RESEARCH ARTICLE

Geometry and vertical extent of the late Weichselian ice sheet in northwestern Oppland County, Norway

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The position of the ice margin during the last deglaciation is well known in Scandinavia, in particular during the Younger Dryas (YD) chronozone from when large ice marginal deposits easily can be traced at or close to the Norwegian coast. However, inland of the YD marginal deposits, the vertical extent and geometry of the Scandinavian ice sheet is still debated. In this study we have used detailed Quaternary geological mapping to reconstruct the ice sheet surface and slope in core areas around the valleys of Gudbrandsdalen, Romsdalen, Eikesdalen/Litledalen and around lake Aursjøen. In these areas we typically find morphologically distinct lateral moraines at 1300–1500 m a.s.l., which slope down towards the coast and seem to correlate with two known YD stages. By using slope and spatial pattern of the lateral moraines we infer a maximum elevation of the YD ice sheet in central areas around Dombås to be at around 2000 m a.s.l., and mostly lower at 1800 m.a.sl. during significant portions of the YD chronozone. Most inland areas in Norway were thus ice covered during YD, except for high peaks in for example Dovre, Rondane and Jotunheimen, which acted as accumulation area nunataks. Our data also show that the first order ice divide during this stage was situated over Jotunheimen from where significant ice streams emanated and were flowing down into the major valleys and out towards the coast. We stress that this study is preliminary, lacking absolute dates of the lateral moraine zones, but the spatial pattern is very consistent and correlates well with known glacial stages. A dating campaign is underway to elucidate the precise timing of these glacial events, but the picture emerging from this work shows the importance of careful Quaternary geological mapping to understand past ice-sheet configurations.

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Introduction

The geometry and vertical extent of the Upper (late) Weichselian Scandinavian ice sheet has been debated and different models have been proposed (e.g., Vorren 1977, Andersen, 1981, 2000, Bergersen and Garnes 1983, Boulton et al. 1985, Nesje et al. 1988, Dahl et al. 1997, Andersen et al. 1995). The different models can be grouped in two classes: the 'thick-ice models' and the 'thin-ice models'—see for example discussions in Dahl et al. (1997), Kleman and Hättestrand (1999), Mangerud (2004) and Paus et al. (2006). These models contrast in the reconstructions of the ice thickness in central Norway. In the maximum models it is suggested that a massive central ice dome existed and covered the landscape completely in central Norway during the late Weichselian glaciation (Andersen et al. 1995, Andersen 2000, Mangerud 2004). The thickness of the ice is considered to have been several thousand metres, and much of the terrain was probably ice covered. In contrast, the minimum glaciations model suggests thinner ice, several local ice domes, and nunataks in core areas (e.g., Nesje et al. 1988) with an ice surface as low as 1100 m a.s.l. in the interior areas of Norway at an early late-glacial interval (Dahl et al. 1997, Paus et al. 2006). In this case, large mountain areas in central Norway and in the Østerdalen valley and Gudbrandsdalen valley are thought to be almost ice free in the late Weichselian.

Based on the data collected through the Quaternary mapping program of the Geological Survey of Norway, the exact vertical extent of a Younger Dryas (YD) glacier surface is established based on the distribution of ice marginal moraines and meltwater channels. This ice surface will be discussed in relation to the existing models for the vertical extent of the late Weichselian Scandinavian ice sheet in central Norway.

General physiographic setting

The investigated area is located in the northwestern part of Oppland County and in the eastern part of Møre and Romsdal County (Figure 1) and is dominated by a landmass reaching 1200–2000 m a.s.l. Tectonic uplift during the Neogene (Ebbing and Olesen 2005) successively heaved the distinct upland plateaus, and the valley of Gudbrandsdalen and tributary valleys were formed by river incision prior to the Quaternary glaciation, as described by Bonow et al. (2003). Through the Quaternary, glaciers inundated this area several times. Glacial landforms such as cirques, glacial valleys, lakes on the plateaus, and the fjord basins with marked thresholds were formed. Today these features dominate the scenery in the western parts of the areas.

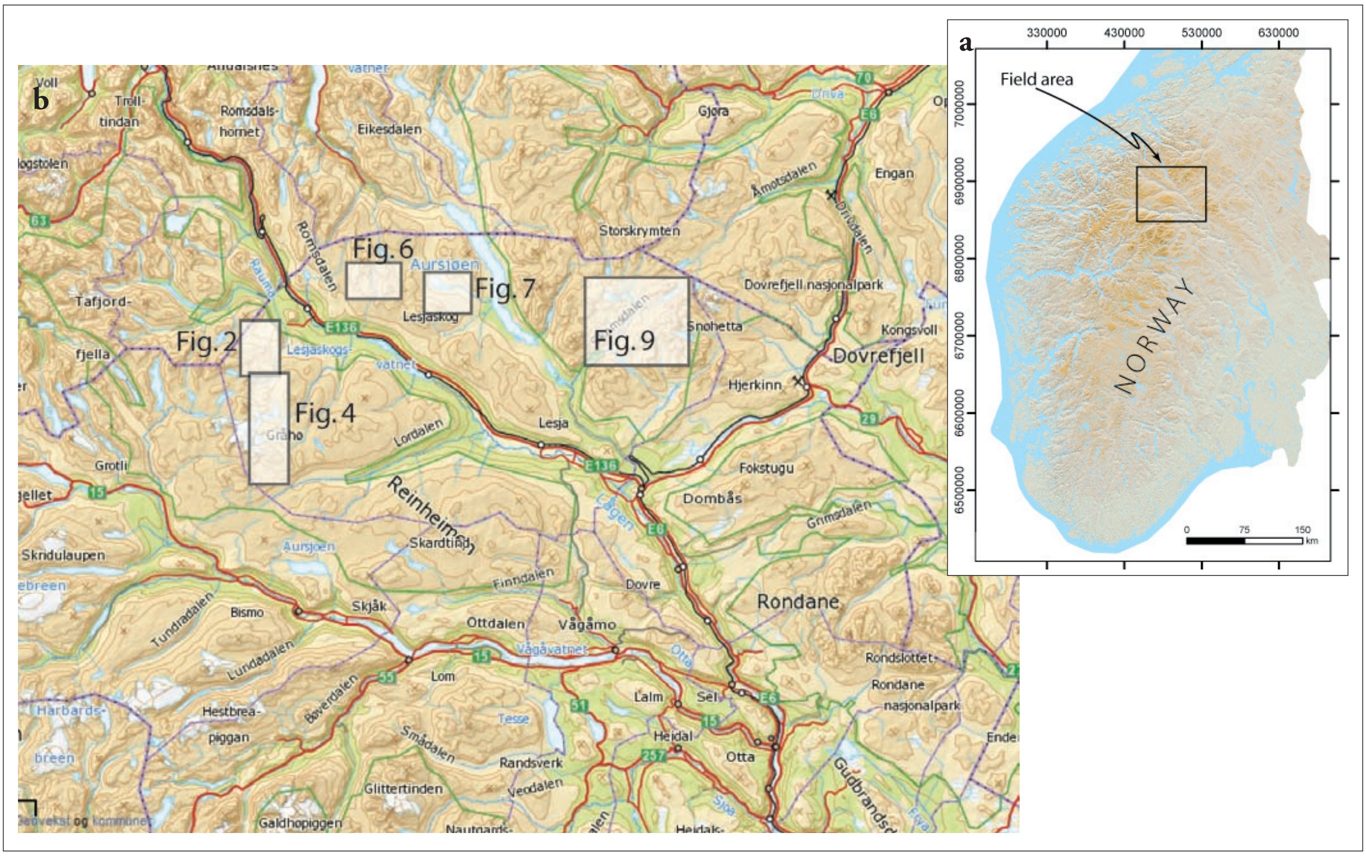


Figure 1. (a) Field area in central Norway. Coordinates are given in UTM 32N. (b) Orientation of key maps used in the description.

Reconstructing former ice extent based on ice marginal deposits

Ice marginal moraines (frontal and lateral moraines) are very diagnostic glacial landforms and directly reflect an ice marginal position (Benn and Evans 1998). In addition, since ice marginal moraines usually are formed and preserved during a glacial advance and retreat, they commonly reflect a significant climatic event. For example, global ice maximums and YD positions have been defined through mapping of ice marginal moraines (Mangerud 2004).

Undås (1963) made an attempt to establish the westward limit for the YD readvances in Western Norway based on the distribution pattern of terminal and lateral moraines. Since then, several authors have used glacial landforms such as lateral and end moraines for reconstructing the glacial chronology in Western Norway (e.g., Andersen 1954, 1960, Anundsen 1972, Follestad 1972, Vorren 1973, Fareth 1987). In the counties of Møre and Romsdal and Sør-Trøndelag similar reconstructions of the ice margin based on ice marginal deposits have been carried out by Sollid and Kristiansen (1984), Reite (1990, 1994), Follestad (1994), Follestad et al. (1994) and Mangerud et al. (in press).

Marginal moraines

Around the Romsdalen valley, well defined lateral moraines are shown in maps and are briefly described by Sollid and Kristiansen (1984). These marginal moraines in the communities of Lesja, Nesset and Sunndal further to the northeast and east, indicate a continuation of a more or less simultaneous glacier surface (Follestad 1987, 1994) in the areas of Gudbrandsdalen, Rondane and Skrymtheimen. Recent data compiled through the Geological Survey of Norway mapping program (Follestad 2006, 2008, 2010) suggest that we can divide these ice marginal deposits into upper and lower systems, which reflect two ice surfaces in the northwestern parts of Oppland County and the southeastern parts of Møre and Romsdal County, respectively. In the following some key localities will be described (Figure 1b).

Ice marginal deposits supporting an upper marginal zone in the eastern parts of the Romsdalen/Gudbrandsdalen valley

Grønhøi–Skarvehøi mountain (Figure 2)

In the area of the Grønhøi mountain (1462 m a.s.l.) a marked ice marginal zone is seen. The zone consists of several distinct lateral moraines, of which the distal moraine ridge reaches some 1380 m a.s.l. From this altitude the distal moraine ridge falls southwestward along the western side of the mountain into the valley west of the Rånåfly area. Here, the ice marginal zone is correlated with four distinct end moraines that run across the

