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The role of cornice fall avalanche sedimentation in the valley Longyeardalen, Central Svalbard

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Abstract

In arctic and alpine high relief landscapes snow avalanches are traditionally ranked behind rockfall in terms of their significance for mass wasting processes of rock slopes. Cornice fall avalanches are at present the most dominant snow avalanche type at two slope systems, called Nybyen and Larsbreen, in the valley Longyeardalen in Central Svalbard. Both slope systems are situated on NW-facing lee slopes underneath large summit plateau, where cornices form annually, and high frequency and magnitude cornice fall avalanching is observed by daily automatic time-lapse photography. In addition, rock debris sedimentation by these cornice fall avalanches was measured directly in either permanent sediment traps or by snow inventories. The results from a maximum of 7 yr of measurements in a total of 13 catchments show maximum avalanche sedimentation rates ranging from 8.2 to 38.7 $\mathrm{kg\,m^{-2}}$ at Nybyen and from 0.8 to 55.4 $\mathrm{kg\,m^{-2}}$ at Larsbreen. Correspondingly, the avalanche fan-surfaces accreted annually in a maximum range from 3.7 to 13 $\mathrm{mm\,yr^{-1}}$ at Nybyen and from 0.3 to 21.4 $\mathrm{mm\,yr^{-1}}$ at Larsbreen. This comparably efficient rock slope mass wasting is due to collapsing cornices producing cornice fall avalanche with high rock debris content throughout the entire winter. The rock debris of different origin stems from the plateau crests, the adjacent free rock face and the transport pathway, accumulating distinct avalanche fans at both slope systems and contributing to the development of a rock glacier at the Larsbreen slope system.

1 Introduction

The role of snow avalanches (hereafter called avalanches) as sediment erosion, transportation and accumulation agents is often underrated or simply not well enough documented, but they can be of significance in the alpine sediment cascade (Sass et al., 2010). Their geomorphological importance depends on the slope relief, the lithology and the climate favorable for avalanche release (French, 2007; Caine, 1976; Decaulne and Saemundsson, 2006; Luckman, 1977). As a result of avalanche sedimentation, the formation of avalanche fans (no fall-sorting, concave slope profile) exhibits a morphologically distinguishable talus slope type (Luckman, 1988). Avalanche sedimentation rates are the quantification of rock debris transported and deposited by avalanches on avalanche fans, and are thus the most direct measure of the geomorphological work of avalanches (Blikra and Selvik, 1998; Christiansen et al., 2007). As avalanche erosion and accumulation are a factor in backweathering of a rock slope, rockwall retreat rates are also an important parameter to quantify the geomorphological work of avalanches (Krautblatter and Dikau, 2007). Such quantification is done either by indirect methods using talus slopes as an inventory of long-term deposition (Schrott et al., 2002), or by direct measurements quantifying debris deposition (Luckman, 1978b). Both approaches were pioneered by Rapp in the 1950s (Rapp, 1960a,b). A comprehensive review of the methodologies is given by Krautblatter and Dikau (2007).

In past studies worldwide, avalanches are primarily considered as subsidiary sediment transport agents on rock walls, cliffs or talus slope, with rockfall and debris flows being more dominant (Luckman, 1978a). The longest slope monitoring to date was carried out in the Canadian Rocky Mountains. A 13 yr record of sediment transport and accumulation quantified the geomorphological work by avalanches, through direct measurements (Luckman, 1978a, 1988). Debris accumulation by avalanches averaged 0.6 to 4.8 $\mathrm{mm\,yr^{-1}}$ over the 8 yr period and up to 5 $\mathrm{mm\,yr^{-1}}$ during the 13 yr period. However, in both cases, rockfall was the dominant debris transport agent. Also in other studies, rockfalls of different magnitude and frequency have been ascribed as the most significant agent of rockwall retreat (Whalley, 1984; Matsuoka and Sakai, 1999) and talus cone formation (Krautblatter and Moser, 2009).

Studies focusing solely on avalanche sedimentation are sparse. Rapp (1960b) quantified avalanche sedimentation in Kärkevagge, Northern Sweden, which originated from a series of individual events. He ranked sediment transport by avalanches second after debris flows, but emphasized that for both types of mass movement, frequency and magnitude mostly govern their geomorphological significance (Rapp, 1960a).

Ackroyd (1987) in the New Zealand Alps and Bell et al. (1990) in the Himalayas quantified sedimentation of single avalanche events. Ackroyd observed the redeposition of large boulders by avalanches, and Bell et al. (1990) estimated depositional area accretion of 0.74 and 0.21 mm after two avalanches. Heckmann et al. (2002, 2005) quantified and modeled the contribution of avalanches to the sediment balance of two alpine catchment areas for two years in the Bavarian Alps. They concluded that avalanches contributed significantly to the sediment balance and relief development of high mountain areas. Most recently, Sass et al. (2010) calculated rockwall retreat rates by avalanches based on a six-year record in the Tyrolean Alps. They documented that avalanches eroded 4–5 mm of debris since a wildfire cleared the catchment.

1.1 High Arctic Svalbard perspective

In Svalbard the dynamics of rockwall weathering, talus formation and avalanche sedimentation have been studied by Rapp (1960a), Jahn (1967, 1976, 1984), Åkerman (2005, 1984), André (1990, 1995, 1996, 1997) and most recently by Humlum et al. (2007) and Siewert et al. (2012). Åkerman (1984) and André (1990) assigned full-depth, slush avalanches and dirty spring avalanches high erosional significance. André (1990, 1996), however, did not find evidence for significant avalanche sediment erosion in schist and gneissic bedrock, as she observed avalanches only slightly reshaping the talus slopes. Also Jahn (1976), working on periglacial slope processes in the valley Longyeardalen ascribed avalanches only minor importance for the overall slope denudation. However, Humlum et al. (2007) studied a rock glacier in the Longyeardalen valley, and found that rock debris transport by cornice fall avalanches was primarily responsible for the considerable amount of sedimentation that enabled the development of a rock glacier during the Holocene. Rock debris accumulation rates, quantified by direct measurements with permanently installed sediment traps, through 2 yr, ranged from 0 to 50.4 $\mathrm{kg\,m^{-2}\,yr^{-1}}$, averaging 13 $\mathrm{kg\,m^{-2}\,yr^{-1}}$ on this NW facing slope (Humlum et al., 2007). The assumption that avalanche sedimentation is of high significance in the sedimentary bedrock of Central Svalbard was confirmed by Siewert et al. (2012) in their study also from Longyeardalen. They estimated rockwall retreat rates using electrical resistivity tomography (ERT) to quantify the volume of the talus deposits. Their results showed that rockwall retreat was 100 % higher on NW facing slopes compared to SE facing slopes. This is mainly attributed to significant higher cornice fall avalanche activity on these NW facing slopes, due to a prevailing winter wind direction from the SE (Eckerstorfer and Christiansen, 2011a; Humlum et al., 2007). Snow cornices have been found to largely control plateau edge erosion likewise in the Longyeardalen valley by favouring rock weathering by ice segregation. As the cornices grow over the plateau edge, they keep it in the frost cracking window of −3 to −8 °C for large parts of the year (Eckerstorfer et al., 2012). When the cornice accretes in autumn, the weathered sediment is incorporated and later plucked out of the cornice rockwall by the downslope growing and deforming cornice. Sediment is either transported downslope by a collapsing cornice, inducing a cornice fall avalanche (Vogel et al., 2012) or by in situ melting of the cornice in late spring (Eckerstorfer et al., 2012).

1.2 Scope of the study

The geomorphological work of cornices and cornice fall avalanches on NW facing slopes in Longyeardalen seems to be of significance for rock slope sedimentation at present. This assumption is based on previous studies on these slopes (Eckerstorfer et al., 2012; Siewert et al., 2012; Humlum et al., 2007). A detailed quantification of avalanche sedimentation, causing the formation of well-defined avalanche fans is still lacking. The main aim of this study is to present avalanche fan-surface accretion and rockwall retreat rates from two slope systems in the valley Longyeardalen, Central Svalbard. Secondary goals of this study are to (1) present a new methodology of avalanche activity monitoring, (2) investigate the interannual and inter-slope system differences between avalanche fan-surface accretion and rockwall retreat rates, and (3) postulate the significance of avalanche sedimentation for the slope system evolution and the formation of sedimentation-derived landforms such as rock glaciers. We hypothesize that cornice fall avalanche sedimentation is currently the dominant rock erosion, transport

TCD
6, 4999–5036, 2012

and sedimentation process at both slope systems. We further hypothesize that cornice fall avalanche sedimentation is not a linear process of erosion, transport and accumulation, but dependent on other slope processes involved, the sediment cover on the slope and the topographic complexity of the slope system.

