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Relict lateral moraines in northern Sweden — evidence for an early mountain centred ice sheet

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Abstract

Glacial geomorphology along the eastern rim of the Scandinavian mountain range includes glacial landforms from the last deglaciation as well as from earlier glacial stages. One of the most prominent landform groups from earlier glacial stages, and the most diagnostic for ice sheet reconstruction, is a set of lateral moraines. In this paper, we describe these lateral moraines within a key area around Kvikkjokk, northern Sweden. Position of these lateral moraines in relation to the last deglaciation patterns indicates that they were formed before the last glacial maximum (LGM). The location and morphology of moraines show that they were deposited by a mountain centred ice sheet with outlet glaciers along major valleys, emanating from the highlands west of the Kvikkjokk area. This ice sheet was likely less than 170-km wide and no more than 600-m thick. Climatologically and glaciologically, we expect the relict lateral moraines to have been deposited before 75 ka BP (marine oxygen isotope stage 4). Their preservation is a consequence of subsequent overriding of nonerosive cold-based ice. Ice-marginal landforms and deposits from mountain centred ice sheet configurations in Fennoscandia are scarce. Therefore, the relict lateral moraines are important tools for reconstructing these elusive early glacial stages, possibly correlated to the ice sheet inception. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Lateral moraines; Ice sheet; Pre-LGM; Weichselian; Reconstruction

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1. Introduction

Investigations of the last glacial maximum (LGM) and deglaciation in Scandinavia have a long history and these stages are well understood (e.g., Andersen, 1981; Lundqvist, 1986; Kleman and Hättestrand, 1999). In contrast, initiation of the Weichselian ice sheet, or any ice sheet, is much less investigated. Consequently, dynamics of the early ice sheets are not well known. This is unfortunate since the aerially restricted mountain centred ice sheets, which likely dominated during the ice sheet initiation and intermediate stages, seem to have persisted for long periods of the Pleistocene (Porter, 1989; Kleman and Stroeven, 1997). We may thus have underestimated the geomorphological impact of these ice sheets.

Based on studies of glacial striae, Ljungner (1949) recognised that the Weichselian glaciation in Fennoscandia was centred in the Scandinavian mountain chain during its early and intermediate stages. Kleman et al. (1997) and Boulton et al. (2001) showed that the Weichselian glaciation probably was initiated in two areas, one in the highlands of southern Norway and one in the high, northern part of the Scandinavian mountain chain. Later, the ice grew

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thicker and became independent of topography. In this process, the ice dispersal centre migrated eastward towards the Gulf of Bothnia. Finally, the dispersal centre migrated back towards the Scandinavian mountains during the ice recession (Fig. 1). This general pattern of the ice divide migration has been confirmed by various methods, including stratigraphic records (e.g., Lagerbäck, 1988b; Mangerud, 1991; Lundqvist, 1992; Helmens et al., 2000), ice sheet modelling (e.g., Holmlund and Fastook, 1995), and glacial geology (e.g., Kleman et al., 1997; Boulton et al., 2001). Most work on glacial history in North America also indicate that the Laurentide ice sheet probably originated in the highlands, although the exact mechanisms cause controversy (e.g., Flint, 1943; Ives, 1957; Ives et al., 1975).

Geomorphological and stratigraphical records from stages before LGM in Fennoscandia have been described by Lundqvist (1967), Hirvas et al. (1981), Lagerbäck (1988a), Lagerbäck and Robertsson (1988), Rodhe (1988), Kleman (1992) and Helmens et al. (2000). Kleman (1992) identified large areas of the northern Sweden as a “palimpsest” landscape because of the multitude of superimposed glacial landform systems. Most data point at several early Weichselian ice sheet advances and retreats, although

