

SPATIAL DISTRIBUTION OF ROCKSLIDE DEPOSITS AND THEIR MORPHOLOGICAL FEATURES SUGGEST TIMING AND PALAEO-ENVIRONMENTAL CONDITIONS FOR ROCK SLOPE FAILURES IN INNERDALEN AND INNFIJORDDALEN, MØRE OG ROMSDAL COUNTY, WESTERN NORWAY

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ABSTRACT

Rock avalanches dropping into a fjord or lake, initiating displacement waves or damming narrow valleys, are severe hazard scenarios in glacial overprinted mountain areas and have strong influence on the quaternary valley development. Several investigations show, that the collapse of a rock avalanche increases the probability for prospective similar events at the same rock slope. Moreover, data for the Storfjord area in Western Norway indicates that catastrophic rockslides were more frequent during late Pleistocene than in Holocene. This study is to test these hypotheses, to reconstruct the palaeo-environmental conditions of multiple landslide deposits, and to study the effect of rock avalanches on decaying ice bodies and landforms influenced by isostatic rebound. For investigation, the two valleys of Innerdalen and Innfjorddalen in Western Norway were chosen, where multiple landslide deposits have developed on the valley floor. Its spatial and temporal distribution is studied by detailed field investigations, including morphological and sedimentological analyses. In Innerdalen glacial and postglacial rock avalanches have occurred, whereas the first was partly deposited on the decaying ice body. In Innfjorddalen several post glacial rock avalanches occurred, whereas the first was deposited on highly water saturated valley fill sediments. In both valleys distinct morphological features have developed.

KEY WORDS: multiple landslide deposits, rock avalanche, morphological analyses, palaeo-environmental conditions, Western Norway

INTRODUCTION

In glacial overprinted mountain areas like in Western Norway, important hazards are large rock slope instabilities that might develop into large rock avalanches. The most severe scenarios are large volumes of rock dropping into a fjord or lake, causing displacement waves or damming narrow valleys causing upstream and potential downstream flooding, (HERMANN *et alii*, 2004; EVANS *et alii*, 2011; HERMANN *et alii*, 2011a; HERMANN *et alii*, 2012; HERMANN & LONGVA, 2012).

Furthermore, large rock avalanches and their deposits which developed across valleys and built dams play a major role in late quaternary landscape evolution (HEWITT *et alii*, 2011). The detailed study of multiple landslide deposits as for example presented in (HERMANN *et alii*, 2006; WELKNER *et alii*, 2010; BLAIS-STEVENS *et alii*, 2011) provides important information to understand palaeo-environmental conditions, failure mechanisms, activity of steep rock slopes, and to estimate recurrence periods for similar events which is important for hazard assessments.

Data on the temporal distribution of rockslide deposits in Storfjord (Møre og Romsdal County, Western Norway) suggest that catastrophic rockslides were larger and more frequent during the late Pleistocene than in

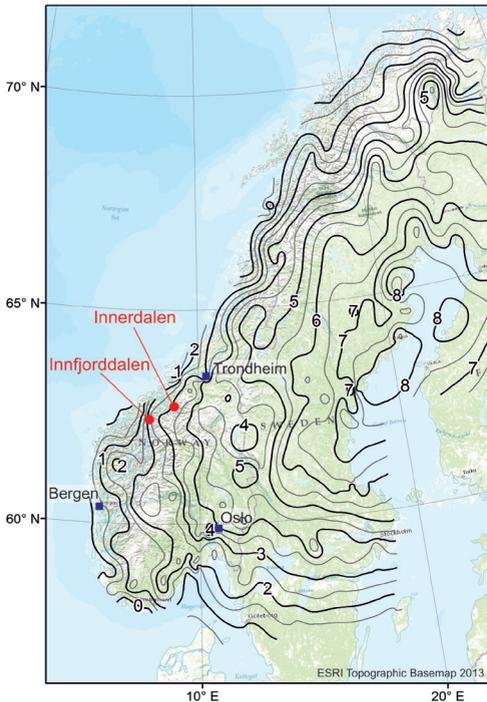


Fig. 1 - Map of Norway showing the locations of the study areas (red dots) and the current apparent uplift of Fennoscandia. Values are uplift rates in mm/yr following DEHLS *et alii* (2000)

the Holocene (HERMANN & LONGVA, 2012). With this study we want to test if similar temporal pattern can also be expected for other valleys in Norway. In addition we aim to study the effect of rock avalanching on decaying ice bodies and landforms subjected to isostatic rebound.

We selected the Innerdalen and Innfjorddalen in Møre og Romsdal County in western Norway, where multiple rock avalanche deposits occur. During field investigations the spatial distribution of the multiple rockslide deposits, soft sediments and the morphological structures were mapped. The different sediments were described by plotting grain size and grain shape. Furthermore, samples for dating the different deposits with in-situ terrestrial cosmogenic nuclides were taken to determine the exact chronological distribution.

The main aims of this publication are:

- 1) to distinguish the multiple rock avalanche deposits spatially and stratigraphically,
- 2) to reconstruct the palaeo-environmental conditions under which all events formed,
- 3) to describe the facies of rock avalanches onto different type of substrate.

STUDY AREA

The two study areas, the valleys of Innerdalen and Innfjorddalen, are located in Møre og Romsdal County in Western Norway (Fig 1).

These areas are located in the Western Gneiss Region of Norway. The exposed rocks are Proterozoic gneisses, mainly orthogneisses, partly overlain by continental and oceanic sediments which have been affected by the Caledonian orogeny (HACKER *et alii*, 2010). The bedrock and the deposits in the study areas are composed out of the typical hard gneisses of this region. Based on the geological map of Ålesund (TVETEN *et alii*, 1998), the main rock types can be described as follows:

In the Innerdalen area, the disclosed rocks consist of three main lithologies, 1) coarse-grained granitic gneiss, augengneiss, gneissic granite, 2) meta-arkose, quartzite and 3) coarse to fine-grained granitic to dioritic, biotite containing gneiss. The additional quartzitic rock layers in Innerdalen are located at the border of a main thrust fault. The multiple landslide deposits contain all of these lithologies.

