N-7002 Trondheim, Norway

ABSTRACT. Flood waves generated by large rock avalanches have caused major disasters in Norway. Many of these events are restricted to a relatively limited zone in the counties Møre & Romsdal and Sogn & Fjordane. Geological studies confirm that this zone has been affected by large-scale rock avalanches throughout the postglacial period. The number of rock-avalanche events is much higher than expected, and many of them are from the latest part of the postglacial period (the last 5000 years), thus in contrast to the general assumption that most of these events occurred shortly after the deglaciation. Rock avalanches and related flood waves often represent a higher risk than other types of avalanches in the region, due to the potential of causing extensive damage. It can be concluded that the avalanche probability limit of 10^{-3} pr. annum which is used for normal buildings in Norway, is not applicable for rock-avalanche hazard. The study indicates that rock-avalanche hazard should be taken into account in several inhabited areas. More work needs to be done in order to produce hazard-zone maps.

INTRODUCTION

More than 220 persons have been killed by rock avalanches and related flood waves within a relatively limited zone in the counties of Møre & Romsdal and Sogn & Fjordane during the last three centuries. In the Tafjorden disaster in 1934 no fewer than 40 people were killed (Bugge, 1937). Three mill. m^3 of rock and debris avalanched into the fjord and generated a flood wave which destroyed parts of two villages along the shore of the fjord.

Only limited research has been done in the 'rock-avalanche field' in Norway. The historically documented rock avalanches provide a warning, but they are too few over a limited time period to give reliable hazard predictions. The aim of the present project, initiated by the county council of Møre & Romsdal and the Geological Survey of Norway, is thus to describe the rock-avalanche and related flood-wave hazard in the region (see locality in Fig. 1). In this paper we give a short geological description of some typical rock avalanches, and their geographical and geological-historical distribution (Fig. 1). The consequences and risks of rock avalanches are discussed.

THE GEOLOGY OF ROCK AVALANCHES

The term *rock avalanche* is here used to describe a rapid mass movement triggered by a large bedrock failure, which often evolves into a large massflow. We have restricted the registration of rock-avalanche events to those with a minimum volume of 10^5 m^3. Smaller-scale events are difficult to identify by geological criteria. A geomorphic classification of rock avalanches has been proposed by Nicoletti & Sorriso-Valvo (1991). They found that the local morphology controls the shape and motion of rock avalanches, and they grouped the rock avalanches into three main categories. This has also been confirmed by our studies, but the geomorphology of rock avalanches is actually more complex. The study has demonstrated that individual rock avalanches consist of very different deposits, a recognition which has important implications for avalanche dynamics and run-out estimates. These deposits are discussed below.

Rock-avalanche deposits

These are bouldery deposits derived from bedrock failure and collapsed, coarse colluvium on the mountain slopes. These coarse-grained deposits are often characterised by classical, steep, frontal lobes, 5-20 m high (Blikra & Anda, 1997). Avalanches derived from higher mountain slopes have greater run-out distances and spread the debris over a more extensive area (Fig. 2). The geomorphic features seem to be controlled primarily by the local topography, and might also include transverse ridges/depressions, but they are often characterised by a chaotic morphology with ridges, mounds and intervening basins/pounds. Parts of these deposits also show the formation of lateral levees. The sedimentology is often

