Holocene glacial and colluvial activity in Leirungsdalen, eastern Jotunheimen, south-central Norway

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Two terrestrial sections have been studied in order to reconstruct the Holocene glacial and colluvial history in Leirungsdalen, eastern Jotunheimen. The interpretation of individual sedimentary units is based on the grain-size distribution and compared with modern analogue samples collected in the respective streams and at sites close to the present glaciers. Stages of enhanced debris flow or glacial activity are recognized as sand and silt layers, respectively, while periods of low colluvial and glacial activity in the catchment are characterised by continuous peat accumulation. Age/depth curves based on radiocarbon dates from the Svarthammarbu and Steinflybekken sections indicate debris flow activity >7500, 7300–6800, 6600–5500, 5800, 5700, 5300–4900, 4700, 4500, 4300, 2300, 2100–1500, 1300, 700–600 and 500–400 cal. yr BP. The first Holocene glacial signal is detected ca. 5300 cal. yr BP. The frequency of glacial events seems to have increased during the Late Holocene, especially during the last 1500 cal. yr BP. Periods of enhanced debris flow activity back to 7000–6000 cal. yr BP, are largely in agreement with a similar record obtained from Leirdalen, western Jotunheimen.

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Introduction

In areas where glacier meltwater drainage is the primary source for minerogenic deposition, sedimentary sequences in downstream lakes and peat bogs can be used to infer a more continuous record of upstream alpine glacier fluctuations compared to the use of terminal moraines (Karlén 1976, 1982, 1988; Leonard 1985, 1986a, b; Nesje et al. 1991; Nesje & Dahl 1991a, b; Nesje & Kvamme 1991; Dahl & Nesje 1994, 1996; Matthews 1994). Lithostratigraphic evidence from gullies containing peat layers have been used by Nesje et al. (1991), Nesje & Dahl (1991a), Dahl & Nesje (1994, 1996) to infer Neoglacial phases in southern Norway. Understanding of the sedimentological processes is important for the use and interpretation of glacial activity from proglacial exposed river gullies. A major question is to what extent the minerogenic sequences are of glacial or fluvial/colluvial origin. Nesje & Dahl (1991a, 1991b) excluded a non-glacial origin for bluish-grey sand/silt sediments, while sand, on the other hand, was interpreted to be a result of fluvial/colluvial activity. Matthews et al. (1997) used a non-glacial stratigraphic succession of alternating peat and minerogenic sediments in Leirdalen, western Jotunheimen, to provide the basis for reconstructing Holocene colluvial history and mountain-slope activity. Fine-grained sediments were correlated to modern analogue samples of the distal parts of debris flows. The minerogenic layers were interpreted to represent debris flow activity instead of glacially induced sedimentation. This raises some interesting questions. Do sand/silt-related sediments necessarily represent periods of increased glacial activity and subsequent increased glacial erosion? Does outwash during heavy summer rainfall cause erosion and redeposition of "old" glacial deposits containing fine-grained material? This could imply the input of glacigenic sand/silt into the gully during periods without glacial activity. However, fine-grained sediments generally require a certain time to deposit sequences of considerable thickness, which in turn support a continuous inflow of sediments, rather than a short-lived flooding event. According to Sundborg (1956), erosion in consolidated fine grained material also needs a higher mean water-flow velocity than transport of the same material. Short-term outwash events may not be representative for the sedimentation of "old" glacial material. In contrast, a sequence consisting of only coarse sand has the potential of being deposited during a short time span. Furthermore, the use of minerogenic sediments as a glacial signal anticipates an equilibrium between sediment production and sediment deposition rates. This is not always the case, and led Church & Ryder (1972) to introduce the term "paraglacial" for non glacial processes that are conditioned by glaciation. For certain types of glaciers, enhanced glacial activity may not necessarily involve increased fine-grained sediment production, or at least the relationship between the two factors are not linear. The glacial signal may then be recognized indirectly as sedimentation of non-glacial sediments or by re-sedimentation of older glacier-related deposits.

Debris flow deposits are normally described as coarse, poorly sorted sediments commonly concentrated in well-defined frontal lobes and lateral levées (Innes 1983; Costa 1984; Selby 1993; Blikra & Nemec 1998; Matthews et al. 1999). However, Matthews et al. (1997) used this term for distal extensive and well-sorted sedimentation events on an alpine footslope, associated with fast moving thin sheets of fluid slurries escaping from the slower moving main body of the debris flow (Blikra & Nemec 1998). Such fluid slurries have larger runout distances and may form thinner sheetlike deposits over relatively large areas at the base of the slope.

Stream flow in proglacial rivers, conditioned as it is by snow and ice melt, is highly variable both on daily, seasonal and annual time scales. The runoff is extremely sensitive to changes in the climatic conditions, especially the ablation-season temperature (Gilbert & Church 1985). During major glacial expansions, large volumes of water are stored as ice and released for runoff when the glacier starts to melt. In periods of climatic deterioration and glacial advance, meltwater discharge is normally relatively small compared to intense melting under more favourable conditions (Sundborg 1956). In this manner, an increase in water-runoff and sediment input might be a signal of enhanced ice melting and subsequent climatic amelioration instead of increased glacial activity.

The main aim of this paper is to study the organic material and minerogenic sediments in two adjacent sections in eastern Jotunheimen and use several approaches, to try to separate sediments deposited by debris flows from those of a glacial origin in order to reconstruct the Holocene glacier and debris flow activity in eastern Jotunheimen.

Methods

Two terrestrial gullies were excavated and examined in the study area, Steinflybekken (1135 m a.s.l.) and Svarthammarbu (1220 m a.s.l.) (Figure 1). The sites were described in the field and 5 cm diameter half-cores were retrieved for further laboratory analyses. The colours were classified according to the Munsell soil colour chart, and the cores were photographed in different scales. Magnetic susceptibility measurements were carried out using the Bartington MS2 System, with sensors MS2B and MS2F. Measurements were taken every 1 cm, except from the lower part of the Steinflybekken section, where samples covered up to 10 cm of similar material. Detailed grain-size analyses of the finest sediments were carried out using a Micromeretics Sedigraph 5100 Particle Size Analyses System on selected sequences. Thin (~1cm) slices of peat were sampled for radiocarbon dating, and care was taken to avoid contamination of the peat samples, which in the field were immediately sealed in plastic bags. The samples were stored in a cold-storage chamber before submission for dating. The radiocarbon ages (Tables 1 and 2) are corrected for $\partial^{13}C$. Calibration of the radiocarbon ages to calendar years BP (BP = AD 1950) is according to the age calibration program of Stuiver et al. (1998). The major peat horizons in Svarthammarbu were also characterized and described in an attempt to indicate the degree of decomposition of the organic substance, as well as the proportion of the elements of which the deposits were composed. Organic content was determined by loss-on-ignition (LOI). Samples taken at 2cm intervals were dried at 105 °C overnight and stored in a desiccator. Weight LOI was measured after igniting at 550 °C for 1 hour.

Svarthammarbu

Svarthammarbu is an exposed river gully located 1220 m a.s.l. south-east of Steinflybreen and Høgdebrotebreane (Figure 1) and the area surrounding the site is characterized by soligenous mire covered with *Salix*. The valley slope above the site shows some evidence of modern and former debris flow activity. The sediments have accumulated at the foot of a well-vegetated valley side, and a small non-glacial stream passes through the site at present. In the past, however, the site was fed with minerogenic sediments by a river passing a local water divide at Steinflyi 1650 m a.s.l. during periods with enhanced glacial meltwater from Steinflybreen and Høgdebrotebreane when these were more extensive than at present, and/or by colluvial outwash during extreme rainfall events. Increased input of minerogenic sediments is likely to represent periods of geomorphological instability, while undisturbed peat production suggests general climatic and geomorphological stability.

The descriptions and analyses refer both to a 3 m wide and 260 cm deep gully section, and a 5 cm diameter box-core. Although the site lies close to the main river Leirungsåa, an overbank origin for the minerogenic sediments is eliminated as a possibility since the site is located too far up-slope and the sediments wedge out towards the river. It is possible, however, that there may have been some minor influence by Leirungsåa at a very early stage.