The disclosed lithologies in the Innfjorddalen area are 1) coarse-grained granitic gneiss, augengneiss, gneissic granite, 2) sillimanit containing quartzitic gneiss, partly containing kyanite and 3) undifferentiated gneiss, mostly quartzdioritic, partly migmatitic.

The quaternary landscape evolution is also important for the presented study of rock avalanches onto different substrates. In Western Norway the present distribution of marine sediments at elevations up to 220 m a.s.l. show that the land mass near the shoreline partly raised up for several hundred meters since the Last Glacial Maximum (HERMANN *et alii*, 2012). This development is part of the dome-like postglacial uplift of Fennoscandia, which is explained generally as movements of solid earth originated in glacioisostatic rebound due to melting of the thick ice sheets and attended unloading of the crust (FJELDSKAAR *et alii*, 2000). This uplift is a still ongoing process and following the neotectonic map of Norway (DEHLS *et alii*, 2000), the present apparent uplift rates are up to 8 mm/yr, showing values of 2 to 3 mm/yr for the study areas (Fig 1).

Therefore, the glaciation during the last ice age and the following deglaciation, the crustal uplift and sea level changes have enormous influence on the landscape evolution due to deep valley incisions, changes in sedimentation, erosion, and stress fields in rock slopes as well as induced seismicity.

Both, the Innerdalen and the Innfjorddalen are steep glacial affected valleys which show high topographic relief with mean elevation differences of around 1,000 m between valley bottom and surrounded mountain crests.

METHODS

In order to determine and describe the different multiple landslide deposits in the two study areas and to reconstruct the palaeo-environmental conditions an area of ~16 km² was mapped in the valley of Innerdalen and ~4 km² in Innfjorddalen (Fig. 2, Fig. 5).

We mapped the spatial distribution of Late Pleistocene and Holocene deposits and their geomorphological features and, described their grain size and shape by statistically sampling of 100 randomly connected boulders. We used the six roundness classes after Folk as described in (BOGGS, 2001). For Innerdalen such data was collected at 75 sample sites, distributed in the different landslide and moraine deposits and 13 sample sites for the multiple deposits in Innfjorddalen.

We also assessed the mean thickness of the deposits to estimate volumes of different events.

The Fahrböschung angle (angle between the horizontal and the connecting line of main scarp's upper limit and the deposit's most distal part) was calculated for the rock avalanche deposits, showing the apparent friction angle (HEIM, 1932).

In order to determine the absolute ages of the multiple deposits and therefore to reconstruct the valley history and to estimate the recurrent period, surface exposure dating with in-situ terrestrial cosmogenic nuclides using ¹⁰Be were taken in both valleys. Results are not yet available.

RESULTS AND DISCUSSION

DEPOSITS WITHIN THE INNERDALEN

In Innerdalen multiple deposits composed of rock boulders several meter in diameter occur. They can be divided in two groups: a) continuous rock avalanche deposits with typical lobate shapes with boulders several meters to tens of meters in diameter that cover the entire surface of the deposits, b) suspicious discontinuous boulder deposits that form various morphological units, and that are separated from each other by several km, and that are covered by almost identi-

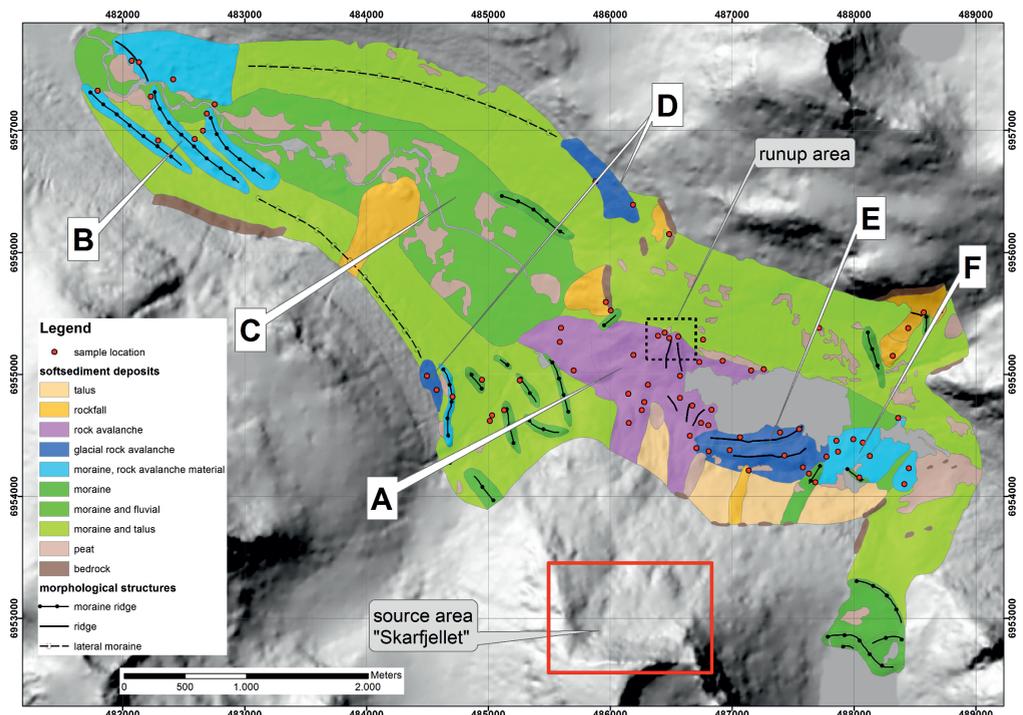


Fig. 2 - Map of multiple landslide deposits in Innerdalen. A-F mark the main deposits described in the text. The source area of the multiple landslides is marked with red rectangle. The runup area is marked with dotted rectangle

cal boulders. We divided all deposits in six units, A-F (Fig. 2, Fig. 3).