With its frost weathering susceptible sedimentary bedrock and the active cornice fall avalanching, the Longyeardalen valley offers good conditions for such quantification work. We have therefore combined monitoring of cornice fall activity with automatic time-lapse photography and field observations and direct measurements of annual avalanche sedimentation rates to quantify the geomorphological work of cornice fall avalanches. We define avalanche sedimentation as the transport and deposition of rock debris by avalanches forming distinct avalanche fans. The rock debris being transported this way can have its origin from erosion by cornices and/or cornice fall avalanches, as well as rockfall, but has been transported by an avalanche, contributing to avalanche fan deposition (Sass et al., 2010). The dataset was collected at two slope systems, Nybyen and Larsbreen (named after the adjacent Larsbreen glacier) about 700 m apart below the same plateau edge on the NW facing slope of Gruvefjellet, delimiting the valley Longyeardalen on its east side (Fig. 1). Data from a total of 13 catchments (5 at Nybyen, 7 at Larsbreen) with a record of a maximum of 7 yr is presented.

2 Study area and slope systems

Large parts of the landscape in Central Svalbard are periglacial, with only minor glaciers. In 2011 the mean annual air temperature (MAAT) was −3.4 °C, and the 2011 annual precipitation (MAP) was 199 mm water equivalent (w.e.) at sea level in Longyearbyen (Met.no, 2012). This present-day MAAT is 2.6 °C warmer than the entire 1912–2011 average, while MAP is close to the almost 100 yr long record average of 196 mm (Met.no, 2012). The largest fraction of precipitation falls as snow, but due to the low amounts and the barren, windswept landscape, the snow cover is generally thin and discontinuous (Eckerstorfer and Christiansen, 2011b).

Both the Nybyen and the Larsbreen slope systems (hereafter called Nybyen and Larsbreen) are situated within the same bedrock region of near horizontal sedimentary layers of sandstones and shales in the Van Mijenfjorden Group; lower Tertiary age (Hjelle, 1993). This geological setting with horizontal bedrock structures forms the basis for the extensive plateau mountain topography in Central Svalbard. This large-scale plateau topography (Fig. 1), in combination with snow transport by wind, with a prevailing regional winter wind direction from the SE, favours cornice formation on lee-side slopes (Eckerstorfer and Christiansen, 2011a; Vogel et al., 2012; Eckerstorfer et al., 2012). Into this plateau topography large V or U-shaped valleys are incised, primarily eroded by either fluvial/periglacial and/or glacial processes. The valley sides of these large valleys are, however, shaped by a combination of gravitational periglacial processes such as mainly avalanches and rockfalls. Additionally smaller V-shaped gullies or ravines are cut into the plateau edges. These ravines are located between protruding bedrock-noses in the more resilient bedrock formations. The detailed morphology of these ravines varies depending somewhat on the bedrock setting, but they are in many places funnel-shaped, with one or more contributing couloirs that run from the funnel-shaped upper part down to the lower less steep rock slope areas of the avalanche fans.

3 Methods

3.1 Geomorphological mapping

To determine past and present slope activity, sediment cover and landforms, detailed geomorphological mapping was carried out. The area was first studied using infrared-composite aerial photographs to assess the general setting, and to determine the most prominent landforms and slope processes. After the production of a first raw map,

TCD
6, 4999–5036, 2012

fieldwork was conducted to verify the aerial photograph interpretation and to determine sediment compositions and geomorphological processes. Fieldwork observations were directly integrated into the map in the field, using ArcGIS 10. The final geomorphological maps for both slope systems were constructed using stereo analysis of aerial photographs from 1990 (courtesy of the Norwegian Polar Institute).

3.2 Avalanche activity monitoring

Seasonal avalanche activity was monitored by field observations and automatic time-lapse photography (Christiansen, 2001; Vogel et al., 2012) (Figs. 2, 3). Time periods without photo coverage were mainly due to technical problems with the camera, bad visibility, or darkness during the Polar Night (Fig. 2). Up to six, but at least one daily photograph was taken of the Nybyen and Larsbreen slope system. Additionally, one daily photograph was taken of the catchments L1–L3 at Larsbreen (Lars-cam). All Nybyen catchments were monitored between 2007/2008 and 2010/2011. At Larsbreen, avalanche monitoring started in 2003/2004 in catchments L2 and L3, both having the longest records, with 7 yr at L2 and 6 yr at L3. No observation and sampling took place in 2004/2005 on Larsbreen (Fig. 2). Therefore, rock debris sampled in catchment L3 in 2006/2007 is from two years of debris deposition.

Each avalanche release was stored in a database with date and time of release, location of release (number of catchment) and extent. The extents of the avalanche snow-deposits (m^2) were calculated by digitizing the outlines of each avalanche in ArcGIS 10. For these calculations a DEM with 2 m spatial resolution, derived from aerial Lidar data was used. Only avalanches that reached the primary fan were included in the calculations.

The visible rock debris content, estimated in situ, or from the time-lapse photographs was classified into three classes; “no visible rock debris”, “some visible rock debris” and “high amounts of visible rock debris”, corresponding to $> 75\,\%$, $> 50\,\%$ and $< 25\,\%$ of the avalanche snow-deposit area covered with visible rock content respectively.

TCD
6, 4999–5036, 2012

3.3 Rock sediment collection

We used a direct approach to measure rock debris deposition by avalanches, following Luckman (1978a). In two catchments (L2 and L3) at Larsbreen, four 16 m^2 large polyethylene squares were installed in 2003/2004 (T1 to T4 in Fig. 4a, b). These squares were anchored along the entire periphery with a line of boulders and emptied each year in September (Fig. 2). At this time of the summer, the avalanche snow-deposits had melted enough to make the plastic sheets partly visible. In some years, the plastic sheets had to be replaced due to holes in them, and the sediment traps needed to be slightly moved. In catchment L2, additionally a large, flat-topped boulder (T5 in Fig. 4a, c) was used as another sediment trap, also only cleared in September each year.

Rock debris quantification based on snow surface inventories (Luckman, 1978a) were carried out in all catchments at both sites since 2007/2008. These were done when the rock debris, due to melting of the snow, had concentrated on the snow surface, with a still intact boundary to the avalanche fan-surface of the previous year below (Fig. 4d). These snow inventories, in average 4–8 m^2 parcels (Fig. 4e), were taken at the furthest possible downslope locations on the avalanche fans, where maximum amounts of rock debris was visible on the snow surface. All catchments at Nybyen were sampled in June each year (Fig. 2) as the snow melts earlier at this lower slope system. At Larsbreen some sampling took place either end of July or in September each year. In all cases the rock debris transported downslope by all avalanches in a particular year and catchment was sampled. The rock debris in each sampling parcel or in the permanent sediment traps were weighed in a cotton bag using a hand scale. The weight of small fragments was estimated visually and the sum of all rock debris rounded to the next kg. Large, heavy boulders were hammered into smaller pieces for weighing.

TCD
6, 4999–5036, 2012

3.4 Avalanche fan-surface accretion and rockwall retreat rates

To quantify the geomorphological work of cornice fall avalanches, avalanche sedimentation rates (kg yr^{-1}), avalanche fan-surface accretion rates (mm yr^{-1}) and rockwall retreat rates (mm yr^{-1}) were calculated for each catchment annually. These rates were only calculated for a particular catchment and year, if avalanche activity was recorded and rock debris deposition was directly measured (Fig. 2). We first defined the annual maximum extent of avalanche snow-deposits (m^2) per catchment, by calculating it in ArcGIS 10, based on the outlines of all avalanches observed.

The total amounts of avalanche deposited rock debris (kg), directly measured in the sediment traps or in the snow inventories were calculated by summing the amounts of rock debris weighed in each sampling parcel. Mean annual avalanche sedimentation (kg m^{-2}) was obtained by dividing the total amount of rock debris (kg) by the total area of permanent sediment traps or snow inventories (m^2). Annual total avalanche sedimentation (kg yr^{-1}) was calculated by multiplying the annual maximum area of avalanche snow deposition (m^2) with the mean annual rock debris sedimentation rate (kg m^{-2}). To receive avalanche fan-surface accretion rates (mm yr^{-1}), and rockwall retreat rates (mm yr^{-1}), the volume was calculated by dividing the total avalanche sedimentation rate (kg yr^{-1}) by the mean rock density of $\sim$2250 kg m^{-3} measured by Siewert et al. (2012) in the laboratory on sandstone rock samples from the study area. Dividing the total sediment volumes (m^3) by the area of the avalanche fans (m^2) (depositional areas) enabled avalanche fan-surface accretion rates (mm yr^{-1}) to be calculated. Likewise by dividing the total sediment volumes (m^3) by the area of the rockwall (source areas) (m^2), rockwall retreat rates (mm yr^{-1}) could be determined assuming all debris comes originally directly from the backwall (see later discussion for more details on this). The source and depositional areas are marked in Fig. 5b with a white outline, separated by the green dashed line. In Fig. 6b the source and depositional areas are also marked with a white outline, separated by the yellow dashed line.

The source, depositional areas and the area of the annual maximum extent of avalanche snow-deposits (m^2) were mapped in ArcGIS 10 using the "3-D analyst" tool "interpolate polygon to multipatch", to receive the area of the three dimensionally delimited landform (as opposite to a planimetric area). A DEM with a spatial resolution of 2 m was used for these calculations.

