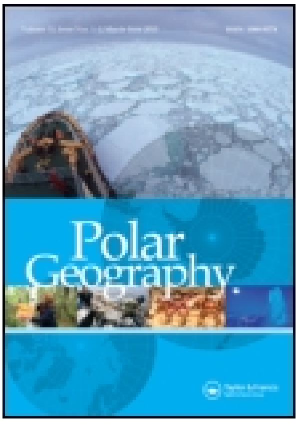

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Formation, Meltout Processes and Landscape Alteration of High-Arctic Ice-Cored Moraines——Examples From Nordenskiold Land, Central Spitsbergen

Sven Lukas, Lindsey I. Nicholson, Fionna H. Ross & Ole Humlum

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FORMATION, MELTOUT PROCESSES AND LANDSCAPE ALTERATION OF HIGH-ARCTIC ICE-CORED MORAINES—EXAMPLES FROM NORDENSKIÖLD LAND, CENTRAL SPITSBERGEN[1]

Sven Lukas,[2] Lindsey I. Nicholson, and Fionna H. Ross
School of Geography and Geosciences, University of St Andrews, Irvine Building, North Street, St Andrews KY16 9AL, Scotland

Ole Humlum
Department of Physical Geography, Institute of Geoscience, University of Oslo, P.O. Box 1047 Blindern, N-0316 Oslo, Norway

Abstract: The debris-covered ice-margins of three largely cold-based glaciers in central Spitsbergen were investigated to reconstruct their formation and degradation. Clast shapes indicate dominant englacial and supraglacial transport with a smaller subglacial component. Emplacement of material is inferred to have been through meltout along flowlines due to the relatively uniform and continuous debris cover along the glacier margins; no evidence of thrusting has been found. Degradation of all three belts is rapid and involves debris flows at unstable places—e.g., the margins of meltwater channels. Resultant exposure of underlying ice initiates or accelerates melting, thereby leading to further debris flows. Hence, once degradation starts, a self-reinforcing cycle that removes material from the glacier commences. Landform preservation potential on millennial time scales in a high-arctic, continuous permafrost environment is thus limited. This work has implications for the interpretation of Pleistocene landform associations that use modern analogues from Svalbard.

INTRODUCTION

Extensive complexes that have been termed "ice-cored moraines" characterize the margins and mark the neoglacial maximum positions of central Spitsbergen glaciers. These "ice-cored moraines" in fact consist of a zone of marginal supraglacial debris between 0.1 and 4 m thick, which retards the melting of underlying glacier ice (cf. Etzelmüller, 2000; Lyså and Lønne, 2001; Sletten et al., 2001; Sørbel et al., 2001). Because these features consist of supraglacial material covering the frontal part of the

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[2]Corresponding author; email: SL33@st-andrews.ac.uk

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glacier, as opposed to isolated pockets of buried ice that occur within larger bodies of sediment, we refer to them as *debris-covered ice-margins* or *zones* in this paper.

Investigations on debris-covered ice-margins on Spitsbergen have aimed at understanding the geomorphic significance of small, high-arctic valley glaciers (e.g., Etzelmüller, 2000; Etzelmüller et al., 2000), while the few process investigations focus on moraine formation rather than longer-term landscape evolution and largely deal with glaciers that have undergone marginal retreat (e.g., Lyså and Lønne, 2001; Sletten et al., 2001). Such studies have been undertaken on ice-cored moraines in the North American arctic (e.g., Johnson, 1971; McKenzie and Goodwin, 1987; Mattson and Gardner, 1991), and the fundamental processes appear to be well understood in temperate, non-permafrost environments (Østrem, 1959; Krüger and Kjær, 2000; Kjær and Krüger, 2001; Everest and Bradwell, 2003).

We present results from geomorphological and sedimentological investigations carried out during the summers of 2002 and 2003 with the following objectives: (1) to determine the processes leading to the formation of the supraglacial debris cover and geomorphological features developed within it; (2) to improve understanding of sedimentary processes associated with the decay of stagnant glacier ice in a high-arctic environment; and (3) to develop a conceptual model of landform evolution.

STUDY AREA AND GLACIER CHARACTERISTICS

The Svalbard archipelago is underlain by continuous permafrost up to 500 m thick (Landvik et al., 1988; Humlum et al., 2003), and the mean annual air temperature at Longyearbyen airport is –6°C (Hagen et al., 1993). With about 25% glacier cover, the study area of Nordenskiöld Land in central Spitsbergen is one of the least glaciated areas in Svalbard due to its aridity. The margins of three glaciers were investigated (Fig. 1): Larsbreen, Longyearbreen, and an unnamed glacier on the northern side of Nordenskiöldtoppen, hereafter termed Nordenskiöldtoppenbreen. All three glaciers are part of the Longyeardalen catchment. Mean annual precipitation at the equilibrium-line altitudes of these glaciers is between 500 and 700 mm water equivalent (Humlum, 2002).

Radio-echo soundings and glaciological investigations at Longyearbreen and Larsbreen demonstrate that these are largely cold-based and that subglacial topography is V- rather than U-shaped, indicating that subglacial erosion has been minimal (Tonning, 1996; Etzelmüller et al., 2000). In contrast, Nordenskiöldtoppenbreen occupies a broad, flat, cirque-like depression that leads into a plateau (Platåberget, ca. 450m asl). Nordenskiöldtoppenbreen is smaller and at a higher altitude, so it is assumed to also be predominantly cold-based due to the penetration of permafrost underneath thin glacier margins (cf. Björnsson et al., 1996). There is no known surging history for these three glaciers (Liestøl, 1969, 1993; Hagen et al., 1993; Etzelmüller et al., 2000).

Glaciers on Svalbard reached their Little Ice Age (LIA) maximum around 1900 AD (Svendsen and Mangerud, 1997), and the surface of Longyearbreen has lowered by up to 50 m since ca. 1936 (Justad, 1997), with similar figures having been obtained for nearby Rieperbreen (Lyså and Lønne, 2001) and other glaciers in the area (Ziaja, 2001). Signs of frontal retreat cannot be found at any of these three glaciers, which is characteristic of many non-surging central Spitsbergen glaciers (Etzelmüller, 2000;

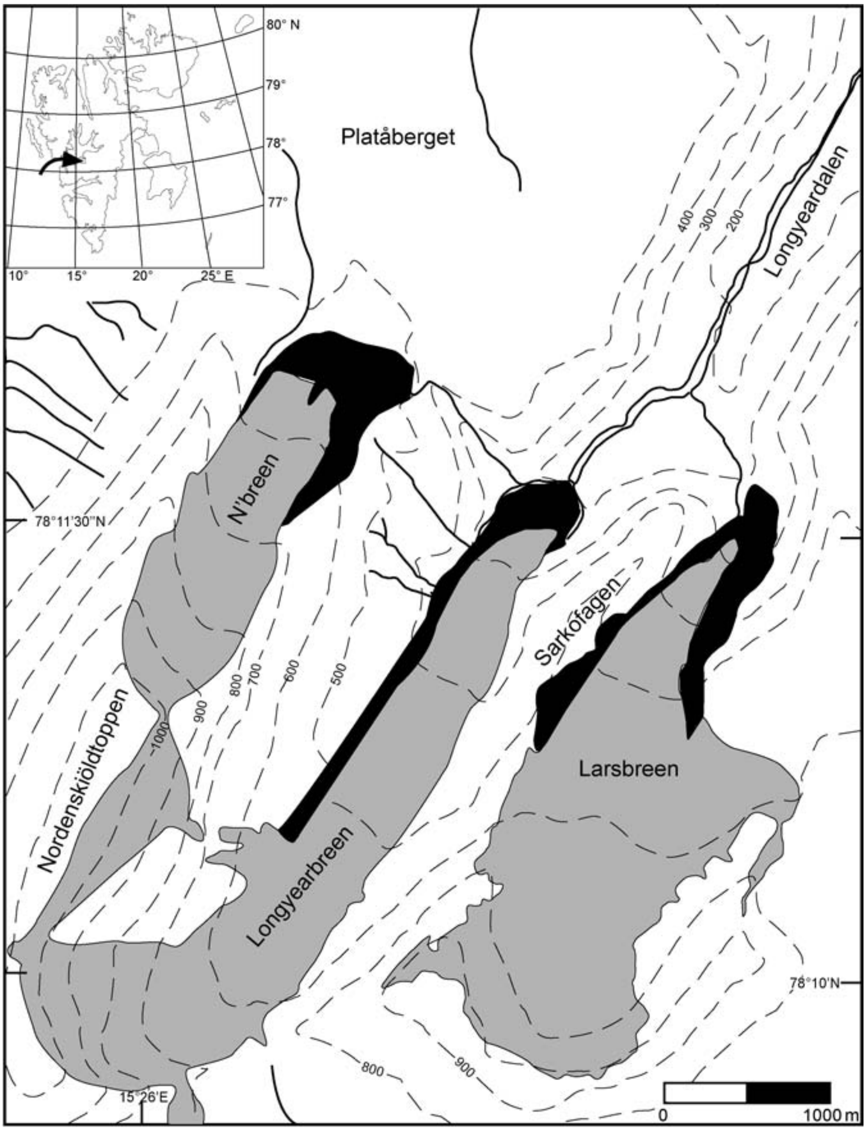

Fig. 1. Overview map of the study area in Central Spitsbergen, showing the three glaciers studied. Black shading indicates the location of the debris-covered ice-margins. Note the frequent occurrence of meltwater channels radiating out from the glaciers.

Etzelmüller et al., 2000; Ziaja, 2001). Hence, the marginal positions of these glaciers are out of equilibrium with climate by >100 years in this part of Svalbard, as they have been stagnating and downwasting since reaching their LIA maximum extent around 1900 AD.

At all three glaciers the LIA maximum is marked by accumulations of supraglacial debris along the presently buried ice front. The width of these debris-covered ice-margins is up to 600 m on Nordenskiöldtoppenbreen, 400 m on Longyearbreen,

TABLE 1
Summary of Characteristics of the Three Glaciers Studied

Glacier	Unit of measure	Nordenskiöld-toppenbreen	Longyearbreen	Larsbreen
Size	km	1.70	3.00	3.20
Area of frontal belt	km^2	0.55	0.55	0.50
Area covered by debris	Percent	32.40	18.30	15.60
Average debris thickness	m	0.38	1.84	1.33
Standard deviation	m	0.34	1.32	0.72
Number of measurements	*N*	32	10	12
Minimum (maximum) thickness of debris	m	0.05 (1.2)	0.2 (4.0)	0.2 (2.5)

and ca. 200 m on Larsbreen (Fig. 1), covering up to a third of the glacier surface. Debris thickness varies across individual zones (Table 1). Larsbreen and Longyearbreen share a similar surface form—concave in the accumulation zone and convex at lower altitudes, while Nordenskiöldtoppenbreen has a more linear slope. Larsbreen and Nordenskiöldtoppenbreen flatten out where the debris cover begins.

Tertiary sandstones, siltstones, shales, and localized coal seams of the Palaeocene and Eocene Van Mijenfjorden Group, which dip gently to the WSW, underlie the study area (Hjelle, 1993; Dallmann et al., 2001). One of the most prominent strata is the Grumantbyen Formation, which consists of sandstones and forms prominent cliffs and plateau surfaces such as those surrounding Longyeardalen and Platåberget (Dallmann et al., 2001). Fossils such as bivalves, calcareous foraminifera, worm tracks, and impressions of leaves and other plant remains are common in the Battfjellet Formation, which partly overlooks the slopes in the accumulation areas of all three glaciers (Major et al., 2000; Dallmann et al., 2001), providing ideal tracers for the source area of glacial debris.