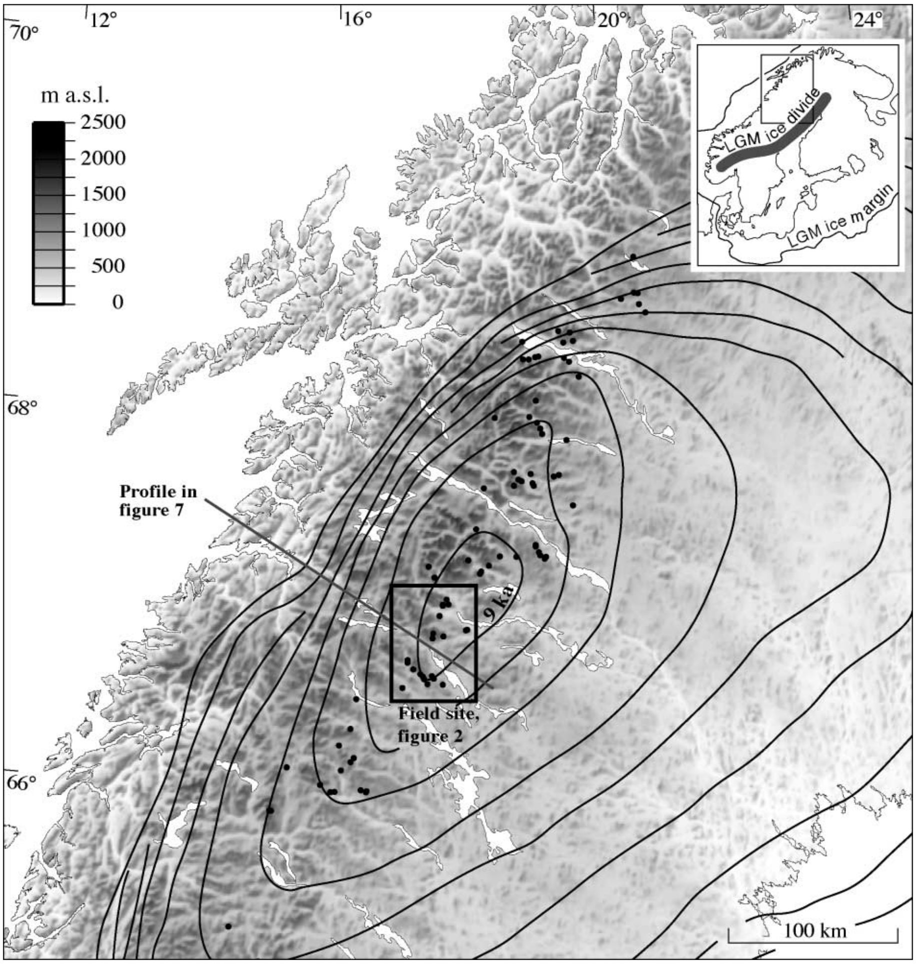

Fig. 1. Location map. LGM ice margin and LGM ice divide is from Kleman (1990) and Boulton et al. (2001). Weichselian deglaciation pattern is from Boulton et al. (2001) and Kleman et al. (1997). Filled circles are marginal moraines found on the eastern rim of the Scandinavian mountains (Kleman, 1992; Hättestrand, 1998; Fredin, unpublished). The morphology of all moraines implies ice flow from west.

Forsström and Punkari (1997) suggested only one single ice sheet advanced. However, detailed configuration of these pre-LGM ice sheets remains elusive.

One set of ice marginal landforms from this period is a set of lateral moraines, together with the glacial meltwater channels. All lateral moraines are situated

