Deglaciation dynamics following the Little Ice Age on Svalbard: Implication of debris-covered glaciers dynamic and morphological setting

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Abstract:
Recently debris-covered glacier near Longyearbyen in central Spitsbergen has been studied to understand the deglaciation process following the Little Ice Age. This study presented new geomorphological data for some of the same glacier. Through a careful description of the dynamic of debris-covered glacier, what its means for the interpretation of the moraines, and an analyse of the geomorphology in relation to the ongoing glaciofluvial processes the preservation potential are considered in relation to the underlying morphological setting. The two studied glaciers represent two different morphological settings respectively a plateau and a confined steep-sided valley. It is conclude that flat lying moraine on a plateau has a high preservation potential and moraine on a steep valley side has low preservation potential. At the steep valley side gravity and water working together to transport the sediment, in contrast, water on a plateau can make channels witch the water follows and therefore maybe not affect the entire moraine.

Introduction
Svalbard is an archipelago located at high latitudes (76-81°N). In the recent years deglaciation of glaciers on Svalbard has been studied. The task has being understanding of deglaciation, thereby reconstructing deglaciation and the different geomorphic features preservation potential. On Svalbard the Little Ice Age (LIA) was culminating late, this provides a better opportunity to reconstruct the following deglaciation in detail.

Recently glaciers nearby Longyearbyen, the main city on Svalbard, have been studied geomorphic for deglaciation (Lønne and Lyså, 2005, Lukas et al., 2005). Lønne and Lyså (2005)’s work has started a discussion about terminology and how to understand these glaciers (Lønne, 2006, Lukas et al., 2006). This article presents new geomorphological data for two of the same glaciers and thereby answers some of the main open questions for understanding these glaciers. The geomorphology of the two glaciers moraines will be compared in a discussion of glaciofluvial processes and preservation potential, in relation to the different underlying morphology.

Study area
Longyearbyen is located at the mouth of the Longyear valley, Central Spitsbergen. At the head of the Longyear valley three glaciers are located, see figure 1.
Longyearbreen is laying in the main valley. East of Longyearbreen is Larsbreen. The southern part of Larsbreen is lying on a plateau, where the northern part is a glacier tongue reaching down in a confined steep-sided valley. On the western side of Longyearbreen is another glacier, this has now name. It is starting at the top of Nordenskiöldfjellet and ending on the flat Platåberget.

The geomorphologic mapping has been carried out on Larsbreen and the unnamed glacier. These two are chosen because the difference between the moraines. Through this article the unnamed glacier will be called Platåbreen, after the location of the moraine, with is the interesting part in this study. This name is also used by Lønne and Lyså (2005). Lukas et al. (2005) named it Nordenskiöldtoppenbreen.

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**Figure 1.** Overview map of the head of Longyear valley, Central Svalbard. Redrawing of Norwegian Polar Institute (2000). Data to the overview map of Svalbard is from ESRI (2000).
Previous work

Lønne and Lyså (2005) have made a detailed geomorphologic map of Platåbreen. They divide the ice-marginal landscape into five different zones: 1) glacier ice, with a thin debris mantle locally, including medial moraines; 2) proglacial areas influenced by glacial meltwater; 3) ice-cored termino-lateral moraines; 4) areas deglaciated after the LIA maximum, and 5) areas not directly affected by this glacial event.

They describe the five zones and document with pictures. From historical aerial photos they find the terminus at different years. They end up with a four stage model of the evolution of Platåbreen, from early LIA to fully deglaciated basin. Every stage show shifting in geomorphologic zones in different areas.

They conclude that the evolution of the landscape can be divided into tree phases: Temperate glacier, cold-based ice and non-glacial conditions. Erosion by glacial meltwater is the most notable landscape process, and study of modern analogical glacial meltwater processes can improve reconstruction of glacier.

Lukas et al. (2005) has made a detailed study of the debris-covered frontal ice-margins of Longyeear-, Lars- and Platåbreen. They have mapped the geomorphology of the glaciers and measured clast shape and roundness. They conclude that cold-based to polythermal, high-arctic glaciers can not be used as modern analogues for well-preserved Quaternary glacial landforms such as those in the Scottish Highland. This building on the remains of de-glaciating of the three present glaciers is dump moraine due to glaciofluvial rework and removal.