4 Results

4.1 The geomorphology of the Nybyen and Larsbreen slope systems

The Nybyen slope system consists of a multi-stepped erosion, transport and sedimentation system with a vertical relief of 300 m, and a 1000 m long horizontal ridgeline (Fig. 5). The detailed geomorphological description of the Nybyen slope system is presented in Table 1.

The Larsbreen slope system is between 130–160 m high, and about 600 m long. The varying height is due to some variation in plateau height but primarily because the foot of the slope system is based at the lateral moraine of Larsbreen glacier (Fig. 6), which acts as a topographical barrier. Hence, the slope deposits extend onto the ice-cored moraines (Etzelmueller et al., 2000). The slope system is relatively simple with avalanches and rockfall and as the predominant transport processes, and a clear connection between erosional and depositional areas, with no long-term intermediate storage (Table 1).

4.2 Cornice fall avalanche activity and rock debris quantification

At both slope systems, all avalanches were exclusively cornice fall avalanches. Only at the end of spring, these cornice fall avalanches were full depth avalanches, incorporating rock debris of different origin in the transport couloirs, when sweeping through. However, collapsing cornices frequently cleared during mid-winter the backwall from rock debris. Thus, rockfall deposits from the backwall are transported downslope together with avalanche deposits during the entire winter, while the transport couloirs are only swept in late spring. Rockfall depositing on snow was rarely observed due to the slope systems being in continuous permafrost.

The peak activity of avalanches at both slope systems was from May to July (Figs. 7b, 8b), which is late compared to the overall registration of avalanche activity in the Longyearbyen area, with an activity maximum between April and June (Eckerstorfer and Christiansen, 2011a). However, at both slope systems, cornice fall avalanches were registered throughout the entire snow season, as early as December at Larsbreen (Fig. 8b). At least one avalanche released annually in each of the 13 catchments at both slope systems, however, not all of them were sampled for rock debris deposition.

At Nybyen, 77 avalanches were recorded during the observation period 2007/2008–2010/2011. Rock debris was quantified in 41.5 % (32 avalanches) of the total. In 60 % of the 32 avalanches analyzed, the debris terminus reached the lower third of the primary fans, 37 % reached the middle third and 3 % stopped in the upper third of the maximum runout zone (white line, Fig. 5b). 97 % of all avalanches had visible rock debris in their avalanche deposits, with 68 % of them having "high amounts of visible rock debris" (> 75 % of the avalanche snow-deposit area covered with rock debris). This underlines that not only "dirty" spring cornice fall avalanches contribute to the avalanche fan accumulation. It furthermore stresses that rock debris, plucked from the backwall by cornices (Eckerstorfer et al., 2012) as well as rockfall deposited in the source area is transported downslope by cornice fall avalanches during the entire avalanche season, as we recorded cornice fall avalanches in every month of the winter (Figs. 7b, 8b). The picture in Fig. 7b exemplifies a cornice fall that released in March 2011 in catchment L4. The high visible rock content, covering the majority of the avalanche snow-deposits is clearly visible. With an almost continuous snow cover on the slope, the rock debris could not have been picked up in the upper fans or in the transport couloir. The rock debris was definitely plucked from the plateau edge by the cornice, and transported downslope. The falling cornice must have also incorporated loose rock debris from the horizontal ledges of the vertical free rock face, originated by melting cornices and rockfall, visible by the cleared snow-free area.

The largest maximum extent of avalanche snow-deposits (m^2) was measured in catchment N1 in 2007/2008 and 2008/2009 (Fig. 7), with over 26 000 m^2 in both years (Table 2). In the same year in catchment N1, the most extensive rock debris quantification was carried out, with 28 parcels of snow inventories being sampled (Fig. 7a), covering an area of 220 m^2 (Table 2). In all catchments during the entire observation period, a minimum of 12 m^2 of snow inventories (Table 2) was sampled.

At Larsbreen, from 2003/2004 to 2010/2011, with the exception of 2004/2005, 120 avalanche deposits were analyzed (Fig. 8b). A total of 156 avalanches were recorded, thus 77 % of all avalanches are taken into account. However, not all catchments were sampled equally over the entire observation period, as done at Nybyen (Fig. 2, Table 2). Out of 120 avalanches, 55 % stopped in the lower third, and 45 % in the middle third of the maximum runout zone (white line, Fig. 6). Rock sediment was visible in 91 % of all investigated deposits, with 66 % having "high amounts of visible rock debris" (> 75 %).

The maximum extent of avalanche snow-deposits is comparably smaller at Larsbreen than at Nybyen (Table 2), owing to the slope system being shorter in vertical height and slide distance. However, the largest avalanches in all catchments approached closely the furthest visible slope deposition, which is at present found on the ice-cored marginal moraine of Larsbreen glacier (Fig. 8).

In 2003/2004, 2006/2007 and 2009/2010 all five permanent sediment traps (Fig. 8a) were cleared and the rock debris weighed. In all the other years, some of the plastic sheets were either destroyed or remained snow covered throughout the summer (L3 in 2005/2006). However, we also carried out snow inventories both in L2 and L3, therefore the long records exist from these two catchments. T2, the large boulder, located the furthermost down on the avalanche fan (Fig. 4a, c), was covered with rock debris and thus sampled each year, except in 2007/2008. This indicates that avalanches must be the primary rock debris transport agent, as rockfalls are unlikely to move debris this far down on the avalanche fan and up a large boulder. Due to the permanent sediment traps, catchments L2 and L3 have the longest and most continuous sediment quantification record, followed by catchment L1 (Table 2). In September 2010, sediment trap T3 was filled with almost 6700 kg of rock debris. As T3 was emptied the year before, these large amounts of rock were deposited during the winter 2009/2010, possibly a cornice that plucked large rock pieces from the headwall.

4.3 Avalanche sedimentation rates (mm yr^{-1})

For each catchment at both slope systems, we have calculated mean rock debris sedimentation rates (kg m^{-2}) (Table 2) that have a large interannual variability. Mean annual rock debris sedimentation at Nybyen ranged from 8.2 kg m^{-2} (N1 in 2008/2009) to 38.7 kg m^{-2} (N2 in 2009/2010) (Table 2). At Larsbreen, rock debris sedimentation was as low as 0.8 kg m^{-2} (L2 in 2006/2007) and as high as 55.4 kg m^{-2} (L4 in 2008/2009) (Table 2). Corresponding (avalanche) sedimentation rates ranged at Nybyen between 225 190 kg yr^{-1} (N1 in 2008/2009) and 704 105 kg yr^{-1} (N4 in 2010/2011) (Table 2). At Larsbreen, annual avalanche sedimentation rates exhibit a larger range from 5615 kg yr^{-1} (L2 in 2006/2007) to 283 686 kg yr^{-1} (L4 in 2008/2009) (Table 2). There is no correlation between the maximum area of avalanche snow-deposition, and corresponding avalanche sedimentation rates on an annual basis for each catchment at both slope system, with R^2 values of 0.003 for Nybyen and 0.004 for Larsbreen. Also, large rock debris sampling areas did not result in larger annual avalanche sedimentation rates for each catchment at both slope systems ($R^2 = 0.05$ for Nybyen and $R^2 = 0.06$ for Larsbreen).

4.4 Avalanche fan-surface accretion and rockwall retreat rates (mm yr^{-1})

At the Nybyen slope system, the source and depositional areas of rock debris are larger than at Larsbreen, consisting of the free vertical rock faces, the first depositional areas and the transport couloirs (Fig. 5b). However, this did not lead to larger avalanche fan-surface accretion and rockwall retreat rates (Table 3). But in both slope systems, the highest avalanche fan-surface accretion rates with 13.5 mm at Nybyen and 21.41 mm yr^{-1} at Larsbreen respectively were calculated in the catchments with the largest source areas (N4 and L4).

At Nybyen, the size of the maximum avalanche snow-deposits does not determine annual avalanche surface fan accretion rates ($R^2 = 0.01$) for each catchment. The same accounts for Larsbreen, where the size of the maximum avalanche snow-deposits also does not determine annual avalanche fan accretion rates ($R^2 = 0.01$). However, annual average maximum avalanche snow depositional areas correlate weakly with surface fan accretion rates ($R^2 = 0.28$) at Nybyen. Strong correlations were found at Larsbreen between annual average maximum avalanche snow depositional areas and annual average avalanche fan accretion rates ($R^2 = 0.86$ for both).