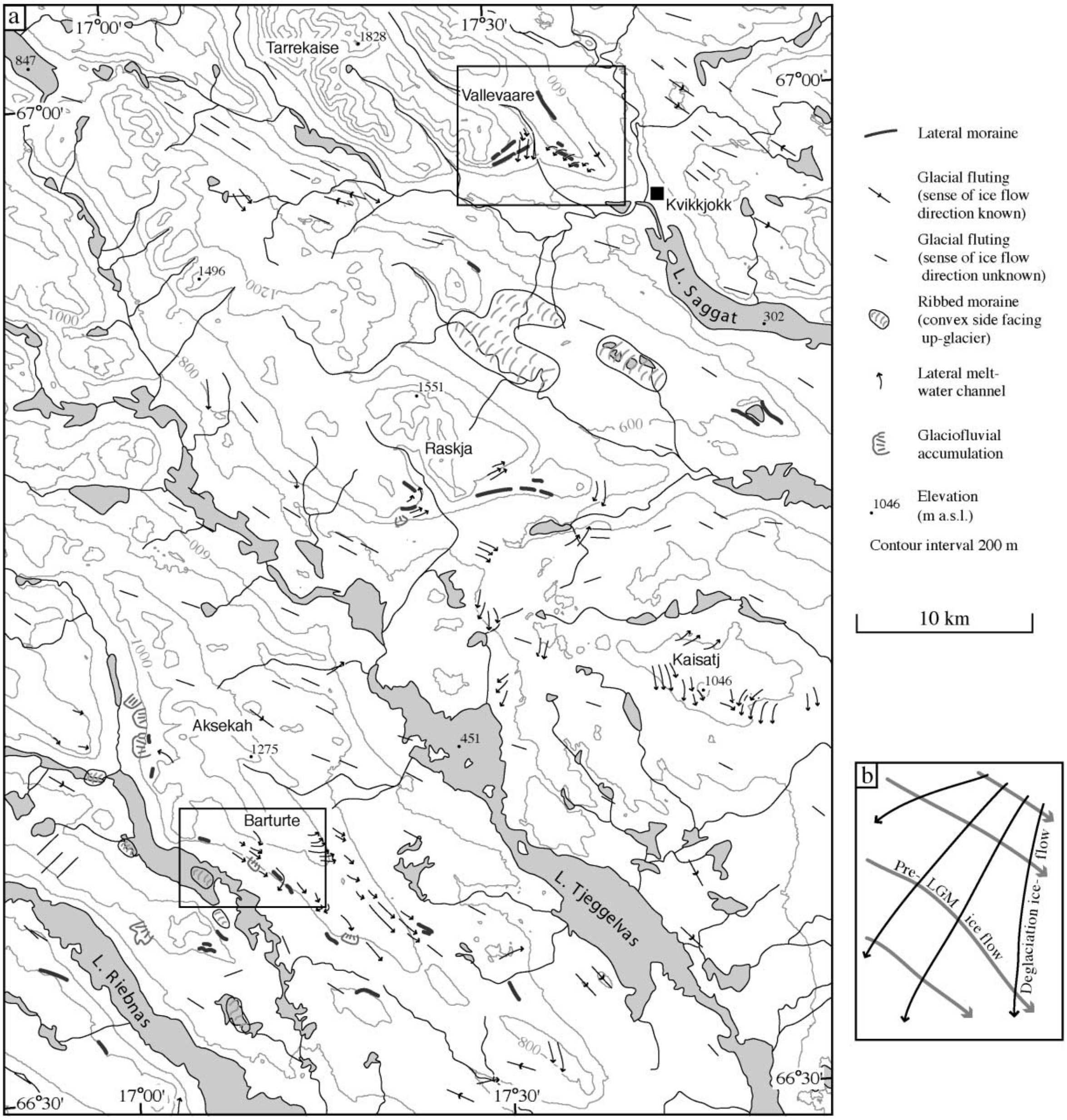

Fig. 2. (a) Glacial geology in the investigated area. Boxes refer to maps in Figs. 5 and 6. (b) Different ice flow regimes in the Kvikkjokk area. The map shows the same area as in (a). LGM ice flow is poorly constrained over this area and therefore not depicted, but as the ice divide during this time was positioned over the Gulf of Bothnia, LGM ice flow is likely to have been from the east. Elevation model courtesy of Lantmäteriverket (National Land Survey), 2000. Excerpt from GSD-elevation data, case number L2000/646.

in the east–west trending valleys, along the eastern fringe of the Scandinavian mountain range (Kleman, 1992). They were found in a relatively narrow zone from north to south, which was named the Torne träsk–Hornavan zone (Kleman, 1992). These landforms may also correlate to pre-LGM lateral channels described by Rodhe (1988). The ice flow direction indicated by these moraines contrast in the direction from glacial meltwater channels and glacial fluting produced during the last deglaciation (Fig. 1). Hence, Kleman (1992) suggested that these moraines were of a pre-LGM origin. Hättestrand (1998) mapped more of similar moraines and extended their zone of occurrence to the north and south.

In this paper, we describe the morphology of several of these lateral moraines in the northern Sweden in detail and discuss the possible age and extent of the ice sheet that deposited them.

2. Field site description

The Kvikkjokk area is located in the northeastern part of the Scandinavian mountain range (Figs. 1 and 2a). We selected the area because it contains a large number of lateral moraines.

The Kvikkjokk area belongs to the Caledonian orogenic belt with a bedrock geology consisting of various allochthonous rocks. The western part consists mainly of mica schists, marble, and quartzitic rocks (Kulling, 1972). Towards the east, geology is more complicated with different schists and igneous rocks. Around Mt. Vallevaare, a key locality, the dominant rock is amphibolite (Fig. 2a). The southeastern corner is outside the Caledonian belt and is comprised of crystalline pre-Cambrian rocks (Kulling, 1972).

The main elevation axis of the mountain range is located west of the Kvikkjokk area and all rivers drain eastward towards the Gulf of Bothnia. Most major valleys are glacially sculptured U-shaped valleys and commonly exhibit a local relief of more than 500 m. Upland areas between major valleys often have a "relict" appearance with tors, fluvially shaped valleys, and blockfields (cf. Rea et al., 1996; Kleman and Stroeven, 1997; Ballantyne, 1998). Periglacial landforms are common above the tree line at approximately 700 m a.s.l. (Ulfstedt, 1980).

The Weichselian glacial history, and in particular the deglaciation, of the area is well understood. During the early stages of the Weichselian glaciation, ice emerging from highlands in Norway reached the Kvikkjokk area and beyond (Ljungner, 1949; Kleman et al., 1997; Boulton et al., 2001). Through later stages, the ice dispersal centre moved eastward, implying ice flow towards the west over the area (Lundqvist, 1947; Ljungner, 1949; Kleman et al., 1997). The deglaciation pattern is more complicated because the Kvikkjokk area hosted the last remnants of the Weichselian ice sheet (Kleman, 1992; Kleman et al., 1997; Boulton et al., 2001). Nevertheless, the Kvikkjokk area experienced ice flow towards the southwest during most of the deglaciation (Figs. 1 and 2; Ulfstedt, 1980, Nordkalott project, 1986a,b; Kleman, 1992; Kleman et al., 1997; Boulton et al., 2001).

3. Methods

Glacial geomorphology was mapped from colour infrared aerial photographs (approximate scale 1:60 000), using a Zeiss Jena interpretoscope with variable magnification. Aerial photo interpretations were transferred onto a topographical base map (Fig. 2a) in a CAD computer environment.

Mapped glacial landforms include lateral moraines, glacial fluting, ribbed moraines and glaciofluvial erosional and depositional landforms. Special attention was paid to obliquely crosscutting landforms where relative age relationships could be established. Large-scale glacial erosional landforms, such as cirques and U-shaped valleys, were not mapped. Rudberg (1988) showed that the U-shaped valleys are probably formed by cumulative erosion during several glaciations and they are therefore not useful in this context. Neither were nonglacial landforms, such as fluvial- and periglacial landforms, mapped because of their limited value for ice sheet reconstructions.