A) This is a typical lobate rock avalanche deposit spanning the valley bottom and impounding a lake, B) three prominent frontal moraine ridges in the outer valley, C) scattered isolated hills composed of boulders on the valley floor in the lower part of Innerdalen, D) isolated patches of boulders on the slope several 100 m above the valley floor, E) distinctive valley parallel ridges along and F) flat boulder patches in the upper Innerdalen. In total an area of around 2.4 km² is covered by these deposits and their total estimated volume is $\sim 64 \times 10^6$ m³. The main geometrical characteristics of the

multiple landslide deposits are summarized in Tab. 1. ROCK AVALANCHE DEPOSIT ALONG VALLEY BOTTOM THAT IMPOUNDS A LAKE (A)

The rock avalanche deposit (A) stretches on the valley floor over a length of ~ 1700 m and a width of 1100 m in the upper part and 270 m (mean 800 m) in the most distal part, covering an area of around 1,303,000 m². That represents a volume of $\sim 39 \times 10^6$ m³ (Tab. 1). The deposit shows lateral levees and frontal rims. It covers the valley on its whole width and indicates a runup on the opposite valley slope of around 65 m. The deposit forms a natural dam that impounds a lake. Furthermore the deposit part-

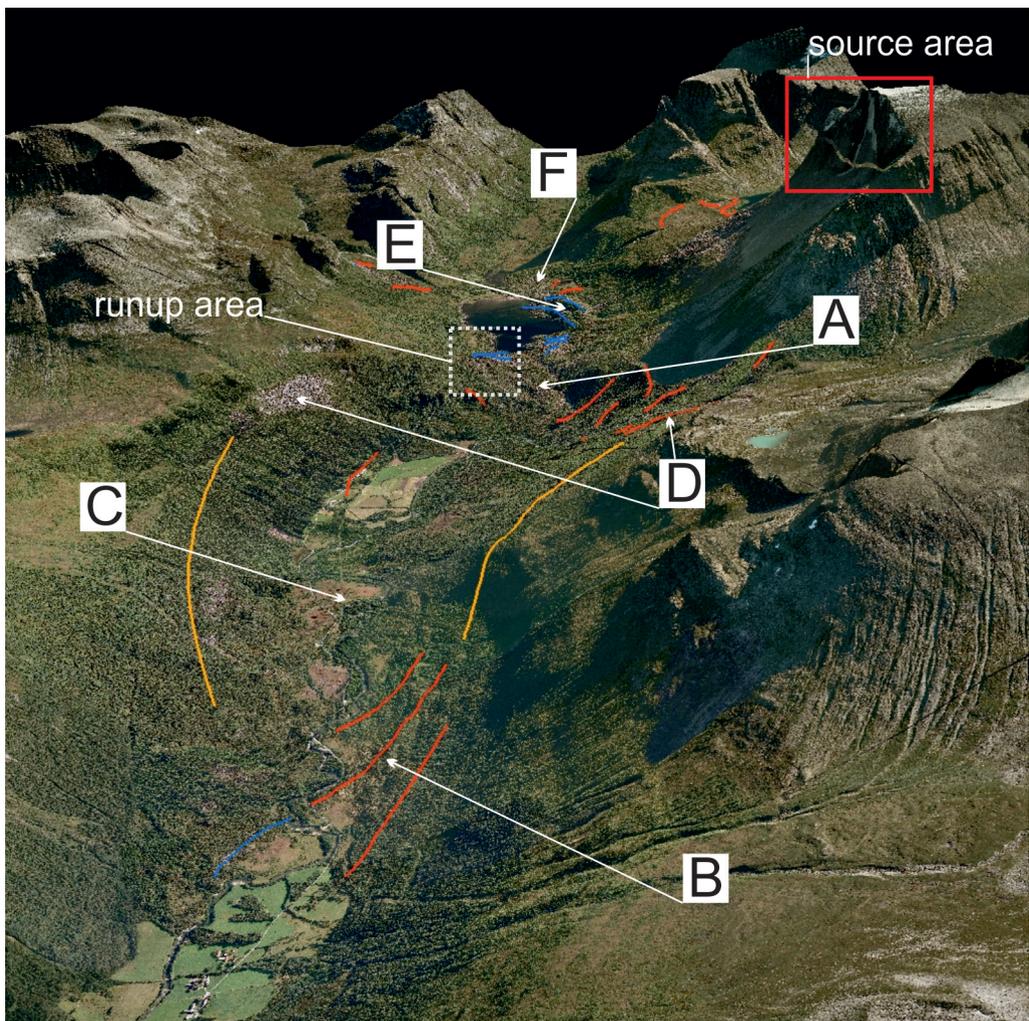


Fig. 3 - Oblique view of Innerdalen valley showing the main part of the multiple landslide deposits. View direction to WSW. A - F mark the main deposits described in text. The rock face of the source area is marked with red rectangle, the runup with dotted rectangle. Orange lines mark lateral moraines, red lines mark the frontal moraines

ly covers moraine deposits. The source area of this event is located at the steep northern rock face of the “Skarfjellet” south of the lake (Fig. 3). The horizontal distance of the top of the scarp to the end of the runup deposit is ~3270 m and the elevation difference is ~1290 m. Therefore the Fahrböschung angle is 21.5°. The distal part of the deposit has a distance from the source of 3320 m and an elevation difference of 1460 m, therefore is the Fahrböschung angle 23.7°. The mean grain size of this rock-avalanche deposit is 1.5 m. The distribution shows a concentration between 0.5 and 2 m with maximum size boulders >10 m in diameter. The mean roundness is subangular (57%) to angular (37%).

PROMINENT FRONTAL MORAINE RIDGES IN THE OUTER VALLEY (B)

In the outer part of the valley three distinct frontal moraines (B) occur that are closely spaced. These are one km long and have elevations of 12 to 15 m above the current valley floor. The mean width of the deposits ranges from 100 to 140 m. These moraine deposits cover an area of around 395,000 m² and contain an estimated volume of 7.3x10⁶ m³. The sedimentological features of the three ridges are identical. They are entirely covered by boulders several meters to tens of meters in size with no finer grained material (matrix) visible. However in fluvial cuts the core is visible that contains a sandy matrix with angular but also well rounded grains (Fig. 4). The deposits have a mean grain size of ~1 m with clasts that exceed 5 m in diameter. According to the grain roundness they show normal distribution with a peak for subangular boulders (54%). Angular (25%) and subrounded (21%) boulders are almost equal distributed.