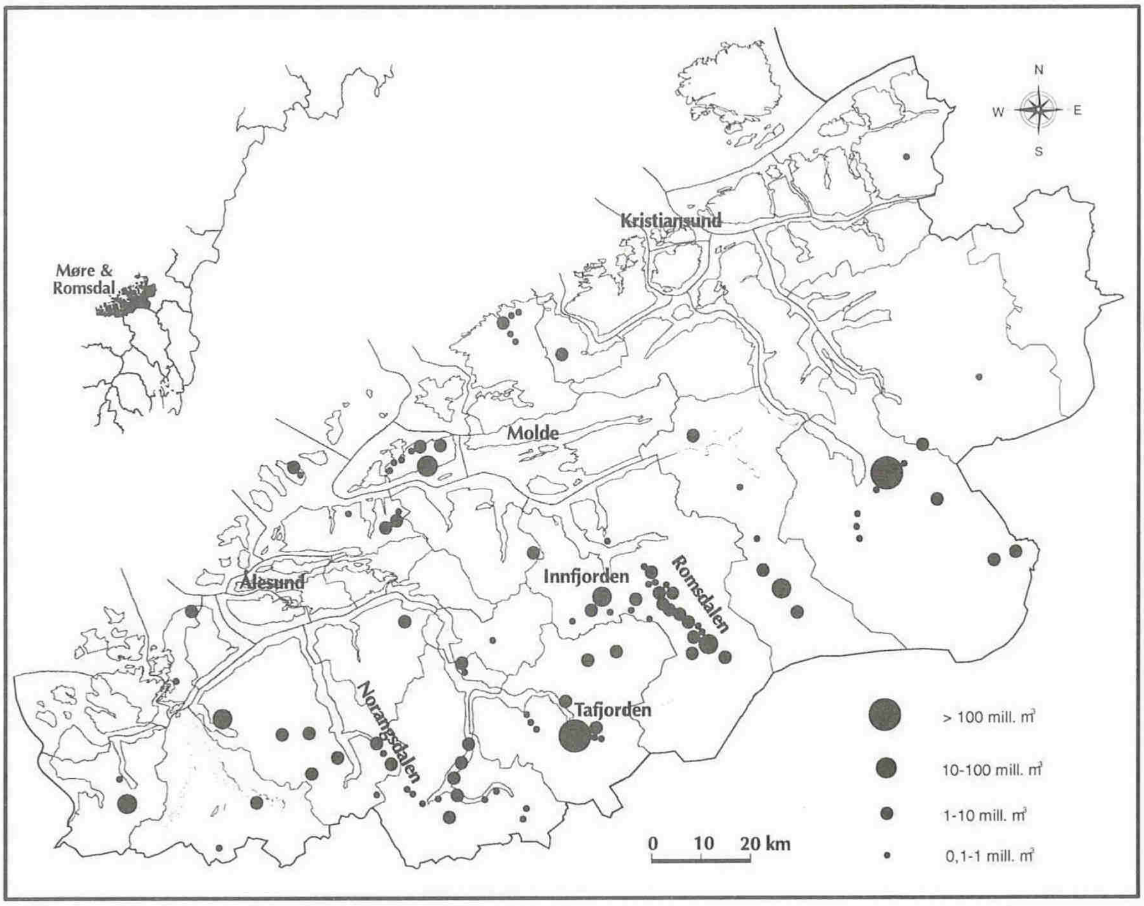

Fig. 1. Location and registration map of rock avalanches in the county of Møre & Romsdal.

characterised by a bouldery and clast-supported texture but with an openwork upper part. Some events demonstrate a clast- to matrix-supported texture with clear evidence that the deposits has been transformed into a massflow. Large outcrops of the failed rock mass have, in some cases, undergone only minor disruptions such as sliding along shear zones .

Secondary debrisflow deposits and deformations

Debrisflow deposits are found outside the bouldery rock-avalanche deposits at several localities (Fig. 3). These are normally less than 1 m in thickness, and characterised by a massive, matrix-supported texture with scattered boulders. The debrisflow deposits include material derived from primary valley-fill sediments and may consist of finer-grained sand and silt (marine and fluvial origin) and coarser grained fluvial gravel. Surface morphology is generally irregular with hummocks 1 to 3 m in height, but these features are mainly controlled by underlying deformed sediments (see below). Similar deposits have been described from the Frank slide in Canada, and Cruden & Hungr (1986) termed this the 'splash' area which occurs some 100 m distal to the rock avalanche. The present deposits, however, have much greater run-out distances.