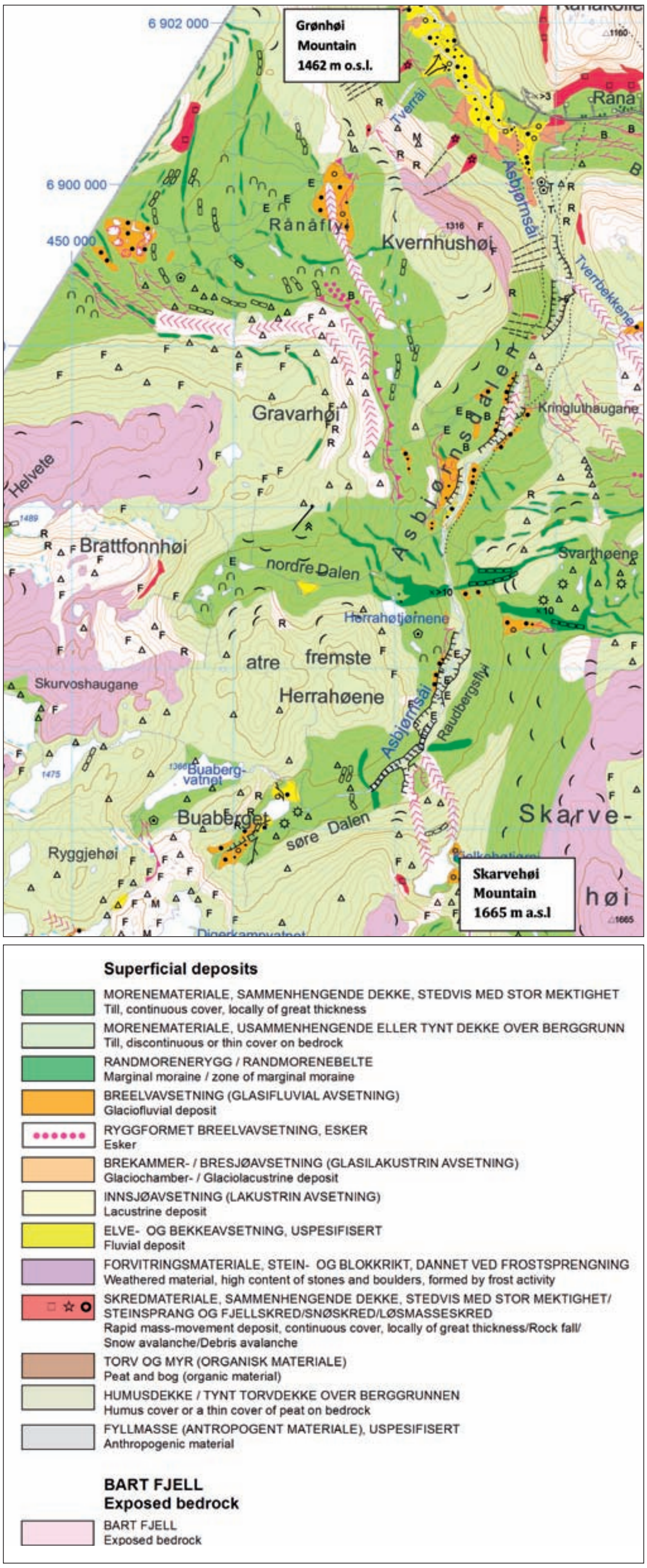


Figure 2. Lateral moraines shown in dark green are seen from the Grønhøi mountain (1462 m a.s.l.) in the northwest to the Skarvehøi mountain (1665 m a.s.l.) in the southeast. The figure is copied from the Lesja Community Map, M 1:80,000 (Follestad 2010). For use of colour and signs, see the map legend for Quaternary maps (Follestad 2010).

valley floor. The valley floor is situated at about 1200 m a.s.l.

As the horizontal distance for the distal moraines from the valley bottom to the top of the Grønhøi mountain is 1.3 km, this implies a surface gradient for the lateral moraine of about 150 m km^{-1}.

To the southeast the moraine zone continues along the northern flank of Gravarhøi mountain (1473 m a.s.l.). The distal moraine is 5–10 m high and consists of a diamicton with some blocks at the surface. Juxtaposed to the lateral moraine is a system of glacial meltwater channels (Figure 2). Since the meltwater channels exhibit the same gradient as the lateral moraine, we suggest that they were formed synchronously. These channels point towards the northwest and it seems probable that they represent the continuation of a large glacial drainage system, which has washed the rock surfaces along the northern and western slope of the Gravarhøi mountain a few metres below the uppermost distal lateral moraine. Further southeastward and into the Nordre-Dalen valley a set of lateral moraines shows the continuation of the same moraine zone. The distal moraine reaches an altitude of 1400 m a.s.l. on the eastern flank of Gravarhøi mountain, and falls thereafter into the valley of Asbjørnsdalen. The valley floor in the Asbjørnsdalen valley is situated at about 1200 m a.s.l. Since the horizontal distance for the distal moraines from the valley bottom to the top along the hillside of Gravarhøi mountain is 1.7 km, this gives a surface gradient for the distal lateral moraines of 130 m km^{-1}. In addition, from the Asbjørnsdalen valley to the Rånåfly area a marked erosion terrace, 5–20 m wide, was formed sub-/semi-laterally to the inland ice along the Gravarhøi mountain (Figure 3). This terrace shows that meltwater most probably followed the present course of the Asbjørnsåi river to the north, then turned northward and drained through the Rånåfly area during the deglaciation. Some 20 m below the erosion terrace, a marked area of washed bedrock is seen in the runoff pass between the Asbjørnsdalen valley and Rånåfly area. This feature, which can be followed northward for 1 km, cuts through the proximal lateral moraine. Thus the northward-draining meltwater channels from the Asbjørnsdalen valley show that a glacier surface higher than the hydrographic threshold existed in this valley, at the same time as when the ice already had disappeared in the westen parts of the Rånåfly area. Later, the glaciofluvial meltwater drainage turned eastward through the Asbjørnsdalen valley and ended in the distinct glaciofluvial deposit in the Asbjørnsdalen valley.

Furthermore in the Asbjørnsdalen valley, three 10–30 m-high lateral moraines (Figure 4) indicate the continuation of the ice margin to the east and south along the Skarvehøi mountain, which reaches altitudes of 1579 m a.s.l. and 1665 m a.s.l. in the northern and southern parts, respectively. The two well defined moraine ridges further south in the Søre-Dalen valley (the continuation of the Asbjørnsdalen valley to the southwest), are considered to have formed prior to the formation of the ice marginal zone.

A well developed ice marginal terrace situated 1300 m a.s.l. was formed between the distal lateral moraine and the northern mountain side of Skarvehøi from meltwater which followed the meltwater channel distally of the moraine ridge. An obvious glaciofluvial deposit is situated at the same altitude in Søre-Dalen valley (the upper parts of the Asbjørnsdalen valley), which indicates that a ice-dammed lake was formed here during the formation of the moraine zone.

Skarvehøi mountain–Løyfthøene mountain

A well defined ice marginal zone consisting of lateral moraines is seen in the areas north and east of the Skarvehøi mountain (Figure 5). The distal lateral moraine is 3–10 m high and consists of coarse diamicton with blocks at the surface. This moraine can be followed continuously from 1400 m a.s.l. in the north to 1540 m a.s.l. south of Skarvehøbotn (1462 m a.s.l.).

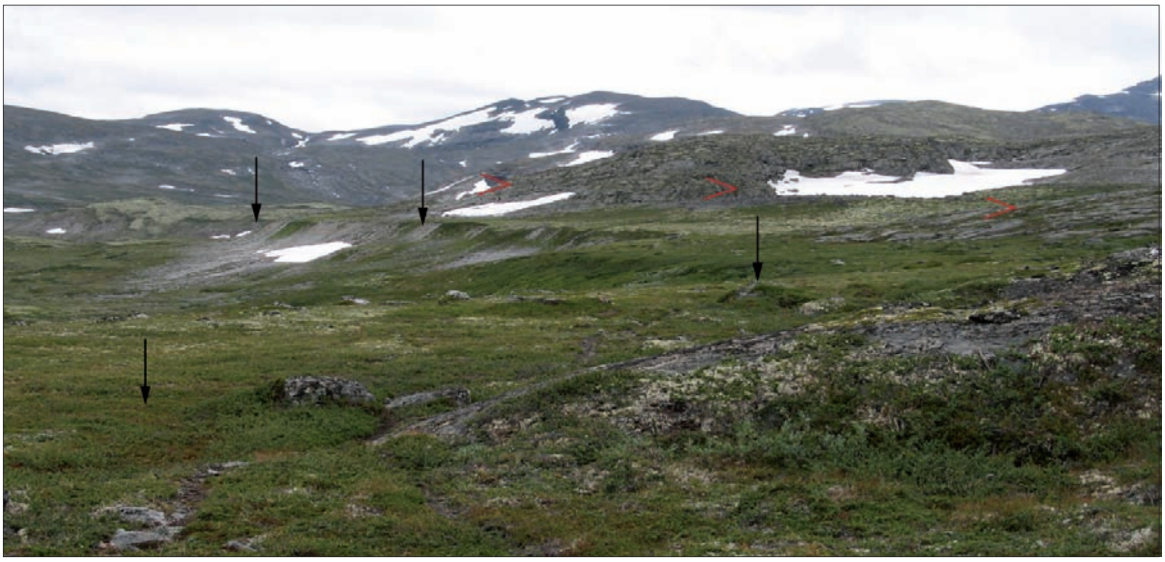


Figure 3. A marked erosion terrace is seen along the lower part of the Gravarhøi mountain. The front of the terrace is indicated by the black arrows. The proximal rock surface is washed and eroded by meltwater. The altitude of the terrace is determined by the rock threshold in the front of the photo. The photo is taken from the threshold in the northern part, looking southward.

Figure 4. Marked lateral moraines at the ice marginal zone east of Herrahøtjørnene lakes. The ridges are up to 30 m high. The photo is taken from the lateral moraine east of Herrahøtjørnene, looking west.

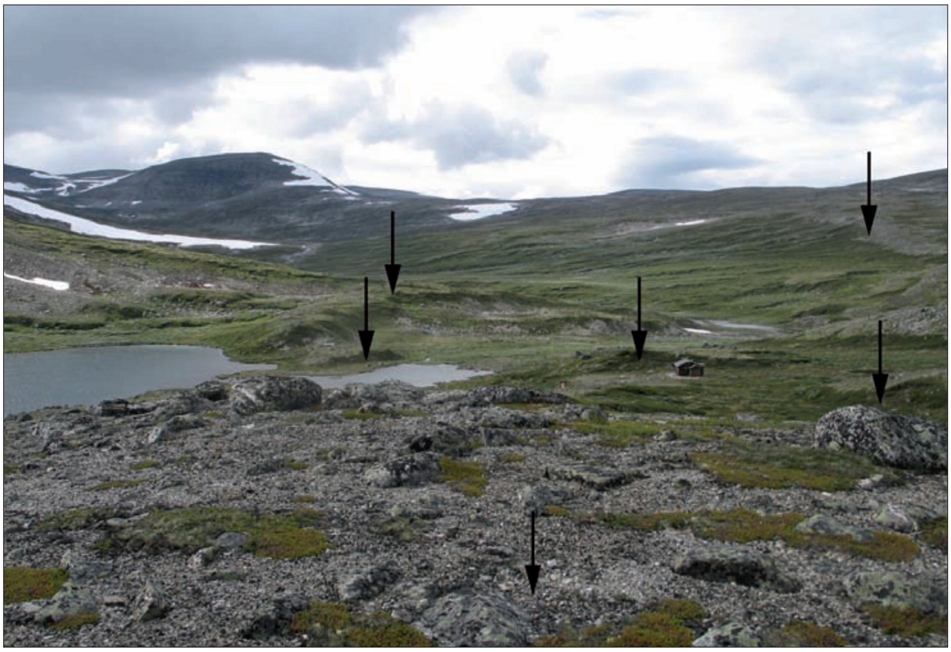


Figure 5. Lateral moraines shown in dark green as seen from the Skarvehøi mountain (1665 m a.s.l.) in the north to the Løyfthøene mountain (1579 m a.s.l.) in the south. The figure is copied from the Lesja Community Map, M 1:80,000 (Follestad 2010). The grid net is based on the M711 map series with a grid cell size of 1 km x 1 km. For use of colour and signs, see the map legend for Quaternary maps (Follestad 2010).

Since the horizontal distance is 5 km and the altitude difference is 140 m, this gives a slope gradient of 28 m km^{-1} for the distal moraine. The meltwater channels northeast of Skarvehøi mountain formed simultaneously with the moraine zone, but somewhat later than the distal moraine. It should also be noted that the moraine zone here is formed only a few metres below the allochthonous block fields seen in the Skarvehøi areas and marked with violet colour in the Quaternary maps.