METHODS

Geomorphological field mapping and aerial photograph interpretation at a scale of 1:6,000 was used to produce geomorphological maps of the debris-covered margins of the glaciers. Sedimentological logging of sections was carried out on square-millimeter paper and later corrected on overlays of enlarged photomosaics to ensure planimetric accuracy. Sedimentary units were identified on the basis of physical properties including grain size range, compaction, sedimentary structures, and clast shape following guidelines detailed by Evans and Benn (2004) and logged utilizing a modified version of the lithofacies code of Eyles et al. (1983). Clast shape was determined using the method of Benn and Ballantyne (1993, 1994). Fifty clasts were measured at each site and compared to control samples of known environments (glaciofluvial outwash, avalanche deposits, stratified slope deposits, scree). Control samples for subglacially transported clasts could not be obtained, and published subglacial control samples with similar lithological characteristics were used. Particle-size analysis of

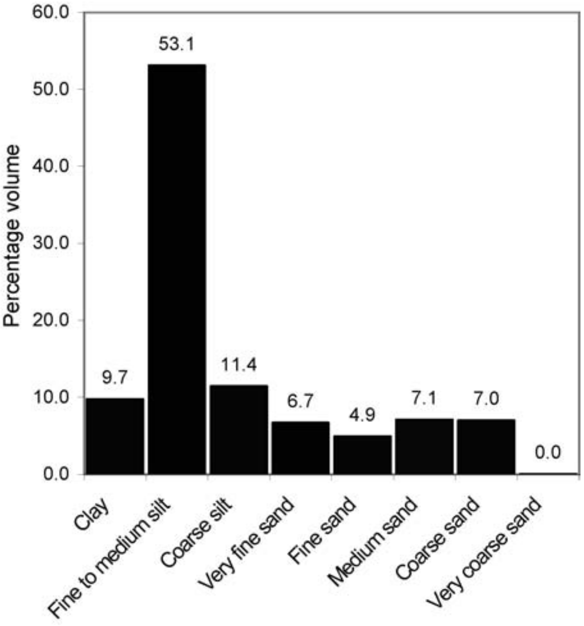

Fig. 2. Particle size fractions of matrix material in the debris-covered ice-margins of Larsbreen.

the matrix material of the Larsbreen debris cover was carried out by Coulter LS230. The retreat rate of four debris flow head-scarps was measured with reference to a stake over a period of 10 days in July 2002. Ablation beneath debris cover was measured on Larsbreen from 9–20 July 2002. Ten plots of ~0.3 m^2 were prepared by clearing the ice of debris, then leveling the ice surface, and drilling in an ablation stake before replacing the debris to the original depth. As far as possible, the debris was replaced in its original stratigraphic position. The debris was left to settle for at least 12 hours prior to measurement. Ablation was measured as the increase in length of the exposed stake, measured above a rule laid across the general ice surface. Debris thickness was measured at the start and end, as settling and minor migration caused the debris thickness to change. Representative debris thickness was taken to be the mean of the two measurements.

DEBRIS-COVERED ICE-MARGINS

Physical Characteristics

All three margins are covered by a compact, structureless (massive) clast- to matrix-supported diamicton (Fig. 3A and Table 1). Its matrix is usually silt rich (Fig. 2), and the a-axes of embedded clasts vary from 0.2 to 4 m with all local lithologies present, although larger clasts are predominantly sandstone. On Nordenskiöld-toppenbreen and Larsbreen, blocks of siltstone and shale of up to 7 m in diameter stand out at the surface, surrounded by weathered aprons of scree (Figs. 3D, 4, and 5).

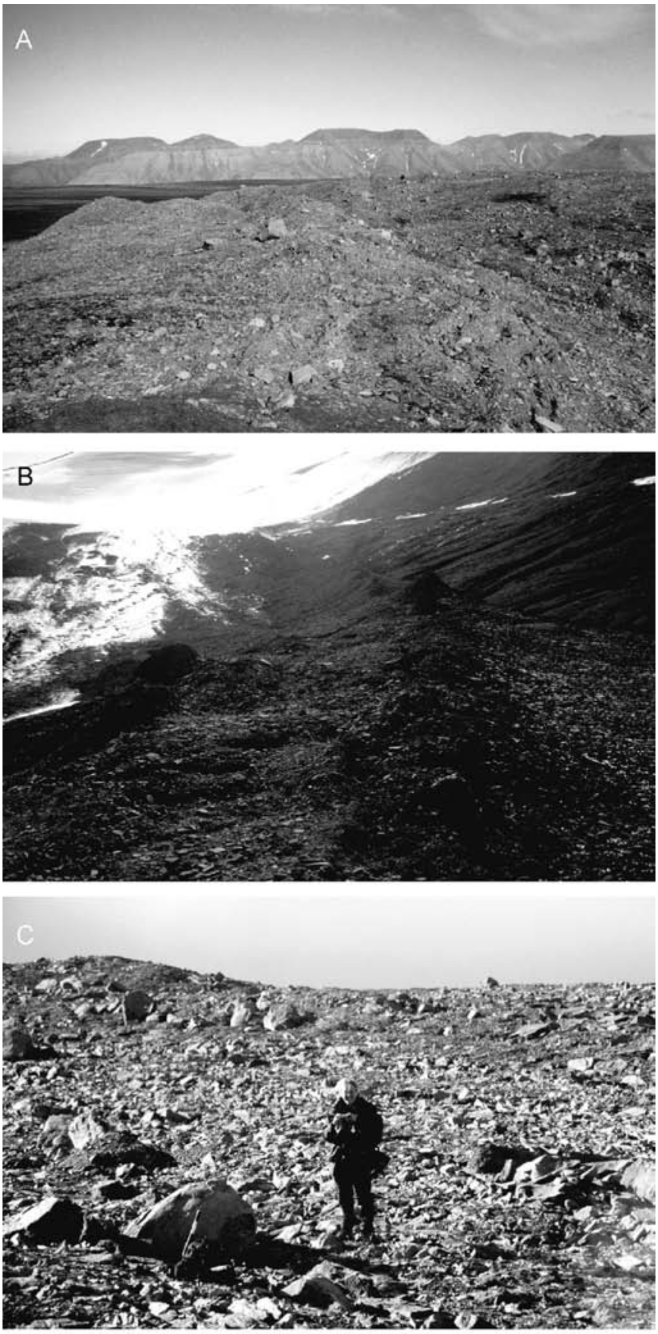

Fig. 3. A. Surficial "ridges" on the surface of the debris-covered zone of Nordenskiöldtoppenbreen (view to the east). B. Western lateral moraine on Nordenskiöldtoppenbreen (view to the south). C. Close-up of subangular, blocky and partly striated clasts on the surface of Nordenskiöldtoppenbreen (FHR for scale). (*Figure 3 caption continues on following pages*)

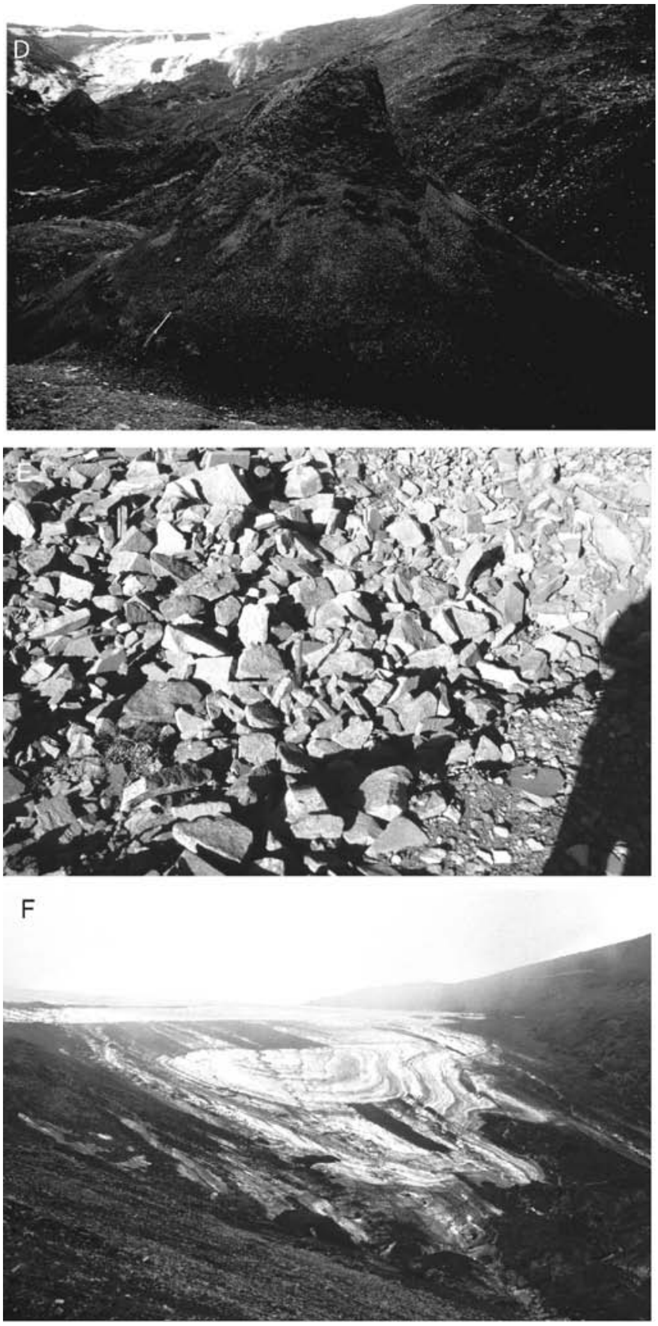

Fig. 3 (continued). D. Detail of a large shale bedrock fragment with surrounding scree slopes on the western side of Larsbreen. Rifle at the bottom left is 1.10 m long. E. Close-up of openwork angular, prolate and oblate clasts in an area connected to a meltwater channel on Nordenskiöldtoppenbreen. Openwork structure is interpreted as evidence of winnowing of fine material. F. Englacial debris bands cropping out on the surface Larsbreen, suggesting horizontal stratification (view to the southwest). (*Figure 3 caption continues on following pages*).

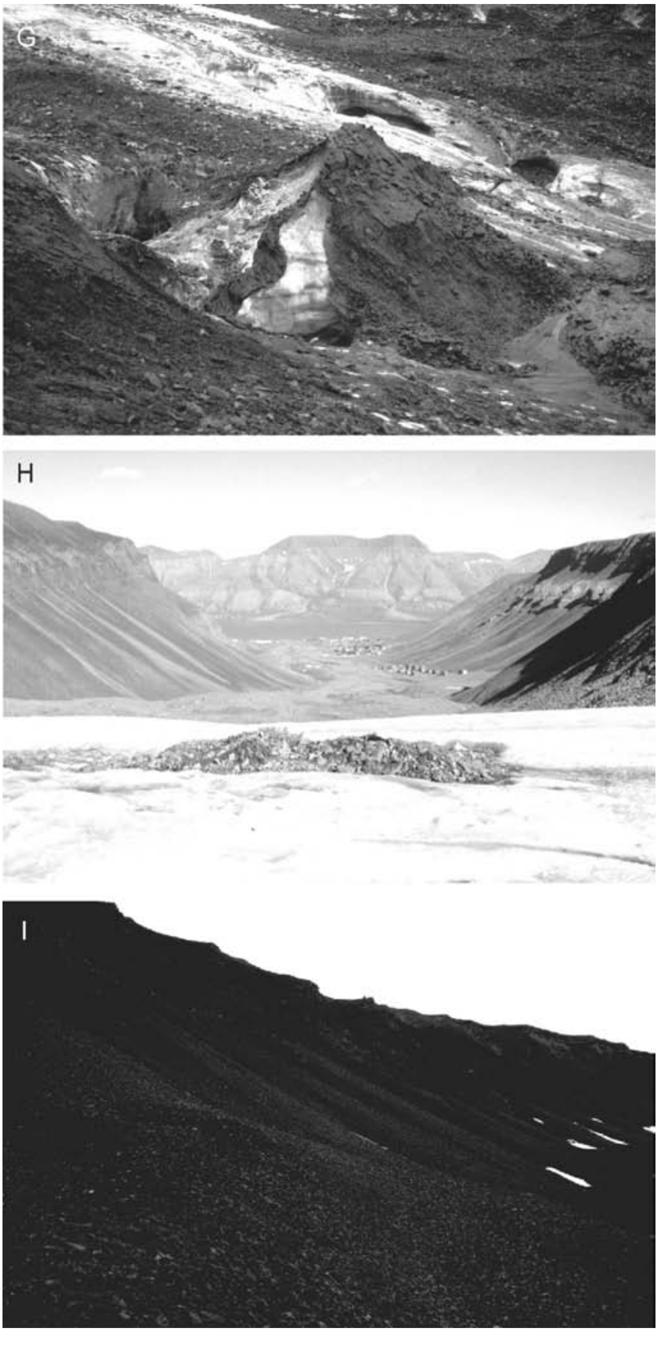

Fig. 3 (continued). G. Cross-bedded sand filling a buried crevasse trace on Larsbreen. H. Discrete debris accumulation on the surface of Longyearbreen perpendicular to ice flow. The thickness of this debris accumulation is < 0.2 m (view to the northeast). I. Avalanche debris cones on the eastern side of Larsbreen linking the free faces (left) with the glacier surface (outside right margin). (*Figure 3 caption continues on following pages*).

Fig. 3 (continued). J. Overhanging rock towers overlooking the surface of Nordenskiöld-toppenbreen in its source area (view to the northeast).

