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The glacial geomorphology of central and northern Sweden

Clas Hättestrand

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Cover: Moraine ridge at Nakervare, eastern Abisko mountains, viewing north (Photo: Clas Hättestrand).

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ABSTRACT

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The glacial geomorphology of central and northern Sweden mostly records the decay of the Fennoscandian ice sheet during the Late Weichselian deglaciation. As the ice margin retreated, a series of glacial landforms, including glacial lineations (drumlins, fluting), eskers and ribbed moraines, were formed successively inwards. This landform assemblage is commonly found in the interior parts of central and northern Sweden. De Geer moraines also occur in many parts of the study area and are found below the highest post-glacial shoreline. However, their distribution is confined to areas of low relief, such as the sub-Cambrian peneplain of south-central Sweden and along the northern coast of the Bothnian Bay. In areas above the highest post-glacial shoreline, there are glacial meltwater channels that increase in abundance towards the position of the final ice remnants. This is interpreted to be associated with an increasing fraction of the bed being cold-based towards the central part of the ice sheet. Within these cold-based zones, meltwater channels are commonly superimposed on remnants of older glacial landscapes. This is most prominent in northeastern Sweden, where several generations of older glacial and non-glacial landforms are found. A nearly undisturbed Early Weichselian deglacial landscape, that includes drumlins, end moraines, Veiki moraine, eskers, meltwater channels, and minor occurrences of ribbed moraine, occupies much of northeastern Sweden. The Veiki moraine and its associated terminal moraines outline two ice marginal positions of an Early Weichselian ice sheet, each comprising several well-defined lobes. In addition, a set of marginal meltwater channels and glacial lineations, indicating ice flow from the north, is described from northeastern Sweden. This set of landforms is tentatively correlated with a north-centred ice sheet during the second Early Weichselian stadial. In the eastern part of the Scandinavian mountain range, segments of large lateral moraines are found. These mark the upper surface of outlet glaciers draining ice eastwards from a pre-Late Weichselian ice sheet centred over, or to the west of, the mountain chain's elevation axis. A specific type of moraine ridges, "complex moraines", are found to be geographically and morphologically integrated with these lateral moraines, and are interpreted to have formed by down-slope sliding of lateral moraine segments. In the central and western parts of the mountain chain, much of the Late Weichselian ice sheet seems to have been fully warm-based and scouring its bed. Therefore, the ice sheet produced very few glacial landforms in the unconsolidated deposits, with the exception of some glacial lineations, small eskers and glacial meltwater channels.

Key words: Glacial geomorphology, drumlins, fluting, ribbed moraine, De Geer moraines, Veiki moraine, glacial meltwater channels, ice sheet dynamics, Weichselian glaciation, Fennoscandian ice sheet, Sweden.

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Introduction

Aims and scope

Regional maps of glacial geomorphology are important sources of input data for reconstructions of past ice sheet evolution (G. Lundqvist 1961; Dyke & Prest 1987; Boulton & Clark 1990; Kleman & Borgström 1996; Kleman et al. 1994, in press). For example, glacial lineations are used to infer ice-flow directions under warm-based ice sheets, end moraines are used to mark the position of ice margins at interruptions or re-advances during the deglaciation of ice sheets, and extensive series of lateral meltwater channels are interpreted to mark the retreat of cold-based parts of ice sheets. Detailed and accurate maps of these landforms are therefore essential for the success of ice sheet reconstructions. In this work, emphasis has been put on landforms that are of potential importance for the interpretation of glacial dynamics, i.e. glacial lineations, ribbed moraines, end moraines, Veiki moraine, eskers and glacial meltwater channels. Glacial bedrock landforms, such as cirques, u-shaped valleys, and roches moutonnées, are not included in this study, because they may be formed over many glaciations, and are therefore difficult to interpret in terms of ice-flow and configuration changes of individual ice sheets.

There have been many recent advances in the understanding of the behaviour of past ice sheets. In particular, the recognition of landforms and landscapes, derived from earlier glacial phases and subsequently preserved under cold-based ice has changed the view on Fennoscandian and Laurentide palaeoglaciology (e.g., Sollid & Sørbel 1984, 1988; Lagerbäck 1988a, b; Lagerbäck & Robertsson 1988; Kleman & Borgström 1990; Kleman 1992, 1994; Kleman et al. 1992, 1994; Dyke 1993). Such preserved glacial landscapes, predating the last glaciation, can locally yield detailed information concerning flow patterns and dynamics of earlier ice sheet configurations. Therefore, when mapping landforms, I have paid special attention to cross-cutting relations, to sort out the relative age between different glacial landform systems.