To the southwest of Skarvehøi mountain the continuation of the glacier margin is again shown by a continuous moraine zone. This consists of 2–3 marked lateral moraines which fall into the areas of the Kolvatnet lake and the Kjelkehøtjønne lake (1397 m a.s.l.). The altitude of the distal moraines is at 1580 m a.s.l. at the southern valley side of Skarvehøi mountain and 1400 m a.s.l. in the area of Kjelkehøtjønne lake. In all this implies a slope gradient of 72 m km^{-1}.

At the northern side of Kjelkehøtjønne lake, there are two areas with significant glaciofluvial washing and scouring. These features can be followed continuously to the base of Søre-Dalen valley to the north. This indicates that water runoff continued in this direction for some times after the breakup of the suggested ice-dammed lake.

From the Kjelkehøtjønne lake (1397 m a.s.l.) a distinct lateral moraine follows the eastern side of the Kjelkehøi mountain (1692 m a.s.l.) and points at a continuation of the ice margin into the Istjørni lake (1514 m a.s.l.) areas. Since

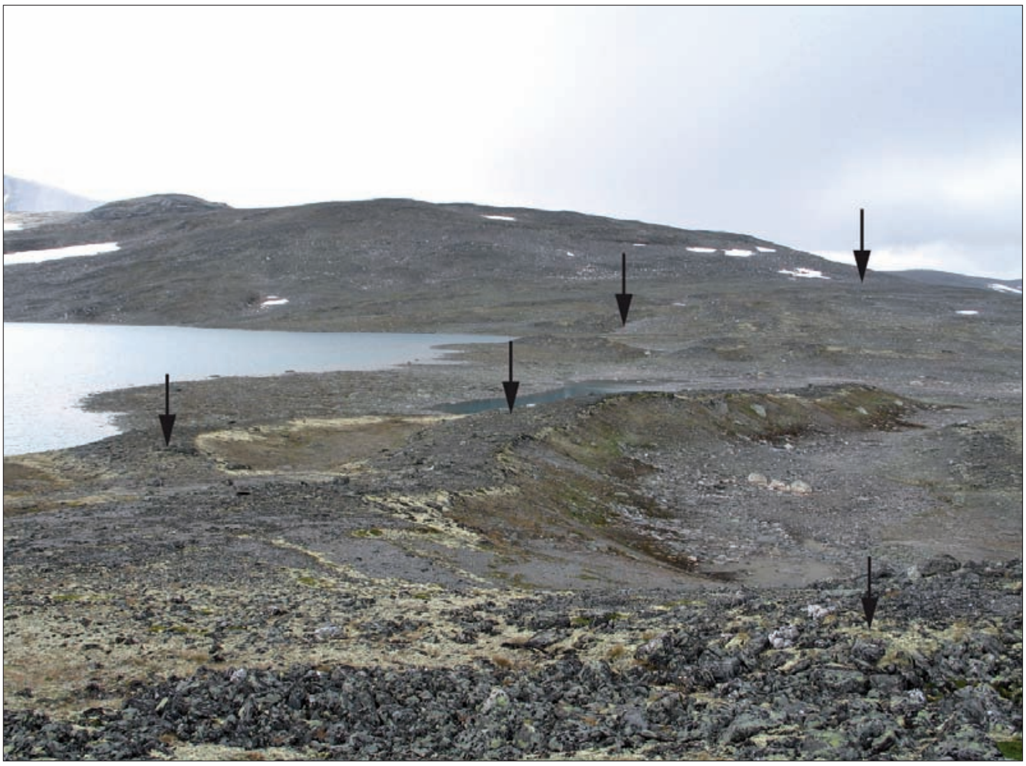


Figure 6. Marked lateral moraines are seen in the rand zone east of the Istjørni lake. The ridges can here be up to 20 m high. The photo is taken from the lateral moraine east of Istjørni lake, looking northwest.

the distal moraine reaches an altitude of 1580 m a.s.l. and the vertical altitude is 66 m over a horizontal distance of 1 km, this gives a surface gradient of 66 m km^{-1}. In the Istjørni lake area the distal moraine is very distinct and 5–10 m high (Figure 6).

Further on, from the Istjørni lake area, an obvious lateral moraine can be followed along the eastern flank of the Holhøe mountain (1806 m a.s.l.). At this site, the distal lateral moraine reaches an altitude of 1580 m a.s.l. before falling southward

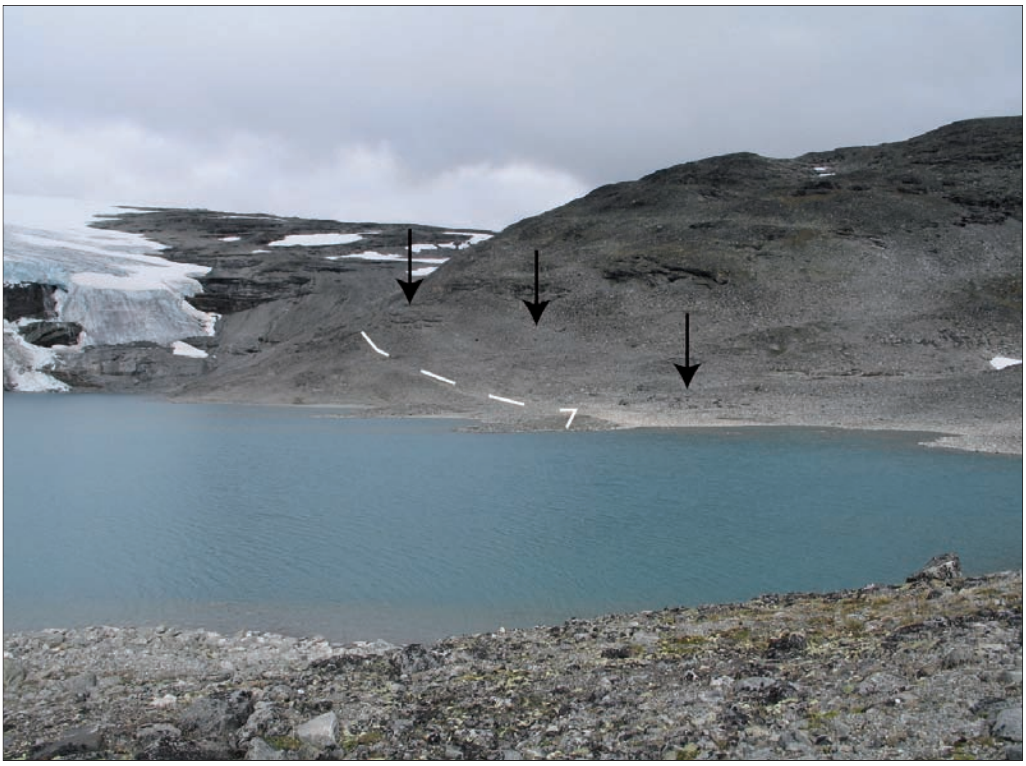


Figure 7. Two lateral moraines are seen in the front of the glacier outlet in the Dordihol area, here marked with arrows and a white dashed line. Photo is taken from the distal moraine, looking westward.

into the area east of "unnamed lake" (1513 m a.s.l.) in the Dordiholet area. The vertical distance between these localities is 67 m and the horizontal distance some 1.5 km, which gives a slope gradient of 42 m km^{-1} for the distal lateral moraine ridge. Further to the south a lateral moraine can be followed along the northern side of Løyfthøiene mountain (1921 m a.s.l.) up to an altitude of 1610 m a.s.l. Here, further evidence for a moraine zone is missing. However, the marginal moraines shown in the areas southwest of Storbreen glacier and in the Storvatn lake (1495 m a.s.l.) might represent a continuation of the marginal system in a westward direction (Sollid and Kristiansen 1984).

Also in the areas of Istjørni and Dordiholet lakes, fresh-looking lateral moraines are observed. Around the Dordiholet lake (Figure 7) two terminal moraines are seen, which indicates that the Storbreen glacier has reached further east than the present extent. However, since there are no signs that outlet glaciers from the area occupied by the present Storbreen glacier reached into the described moraine zone, these 'fresh-looking' lateral moraines are considered to be young and representative for the Little Ice Age readvance around AD 1750 or later.

Summary and conclusions

From the above descriptions we document an ice marginal zone consisting of well defined lateral moraines in the alpine areas of Grønhøi–Skarvehøi–Løyfthøene along the southern valley side of Romsdalen and Gudbrandsdalen valleys. Furthermore, it is documented that the glacier branches shown by the distal lateral moraines in the valley west of Rånåfly, in the valley of Nordre-Dalen and in areas east of Kjelkehøene mountain and in the basin of the Istjørni lake, have steep slope gradients (with a range from 150 m km^{-1} to 40 m km^{-1}) which are characteristic of advancing glaciers. Within the ice marginal zones, marked meltwater landforms are seen in the westerly areas. The distal lateral moraines in the areas of the Skarvehøi mountain reach an altitude of 1540 m a.s.l., which is only some tens of metres below the mountain areas dominated by allochthonous block fields. Since this type of superficial deposit is considered to have survived under cold-based glacier ice (e.g., Kleman and Hättestrand 1999, Stroeven et al. 2002), it is suggested that the transition from cold-based ice to warm-based ice was at about 1550 m a.s.l. Thus the temperature regime at that time is thought to have been closer to a sub-arctic climate than an arctic climate.

Ice marginal deposits supporting an upper marginal zone north of the Romsdalen/Gudbrandsdalen valley

The Svarthøi mountain–Storhøi mountain (Figure 8)

In the mountain areas northeast of the Romsdalen/Gudbrandsdalen valley an ice marginal zone consisting of distinct lateral moraines (Figure 8) can be found in the areas south of the Svarthøi mountain. The lateral moraines follow the southern flanks of the mountains nearly continuously from the

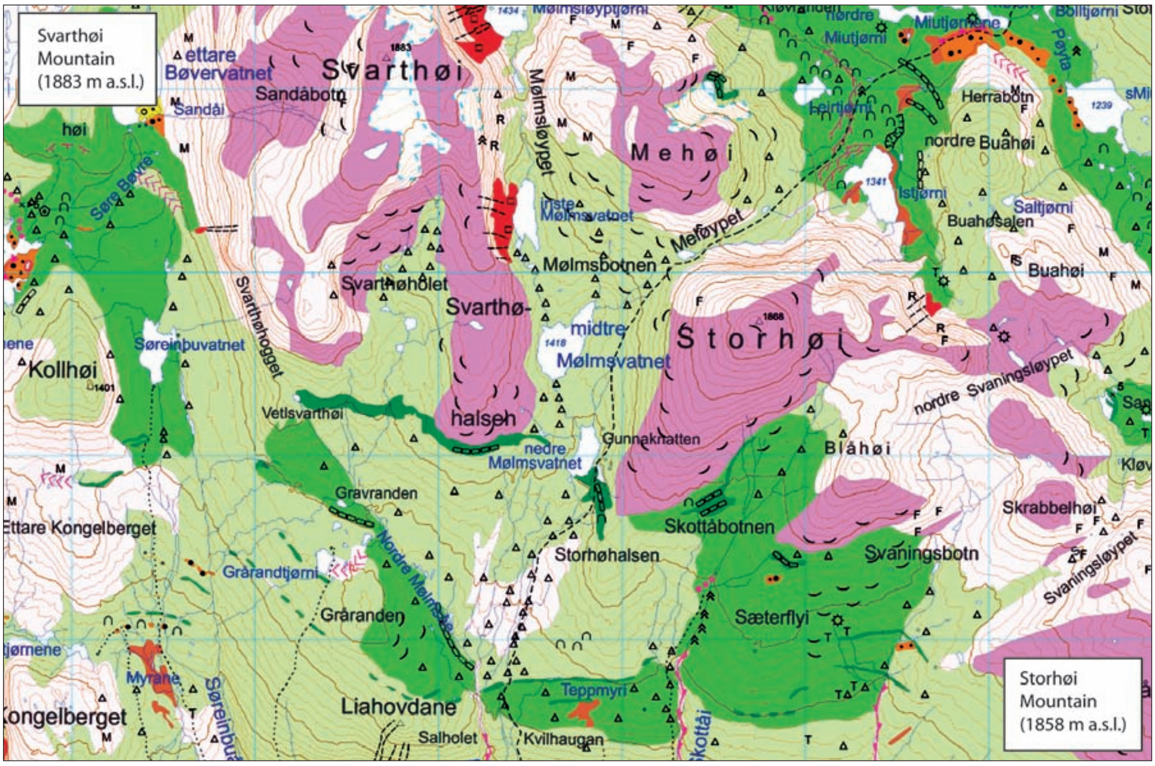


Figure 8. Lateral moraines shown in dark green as seen from the Svarthøi mountain (1883 m a.s.l.) in the northwest to the Storhøi mountain (1858 m a.s.l.) in the east. The figure is copied from the Lesja Community Map, M 1:80,000 (Follestad 2010). The grid net is based on the M711 map series with a grid cell size of 1 km x 1 km. For use of colour and signs, see the map legend for Quaternary maps (Follestad 2010).