All three glaciers show ice-cored lateral moraines of varying dimensions (e.g., Fig. 3B). Concentric ridges mimicking the buried ice margin can be traced throughout the debris-covered margin of Nordenskiöldtoppenbreen (Figs. 3A and 5). On both sides of Larsbreen, lateral moraines grade into an amorphous, debris-covered zone (cf. Fig. 1). On Longyearbreen, the entire western side is flanked by a prominent lateral moraine (Fig. 1); along the eastern margin, the ice-cored lateral moraine is less well developed. In all cases, test pits have shown that the thickness of debris does not exceed 0.15 m. Moreover, the debris surface closely mimics the surface of the underlying ice, so that "ridges" on the surface are the result of ridges in the glacier ice.

The northeastern margin of Larsbreen is bounded by three ridges, separated by steep-sided gullies (Fig. 4). Clast shape effectively links these ridges (Figs. 6B–6D), which are devoid of fine matrix material, to avalanche debris cones originating from the eastern valley side (Figs. 3I, 6A, and 6F); both consist of very angular to angular, prolate clasts of sandstone and siltstone with very few subangular clasts. These ridges are interpreted as a talus-derived rock glacier that was pushed up in front of the glacier during its neoglacial advance (Humlum, 2005). Avalanche material also overlaps the sides of Larsbreen and Longyearbreen, indicating a potential source area (Figs. 6E and 6G), although some mixing with rounded material is evident (see below). Steep sandstone cliffs (Fig. 3J) overlook the three glaciers in their source areas, and accumulations of openwork, very angular to angular rockfall material are frequently found at the foot of such cliffs on the glacier surface.

Localized sediment accumulations are found on all three glaciers. A discrete debris ridge unequivocally associated with an englacial wedge was found on the surface of Larsbreen (Figs. 3G and 4). This ridge, which is lithologically anomalous to the rest of the debris layer, consists of laminated and cross-bedded sands. Due to the preservation of bedding structures that would undoubtedly be destroyed during prolonged glacial transport, this ridge is interpreted as a crevasse-fill formed from supraglacial stream deposits. Moss fragments contained within the sands gave an uncalibrated ^{14}C age of 150 ± 39 yr (calibrated 1δ age: AD 1682–1947; AAR-7999).

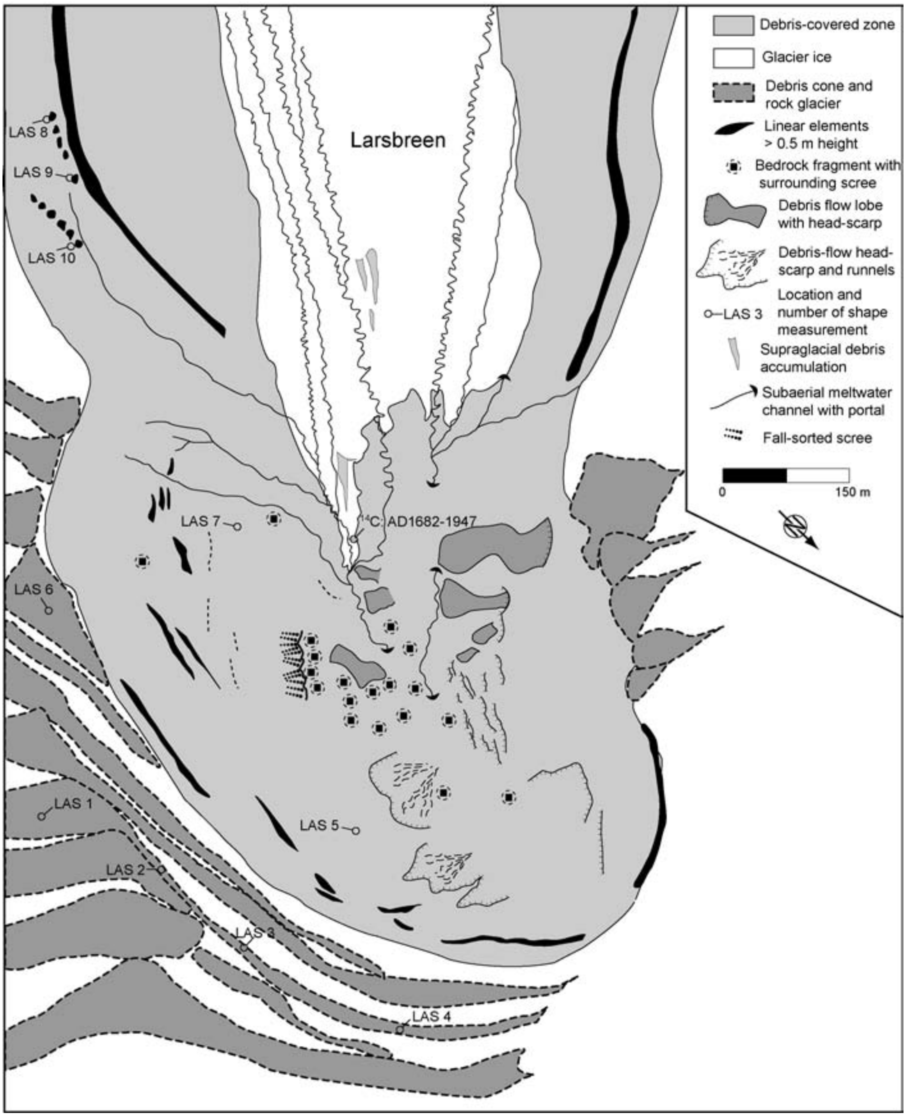

Fig. 4. Geomorphological map of Larsbreen showing the major elements that were identifiable in 2002 and 2003. Compare with Figure 15.

The source area for both sands and moss is inferred to be nivation niches just above the LIA trimline on the slopes north of Trollsteinen ca. 3 km southeast of the sampling site; the ^{14}C age is consistent with a formation during, or since, the Little Ice Age.

Six mounds with heights of up to 1.2 m, widths of up to 4 m, and lengths of up to 5.2 m occur at the eastern side of Larsbreen; they are aligned and regularly spaced. Artificial exposures revealed well-sorted, rounded to well-rounded sand and gravel (Figs. 6J and 6K) beneath a thin (<0.1 m) veneer of angular, supraglacially derived clasts. Towards the margins of these mounds, stratification is disturbed, and the deposits show normal faults, interpreted as collapse features. The sand and gravel

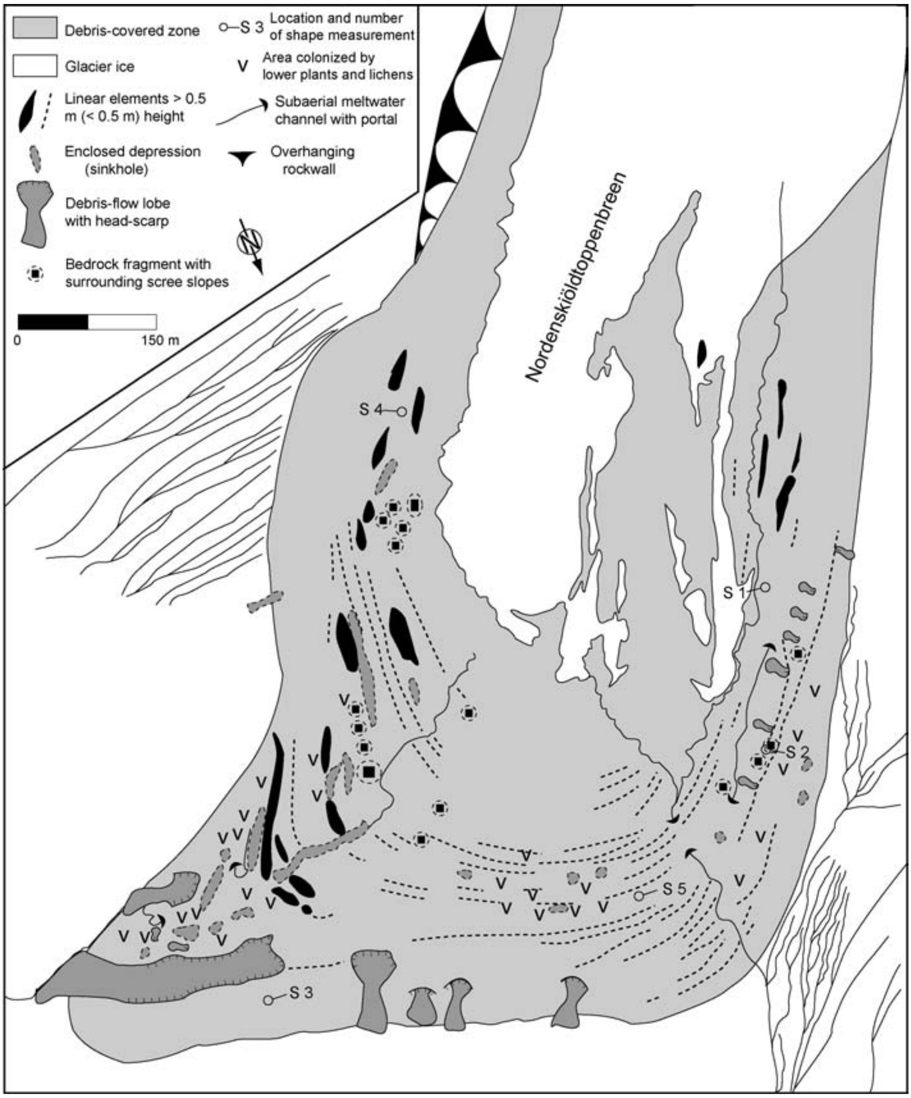

Fig. 5. Geomorphological map of Nordenskiöldtoppenbreen.

rests on diamicton. These isolated, yet aligned deposits are interpreted as pool fills of former supra- or englacial meltwater channels that were topographically inverted during downmelting. Clast shape analysis of neighboring deposits shows, however, that mixing of supraglacial and glaciofluvial material has occurred near the cones (Figs. 6H and 6I).

Upglacier of the main debris-covered zone on Longyearbreen, a ridge of matrix-supported diamicton trends perpendicular to ice flow (Fig. 3H). Similar features can be found in the accumulation area of Nordenskiöldtoppenbreen, where they trend both parallel and perpendicular to ice flow. In all cases the clasts are angular, the

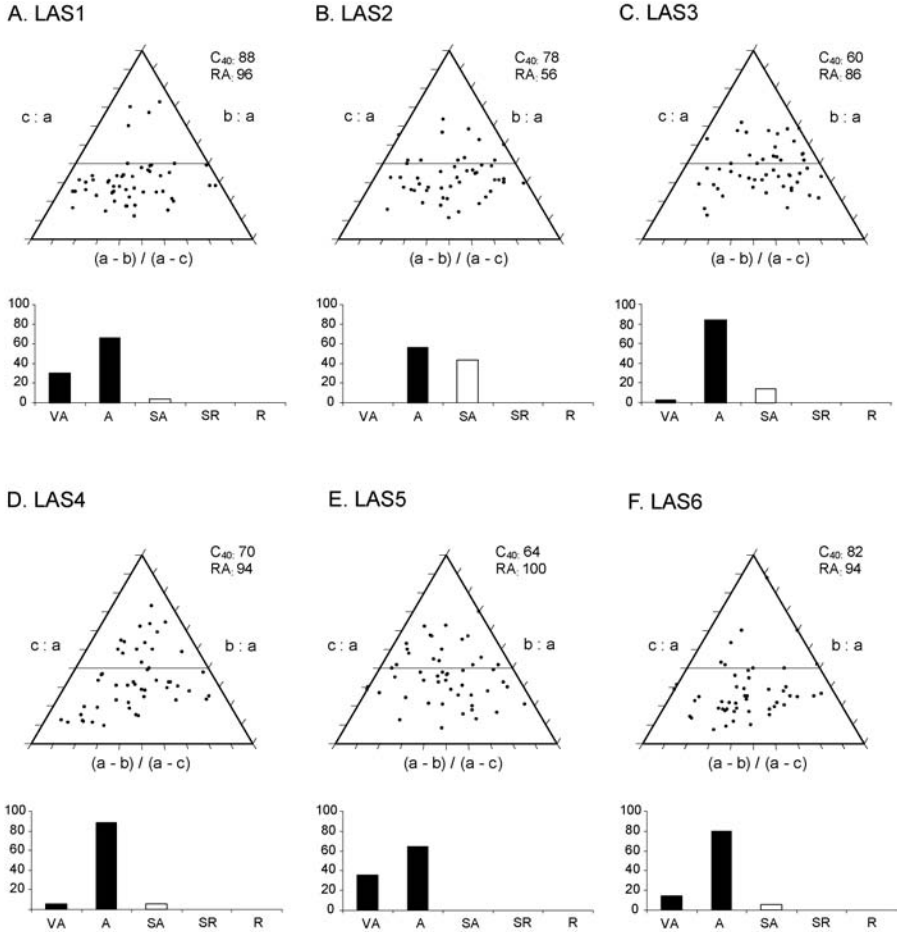

Fig. 6. Shape diagrams (ternary diagrams and clast form frequency plots) for clast shape samples taken at Larsbreen (cf. Fig. 4).

debris cover is < 0.2 m thick, and excavation shows no evident connection to englacial debris bands. This material might represent rockfall onto the ice surface, which was then transferred englacially until it melted out at the surface (see Kirkbride, 1995; Sletten et al., 2001).