A large number of glaciofluvial channels are visible in the aerial photographs but only strictly the lateral channels were mapped. Lateral meltwater channels are excellent indicators of ice flow direction and are one of few possible ways of mapping ice movement of cold-based ice sheets (Mannerfelt, 1945; Maag, 1969; Ives and Kirby, 1964; Borgström, 1989; Dyke, 1993; Sollid and Sørbel, 1994). Lateral channels are easily identified in aerial photographs because they gently trend downslope. Given favourable conditions, they also provide a rough estimate on paleo-ice sheet elevation and slope (e.g., Mannerfelt, 1945; Maag, 1969).

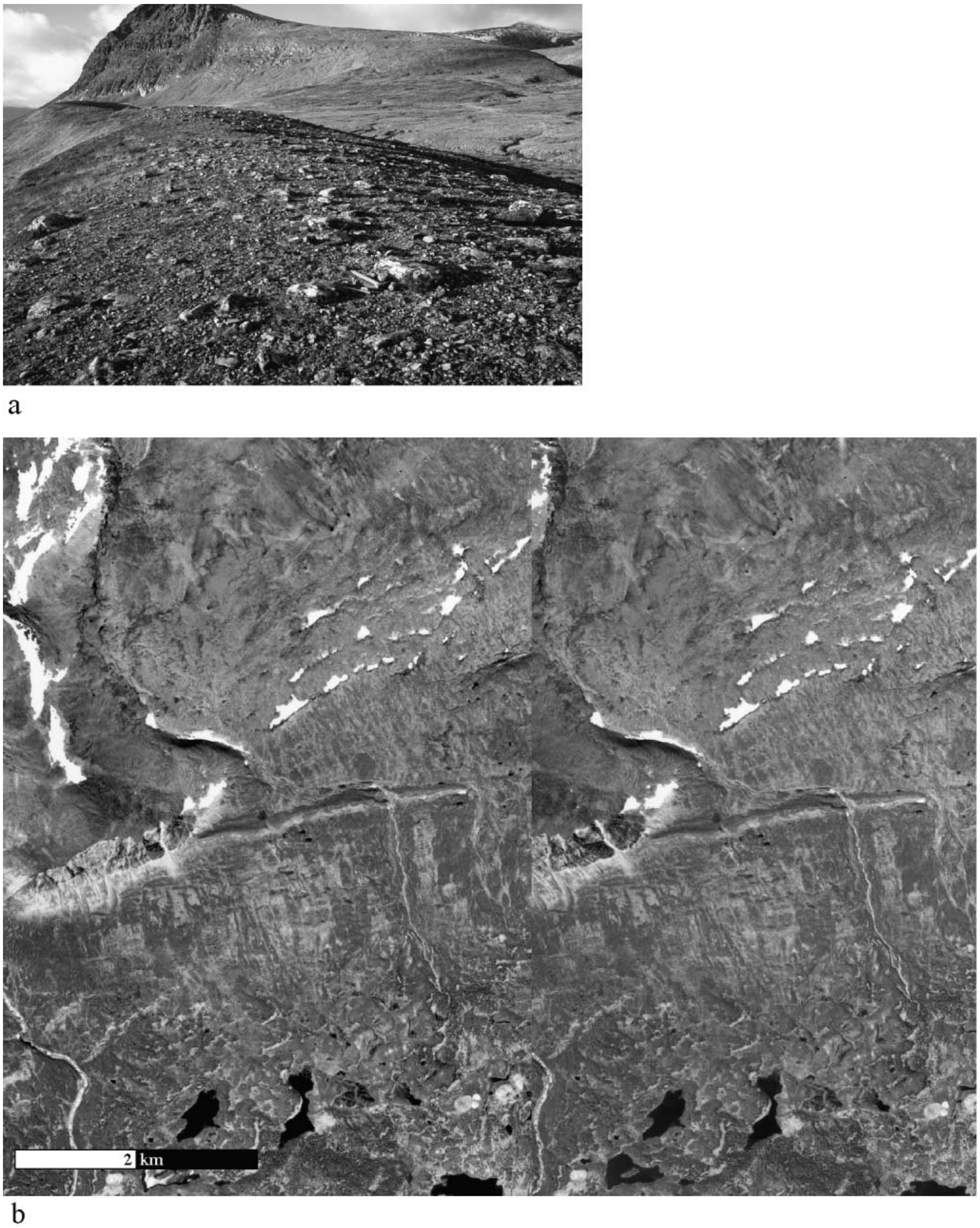

Fig. 3. (a) Photograph showing the main lateral moraine at Raskja seen from east. The ice flow was towards the viewer at the time of moraine formation. The lateral moraine starts at the steep cliff in the distance. Note that the sledgehammer in the foreground is for scale. (b) Aerial photo stereogram of lateral moraine at Raskja. North is towards top of photographs. Aerial photographs are copyright of the National Land Survey of Sweden.

Particular attention was also paid to lateral moraines because they likely reflect a stationary ice margin (Boulton and Eyles, 1979), and give a precise estimate on paleo-ice surface elevation. In addition, lateral moraines are landforms that can be attributed to a distinct glacial event compared to, for example, drumlin fields or eskers, which are formed in a time transgressive manner. In this context, we rely on Boulton and Eyles' (1979) classification of lateral moraines. That is, lateral moraines can be derived from ice-contact scree and lateral dumping of sub-, en-, or supraglacial material. Lateral moraines (and frontal moraines) mainly belong to the proglacial or supraglacial landform association (Boulton, 1976).