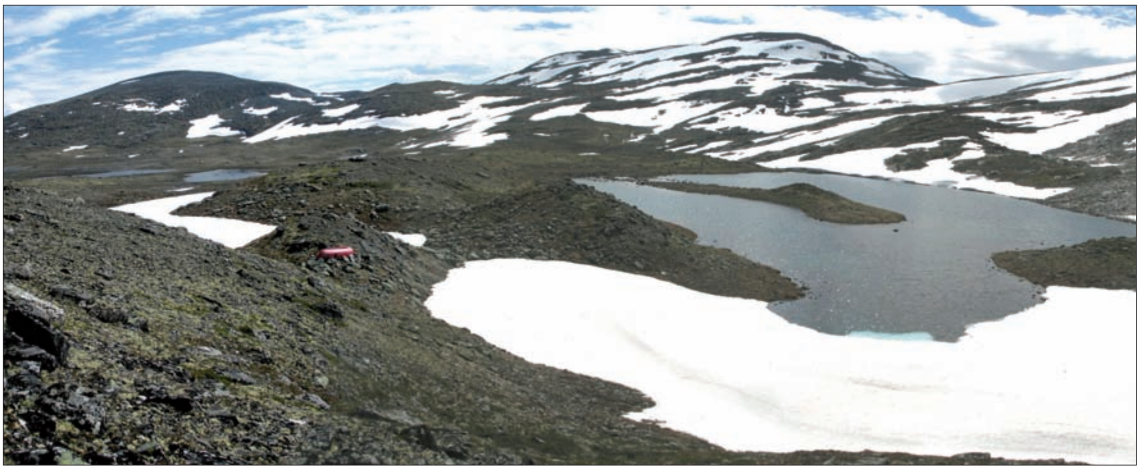


Figure 9. Two distinct end moraines were formed in the western parts of the Sandåflatene area, here damming a small lake. The distal moraine is up to 15 m high (cf., the red rowboat, which is 3 m long). The proximal ridge seen in the lake is 3–5 m high. The forms of the moraines indicate that they were deposited along a glacier outlet entering the areas from the west. Photo is taken from the distal moraine towards south.

Svarthøi mountain to the Svarthøhalsen mountain and further to the east. The distal moraine is 2–4 m high and consists of gravelly to sandy till with blocks and boulders at the surface. Distally to the moraine ridges some minor lateral meltwater channels can be seen. The most prominent features are seen in the areas south and west of the Bøvervatnet lake where washed rock surfaces together with some glaciofluvial deposits indicate a westward run-off direction. However, the number of lateral meltwater channels is low compared to the number of meltwater channels seen in the areas of Asbjørnsdalen valley (Figure 2).

In the areas south of Svarthøi mountain the distal moraine is situated at 1420 m a.s.l. In an eastward direction the altitude

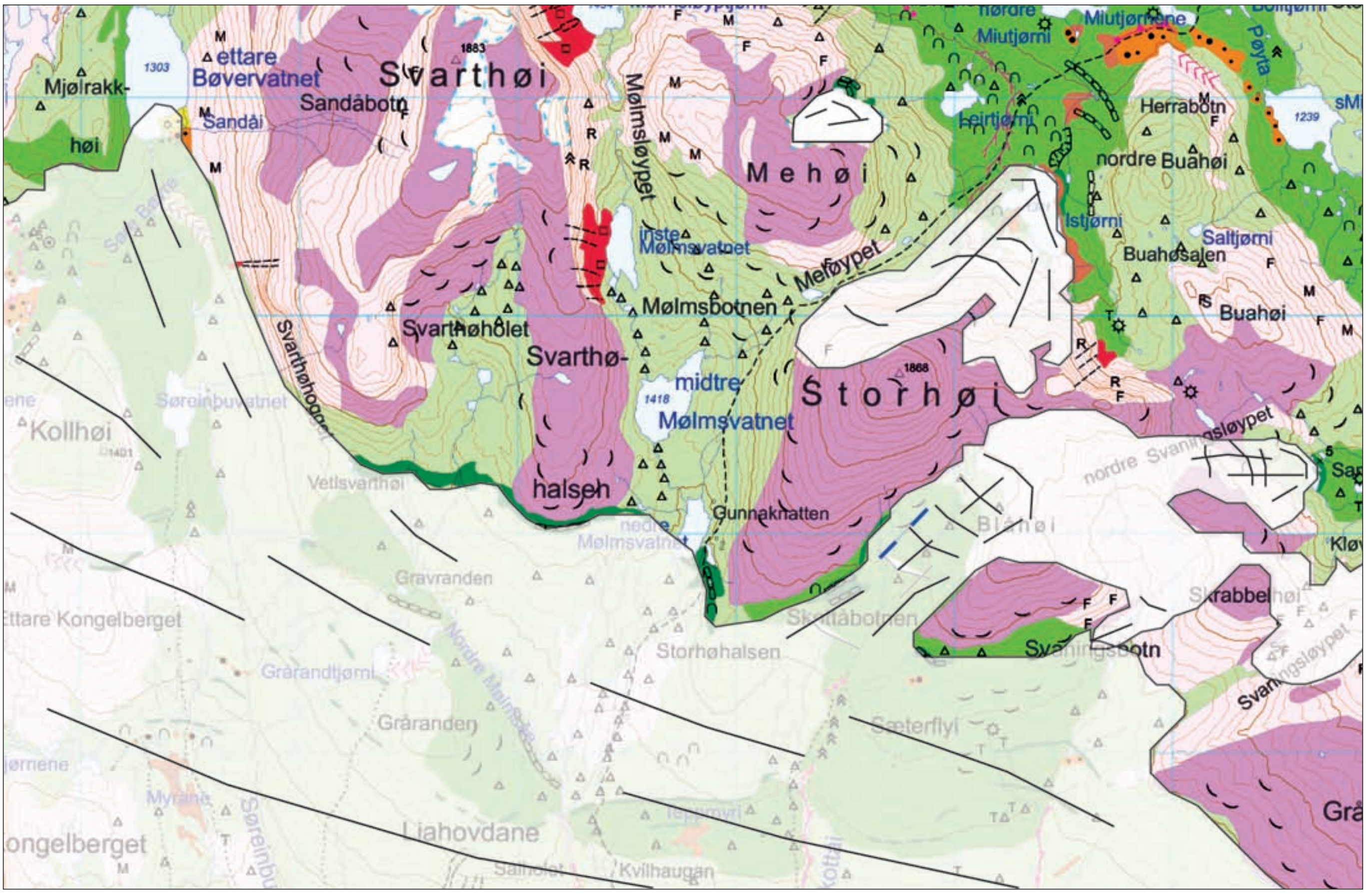


Figure 10. A tentative reconstruction of the suggested plateau glacier in the areas of the Storhøi mountain. Outlet glaciers are indicated to the southwest (against the Romsdalen/Gudbrandsdalen valley) and to the east against the Sandåflatene area from the plateau of the Storhøi mountain. For use of colour and signs, see the map legend for Quaternary maps (Follestad 2010).

of the distal moraine rises to about 1460 m a.s.l. at the Svarthøhalsen mountain. Southeast of the Storhøi mountain (1868 m a.s.l.) distal lateral moraines reach an altitude of 1480 m a.s.l. Since the distance from the areas south of Svarthøi mountain to the Storhøi mountain is 4.5 km and the difference in altitude is 60 m, this gives a slope gradient for the distal moraine of 13 m km^{-1}.

From the marginal zone southeast of Storhøi (Figure 8), a lateral moraine can be followed northwards into the valley between the mountains of Storhøi and Blåhøe (1668 m a.s.l.). This lateral moraine terminates at an altitude of 1560 m a.s.l. The gradient for this lateral moraine is calculated to about 80 m km^{-1}.

North and east of the Storhøi mountain plateau, distinct end moraines are seen in the Istjørni lake (1341 m a.s.l.) and the little lake west of Sandåflatene, east of the plateau of the Storhøi mountain (Figure 9). Cirque glaciation simultaneous with the formation of the lateral moraines along the Romsdalen/Gudbrandsdalen valley might explain the formation of the end moraine in the Istjørni lake. However, no sign of a cirque glaciation is seen in the areas west of the Sandåflatene area. Instead, we argue that the most reasonable explanation for these moraines is formation from an outlet glacier emanating from the plateau and terminating in the lake, as indicated in the tentative reconstruction of the ice margin (Figure 10).

The Vangshøi mountain–Vangsvatnet lake–Aursjøen lake

In the areas of the Vangsvatnet lake (Figure 11) a very well defined ice marginal zone can be observed. The distal lateral moraine is very pronounced (Figure 12). It can be followed nearly continuously from 1310 m a.s.l. on the northeastern slope of the Vangshøi mountain to northern end of the Vangsvatn lake (1166 m a.s.l.), over a distance of more than two kilometres. The upper boundary for a continuous cover of till might indicate a possible continuation of the lateral moraine to the southeast for another 0.5 km. The corresponding ice margin on the mountain slope southeast of Vangshøi mountain would be at an altitude of about 1530 m a.s.l., assuming a slope gradient of 13 m km^{-1}. The horizontal distance from the lateral moraines in the Storhøi area is about 4 km. This indicates that the lateral moraine seen at 1380 m a.s.l. is too low to justify a simultaneous formation to the uppermost ice marginal zone. Thus the deposit is assigned to the formation of the lower ice marginal zone seen in the areas of the Romsdalen/Gudbrandsdalen valley.