CLAST PROVENANCE

Based on the V-shaped subglacial topography of Larsbreen and Longyearbreen and absence of substantial temperate ice patches, Tonning (1996) and Etzelmüller et al. (2000) suggested that basal erosion is minimal. This implies that the primary debris source is supraglacial. Etzelmüller et al. (2000) noted that clasts in the supraglacial debris belts of Larsbreen and Longyearbreen appear to be dominantly angular, which is also suggestive of subaerial debris sourcing. These assumptions are likely to apply at Nordenskiöldtoppenbreen as well, although the overall topography is less

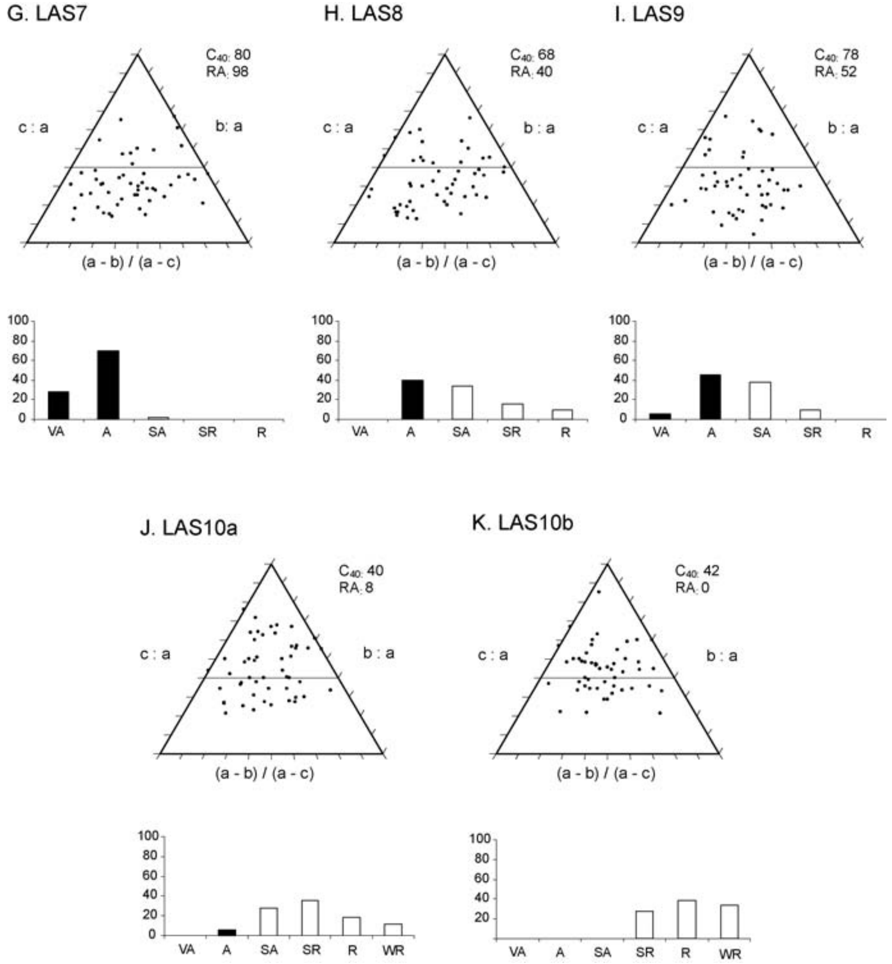

Fig. 6 (continued).

confined than for the former two glaciers. Clast shape analyses were employed to determine the origin and modification of clasts and to identify sedimentary processes.

Some clasts can be traced to source areas due to their containing distinctive fossil assemblages; on Nordenskiöldtoppenbreen, for example, a distinct unit of the Battfjellet Formation crops out in a narrow zone in the glacier source area above the ice, and several blocky and rod-shaped clasts of this unit were found in the debris-covered zone, allowing a reconstruction of the respective transport paths. Embedded clasts of up to 1 m are dominantly rod-shaped and very angular (VA) to angular (A) (Figs. 7A, 7B, and 7D), indicating little alteration during transport and, thus, supraglacial or englacial transport paths (see Boulton, 1978; Benn and Ballantyne, 1993, 1994). However, some larger clasts in the same samples are blocky (having a high c:a ratio) and/or subangular (Figs. 7A–7C). Together with striae on such clasts, this indicates that they have been transported subglacially. Frost shattering of the finer-grained lithologies is evident in the production of very angular prolate and oblate

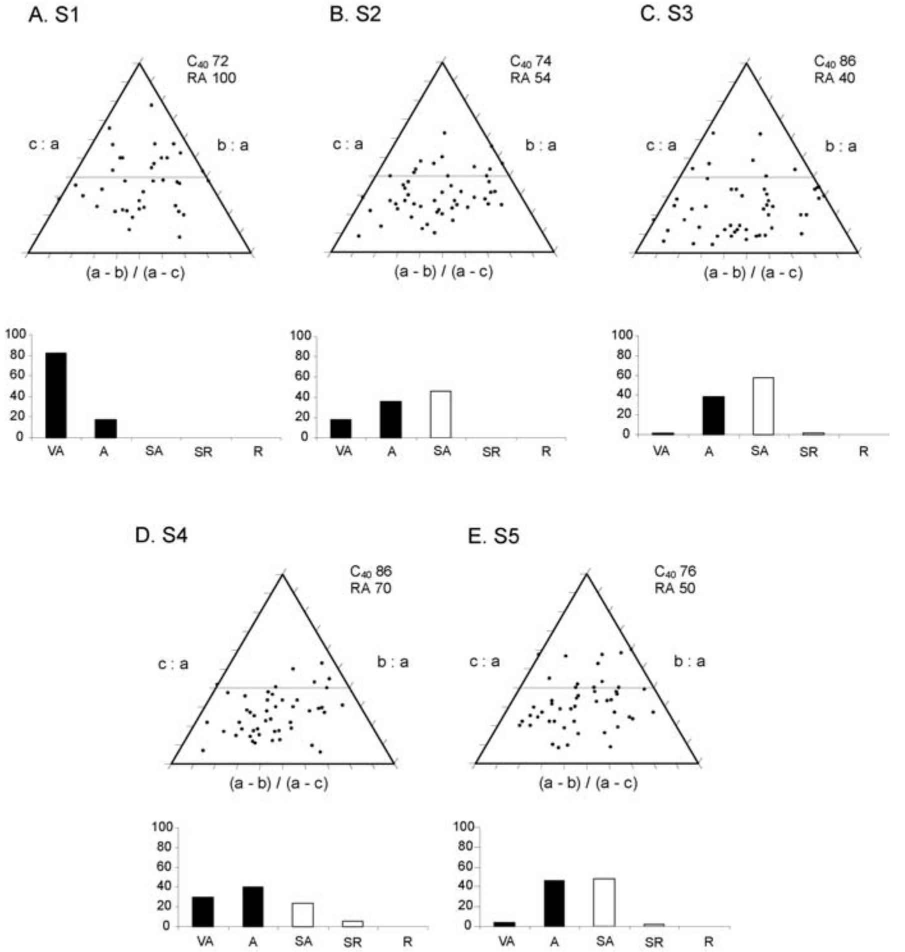

Fig. 7. Shape diagrams (ternary diagrams and clast form frequency plots) for clast shape samples taken at Nordenskiöldtoppenbreen (cf. Fig. 5).

shards, whereas sandstones tend to produce blockier shapes. Coal is rare in the debris-covered zones due to its low strength and, where present, tends to be blocky.

Clasts in all three ice-marginal debris-covered zones (Figs. 6, 7, and 9) have high C_{40} indices, indicating predominantly oblate and prolate clasts with few blocky clasts. Larger proportions of subrounded, or even rounded, clasts only occur under special circumstances as described for Larsbreen above. On Longyearbreen, the admixture of subangular and subrounded material (Figs. 8 and 9C–9D) appears to indicate more efficient rounding during subglacial and/or fluvial transport, which might be linked to this being the longest glacier. Admixture of a small portion of fluvially rounded clasts in sample LS5 (Fig. 9E) might relate to localized fluvial reworking of subglacial material.

The difference between purely subaerially sourced and transported material and the mixed composition of the ice-marginal debris-covered zones can best be seen at

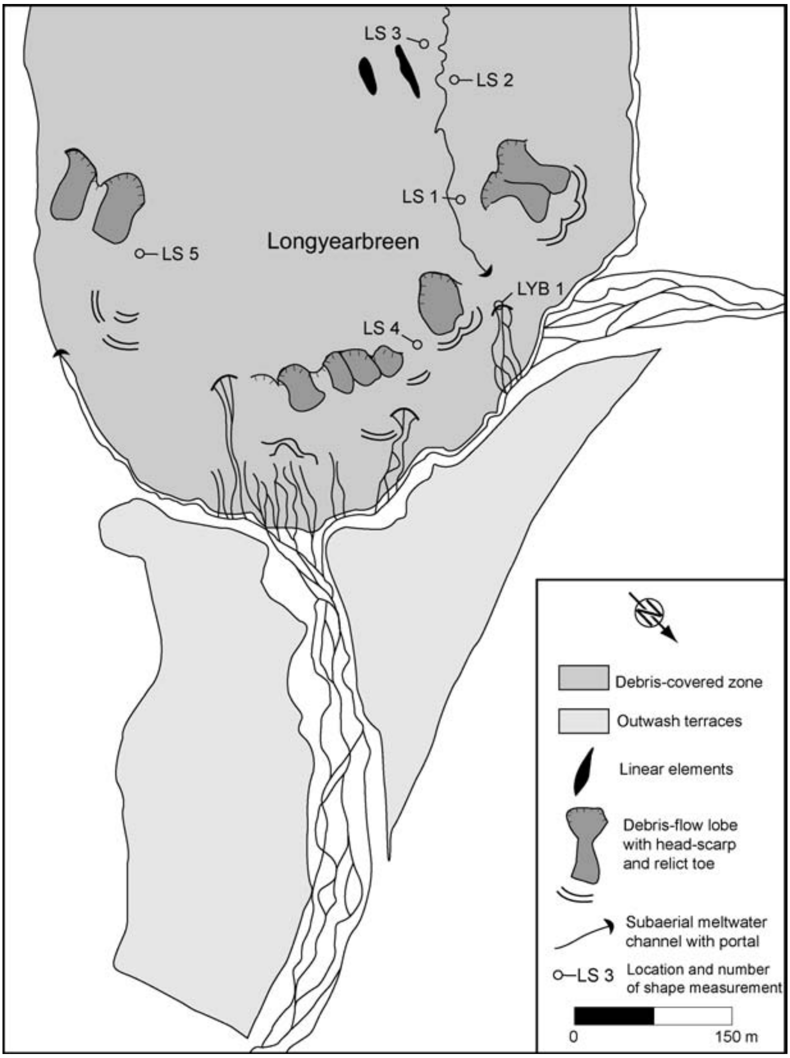

Fig. 8. Geomorphological map of the frontal part of the ice-marginal debris-covered zone of Longyearbreen.

the margin of Larsbreen. Here, control samples taken from avalanche cones (Figs. 6A and 6F) have a high C_{40} index and a negligible subangular component. The latter is attributed to edge-rounding as a result of clast impacting during avalanches. Clast shape largely falls in the continuum between slabs and blocks. This compares well with samples taken from the rock glacier ridges in front of the debris-covered zone (Figs. 6B–6D), although the C_{40} index is somewhat lower, probably due to weathering. A good example of the influence of weathering is given by sample LAS2 (Fig. 6B), which contains an unusually large proportion of subangular clasts. This was found to be due to the presence of voids underneath larger clasts at the surface that had been infilled with smaller clasts that had undergone weathering and rounding. In