SCATTERED ISOLATED HILLS ON VALLEY FLOOR (C)

Within the area between deposit (A) and (B) the valley floor is characterized by scattered single isolated hills (C) of boulder accumulations only few meters high and several meters in diameter which occur scattered on the normal valley sediments. These boulders are surrounded by valley fill material.

ISOLATED BOULDER PATCH ON THE SLOPE ABOVE THE VALLEY FLOOR (D)

Within the slope and ~270 m to 370 m above the valley floor several-100-m²-large boulder fields occur on both sides of the valley that are separated from each other. These patches lower towards the outer valley and terminate in the frontal moraines. The most prominent boulder patch is located on the northern valley slope. It covers an area of 147,000 m². Its estimated volume is 2.2x10⁶ m³ (Tab. 1). Another isolated boulder patch is located on the opposite southern valley slope at similar elevation but it has a smaller extent (Fig. 2). It is obvious that there exists no connection to any possible scarp upslope at any of the localities (Fig. 3). The grain size distribution of these deposits shows a mean diameter of ~1 m with maximum clast size reaching >10 m. The deposit shows a relatively wide and not distinct grain roundness distribution with angular (46%) and subangular (43%) boulders with a tendency towards very angular boulders (12%).

PROMINENT VALLEY PARALLEL RIDGES ALONG THE LAKE (E)

There are two prominent morphological ridges parallel to the valley along the southern shore of the lake. The lower one (E1), has a length of 870

Area	Description	Mean est. thickness [m]	Measured area [m ²]	Est. Volume [m ³]	Fahrböschung angle [°]
A	Rock avalanche deposit	30	1,302,884	39,086,520	21.5 (runup), 23.7 (distal)
B	1 st moraine	20	115,496	2,309,920	
	2 nd moraine	20	152,147	3,042,940	
	3 rd moraine	15	127,646	1,914,690	
D	Isolated boulder patch	15	146,669	2,200,035	
E..1	1 st ridge	40	101,559	4,062,360	
...2	2 nd ridge	50	167,523	8,376,150	
F	Flat boulder patch	10	264,592	2,645,920	
Sum			2,378,516	63,638,535	

Tab. 1 - Geometrical characteristics of multiple landslide deposits in Innerdalen

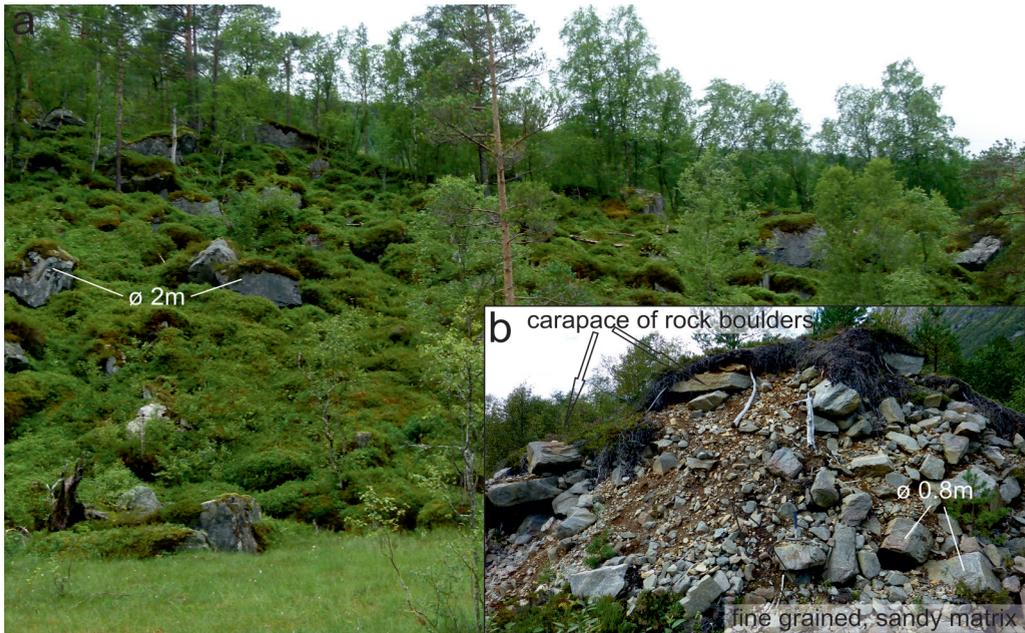


Fig. 4 - Morphological end moraine ridge in Innerdalen, around 12 meter high (a). Four meter high fluvial cut (b) shows fine grained sandy matrix in subsurface. For scale consider mean diameter of visible boulders marked in (a) and (b)

m and a mean width of 110 m and a mean height of 30 m above the lake (water level 395 m a.s.l.). Its deposit covers an area of 102,000 m². The second higher ridge (E2) is 1060 m long, 150 m wide and 50 m higher than the shoreline. The deposit spans an area of around 168,000 m². The depth of the lake is at least 18 m in the front part (west). Therefore the mean thickness of the deposit of the lower ridge can be estimated to be 40 m and 50 m for the higher ridge. This results in a volume of 4x10⁶ m³ for the lower and 8.4x10⁶ m³ for the upper ridge (Tab. 1). No deposits of similar composition can be found on the opposite (northern) shore of the lake. The material of the ridges (deposit E) is similar. They show a mean grain size of surficial boulders of around 1.5 m. The roundness of boulders for both ridges shows a distinct peak for subangular boulders (76% for E1 and 60% for E2). In addition also angular boulders occur whereas its amount is higher in E2 (34%) and there also few subrounded boulders exist.

FLAT BOULDER PATCH SE OF LAKE (F)

At the SE boarder of the lake patches of boulder deposits occur (F). Morphologically these patches are relatively flat (no ridges). The depo-

sit covers an area of ~265,000 m² and its mean thickness is estimated with 10m, therefore it is containing a volume of ~2.6x10⁶ m³. The mean grain size of deposit (F) is around 1 m with no distinct concentration. This deposit shows a widely distribution of grain roundness with a peak for subangular (58%) and angular boulders (30%), but also subrounded (10%) and less very angular (2%) boulders occur.