Lithostratigraphy

The lithostratigraphy of the section is summarized in Figure 2, which also shows the radiocarbon dates, magnetic susceptibility profile and LOI curve. The stratigraphy

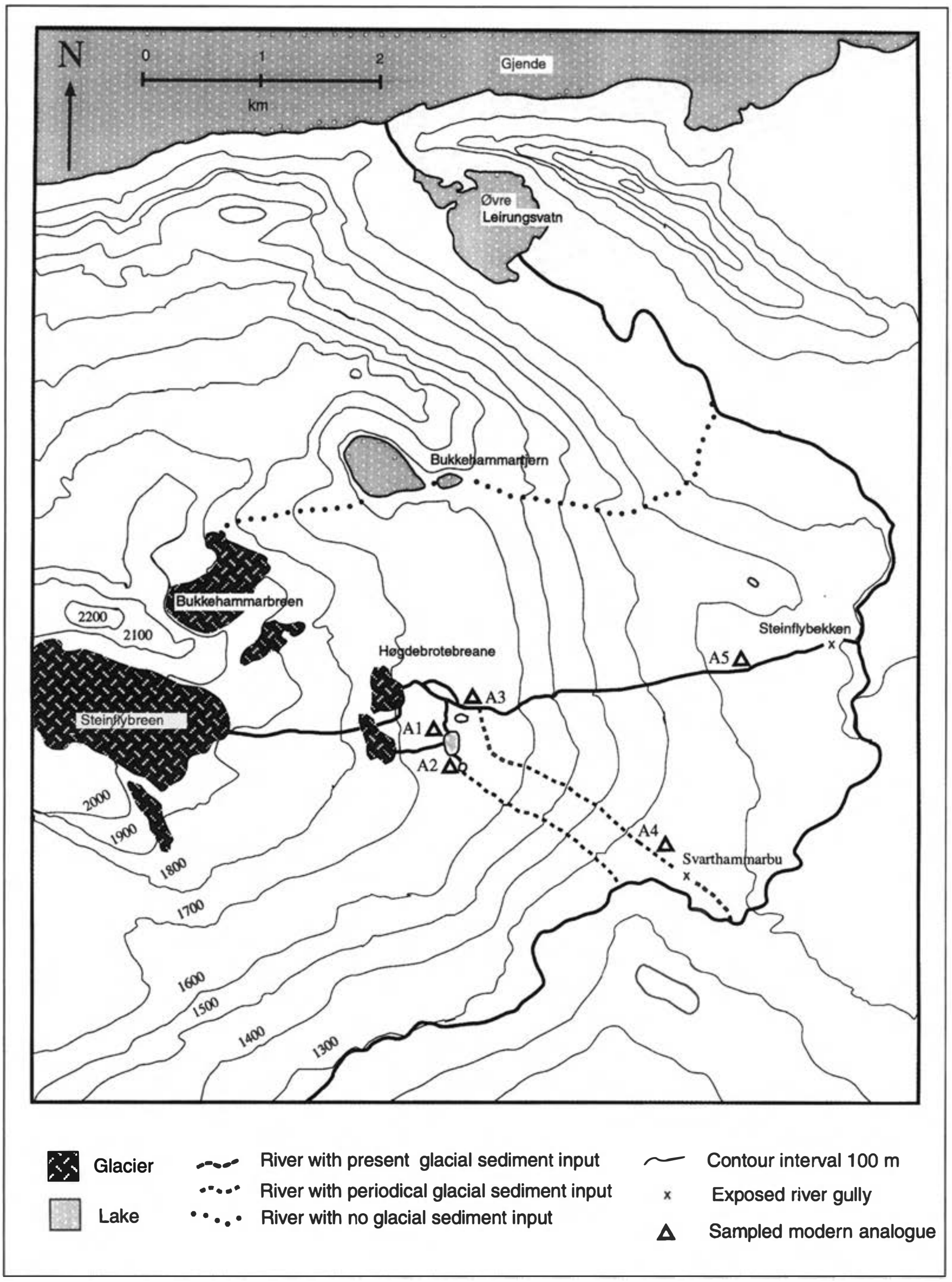

Figure 1. Location map of the study area.

Table 1. Radiocarbon datings from the Svarthammarbu site.

Depth (cm)	Material	Lab. no	^{14}C age	Intercept cal. BP	1 sigma cal. BP
70	Peat	T-12275	1650±80	1540	1420–1690
130	Peat	T–12276	3790±60	4150	4090–4245
175	Peat	T-12277	4710±100	5345	5315–5590
195	Pine	T-12710	4635±70	5420	5305–5465
245	Peat	T-12278	4590±70	5310	5085–5445
255	Birch	T-12279	5365±65	6125	6000–6275

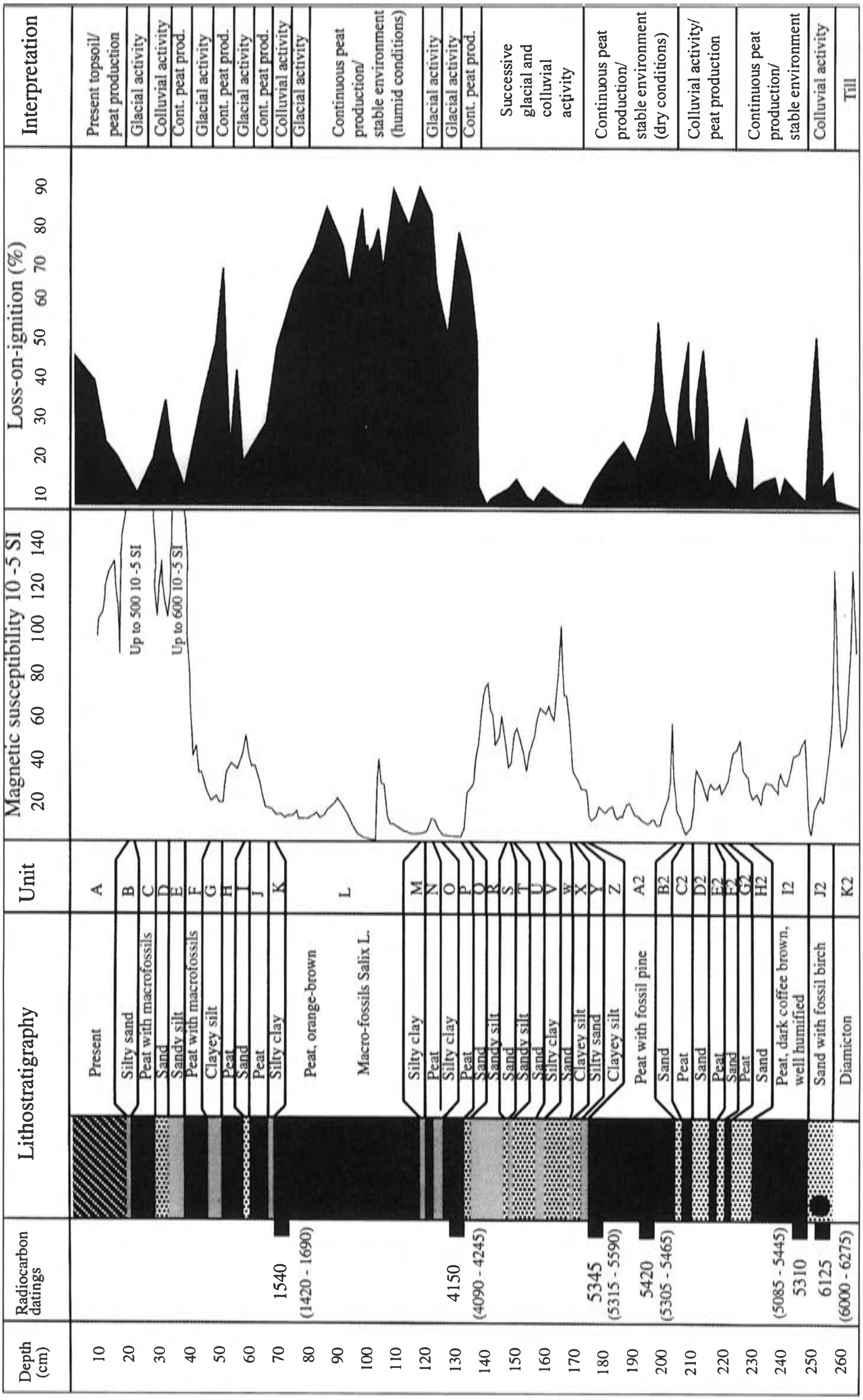

Figure 2. The Svarthammarbu site 1220 m a.s.l.; lithostratigraphy, radiocarbon dates in calendar ages with one standard deviation in brackets, magnetic susceptibility, loss-on-ignition, and interpretation of the units in the section.

reveals a 270 cm deep gully with 13 distinct peat layers, separated by 24 minerogenic layers, changing from silty clay to sand. In the basal part, a bluish-grey diamicton contains angular to sub-angular cobbles and boulders (unit K2). Above this, a 15 cm layer of sand and gravel (unit J2) is followed by a 80 cm section with intervening thin minerogenic and organic sequences (units A2–I2). The organic sequences in these units are mostly represented by sandy peat, often with small macrofossils of *Salix*. Between 130 and 175 cm, a distinct section of ten minerogenic layers is detected, consisting of sand, sandy silt and clayey silt (units Q-Z). At a depth of 70 to 134 cm a major peat section (units L, N and P) is intervened by three thin layers of silty clay (units K, M and O). From 20 to 70 cm four peat horizons (units B, C, F, H and J) are intercalated with both sandy layers (units D and I) and more fine-grained minerogenic layers (units E and G). Unit B, consisting of silty sand, separates the present topsoil (A) from unit C.