5 Discussion

5.1 Avalanche sedimentation rates and their geomorphological effect

Monitoring the Nybyen and Larsbreen slope systems enabled us to establish an improved understanding of the role of cornice fall avalanche sedimentation and the particular process dynamics involved. Due to the geomorphological work of cornices (Eckerstorfer et al., 2012) a significant majority of cornice fall avalanches throughout the entire winter at both slope systems have a high visible rock debris content (Fig. 9b, c), making avalanche sedimentation very efficient. Moreover, cornice fall avalanching is very frequent at both slope systems, with high activity for up to 8 months of the year, transporting rock debris of different origin. This is opposed to many earlier studies that did not recognize such efficient rock debris transport by avalanches. In addition, both slope systems consists of for frost weathering very susceptible sandstones and shales, with a rather moderate rock strength and high amount of fractures (Siewert et al., 2012). As a result, the annual avalanche fan-surface accretion rates we present for each catchment are comparably high. The rock debris, accumulated on the avalanche fans are the sandstones from the Grumantbyen formation, varying in clast size from boulders to stones, and shales from the Basilika formation (only at Nybyen) accounting for all the fines, as these shales are broken down in the transport process (Fig. 4e). Direct sedimentation by rockfall would produce primarily coarse-grained debris. During the many snow inventory samplings, we found perched rock debris on larger blocks (Fig. 9f). Rock debris only get perched this way by avalanche sedimentation, when rock debris settle on top of each other during avalanche snow melting. All primary fans at both slope systems consist primarily of avalanche deposits, containing unsorted rock debris of very different clast sizes. Only avalanches are able to transport rock debris as far out on the slope systems, as we observed it. At some places these avalanche deposits reach at Nybyen almost as far as the outermost fans that consist of slush flow and periglacially-reworked deposits. At Larsbreen, avalanche deposits are clearly visible beyond the slope system limit, having been transported up the rock glacier ridges and quite some distance onto the otherwise much more fine-grained ice-cored moraine of the Larsbreen glacier (Fig. 9a, d). Furthermore, at several of the avalanche fans at Larsbreen, avalanche snow has been turned to ice by the relatively high sedimentation rates and is thus preserved underneath the talus (Fig. 9e). This stratigraphy of rock debris and avalanche snow turned to ice was visible in a cave underneath the rock glacier (Humlum et al., 2007). Thus the cornice fall avalanches provide enough fresh rock debris and snow to the root of a rock glacier to allow it to have grown to its relatively large size (Humlum et al., 2007) (Fig. 9a). Presumably the prevailing southeasterly airflow over the Gruvefjellet plateau favours the build-up of the largest cornices at Larsbreen compared to Nybyen, resulting in a higher release frequency, providing enough snow and debris to supply the Larsbreen rock glacier. It is also likely, that the avalanche derived rock glacier at Larsbreen is located right above the rock glacier initiation line altitude (based on climate), which could coincide with the equilibrium line altitude for the cirque glaciers in the area. The fact that cornice fall avalanche sedimentation lead to the formation of a rock glacier at Larsbreen yields that the processes involved are prevailing since large parts of the Holocene.

TCD
6, 4999–5036, 2012

5.2 The differences in avalanche sedimentation rates between the Nybyen and Larsbreen slope systems

Both the Nybyen and Larsbreen slope systems are developed in a similar geological setting with roughly similar slope aspect towards W and NW. The slope systems are part of the same plateau edge that steadily rises in elevation from north to south (Fig. 1). The Nybyen slope system has a larger vertical relief than Larsbreen, as well as a larger run (600 m and 200 to 350 m respectively). The relationship between height and run is roughly similar for the two systems (ranging from 0.48 to 0.6), but the slope profiles are quite different with much deeper incised gullies or couloirs at Nybyen, which cause intermediate depositional areas to exist in the upper part of the slope as well (Fig. 5). The Larsbreen slope system is topographically smoother with a much larger source-to-depositional area ratio, and no intermediate storage landforms (Fig. 6).

Thus the different slope system-specific avalanche sedimentation rates are a function of the complexity of the catchments. The intermediate storage (Krautblatter and Dikau, 2007) at the Nybyen slope is, in contrast to Larsbreen, well developed as several catchments have a thick sediment cover already in the first depositional area (Fig. 5a). In the upper catchments, the vertical free rock face transitions immediately into the primary fans. When cornices melt down in-situ instead of collapsing, embedded rock debris is deposited on the plateau edge, the horizontal ledges of the free rock face and the upper fans, acting as yet another intermediate storage. This intermediate storage is also to some degree filled with rockfall debris from the free face above. Consequently, large cornice fall avalanches not only transport plucked rock debris from the plateau edge, but also sweep rock debris deposited by melting cornices and rockfall the previous years from the ledges on the free rock face and the upper fans. Avalanche and rockfall deposits stored temporarily in the transport couloirs are typically only swept away by cornice fall avalanches at the end of the snow season, during full-depth avalanching, when just little snow is left on the slopes. Only by cornice fall avalanche transportation can larger quantities of rockfall debris reach the primary fans. The majority of rockfall

TCD
6, 4999–5036, 2012

debris from the protruding rock noses accumulates in very steep, well-sorted fans between the primary avalanche fans, especially at Nybyen, but also at Larsbreen in the northern part (Fig. 5a).

The sedimentology and geomorphology of the individual catchments also lead to different avalanche sedimentation rates. The most striking geomorphological difference is the steeper transition from the plateau to the free rock face at Larsbreen, being almost entirely vertical above catchments L5–L7. Due to this vertical backwall, about 15–20 m high, a downwards-deforming cornice very quickly becomes unstable, as it is relatively unsupported compared to a cornice accreting on a less steep backwall. When such a cornice detaches from the plateau it often results in entire cornice collapses, which very efficiently plucks rock debris from the backwall. A significant sedimentological difference between catchments is the sediment thickness particularly in the transport couloirs at Nybyen (Fig. 5a). When an avalanche sweeps down these couloirs containing a thick sediment cover, it can entrain more rock debris of different origin.

5.3 Present-day and Holocene rockwall retreat rates

Having quantified avalanche sedimentation it is possible to contribute to the discussion on how much of the rockwall retreat is caused by the geomorphological activity of avalanches, and how much is the effect of rockfalls. The average annual rockwall retreat rates are as high as 0.94 mm yr^{-1} at Nybyen and 1.13 mm yr^{-1} at Larsbreen (Table 3), with catchment specific rockwall retreat rates as high as 1.40 mm yr^{-1} (N4 in 2010/2011) at Nybyen, and 5 mm yr^{-1} (L6 in 2009/2010) at Larsbreen. In this catchment L6, the depositional area is only 11 % smaller than the source area.

We assume, based on almost 10 yr of frequent field observations, that rockfalls contribute to the rockwall retreat rates with a maximum of 10 %. This assumption is supported by our time-lapse photography monitoring, showing that at least one cornice fall avalanche released in each catchment at both slope systems every year. Therefore the upper depositional areas at Nybyen and the transport couloirs at Larsbreen got swept annually. This keeps the rockfall contribution small and makes the rockwall retreat rates annual rates.

Siewert et al. (2012) calculated Holocene rockwall retreat rates, based on GPR mapping of the thickness of the entire avalanche fan deposits at both sides of the Longyeardalen valley. Their calculations indicate slightly higher average Holocene rockwall retreat rates of 1.1 mm yr^{-1} at the Nybyen slope system, and 0.5 mm yr^{-1} on the SE facing side of the valley. Hartmann-Brenner (1974) also calculated average Holocene rockwall retreat rates of 0.7 mm yr^{-1} for the SE facing slopes in the Longyeardalen valley.

The average Holocene rockwall retreat rates are within the range of our present-day rates (Table 3), but generally in the lower end of the present-day rates at both the Nybyen slope system, but primarily at the Larsbreen slope system. This is most likely due to the large activity of cornice fall activity at the two slope systems, dominating the NW facing side, while a combination of avalanches and rockfalls dominate the SE side of the Longyeardalen valley. From a large debris flow event in 1972 Larsson (1982) reported rockwall retreat rates of maximum 0.0125 mm yr^{-1}, which shows that also debris flows are of much less importance for rockwall retreat than cornice fall avalanching in the Longyeardalen valley.

5.4 Possible errors and uncertainties

Cornice fall avalanche activity was monitored by automatic time-lapse photography and direct field observations and we are sure that this combination of methods enabled us to have observed the entire record of major avalanche activity. The extent of each avalanche was calculated in ArcGIS 10, based on an outline drawn from the photographs. There might be a small overestimation of the depositional area due to a more generalized outline drawn in ArcGIS 10, but this error is consistent throughout the dataset.

Rock debris was collected in five permanent sediment traps and in numerous snow inventories. The permanent sediment traps provide the longest and most persistent record of avalanche sedimentation, unbiased by the choice of sampling location. These sediment traps were not moved during the monitoring period. The snow inventories on the other hand are somewhat biased by the individual sampling location, and its position on the avalanche deposits. Obviously, sampling locations were chosen to be where large quantities of rock debris were seen to ablate out of the snow. Still, in many catchments a high number of sampling sites could be established each year, giving this preferential sampling less significance. Moreover, in Table 2 and Table 3 we have underlined the rates that were collected in years when only rock debris in the permanent sediment traps in L2 or L3 was sampled. These from the sampling methodology unbiased rates are not significantly different from all others. Avalanche sedimentation rates ($kg\,yr^{-1}$) and consequently derived avalanche surface accretion and rockwall retreat rates are for example the lowest in 2008/2009 in L3, but at the higher end for L3 in the total observation period. Comparably, these rates are a medium rates in 2010/2011, and a total maximum for L2 over the entire observation period.

A large difference between the permanent sediment traps and the snow inventories is their timing of collection. Summer rockfall is only to a very small degree affecting the avalanche fans as far down on the primary fans where the sediment traps were located. But due to the timing of sampling at the snow minimum in September, potentially some few rocks from really large rockfalls could have been included in the quantification of the permanent sediment traps.