The avalanche at Venje in Romsdalen can be used as an illustration (Fig. 2). A rock avalanche of 0.5-1 mill. m^3 was initiated by a bedrock failure 500-700 m above the valley floor. A major part of the bedrock debris was deposited within 400-500 m of the base of the mountain slope (Fig. 3). The avalanche impact on the valley floor generated a secondary debrisflow of sandy, valley-fill sediments, which moved 500-700 m further out. These deposits are 0,5-1 m thick (Fig. 4B) and have a volume of 0,2-0,4 mill m^3. The avalanche debris also consists of scattered boulders up to 5 m in diameter. The deposits are characterised by a pseudo-hummocky topography with individual hills up to 4 m high (Fig. 4A). This morphology is primarily reflecting the features of underlying deformed valley-fill sediments. The hummocky terrain is believed to have been formed by deformation caused by the rock-avalanche impact itself, but possibly also following the secondary debrisflow. The deformed valley-fill sediments have been partly eroded by the secondary debrisflow, either due to a high-velocity and turbulent flow, or by blocks which were dragged along the base of the flow. Radiocarbon dates of charcoal found between the valley-fill sediments and the secondary

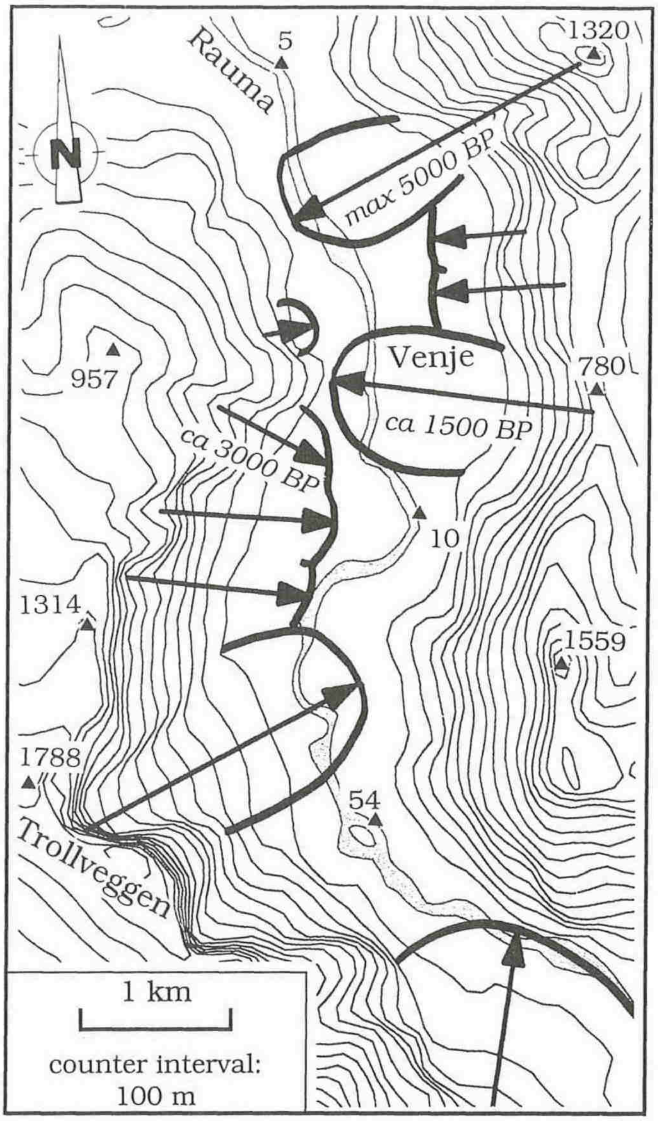

Fig. 2. Rock avalanches in the lower (northern) part of Romsdalen. Aavalanche directions (arrow) and run-out distances are shown. Age is indicated in radiocarbon years BP (for locality, see Fig. 1).

debrisflow indicate that this avalanche occurred some 1500 years ago.