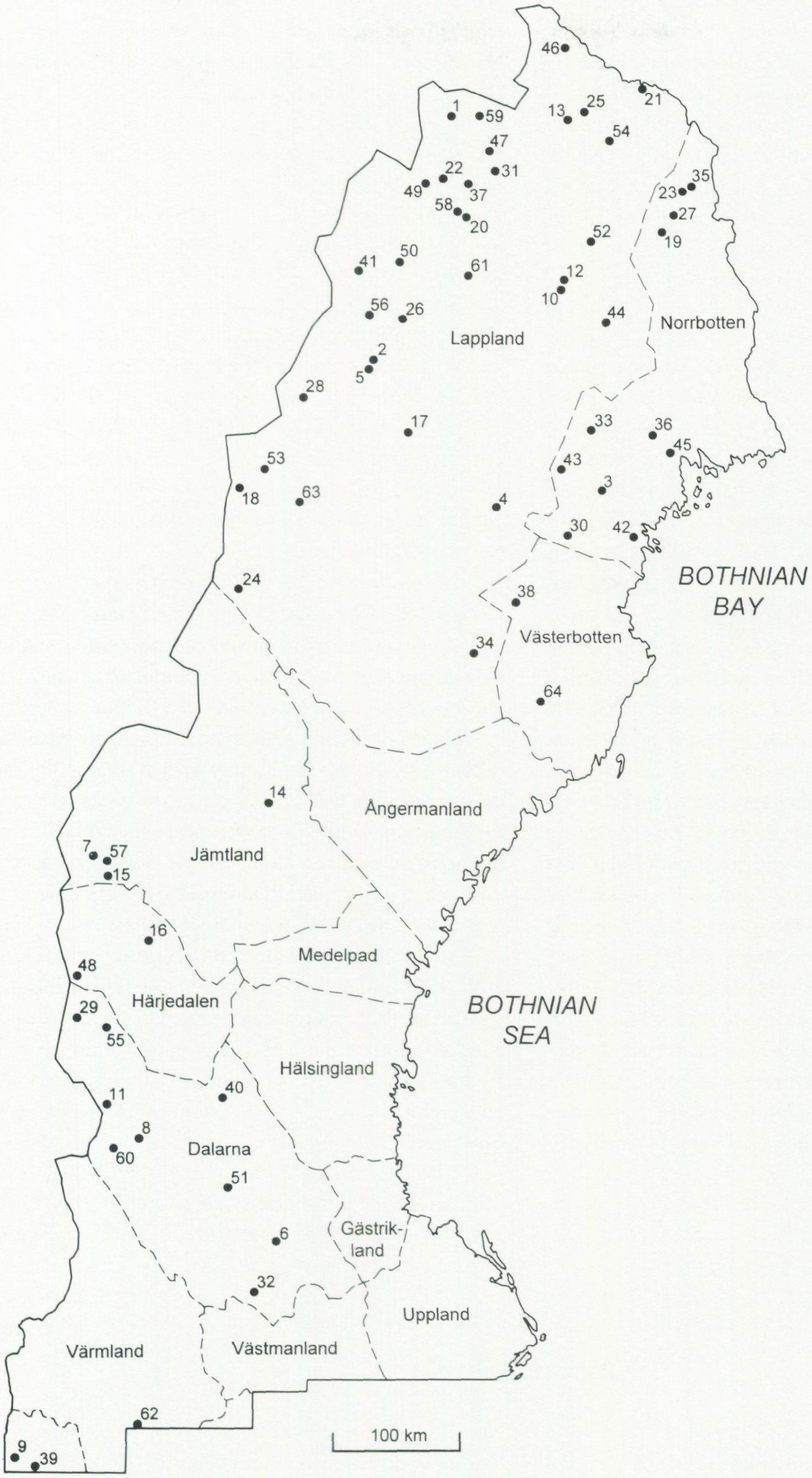
A problem with regional glacial geomorphology maps is that they often are compilations of different data sources, gathered by scientists with different backgrounds, interests, experiences, and research methods (i.e., field-based versus aerial photograph-based studies). This may result in variations in the level of generalisation, classification system, and accuracy of the maps. One of the primary objectives of this work is to present a homogeneous map, mapped consistently using a single classification system, throughout the study area. This has been made possible by the availability of new high-altitude aerial photographs, at the scale 1:150,000, covering most of Sweden. Because of their small scale, it is possible to map large areas in a reasonable period of time, while retaining the high spatial resolution of aerial photographs when compared to satellite images.

The map presented in this paper shows the distribution of glacial landforms in central and northern Sweden. The study area (Fig. 1) covers all of the Norrland terrain typical of central and northern Sweden (Lidmar-Bergström 1995), and extends down to the sub-Cambrian peneplain of central Sweden. This area comprises the core area of glaciation in Fennoscandia and also includes some of the main palimpsest regions where glacial landscapes of different age are superimposed on each other.

The course of deglaciation of the Late Weichselian Fennoscandian ice sheet, and its associated landforms and deposits, have been studied extensively during the last century. The works of many geologists and geomorphologists have probably made the late-glacial history of Fennoscandia some of the best known in the world. Despite the many recent advances in palaeoglaciology referred to earlier, the evolution of earlier glacial events is considerably less well known. For example, Ljungner's (1949) scheme on the ice divide positions of the Fennoscandian ice sheet, still stands more or less unchallenged. Therefore, when discussing the distribution patterns of different landforms, I will focus on glacial landforms and landscapes that derive from pre-Late Weichselian glaciations. Thus, to use the metaphor of Lagerbäck (1988a, p. 485), clearing away some small parts of the cosmic dust that obscure the "Weichselian Galaxy".

Previous work

Mapping of glacial geomorphology has a long tradition in Sweden and the first regional maps were published in the early 1900's (e.g., Högbom 1906; Frödin 1925). The general distribution pattern of distinct and easy-detectable landforms related to the deglaciation, such as eskers, deltas, end moraines and De Geer moraines, have long been known. Such features are mostly included in Geological Survey maps of the Quaternary deposits (the Aa-, Ae- and Ca-series of the Geological Survey of Sweden). For example, the distribution of eskers in Sweden is shown fairly accurately in the 1952 "Atlas över Sverige" (G. Lundqvist 1952).



1. Abisko
2. Aksekah Mt
3. Älvsbyn
4. Arvidsjaur
5. Bartaure L
6. Borlänge
7. Bunnerfjällen Mts
8. Dala sandstone plain
9. Dals-Ed
10. Dundret Mt
11. Fulufjället Mt
12. Gällivare
13. Golgukjaure L
14. Hammerdal
15. Härjångån R
16. Håsjövålen
17. Hornavan L
18. Jofjället Mt
19. Junosuando
20. Kaitumjaure L
21. Karesuando
22. Kebnekaise Mts
23. Keräntöjärvi
24. Klimpfjäll
25. Kuortovaara Mt
26. Kvikkjokk
27. Lainioälven R
28. Laisälven R
29. Långfjället Mt
30. Långträsk
31. Lävasjåkka R
32. Ludvika
33. Lule R
34. Lycksele
35. Naakajärvi
36. Niemisel
37. Nikkaluokta
38. Norsjö
39. Ödsköt
40. Orsa Finnmark
41. Padjelanta
42. Piteå
43. Piteälven R
44. Purnu
45. Råne R
46. Råsto Mt
47. Rautasjaure L
48. Rogen L
49. Sälka
50. Sarek Mts
51. Siljan L
52. Skaulo
53. Södra Storfjället Mt
54. Soppero
55. Städjan-Nipfjället Mts
56. Staika Mt
57. Stor-Stensdalen
58. Tjuoltajaure L
59. Torne Träsk L
60. Transtrand Mts
61. Ultevistuottar Mt
62. Vänern L
63. Väretsfjället Mt
64. Vindeln

Fig. 1. Location map. The numbered locations refer to names mentioned in the text (mountain(s) – Mt/Mts, lakes – L, and rivers – R).

The use of aerial photographs in the mapping of glacial geomorphology has greatly increased the knowledge of the distribution of landforms which are difficult to map during exclusively field-based work. Examples of such landforms are drumlins, ribbed moraine and various types of hummocky moraine. However, despite a complete set of high-quality aerial photographs covering Sweden, few studies of regional glacial geomorphology have been made. In the late 1970's and early 1980's the geomorphology of the Swedish part of the Scandinavian mountain range was mapped at the scale 1:250,000 (Soyez 1971, 1974; Melander 1980; Ulfstedt 1980; Hoppe 1983; Borgström 1989). The northern part of this area was later mapped by Kleman (1992). The glacial geomorphology of northernmost Sweden (north of approximately 66°N) was also mapped by Robert Lagerbäck, Hugo Minell, and Lars Rodhe, as a part of the Nordkalott project (1986a, b). In addition, glacial geomorphology is included in an on-going survey of the surficial deposits of the coastal and interior parts of northern Sweden (the "Ak"-map series of the Geological Survey of Sweden). However, each of the mentioned maps covers only small parts (<15%) of Sweden's total area. The nation-covering maps of the glacial geomorphology of Sweden (e.g., Rudberg 1987, Fig. 4.4–10; Fredén 1994, pp. 134–135) are compilations, based primarily on Geological Survey of Sweden maps of surficial deposits.