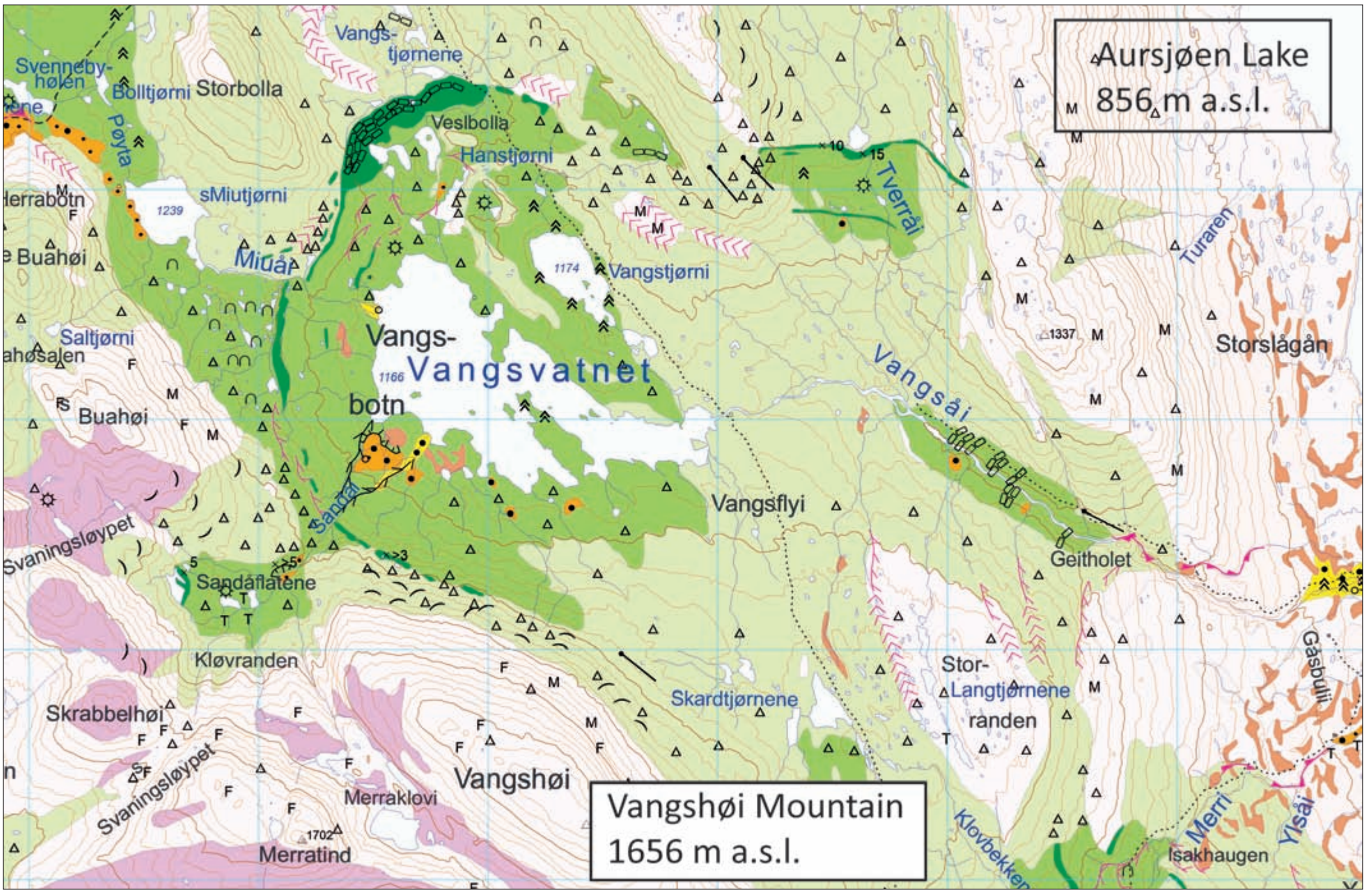


Figure 11. The ice marginal zone in the Vangsvatnet lake areas. For use of colour and signs, see the map legend for Quaternary maps (Follestad 2010).

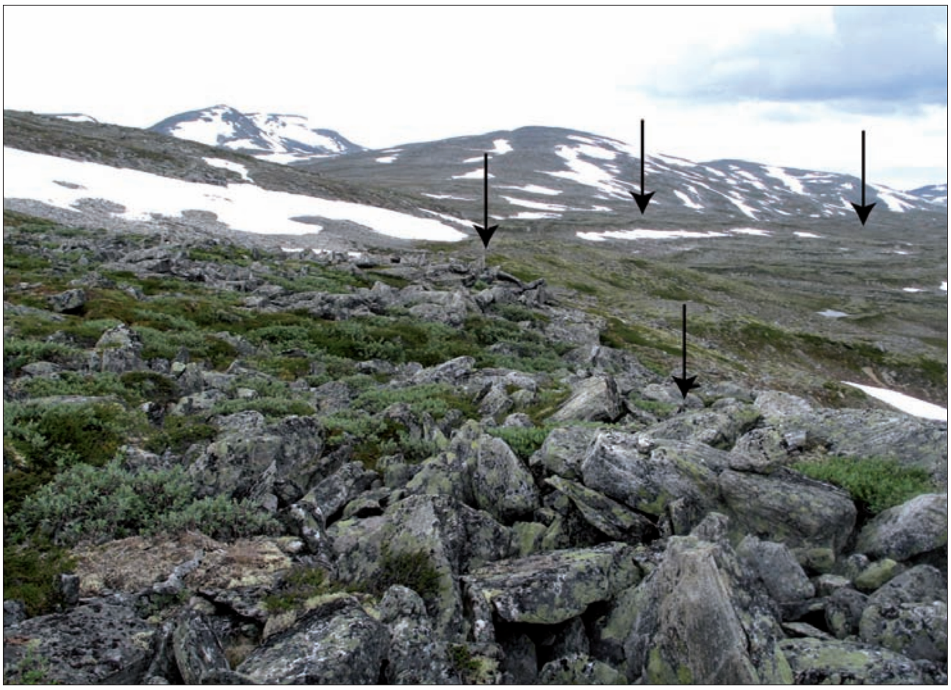


Figure 12. The lateral moraine along the northeastern hillside of Vangshøi mountain. The moraine ridges are characterised by a sandy gravely matrix with blocks on the surface. In some cases the sandy gravely matrix is washed away, leaving the blocks as a lag deposit. The Vangsvatnet lake is seen to the right. The photo is taken from the distal moraine, looking eastward.

To the north, in the valley of Vangsvatnet lake, a marked end moraine occurs. This end moraine consists of several distinct moraine ridges. Some of the ridges consist of a sandy matrix with blocks on the surface, while other ridges are blocky throughout (Figure 13). Commonly glacial meltwater channels run between the moraine ridges. This in turn indicates that meltwater was present during the formation of the lateral moraines.

In the Miua valley, west of the Vangsvatnet lake, there is a marked area of continuous till cover with blocks and mounds continuing northwestward into the Pøyta area. Here some marked glaciofluvial lateral terraces have been formed when the meltwater drained through this valley to the north. These forms, together with the end moraines west of Sandåflatene (Figure 10), show that the glacier tongue in the Vangsvatnet area never penetrated into these areas during the formation of the lateral moraines. Thus the ice margin north of the Vangsvatnet lake is most likely simultaneous with the described ice marginal zone in the Romsdalen/Gudbrandsdalen valley.

Figure 13. Lateral moraines northwest of the Vangsvatnet lake.

From the ice marginal position north of the Vangsvatnet lake two distinct lateral moraines in the Tverråi areas show the further continuation of the ice marginal zone into the Aursjøen area. These lateral moraines are commonly more than 10 m high and consist of a gravelly sand matrix with blocks at the surface. The uppermost lateral moraine ends in the steep valley side of Aursjøen (856 m a.s.l.) at an altitude of 1320 m a.s.l. As the distance between the end moraines in the Vangsvatnet area to the lateral moraines along the southern side of the Aursjøhøi mountain is 2 km, this gives a gradient of some 75 m km^{-1}.

On the steep valley side of the Aursjøen lake (856 m a.s.l.) no marginal deposits have been observed south of the Nesset area (cf., Follestad 1994).

However, indications of a possibly simultaneous inland ice are seen in the tributary valleys along the eastern side of the Aursjøen lake. In the Geitådalen valley, a marked lateral moraine occurs east of Grynningskampen (1549 m a.s.l.) at an altitude of 1520 m a.s.l. The lateral moraine can be followed continuously for one kilometre, to an altitude of 1500 m a.s.l. (20 m km^{-1}). A gradient of this magnitude leaves us with an ice surface that indicates that the end moraines west of lake 1423 m a.s.l. might have formed simultaneously. On the southern flank of the Geitådalen valley two marked end moraines can be seen some at 1410 m a.s.l., in front of a marked cirque valley. As this altitude is about 100 m below the extrapolated ice surface, they are considered to be younger than the above described moraines. Southwest of the Aursjøen lake marked lateral moraines at lower altitudes are seen at the mouth of Vangsvatn valley (Figure 11) and in the valley of Veslsvartådalen. These moraines might be synchronous with the lower ice marginal zone in the Romsdalen/Gudbrandsdalen valley (see below).

The lower ice marginal zone in the Romsdalen/Gudbrandsdalen areas

A lower ice marginal zone is seen along the northern, south-facing valley side of Romsdalen/Gudbrandsdalen valley. In the following a brief description is given, starting with the deposits south of the Romsdalen/Gudbrandsdalen valley.

The Asbjørnsdalen–Grøndalen valley

In these areas a pattern of marked lateral moraines trending west-, north- and eastward of the Nonshøi mountains seem to represent deglaciation ice margins (Figure 14). The ice marginal zone is situated approximately 200 m below the upper marked zone along the northern flank of the Skarvehøi mountain (Figure 2). The different ridges in the zone can be followed continuously for some hundreds of metres and are several metres high. They consist of a gravely sandy matrix, with blocks on the surface.In the Grøndalen valley the glacier in the main Romsdalen/Gudbrandsdalen valley dammed the rivers in the Grøndalen valley and glaciofluvial deposits were formed in sub-/semi-lateral positions. These deposits are seen at an altitude of 1200–1160 m a.s.l. and 1100–1080 m a.s.l., respectively. In connection with the lowest glaciofluvial deposits, several marked meltwater channels are seen (Figures 14 and 15).

The morphology and the westward run-off direction of the meltwater channels show that they are eroded in a sub-/semi-lateral position to an ice surface in the Romsdalen/Gudbrandsdalen valley falling in this direction. As the meltwater channels were formed nearly parallel to the lateral moraines, even though a few of the channels cut through some of the lateral moraines, they are considered to have a nearly simultaneous origin.

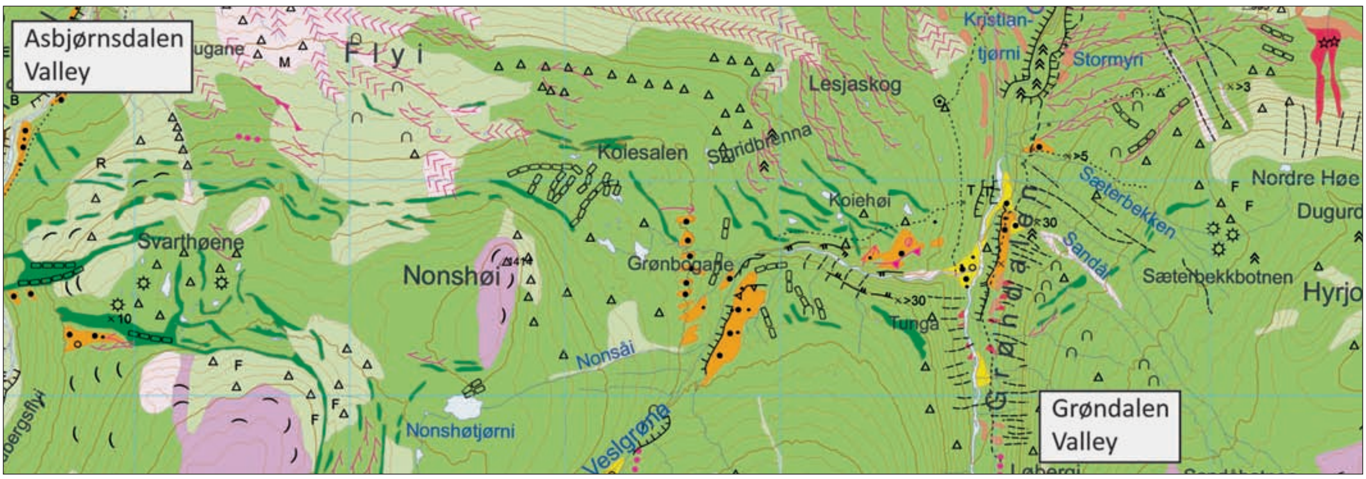


Figure 14. Lateral moraines shown in dark green as seen from the Asbjørnsdalen valley to the Grøndalen valley in the east. The figure is copied from the Lesja Community Map, M 1:80,000 (Follestad 2010). For use of colour and signs, see the map legend for Quaternary maps (Follestad 2010).