Impact-generated deformations in the valley-fill sediments have been found in connection with several large rock avalanches, both below and distal to the avalanche deposits. Ground-penetrating radar measurements demonstrate distinct folds down to a depth of 15 m, and the fold structures are visible at the surface as gentle wave-shaped features.

THE DISTRIBUTION AND AGE OF ROCK AVALANCHES

More than one hundred rock avalanches with volumes over 10^5 m^3 have been identified in the region (Fig. 1). The real number is certainly considerably higher since not all areas have been sufficiently well investigated, especially in the fjords. Many of the avalanches are located in a relatively concentrated zone in the inner part of the county. The largest concentrations within this zone is found in Romsdalen, where 10-15 large rock avalanches cover almost the entire valley floor over a distance of 25 km. Figure 2 shows rock avalanches in the lower part of Romsdalen. The avalanche at Venje (described above) occurred some 1500 years ago, and another avalanche close by has been dated to about 3000 years before present. According to shore-displacement data (Svendsen & Mangerud, 1987), a third rock avalanche in this zone occurred within the last 5000 years. Another large rock avalanche at Innfjorden 15 km west of Romsdalen (Fig. 1), has been radiocarbon dated to some 3500 years before present. Older avalanches may be present, buried by fluvial sediments or by younger rock avalanches.

The largest rock avalanche in Møre & Romsdal has been found in Tafjorden (Fig. 1), where a collapse of ca. 100 mill. m^3 of bedrock from an elevation of 500-1000 m a.s.l. generated gigantic massflows which moved 6 km into the fjord. According to the sea-level data, this event is some 3000 years old. Besides the catastrophic rock-avalanche in Tafjorden in 1934, minor rock avalanches occurred in this area in 1989 and 1991. Nesje *et al.* (1994) have dated two prehistoric rock-avalanches in Norangsdalen by measuring the relative degree of rock-surface weathering with the 'Schmidt-hammer'. These two events were estimated to have occurred within the periods 8000-4000 and 5000-3000 years ago. A third rock-avalanche occurred in this valley in 1908 AD (Ahlmann, 1919).

It has been commonly accepted that most rock avalanches formed shortly after the deglaciation, but the present studies have demonstrated that many of them were generated during the last 5000 years. Similar conclusions have also recently been made from studies of rock-avalanche activity in the Alps (Abele, 1987).

We know, so far, little about the causes of the concentrations of these rock-avalanche events. A basic presupposition is the topography created by intense glacial erosion and formation of 'over-steep' slopes. Postglacial tectonic (neotectonic) may also be important. The concentrations of events in Romsdalen might be correlated with a 500-700 m high regional escarpment of the land surface. This large-scale geomorphic feature indicates a distinct 'fault zone' associated with the Cenozoic uplift in Norway (Anda, 1995).

CONSEQUENCES AND RISKS OF ROCK AVALANCHES AND RELATED FLOOD WAVES

Preliminary estimates of rock-avalanche hazard indicate that several zones have avalanche probabilities of between 10^{-3} and 10^{-4} pr. annum. Probabilities of related flood waves along fjord shorelines in some areas are estimated to reach maximum values in the order of, or even above 10^{-3} pr. annum. However, the material available at present is insufficient for compiling maps of predicted probabilities of rock-avalanche hazard and related flood waves.