Lønne and Lyså (2005) and Lukas et al. (2005) agree in the importance of glacio-fluvial processes for preservation of modern Svalbard glacier’s moraines.

Lukas et al. (2006) comment on the work of Lønne and Lyså (2005). Here is a review of some of the points. Use of the term “ice-cored moraine”: Lukas et al. (2006) claim that with using the term “ice-cored moraine” it implicit say that the ice in the moraine is dead-ice that is detached from the glacier. Lukas et al. (2006) has made a cross profile of the debris-cover of Platåbreen, with show supraglacial debris on clean glacier ice. This means the front of the glacier is a debris-cover glacier and not a dead-ice “ice-cored moraine”. Lønne and Lyså (2005) have identified former ice-front positions through aerial photos, but Lukas et al. (2006) observations claimed the active glacier continued under the debris and therefore the real ice-front is still at LIA position.

Lukas et al. (2006) have not found any thrusting on Platåbreen and therefore they say it is unlikely that a subglacial transport is a source for some of the debris at the surface. Farther more the shale would have been crushed under the subglacial transport.

Lønne (2006) is a reply on Lukas et al. (2006) comment. One of the points is that moraines can be ice-core with out the ice being dead-ice.

In the forefield of Larsbreen are rock-glaciers. These and the additional talus cones has been monitored and studied by Humlum (2005), since 1999.

Glasser and Hambery (2006) presented a landsystem model for a typical terrestrial Svalbard polythermal glacier. The model is based on observation of modern Svalbard glacier and the published literature. This model will be used for comparison with Larsbreen and Platåbreen, as a reference model for Svalbard glacier. The model divides the glacier forefield in tree, see figure 2:

Outer moraine ridges: steep ridges up to 15-20 m height, with usually are ice cored.
Moraine-mound complexes: rich relief, long and short linear ridges, slopes around 30° and thrusting.

Inner zone: field with flutes, streamlined ridges and melt out debris, usually reworking by glaciofluvial processes.

Based on radio-echo soundings and glaciological investigations it is believed that Larsbreen is largely cold-based. Platåbreen is smaller and lying at a higher altitude, therefore it is also believed to be largely cold-based (Lukas et al., 2005). For analytic purpose it is assumed to be valuable to compare the two glaciers with Glasser and Hambery (2006) model for a typical terrestrial Svalbard polythermal glacier even though they are largely cold-based. The different between a cold-based and a polythermal glacier are that polythermal glacier has only the terminus frozen to the ground while the cold-based glacier is total frozen to the ground. The comparison is assumed to be valid because both types have a frozen terminus and thereby nearly the same land-forming processes at the terminus.

**Geological settings**

The bedrock in the study area is sedimentary, mostly shale and some layers of sandstone. The bedrock is soft therefore glaciers, running water and frost shattering easily erode it (Lønne and Lyså, 2005). Weathering of the bedrock and the enclosed debris is dominating along the slopes. There are coal bearing layer and fossil leaves and other plants remains can be found, some places they are common.

The mean annual air temperature is -6° C, measured at the Longyearbyen Airport. The airport is situated 5 km north of Platåbreen, around 25 m altitude, at the foot of Platåbjerget (Lukas et al., 2005).
The front moraine of Larsbreen is starting around 150 m altitude and the clean glacier ice is reach from ca. 250 to 800 m altitude, see figure 1. The outlet valley part of the glacier is only the northern part, from 500 m altitude and down.

At the front of Larsbreen's moraine are rock-glacier, these are laying largely parallel with the frontal moraine. Under the LIA advance Larsbreen has pushed to rock-glaciers (Humlum, 2005).

Platåbreen starts on the northern side of mountain top Nordenskjöldfjellet (1050 m) and follow a broad flat valley down to the plateau at Platåbjerget. The front moraine is lying around 450-600 m altitude.

The valley under Larsbreen is more V-then U-shaped, with indicated less erosion and therefore a cold-based glacier (Lukas et al., 2005).