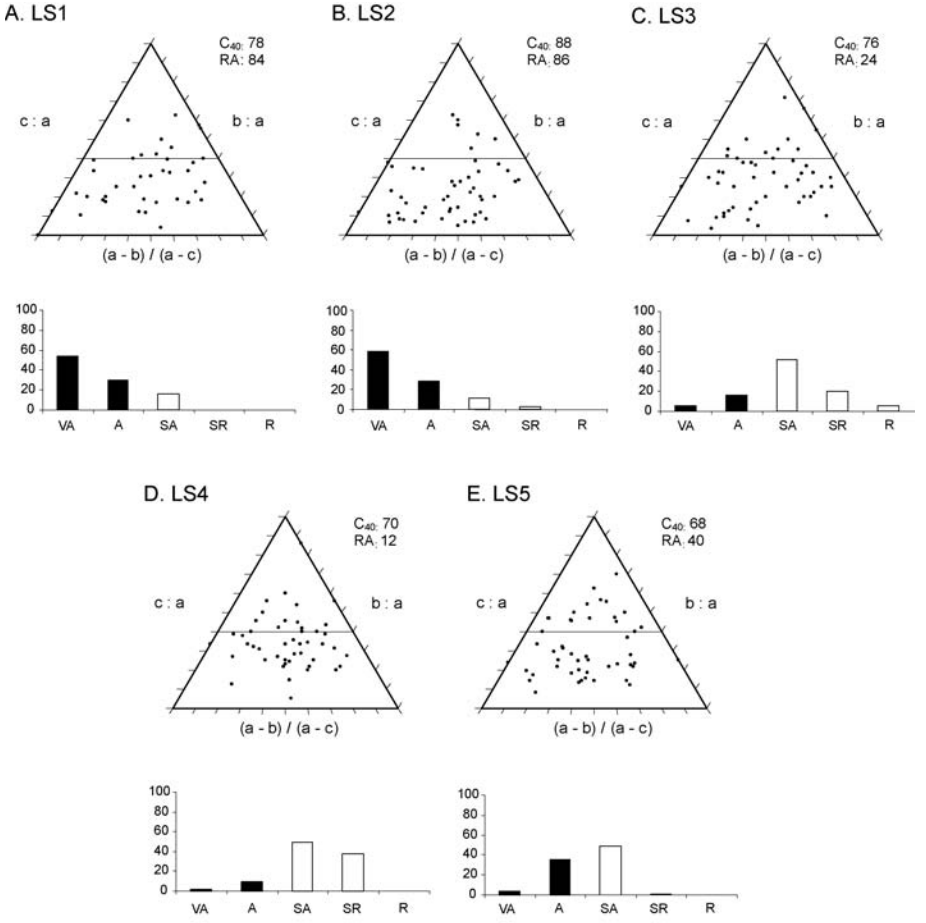

Fig. 9. Shape diagrams (ternary diagrams and clast form frequency plots) for clast shape samples taken at Longyearbreen (cf. Fig. 8).

contrast, samples taken from within the debris-covered zone show a much wider spread of the C_{40} and RA indices (Figs. 6E, 6G–6I), which is attributed to mixing of supraglacial and englacial with subglacial material rather than purely subaerial weathering.

MODE OF FORMATION

Comparison of clast shapes that dominate the debris-covered zones (Figs. 6, 7, and 9) with control samples (Figs. 6A and 6F) indicates supra- or englacial transport. The fact that many clasts on Nordenskiöldtoppenbreen and Longyearbreen can be traced to distinct strata in the headwall indicates that rockfall is the predominant source of material. This material will then be buried by snow and incorporated into the glacier, most likely being transported englacially (e.g., Kirkbride, 1995; Spedding and Evans, 2002). Along the frontal margin of Larsbreen, cliffs are separated from the glacier surface by debris cones over a horizontal distance of up to 100m. Thus, in this case it is not the immediate effect of larger blocks fallen onto the glacier surface, but the weathered and smaller avalanche material that largely contributes to the formation of the finer-grained debris-covered zone. In all three cases, however, supraglacial and englacial transport of supraglacially derived (rockfall and avalanche) deposits appears to dominate in the present glacial transport systems.

Subglacial transport has played a minor role in the formation of all three debris-covered zones, as evident from the presence of striae and clearly subglacially transported (blocky) clasts. Also, although there is a large component of very angular and angular oblate and prolate clasts indicative of supraglacial and englacial transport in the debris-covered zones, a large matrix component is present. Supraglacial transport does not generate large amounts of fine material due to the absence of crushing and grinding (Boulton, 1976; Benn and Evans, 1998); additional and potentially significant nival (see above) and aeolian dust sources are suspected. The former is evident from the presence of nivation hollows surrounding the glacier and the notion that nivation is an important geomorphic factor in high-arctic areas (e.g., Christiansen, 1998). The latter can be deduced from the surrounding landscape being largely unvegetated and local wind velocity being generally high, with a mean of 3.8 ms^{-1} at Gruvefjellet station (477 m) for the period of 18.08.2001 to 06.09.2004 (Ole Humlum, unpublished data). Hence, subglacial transport, as evident from the presence of striated boulders, contributed to the formation of the debris-covered zones; subaerial weathering, nivation, and aeolian processes alone can probably not account for the large amount of matrix material. It is likely that all three glaciers had larger temperate areas and were more active than today close to reaching their Little Ice Age maximum due to an increased thickness (cf. Sletten et al., 2001; Lyså and Lønne, 2001), explaining the widespread occurrence of subglacially transported clasts.

On Larsbreen and Nordenskiöldtoppenbreen the outcrop pattern of englacial, debris-rich layers on the glacier surface (Fig. 3F) is concentric and characterized by an absence of folds or shears within the ice; we interpret this as evidence of subhorizontal, parallel stratification. Outcrop patterns of isolated debris patches and the continuity of all three debris covers suggests dominant transport along glacier flowlines. The occurrence of a bedded sand wedge on the surface of Larsbreen cannot be used to infer en bloc elevation of older material within a thrust as the material is: (1) likely to have formed at the time of, or since, the LIA glacier advance; and (2) is unlikely to have retained clear and undisturbed bedding structures during thrusting or squeezing. The same complications hold true for isolated sediment bodies on the other two glaciers, where a connection to englacial debris septa could not be found. Such discrete debris lenses could resemble “fossil crevasse fills” that have retained their original coherence during transport and downglacier rotation (Small and Gomez, 1981); transport along flowlines and subsequent meltout appears to be the most reasonable explanation in these cases (cf. Type C Ridges, Sletten et al., 2001). Where relatively thin (≤0.3m), isolated debris patches melt out, cones tend to form, as ice beneath the thickest part of the debris patch is protected from ablation. As the surrounding ice surface melts down, the slope angles of the cone increase until debris becomes unstable, resulting in radial redistribution (cf. Figs. 3G and 3H), explaining the relatively even debris cover parallel to the underlying ice surface along “medial moraines” (see above). Evidence of thrusting, as inferred at the margins of some Svalbard glaciers

Fig. 10. A. Close-up of debris-flow scarp on eastern side of Larsbreen showing numerous tension cracks and dried material of previous slump. B. Overview of northeastern funnel-shaped debris flow complex showing several inset flow lobes, runnels and skinflows. C. Tension cracks in thin (0.15 m) debris cover on Nordenskiöldtoppenbreen. The ice surface in the foreground has been cleaned to show the conditions at the sediment-ice interface where fine material has been winnowed by topmelting of the ice to form an openwork fine gravel lag on which the debris cover rests. D. Wider (0.2 m) tension cracks on ca. 1.0 m–thick debris cover on western lateral moraine of Nordenskiöldtoppenbreen. E. Exposed ice along the main meltwater channel on Larsbreen. Debris flows along this channel propagated upslope and led to increased melting of the formerly buried ice surface during the observation period in 2003. F. Smaller-scale erosion of a former englacial meltwater channel flanked by debris flows and unstable material upslope in the northeastern part of Nordenskiöldtoppenbreen (view to west). G. Alternating units of clast-supported, stratified diamicton interpreted as stacked debris flows in the steep "frontal wedge" of Longyearbreen. Compare with Figure 13. (Figure continues on following page).

(e.g., Hambrey et al., 1997, 1999; Bennett et al., 1998), was not found; this generally agrees with findings from glaciers nearby (Lyså and Lønne, 2001; Sletten et al., 2001).

Melting out of the bedload of former drainage channels (Pelto, 2000; Spedding, 2000), individual rockfalls and crevasse-fills form localized concentrations of debris that are likely to be reworked by meltwater and gravitational sliding to form a more

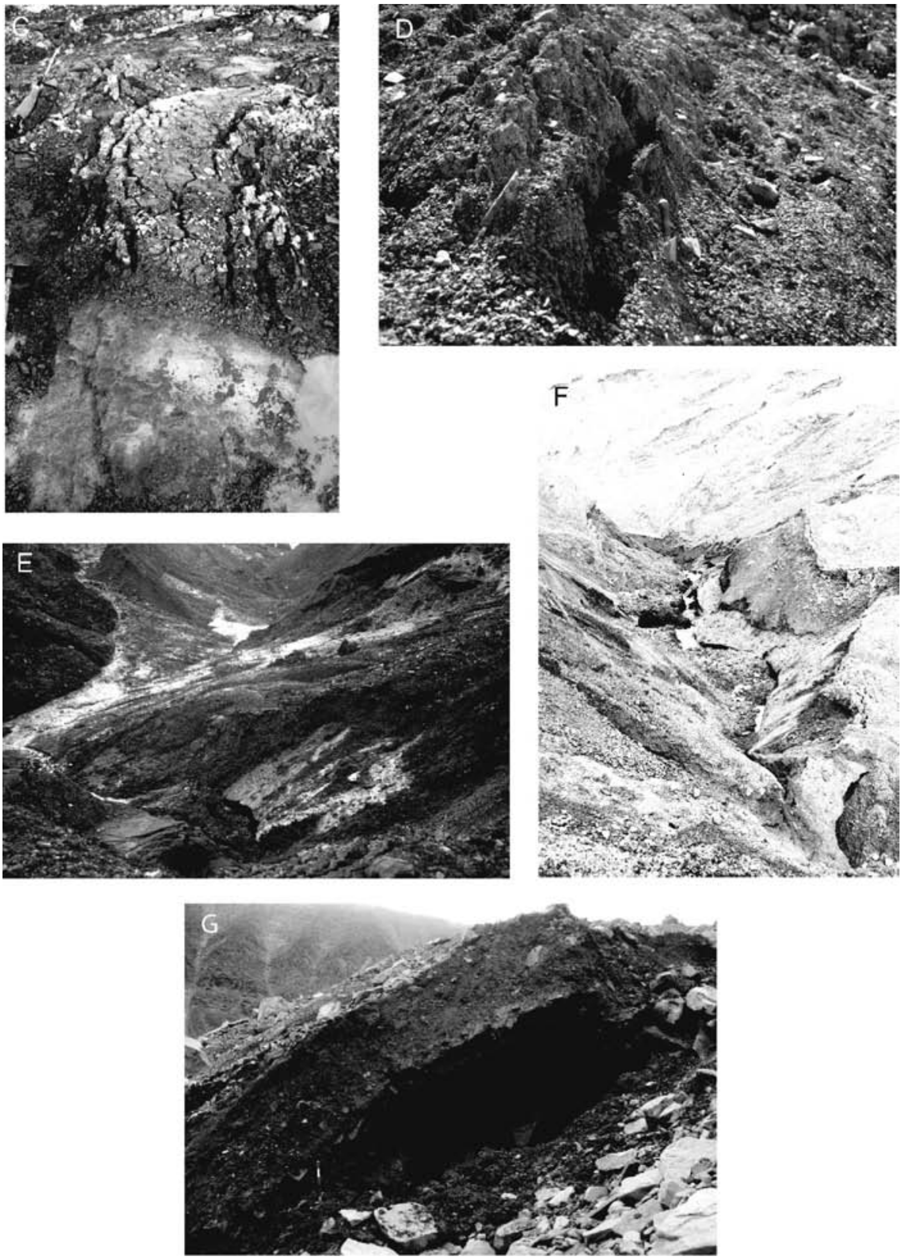

Fig. 10 (continued).

continuous debris cover. Emerging debris bands or crevasse fills containing fine debris would probably become liquefied to form extensive debris covers (cf. "flow tills", Boulton, 1968). In addition, compressional longitudinal flow towards the margins tends to cause medial moraines and surface debris to spread laterally across the glacier terminus (Anderson, 2000).

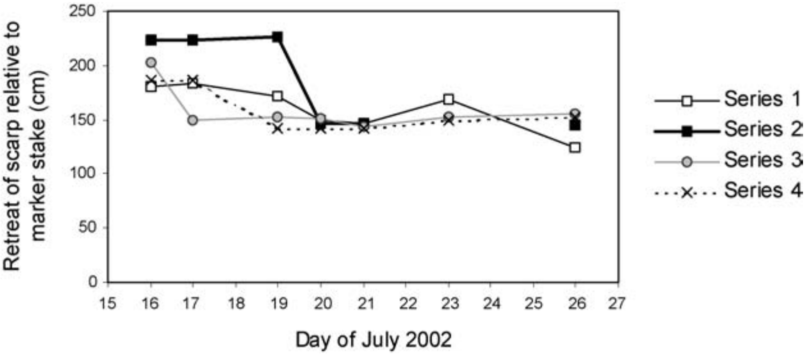

Fig. 11. Scarp retreat rates of four debris flows on the eastern side of Larsbreen during July 2002.