All these permanent sediment traps and snow inventories are single point measurements of rock debris that were summed up and extrapolated onto the entire avalanche snow deposit area, which is the annual maximum extent, all avalanches have reached in one year in a catchment. However, a larger number of rock debris samples did not necessarily result in a larger amount of rock debris. We therefore know that the determined avalanche sedimentation rates and avalanche fan-surface accretion rates are maximum rates.

TCD
6, 4999–5036, 2012

6 Conclusion

In this study, we present a record of maximum 7 yr of avalanche sedimentation rates from two slope systems in the valley Longyeardalen, in Central Svalbard. Avalanche monitoring was carried out by daily time-lapse photography and direct field observations ensuring a complete record. Measurement of rock debris transported by avalanches was carried out directly by sampling it in permanent sediment traps on avalanche fans at end of summer and by snow inventories during the snow-melting season. Annual avalanche sedimentation rates are expressed as the amount of rock debris accumulated by avalanches in kg, as well as the annual surface accretion on the avalanche fan in mm. These rates are calculated by extrapolating mean rock debris weight sampled and extrapolated onto the total avalanche snow-deposit area. At both slope systems these rates are high due to the highly weathered, moderately strong sedimentary rock, and the high magnitude and frequency of dirty cornice fall avalanches. These avalanches efficiently pluck and transport rock debris from the free rock face onto the primary fans, and sweep the transport couloirs clean of rock debris deposited by melting cornices and rockfall. This process took place every year in all catchments at both slope systems, however, we did not quantify it every year. The significant geomorphological work of cornices and cornice fall avalanches cause erosion of the plateau edges, and a high ice-content in the aggrading permafrost in the distinct avalanche fans, consisting of a layering of avalanche snow and rock debris. Most evidently, cornice fall avalanching causes the formation of a large avalanche-derived rock glacier right below the Larsbreen slope system. The calculated avalanche sedimentation rates reflect the magnitude and frequency of this cornice fall avalanching in the present climate. Humlum et al. (2007) suggested that the rock glacier is of late Holocene age (< 5000 yr), which means that significant cornice fall activity and rock debris transport must have occurred since then. Magnitude and frequency of avalanching must have been comparable, as the median Holocene rockwall retreat rate, calculated by Siewert et al. (2012) is comparable to the present-day rates.

TCD
6, 4999–5036, 2012

The larger avalanche sedimentation at Larsbreen is caused by a simpler system with a shorter distance from the cornice source area to the one depositional area. The Nybyen slope system has more complex, deeper insist catchments, where rock debris gets deposited in intermediate storage landforms, both by avalanches and rockfall.

Differences in avalanche sedimentation rates between years within each slope systems are mainly due to a higher cornice fall frequency resulting in larger avalanches, transporting more rock debris downslope.

In conclusion, cornice fall avalanches are at present by far the most efficient sediment erosion and transport agent on NW facing slopes in the valley Longyeardalen. As cornice fall avalanches are the most dominant type of avalanche in the Longyearbyen area, with 45.2 % of the total (Eckerstorfer and Christiansen, 2011a), they are likely to be the dominant mode of sediment transport of any leeward slope.

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TCD
6, 4999–5036, 2012

Table 1. Geomorphology of the Nybyen (N) and Larsbreen (L) slope systems The number codes for each sedimentological unit in Figs. 5 and 6 are given.

	Landform	Slope	Characteristics
N	Plateau edge and weathering rim	15–85°	Thin rim of frost-shattered bedrock of Grumantbyen sandstone (code 73), transitioning into free rock face (code 130). The plateau edge consist of highly weathered rock debris without lichen-cover, unlike the rocks of the summit plateau blockfield and the plateau edges facing other directions than NW (Eckerstorfer et al., 2012)
L			Slightly more resilient Grumantbyen sandstone than at Nybyen. Above catchments N4-N7, the rim is vertical (code 130)
N	Vertical free rock face	85–90°	Undulating lateral morphology, forming the upper part of the funnel-shaped gullies below. Primary source area for slope deposits
L			In the southern part, the cliff is laterally almost vertical, while couloirs are developed in the northern part, increasing in depth towards north
N	First depositional area	40–45°	Covered by a layer of rockfall and avalanche deposits (code 81, 82), in the Basilika shale formation. Large parts are lichen covered, showing slow rates of deposition (code 326) (N1–N3)
L			Not existing at Larsbreen
N	Rock noses and transport couloirs	35–45°	Primarily erosional landforms, with only little sediment between the rock noses, developed in the Firkanten Formation. The rock noses are rockfall source areas (code 130). The couloirs act as transport funnels. The thin sediment cover consists of fines and sandstones and shales from rockfall and avalanche deposits (code 82)
L		45–55°	The free rock face gradually declines in steepness downwards, but the general steepness of the slope prevents any long-term storage (code 82). The thin sediment cover is a mix of in-situ weathered material, rockfall deposits and to some smaller degree avalanche deposits
N	Upper fans and rockfall deposits	40–50°	The upper fans and the areas in between mainly consist of rockfall deposits (code 307), accounting for a steep, relatively homogenous slope (vertical grain-size distribution)
L			Not existing at Larsbreen
N	Primary fans	45–20°	Almost coalescing, large avalanche fans, with concave curvature. Grain size varies from silt/sand to boulders. The bimodal rock composition in the source areas, with sandstones and black and grey shales cause the almost bimodal grain size distribution
L		45–15°	The avalanche fans are visibly highly intermixed with snow and ice at depth in the active layer. The fans have a concave curvature. The morphology and development of this section of the slope system is very uneven along the slope itself. In the southernmost part (L6–7) there are no real individual fans distinguishable morphologically. The fans in the north (L5 and north) are well-developed avalanche fans, with a concave cross-profile. The avalanche fans have clear apex and fan-foots, connected to well distinguishable couloirs. The northernmost fans (L1–L4) continue directly into the upper end of a rock glacier (code 88) that is located north of the large ice-cored frontal moraine of Larsbreen
N	Furthest slope deposition	15–5°	Consisting of debris and slush flow levees on both sides of distinct erosional channels (Debris flow track arrows), recently periglacially reworked by frost sorting and solifluction (code 325, 326). The weathering of stones, lichen and the general vegetation cover of these landforms the degree of periglacial reworking show that they have not been active recently
L		0–15°	The lowermost part of the avalanche deposition is a thin sediment cover (code 310), with larger grain sizes then the glacial till (code 15), on top of the ice-cored lateral moraine ridges

Table 2. All calculations of avalanche sedimentation rates ($kg\,yr^{-1}$) for each catchment at the Nybyen (N1–N5) and Larsbreen (L1–L7) slope systems. The annual averages or sums for Nybyen and Larsbreen are given in bold. The highest values and rates for each calculation step are given in italic. The values and rates marked with a star are from 2 yr of observations. The avalanche sedimentation rates from Larsbreen underlined are only calculated from permanent sediment traps.

	2007/2008	2008/2009	2009/2010	2010/2011		2003/2004	2005/2006	2006/2007	2007/2008	2008/2009	2009/2010	2010/2011
Annual amount of avalanche per catchment (N)												
N1	2	2			L1				5	4	7	5
N2			6	3	L2	2	4	5	4	5	***10***	8
N3				2	L3	2		5	4	7	***10***	7
N4		4		2	L4					3		
N5	4		***7***		L5				5		3	
					L6						7	
					L7						3	
	6	**6**	**13**	**7**		**4**	**4**	**10**	**18**	**19**	**40**	**20**
Annual maximum area of avalanche snow deposition (m^2)												
N1	26 894	***27 508***			L1				6989	6168	6884	7106
N2			9482	13 948	L2	7209	7490	6811	6186	7241	7932	***8567***
N3				18 822	L3	4564		4877	4088	6487	5698	7653
N4		14 955		21 844	L4					5123		
N5	15 944		11 640		L5				8183		2685	
					L6						4896	
					L7						3218	
	42 838	**42 463**	**21 122**	**54 614**		**11 773**	**7490**	**11 688**	**25 446**	**25 019**	**31 313**	**23 326**
Annual amount of avalanche deposited rock debris, directly measured (kg)												
N1	290	***1801***			L1				160	147	225	587
N2			619	467	L2	209	368	74	544	651	***11 135***	717
N3				669	L3	144		*328	73	207	632	530
N4		201		967	L4					443		
N5	298		685		L5				98		120	
					L6						370	
					L7						220	
	588	**2002**	**1304**	**2103**		**352**	**368**	**402**	**875**	**1448**	**12 702**	**1834**

TCD
6, 4999–5036, 2012

TCD
6, 4999–5036, 2012

The role of cornice fall avalanche sedimentation in Longyeardalen

M. Eckerstorfer et al.

Table 2. Continued.