Most of the glaciers on Svalbard have retreating since the LIA maximum ca. 1890-1900 (Glasser and Hambrey, 2006). This is also the case for Lars- and Platåbreen. The two glacier is believed to be more than 100 years out of climate equilibrium, with mean they still responds on the climate that was around 100 years ago (Lukas et al., 2005).

There is no observation of surging of these glaciers (Lukas et al., 2005).

**Methods**

Mapping of Larsbreen and Platåbreen was carried out in the last half of September 2006. The basic map was a digital redrawing of the topographic map in 1:100,000 from Norwegian Polar Institute (2000). On the basic map, in the scale 1:5000, observations were drawn in the field and later digitalised. In the field a compass was used for orientation and measurements.

Figure 3 and 5 are showing the result of the mapping. There are two sets of contour lines some from Norwegian Polar Institute (2000) (solid lines) and approximated contour lines (dash lines) from field investigations. The contour lines from Norwegian Polar Institute (2000) are assumed to be right, even though the scale is bigger. This means there could be some inaccuracy. The contour lines are for giving the reader a principle picture of the morphology and therefore the inaccuracy is not considering as a problem.

The field data have been compared with aerial photos from Norwegian Polar Institute (1990) and the Geomorphological and Quaternary Geological map of Adventdalen from Tolgensbakk et al. (2000).

**Observations**

**Platåbreen**

The moraines of Platåbreen is mainly a symmetric concave form, apart from a tongue reaching down towards Tverrdalen, see figure 1 and 3. There is a medial moraine consisting of three groups, with a form like drops. The lateral moraines is around 100 m, the frontal moraine is ca. 500 m wide, the distance from the clean glacier ice to the end of the moraine reaching down to Tverrdalen is 800 m. The medial moraine is 500 m long. On the top of the frontal moraine are some long small hills largely following the concave shape of the moraine, see figure 4.

The western lateral moraine is mainly one long hill, when it reach the frontal moraine it splits op in the previous mentioned small hills. Outside the lateral moraine is the weathering bedrock of black shale and water has cut channels into it. These channels are merging with channels running on the lateral moraine. On the glacier-side of the western lateral moraine melt-water channels from the glacier is running. These meltwater channels are meting in one channel before its run over the frontal moraine. It is one of the two large meltwater channels there are parsing through the frontal moraine. The channel is eroded down into the frontal moraine and making steep channel sides. Outside of the
Figure 3. Geomorphology map of Platåbreen. Contour lines with 50 m intervals (solid lines) are from Norwegian Polar Institute (2000).

moraine the channel met with other smaller channels and as one they run toward west over Platåbjerget.

The frontal moraine has a steep front, rising around 30 m higher than the plateau. The frontal moraine is continuously raising upglacier, the first part is flat with small long hills, upglacier the amplitude of the relief getting larger and less continuing hills along the moraine. At the front of the moraine there are streamlines spreading out in different directions. A streamline is here defined as a line formed by running water, but only used periods or maybe not
at all any longer. There are not observed any signs of meltwater channel passing the frontal moraine, only the two main channels.

The moraine tongue towards Tverrdalen has like the rest of the frontal moraine a steep edge and is generally raising up-glacier. There are observed debris-flow several places. North of the moraine streamlines are running parallel with the moraine towards Tverrdalen. The second main meltwater channel has eroded its way through the moraine toward Tverrdalen. A characteristic ridge around 300 m in north direction is seen. The sediments on northern end was weathering black shale, the rest was diamicton like other places on the moraine, some places black shale could be seen locally. South-west of the ridge is another ridge next to the clean glacier ice. The sediments here are black shale.

The eastern lateral moraine is lying on a mountain ridge between the two valleys with Platåbreen and Longyeardalen lying in respectively. Outside the moraine several parallel streamlines is seen, merging in to one channel and running towards Longyeardalen.

West of the medial moraine the glacier surface is dominated of debris.

**Larsbreen**

The moraine of Larsbreen is lying in a confined steep-sided valley. The lateral moraines are mainly 100 m wide, with variation from 50-200 m, see figure 5. The frontal moraine is up to 500 m wide.