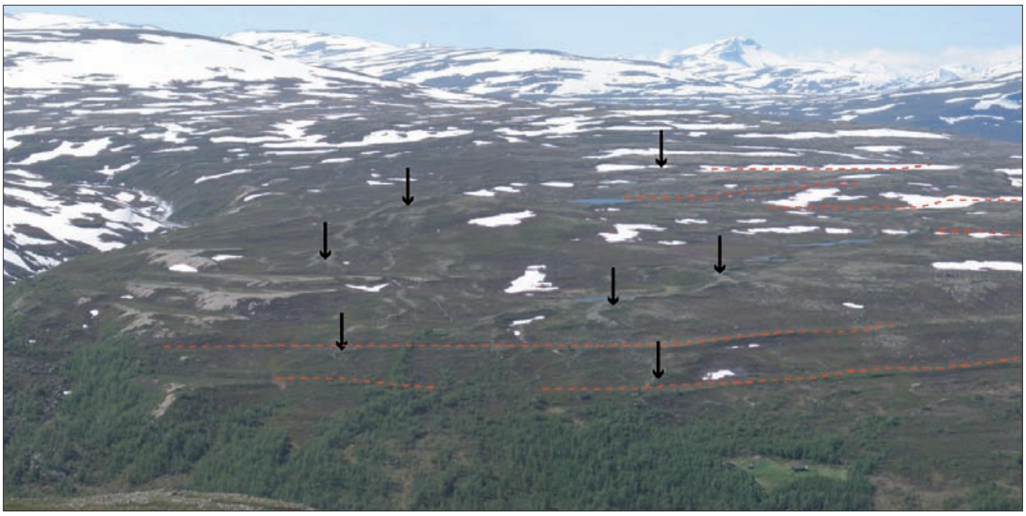


Figure 15. Laterally formed moraine ridges representing the lower rand zone in Romsdalen/Gudbrandsdalen valley are seen west of the Grøndalen valley (marked with black arrows). Several lateral meltwater channels were formed in these areas during and after the formation of the lower rand zone (red dots). Glaciofluvial terraces were formed marginal (or sub-/semi-lateral) to the ice margin when the inland ice was shrinking. The lowest terrace are seen to the left. Photo is taken from the eastern valley side of Grøndalen, looking westward.

A marked bending and change of run-off direction for the meltwater channels are seen at 800 m a.s.l. along the eastern side of the present river Grøna. This shows that behaviour of the meltwater changed when ice in the main valley had melted down to a thickness of about 200 m. The same changes in run-off direction are also seen in the areas east of the Asbjørnsdalen valley. Further eastwards, no obvious lateral moraines have been observed. However, the marked glaciofluvial deposit formed in the south of the Kampen mountain (1369 m a.s.l.) at an altitude of some 1320 m a.s.l., might indicate a continuation of the lower ice marginal zone.

In the Lordalen valley marked lateral moraines are seen along the northern and southern valley sides. Along the northern slope a lateral moraine more than 3–5 m high can be followed 1 km to the east along the southeastern side of Digervarden (1778 m a.s.l.). This lateral moraine is situated at approximately 1400 m a.s.l. in the central parts. The morphology and position in the terrain of the moraine ridge point at a likely formation by a valley glacier coming through the Lordalen valley. Along the southern side of the Lordalen valley, several distinct lateral moraines form a well defined ice marginal zone in the outermost parts of the Lordalen valley. The most marked distal lateral moraine is 2–4 m high and is situated at 1420 m a.s.l., northeast of Sletthøi mountain (1536 m a.s.l.). Further to the east two minor ridges are seen, reaching some 1560 m a.s.l.

Liahovdane

Marked lateral moraines are seen along the valley sides west and east of Liahovdane (Figure 8) from the Grårandtjønne lake (1281 m a.s.l.) to the Gråhøi mountain (1565 m a.s.l.) in the east. In these areas the lateral moraines reach an altitude of 1280 m a.s.l. and 1380 m a.s.l., respectively. Since the distance between the Grårandtjønne lake and the deposits at Gråhøi mountain is 7 km, the slope gradient is 14 m km^{-1} for the lower-lying marginal zone.

In the northeastern end of the Merrabotn valley lateral moraines have been deposited by glaciers flowing in the valleys of Merrabotn, Ylsbotn and Aursjøen. These moraines are situated at 1225 m a.s.l., east of the mountain peak 1258 m a.s.l. The moraine ridge deposited through the Merrabotn valley can be followed about 500 m to the northwest, where it reaches an altitude of 1275 m a.s.l. on the northeastern side of the Måni mountain. To the north this moraine is cross-cut by a lateral moraine deposited by a glacier, which came into this area through the Aursjøen valley. This clearly demonstrates that the ice movement through the Aursjøen valley took place somewhat later than the movement through the Merrabotn valley. The northward continuation of this former glacier is given by the marked 3–5 m-high lateral moraines which cross the Merraboten valley. North of the Merri river, these lateral moraine ridges are 2–10 m high. Further northwards moraine ridges, seen in the valley of the Vangsåa river, might have been deposited more or less simultaneously with the lateral moraines in the Merrabotn areas.

Summarising discussion

The above descriptions from the valley flanks of the Raumadalen and Gudbrandsdalen valleys illustrate that an ice marginal zone some 200 m below the upper ice marginal zone seems to have been deposited during the deglaciation. Sets of meltwater channels were formed simultaneously and follow the lateral moraines closely down to about 800 m a.s.l. At that time the ice remnant in the main valley was only about 200 m thick.

Profiles with projected lateral moraines in the Romsdalen/Gudbrandsdalen areas

In the Raumadalen/Gudbrandsdalen areas the lateral moraines, as seen in Figure 16, are projected and plotted in digital elevation profiles (Figures 16 and 17). Lateral moraines occur along

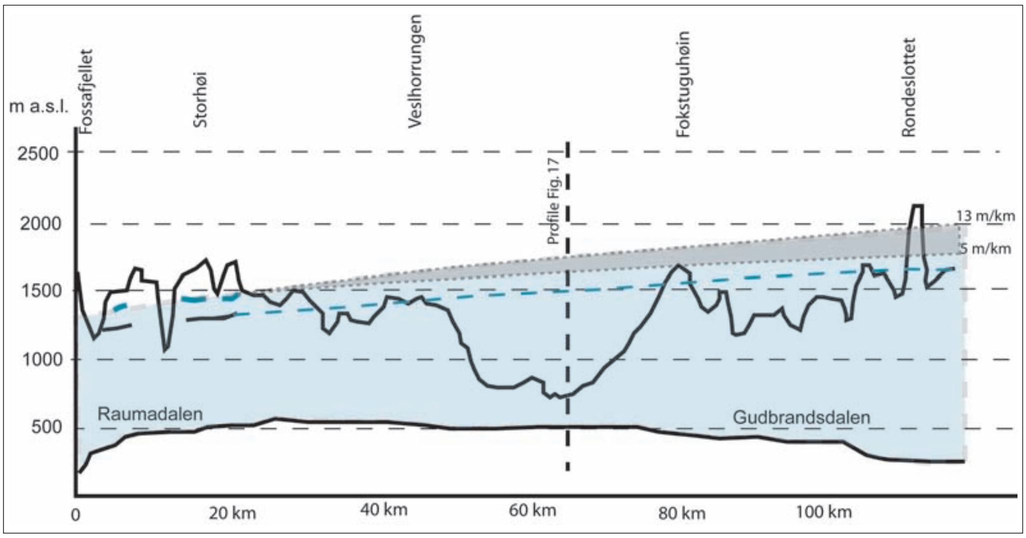


Figure 16. Reconstruction of a tentative glacier profile on the basis of lateral moraines which are projected and plotted in digital elevation profiles. The upper and lower ice marginal zones are shown and extrapolated in a southeastward direction.

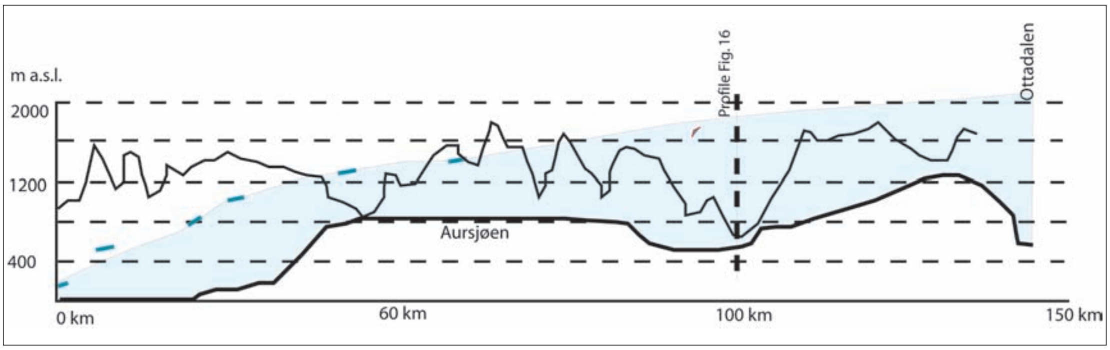


Figure 17. Reconstruction of a tentative glacier profile on the basis of lateral moraines which are projected and plotted in digital elevation profiles through the Eresfjord–Aursjøen lake valley to the valley of Gudbrandsdalen and further southwestward through the valley of Lordalen to the Otta valley. The upper ice marginal zones are shown and extrapolated in a southeastward and southwestward direction.

the mountain sides of the valley Raumadalen from the Hatten mountain area to the Skarvehøi mountain in the valley of Gudbrandsdalen (Figure 16). As the Hatten lateral moraines are situated at 1250 m a.s.l. and the moraines along the Skarvehøi mountain are some 1580 m a.s.l. (over a distance of 21 km), this gives a slope gradient of 15 m km^{-1} for the valley glacier. The glacier thickness is about 1000 m to the west and 1200 m at the mouth of Lordalen valley.

If a similar tentative glacier profile is constructed on the basis of lateral moraines in the areas of the Aursjøen lake to the Gudbrandsdalen valley and southward through Lordalen valley to the valley of Otta (Figure 17), a marked drop in the lateral moraines is here seen west of Aursjøen lake (to the left in Figure 17). In the Aursjøen lake areas the lateral moraines indicate an ice surface some 1300 m a.s.l. and a thickness of the glacier of some 500 m. In the Gudbrandsdalen areas and southward through the Lordalen valley, the surface of the ice continues to rise (if we use a gradient of 28 m km^{-1}). In the areas of the Ottadalen valley the surface of an inland ice would be more than 2000 m.

The marginal zones in the areas east of lake Aursjøen

The scenery of these areas is dominated by mountains, reaching up to 2000 m a.s.l. (Figure 18). The valley of the Jori river and its tributary valleys run through the area. In the sides of the valleys lateral moraines were formed. These moraines show that a glacier outlet from the inland ice penetrated the area. Distinct lateral moraines are seen along the mountain of Skulan (1690 m a.s.l.) and Salhøe (1767 m a.s.l.). The lateral moraines are here situated 1460 m a.s.l. in the west and 1420 m a.s.l. in the eastern areas. As the distance between the measured points are 2.5 km this leaves us with a gradient of 16 m km^{-1} for the glacier falling into the upper parts of the Åmotdalen valley. The valley floor is here at some 1361 m a.s.l. in the area of lake Drugshøtjønnin. Together with the altitude of the lateral moraines (1420 m a.s.l.) this shows that the valley glacier was 60 m thick when these lateral moraines were deposited.