Methods

The glacial geomorphology was mapped by aerial photograph interpretation and field control. The aerial photographs used were panchromatic high-altitude pictures taken at 1:150,000 scale. These small-scale photographs represent an intermediate tool between ordinary 1:30/60,000 aerial photographs and satellite images, and were found very useful for this kind of mapping. Each photograph covers 35x35 km, and has a potential geometric resolution of about 5 m. A wide range of landforms, ranging from mega-scale drumlins (10-kilometre scale) to minor eskers and channels (10-meter scale), can be mapped using these pictures. To be able to fully utilise these aerial photographs, a high quality stereoscope with variable magnification is essential. In this study, a Zeiss Jena Interpretoscope with 2–16x magnification was used. Each stereopair of aerial photographs was interpreted in both 2x and 7x magnification, to be able to map both large- and small-scale features. At locations of special interest, up to 16x magnification was necessary. Transfer of information onto transparent overlays (an intermediate stage towards manuscript maps) was made in 7x magnification.

In the western part of the map, covering the mountain range (about 10% of the total study area), 1:150,000-scale aerial photographs are lacking. Therefore, this area was mapped using black-and-white prints of infra-red 1:60,000 aerial photographs. In order to retain the same generalisation level in this area, a lower magnification (3x) was used while transferring information onto transparent overlays.

Field work was conducted during the summers of 1992, 1993, 1995, and 1996. During these field controls, localities of special interest and importance were visited and checked against the aerial-photograph interpretations. The locations visited are distributed over much of the study area, but emphasis was put on the eastern part of the mountain range (the premontane region) and northeasternmost Sweden.

Glacial landforms

This section provides a description of mapped landforms and symbols used. In addition, the anticipated accuracy of the mapping of each landform is discussed. For this purpose, comparisons are made with detailed maps of glacial geology, based on air-photo interpretations of large-scale aerial photographs and extensive field controls (Hoppe 1983; Nordkalott project 1986 a, b; Borgström 1989; Hättestrand 1994; and the Ak-series maps of the Geological Survey of Sweden).

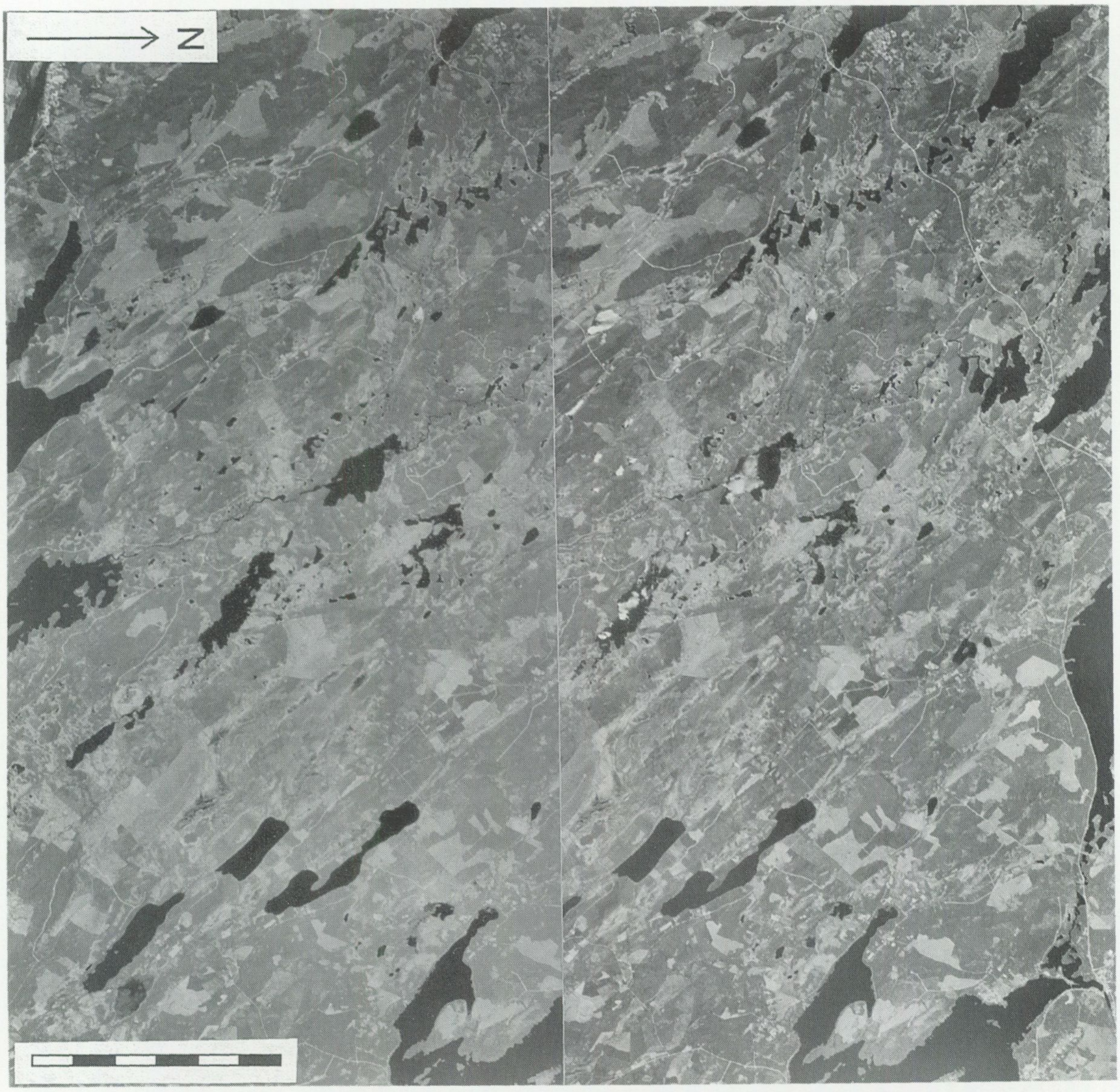


Fig. 2. Stereogram showing the typical appearance of large-scale glacial lineations in the interior parts of northern Sweden (near Norsjö, Västerbotten). The largest of these crag-and-tail drumlins are c. 7 km in length, from its rock cored head to the end of the tail. Between the lineations are scattered occurrences of ribbed moraine. Late-glacial ice flow was from the northwest. Scale bar is 6 km.