DEGRADATION OF ICE-MARGINAL ZONES

Wet, cohesive debris flows are ubiquitous on sloping surfaces in the marginal zones (Figs. 4, 5, 8, 10A, 10B, 10E, and 10F). Active debris flows commonly incise relict flow lobes, in places giving the hillside a staircase-like appearance (Figs. 4, 5, and 8). No relationship between debris-flow activity and slope angle was found, with both active and inactive flows on Larsbreen existing on slopes ranging from 9° to 43°, suggesting that the trigger for debris flows is likely to be a result of variation in moisture conditions rather than a critical slope angle. Mean slope angle of active debris flows was 21°, while that of inactive debris flow was 20°, suggesting that drying out rather than slope angle may be responsible for debris stabilization. Active flow scarps are located around the crestlines of ridges, such as along the lateral moraines (Figs. 4 and 5). The largest debris flows are bounded by head-scarps up to 2 m high (Figs. 10A and 10B) that usually show signs of inherent collapse by opening tension cracks (Figs. 10A and 10C). The rate of retreat of the head-scarps was measured above four active debris flows on Larsbreen in July 2002 (Fig. 11). The mean retreat rate ranged from 3.5–7.8 cm day^{-1}, suggesting that, in summer conditions, up to 0.5 m width of debris around head-scarps of up to 2 m in thickness and several tens of meters in length can be removed in a week. Failure occurs in discrete events with surface cracks expanding behind the scarp in the days preceding the toppling failure of the scarp face (Fig. 10A). Failed material is then liquefied by meltwater and flows downslope, forming flow lobes and runnels (Fig. 10B).

Debris flows are mainly found on unstable slopes. The largest flows are on the distal terminal slopes of Longyearbreen and Nordenskiöldtoppenbreen and flanking the central supraglacial drainage channel on Larsbreen (Figs. 4, 5, and 8). Smaller debris flows form near meltwater channels where the roof of a formerly englacial channel has collapsed (Figs. 10E and 10F). These propagate upslope, creating further instability, and the remobilized material is rapidly evacuated from the debris-covered zone via the fluvial system (Figs. 10E and 10F; cf. Barsch et al., 1994; Alley et al., 1997; Etzelmüller, 2000). Where debris flows occur, they expose the underlying buried glacier ice, allowing rapid melting. The sub-debris ablation rate measured over 10 summer days at Larsbreen showed rates decreasing non-linearly with increasing

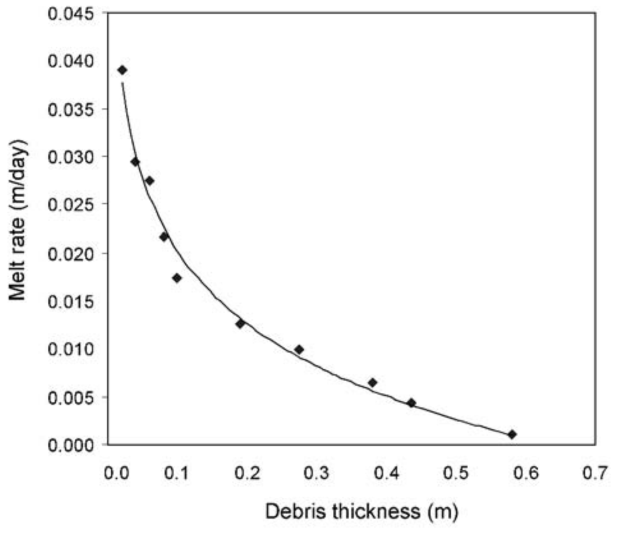

Fig. 12. Relationship between debris thickness and ablation rate measured at Larsbreen from July 9 to 20, 2002, with a logarithmic line of best fit.

debris thickness (Fig. 12), as has been found in previous studies (e.g. Østrem, 1959; Loomis, 1970; Nakawo and Young, 1981; Mattson et al., 1993). These measurements suggest that, beneath debris of >0.40 m in thickness, less than 0.005 m of surface lowering occurs per day and that very little melt is likely if debris thickness is >0.60 m. Maximum measured melt, of just below 0.04 m day^{-1}, occurred beneath the thinnest debris cover, which was 0.02 m thick. Where the debris cover is completely removed, surface melt increases tenfold, so that areas of exposed ice or very thin debris cover are responsible for a disproportionate amount of ablation in relation to their area (Johnson, 1971; Sakai et al., 2000; Iwata et al., 2000). Experiments have shown that light dustings, or thin surface washes of debris, produce ablation rates in excess of that of clean ice (e.g., Adhikary et al., 2000). Variation in the distribution of debris thickness results in differential ablation beneath the debris cover and the creation of local relief at the ice surface. Meltwater at the ice-sediment interface facilitates translational failure of the whole layer as a cohesive unit, with incipient failures indicated by tension cracks (Figs. 10C and 10D). Removal of material in a narrow zone subparallel to the channel by thin flows results in further instability, which in turn is compensated for by additional debris flows upslope. The effectiveness of the ensuing chain reaction can best be seen at Larsbreen, where comparison of photomosaics suggests that the glacier surface has lowered by up to 5 m around the central former englacial tunnel between August 2002 and August 2003 following its partial roof collapse (see Fig. 15).

Meltwater saturation of debris can also result in large skinflows (Fig. 10B). Increased mobility of thinner debris, which is more likely to be saturated by meltwater, creates a positive feedback for mass movement processes, in which areas of more rapid melt maintain local slope angles, leading to rapid widening of the channel and downslope movement, destabilizing the debris cover upslope and thus perpetuating the

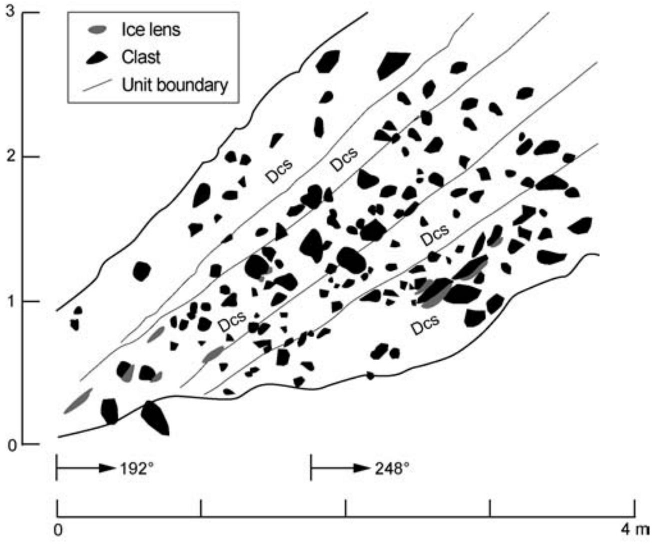

Fig. 13. Sedimentary log of section LYB 1 exposing alternating units of clast-supported, stratified diamicton (Dcs) interpreted as stacked debris flows.

erosive undercutting of the surrounding debris cover. Therefore, enhanced melting leads to further debris flows, and the system enters a self-reinforcing cycle.

The observed increase in debris thickness toward the glacier margin can be accounted for by a combination of supra-, en- and subglacial debris concentrations being greatest at the margins and ice flow further concentrating debris toward the terminus (Kirkbride, 2000). Our study shows that, in the case of central Spitsbergen glaciers, these effects are exacerbated by ubiquitous debris flows that shift debris centrifugally thereby constantly increasing the "frontal wedge" by stacking (Fig. 10G). Indeed, this may be the dominant process in this environment. Only one section exposing the sedimentary endproduct of this process was found (LYB1 in Fig. 8). Figure 13 shows compact, crudely stratified, clast-supported diamict units that steeply dip toward the NNE by ca. 20° and are interpreted as stacked debris flows. The matrix throughout the exposure is composed of silty to fine sand with numerous aligned clasts in the fine to coarse gravel fractions and boulders, with a-axes of up to 2 m; the alignment of clasts causes the apparent stratification. At a unit scale, however, stratification is rapidly lost. Numerous ice lenses were observed in cracks parallel to the dip of the units and around larger boulders. Undercutting by an emerging englacial stream led to collapse of a large part of the exposure two days after it had been logged.

Slope steepening and undercutting due to incision of supraglacial meltwater is a frequent process that leads to surface lowering, inducing instabilities and leading to debris flows. The association of the largest flows around the frontal distal slopes of Nordenskiöldtoppenbreen with supraglacial and englacial channels is best explained this way, as indeed some of the largest debris flows appear to have deposited very little sediment at the foot of the flow. Meltwater activity also tends to winnow out fine material from the diamicton, leaving localized areas of coarse, openwork deposits (Fig. 3E).

Subhorizontal marginal areas support a thin cover of lichens, mosses, and small vesicular plants (Figs. 4, 5, and 8). Enters (2000) has described such small plant colonies on Rieperbreen in neighboring Endalen and was able to link the occurrence of vegetation to relatively stable areas that were not disrupted by debris flow activity. This evidence of marginal stability emphasizes the importance of supraglacial meltwater in destabilising the debris cover.

SYNTHESIS OF DEGRADATIONAL PROCESSES

The observations and data presented above suggest complex links between individual processes. Figure 14 shows a conceptual model that synthesizes the observed evidence into a degradational process–response system. Conditions of the central Spitsbergen glacier system are initially characterized by a steep frontal slope that presents the initial instability along which material is mobilized and transferred away from the glacier front. Collapse of englacial meltwater channels forms steep gradients within a formerly continuous debris cover. Debris flows into these channels result in removal of material and probably enhance fluvial downcutting into the ice. Removal of material in a zone close to the channel induces further debris flows upslope. In all steps, debris flows result in the thinning or complete removal of supraglacial debris, hence enhancing melting. Enhanced melting results in further debris flows. Supraglacial material—once mobilized by debris flows—thus enters a self-maintaining and self-reinforcing cycle of degradation (Fig. 14).

The strong link between the degradation of ice-marginal debris-covered zones and the occurrence of roof collapse triggered by fluvial undercutting is particularly evident on the three glaciers studied. The main drainage routes on Larsbreen and Nordenskiöldtoppenbreen cross the ice-marginal debris-covered zones, as opposed to those of Longyearbreen that run largely parallel to the debris-covered zones in a marginal position (Etzelmüller et al., 2000). Our data, therefore, support the notion that: (1) most surface-debris reworking is due to erosion and destabilization by surface meltwater, rather than gravitational processes; and (2) once fluvial erosion has commenced, rapid degradation of the debris-covered zones ensues (King and Volk, 1994; Etzelmüller, 2000). These observations confirm theoretical reasoning that, where a glacier links sediments and meltwater, most of the sediment will be removed (Alley et al., 1997). This effect can best be seen at Larsbreen, where large-scale debris removal along the central channel initiated enhanced melting and degradation (Figs. 15A and 15B).

PRESERVATION POTENTIAL AND LANDFORM GENESIS

Debris flows redistribute material where the supraglacial debris cover is thinner than the active layer. On some glaciers, mass movements redistribute debris in talus fans to topographic lows (Iwata et al., 1980), within which ablation is then retarded. Debris redistribution can cause topographic inversion, where hollows become highs and vice versa (Clayton, 1964; Hands, 2004). Such inversion may happen several times during a period of glacial retreat and is an important process by which debris is distributed more uniformly across the glacier (Clayton, 1964; Drewry, 1972; Watson, 1980; Anderson, 2000). However, in the case of the glaciers studied here, most of this

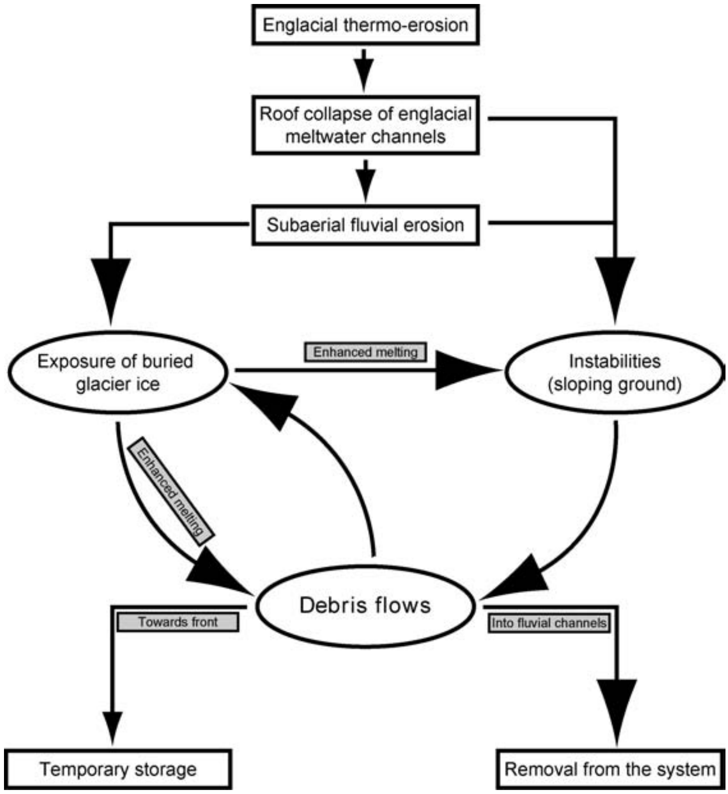

Fig. 14. Conceptual model of the process-response system of the degradation of ice-marginal debris-covered zones of cold-based to polythermal Central Spitsbergen glaciers. Temporarily stored material will be subject to reworking due to gradual degradation of the underlying ice.

material is evacuated along meltwater channels. Consequently, it is unclear what features would identify the sedimentary endproduct of this style of marginal deposition.