DISCUSSION OF DEPOSITS WITHIN THE INNERDDALEN

In this glacial affected, U-shaped valley, multiple landslide deposits occur that have similar sedimentological features of their bouldery carapace (grain size, grain roundness). However, they show strong differences in the morphology of the deposits thus strongly differing palaeo-environmental conditions of their formation.

The post glacial event is a very distinct rock avalanche deposit (A). It shows the typical morphological characters of a rock avalanche with the carapace composed of large rock boulders of subangular (57%) and angular (37%) forms. This indicates that the deposit was not reworked after deposition. In addition, the lateral levees and frontal rim (DUFRESNE & DAVIES, 2009) with a run-up of 65 meters indicate the typical high mobility

of a rock avalanche. The source area can be located at the steep northern rock face of the "Skarfjellet" mountain. Evidence for its postglacial origin is that the deposit partly covers some moraine deposits and that it fills the valley floor over its whole width. This deposit dams a lake that is evidently stable since formation. Following the description of rockslide dams of (HERMANN *et alii*, 2011b) this dam can be classified as an IIa ii 2 event.

Grain sizes of the carapaces of other landforms as well as grain roundness suggest a further rock avalanche event in the valley. For example are the three closely spaced distinct morphological moraine ridges (B) also covered by a carapace of rock boulders several meters in diameter. These deposits (B) show the smallest mean grain size of boulders (chiefly <0.5 to 1 m) and mainly subangular (54%) forms however with a trend towards subrounded forms (21%). This suggests more reworking and mixture of material during transport has taken place. In fluvial cuts it gets visible that the moraine material is not pure rock avalanche material but that the boulders are imbedded in fine grained, sandy matrix. Suspicious are also the isolated hills composed of rock boulders surrounded by fluvial sediments (C) that are scattered in the whole valley bottom between the post glacial rock avalanche deposit (A) and the moraine ridges (B).

The isolated boulder patches on both sides of the valley (D) suggest that these landforms formed when a landform occupied that valley that does not exist anymore. The mean elevation of around 350 m above valley suggests the thickness of that landform at that time. The high amount of angular (46%) and even very angular boulders shows less reworking of those boulder patches.

Both of the valley parallel ridges (E) are also entirely covered by subangular boulders (76%) and no subrounded boulders could be found, that indicates no significant transportation. Their location at only one side of the lake suggests a process that leads to concentration of sediments into these ridges.

Therefore we interpret that a rock avalanche occurred in this valley, when it was filled by a glacier at the end of the Younger Dryas. This rock avalanche would have traveled over the glacier and deposited the bouldery patches above the valley floor on unglaciated ground, thus marking the thickness of the ice body at that time. However most of the material would have been deposited onto the glacier where it was redeposited with the

normal supra- and subglacial load into the three closely spaced frontal moraine ridges. According to (HEWITT, 2009; SHUGAR & CLAGUE, 2011) rock avalanche material that covers the glacier protects the ice from melting. In addition fine grained material is washed out by supraglacial processes and therefore rock boulders are concentrated. Following our model, the formation of the two morphological ridges (D) is related to that process. A decaying ice body as at the end of the Younger Dryas is rather stagnant. Insulation on the N side and hence S-facing side of a valley would cause such a stagnant ice body decay asymmetrically leading to the concentration of boulders on the S (and thus N facing) valley side.

We see the boulder patch (deposit F) east and up-valley disconnected to this process, although composed of similar material (grain size and grain roundness). Due to its relatively flat surface, and its coincidence with moraine deposits, we suspect that this material is related to retransported rock fall and rock avalanche material from higher up in the catchment as catastrophic landslides are also very abundant in the upper catchment (HERMANN *et alii*, 2013).

DEPOSITS WITHIN THE INNFJORDDALEN

In the lower Innfjorddalen a succession of multiple rock avalanche deposits with lobate forms overly each other. These are covered with rock boulders, meter to several meters in diameter. The second of those deposits is damming a lake, however also the older deposits span the entire width of the valley suggesting that similar dams also existed before (Fig. 5).

Several distinguishable morphological features can be mapped: a marine terrace deposit (A), a first stratigraphically lowest rock avalanche deposit that can be divided into a continuous deposit (B) in the upper valley and a distal part (E). In between there are an area of deformed (C) and an area of undeformed (D) valley fill deposits. The proximal part of the stratigraphically lowest rock avalanche deposit is overlain by a second rock avalanche deposit with a smaller extension (F) and these are overlain by a third rock fall deposit with much smaller extension (G).

MARINE TERRACE DEPOSITS (A)

A distinct terrace occurs in the inner part of the valley. This deposit (A) is composed out of fine grained material, chiefly rounded and well rounded sand and gravel and shows typical graded and with