Glacial lineations

The glacial lineations are here subdivided into large scale drumlins and fluting. Drumlins are well-defined individual streamlined landforms (Fig. 2), while fluting is defined here as a mere striation of the land surface, commonly superimposed on other landforms (Fig. 3). The drumlins may or may not have a bedrock-core. However, pure rock drumlins and whale backs are not included, because they are often controlled by bedrock structures and are formed over several glaciations, and are therefore less useful for ice sheet reconstructions. Where the direction of the ice-flow can be inferred, typically by crag-and-tail morphology, this is marked with an arrowhead. The use of high-altitude pictures enables mapping of not only normal sized glacial lineations (100 m to a few kilometres long), but also mega-scale drumlins (up to 10–15 km). The small-scale fluting commonly found in front of present glaciers has not been included on the map. Comparisons of the present map with the glacial lineation map of the Nordkalott project (1986b) for the northernmost part of the study area, reveal a good match in distribution and orientation of the large-scale lineations, while the present map includes more faint fluting, especially in mountain regions.

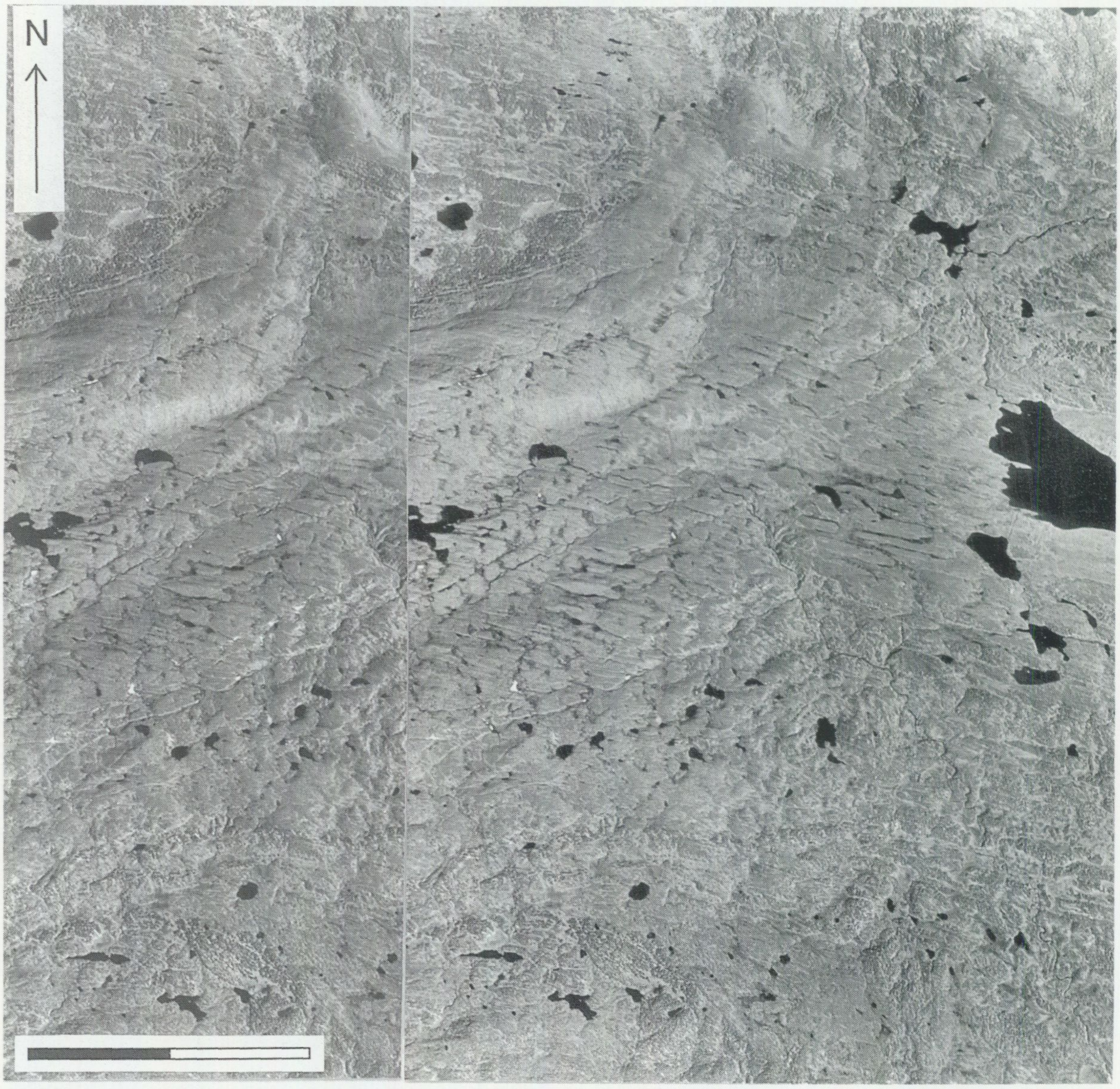


Fig. 3. Stereogram of small-scale glacial lineations (fluting) from Jofjället, southern Lappland mountains. Typical for this type of lineations is that they are superimposed on other landforms, in this case bedrock ribs covered by a thin till-cover. Late-glacial ice flow was from the east-southeast. Scale bar is 2 km.

Ribbed (Rogen) moraine

Ribbed moraine is defined here as an area with large, regularly and closely spaced, moraine ridges consisting of glacial sediments, usually till (Fig. 4; Hättestrand 1997; Hättestrand & Kleman in press). The ridges are generally oriented transverse to the ice flow direction associated with their formation, although variations in orientation between individual ridges may occur within a single ribbed moraine field. Ribbed moraine ridges are commonly asymmetrical in plan view, having crescentic segments with their convex side facing the up-glacier direction. Typically, the ridges are asymmetric also in cross-section, having steeper distal sides. On the map, this is shown as crescent-shaped symbols (convex side up-glacier) in the ribbed moraine areas. In general, ribbed moraine is easily mapped in the aerial photographs used here, especially where depressions in-between ribs are occupied by small lakes or mires, a very common situation. Occasionally, well developed ribbed moraine grade into a non-oriented hummocky moraine, without a distinct border, but the ribbed moraines shown on the map are only those which display a