	2007/2008	2008/2009	2009/2010	2010/2011		2003/2004	2005/2006	2006/2007	2007/2008	2008/2009	2009/2010	2010/2011
Annual sums of rock debris collection area (m^2)												
N1	32	***220***			L1				8	11	16	16
N2			16	25	L2	54	36	90	44	26	***543***	36
N3				25	L3	36		*90	8	18	34	32
N4		12		30	L4					8		
N5	20		28		L5				8		4	
					L6						12	
					L7						16	
	58	**232**	**44**	**80**		**90**	**36**	**180**	**68**	**63**	**625**	**84**
Annual amount of avalanche deposited rock debris (kg)/Annual sums of rock debris collection area (m^2) = Mean rock debris sedimentation rate ($kg\,m^{-2}$)												
N1	9.1	8.2			L1				20.0	13.4	14.1	***36.7***
N2			***38.7***	18.7	L2	3.9	10.2	0.8	12.4	25.0	20.5	19.9
N3				26.8	L3	4.0		*3.6	9.1	11.5	18.6	16.6
N4		16.8		32.2	L4					***55.4***		
N5	14.9		24.5		L5				12.3		30.0	
					L6						30.8	
					L7						13.8	
	11.3	**8.6**	**29.6**	**26.3**		**3.9**	**10.2**	**2.2**	**12.9**	**23.0**	**20.3**	**21.8**
Annual maximum area of avalanche snow deposition (m^2) * Mean rock debris sedimentation rate ($kg\,m^{-2}$) = Avalanche sedimentation ($kg\,yr^{-1}$)												
N1	243 727	225 190			L1				139 780	82 427	96 806	260 701
N2			366 835	260 549	L2	27 835	76 502	5615	76 481	181 304	162 651	170 626
N3				503 677	L3	18 218		*17 755	37 303	74 601	105 916	126 753
N4		250 496		***704 105***	L4					***283 686***		
N5	237 566		284 764		L5				100 242		80 550	
					L6						150 960	
					L7						44 248	
	484 399	**366 426**	**625 979**	**1 435 666**		**46 072**	**76 502**	**26 093**	**327 430**	**575 040**	**636 360**	**509 284**

TCD
6, 4999–5036, 2012

Table 3. Calculations of annual avalanche fan-surface accretion and rockwall retreat rates (mm yr^{-1}) for each catchment at the Nybyen (N1–N5) and Larsbreen (L1–L7) slope systems. The source and depositional areas for each catchment are visualized in Figs. 5 and 6 with the white outline. The annual averages for Nybyen and Larsbreen are given in bold. The highest values and rates for each calculation step are given in italic. The values and rates marked with a star are from 2 yr of observations. The rates from Larsbreen underlined are only calculated from permanent sediment traps.

	Source area (m^2)	Depositional area (m^2)		Source area (m^2)	Depositional area (m^2)
N1	116 541	***27 422***	L1	54 150	7282
N2	137 665	21 897	L2	42 964	***8623***
N3	169 359	21 454	L3	25 007	7771
N4	***222 854***	23 016	L4	***61 139***	5890
N5	146 252	18 771	L5	47 763	8410
			L6	6561	5835
			L7	13 406	3904
	676 130	**112 560**		**250 990**	**47 715**

	2007/2008	2008/2009	2009/2010	2010/2011		2003/2004	2005/2006	2006/2007	2007/2008	2008/2009	2009/2010	2010/2011
					Total avalanche sedimentation rate (kg yr^{-1})/Mean rock density of 2250 kg m^{-3} = Volume rock debris (m^3)							
N1	108.32	100.08			L1				62.12	36.63	43.03	115.87
N2			163.04	115.80	L2	12.37	34.00	2.50	33.99	80.58	72.29	75.83
N3				223.86	L3	8.10		*7.89	16.58	33.16	47.07	56.33
N4		111.33		***312.94***	L4					***126.08***		
N5	105.58		126.56		L5				44.55		35.80	
					L6						67.09	
					L7						19.67	
	215.29	**162.86**	**278.21**	**638.07**		**20.48**	**34.00**	**11.60**	**145.52**	**255.57**	**282.83**	**226.35**
					Avalanche fan-surface accretion rate (mm yr^{-1})							
N1	3.95	3.65			L1				8.53	5.03	5.91	15.91
N2			7.45	5.29	L2	<u>1.43</u>	<u>3.94</u>	<u>0.29</u>	3.94	<u>9.34</u>	8.38	8.79
N3				10.43	L3	<u>1.04</u>		<u>*1.02</u>	2.13	4.27	6.06	<u>7.25</u>
N4		4.84		***13.60***	L4					***21.41***		
N5	5.62		6.74		L5				5.30		4.26	
					L6						13.21	
					L7						5.04	
	1.91	**1.45**	**2.47**	**5.67**		**0.43**	**0.71**	**0.24**	**3.05**	**5.36**	**5.93**	**4.74**
					Rockwall retreat rate (mm yr^{-1})							
N1	0.93	0.86			L1				1.15	0.68	0.79	2.14
N2			1.18	0.84	L2	<u>0.29</u>	<u>0.79</u>	<u>0.06</u>	0.79	<u>1.88</u>	1.68	1.77
N3				1.32	L3	<u>0.32</u>		<u>*0.32</u>	0.66	1.33	1.88	<u>2.25</u>
N4		0.50		***1.40***	L4					2.06		
N5	0.47		0.57		L5				0.93		0.75	
					L6						***5.00***	
					L7						0.75	
	0.32	**0.24**	**0.41**	**0.94**		**0.08**	**0.14**	**0.05**	**0.58**	**1.02**	**1.13**	**0.90**

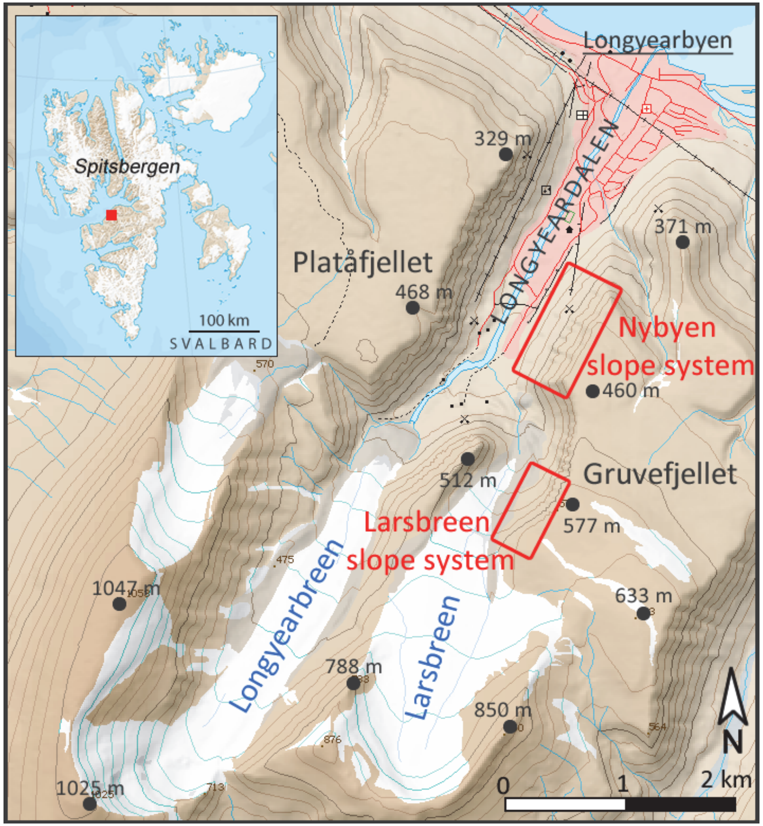

Fig. 1. Topographic map of the location of the two slope systems (red boxes) in the valley Longyeardalen in Central Spitsbergen (inset map). Svalbard's main settlement Longyearbyen is located at the northern end of Longyeardalen. Note the large summit plateau of the Gruvefjellet Mountain.

TCD
6, 4999–5036, 2012

The role of cornice fall avalanche sedimentation in Longyeardalen

M. Eckerstorfer et al.

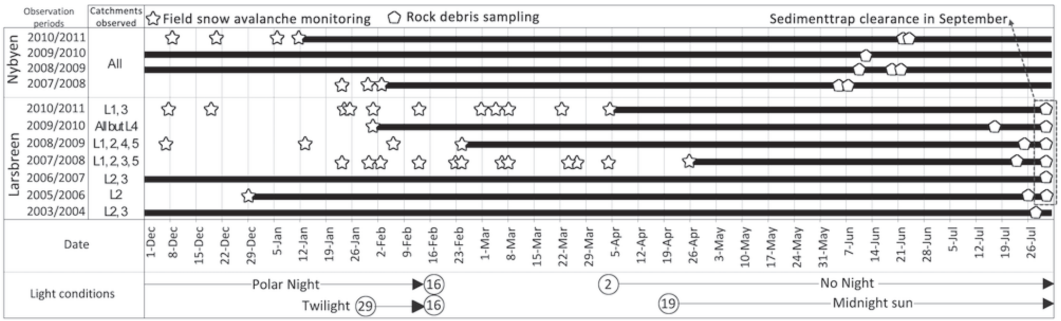

Fig. 2. Annual avalanche monitoring and rock sediment collection for each slope system. The black lines indicate periods with daily automatic time-lapse photography. The stars indicate field avalanche monitoring on site, and the pentagons indicate rock sediment collection in avalanche snow-deposits. The sediment traps at the Larsbreen catchments were all emptied in early September between 2005/2006 and 2010/2011. The daylight conditions are indicated with the date (number in circle) when seasonal changes occur.