The observations made here have implications for long-term landscape evolution. The larger proportion of mobilized material is removed from the system to be stored in outwash plains or the sea, and only a small proportion might survive in what we have termed the "frontal wedge" (Fig. 14). Even this thickening "frontal wedge" will degrade with time due to solifluction under continuous permafrost conditions and little constructional evidence of a formerly glaciated terrain will be preserved on time scales ranging from centuries to millennia. These observations add to a growing body of evidence from Svalbard that the preservation potential of glacigenic sediments in a continuous permafrost environment is quite limited due to a very efficient coupling of the slopes with the fluvial system via glaciers (e.g., Barsch et al., 1994; Blümel et al., 1994; Etzelmüller, 2000; Etzelmüller et al., 2000; Lyså and Lønne, 2001). This also explains the problems of constructive landform preservation encountered in attempts to reconstruct the history of high-arctic glaciers on Svalbard (e.g., Blümel et al., 1994; Landvik et al., 1998; Lyså and Lønne, 2001; Sletten et al., 2001; Sørbel et al., 2001; Eitel et al., 2002). These findings contrast with clear glacial geomorphological

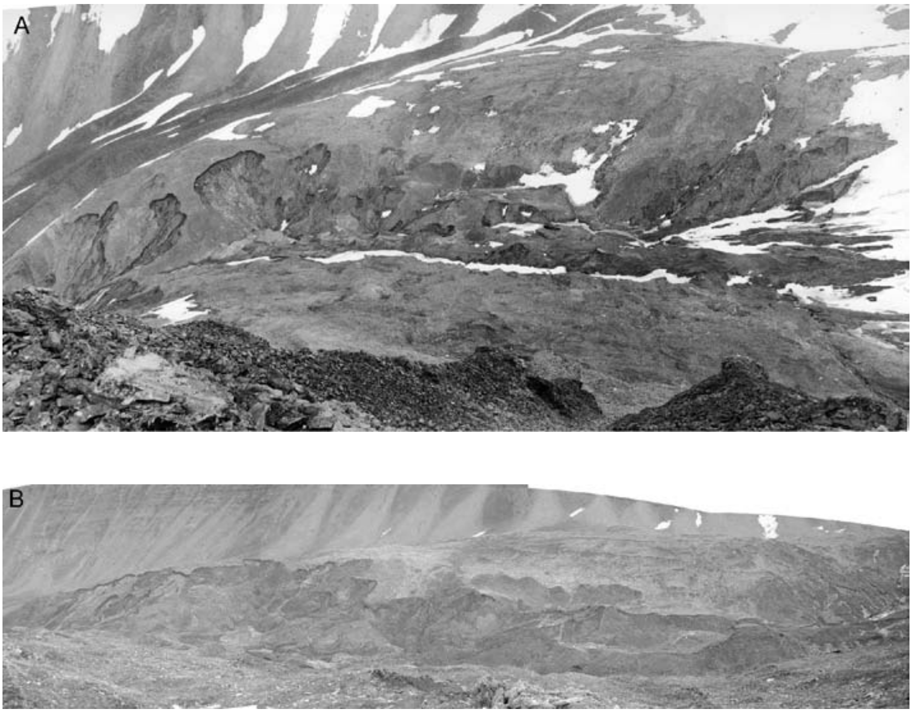

Fig. 15. Panorama picture of the eastern side of Larsbreen. A. August 2002. B. August 2003. Note the enlargement of the failure complex on the left that has grown together in 2003 and the relatively unaltered part farther away from the central meltwater channel on the right.

evidence from high-arctic North America where classic glacial landsystems have been preserved over several millennia (e.g., Dyke and Evans, 2003). The steeper topography in Svalbard and the smaller size of the glaciers compared to the large lowland ice sheet lobes in North America might explain the different response of these two systems to reworking.

In addition, the short-lived nature of the LIA advance in central Spitsbergen might have affected the preservation potential of these moraines. The longer a terminus position is sustained, the more debris can be delivered to it by meltout along englacial flowlines. Consequently a longer LIA could lead to a thicker marginal debris cover. This may inhibit the onset of the decay cycle (Fig. 14), and in some cases this might aid the survival of ice-cored moraines. A thicker debris cover masking the glacier margin could mean that even a decomposed marginal ice-cored moraine may be more likely to leave an observable marginal landform following de-icing. However, two counterarguments can be made. Firstly, a thicker debris layer that accumulated over a longer time span inhibits melt more effectively than a thinner layer. This reduces the amount of ablation that can occur and, assuming constant climatic conditions, would necessitate further glacier advance in order to maintain a mass balance equilibrium. During an advance, the sediment accumulated at the glacier margins would be reworked and redeposited by meltwater and glacial processes. Thus, if an equilibrium situation is re-established, the process of debris accumulation that may lead to ice-cored moraine formation must begin again. Secondly, although a thicker debris cover may inhibit the onset of the positive feedback cycle (Fig. 14), our field observations suggest that thick debris accumulations are as vulnerable to debris remobilization as thinner ones once the cycle is initiated. This second point also applies to the addition of material by gradual meltout of debris contained in buried ice bodies, which will cause the debris cover to become thicker over time. The preservation potential of remnant features could be increased this way. However, as the decay feedback cycle described in Figure 14 is a positive one, regardless of the thickness of debris, a thicker accumulation of debris on an older feature still does not guarantee its survival, as any meltwater or slope failure event could trigger the onset of decay and the inevitable wasting of the buried ice.

Perhaps the most likely geomorphological signature of small high-arctic valley glaciers is meltwater channels and outwash fans radiating out from areas formerly covered by glaciers (cf. Lyså and Lønne, 2001; Sletten et al., 2001), which also corresponds to findings from high-arctic Canada (e.g., Dyke and Evans, 2003). Primary glacial landforms and sediments such as moraines and till will most likely be modified, obliterated, or completely destroyed. Because of this limited preservation potential of constructional glacial landforms, polythermal, high-arctic glaciers can only serve as modern analogues for areas glaciated during the Pleistocene where glacial landforms are obliterated and perhaps only the outermost moraine ridge remains clearly identifiable (e.g., Sollid & Sørbel, 1988). Where clear moraines and glacial sediments are preserved and indicate highly active, oscillatory retreat—for example, in the Scottish Highlands—invoking such a high-arctic analogue is unrealistic (Lukas, 2005).

CONCLUSIONS

The debris-covered ice-margins of three cold-based to polythermal glaciers were dominantly formed by the incorporation of rockfall and avalanche material sourced from free faces overlooking the glaciers in their source areas; a smaller proportion of material indicates subglacial transport. One implication of these findings is that subglacial temperate areas must have been more extensive when the glacier was thicker during the LIA. Fine-grained matrix material was produced by glacial crushing aided by advection of fine-grained sediment through nivation and aeolian processes. Transfer of material was along flowlines as evident from widespread discrete sediment accumulations on the glaciers interpreted as crevasse fills; evidence for englacial thrusting was not found. Meltout at the front and redistribution of debris led to the emplacement of a continuous debris cover.

Debris flows are the dominant means of material transfer on the three glaciers. These are initiated where instabilities are formed along meltwater channels. Debris flows propagate upslope along such channels, leading to rapid enlargement of a debris-free area. Our results support previous findings that regard glaciers as links between slopes surrounding them and the fluvial system, forming an effective denudation system.

Although stacked debris flows have been observed in one exposure, their preservation potential over many centuries is limited due to glaciofluvial reworking and removal. These results confirm the notion that glacier and ice sheet reconstruction in high arctic Svalbard is extremely difficult due to this effective coupling of the slopes and fluvial system. Our observations permit the conclusion that at best a subdued outer dump moraine might be the resulting landform after complete de-icing of the landscape. Instead of constructional glacial landforms, meltwater channels and outwash fans are much more likely to indicate a formerly glaciated terrain. Our findings imply that cold-based to polythermal, high-arctic glaciers cannot be used as modern analogues for areas that show clear and well-preserved glacial landforms and sediments such as those in the Scottish Highlands.

LITERATURE

Adhikary, S., M. Nakawo, K. Seko and B. Shakya. "Dust influence on the melting process of glacier ice: experimental results from Lirung Glacier, Nepal Himalayas," in: M. Nakawo, M., C. F. Raymond, and A. Fountain, eds., *Debris-Covered Glaciers*. Wallingford, UK: IAHS-AISH Publication 264, 2000, pp. 43-52.

Alley, R. B., K. M. Cuffey, E. B. Evenson, J. C. Strasser, D. E. Lawson, and G. J. Larson. "How glaciers entrain and transport basal sediment: physical constraints," *Quaternary Science Reviews*, Vol. 16, 1997, pp. 1017-1038.

Anderson, R. S. "A model of ablation-dominated medial moraines and the generation of debris-mantled glacier snouts," *Journal of Glaciology*, Vol. 46, 2000, pp. 459-469.

Barsch, D., M. Gude, R. Mäusbacher, G. Schukraft, and A. Schulte. "Recent fluvial sediment budgets in glacial and periglacial environments, NW Spitsbergen," *Zeitschrift für Geomorphologie Supplement Band*, Vol. 97, 1994, pp. 111-122.

Benn, D. I. and C. K. Ballantyne. "The description and representation of particle shape," *Earth Surface Processes and Landforms*, Vol. 18, 1993, pp. 665-672.

Benn, D. I. and C. K. Ballantyne. "Reconstructing the transport history of glacigenic sediments: A new approach based on the co-variance of clast shape indices," *Sedimentary Geology*, Vol. 91, 1994, pp. 215-227.

Benn, D. I. and D. J. A. Evans. *Glaciers and glaciation*. London, UK: Arnold, 1998.

Bennett, M. R., M. J. Hambrey, D. Huddart, and N. F. Glasser. "Glacial thrusting and moraine-mound formation in Svalbard and Britain: The example of Coire a' Cheud-chnoic (Valley of Hundred Hills), Torridon, Scotland," *Quaternary Proceedings*, Vol. 6, 1998, pp. 17-34.

Björnsson, H., Y. Gjessing, S. E. Hamram, J. O. Hagen, O. Liestøl, F. Pålsson, and B. Erlingsson. "The thermal regime of subpolar glaciers mapped by multi-frequency radio-echo soundings," *Journal of Glaciology*, Vol. 12, 1996, pp. 23-31.

Blümel, W. D., J. Eberle, and B. Eitel. "Zur jungquartären Vereisungsgeschichte und Landschaftsentwicklung in NW-Spitzbergen (Liefde-, Bock- und Woodfjord) (On the late Quaternary history of glaciation and landscape evolution in NW Spitsbergen)," *Zeitschrift für Geomorphologie Supplement Band*, Vol. 97, 1994, pp. 31-42.

Boulton, G. S. "Flow tills and related deposits on some Vestspitsbergen glaciers," *Journal of Glaciology*, Vol. 7, 1968, pp. 391-412.

Boulton, G. S. "A genetic classification of tills and criteria for distinguishing tills of different origin," *Geografia*, Vol. 12, 1976, 65-80.

Boulton, G. S. "Boulder shapes and grain-size distributions of debris as indicators of transport paths through a glacier and till genesis," *Sedimentology*, Vol. 25, 1978, 773-799.

Christiansen, H. H. "Nivation forms and processes in unconsolidated sediments, NE Greenland," *Earth Surface Processes and Landforms*, Vol. 23, 1998, 751-760.