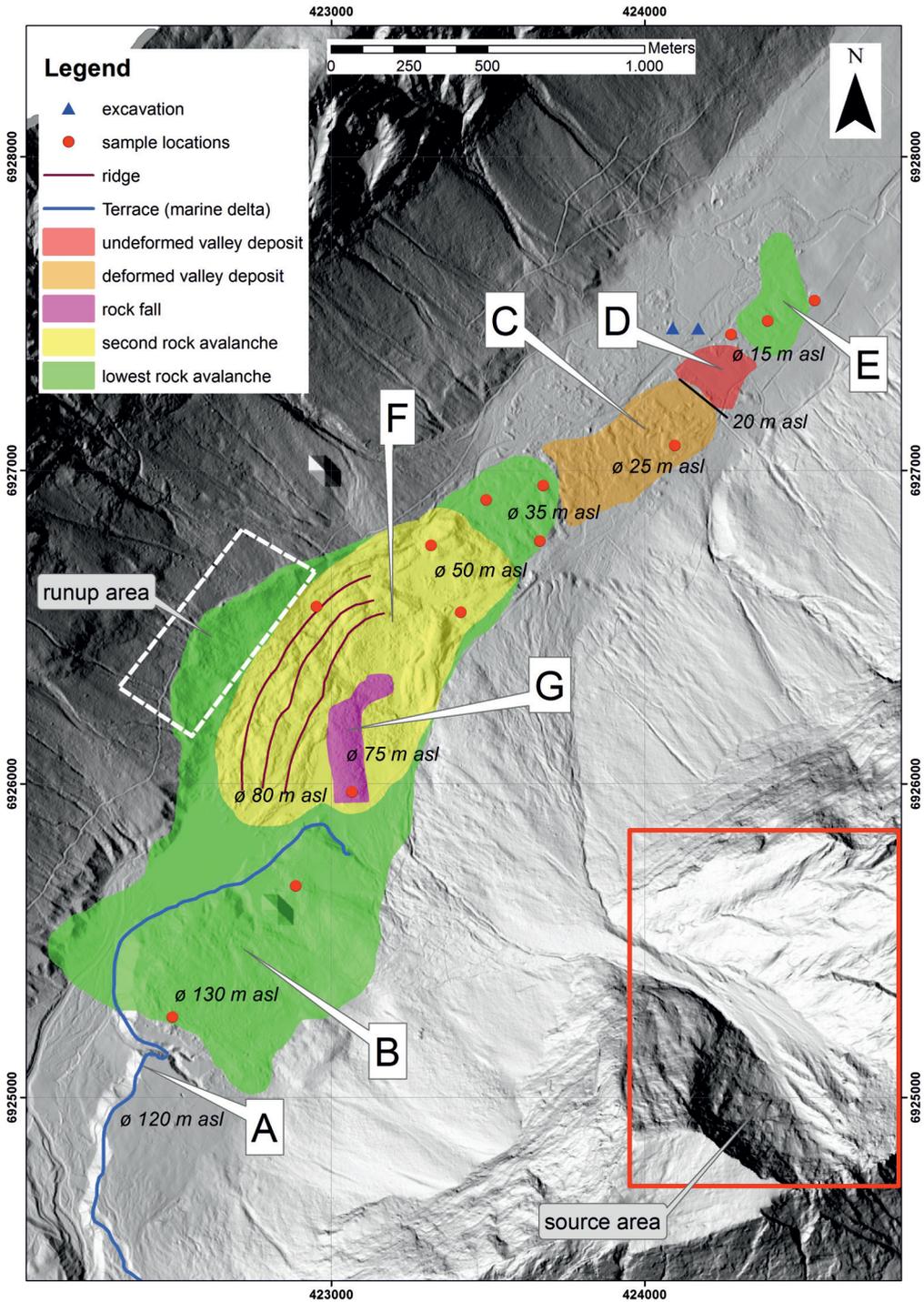


Fig. 5 - Map of multiple Holocene deposits in Innfjordalen. A - G mark the areas which are described in the text. The source area of the multiple rock avalanches and rock falls is marked with red rectangle. The runup area (~110 m above valley floor) is marked with a dotted rectangle. Values showing mean elevation of deposits above sea level

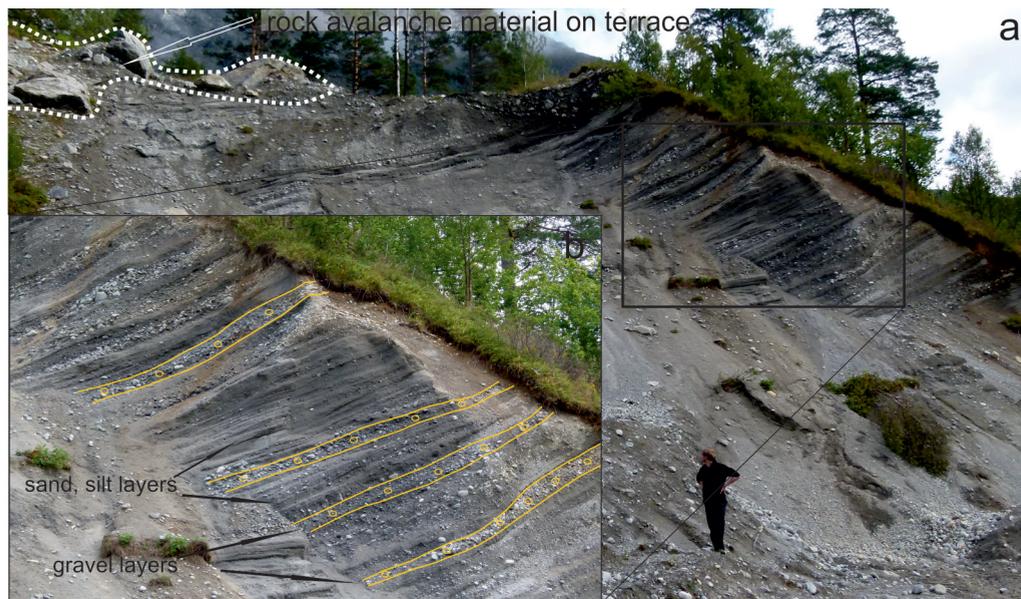


Fig. 6 - Marine terrace deposit in Innfjorddalen valley. Rock avalanche material is deposited on top of the terrace at 120 m a.s.l. (upper left corner) (a). Typical bedding structures of a propagating delta are visible in (b). View towards SSE. For scale consider Geologist in lower right of (a)

Area	Description	Mean est. thickness [m]	Measured Area [m ²]	Est. Volume [m ³]	Mean Elevation [m asl]	Fahrböschung angle [°]
B	Continuous deposit of lowest rock avalanche	15	1,407,376	21,110,640	130 to 35	22.3
E	Distal part of lowest rock avalanche deposit (isolated hills)	5	50,393	251,965	15	19.6
F	Second rock avalanche	10	542,555	5,425,550	80 to 50	25.1
G	Rock fall	5	38,999	194,995	75	28.8
Sum			2,039,323	48,351,180		

Tab. 2 - Geometrical characteristics of multiple landslide deposits in Innfjorddalen

25 degrees inclined bedding structures of a propagating marine delta (Fig. 6). This terrace surface lies at an altitude of 120 m a.s.l., marking an isostatic rebound of that area of at least 120 m. All rock-avalanche deposits lie on top of this terrace.