TCD

6, 4999–5036, 2012

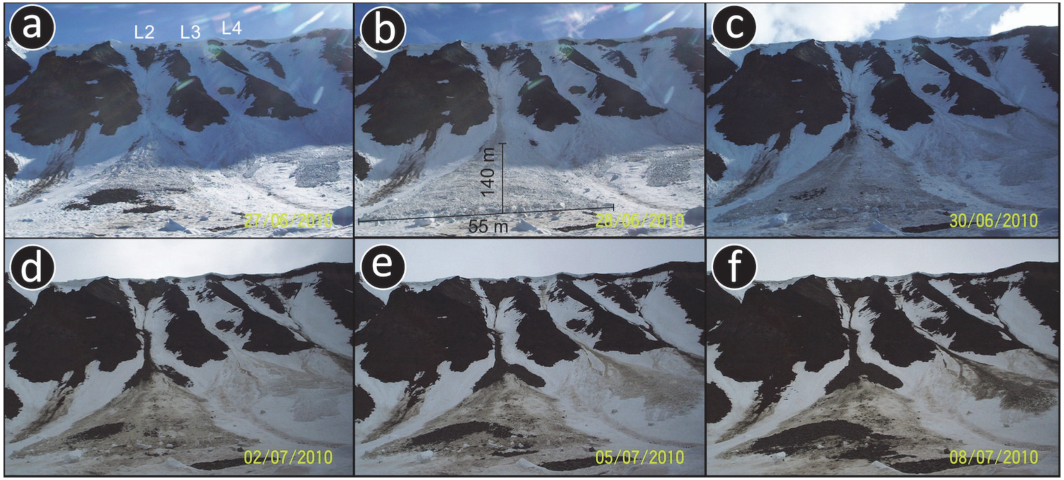

Fig. 3. Time lapse photography series from the camera (Lars-cam) overlooking catchments L1–L3. The time series shows a late spring cornice fall avalanche, followed by the progressive melt out of rock debris through summer on the avalanche fan in catchment L2 at Larsbreen. Note that visible rock debris content becomes more apparent as the avalanche snow deposition melts.

TCD
6, 4999–5036, 2012

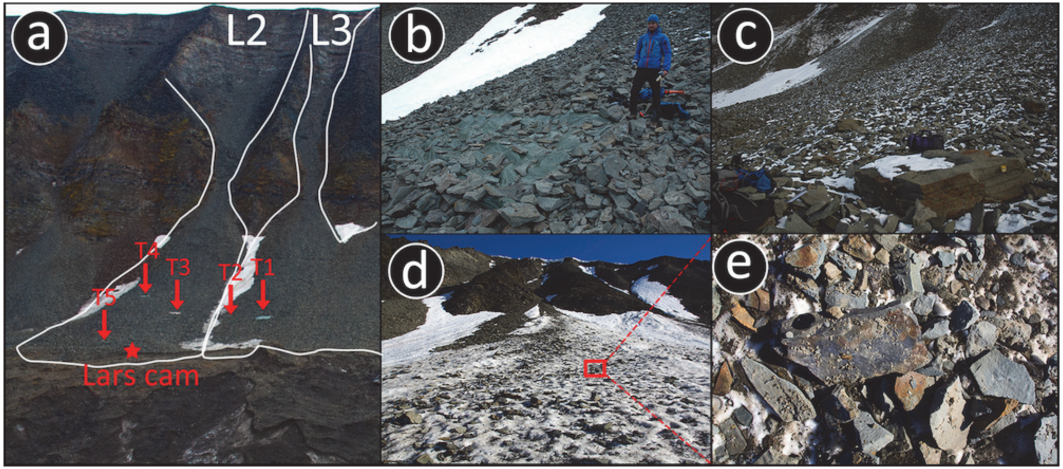

Fig. 4. (a) Locations of all four permanently deployed, 16 m^2 large polyethylene sheets (T1–T4) and one large, flat-topped boulder (T5) in catchments L2 and L3 at Larsbreen. The Larsbreen glaciers ice-cored moraine is visible in the foreground. The location of Lars-cam is marked with a star. **(b)** A 16-m^2 large polyethylene sheet (T4) with a border of lined up stones, containing rock debris to be weighed at the end of summer 2009. **(c)** The large flat-topped boulder (T5), acting as sediment trap in catchment L2. **(d)** Avalanche deposited rock debris, concentrating at the surface in catchment L7 in September 2010. **(e)** Close-up of avalanche deposited rock debris with rocks of different clast sizes (from boulders to fines) in catchment L7 in September 2010.

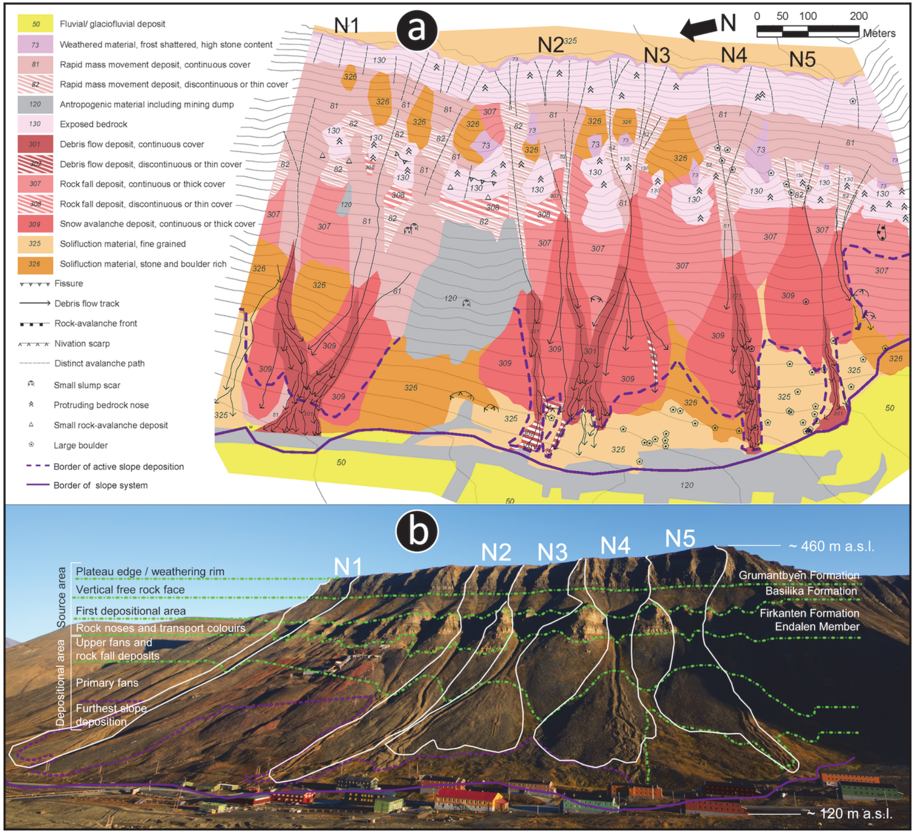

Fig. 5. **(a)** Geomorphology and sediments of the Nybyen slope system based on detailed geomorphological field mapping and 3-D aerial photogrammetry. **(b)** Nybyen with the five investigated catchments (N1–N5) (white line). The white line indicates the observed maximum modern runout distance of cornice fall avalanche sedimentation. The green dashed lines indicate different parts of the source and depositional areas or delimit the geological formations. The debris flow channels located in the overall depositional area are, however, erosional features.

TCD
6, 4999–5036, 2012

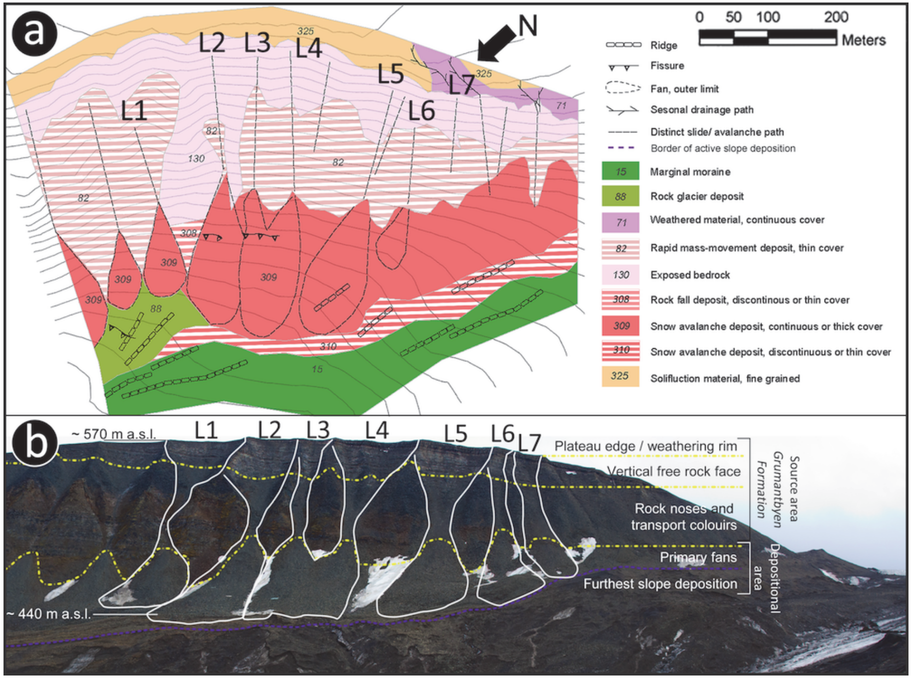

Fig. 6. (a) Geomorphology and sediments of the Larsbreen slope system based on detailed geomorphological field mapping and 3-D aerial photogrammetry. **(b)** Larsbreen with the seven catchments (L1–L7) (white line). The white lines indicate the maximum runout distance of cornice fall avalanches observed. The yellow dashed lines indicate different parts of the source and depositional areas or delimit the geological formations.