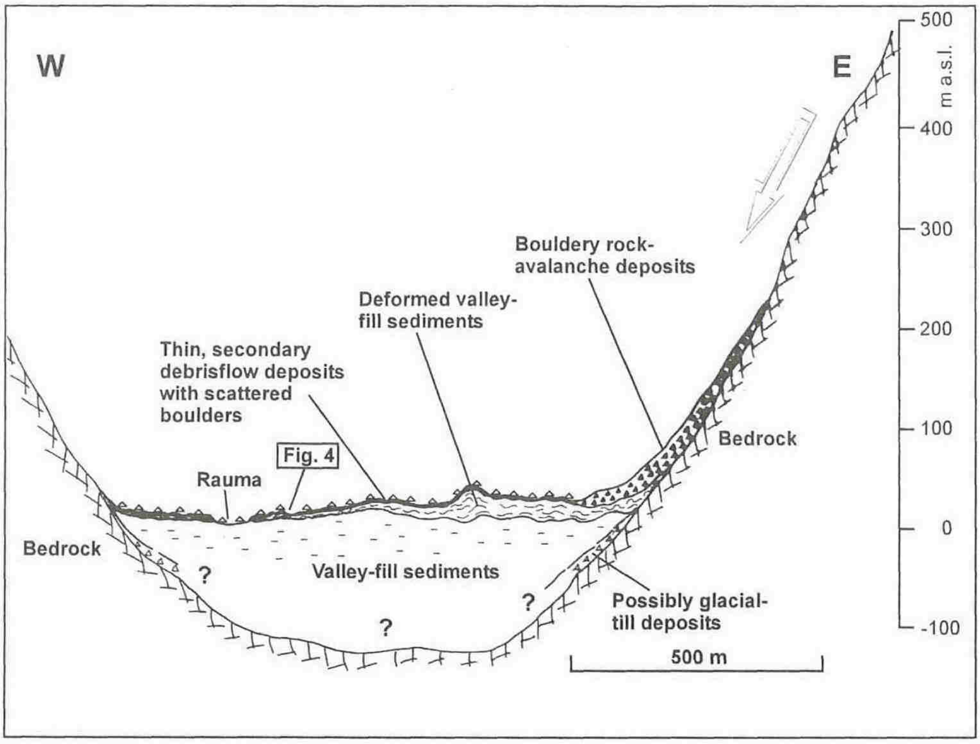

Fig. 3. A simplified model of the avalanche at Venje in Romsdalen. The rock-avalanche impact generated a secondary debrisflow with a large run-out distance. Note also the large deformations of the valley-fill sediments. For locality (see Fig. 2).

The commonly used limit of avalanche hazard in Norway for new, ordinary buildings is an event probability of 10^{-3} pr annum (Ministry of Local Government and Regional Development, 1997). But what risk does a distinct avalanche-probability actually represent? Risk is a product of the probability of an unwanted event and the consequences of the event. A given avalanche probability does not normally give an equivalent death probability for a person living in the hazard zone. If this were the case, an avalanche-related death probability of, e.g., 10^{-3} pr annum, would represent a very high risk. The annual death-rate in the traffic in Norway, for example, is in the order of $6 \cdot 10^{-5}$ (1/15 000). The risk of avalanches demolishing settlements is an absolutely 'involuntarily' risk; thus, it should be as low as possible.

The annual death probability for a given person living in an avalanche- or wave-hazard zone (P), can be expressed as a product of three probabilities:

$$P = P_1 \cdot P_2 \cdot P_3,$$

with P_1 being the annual probability of an avalanche or flood wave, P_2 the probability of the person being at home, and P_3 the probability of the present person being killed. We have used the value 0.65 for P_2. P_3 is the 'dark horse' in this equation. It will vary with the type and magnitude of the avalanche, but also with the position of the building relative to the path of the avalanche. Experience from the last 15 years in Møre & Romsdal indicates that an average value of $P_3 = 0.1$ could be used, except for large rock avalanches. The values $P_1 = 10^{-3}$, $P_2 = 0{,}65$ and $P_3 = 0{,}1$ will give P a value which is in the order of the annual traffic death-rate in Norway (see Table 1).

Rock avalanches will naturally generate extensive damage within the avalanche path, and the value of P_3 will be approximately 1.0. If we consider the yearly death-rate in traffic as an acceptable limit for P, the avalanche probability (P_1) should not be above 10^{-4} pr annum (Table 1).