The Munsell colours are described from a retrieved half-core (box section) which may give lighter colours due to drying of the sediments, especially the peat horizons, even though the cores were stored in a cold chamber and sealed in black plastic bags. Visually, there seems to be no relationship between the type of sediment and colour. Coarser sediments often have the same colour as finer ones and the same fraction may have different colours throughout the section. This is probably caused by the surrounding layers influencing physical and chemical processes. Dark peat layers may influence the colouring of underlying minerogenic sediment, while others are more protected from humic acid.

Plant macrofossils and peat humification

A well-preserved subfossil birch-stump (*Betula pubescens*) dated to 6125 cal. yr BP (Table 1), was found in a sandy layer (unit J2) just above the basal diamicton. The macrofossil had a diameter of 10 cm and a length of 40 cm. The present local birch-tree limit is situated at an altitude of about 1100 m. Thus, around 6000 cal. yr BP the local birch-tree limit reached approximately 100 m higher than at present. However, the Svarthammarbu site is a fairly exposed site thought to reveal minimum birch-growth altitude only. In the fine grained minerogenic layers (units B, I, Q, U, B2, D2, F2 and H2) some amounts of plant macrofossils are found, mainly small roots of *Salix*. No further detailed investigation have been carried out on the plant fragments.

A subfossil pine stump (*Pinus sylvestris L.*) was detected in the organic layer at 180–210 cm depth (unit A2). The stump had a diameter of 10 and a length of 35 cm, and was radiocarbon dated to 5420 cal. yr BP (Table 1). The pine megafossil is a remnant from a regionally higher pine tree-limit during the Holocene thermal optimum, consistent with results presented from other parts of southern Norway (e.g. Aas & Faarlund 1988).

In the Svarthammarbu site, differences are seen in humification and structure of the peat layers. Visual examination using a 10-class scale of humification (Aaby & Tauber 1974), indicates that the peat layers between 175 and 250 cm (units A2, C2, E2, G2 and I2) are well humified with a dark coffee-brown, giving a humification value of 8. The units L, N, and P reveal a lighter chocolate-brown and are less humified, giving a humification value of 5. Units F, H and J have an orange-brown colour with a poorly decomposed organic structure, furnishing a humification value of 3.

Grain-size distribution

Grain-size analyses have been carried out in an attempt to trace soils and sediments from different source areas and distinct transport histories (Figure 3). Except from a sample taken at 195 cm (unit A2), all samples were picked from separate minerogenic layers. Based on the Sedigraph data, a subdivision of the clay and silt fractions was made in an attempt to trace critical factors distinguishing non-glacial and glacial sediments.

The coarsest layer is located at 169 cm (unit W, Figure 3), containing 50% fine sand and 20% medium sand, closely followed by the sample at 35 cm (unit D, Figure 3) containing 47% fine sand and 15% medium sand. The finest minerogenic layers are detected at 69 and 119 cm depths (unit K and M, Figure 3) containing 20% clay, 26% fine silt, 44% medium silt and 23% clay, 31% fine silt 37% medium silt, respectively. These two thin clayey/silt bands are from in the upper peat section (unit J, L and M, Figure 3) indicating a distinct fine-grained minerogenic sediment input during a period of continuous peat production. The sample at 195 cm has the third finest grain-size distribution with a content of 11% clay, 13% fine silt and 31% medium silt. This sample might reflect the characteristic fine grained content in the peat layers.

Modern analogue stream bank sediments were collected proximal to the exposed gully section (Figure 1). The modern analogue samples are supposed to reveal characteristic grain-size distributions for sediments that are periodically transported by the stream. The aim was to test if the minerogenic layers in the section could be traced back to a source area at an higher altitude, by comparing the grain-size distributions of sediments in the section with those of modern sediments along the stream bank. A modern analogue sample was collected 100 m distal to Svarthammarbu, deposited by the stream running through the present gully. The sample consisted of 5% clay, 83% silt and 9% fine/medium sand.

Radiocarbon dates

Thin (~1cm) peat slices were sampled at selected depths for radiocarbon dating in order to obtain age constraint

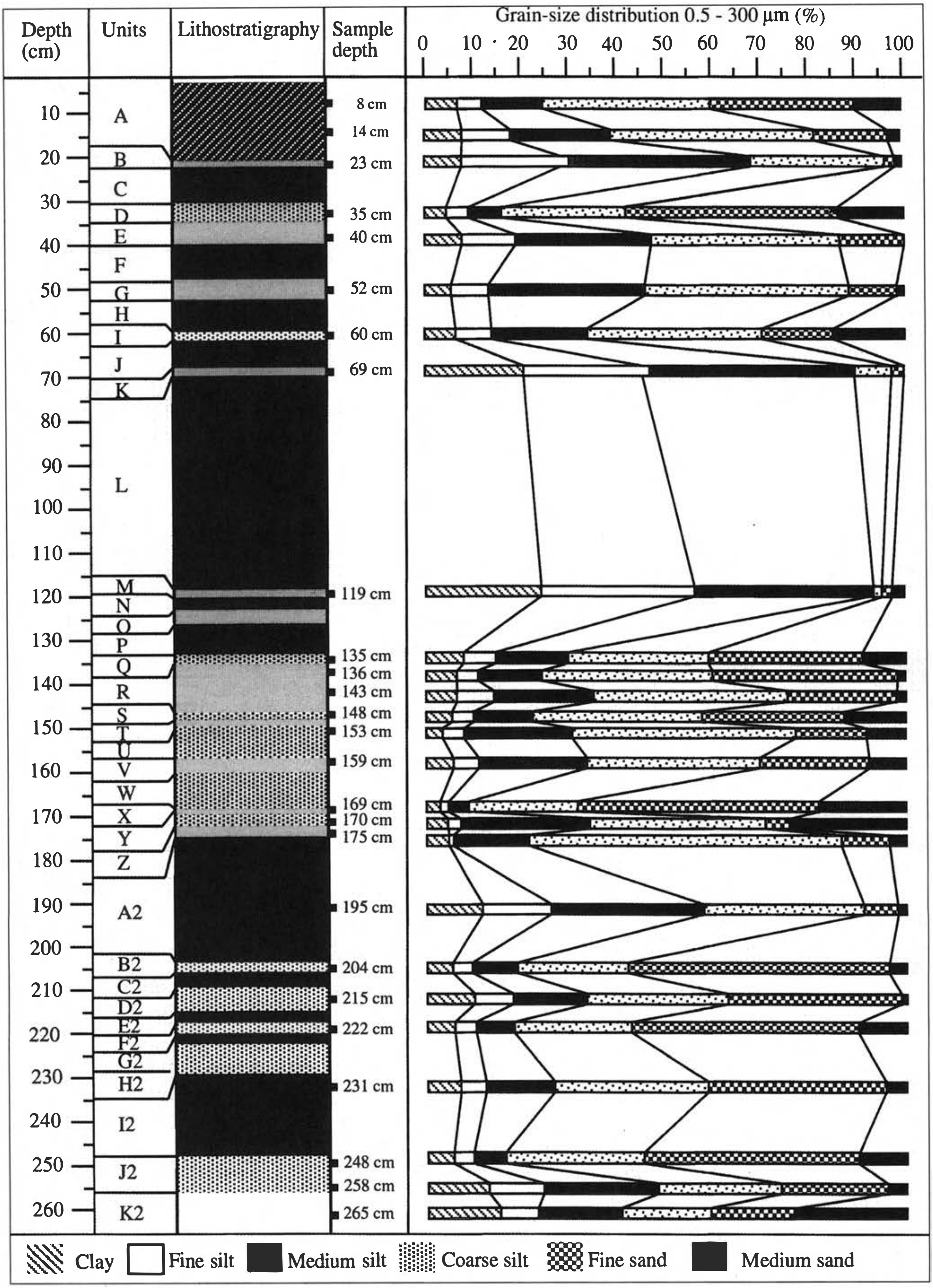

Figure 3. Grain-size distribution at selected depths in the Svarthammarbu section.

for periods of peat accumulation (Table 1). Samples were collected on the top and bottom of the major peat horizons, units I2, A2, P and L (Figure 2). The basal part of unit I2 is dated to 5310 cal. yr BP, which may indicate the start of peat formation at the site. The top of unit A2 was dated to 5345 cal. yr BP. The lower part of unit P was dated to 4150 cal. yr BP, while the upper part of unit L was dated to 1540 cal. yr BP.

The lower part of unit I2 is surprisingly young compared to the other datings. A low growth rate and subsequent autocompaction would normally have favoured a greater timespan between the top and bottom of the peat layer. The young age might be explained by contamination from penetrating roots.