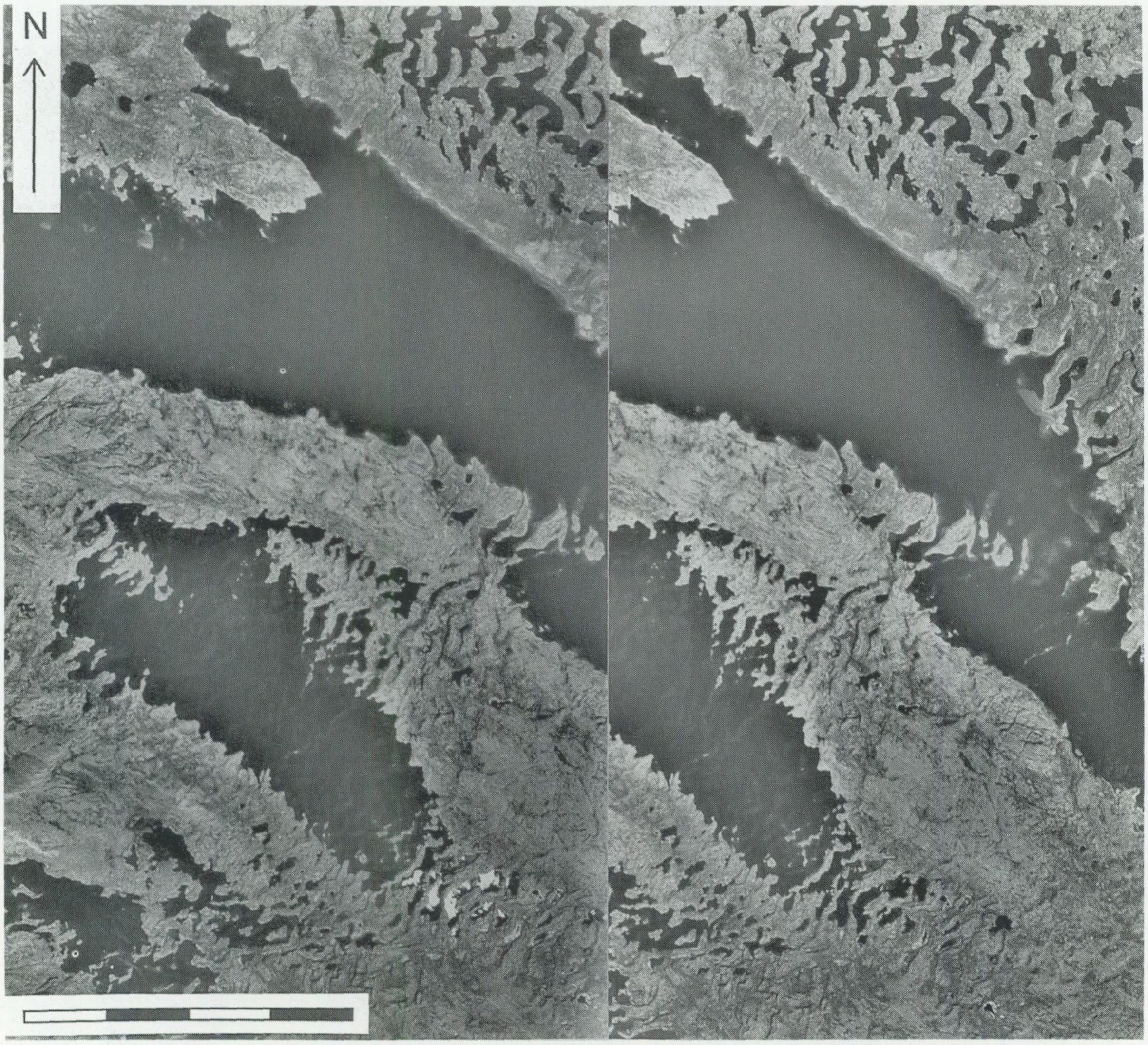


Fig. 4. Stereogram of ribbed moraine from the type locality of Rogen moraine, at Lake Rogen in southwestern Härjedalen. Note the ribbed moraine ridges covering the bottom of the lower lake, seen through the shallow water. Parts of the high elevation areas also show some faint fluting. Late-glacial ice flow was from the southeast. Scale bar is 4 km.

clear ridged topography (even though the orientation of individual ridges can show some variation).

The term ribbed moraine is preferred here over Rogen moraine, a name which is more commonly used in Sweden for the type of morphology described above. The reason for this preference is that the term Rogen moraine only applies to those ribbed moraines that also show the presence of drumlinoid elements (J. Lundqvist 1969, 1981, 1989). Consequently, adhering to this terminology would imply that a large group of areas with transverse moraines, that lack such features, are ignored. However, the North American term ribbed moraine (Hughes 1964) only refers to the ribbed appearance of these fields in general and is therefore considered more applicable for this kind of mapping. Hättestrand (1997) made a detailed mapping of four different ribbed moraine varieties in Sweden, including Rogen moraine, and found that they all have generally the same distribution pattern.

Fig. 5. Stereogram of De Geer moraines at the Bothnian Bay coast, just northeast of Piteå. In this area De Geer moraines are often superimposed on tails of large crag-and-tail drumlins. Late-glacial ice flow was from the northwest. Scale bar is 2 km.

De Geer moraines

De Geer moraines are small transverse near-marginal moraines, mostly occurring in swarms below the highest postglacial shoreline (Fig. 5). Because of their small size (typically 2.5x20x150 m), a complete mapping of De Geer moraines was not possible using the small-scale aerial photographs of this study. Therefore, the mapping of these landforms was complemented with data from earlier studies, mainly field-based surveys of Quaternary deposits (J. Lundqvist 1958; Möller & Stålhös 1971, 1974; Möller 1972, 1977; Magnusson 1978, 1994; Persson 1982, 1984, 1985, 1988; Svedlund 1985, 1993; Sundh & Wiberg 1986; Dahlberg et al. 1987; Rodhe & Garcia Ambrosiani 1987; Grånäs 1990; Svantesson 1991).