In the areas of Nedre Lustjørni lake there are several well defined moraine ridges. These ridges, which are 2–10 m high, have ice contact faces to the west indicating that a glacier flowed

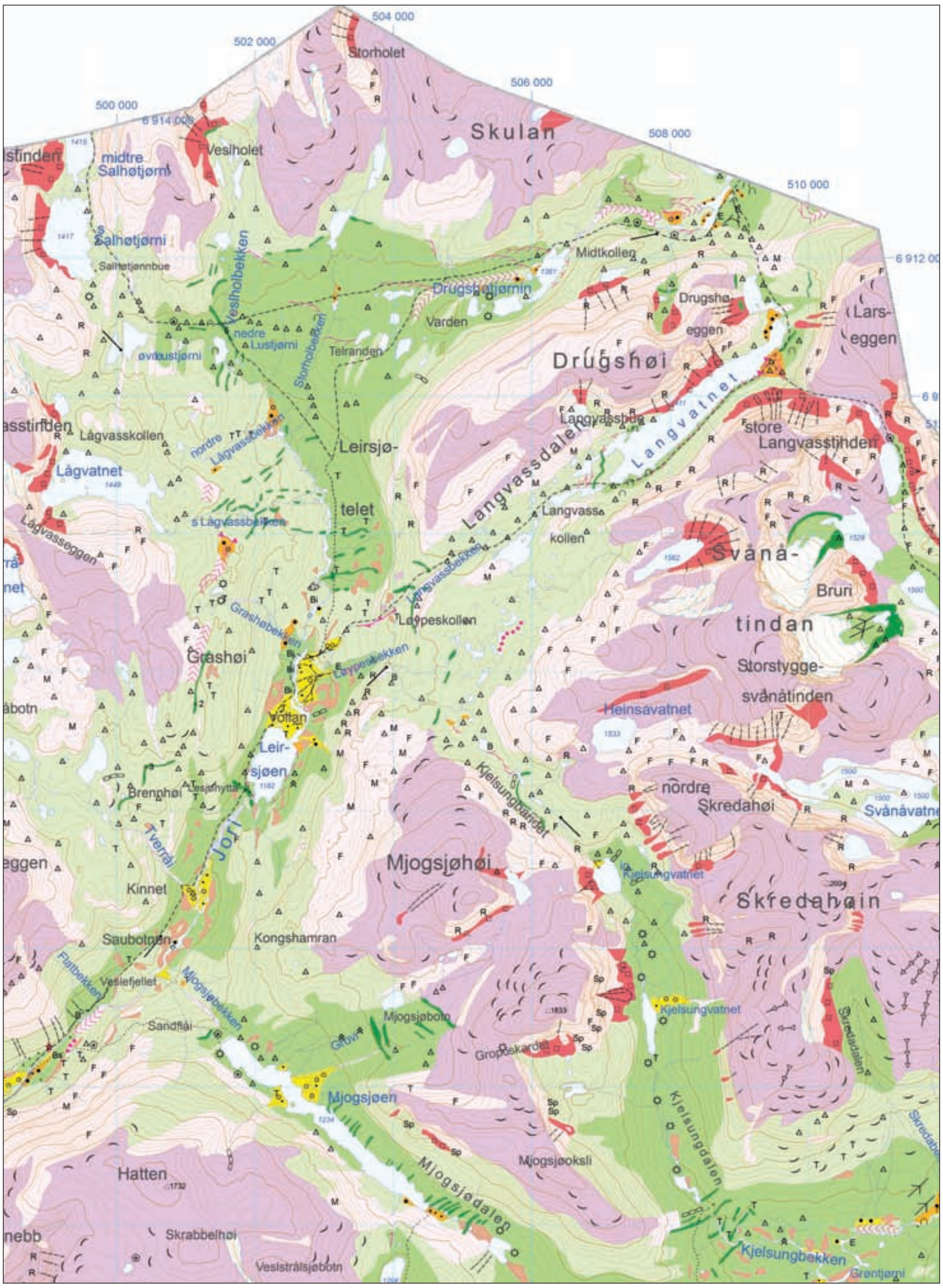


Figure 18. Lateral moraines shown in dark green are seen in the upper parts of the Jori river valley (Skamsdalen valley/Langvatnet lake valley). In the mountains of Svånåtindan the terrain reaches an altitude of 2000 m. The map is copied from the Lesja Community Map, M 1:80,000 (Follestad 2010). For use of colour and signs, see the map legend for Quaternary maps (Follestad 2010).

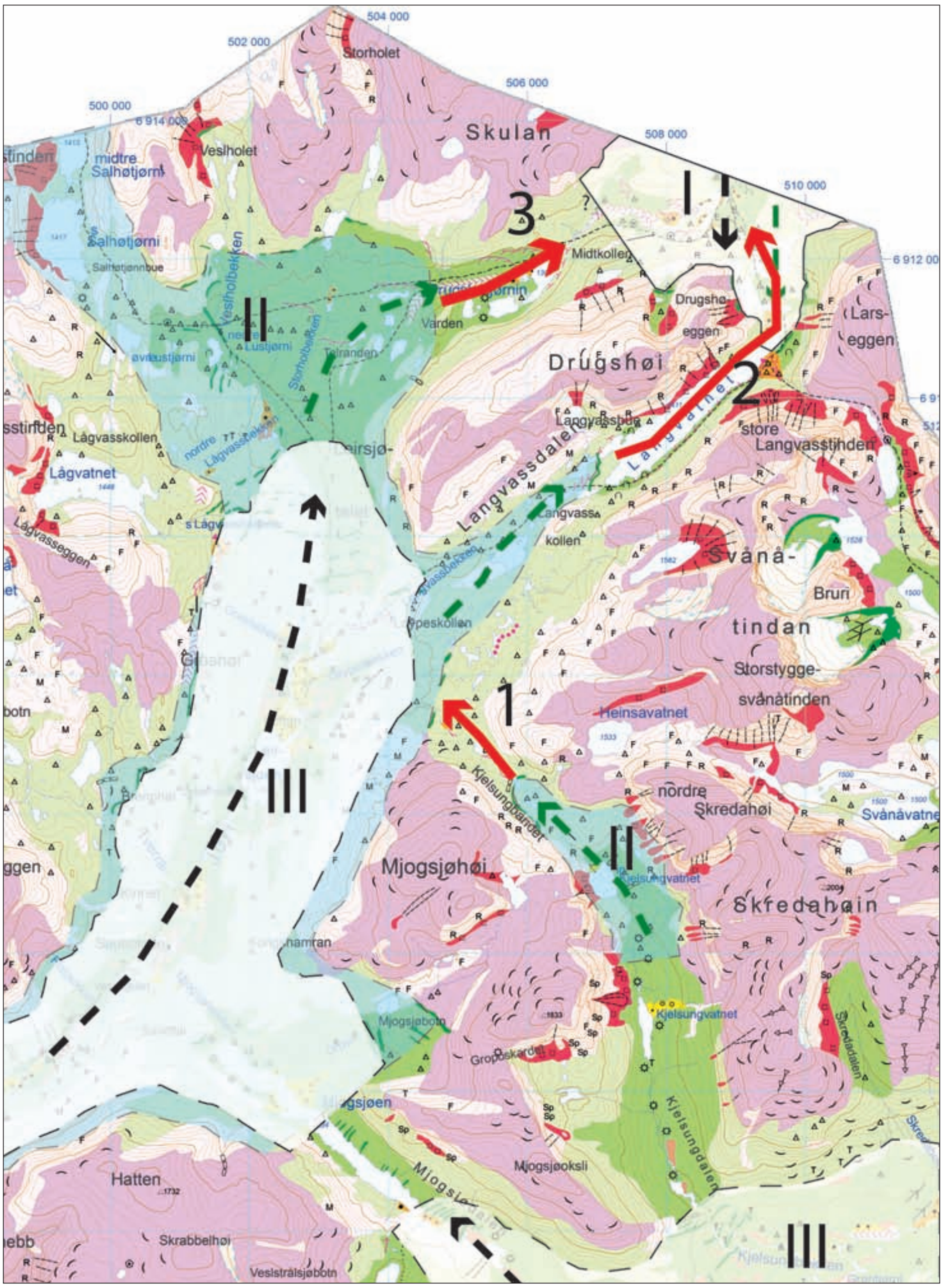
into the upper parts of the Jori river valley from the west. The formation of these moraine ridges took place somewhat later than the formation of the lateral moraines along the valley side of the mountains Skulan and Salhøe.

West of the Lågvatnet lake (1448 m a.s.l.) several defined moraine ridges cross the valley floor in the Jori river valley. These ridges, together with the marked lateral moraine along the western and eastern valley side of the Jori river valley at 1420 m a.s.l., show that a glacier dammed the Jori river valley in the southern part and a glacial lake was formed. This lake was drained through the run-off pass between the mountains of Skulan and Drugshøi into the upper parts of the Åmotdalen valley (Follestad 2011). Here, a set of well defined meltwater channels can be seen at 1380 m a.s.l. The glaciofluvial sand and gravel deposits west of Lågvatnet, situated at 1383 m a.s.l., support the idea of a glacial lake in the area (Figure 18).

In the Langvatn area (1411 m a.s.l.) lateral moraines are seen at both ends of the lake (Figure 18). The morphology of these lateral moraines show that they were formed by two separated glaciers entering the Langvatn lake area, from the west and the east. The lateral moraines along the western valley side of Larseggen mountain (1945 m a.s.l.) can be followed up to some 1500 m a.s.l. The lateral moraines seen along the northern mountainside of Drugshøi mountain support the existence of such a glacier.

The marked lateral moraine in the western parts of the Langvatn lake (1411 m a.s.l.) together with lateral moraines further down towards the southwest, show the existence of at least two

Figure 19. A tentative reconstruction of the development of glacier surfaces in the Jori river valley. Glaciofluvial run-off directions are shown with red arrows. Roman numerals are tentatively used to indicate a sequence of events.



glacier surfaces at some 1420 m a.s.l. and 1400 m a.s.l., respectively. The distinct end moraine in the area of Kjelsungbandet valley (between the mountains of Mjogsjøhøi and Svånåtindan) together with the glaciofluvial deposits in the areas to the west, support a glaciofluvial drainage in this direction after the formation of the upper marginal moraine in the Langvatn area, but before the formation of the lower lateral moraines in these areas (Figure 18). It should here be noticed that the Langvatn lake has marked shorelines 5–6 m above the present water level (1411 m a.s.l.). In the northern parts of lake 1415 m a.s.l. north of the Langvatn lake there is a well defined run-off pass, some 1417 m a.s.l. Thus it is likely that the northern parts of the Langvaten lake and the small lake 1415 m a.s.l. were glacier free when the shoreline formation and drainage in the northern areas occurred. This leads to the conclusion that the formation of the lateral moraine in the western end of the Langvatnet lake succeeded the formation of the lateral moraines in the northern parts of the lake.