A sediment accumulation rate curve has been constructed for the Svarthammarbu site (Figure 4). T-12710 and T-12278 are not used to construct the curve. Apparently, the highest accumulation rate (0.103 cm/yr) in the section was at the lower part. This higher growth rate during the Early compared to the Late Holocene corresponds well with estimates from a site in the Jostedalsbreen area, western Norway, ranging from 0.07–0.009 cm/yr (Torske 1993). Nesje et al. (1991) reported growth rates in terrestrial gullies in the adjacent area of 0.06–0.04 cm/yr, and in some of them even higher organic growth rate in Early Holocene. This trend is most probably caused by higher annual temperatures that are favourable for peat growth. However, due to different altitudes and local climatic factors, comparisons of growth rates should be made with great care. Also autocompaction of the peat layers must be taken into account when comparing growth rates, both within the same site and with other localities.

Steinflybekken

Steinflybekken is a 140 cm deep exposed river gully east of Høgdebrotet (Figure 1). The site, lying at 1135 m a.s.l., is located 4.5 km downstream of the glaciers Steinflybreen and Høgdebrotebreane. Meltwater with glacigenic sediments from these glaciers flows into the gully, which at present has bankfull discharges during intensive melting early in the summer.

Lithostratigraphy

The lithostratigraphy of the section is summarized in Figure 5, which also displays the radiocarbon dates, magnetic susceptibility profile and LOI curve. The section consists of alternating minerogenic layers and peat hori-

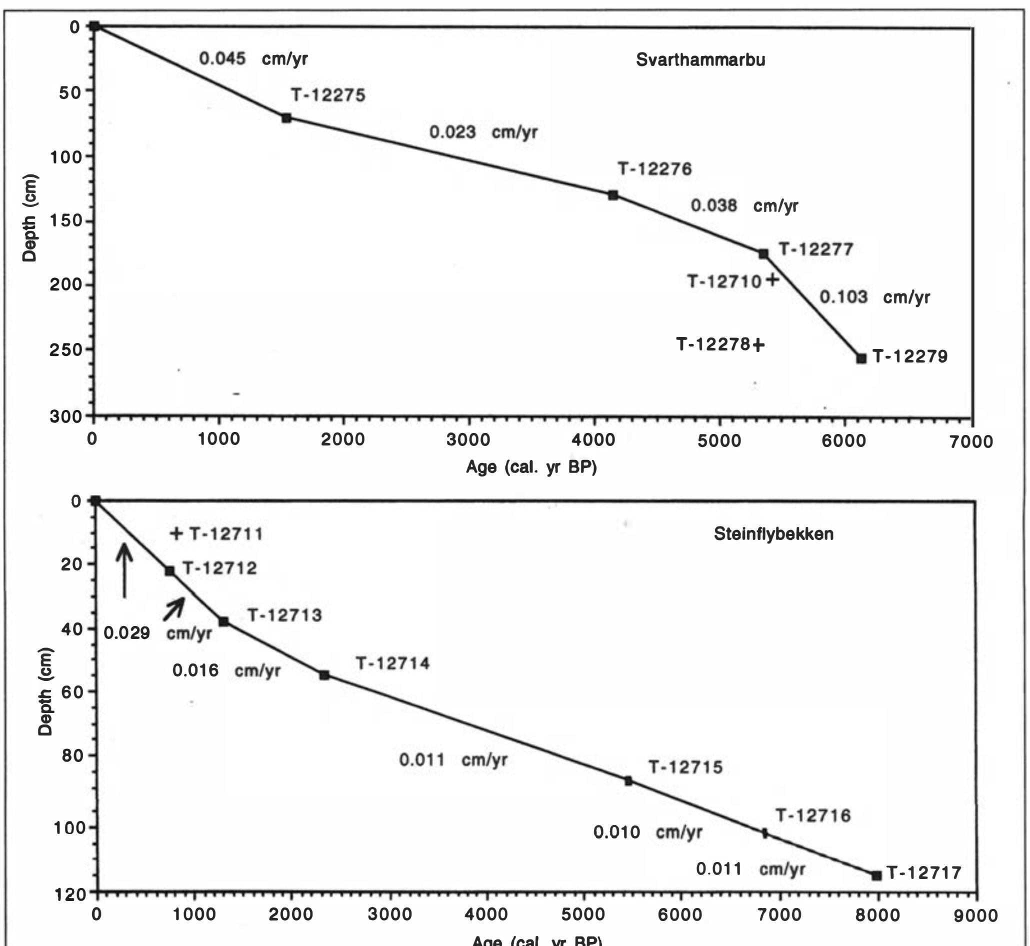

Figure 4. Accumulation rate curves inferred from intercept calibrated ages from the Svarthammarbu and Steinflybekken sites. The dates marked by (+) are not used to construct the age/depth curves (see Tables 1 and 2).

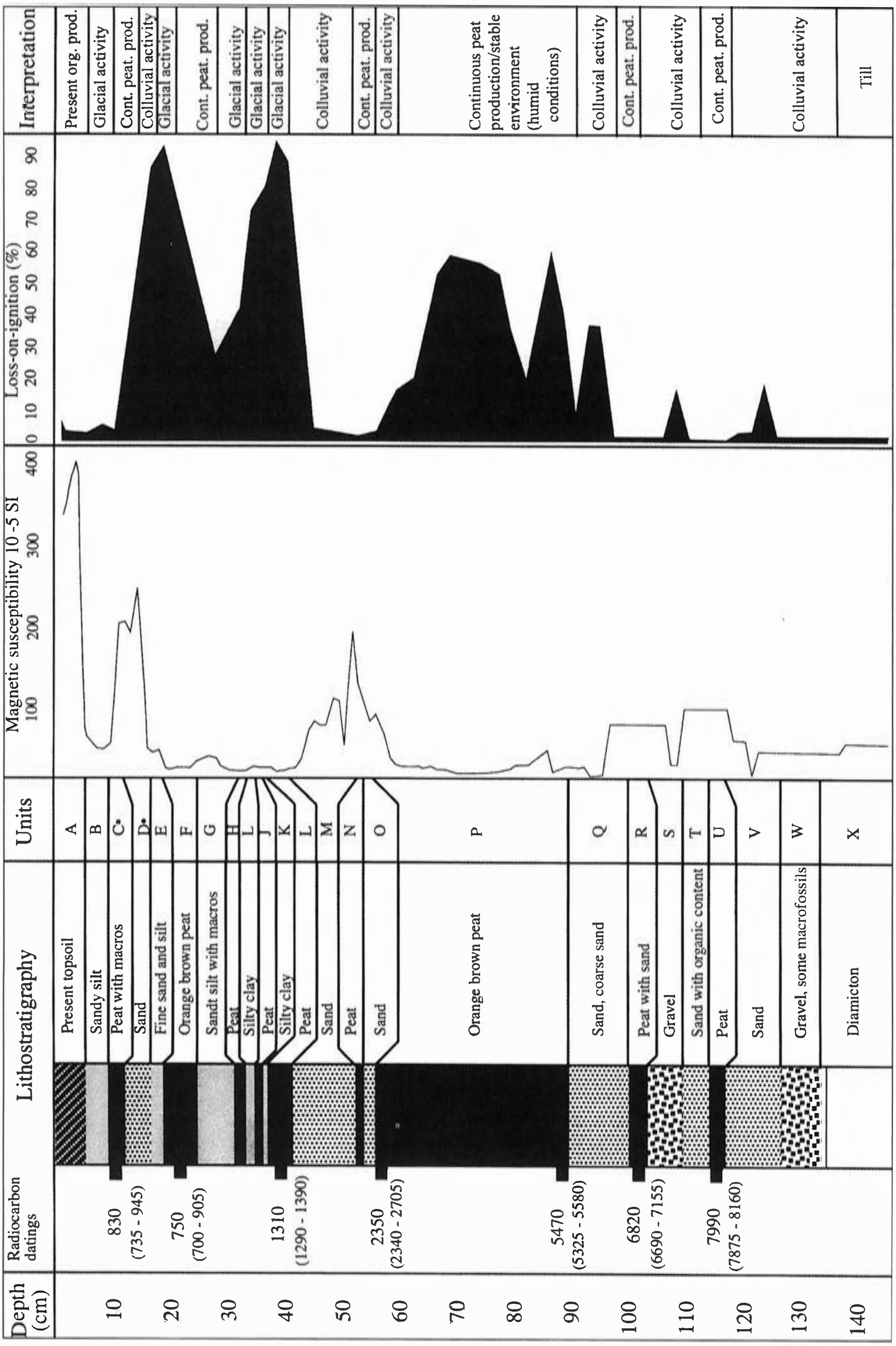

Figure 5. The Steinflybekken site; lithostratigraphy, radiocarbon dates in calendar ages with one standard deviation in brackets, magnetic susceptibility, loss-on-ignition, and interpretation of the stratigraphic succession.

zons. Including the present topsoil, the profile shows ten distinct, well-humified peat horizons, varying from 1 to 35 cm in thickness. The minerogenic sequences mainly consist of fine sand, silt and clayey silt. Each sequence varies from >20 cm to less than 0.5 cm and the dominating Munsell colours are 10 YR 3/2–4/2 and 3/3. The basal sedimentary unit consists of a matrix-supported diamicton (Unit X) with angular boulders and bluish grey clayey silt and sand matrix. The lower minerogenic units consist mainly of fine gravel and silty sand, units S, W and Q, T, V respectively. The sandy unit M includes an organic lense. In general, the most fine-grained layers are found in the upper part, including units B, D, E, G, I and K. The most common Munsell colours in the peat layers are 5 YR 2/2–3/2, while a more reddish peat (10 YR 3/1 and 7.5 YR 4/2) were observed in the top soil layer, probably due to formation of iron oxide. Plant macrofossils of *Salix* were found in some organic peat horizons. Plant macrofossils detected in some of the minerogenic layers may indicate erosion and resedimentation.