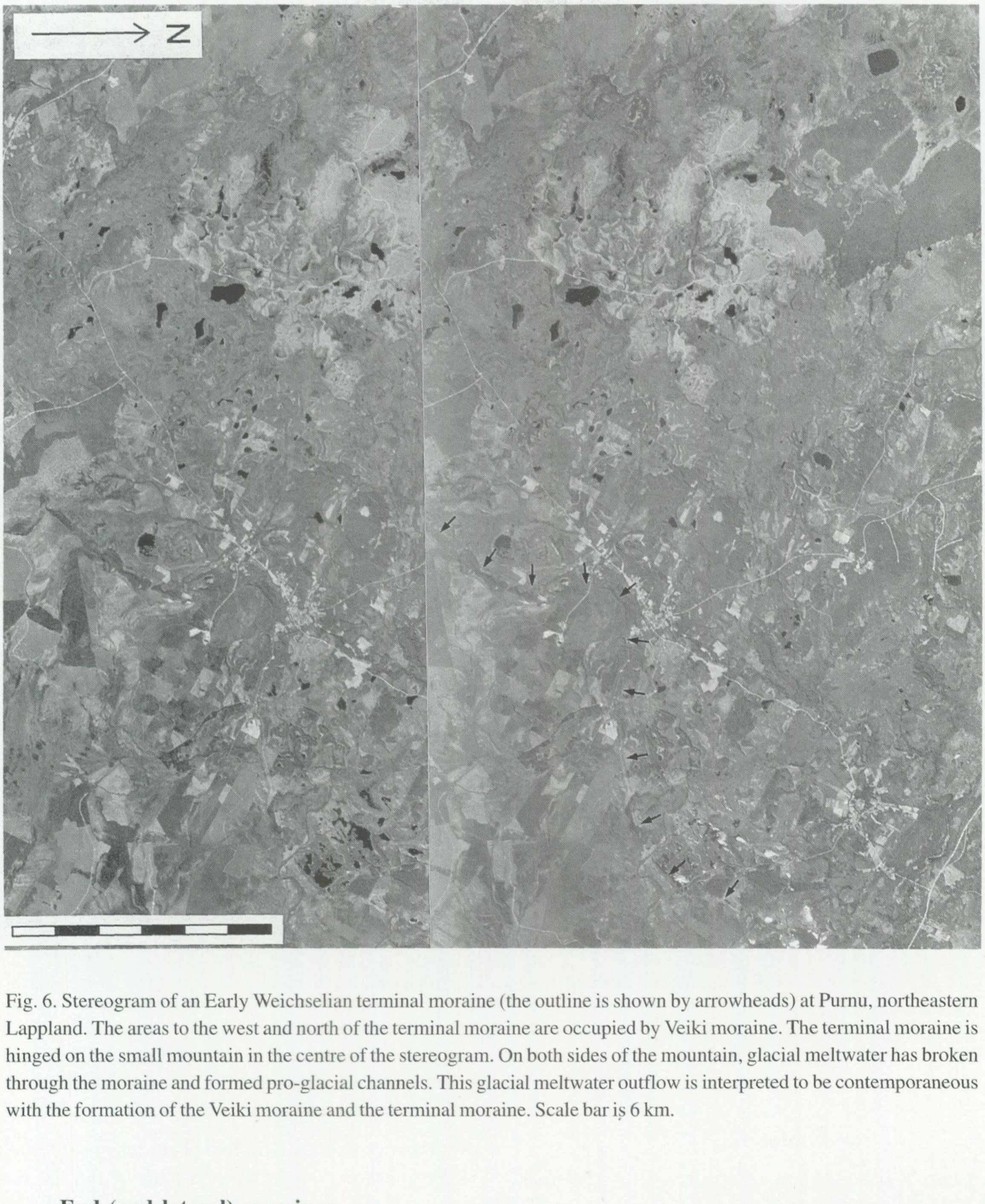


Fig. 6. Stereogram of an Early Weichselian terminal moraine (the outline is shown by arrowheads) at Purnu, northeastern Lappland. The areas to the west and north of the terminal moraine are occupied by Veiki moraine. The terminal moraine is hinged on the small mountain in the centre of the stereogram. On both sides of the mountain, glacial meltwater has broken through the moraine and formed pro-glacial channels. This glacial meltwater outflow is interpreted to be contemporaneous with the formation of the Veiki moraine and the terminal moraine. Scale bar is 6 km.

End (and lateral) moraines

This category includes (i) large end moraines in the forested lowlands, predominantly associated with the outer limits of Veiki moraine areas, although some of these also occur within Veiki moraines (Fig. 6), (ii) lateral moraines on valley sides in the eastern part of the mountain chain, and (iii) minor frontal moraines on valley floors in the mountain chain, not associated with recent glaciation (Fig. 7). In addition, a part of the Younger Dryas end moraine belt extends into the southwestern corner of the map area. Thus, moraines built during neoglaciation, such as Little Ice Age moraines are not included. Neo-glacial moraines have earlier been mapped during the geomorphological mapping of the Swedish mountains (see Hoppe 1983). The three types of end moraines discussed here all show up distinctly in aerial photographs, and a good accuracy of the distribution of these is anticipated. However, there may be single small end moraines in the forested lowlands which have not been detected in this study.