Fieldwork was carried out at the lateral moraines of Mt. Vallevaare and Mt. Barturte (Fig. 2a) by detailed mapping of moraine morphology and soil sampling. Soil samples were used for soil type description and analysis of grain size, lithology, and clast shape.

The elevation model in Fig. 1b was obtained from freely available data (Hastings and Dunbar, 1998). Elevation contours in Fig. 2a were extracted from a digital elevation model with a horizontal resolution of 50 m. Digital elevation models were processed using software described by Smith and Wessel (1990) and Wessel and Smith (1998).

4. Description of the glacial geology

There are geomorphological traces from several glacial stages in the Kvikkjokk area. Deglacial landforms are, in general, rather scarce but prominent deglacial traces can be seen on Mt. Vallevaare and Mt. Kaisatj (Fig. 2a) as numerous southward trending lateral meltwater channels. Glacial fluting north of lake Riebnas also belongs to a late stage in the deglaciation (Fig. 2a). Several other glacial meltwater channels and glaciofluvial accumulations can probably also be attributed to the deglaciation. All these landforms indicate that the final ice flow direction in the area was from north–northeast (Fig. 2b). The reason why glacial meltwater channels are dominant deglacial landform features, instead of glacial lineations, could be cold-based conditions during the deglaciation (cf. Borgström, 1989; Dyke, 1993; Sollid and Sørbel, 1994).

Many of the glacial landforms seem to be older than the last deglaciation. These landforms include ribbed moraines, meltwater channels, and lateral moraines. Relative ages can be interpreted by crosscutting relationships and by correlating landforms to Fennoscandian glaciation models (Kleman et al., 1997; Boulton et al., 2001). For example, meltwater chan-

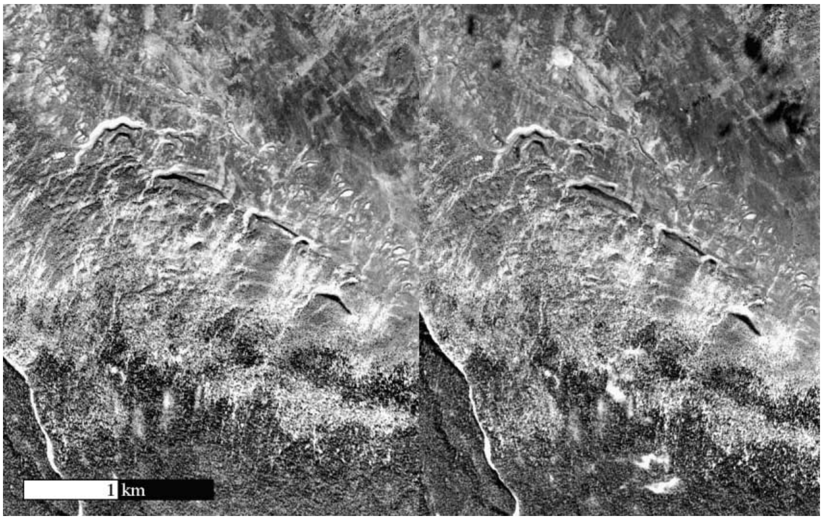

Fig. 4. Aerial photo stereogram of the lateral moraines at Mt. Vallevaare. North is towards top of photograph. For the location of the stereogram, refer to the map in Fig. 6. The lateral moraines are dissected by crosscutting meltwater channels in several places. The meltwater channels are clearly morphostratigraphically younger than the lateral moraines and the flow is in a contrasting direction compared to the moraines. Note that the sharp and undegraded appearance of the meltwater channels. Aerial photographs are copyright of the National Land Survey of Sweden.

nels crosscut lateral moraines at Mt. Vallevaare (at almost 180°) and Mt. Barturte (Figs. 2a and 4); hence, lateral moraines must be older than meltwater channels. Ice flow emanating from northwest of the Kvikkjokk area appears to have formed all lateral- and ribbed moraines in the area. Such an ice flow direction is not consistent with deglaciation ice flow and must be attributed to an ice sheet with a completely different configuration (Figs. 1 and 2b). It is thus possible to use regional data and interpretations in conjunction with the present investigation to infer likely age relationships between landforms.

All lateral moraines, except two south of lake Saggat (Fig. 2a), are located high on valley slopes in major U-shaped valleys at an elevation of ~ 800 m a.s.l., or 200–400 m above the valley floor. Their morphology is typical of lateral moraines, sloping towards the east or southeast by a gradient of 1.5–3°, and was easily distinguishable in aerial photographs. Most lateral moraines in the area are relatively distinct