Grain-size distribution

Grain-size distribution at 14 selected depths, mainly minerogenic units, are shown in Figure 6. The dominating fractions in most samples are medium silt, coarse

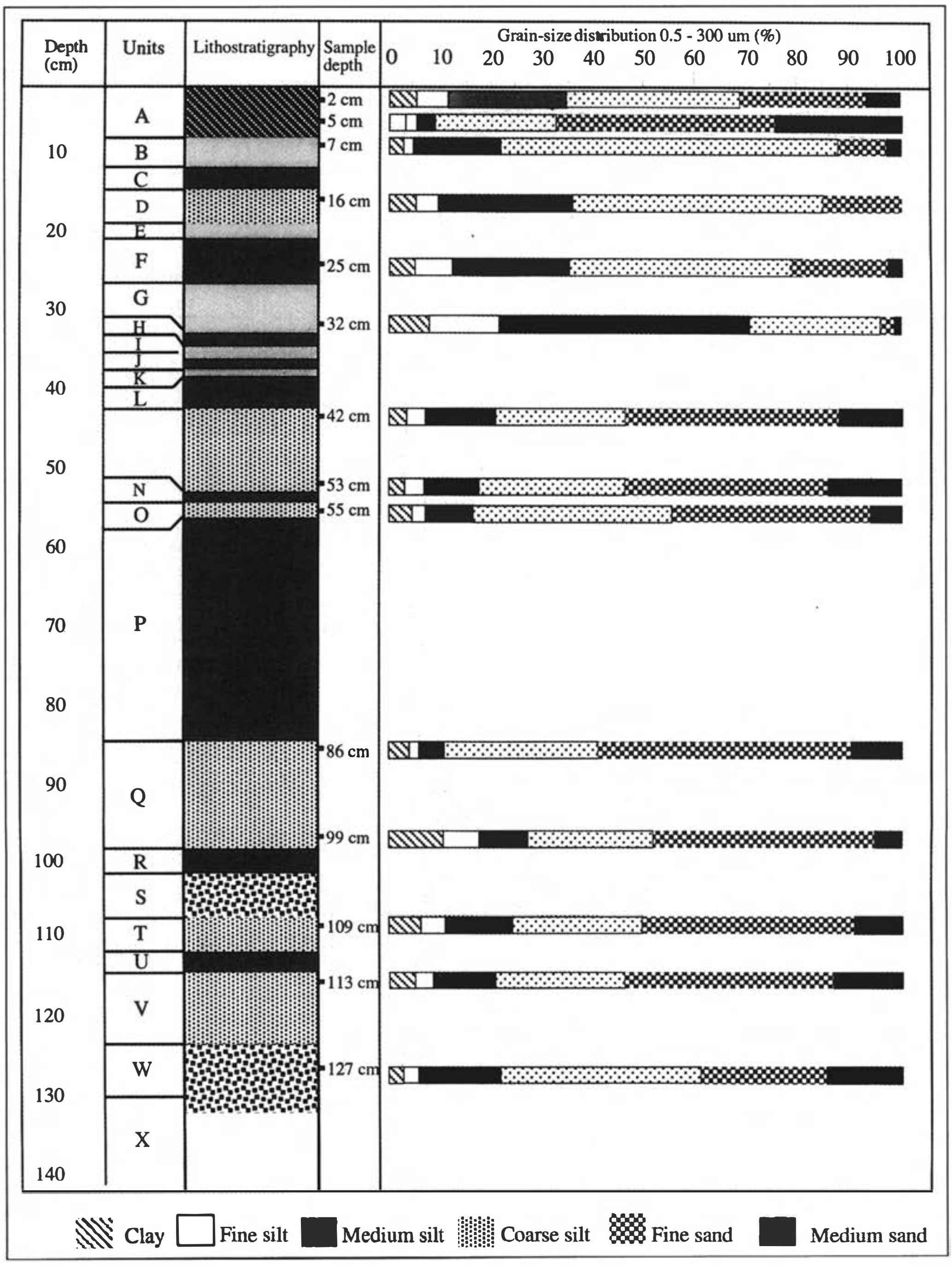

Figure 6. Grain-size distribution at selected depths in the Steinflybekken section.

silt and fine sand. The clay fraction is present in all samples. Due to great internal variability, the arithmetic mean may not be an appropriate indicator of the grain-size distribution in the minerogenic sequences. Thereby, detailed analyses of each single minerogenic layer have been carried out in an attempt to sort out the characteristic distribution of fine-grained sediments. In units M and Q, samples were analysed at the top and bottom to look for variability within one distinct layer. Similar grain-size distribution within the same unit could give indications of one single sedimentological event or a relatively steady depositional environment over a longer time span. The samples from the top and base of unit M do not show much difference. The sample from the basal part of unit Q, however, is more fine-grained than the sample from the top of the same unit. The finest minerogenic layers tend to have accumulated in the upper 32 cm of the section. As at the Svarthammarbu site, one sample for Sedigraph analyses was collected in a distinct peat layer, to see if peat layers had accumulated fine sediment penetrating from overlying minerogenic sequences. Unit F at 25 cm has a grain-size distribution of 6% clay, 72% silt and 22% fine/medium sand, slightly coarser than a similar sample from the Svarthammarbu site.

Modern analogue samples

Modern analogue samples of deposited stream bank sediments were collected 150 m proximal to the pit (Figure 1). It is presumed that similar sediments are deposited at the site during events favourable for bankfull discharge. The sample consists of 5% clay, 86% silt and 9% fine/medium sand. In addition, samples of stream bank sediments in the proglacial area distal to Høgdebrotebreane (Figure 1), produced by both Steinflybreen and Høgdebrotebreane, contain 11–28% clay, 70–84% silt and 2–6% fine/medium sand, all three samples more fine grained than the modern analogue sample A4. It must be stressed that the sediments from Svarthammarbu-bekken were deposited by a small stream from a perennial snowpatch. The grain-size distribution might thus have been influenced by nivation processes washing out the underlying till. However, the stream is not capable of depositing a continuous minerogenic sequence in Svarthammarbu under present conditions.

Radiocarbon dates

Seven distinct peat layers were collected for radiocarbon dating, units C, F, L, P, R and U (Figure 6). The radiocarbon datings are summarized in Table 2. Unit U is the oldest, dated to 7990 cal. yr BP. Unit R, a layer of similar thickness as Unit U, is dated to 6820 cal. yr BP. The most extensive peat horizon (unit P) is sampled at bottom and top, dated to 5470 cal. yr BP and 2350 cal. yr BP, respectively. Unit L at 40 cm depth is dated to 1310 cal. yr BP, while unit F at 20 cm has an age of 750 cal. yr BP. The youngest dated peat layer (Unit C) is dated to 830 cal. yr BP.

Interpretation

The Svarthammarbu and Steinflybekken sites display phases with alternating minerogenic sedimentation and organic peat production since the Early to Mid Holocene (Figure 7). In the case of Svarthammarbu, we suggest that the site was influenced by a local water divide at Steinflyi during periods with enhanced glacial activity relative to the present. The minerogenic units therefore represent more extensive glaciers than at present, while the organic units indicate contracted or non-erosive glaciers. In contrast, Steinflybekken may illustrate a continuous Holocene on/off signal for glacial activity at Steinflybreen and Høgdebrotebreane, as the present river, in contrast to Svarthammarbu-bekken, is transporting large amounts of glacigenic sediments. This interpretation is, however, probably too simple as it does not take into account paraglacial processes, erosion/resedimentation or alternating source areas for the sediments. The streams might also have changed drainage in the past, resulting in the absence of minerogenic units.

Table 2. Radiocarbon datings from the Steinflybekken section.