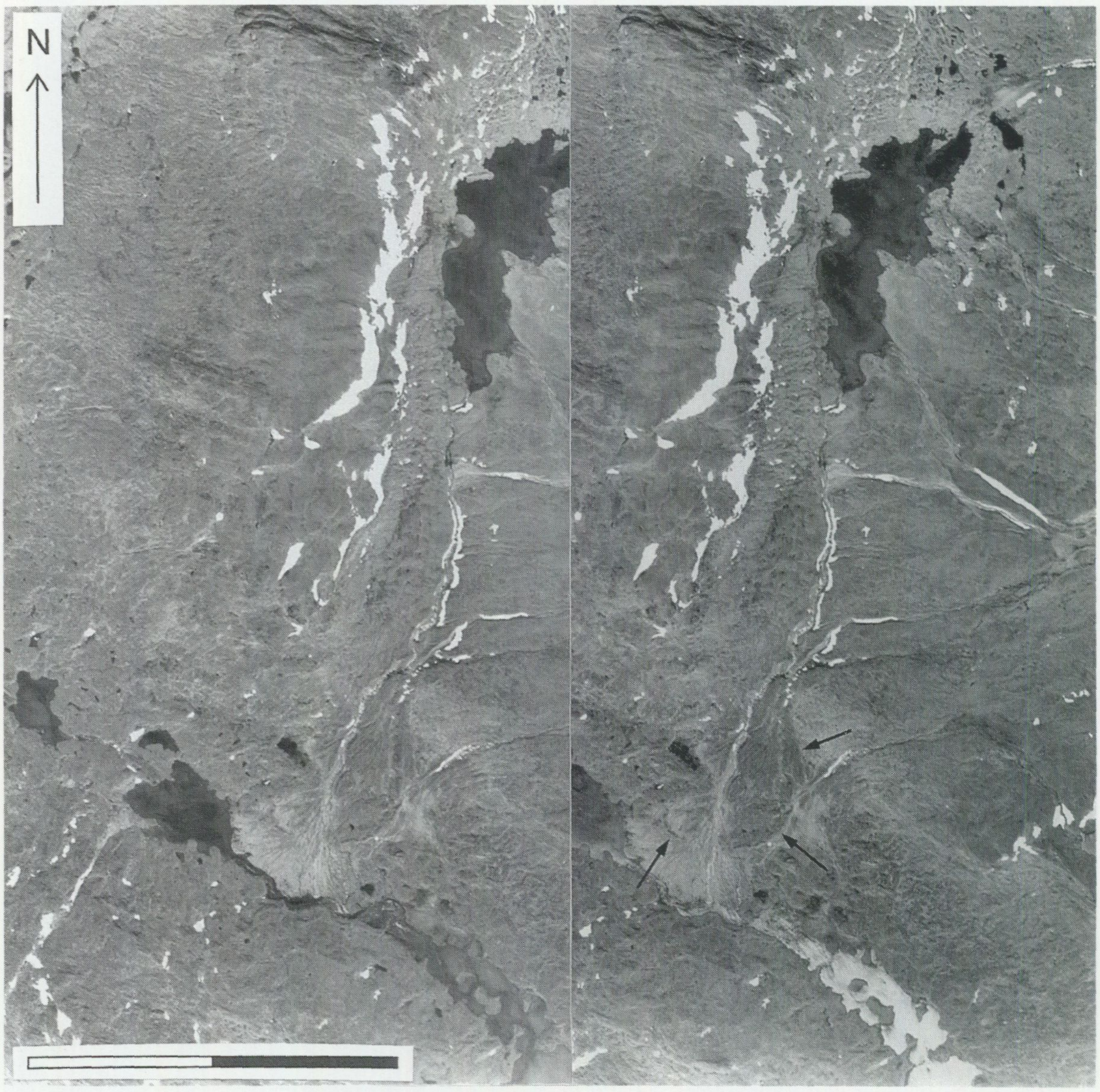


Fig. 7. Stereogram of an Early-Holocene end moraine in the Staika massif, central Lappland mountains. The end moraine (at the arrow heads) is located on the floor of a large U-shaped valley, just outside the mouth of a smaller tributary valley. The end moraine has been partly eroded and buried by the subsequent formation of an alluvial fan. Scale bar is 2 km.

Veiki moraine

Veiki moraine is a type of hummocky moraine characterised by plateaus, with rim ridges, separated by (commonly water-filled) depressions (Fig. 8; Hoppe 1952; Lagerbäck 1988a). Similar features, such as Puljo moraines (Kujansuu 1967), which have open ridges rather than closed plateaus, are also included in this category (cf. Lagerbäck 1988a). Commonly, the outer (eastern) edges of the Veiki moraines are marked by end moraines, often referred to as terminal moraines (Lagerbäck 1988a). Although shown as one class on the map, it is possible to separate two types of Veiki moraine in northern Sweden. The Veiki moraine in the central part of northern Sweden occurs mostly in low positions in the terrain and displays a morphology as described above, but in mountainous terrain, Veiki moraine mostly occurs on high interfluves and has a morphology characterised by low-relief flat plateaus, lacking rim ridges (Fig. 9). Still, the distinct morphology of both types of Veiki moraine, with the small-scale hill-and-hole morphology, makes it fairly easy to map using aerial photographs. Another type of hummocky moraine was also found in many areas of northern Sweden . This moraine has a morphology similar to Veiki moraine, with it's hill-and-lake topography, but lacks rim ridges and well-defined plateaus, which are distinct to Veiki moraine. These hummocky mo-

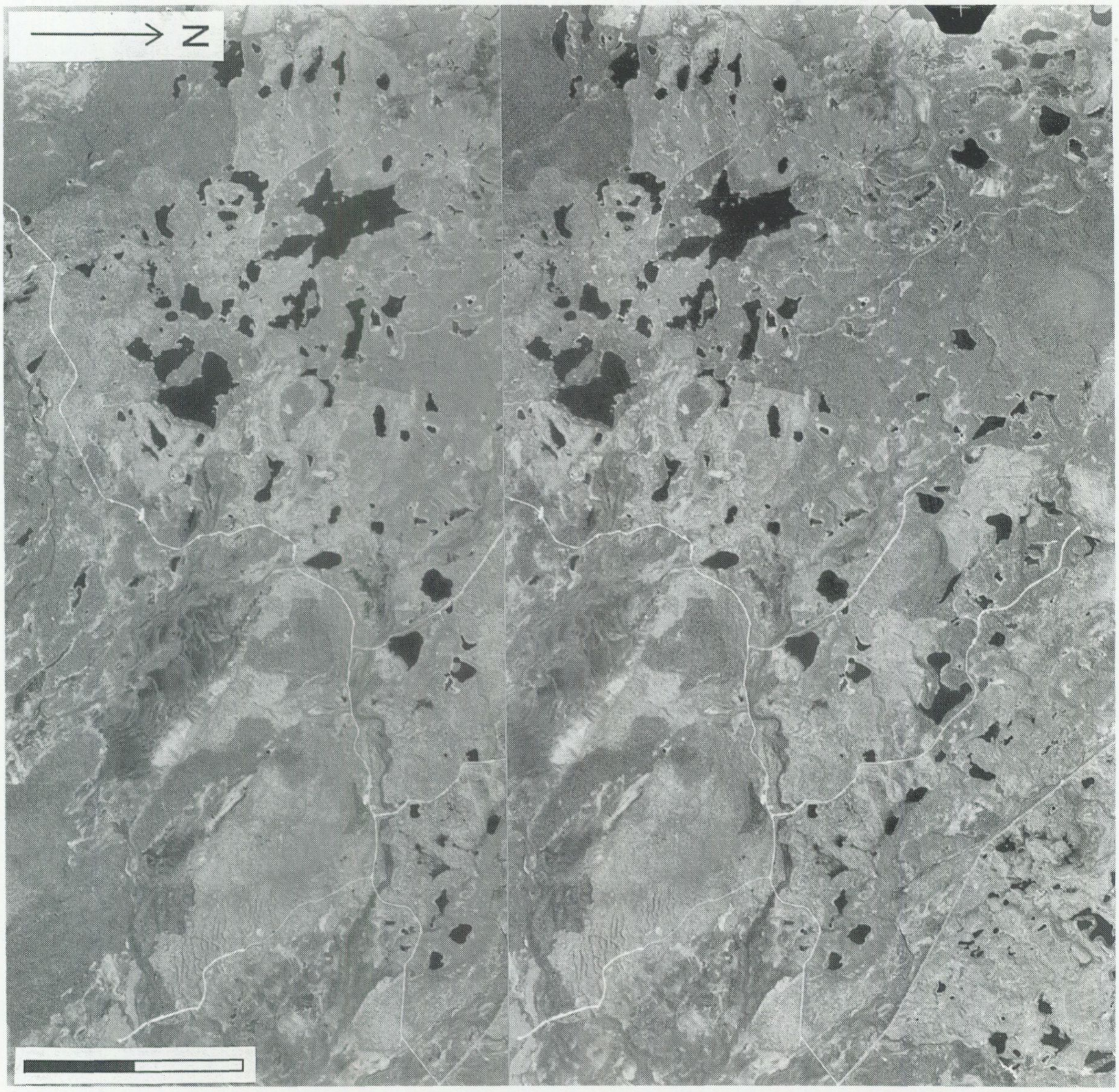


Fig. 8. Stereogram of Veiki moraine from the type locality, north of Gällivare. Well-developed plateaus with rim ridges, with water-filled depression between, occur in the upper part of the stereogram. Note the two Early Weichselian large crag-and-tail drumlins on the lower left hand of the stereogram. The western crag-and-tail drumlin is breached by glacial meltwater erosion formed during the deglaciation of the Late Weichselian ice sheet. Scale bar is 2 km.

raines are only rarely grading into Veiki moraine and are not included in the Veiki moraine class on the map.