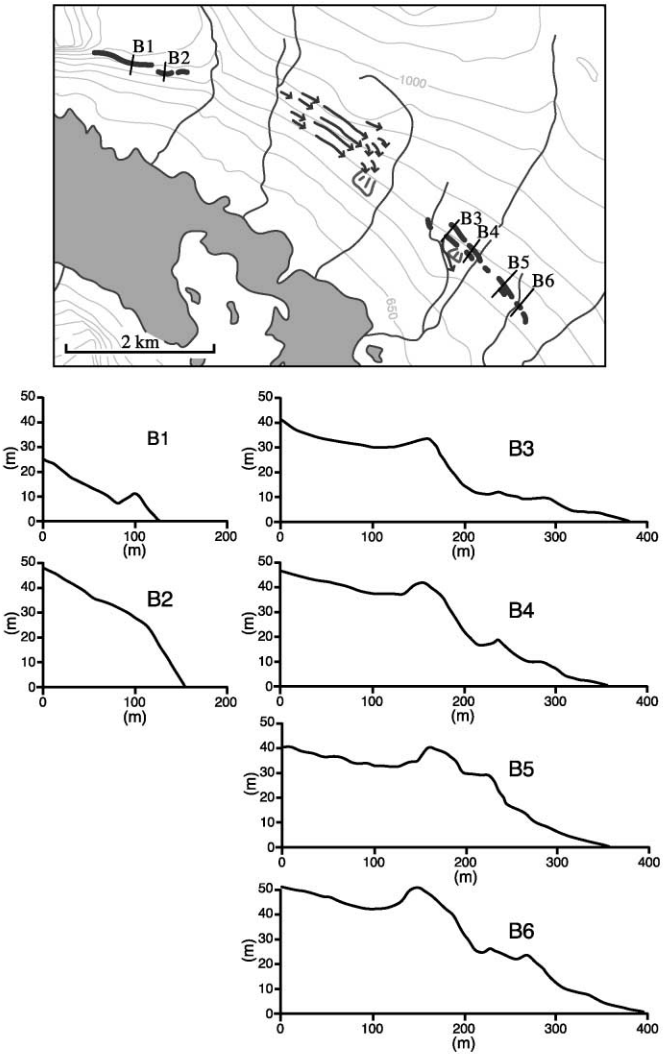

Fig. 5. Profiles across the lateral moraines at Mt. Barturte. Vertical exaggeration is 2.7. Lateral moraine in the profile B3–B6 is ~ 20-m thick for the main ridge and 5–10 m for the downslope minor ridge, while the lateral moraine in profile B1 and B2 is just a few metres thick and lacks parallel ridges. For the map legend, see Fig. 2a.

and well preserved (Fig. 3), although younger glacial meltwater channels have dissected several moraines (Fig. 4). We observed a typical moraine thickness of 10–20 m in these natural sections (Figs. 5 and 6). Some lateral moraines have a subdued topography and their morphology is more of a lateral terrace (Figs. 5 and 6).

Another common feature of the lateral moraines is that they are double-crested. Several profiles across moraines at Mt. Barturte (Fig. 2a) show that there are minor parallel ridges downslope of the major ridge (Fig. 5). The ridges are vertically separated by 15–30 m (Fig. 5). The two westernmost moraines at Mt. Vallevaare are vertically separated by ~ 130 m (Figs. 2a and 6). The eastern lateral moraines at Mt. Vallevaare also have double-crested morphology, although very subdued, with a smaller ridge located closely upslope from the main ridge.

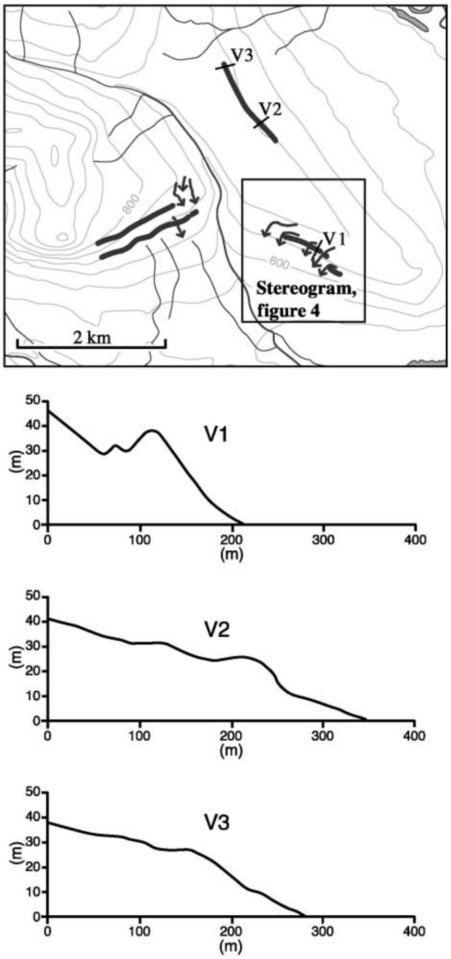

Fig. 6. Profiles across the lateral moraines at Mt. Vallevaare. The vertical exaggeration is 2.7. The main lateral moraine shown in profile V1 is ~ 25-m thick, while the minor moraine upslope is 2–3-m thick. Profiles V2 and V3 show a height of less than 10 m for the main lateral moraine, while the upper parallel minor moraine has a more terrace-like appearance. For the map legend, see Fig. 2a.

The lateral moraines are generally situated where the slope breaks from a gentle upper slope to steeper lower slopes. The distal (upslope side) depression is often infilled by various sediments. The main lateral moraine at Mt. Barturte (Fig. 5, profiles B3 to B6) also dams two small lakes. An approximately 4-km-long central portion of the lateral moraine at Mt. Barturte seems to be "missing." Hättestrand (1998) argued that the post-depositional mass movement processes might have transported it down slope, a phenomenon observable at several similar lateral moraines in the Swedish mountains.