SUCCESSION OF MULTIPLE ROCK AVALANCHE AND ROCK FALL DEPOSITS (B, F, G)

The deposits of the lowest (B) and intermediate (F) rock avalanche and the upper (G) rock fall deposit are composed of rock boulders, several meters in diameter building a typical carapace. The deposit (B) covers an area of 1,407,000 m² and has an estimated volume of 21x10⁶ m³ (Tab. 2). This deposit shows a runup of 110 m on the opposite valley slope. It is the largest deposit and has

a Fahrböschung angle of 22.3° (only including the continuous deposit B), which is smaller than those of the other events. The elevations above sea level of the deposits in the inner valley (proximal part) are 130 m and only 35 m in the outer valley (most distal part).

The intermediate rock avalanche deposit (F) is the second largest with a volume of 5.4x10⁶ m³ covering an area of 542,500 m². The Fahrböschung angle of this deposit is 25.1°. Altitude of this deposit above sea level is 80 m down to 50 m. This deposit is damming a lake.

The uppermost deposit (G) that partly covers the intermediate is much smaller with an area of 39,000 m², and a volume of 0.19x10⁶ m³. This deposit is thus a rock fall deposit. This is also indicated by the Fahrböschung angle of 28.8° and therefore that of a rock fall. It is lo-

cated at 75 m a.s.l.

Deposit (B) has a mean grain size of surficial boulders of 1.5 m in diameter with a spread from <0.5 to 10 m. The grain roundness is subangular with (60%) to angular and subrounded boulders with 20% each. Deposit (F) has a mean grain size of 2 m. Boulders also range from <0.5 to 10 m. These boulders are similarly to deposit (B) subangular (around 65%) with 26% of angular and 5% of subrounded clasts. In contrast to deposits (B) and (F) the rock fall deposit (G) shows a different distribution. The mean grain size of large boulders is 4.5 m. Although there is a concentration of boulders between 2-5 m in this deposit all of the grain sizes are well distributed in the range between <0.5 up to 10 m. Compared to the other deposits they show a relatively high amount of boulders >5 m. Angularity of boulders is more pronounced with 68% angular and 23% subangular boulders.

DEFORMED (C) AND (D) UNDEFORMED VALLEY FILL DEPOSITS

The stratigraphically lowest rock avalanche deposit is split into two parts by valley fill deposits that are deformed valley deposits (C) between 30 and 20 m a.s.l. and undeformed below 20 m a.s.l. In the deformed area (C) no connected boulder deposits occur, however isolated boulders could be found. The surface is undulated with small “valleys and ridges” that are oriented perpendicular to the axis of the valley. Within those deposits and along its frontal part where the undulated valley floor deposits limit towards the undeformed valley fill deposits (D), two excavations (see Fig. 5 for location)

were opened to describe the deformation of valley fill deposit (see Fig. 7 as an example). The excavation shows five different units which are composed of silt, sand, pebbles and gravel. Layered silt and sand (E1) is covering the top of most of the excavation including a channel (E2) that occurs only in one part. Most of the excavation is characterized by well homogenized deposits without any sedimentological structures such as layering. Within this matrix there float two islands of gravelly deposits E3 and E5 also without any layering. The homogenized deposit and the islands of gravel deposits are underlain by layered sand and silt E4.

The lower part of the valley fill deposit (15 m a.s.l.) is undeformed (D). Again no rock boulders are present.

The mean diameter of the boulders imbedded in this undulated surface (C) is 1m. Its grain size distribution shows a characteristic peak for grain sizes <0.5 to 1 m. Biggest boulders found are 6m in diameter. Boulders are subrounded (58%) and subangular (33%).

ISOLATED ISLANDS OF ROCK AVALANCHE MATERIAL (E)

Isolated hills composed of rock avalanche boulders (E) lie in the outer part of the valley at 15 m a.s.l.. This deposit covers an area of 50,000 m² and has a volume of 0.25x10⁶ m³ (Tab. 2). The deposit shows rather isolated centric hills, which are composed out of rock boulders of meters to several meter diameter embedded in fine grained material. These hills are up to three meters high and

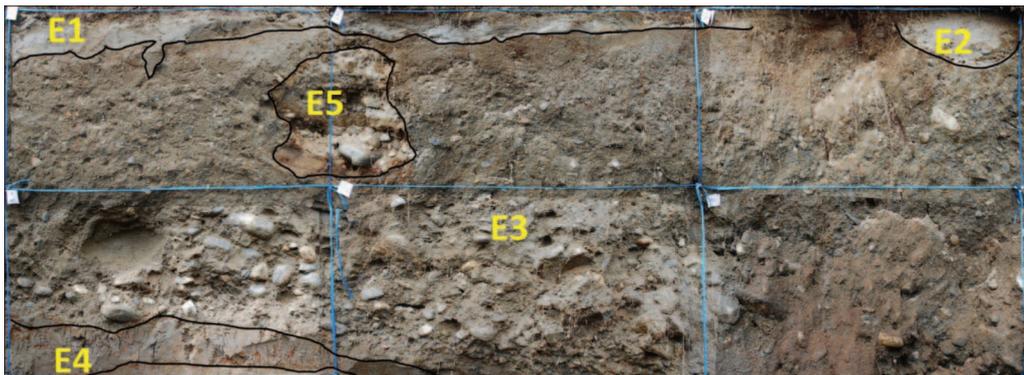


Fig. 7 - Exemplary excavation of the deformed valley fill deposits at the border between deformed and undeformed valley sediments. The blue raster shows 6 cells (1 m length, 0.5 m width). (E1, E2: layered silt and sand; E3, E5: islands of gravelly deposits without layering; E4: layered sand and silt)

its mean thickness is estimated in the field to be 5 m (Fig. 8). The grain size distribution of deposit (E) is similar to (B) and (F). The mean grain size is 1m, with a peak at 0.5-2 m. Boulders >3.5 m are less common but exceptional boulders are 10 m large. The boulders are subrounded (57%) to subangular (29%) with also some rounded boulders (14%) present.