Depth (cm)	Material	Lab. no	^{14}C age	Intercept cal. BP	1 sigma cal. BP
10	Peat	T-12711	935±95	830	735–945
22	Peat	T-12712	865±60	750	700–905
38	Peat	T-12713	1435±65	1310	1290–1390
55	Peat	T-12714	2375±80	2350	2340–2705
88	Peat	T-12715	4720±55	5470	5325–5580
102	Peat	T-12716	6040±130	6820	6690–7155
115	Peat	T-12717	7200±115	7990	7875–8160

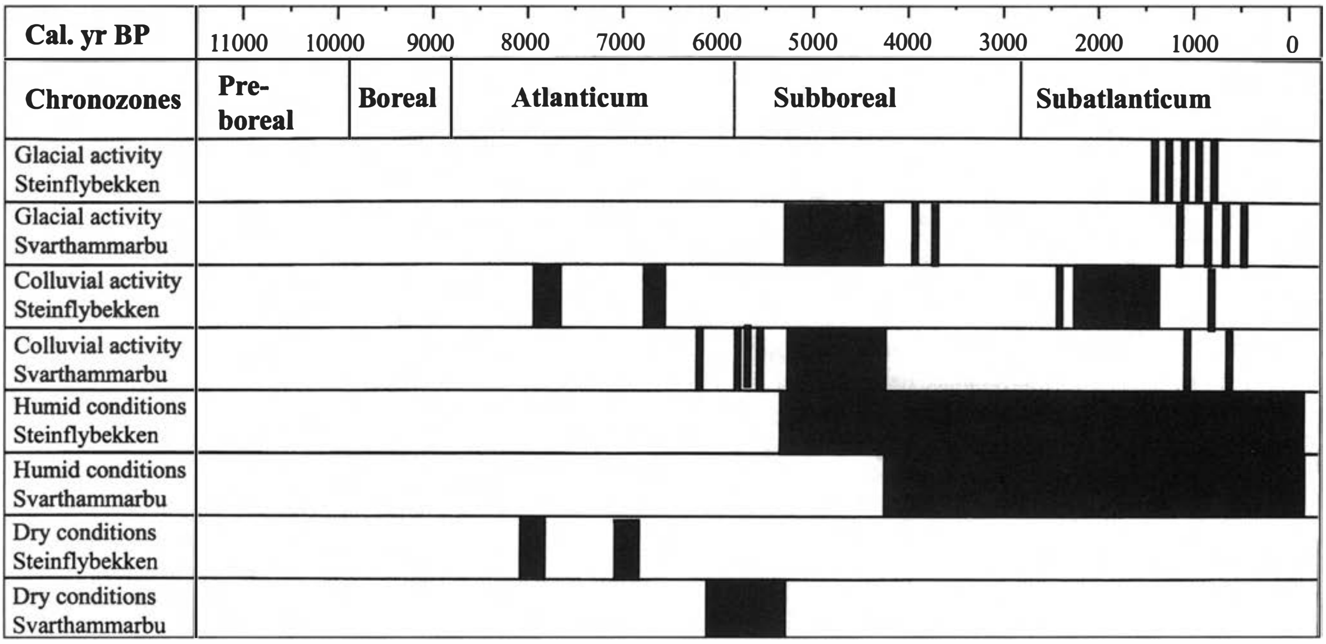

Figure 7. Summary of the interpretation of the Steinflybekken and Svarthammarbu sites.

Svarthammarbu

It is uncertain whether the basal diamicton is an in situ till or later reworked by paraglacial processes. As the subfossil birch in unit J2 indicates an age of 6125 cal. yr BP, the hiatus since the presumed regional deglaciation may have been caused by the influence of the main river. Gunnarsdottir (1996) obtained a minimum date of the first organic production in Smådalen in the north-eastern part of Jotunheimen (altitude 1250 m) of 10 770 cal. yr BP. A similar peat growth as recorded in Steinflybekken dated at 7990 cal. yr BP (unit V, Figure 5) might have been removed, and the fossil birch deposited in the sandy layer unit J2 (Figure 2). 6125 cal. yr BP is considered a maximum age of the sedimentation of unit J2, and subsequent initiation of peat accumulation in unit I2. The initiation of peat growth depends, however, largely on local topographical conditions. Although lower parts of the sequence might have been influenced by the main river Leirungsåi, the remaining section is interpreted as a signal from the minor stream Svarthammarbu-bekken. Prior to the accumulation of unit H2, a well-humified peat layer has developed undisturbed, indicating conditions more favourable for peat accumulation than at present. According to the discussion concerning the radiocarbon dating at 245 cm (T-12278, Figure 2), determination of the absolute timing of the peat initiation is difficult. Unit I2 is followed by a period of four minerogenic sequences, separated by three distinct peat layers, representing a more unstable period than unit I2.

Grain-size analyses of three samples (units B2, C2 and D2) showed a distribution, similar to those interpreted by Matthews et al. (1997) as colluvial debris flow activity. Compared to the collected modern analogue samples, these three layers are coarser than both the modern analogue sample A4 and the pure glacial signal in the modern analogue samples A1-A3. As a consequence, units B2, C2 and D2 represent colluvial events. It is hard to determine how one flooding event affects the minerogenic signal in stratigraphic sections like Svarthammarbu and Steinflybekken. Under present conditions, the banks of the rivers and surrounding slopes are well vegetated and thereby protect the underlying sediments from erosion. As a consequence, more than one erosive event may be necessary to register a minerogenic signal in the terrestrial gullies; the first event removing the vegetation cover and exposing the minerogenic sediments to erosion. According to the well-humified peat layers, implying relatively dry conditions, units H2, F2, D2 and B2 are probably caused by extreme events, not connected to a general higher moisture availability. This also supports a non-glacial origin for the minerogenic layers, as enhanced glacial activity is often caused by increased winter precipitation. Thus, the period is interpreted as relatively dry but with severe rainfall/snow-melt events initiating colluvial activity (slope wash or debris flow).

An attempt was made to trace minerogenic sediments directly sampled from a peat horizon (Unit A2, 195 cm). The sample showed a fine-grained distribution of 11.8% clay, 78.4% silt and 9.8% sand, probably caused by percolation in the water-saturated peat layer. It must be noted, however, that the sediment concentration was very low. However, it shows the potential of using Sedigraph even on terrestrial organic sediments with low minerogenic content.

The period between 5345 and 4150 cal. yr BP was characterized by increased input of minerogenic material. The Sedigraph results show variability in grain-size distribution, but the units are generally more fine-grained than the minerogenic layers below. Units R, U and Z have a silt content close to the analogue samples representing a pure glacial signal. This suggests that the layers with the finest grain size between 135 and 175 cm represent increased input of glacigenic sediments, and subsequent increased glacial activity.

The period between 4150 and 1540 cal. yr BP, represents ~2600 years of relatively stable conditions, where unit L has an orange brown tint typical of poorly humified peat, indicating increased moisture availability, either through elevated water tables or increased average precipitation (c.f. Matthews et al. 1997). The peat growth was interrupted only by units O and M around 4000 cal. yr BP. Interestingly, the grain-size distribution of unit M is the most fine-grained layer detected. These layers are interpreted as events of glacigenic input in the early phase of a climatically stable period. The glacigenic sediment input on top of humidity-dependent peat production (as present), suggest glacial activity ca. 4000–3800 cal. yr BP.

From 1540 cal. yr BP to the present, the minerogenic layers change from colluvial type to more glacigenic. Unit K at 69 cm displays a rather clear glacial signal, with 20.5% clay and 78% silt. Similar to units M and O, unit K is interpreted as a short event of glacial sediment input followed by peat growth. The sandy sequences units I and D are interpreted to be colluvial sediments, while unit G, E and B are related to sediments of glacial origin. The glacial unit E was followed by a coarse colluvial unit D. The upper 70 cm of the gully is interpreted as representing a rather unstable environment since 1540 cal. yr BP. Six minerogenic layers of probable glacial and non-glacial origin separate five peat layers including the present topsoil. The peat layers are poorly humified, indicating relatively humid conditions. The climatic deterioration related to the "Little Ice Age" is represented in the upper 70 cm, exhibiting more frequent input of both glacial and non-glacial minerogenic sediments during the last 1500 years. However, similar to the conclusions made by Matthews et al. (1997), data from Svarthammarbu indicate debris flow activity before the "Little Ice Age", not supporting a hypothesis of vegetation impact and subsequent debris flow initiation by cattle grazing and/or summer farming, in agreement with Matthews et al. (op cit.). Human-induced impacts in the investigated area are therefore considered minimal, suggesting that the colluvial processes are primarily driven by natural climatic change.