The lateral moraines are largely following the slope of valley sides, towards the glacier the slope angel is getting smaller, see figure 5 and 6. On the eastern lateral moraine amplitude of the relief is
Figure 5. Geomorphology map of Larsbreen. Contour lines with 50 m intervals (solid lines) are from Norwegian Polar Institute (2000).

bigger, than the western. Meltwater channels are eroding down into the moraine.

The frontal moraine is highest at the sides and falling in altitude towards the main surface meltwater channels in the middle. At the front of the frontal moraine a meltwater tunnel is seen, see figure 7. Observation of this channel, from late August to total frozen middle October, show that largely all meltwater running through this tunnel. On the surface of the frontal moraine there are observed ice caves and channels leading meltwater into the caves, see figure 7.

On the eastern side of the main surface meltwater channel debris-flow toward the channel is dominating. Along the main surface meltwater channel two meltwater lakes are present. On the western side of the channel hills and some debris-flow is observed. The western margin of the frontal moraine has also debris-flow; in these areas the slope angle of the moraine is larger.
At the eastern margin of the frontal moraine there is a ridge. Toward the main surface meltwater channel there is a gentle slope and towards moraine margin the slope is steeper. The ridge is continuing towards the front of the frontal moraine. On the outside of this ridge are rock glaciers. There is a clear shift in sediments between the moraine and the rock glaciers, see figure 6. The moraine is consisting of diamicton from clay to clasts, where the surface of the rock glacier is only clasts. Talus cones are present along the eastern valley side. The sediment on the talus cones and the rock glaciers is the same type.

**Discussion**

*Debris-covered glaciers*

Classification of Larsbreen and Platåbreen as debris-covered glacier, like Lukas et al. (2006) points out, are important for understanding the two glaciers moraines. Lønne (2006) is also making it clear that the moraine at Platåbreen is not cored with dead-ice. This means that the active glacier...
ice, not dead-ice, is under the moraines largely all the way to the front of the moraines.

With this understanding model of the moraines it is possible to explain why this glacier is not following the model for Svalbard glaciers and why they are still at the LIA maximum front.

When a debris-covered glacier melts debris from the glacier ice will be released and the thickness of the debris cover will increase. The debris cover is isolating the glacier ice from the air temperature. Increasing debris cover thickness decrease the melt rate logarithmic, see figure 8.

**Figure 8.** Relationship between debris thickness and ablation rate measured at Larsbreen from July 9 to 20, 2002, with a logarithmic line of best fit (Lukas et al., 2005, Fig 12).

In this way the melt rate decreases to near zero and preventing the glacier terminus of retreating. The retreating of debris-covered glacier is instead thinning of the glacier (Benn et al., 2006). From aerial photos, where the oldest was from 1936, Lønne and Lyså (2005) conclude about Platåbreen: “There have been no apparent changes in the structures of the glacier ice and moraines since 1936... but the glacier surface has lowered by approximately 40 m” (Lønne and Lyså, 2005, Page 302). In the same analysis Lønne and Lyså (2005) claim to identify different ice-fronts while Platåbreen retreat after the LIA. The term ice-front is not precise, it could referred to where the glacier ice-front met dead-ice, but according to the understanding model of Platåbreen being a debris-covered glacier, the glacier ice is underlying the moraine largely out to the front of the moraine, and therefore the identified ice-front is the border between clean glacier ice and debris-covered glacier ice (Lukas et al., 2006). A more precise term will be the front of the clean ice.

During negative net balance of a debris-covered glacier the front of the clean ice could move upglacier. The clean ice has unlike the debris-covered part of the glacier no isolation against the warm summer air temperature, and therefore ablation of the clean ice will be larger than the debris-covered ice. When the clean ice melts it releases debris, debris is accumulated on the surface and resulting in a debris cover. While this process goes on the clean ice front moves. The amount of lowering of the surface during this process is depending of the concentration of debris in the glacier ice. According to figure 8 lowering of the surface are inconsiderable on Larsbreen when the debris-cover is over 0.6 m.