The abundance of boulders and cobbles in the moraines varies, but in general, coarser fractions are more dominant on moraine segments immediately down-ice of vertical cliff faces. Surficial boulders on lateral moraines at Mt. Vallevaare and Mt. Barturte are often ventifacted, other boulders are heavily weathered causing granular disintegration.

Analysis of soil samples shows that moraine sediments at both Mt. Vallarvaare and Mt. Barturte are a diamicton interpreted to be a glacial till. In the case of Mt. Vallevaare, the till seems to be transported relatively short since dominant rocks are local mica schist and amphibolite. Material in the Mt. Barturte moraine is of a more mixed origin with a high percentage (c. 50%) of crystalline rocks in the pebble fraction. This might be explained by the presence of a large crystalline window in the Caledonian bedrock west of Mt. Barturte (Kulling, 1972). Pebbles and cobbles are generally slightly rounded in all samples, indicating a relatively short subglacial transport. There are also intermixed angular rock fragments indicating a supraglacial or englacial origin. Steep-sided valley walls upstream of most lateral moraines (e.g., Fig. 3) offer proximal sources for rock fall onto the glacier surface, producing supraglacial fragments. However, the clast lithology data does not support inferences on transport pathways.

5. Discussion

All lateral moraines, also those outside the Kvikkjokk area, occur within a well-defined zone, some tens of kilometres wide (the Torne Träsk–Hornavan zone; Kleman, 1992; Hättestrand, 1998). It is therefore likely that they were all formed within a well-defined time-interval, corresponding to a glacial standstill.

The lateral moraines could not have been deposited during one single event because of their double-crested morphology. The small vertical distances between the two crests at Mt. Barturte and eastern Mt. Vallevaare indicate a deposition within a relatively short period of time where the upper crest was deposited before the lower one (cf. Boulton and Eyles, 1979). The westernmost lateral moraines at Mt. Vallevaare suggest a more substantial shift in ice-surface elevation between deposition events. Since they are not superimposed with each other, we cannot infer their relative age relationship.

It is somewhat puzzling that there are well-preserved lateral moraines but no associated frontal moraines. We see two possible explanations for this; first, displacement of the glaciers front can be dramatic due to the varying mass balance. However, this is accompanied by a relatively small change in ice surface elevation (cf. Vialov, 1958; Boulton and Eyles, 1979). Thus, a substantial lateral moraine can be deposited only where small frontal moraines may have the opportunity to form (Boulton and Eyles, 1979). Second, there may have been frontal moraines on the valley floor, subsequently eroded during latter glacial stages. Lateral moraines may have been protected from glacial erosion by their higher position in the landscape and hence, higher probability of being covered by cold-based glacial ice (cf. Sugden and John, 1976; Glasser, 1995; Näslund, 1997). This agrees well with numerous studies from the northern Fennoscandia, showing that relict landforms and landscapes have been preserved beneath cold-based ice throughout much or all of the Weichselian glaciation (Rodhe, 1988; Lagerbäck, 1988a,b; Kleman, 1992; Sollid and Sørbel, 1994; Rea et al., 1996; Kleman and Stroeven, 1997; Hättestrand, 1998; Kleman and Hättestrand, 1999). This model of preservation is consistent with the scarcity of glacial lineations located in topographical positions above major valley floors (Fig. 2a). However, glacial meltwater channels are found at relatively high elevations, sometimes cross-cutting the lateral moraines (Fig. 2).

There are several geomorphological and glaciological constraints on the minimum age that suggest the lateral moraines are older than the last deglaciation (Figs. 1, 2, and 4). However, there is no control on the maximum age of the lateral moraines; they may have been formed during any late Cenozoic glaciation.

Some constraints on the age of the lateral moraines are offered by what is known about the Weichselian glaciation (e.g., Lundqvist, 1992; Kleman et al., 1997; Boulton et al., 2001). It is most likely that the moraines formed before 75 ka BP (prior to marine oxygen isotope (MOI) stage 4). Throughout MOI stages 2, 3, and 4, the Fennoscandian ice sheet was too big and its ice divide located to the east of the Kvikkjokk area, which makes the formation of the described lateral moraines impossible. At the transition between MOI substages 5d and 5e, the Weichselian glaciation commenced with a mountain centred ice sheet in Fennoscandia (Mangerud, 1991; Lundqvist, 1992; Kleman et al., 1997; Boulton et al., 2001). As mentioned before, Boulton et al. (2001) argued that the Weichselian originated in two centres, one in the southwestern Norway, and one in the northern Norwegian/Swedish mountains near the investigated area. During MOI substages 5b and 5d, the ice sheet expanded to marginal positions in the interior of northern and central Sweden (Kleman et al., 1997). Substages 5a and 5c were cool interstadials, probably with persisting ice sheets in the mountains (Lundqvist, 1992; Kleman et al., 1997). If the lateral moraines were at all formed during the Weichselian, we suggest that this happened either during the advance or retreat of one of the early Weichselian ice sheets (MOI substages 5b or 5d), or they may mark the innermost positions of the ice sheet during interstadials 5a or 5c. The lateral moraines would then represent an ice sheet during initial or intermediate stages of the last glaciation. However, it should be stressed that they may also belong to a glacial stage during previous glaciations (e.g., the Saahlian).