Steinflybekken

Similar to Svarthammarbu, the basal diamicton unit X (Figure 5) in Steinflybekken is interpreted to represent a basal till. Unit W, above the basal diamicton, displays a grain-size distribution of 40.6% sand, 56.9% silt and 2.5% clay, while units V and T exhibit a distribution of 50.8–54.2% sand, 41.4–43.3% silt and 4.4–5.9% clay, unit V being slightly coarser than unit T. Compared to modern analogue sample 5 (Figure 1), these layers are interpreted as colluvial slopewash sediments. The same conclusions are made for units S and Q, with almost similar sediment characteristics as units W, V and T. They are likely to represent increased slopewash activity. The peat horizons unit U (7990 cal. yr BP) and unit R (6820 cal. yr BP), both suggest periods of low mountain-slope activity. The peat in unit P represents a period of ca. 3000 yr of uninterrupted peat production between 5470 and 2350 cal. yr BP. Most of the same situation is detected in Svarthammarbu, with peat production from 4150 to 1540 cal. yr BP. Both unit P in Steinflybekken and unit L in Svarthammarbu are characterized by being orange-brown which is normally associated with poorly humified peat formed under humid climatic conditions (John A. Matthews, oral communication 1995).

The lower peat units in Steinflybekken and Svarthammarbu are well humified, indicating drier conditions. In Steinflybekken this is exemplified by units U and R (Figure 5), while in Svarthammarbu a total of five units (units I2, G2, E2, C2 and A2) (Figure 2) are interpreted as poorly humified peat units. However, despite the presumed dry conditions, the non-glacial minerogenic slopewash activity seems to have been high in the same period. Matthews et al. (1997) suggested that similar, highly humified peat layers represent an environment that is less subject to peat accumulation than at present. In Leirdalen, western Jotunheimen, they suggested that lower water tables existed from 8230 to 4230 cal. yr BP, probably as a result of a warmer and drier climate than at present (c.f. Nesje et al. 1991). Interestingly, they reported enhanced debris flow activity both in periods of poorly and well-humified peat production. This is consistent with their idea that debris flows in mountain areas are records of extreme rainfall events, and are not dependent on average or annual rainfall. The same pattern seems to be detected in Early to Mid Holocene parts in both Svarthammarbu and Steinflybekken, indicating that the climate in eastern Jotunheimen was drier and warmer than at present between ca. 7990 and 4150 cal. yr BP. Concerning the temperature, the subfossil pine stump in unit A2 suggests a summer temperature at least 1.5 °C warmer than at present around 5420 cal. yr BP.

In the upper part of the Steinflybekken section, the same conditions as in Svarthammarbu of rapid alternations between peat and minerogenic sediments are detected. Units O and M are interpreted as debris flows, revealing grain-size distributions almost similar to unit Q. Units O and M are separated by a short event of peat development. Except unit D at 12–16 cm, the remaining minerogenic layers are fine grained, with more glacial characteristics. From 1310 cal. yr BP to the present, six minerogenic inflows are separated by six stages of peat development, including the present topsoil. As in Svarthammarbu, the poorly humified peat layers suggest a relative humid climate. The frequency of glacial-minerogenic input in Steinflybekken was considerably higher during the last ca. 1300 years compared to the previous ca. 8000 calendar years, indicating a period of enhanced meltwater activity from the Steinflybreen and Høgdebrotebreane glaciers. The same tendency is observed in Svarthammarbu since 1540 cal. yr BP.

Discussion

Several reconstructions of climate and glacier records have been based on sections of alternating alpine peat and minerogenic deposits in southern Norway (Nesje et al. 1991; Nesje & Dahl 1991a; Dahl & Nesje 1994, 1996). Even though they represent different regional climatic regimes, from western maritime to eastern continental climates, a comparison between the sites is interesting for detecting regional variations (Figure 8).

From the Jostedalsbreen region, Nesje et al. (1991) reported from a peat bog in Glomsdalen in the Jostedalsbreen area peat production around 6890, 6500, 5740–4030 and 3280 cal. yr. BP up to the present. At 6500 cal. yr BP macrofossils of *Betula* were present. These periods of organic production were interpreted to represent low glacial activity, while laminated sand/silt horizons resulted from neoglacial phases. In the same study, stratigraphic investigations from Sunndalen north of Jostedalsbreen revealed peat layers containing tree stumps intercalated with distal glaciofluvial deposits. Radiocarbon dates from the organic layers suggested that the Sandskardfonna glacier was in a contracted state, or had disappeared entirely close to 1220, 1065, 985, 780 and 605 cal. yr BP (Nesje et al. op cit.). Nesje & Dahl (1991a) reported of late Holocene glacier fluctuations inferred from a gully section in Bevringsdalen southwest of Jostedalsbreen. Upvalley glaciers were present 2745, 2225–2130, 1670 and subsequent to 1310 cal. yr BP. Blikra (1986) described in Skjerdingsdalen, north of the main ice cap of Jostedalsbreen, a section of minerogenic layers interpreted to be sheet-flood deposits formed during periods of erosion of till and older avalanche deposits. The minerogenic layers were separated by peat layers containing both pieces of wood and bands of sand. From radiocarbon datings, periods of sheet-flooding were estimated between 6865 and 5285 cal. yr BP and subsequent to 2740 cal. yr BP.

Concerning the deglaciation, the date of 7950 cal. yr BP in Steinflybekken is considered to be considerably younger than the deglaciation. In Steinflybekken the date at 6885 cal. yr BP corresponds well with the 6890 cal. yr BP succession at a site in the upper part of Glomsdalen (730 m a.s.l.). Sheet floods in Skjerdingsdalen (Blikra 1986) at 6865 cal. yr BP indicate a period with stable climatic conditions prior to this event. In the same site in Skjerdingsdalen, peat growth started around 5285 cal. yr BP, almost similar to 5350 cal. yr BP in Steinflybekken. Peat production in Steinflybekken continued until 2350 cal. yr BP, a few hundred years longer than Skjerdingsdalen (2740 cal. yr BP). This stable event is not detected in the Svarthammarbu section, where increased minerogenic input is detected between 5360 and 4145 cal. yr BP. But if the preservation of peat P is controlled by the 'sea-

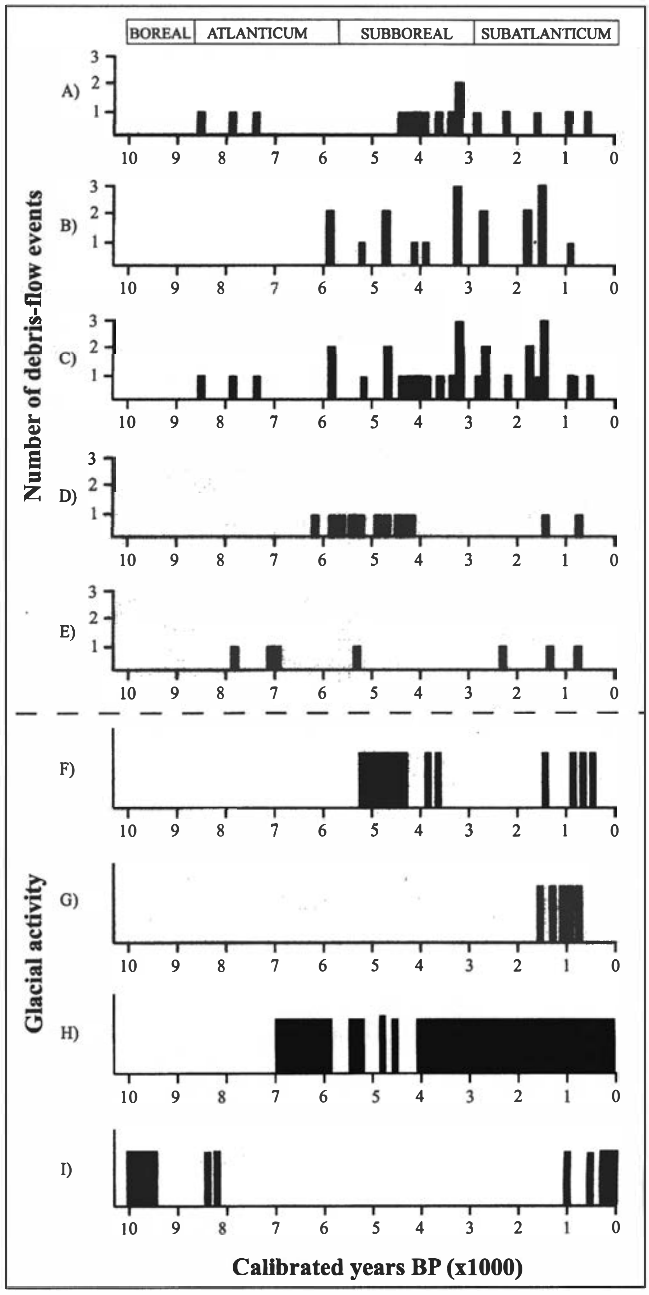

Figure 8. Debris flow events and glacial periods at selected sites discussed in text;
A) Debris flow events recorded in Leirdalen (Matthews et al. 1997); B) Debris flow events in southern Norway (Blikra and Nesje 1997); C) Combination of A) and B) (Matthews et al. 1997); D) Debris flow events recorded in the Svarthammarbu site; E) Debris flow events recorded in the Steinflybekken site; F) Glacial activity recorded in the Svarthammarbu site; G) Glacial activity recorded in the Steinflybekken site; H) Glacial activity recorded in the Nedrefetene site, Finse (Dahl and Nesje 1994, 1996); I) Glacial activity recorded at the Øvrefetene site, Finse (Nesje and Dahl 1991b; Dahl and Nesje 1994, 1996).

ling' effect of unit O, there might be a hiatus between units O and P. The subfossil *Betula* in Glomsdalen dated to 6500 cal. yr BP might correspond with the subfossil birch in unit J2 Svartammarbu (6180 cal. yr BP), indicating a higher birch-tree limit than at present over a more extensive region.