In cases of avalanche-generated waves, P_3 will vary with the wave magnitude, and the position of the buildings within the wave zone. The disaster in Tafjorden in 1934 produced extensive material damage (Furseth, 1985), and we consider buildings in general to represent some form of limited protection. Thus, 0.5 might be a realistic, average value for P_3. If so, an event probability (P_1) of 10^{-3} pr annum will give a relatively high personal risk (see Table 1).

Table 1. Annual death probabilities ($P=P_1 \cdot P_2 \cdot P_3$, explained in the text) for a fixed person, grouped after different hazard zones of rock avalanches or flood waves. $P_2 = 0.65$ in all examples.

P_3 (dependent on the type of avalanche):	P, with $P_1 = 10^{-3}$	P, with $P_1 = 10^{-4}$
0.1 ('normal' avalanches)	$6.5 \cdot 10^{-5}$	$0.7 \cdot 10^{-5}$
0.5 (flood waves)	$3.3 \cdot 10^{-4}$	$3.3 \cdot 10^{-5}$
1.0 (rock avalanches)	$6.5 \cdot 10^{-4}$	$6.5 \cdot 10^{-5}$
annual traffic death-rate in Norway: $\sim 6 \cdot 10^{-5}$		

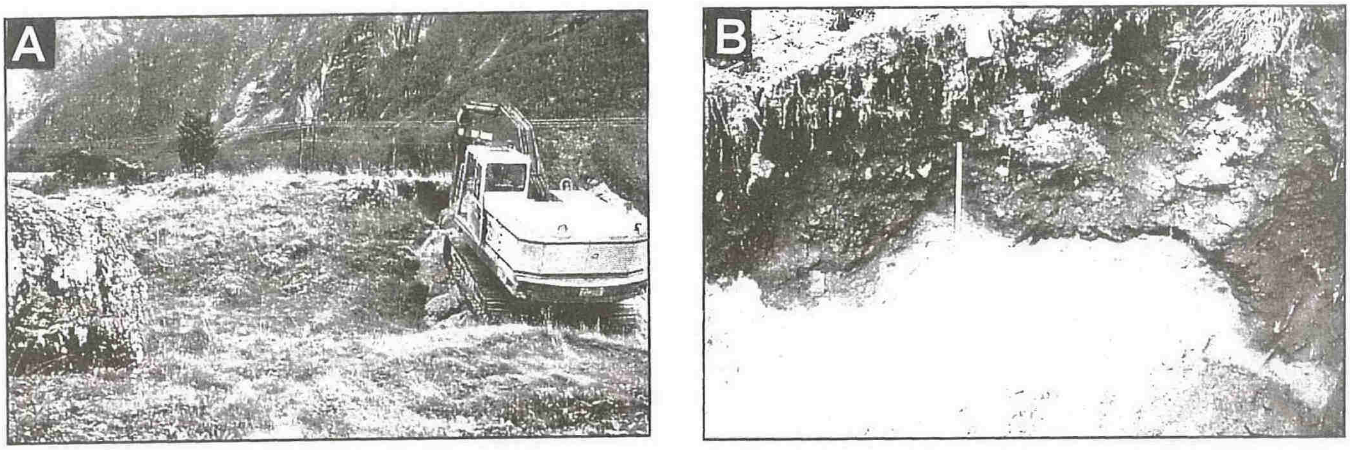

Fig. 4. The Vemje avalanche (see locality in Fig. 3). (A) The surface of the hummocky terrain with a large block in the foreground to the left; (B) Debrisflow deposits capping deformed sandy valley-fill sediments. The stick (scale) is 1 m.

Rock avalanches and related flood waves generally affect large areas. Due to the possible consequences for persons, buildings, and infrastructures, rock avalanches and related flood waves, thus represent a very high risk for the community. The commonly used limit in Norway of an event probability (P1) of 10^{-3} pr. annum is, as we see it, below that of reality. A probability of 10^{-4} pr annum is considered to be a more acceptable limit.

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