Compared to the “Landsystem model for a typical terrestrial Svalbard polythermal glacier” from Glasser and Hambrey (2006) there is a difference in the geomorphology. Where the landsystem model divide the glacier forefield into outer moraine ridges, morine-mound complexes and the inner zone (figure 2), Larsbreen and Platåbreen has a steep front and a largely continuous slope upwards to the clean glacier ice (figure 3 and 5). This morphology can be interpreted as; the steep front is similar to the “outer moraine ridge”, but upglacier it is continuing into
“moraine-mound complex”. Unlike the landsystem model Larsbreen’s and Platåbreen’s moraine-mound complex is ice-cored with glacier ice. The “inner zone” is not exciting because the glacier ice continues under the moraine-mound complex.

In the landsystem model glacier ice from the outer moraine ridge to the present glacier terminus is melted or left as dead-ice. On Larsbreen and Platåbreen debris cover are preventing the glacier ice for melting.

In the text of Glasser and Hambrey (2006) where the landsystem model is presented it is not clear which glacier it is building on. In the text there are mention glacier from twelve locations, see figure 9. If the model is made on the base of these glaciers there can be a problem with the representation. Only one of the twelve locations are in tertiary bed rock, see figure 9. Other glaciers are located in harder bed rock, e.g. tree in the metamorphic Hecla Hoek. A harder basement could release debris slower than the softer rock thereby leaving less sediment to build up a debris cover. The consequent of this is debris-covered glacier are not the typical Svalbard glacier or the model is based on non representative glacier.

Glaciofluvial processes

The areas on the moraines where the biggest amplitude in the relief is observed are in association with meltwater channels. On Larsbreen this is along the main surface meltwater channel in the middle of the frontal moraine, see figure 5. Platåbreen has two main meltwater channels one in each side of the frontal moraine, see figure 3. Especially on Larsbreen debris-flow is concentrated down towards the main channel.

In areas between two near channels are usually a ridge. This is seen at the eastern lateral moraine of Larsbreen, western side of Larsbreen frontal moraine and along the western lateral moraine of Platåbreen. These slopes are often steep towards the channels, suggesting that the debris is transported to the channels. This will be the main transport of sediments away from the glacier forefield.

Rock-glaciers at Larsbreen on the eastern side and weathering material on the bedrock on the western side allow water, and thereby sediments, to escape only through the middle northern channel outlet, on the surface or through the tunnel, of the frontal moraine.

Platåbreen has today two patches for transporting water to lower laying area, one east in Tverrdalen to Longyear valley and one over the Platåbjærg to Bjørndalen west of Platåbjærg. Lønne and Lyså (2005) has identified two more, one way north over Platåbjærg down to Adventfjorden and one over the eastern lateral moraine toward Longyear valley. They suggest that the way north only has been active when the way east in Tverrdalen is blocked and the other has been active when the glacier was thicker. Today there is a well developed channel system outside the eastern lateral moraine.

Lønne and Lyså (2005) suggest that there has been an englacial water way through the moraine. They documented this with mapping of a dead alluvial fan, this is seen on figure 3 as stream line in different direction middle north of the frontal moraine. With the leak of channel on the surface they conclude it to be englacial water way. Lukas et al. (2006) means this is just an erosional feature and not a build up fan.

Larsbreen is lying in a confined steep-sided valley and by comparing the horizontal shape of it’s moraine with the shape of the valley it looks like the valley shape dictating the shape of the moraine. The glacier has during the LIA pushed the rock-glacier at the front (Humlum, 2005). This means that the rock-glacier has

preventing the glacier of reacting farther down the valley. As mention earlier the morphology at front of the frontal moraine provide only one way for meltwater to leave the moraine. Together all these factors force the meltwater to run through the middle of the frontal moraine; only one outlet all other ways is uphill.

The meltwater in the channel will cut down in to the moraine; debris in the sides will be undermined and start to flow toward the channel. In the channel the debris will be transported away with the water only leaving the biggest blocks. When debris flow down of a slope it can leave some of the ice core exposed. The exposed ice will start to melt until it again is covered with debris. At Larsbreen these processes dominate the moraine. Debris from the sides is transported by sliding and
in streams towards the main channel in the middle, and with the channel down of the moraine.