Summarising discussion

Based on the description above a tentative glacial reconstruction is carried out (Figure 19). In the areas of the Langvatn lake it is concluded that these areas were ice free when glaciofluvial drainage (3) took place over the run-off pass in the north. Furthermore it is suggested that the glaciofluvial drainage (1) from the glacier represented by the lateral moraine in the Kjelsungbandet most likely was older or simultaneous with a glacier (marked in blue) depositing the lateral moraine in the western area of lake Langvatnet. An ice surface at about 1420 m a.s.l. at at the western end of lake Langvatnet thus gives a glacier surface of about 1450 m a.s.l. in the areas along the west side of the Drugshøi mountain. Such a glacier surface is in agreement with the formation of the lateral moraines in the valley side of Skulan mountain and the glaciofluvial drainage pattern (3) to the northeast to the Åmotdalen valley. Somewhat later, the lower lateral moraines along the western valley side of the Jori river valley indicate that younger branches of glacier existed in the area (II). The drainage from the uppermost ice surface went eastward (3) to Åmotdalen. This drainage is also demonstrated by glaciofluvial accumulations at this altitude along the western side of the Jori river valley.

The marked Rogen moraines in the valley south of Mjogsjøhøi mountain indicate that deglaciation took place in a southeasterly direction and might be connected to the lower lateral moraines seen in the areas towards Hjerkinn. The higher lying lateral moraines in the southwestern side of the Mjogsjøhøi are thus considered to have formed more or less simultaneously with the highest lateral moraines in the areas to the north, along the Skulan mountain and in the western end of the Langvatn lake.

Glaciation limits in the investigated area

The glaciation limit represents the lowest altitude of a mountain at which glaciers can originate (Enquist 1916). In the western and northern parts of the Møre and Romsdal County cirque and small glacial valleys dominates. Here, well defined terminal moraines in some of the cirques show unequivocal evidence of cirque glaciation. Together with this information the present cirque glacier and the closest lying 'plateau peaks' are shown in Table 1.

In the Sunndalsøra (1420 II) area, Table 1 shows a glaciation limit at about 1685 m a.s.l. (as a mean of cirque 1, 5, 4 and 8) during the final parts of the glaciation. Corrected for the isostatic rebound from at the end of YD (~200 m) this gives a tentative glaciation limit of about 1485 m a.s.l. In the areas of Eresfjord (1320 II) the distribution of the terminal moraines give evidence for a glaciation limit at about 1230 m a.s.l. (as a mean of cirque 17, 19, 20, 21, 24, 26, 28, 29, 30, 31, 32, 34, 35, 36, 39 and 42) during the final parts of the glaciation. Corrected for the shoreline displacement at the end of YD (some 150 m) this indicates a tentative glaciation limit of some 1080 m a.s.l. Compared to the estimates of the modern glaciation limit for the eastern and western parts of the area (Østrem et al. 1988) at about 1800 m a.s.l. and 1450 m a.s.l., respectively, this suggests a general lowering of the glaciation limit in the YD of 350–370 m. Compared to the estimates for the YD depression of 400–500 m in the middle and inner Nordfjord (Fareth 1987) the calculated values in Møre and Romsdal County might be reasonable. It should be remembered that calculation of the YD glaciation limit in this paper is carried out using a 1 km grid on a map sheet. In Andersen (1968) the glaciated mountains are expected to lie at higher altitudes than the values received through use of the summit method. According to the map presented by Østrem et al. (1988), the modern glaciation limit rises from 1500 m a.s.l. to 1900 m a.s.l. over a distance of 60 km in a southeastern direction in the county of Møre and Romsdal. This gives a gradient of 6–7 m km^{-1} for the present glaciation limit.

Summary and discussion

Garnes and Bergersen (1980) and Bergersen and Garnes (1981) have, through detailed field mapping of lateral landforms, striae, texture and till fabric, reconstructed five deglaciation phases in the east Jotunheimen/Gudbrandsdalen area. During the final phases, called the 'C' and the 'D' phases, they found that the ice movements were to the north ('C') and to the northeast ('D') in areas north of the Otta valley. These observations are supported by the observation of northeasterly ice-flow configurations in east-central Norway and Sør-Trøndelag County, which are described by Follestad and Fredin (2007). In the following 'D' phase (Garnes and Bergersen 1980), the ice-directed meltwater drainage was to the northeast in the areas north of the Otta valley. This direction is confirmed by mapping of the drainage features on the Otta Quaternary map, scale 1:50,000, by Follestad and Bergstrøm (2004). According to these authors, the first recognised glaciofluvial drainage took place through the Vasskjelet run-off pass. This run-off pass is situated at 1520 m a.s.l., and is situated in the lower parts of the weathering material preserved on the west-facing slopes of Gråhøi mountain (1646 m a.s.l.). Even though this drainage landform in the Vasskjelet run-off pass is situated several tens of metres below the stipulated surface of an inland ice extrapolated from lateral moraine in the Raumadalen/Gudbrandsdalen area (Figure 9) it supports the view of a high-lying surface for the inland ice in the area of the Rondane mountain. Reconstructions made of the inland YD ice surface of Sollid and Kristiansen (1984) strongly support this view.

In the Littledalen valley west of Sunndalsøra, ^{14}C dating of shells gives a chronology for formation of the ice marginal deposits to some 9700 BP (Follestad 1987). This deposit, together with probably contemporary lateral moraines in the Reinsvatnet lake and in the Skarvdalen valley is evidence for a high-lying ice surface in the Aursjøen area. The ice sheet surface in the Littledalen–Aursjøen valley and the Eikesdalen–Aursjøen valley, together with the surface of the inland ice in the Rauma–Lordalen valley, can be followed up to 1540 m a.s.l. and 1560 m a.s.l., respectively. In the profile (Figure 17) gradients for the inland surface are stipulated to some 26 m km^{-1}. Extrapolations in an eastward direction will give a tentative surface for the

Table 1. Mountain peak, the orientation of the cirque or cirque valleys with or without terminal moraines. The present-day cirque glaciers are indicated.

Sample no	m a.s.l.	Cirque orientation	Terminal moraines	Cirque glacier today (x)
Map sheet: Sunndalsøra 1420 III				
1 Vardefjell	1686	East (E)	X	-
2 Slotthø	1833	North (N)	X	X
3 Midtfonntinda	1707-17950	N	X	X
4 Austvindstrøe	1660	E	X	X
5 Vikesaksa	1809	E	X	-
6 Såtatind	1614	N	X	X
7 Breidtelnebba	1735	N	X	-
8 Topp 1512	1512	N	X	-
9 Ryssdalsnebba	1818	E	X	X
10 Gråfjell	1264	E	X	-
11 Skjorta	1711	E	X	X
12 Topp 1292	1292	South (S)	X	-
13 Trolltind	1396	E	X	X
14 Hjellbønebba	1557	-		-
15 Skrondalsnebba	1463	E	X	-
16 Kleppen	1535	-		-
Map sheet: Eresfjord 1320 II				
17 Nyheitind (i)	1508	N	X	-
18 Nyheitind (ii)	1598	N	X	X
19 Høgseternebba	1241	N	X	-
20 Helvetestind	1373	N	X	-
21 Storbrefjellet	1287-1340	E	X	-
22 Storbreen	1524-1470	E	X	X
23 Topp 1616	1616	E	X	X
24 Blåfjellet (i)	1276	E	X	-
25 Store Vengjetind	1852	E	X	X
26 Kyrkjetaket	1439	E	X	-
27 Klauva (i)	1512	N	X	X
28 Blåfjellet (ii)	1162	E	X	-
29 Kalvgjeltind	1283	West(W)	X	-
30 Snarketind	1149	N	X	-
31Svartevasstind	1160	N	X	-
32 Blånebbå	1320	E	X	-
33 Bjørnabotnhøgda	1470	N	X	X
34 Topp 1324	1324	N	X	-
35 Måsvasstind	1203	N	X	-
36 Såta	1131	N	X	-
37 Nebba	1105	-	-	-
38 Skrokkenfjellet	1057	-	-	-
39 Ryptind	943	E	X	-
40 Dølmørhaugen	1000	E	X	-
41 Nebbeslia	893	-	-	-
42 Langbotn	1100	E	X	-
43 Blåfjellet (iii)	1154	-		-

inland ice at 1700–1800 m a.s.l. in the Dombås area. The lateral moraines can be followed up to 1540 m a.s.l. in the Aursjøen area and to 1560 m a.s.l. in the Storhøe area north of Lesja (Follestad 2010). These numbers might give an indication of the equilibrium line altitude during this time period, and the formation of these deposits at altitudes of 1540–1560 m, or 1340–1360 m, if corrected for the shore displacement. These numbers seem to be acceptable for the general lowering of the snowline in YD compared to the lowering described elsewhere in the country, e.g., in the Nordfjord area (Fareth 1987).

In the till sequences presented by Garnes and Bergersen (1980) there is no evidence for lowering and then regeneration of the ice sheet surface to an altitude of 1700–1800 m in the Dombås area. This implies that the latest ice culmination was in the Jotunheimen mountains with outlet glaciers flowing through the valleys of Lordalen and Grøndalen. This took place before and during the formation of the upper set of YD lateral moraines deposited in the Rauma–Gudbrandsdalen area as well as in the Aursjøen–Littledalen area. The lower set of lateral moraines observed in the Raumadalen–Gudbrandsdalen areas might represent a still-stand or a readvance during the deglaciation. Similar situations are described in the Oppdal–Hjerkinn area. These lateral moraines are here correlated to the readvances in Sør-Trøndelag County (Follestad 2003), dated to late YD chronozone, some 10,300–10,400 ^{14}C years BP (Sollid and Reite 1983).

In Figures 16 and 17 the ice surfaces are used and extrapolated in an eastward direction. If the lowest obtained gradient of 13 m km^{-1} is used, then an altitude of 1750 m a.s.l. for the ice surface is likely in the Dombås–Fokstugumyra area and about 2000 m a.s.l. in the Rondane area. However, as we approach the culmination zone of the ice sheet south of the Rondane mountain in the Ringebu areas (Garnes and Bergersen 1980), the slope gradient might have been considerable lower, as indicated in Figure 16. In this case, using a slope gradient of 5 m km^{-1}, the projected ice-sheet surface will be at about 1600 and 1750 m a.s.l. in the areas of Dombås–Fokstugumyra and Rondane, respectively. Furthermore, the ice divide in the Ringebu areas must have existed for a significant period, as the following meltwater drainage was to the north and northeast (Follestad and Bergstrøm 2004, Follestad 2005). An ice-sheet surface of 1750–2000 m in the Rondane mountains is also consistent with the ice-flow directions indicated by the drumlins in the Fokstugumyra area (Follestad and Fredin 2007).

Conclusions

The lateral moraines in the area of Romsdalen–Gudbrandsdalen valley and in the valleys of Aursjøen–Littledalen/Eikesdalen form a pattern reflecting ice-sheet surfaces at about 1540 m a.s.l. and 1560 m a.s.l., respectively. The slope gradients for the inland ice surface for the upper and lower marginal zones are deduced to 13 m km^{-1} in the main valley of Gudbrandsdalen. This will give a tentative maximum ice surface at 2000–1750 m a.s.l. for the two marginal zones described in the Dombås and Fokstugumyr areas. This leads to the conclusion that the Rondane mountains and surrounding areas were covered by ice or acted as accumulation area nunataks; however, nunataks and ice-free areas probably existed in high-altitude areas during the YD chronozone. Thus, the ice-sheet geometry, deduced from lateral moraines, supports 'a thick-ice model' for the Upper (late) Weichselian Scandinavian ice sheet in Norway, where much of the core areas are inundated by ice. Furthermore it is suggested that continuous melting of the inland ice took place from the Late glacial maximum to the YD chronozone and that the main ice divide was situated in the Jotunheimen mountain, from where major ice streams emanated into the field area.

Acknowledgements

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