TCD
6, 4999–5036, 2012

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M. Eckerstorfer et al.

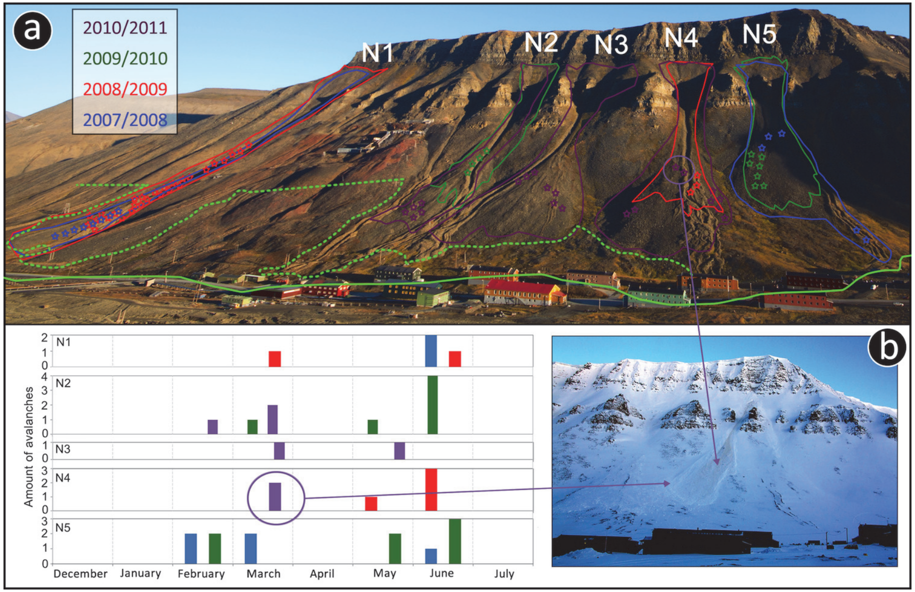

Fig. 7. (a) Outlines of the outermost annual extent of avalanche snow-deposits in the Nybyen slope system. The stars indicate the snow inventory rock debris sampling sites. **(b)** Annual number of avalanches that released in each catchment. The picture shows an avalanche that released in March 2011 in catchment N4 and from which rock debris was sampled in June 2011. Note the high visible rock debris content in the avalanche that originated directly from the plateau edge and the free rock face, as the avalanche was not a full-depth release.

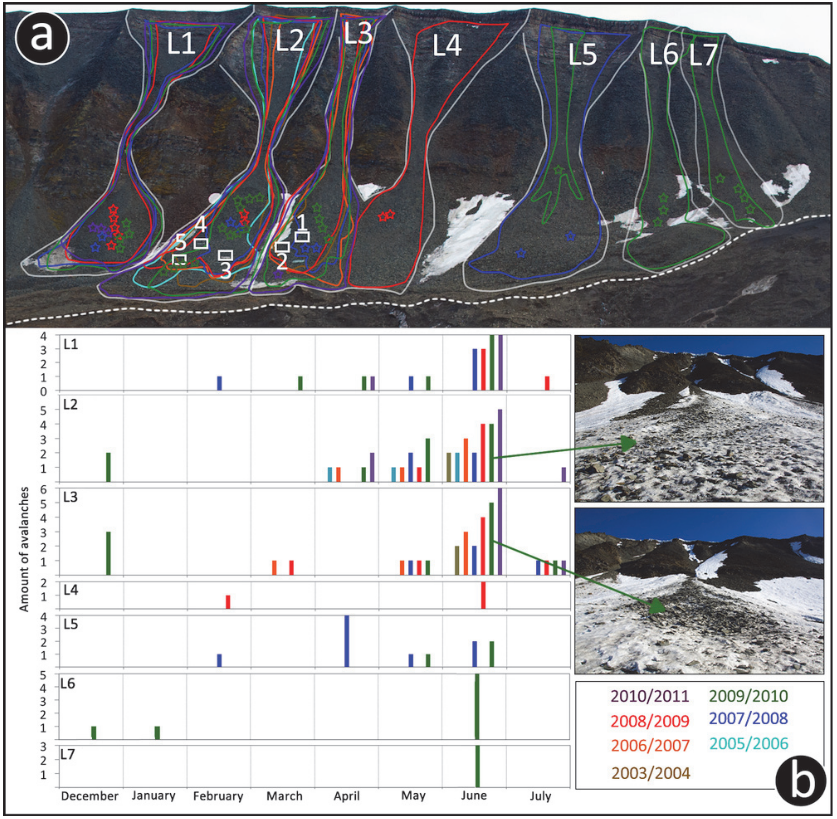

Fig. 8. (a) Outlines of the outermost annual extent of avalanche snow-deposits in the Nybyen slope system. The stars indicate the rock debris sampling sites. **(b)** Annual number of avalanches that released in each catchment. The two pictures exemplify two avalanches snow-deposits in which snow inventories were carried out. The avalanches released in catchments L2 and L3 in 2009/2010. Note the highly visible rock debris content in both avalanches.

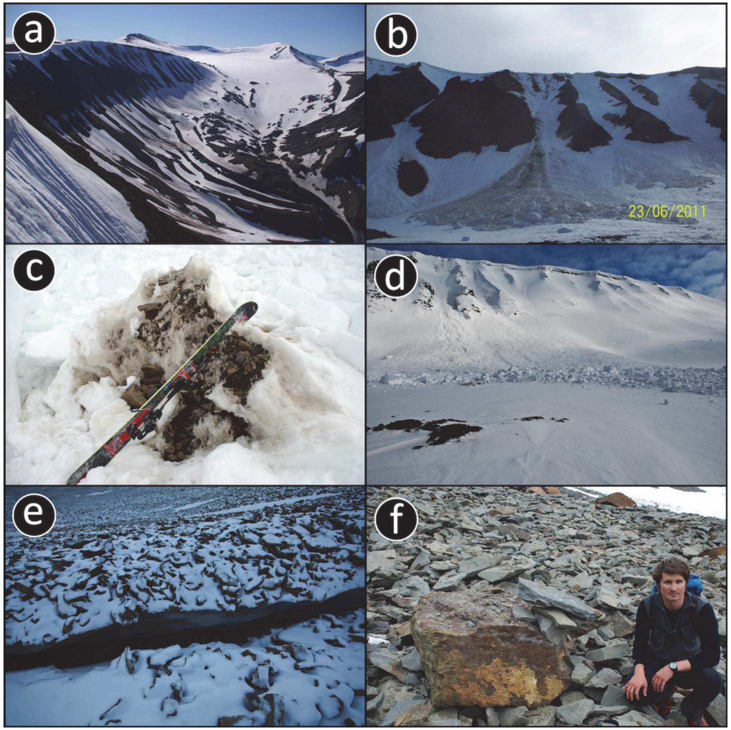

Fig. 9. **(a)** Automatic time-lapse photograph of the entire Larsbreen slope system. The photo shows avalanche activity 10 June 2008. Rock debris is clearly visible in the avalanches, as well as long runouts onto the ice-cored moraine of Larsbreen glacier. The avalanche derived rock glacier, with its three separate ridges is visible in the foreground. It was deflected by the LIA push of Larsbreen glacier. **(b)** Automatic time-lapse photographs covering catchments L1–L3 at Larsbreen. The collapsed part of the cornice is visible, as well as the high rock debris content in the avalanche deposit. **(c)** Collapsed piece of a cornice with rock debris of different grain sizes plucked directly from the plateau edge and transported downslope by a cornice fall avalanche, 12 May 2010 in catchment L3. **(d)** Large cornice fall avalanche 10 May 2011, which nearly hit the time-lapse camera (Lars cam) in front of the avalanche fan, and stopped on the ice-cored moraine of the Larsbreen glacier. **(e)** A fluvial channel eroded through avalanche deposits exposing ice inside the avalanche fan, accumulated due to the insulating effect of the avalanche sedimentation at catchment L5. The crack is about 100 cm in width at maximum **(f)** Perched avalanche deposited rock debris onto a boulder located at the foot of the avalanche fan in catchment L1 at Larsbreen.

TCD
6, 4999–5036, 2012