DISCUSSION OF DEPOSITS WITHIN THE INNFIJORDDALEN

The multiple landslide deposits in Innfjorddalen show a simple succession where the different rock avalanche deposits and the rock falls are deposited on top of each other. The timing of the events is poorly understood. However a historical rock failure in 1665 is described in historical records from that valley in the church books as the event caused the death of farmers, not by the direct impact but due to suffocation due to the enormous dust (FURSETH, 2006). We interpret that this age is the age of the youngest rock slope failure that forms deposit (G).

Further constrain on the age of the oldest deposits can be derived from the valley fill deposits and their elevation a.s.l. This deposit split into two parts. While the proximal deposit is continuous the

distal part occurs in form of separated island hills of rock avalanche material. Following this interpretation the Fahrböschung angle of the whole event is 19.6°. Such island hills have been also described in the distal part of the Flims rock avalanche deposits in the Swiss Alps and called there “Toma-hills” (VON POSCHINGER, 2002). The Flims rock-avalanche is interpreted to have dropped into a lake (VON POSCHINGER *et alii*, 2006) and also at that site the frontal hills (Toma-hills) are separated from the main body of the rock avalanche by valley fill deposits that have no sedimentary structure and are strongly homogenized (Bonaduz gravel). Similarly to Flims the deformed valley fill deposits in Innfjorddalen are strongly homogenized and lack sedimentary structure. Therefore, we interpret that similar to the Flims rock avalanche also the oldest rock avalanche in the Innfjorddalen dropped in its distal part into a water body. As no morphological landforms as moraine dams or rockslide dams exist in the lower Innfjorddalen valley the only water body could have been the fjord itself. The lower limit of deformation structures in the valley fill lie at 20 m a.s.l. This line is interpreted to represent the sea level at the time of the oldest rock avalanche. Following this interpretation, this rock avalanche would have dropped into

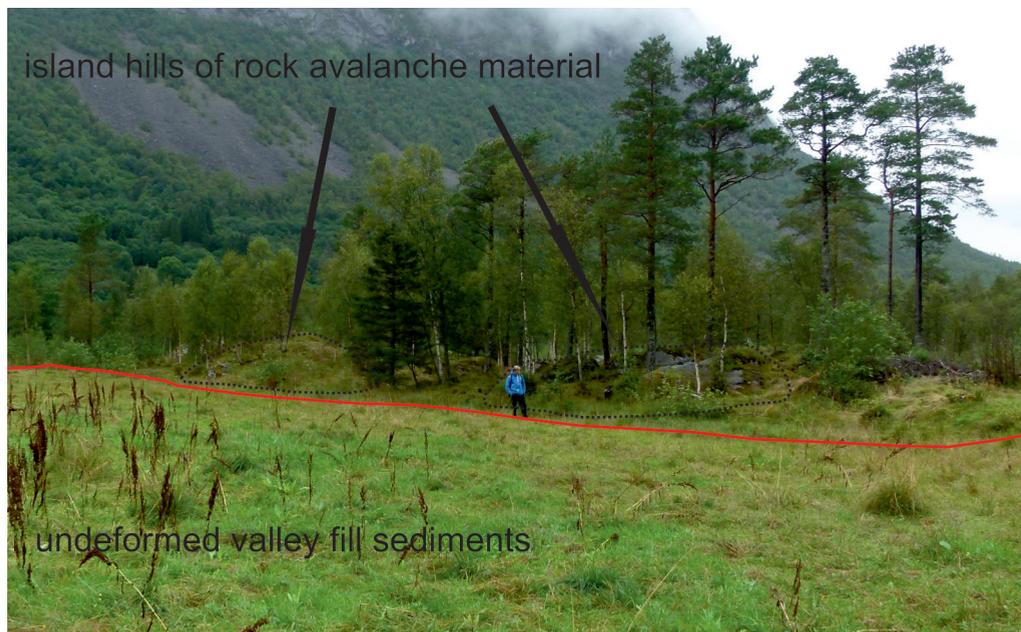


Fig. 8 - Isolated island hill deposits of rock avalanche material in Innfjorddalen at the border to the undeformed valley fill deposits (view towards NNE). For scale consider Geologist in the center

the valley and made a 90 degree turn after a run-up of 110 m at the opposite valley site. The remaining mass would have run down the valley strongly liquefying and deforming the valley fill deposits in those areas where they have strongly been water saturated close to the former shore line of the fjord. Here the rock avalanche may have split into two bodies, one coming to rest onshore and another running out into the shallow fjord. An alternative interpretation is that both bodies are connected below the surface and that the undeformed valley fill deposits have been deposited later under water level covering the connection of both parts.

In Innfjorddalen the sea level drop due to isostatic rebound of Scandinavia is not well dated throughout the Holocene, however in other areas of western Norway the sea level was at ca. 25 m around 3000 years ago (MAIFORTH, 2010). Therefore the limit between undeformed and deformed deposits suggests that this event occurred ca. 3000 years ago.

CONCLUDING REMARKS

Although isolated hills made up of rock avalanche material are similar in the Innerdalen and Innfjorddalen valley, the interactions with other landforms allow to interpret the genesis of these landforms differently:

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INNERDALEN

- 1) Several rock avalanches occurred in late Pleistocene and Holocene age.
- 2) At least one large rock avalanche occurred in late glacial age onto the decaying ice body, creating distinct morphological features (isolated boulder patches above the valley, moraine ridges composed of rock avalanche material, hills on the valley floor composed of rock avalanche material surrounded by valley fill deposits, and valley parallel ridges of rock avalanche material).

INNFJORDDALEN

- 1) Several rock avalanches occurred after deglaciation towards the end of the Holocene, sourcing from the same area.
- 2) The oldest event was deposited onto highly water saturated valley fill sediments above, partly below and close to sea level, that also created isolated island hills of rock avalanche material.

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