The frequent late Holocene alternations of changing peat and minerogenic sequences observed in Sunndalen and Bevringsdalen, are most probably reflected in both Svarthammarbu and Steinflybekken. In Svarthammarbu since 1535 cal. yr BP and in Steinflybekken since 2350 cal. yr BP, several periods of low glacial activity (peat layers) might reflect the same glacial history as Sandskardfonna, or at least the same tendency of climatic fluctuations. Steinflybekken reveals low glacial activity at 1310, 740 and 830 cal. yr BP, which together with undated layers might correspond with datings from Sunndalen (Nesje et al. 1991).

Dahl & Nesje (1994, 1996) reconstructed glacier fluctuations at Hardangerjøkulen partly from distal terrestrial deposits. Peat sequences at the Nedrefetene site, indicated no glacier at the Hardangerjøkulen plateau between 8340 and 7200 cal. yr BP and 6080 to 5590 cal. yr BP and during shorter periods around 5290, 4640 and 4150 cal. yr BP. Nesje & Dahl (1991b) and Dahl & Nesje (1994, 1996) also demonstrated from glacial sediments in a terrestrial deposit at Øvrefetene, north of Hardangerjøkulen, enhanced glacial activity prior to 9540, 8480, 8370, 1035–940 and around 550 cal. yr BP. Nedrefetene was looked upon as an on/off signal for any glacial activity while Øvrefetene represented Hardangerjøkulen/Blåisen in an advanced position. Radiocarbon datings from the same site reveal data of reduced glacial activity around 785 cal. yr BP and between 660 and < 550 cal. yr BP (Dahl & Nesje 1996). As a consequence, the "Little Ice Age" maximum at Hardangerjøkulen is dated to 550 cal. yr BP in addition to two minor oscillations about 1100 and 700 cal. yr BP.

It is not straightforward to compare the peat/minerogenic transitions at Hardangerjøkulen with similar alternations in Svarthammarbu and Steinflybekken. At Nedrefetene and Øvrefetene, the minerogenic layers are interpreted as a signal of glacial activity, or at least, the peat horizons to have accumulated during periods of no glacial meltwater supply on the sites. As mentioned above, Svarthammarbu and Steinflybekken contain signals of both debris flow/colluvial events and enhanced glacial activity. In Svarthammarbu, the first glacial signal is recorded subsequent to 5345 cal. yr BP, while in Steinflybekken pure glacial sediments are not detected before 1310 cal. yr BP.

Peat accumulation at Nedrefetene between 8340 and 7200 cal. yr BP possibly corresponds to unit U in Steinflybekken (Figure 7). Still, unit U in Steinflybekken is too young to indicate the period for Holocene initiation of alpine peat production according to Gunnarsdottir (1996). Between 5290 and 4150 cal. yr BP, five brown (less decomposed) peat layers are detected at Nedrefetene intervening glacial sediments, indicating a humid period suitable for both the existence of glaciers and rapid initiation of terrestrial organic production. This period is perhaps reflected in Steinflybekken as continuous production of orange-brown peat, and in Svarthammarbu as input of both glacial and non-glacial (sheet-flow) deposits. Steinflybekken is best comparable with Nedrefetene as a continuous on/off signal of any glacial activity at Steinflybreen/Høgdebrotebreane, as glacigenic sediments are detected in the present stream. Similar or close to present glacial conditions were most probably initiated between 2350 and 1310 cal. yr BP. If glacial sediments have been deposited earlier in the section, later erosion and transportation by coarser debris/sheet-flow events may have occurred. The increased frequency of glacial events since ca. 1500 cal. yr BP is noted at the mentioned sites. Nedrefetene with an uninterrupted glacial input and Øvrefetene, Svarthammarbu and Steinflybekken with several distinct glacial episodes. Despite regional differences in exact timing and extent, a general trend towards late Holocene climatic instability and subsequent fluctuating glaciers seems evident.

Matthews et al. (1997) based a reconstruction of Holocene colluvial history on a stratigraphic succession of alternating peat and minerogenic sequences at the foot of a steep mountain slope in Leirdalen, central Jotunheimen. The Leirdalen site differs from the sites described above in that it only revealed debris flow signals. The sites around Jostedalsbreen (except of Skjerdingsdalen) and the gullies distal to Hardangerjøkulen only reflect glacial signals, while Svarthammarbu and Steinflybekken are interpreted to represent both glacial and debris flow/sheet-flow activity. In Leirdalen, layers of silty sand and sandy silt were interpreted as distal debris flow facies, representing natural low-alpine landscape instability. Relatively infrequent but large magnitude colluvial activity was detected between 8245 and 4235 cal. yr BP. Low colluvial activity between 7380 and 4150 cal. yr BP was terminated by a succession of debris flow events between 4150 and 3675 cal. yr BP. Little humified peat layers separated six debris flows which occurred between 3515 and 2350 cal. yr BP, while uninterrupted peat accumulation was detected between 2350 and 1415 cal. yr BP, indicating reduced debris flow activity. Increased activity was observed after 600 cal. yr BP, interpreted as a response to climatic deterioration connected to the "Little Ice Age".

Modern analogue samples of the early to mid-Holocene colluvial activity in Leirdalen might be represented in Steinflybekken as five debris flow events prior to 5470 cal. yr BP. Also several minerogenic inputs in Svarthammarbu between 6125 and 5345 cal. yr BP probably indicate the same tendency. Similar grain-size distributions are measured for the layers in the three sites, which make it reasonable to interpret them as sheet-flow/debris flow sediments. Parts of the low colluvial activity in Leirdalen between 7380 and 4150 cal. yr BP might be represented in Steinflybekken as continuous peat production between 5470 and 2350 cal. yr BP. The uninterrupted peat accumulation in Leirdalen between 2350 and 1415 cal. yr BP is partly analogue to the peat production in Svarthammarbu between 4150 and 1540 cal. yr BP. Also the increased colluvial activity in Leirdalen after 600 cal. yr BP is probably represented in both Svarthammarbu and Steinflybekken as enhanced input of both glacial and debris flow sediments since 1540 and 1310 cal. yr BP, respectively. The most pronounced geomorphic change in evolution of the slope, the dissection of the slope after 800 cal. yr BP might be correlated to the increased colluvial activity after 600 cal. yr BP. However, direct comparisons of single events must be carried out with great care as debris flows are caused by extreme events, and might not be representative for regional patterns.

Summary and conclusions

The interpretations of the sediments in the Svarthammarbu and Steinflybekken sections in Leirungsdalen, eastern Jotunheimen, central southern Norway, are mainly based on the grain-size distributions in minerogenic units. These are compared to distributions in modern analogue samples collected in the respective streams and at sites close to the present glaciers. Periods with either enhanced debris flow or glacial activity have been detected, in addition to periods with continuous peat accumulation. Minerogenic units with silt as the dominating grain-size (70–90%) are interpreted to represent glacial activity, while sand-dominated layers are considered to be of colluvial origin. A combined record from the Svarthammarbu and Steinflybekken sections indicates debris flow activity in Leirungsdalen >7500, 7300–6800, 6600–5500, 5800, 5700, 5300–4900, 4700, 4500, 4300, 2300, 2100–1500, 1300, 700–600 and 500–400 cal. yr BP. Relative to the present, dry conditions are inferred between 8000 and 5500 cal. yr BP, while a more humid climate is representative for the last ca. 5500 cal. yr BP. Only colluvial activity is recorded during the presumed dry period prior to ca. 5500 cal. yr BP, further indicating debris flow/colluvial activity dependence upon extreme rainfall events, in contrast to annual precipitation. The first glacial signal is detected ca. 5500 cal. yr BP, synchronously with peat initiation indicating increase in humidity. The frequency of glacial events seems to have increased during the late Holocene, especially the last 1500 cal. yr BP, interpreted to correspond to the climatic deterioration related to the "Little Ice Age". Detection of periods with high debris flow activity back to 7000–6000 cal. yr BP, corresponds with Matthews et al. (1997). The early dates argue against a hypothesis of human induced debris flow/colluvial activity through cattle grazing and summer farming during the last ca. 1000 years. However, the validity of a correlation between colluvial successions in terrestrial gullies and a climatic/glacial history has to be verified by independent data.

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