Clayton, L. "Karst topography on stagnant glaciers," *Journal of Glaciology*, Vol. 5, 1964, pp. 107-112.

Dallmann, W. K., T. Kjærnet, and A. Nøttvedt. *Geological map of Svalbard 1:100,000—Sheet C9Q Adventdalen. Explanatory text.* Tromsø, Norway: Norsk Polarinstitutt, 2001.

Drewry, D. J. "A quantitative assessment of dirt-cone dynamics," *Journal of Glaciology*, Vol. 11, 1972, pp. 431-446.

Dyke, A. S. and D. J. A. Evans. "Ice-marginal terrestrial landsystems: Northern Laurentide and Innuitian ice sheet margins," in: D. J. A. Evans, ed., *Glacial Landsystems*. London, UK: Arnold, 2003, pp. 143-165.

Eitel, B., K. van der Borg, J. Eberle, and H. Megies. "Late Pleistocene/Early Holocene glacial history of northern Andreeland (northern Spitsbergen/Svalbard Archipelago): Evidence from glacial and fluvio-glacial deposits," *Zeitschrift für Geomorphologie*, Vol. 46, 2002, pp. 337-364.

Enters, D. Primäre Sukzession auf dem Gletschervorfeld des Rieperbreen, Spitzbergen (Primary Plant Succession in the Glacier Foreland of Rieperbreen, Spitsbergen). M.Sc. Thesis, University of Karlsruhe, 2000.

Etzelmüller, B. "Quantification of thermo-erosion in pro-glacial areas—examples from Svalbard," *Zeitschrift für Geomorphologie*, Vol. 44, 2000, pp. 343-361.

Etzelmüller, B., R. S. Ødegard, G. Vatne, R. S. Mysterud, T. Tonning, and J. L. Sollid. "Glacier characteristics and sediment transfer system of Longyearbreen and Larsbreen, western Spitsbergen," *Norsk Geografisk Tidsskrift*, Vol. 154, 2000, pp. 157-168.

Evans, D. J. A. and D. I. Benn, eds. *A practical guide to the study of glacial sediments*. London, UK: Arnold, 2004.

Everest, J. D. and T. Bradwell. "Buried glacier ice in southern Iceland and its wider significance," *Geomorphology*, Vol. 52, 2003, pp. 347-358.

Eyles, N., C. H. Eyles, and A. D. Miall. "Lithofacies types and vertical profile models. An alternative approach to the description and environmental interpretation of glacial diamict and diamictite sequences," *Sedimentology*, Vol. 30, 1983, pp. 393-410.

Hagen, J. O., O. Liestøl, E. Roland, and T. Jørgensen. "Glacier Atlas of Svalbard and Jan Mayen," *Norsk Polarinstitutt Meddelelser*, Vol. 129, 1993, pp. 1-141.

Hambrey, M. J., D., M. R. Bennett, J. A. Dowdeswell, N. F. Glasser, and D. Huddart. "Debris entrainment and transfer in polythermal valley glaciers," *Journal of Glaciology*, Vol. 45, 1999, pp. 69-86.

Hambrey, M. J., D. Huddart, M. R. Bennett, and N. F. Glasser. "Genesis of 'hummocky moraines' by thrusting of glacier ice: Evidence from Svalbard and Britain," *Journal of the Geological Society of London*, Vol. 154, 1997, pp. 623-632.

Hands, K. A. Downwasting and Supraglacial Lake Eolution on the Debris-Covered Ngozumpa Glacier, Khumbu Himal, Nepal. Ph.D. thesis, University of St. Andrews, 2004.

Hjelle, A. *Geology of Svalbard*. Oslo, Norway: Norsk Polarinstitutt, 1993.

Humlum, O. "Modelling late 20th-century precipitation in Nordenskiöld Land, Svalbard, by geomorphic means," *Norsk Geografisk Tidsskrift*, Vol. 56, 2002, pp. 96-103.

Humlum, O. "Holocene permafrost aggradation in Svalbard," *Geological Society of London Special Publications*, Vol. 242, 2005, pp. 119-130.

Humlum, O., A. Instanes, and J. L. Sollid. "Permafrost in Svalbard: A review of research history, climatic background, and engineering challenges," *Polar Research*, Vol. 22, 2003, pp. 191-215.

Iwata, S., O. Watanabe, and H. Fushimi. "Surface morphology and in the ablation area of the Khumbu Glacier," *Seppyo (Journal of the Japanese Society of Snow and Ice)*, Vol. 41, 1980, pp. 9-17.

Iwata, S., S. Yamaguchi, T. Aoki, T. Kadota, and K. Seko. "Morphological evolution of the debris cover on Khumbu Glacier, Nepal, between 1978 and 1995," in: M. Nakawo, C. F. Raymond, and A. Fountain, eds., *Debris-Covered Glaciers*. Wallingford, UK: IAHS-AISH Publication 264, 2000, pp. 3-11.

Johnson, P. G. "Ice-cored moraine formation and degradation, Donjek Glacier, Yukon Territory, Canada," *Geografiska Annaler*, Vol. 53A, 1971, pp. 198-202.

Justad, G. H. Morfologiske og sedimentologiske studier av et iskontakt system ved Longyearbreen, Svalbard (Morphological and Sedimentological Investigations of the Ice-Contact System of Longyearbreen, Svalbard). Cand. Scient. thesis, University of Tromsø, 1997.

King, L. and M. Volk. "Glaziologie und Glazialmorphologie des Liefde- und Bockfjordgebietes, NW-Spitzbergen (Glaciology and glacial geomorphology of the Liefde- and Bockfjord area, NW Spitsbergen)," *Zeitschrift für Geomorphologie Supplement Band*, Vol. 97, 1994, pp. 145-159.

Kirkbride, M. P. "Ice flow vectors on the debris-mantled Tasman glacier, 1957–1986," *Geografiska Annaler*, Vol. 77A, 1995, pp. 147-157.

Kirkbride, M. P. "Ice-marginal geomorphology and Holocene expansion of debris-covered Tasman Glacier, New Zealand," in: M. Nakawo, C. F. Raymond, and A. Fountain, eds., *Debris-Covered Glaciers*. Wallingford, UK: IAHS-AISH Publication 264, 2000, pp. 211-218.

Kjær, K. H. and J. Krüger. "The final phase of dead-ice development: Processes and sediment architecture, Kötlujökull, Iceland," *Sedimentology*, Vol. 48, 2001, pp. 935-952.

Krüger, J. and K. H. Kjær. "De-icing procession of ice-cored moraines in a humid, subpolar climate, Kötlujökull, Iceland," *The Holocene*, Vol. 10, 2000, pp. 737-747.

Landvik, J. Y., J. Mangerud, and O. Salvigsen. "Glacial history and permafrost in the Svalbard area," *Permafrost. Fifth International Conference*. Trondheim, Norway: Tapir, 1988, pp. 194-198.

Landvik, J. Y., S. Bondevik, A. Elyerhøei, W. Fjeldskaar, J. Mangerud, O. Salvigsen, M. J. Siegert, J.-I. Svendsen, and T. O. Vorren. "The Last Glacial Maximum of Svalbard and the Barents Sea area: Ice sheet extent and configuration," *Quaternary Science Reviews*, Vol. 17, 1998, pp. 43-75.

Liestøl, O. "Glacier surges in West Spitsbergen," *Canadian Journal of Earth Sciences*, Vol. 6, 1969, pp. 895-897.

Liestøl, O. "Glaciers of Europe—glaciers of Svalbard, Norway," in: R. S. Williams and J. G. Ferriggo, eds., *Satellite image atlas of glaciers of the world.* Reston, VA: USGS Professional Paper, 1993, pp. E127-E151.

Loomis, S. R. "Morphology and ablation processes on glacier ice," *Proceedings of the Association of American Geographers*, Vol. 12, 1970, pp. 88-92.

Lukas, S. "A test of the englacial thrusting hypothesis of 'hummocky' moraine formation: Case studies from the northwest Highlands, Scotland," *Boreas*, Vol. 34, 2005, pp. 287-307.

Lyså, A. and I. Lønne. "Moraine development at a small High-Arctic valley glacier: Rieperbreen, Svalbard," *Journal of Quaternary Science*, Vol. 16, 2001, pp. 519-529.

Major, H., P. Haremo, W. K. Dallmann, and A. Andresen. *Geological map Svalbard 1:100,000 Spitsbergen—sheet C9Q Adventdalen*. Tromsø, Norway: Norsk Polarinstitutt, 2000.

Mattson, L. E. and J. S. Gardner. "Mass wasting on valley-side ice-cored moraines, Boundary Glacier, Alberta, Canada," *Geografiska Annaler*, Vol. 73A, 1991, pp. 123-128.

Mattson, L. E., J. S. Gardner, and G. J. Young. "Ablation on debris covered glaciers: An example from the Rakhiot Glacier, Punjab, Himalaya," in: G. J. Young, ed., *Snow and glacier hydrology.* Wallingford, UK: IAHS-IASH Publication 218, 1993, pp. 289-296.

McKenzie, G. D. and R. G. Goodwin. "Development of collapsed glacial topography in the Adams Inlet area, Alaska, USA," *Journal of Glaciology*, Vol. 33, 1987, pp. 55-59.

Nakawo, M. and G. J. Young. "Field experiments to determine the effect of a debris layer on ablation of glacier ice," *Annals of Glaciology*, Vol. 2, 1981, pp. 85-91.

Østrem, G. "Ice melting under a thin layer of moraine, and the existence of ice cores in moraine ridges," *Geografiska Annaler*, Vol. 51, 1959, pp. 228-230.

Pelto, M. S. "Mass balance of adjacent debris-covered and clean glacier ice in the North Cascades, Washington," in: M. Nakawo, C. F. Raymond, and A. Fountain, eds., *Debris-Covered Glaciers*. Wallingford, UK: IAHS-AISH Publication 264, 2000, pp. 35-42.

Sakai, A., N. Takeuchi, K. Fujita, and M. Nakawo. "Role of supraglacial ponds in the ablation process of a debris-covered glacier in the Nepal Himalayas," in: M. Nakawo, C. F. Raymond, and A. Fountain, eds., *Debris-Covered Glaciers*. Wallingford, UK: IAHS-AISH Publication 264, 2000, pp. 119-130.

Sletten, K., A. Lyså, and I. Lønne. "Formation and disintegration of a high-arctic ice-cored moraine complex, Scott Turnerbreen, Svalbard," *Boreas*, Vol. 30, 2001, pp. 272-284.

Small, R. J. and B. Gomez. "The nature and origin of debris layers within Glacier de Tsidjiore Nouve, Valais, Switzerland," *Annals of Glaciology*, Vol. 2, 1981, pp. 109-113.

Sollid, J. L. and L. Sørbel. "Influence of temperature conditions in formation of end moraines in Fennoscandia and Svalbard," *Boreas*, Vol. 17, 1988, pp. 553-558.

Sørbel, L., J. Tolgensbakk, J. O. Hagen, and K. Høgvard. *Geomorphological and Quaternary geological map of Svalbard 1:100,000—sheet C9Q Adventdalen*. Tromsø, Norway: Norsk Polarinstitutt, 2001.

Spedding, N. "Hydrological controls on sediment transport pathways: Implications for debris-covered glaciers," in: M. Nakawo, C. F. Raymond, and A. Fountain, eds., *Debris-Covered Glaciers*. Wallingford, UK: IAHS-AISH Publication 264, 2000, pp. 133-142.

Spedding, N. and D. J. A. Evans. "Sediments and landforms at Kvíárjökull, south-east Iceland: A reappraisal of the glaciated valley landsystem," *Sedimentary Geology*, Vol. 149, 2002, pp. 21-42.

Svendsen, J.-I. and J. Mangerud. "Holocene glacial and climatic variations on Spitsbergen, Svalbard," *The Holocene*, Vol. 7, 1997, pp. 45-57.

Tonning, T. Bruk av eit geografisk informasjonssystem på glasiologiske problemstil-ingar: døme fra Longyearbreen og Larsbreen på Svalbard (Use of a Geographical Information System for Glaciological Problems: Examples from Longyearbreen and Larsbreen, Svalbard). Cand. Scient. thesis, University of Olso, 1996.

Watson, R. A. "Landform development on moraines of the Klutlan Glacier, Yukon Territory, Canada," *Quaternary Research*, Vol. 14, 1980, pp. 293-300.

Ziaja, W. "Glacial recession in Sørkappland and Central Nordenskiöldland, Spitsbergen, Svalbard, during the 20th century," *Arctic, Antarctic and Alpine Research*, Vol. 33, 2001, pp. 36-41.