The area affected by channels and running water is smaller on Platåbreen than Larsbreen. On Larsbreen the slope gradient towards the main channel is larger; therefore a flow of debris will affect a bigger area. The middle part of Platåbreen’s frontal moraine is largely flat lying, meltwater from the glacier flow in the main channel and does not affect this area. The debris cover prevents the ice core from melting. The only water running in this area is yearly rain and meltwater from seasonal snow cover falling inside the area. Therefore there is a small amount of water to transport sediments away from this area, compare to the main channels. On Larsbreen there is only smaller local area there only drain water falling inside the area and which does not has a meltwater channel near it.

On Larsbreen most of the moraine is sloping, mainly toward the main channel in the middle. At Platåbreen the flat frontal moraine does not have a main slope toward any channel. Transport due to gravity is therefore smaller on Platåbreen than Larsbreen. Further more the gravity forces are not in the same degree working together on Platåbreen’s moraine as on Larsbreen’s moraine.

**Preservation potential**

The combination of cold climate and debris-cover is preventing the frontal glacier ice from melting. The glaciers has been retreating since the LIA, this means the melt rate is higher than the snow accumulation rate. If the temperature continuing to raise the melt rate will be larger and the warmer air temperature will affect ice deeper in the debris-cover. This process will continuing until all ice is gone.

The melting process is slowing down on Platå- and Larsbreen, because they contain large amount of debris. When the glacier melt it release debris, the debris cover getting thicker and thereby isolate more. In addition the ice under the debris are active glacier ice, this means ice continuing to flow towards the front, and therefore more ice has to be melted. In this way the ice-cored moraine will last for longer than a dead-ice ice-cored moraine.

By thinking the deglaciation to the end and how the glaciofluvial process will affect the sediments under the deglaciation, the preservation potential for the moraine of the two glaciers can be estimated.

At Larsbreen water running down the sides of the valley and gravity because the steep sides will work together to transport sediments to valley floor, where they will be reworked by a steam. The stream will transport the sediments out to the Longyear River and with the river to the fjordsystem. Along the valley sides new rock-fall will be mixed with the previous moraine debris and with time only traces of rock-fall is left.

At Platåbreen the main channels may continuing to cut down into moraine and further into the bedrock. In this way the water continue to prefer to flow along the channel and maybe not shifting direction. The flat frontal moraine may therefore not be affected by the runoff of water. In addition the underlying surface is nearly flat, meaning that gravity transport has a low influence or a stabilization effect. These to factor together means the debris from the flat frontal moraine has a high preservation potential and may be found as thick debris-cover on the ground. The lateral moraines at Platåbreen may undergo the same processes as Larsbreen’s moraine.

**Conclusion**

Results of mapping the moraines at Larsbreen and Platåbreen have been presented and compared with other studies of these glaciers and a model for a typical
terrestrial Svalbard polythermal glacier. Larsbreen and Platåbreen are different than the typical Svalbard model, which is caused by the presence of a debris cover. The debris-cover reduces the melt rate and thereby active glacier ice coring the moraines all the way to the front of the moraine. This allows the glacier still to be at the LIA maximum. Retreat of the glacier is manifested by thinning of the glacier instead. By melting debris accumulating on the glacier surface and thereby the front of the clean glacier ice moves upglacier.

Glaciofluvial processes are transporting sediments away from the moraines. Nearest these meltwater channels wasting of the moraines are larges, do to the channels cut down into the moraine, removing of sediments and contributory factor for generating debris-flow. The steep sides of the valley Larsbreen is lying in and thinning of the glacier are causes for a sloping of the moraine toward the middle. The slope of the moraine means the gravity flow and transport with water are working in the same direction. At Platåbreen some areas of the moraine are nearly horizontal and thereby preventing gravity flow. Further more there are now channels observed in these areas, telling that only a small amount of water are running here.

By thinking the deglaciation to the end it is estimated that debris on the flat laying frontal moraine of Platåbreen has a high preservation potential, because the less running water and gravity flow. In contrast moraine lying on steep valley sides, like the moraine of Larsbreen, has a low potential of preservation due to gravity and water working together, transporting the sediments to streams for further transport out of the system.

Reference


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