The ice sheet that deposited the lateral moraines must have been relatively small and restricted to the Scandinavian mountains and highlands. If the inferred ice sheet reached the Norwegian coast, calving must have constrained the western ice margin. The Kvikkjokk area is only 170 km from the Norwegian coast.

This implies that the ice sheet that deposited the lateral moraines was no more than approximately 170-km wide in the area. Mangerud et al. (1981) and Mangerud (1991) showed that the ice reached the fjords in the southern Norway during MOI substages 5b and 5d. However, Sejrup et al. (2000) reported no such advance until MOI substage 5b. Nevertheless, it is clear that the Fennoscandian ice sheets reached the Norwegian fjords and coast even during the relatively moderate ice sheet advances.

An ice thickness profile for the inferred ice sheet can be calculated by constructing a parabolic ice sheet surface profile. The equation used is:

$$h = 3.4\sqrt{x} \qquad (1)$$

where h is ice surface elevation (m) and x is distance from the ice front (m) (Paterson, 1994; Fig. 7). We assume steady-state conditions, no basal sliding, and a horizontal bed for this calculation. None of these assumptions is probably valid, at least not for the inferred ice sheet as a whole, but an approximate ice sheet profile can nevertheless, be calculated in this way. The profile in Fig. 7 indicates an ice sheet with its accumulation area within the highest parts of the mountain range, but with all higher peaks protruding as nunatakks. Maximum ice thickness for this ice sheet was ~ 600 m in the inner parts. Interestingly, the equilibrium line altitude must have been at an abnormally high altitude in the case of the discrete valley glaciers, at least if the lateral moraines were formed at the ablation area (Boulton and Eyles, 1979). This may indicate that the accumulation area constituted an ice cap feeding a network of valley glaciers (Jansson, personal communication, 03/2001) similar to, for example, Jostedalsbreen in the southern Norway, but at a much larger scale. This model is also consistent with the existence of the Svartisen ice cap west of the Kvikkjokk area and large areas of elevated terrain in northwestern Scandinavia. Following the arguments by Ives et al. (1975) and Payne and Sugden (1990a,b), northwestern Sweden and Norway provide excellent settings for ice cap formation, given a moderate increase in mass balance (Jansson et al., 1999). This is in good agreement with the statements by Kleman et al. (1997) and Boulton et al. (2001) pointing at these areas as probable core areas for ice sheet initiation. The lateral moraines may thus be evidence for such an ice sheet initiation.

6. Conclusions

A west-centred ice sheet, flowing roughly towards the southeast in the Kvikkjokk area, deposited lateral moraines during a standstill during either the advance or retreat of the ice sheet. Apart from lateral moraines, ice flow direction is confirmed by the distribution and direction of ribbed moraines, glacial lineations, and lateral meltwater channels. Lateral moraines are clearly older than the late Weichselian, and were possibly formed during the early part of the last glaciation. However, we cannot exclude the possibility that they were formed before the Weichselian.

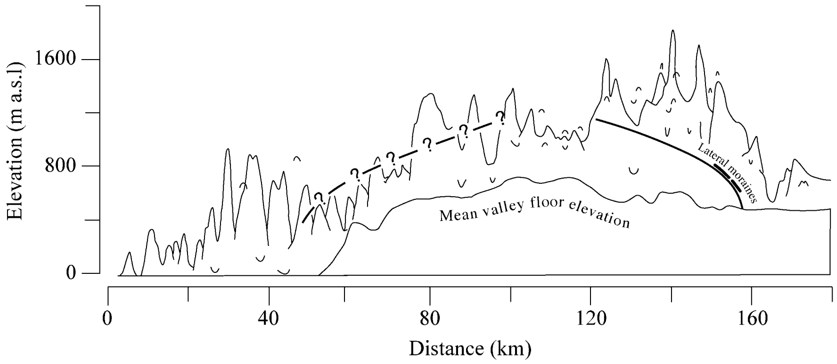

Fig. 7. Profile across the Scandinavian mountains, from the Norwegian coast to the Kvikkjokk area. Vertical exaggeration is 33. For the location of the profile, see Fig. 1. The parabolic ice profile was fitted to the position and elevation of the lateral moraines. Towards the Norwegian coast, control on the ice profile is lacking. Therefore, only a hypothetical profile is outlined. Most of the higher peaks are above the ice surface.

Subsequent glacial advances, following the lateral moraine formation, have covered the investigated area. However, only negligible modification of landforms has occurred, probably due to persistent frozen basal conditions. Ice marginal processes affected the landscape during the last deglaciation and a number of glaciofluvial landforms were produced, as well as glacial flutings.

The inferred ice sheet probably comprised an ice cap drained by outlet glaciers and was at a maximum ~ 600-m thick in the interior parts. Maximum east–west width of the inferred ice sheet was no more than 170 km because calving at the Norwegian coast then would restrain the western ice margin.

The described relict lateral moraines and associated glacial geomorphology give us a better understanding of ice sheets prior to the last glacial maximum, and can provide ice sheet modellers, glacial geologists, and climatologists with constraints on these elusive stages. Lateral moraines are very well suited in this regard because they reflect a discrete glacial standstill and provide a precise input data on the ice position and thickness for ice sheet reconstructions.

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