The distribution of Veiki moraine in central and northern Sweden was mapped by Lagerbäck (1988a). According to Lagerbäck, the Veiki moraine is much more widespread in northern Sweden than the map of this study shows. Because this type of moraine morphology is so easily mapped in aerial photographs, it is not considered likely that much Veiki moraine has been missed during the present mapping. It appears likely that the differences in the reported distribution are due to differences in the definition of Veiki moraine, where Lagerbäck has applied a wider definition than used here.

Eskers

Eskers marked on the map only include those with well-defined crests that are indicative of ice-walled deposition. Eskers buried beneath sediments and glaciofluvial deposits lacking continuous ridge crests, such as valley-fills and kames, are not included in the map. Neither have I included subglacially engorged eskers (Sw. slukåsar) and similar minor ridged glaciofluvial accumulations with an unclear origin. Eskers, with their long anastomosing pattern and almost exclusive confinement to valley floors, are easily mapped features and no significant errors are anticipated.

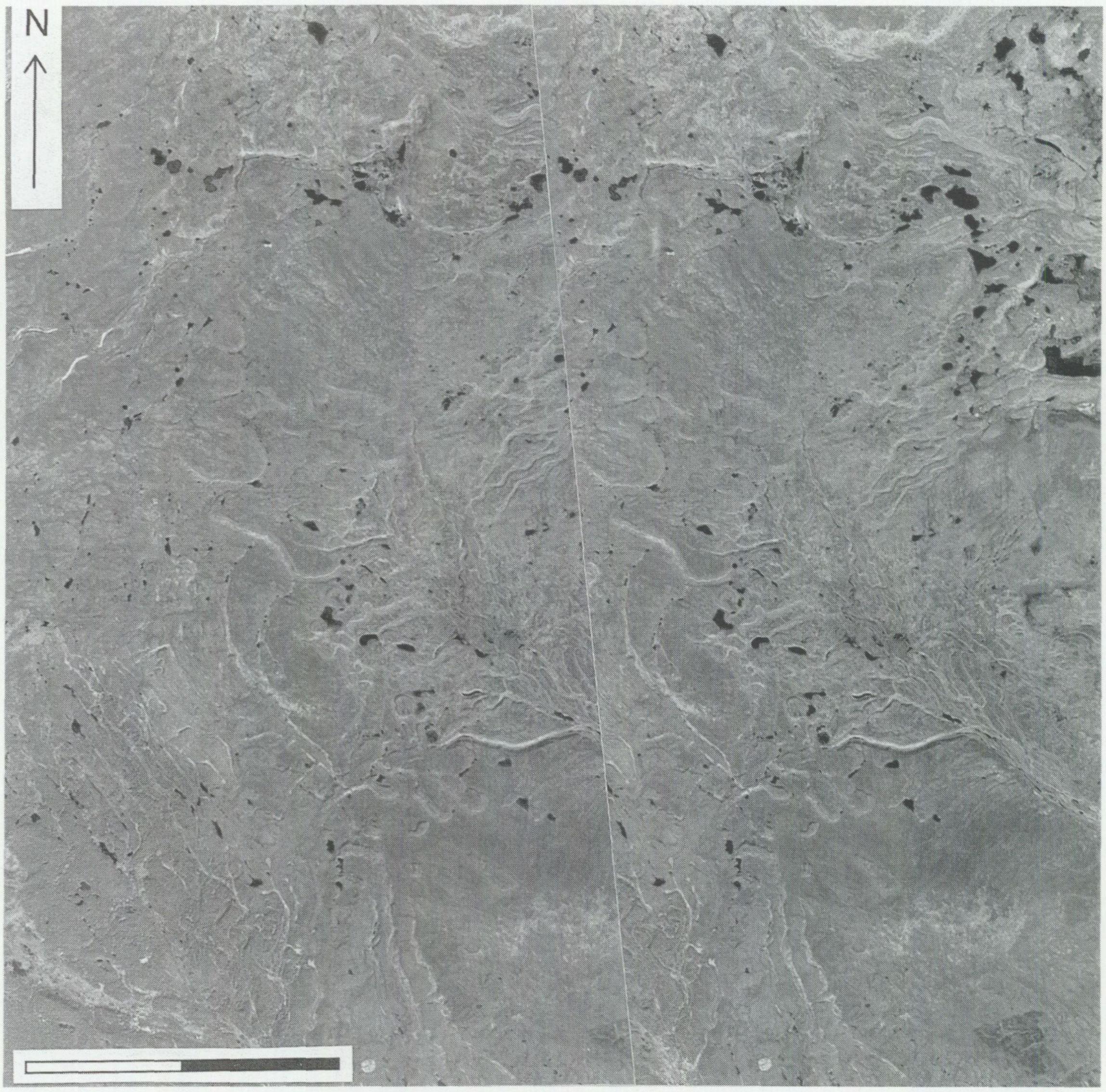


Fig. 9. Stereogram of the typical appearance of Veiki moraine in mountainous terrain. From Ultevistuottar in the east-central Lappland mountains. The glacial meltwater channels in the area are both of Late Weichselian and pre-Late Weichselian age. Scale bar is 2 km.

Meltwater channels

Glacial meltwater channels (Fig. 10) were included in the manuscript maps. However, to be able to use meltwater channels in glacial reconstructions, detailed information on the underlying topography is required. Therefore, as there is no topographic background information, meltwater channels are not included in the map presented here. Instead, a generalised map is presented in Figure 11, showing their distribution and the approximate ice surface slope direction they indicate. The shaded areas in this map delineate zones where series of lateral meltwater channels are frequent. These areas are interpreted to represent zones where considerable meltwater drainage was taking place on the ice sheet surface rather than at the base, even though some eskers, indicating subglacial meltwater drainage, also occur within these zones. In addition, there are scattered series and individual meltwater channels (lateral and pro-glacial) outside these areas, as shown by the distribution of arrows indicating ice-surface slope direction.

The discrimination between Late Weichselian and pre-Late Weichselian meltwater channels is based on the following criteria (see also Fig. 10):

(i) Cross-cutting relationships. The relative age of different generations of channels can firmly be established where the younger of two cross-cutting meltwater channel systems clearly overprints and cuts down into channels of an older system (Rodhe 1988; Kleman et al. 1992).

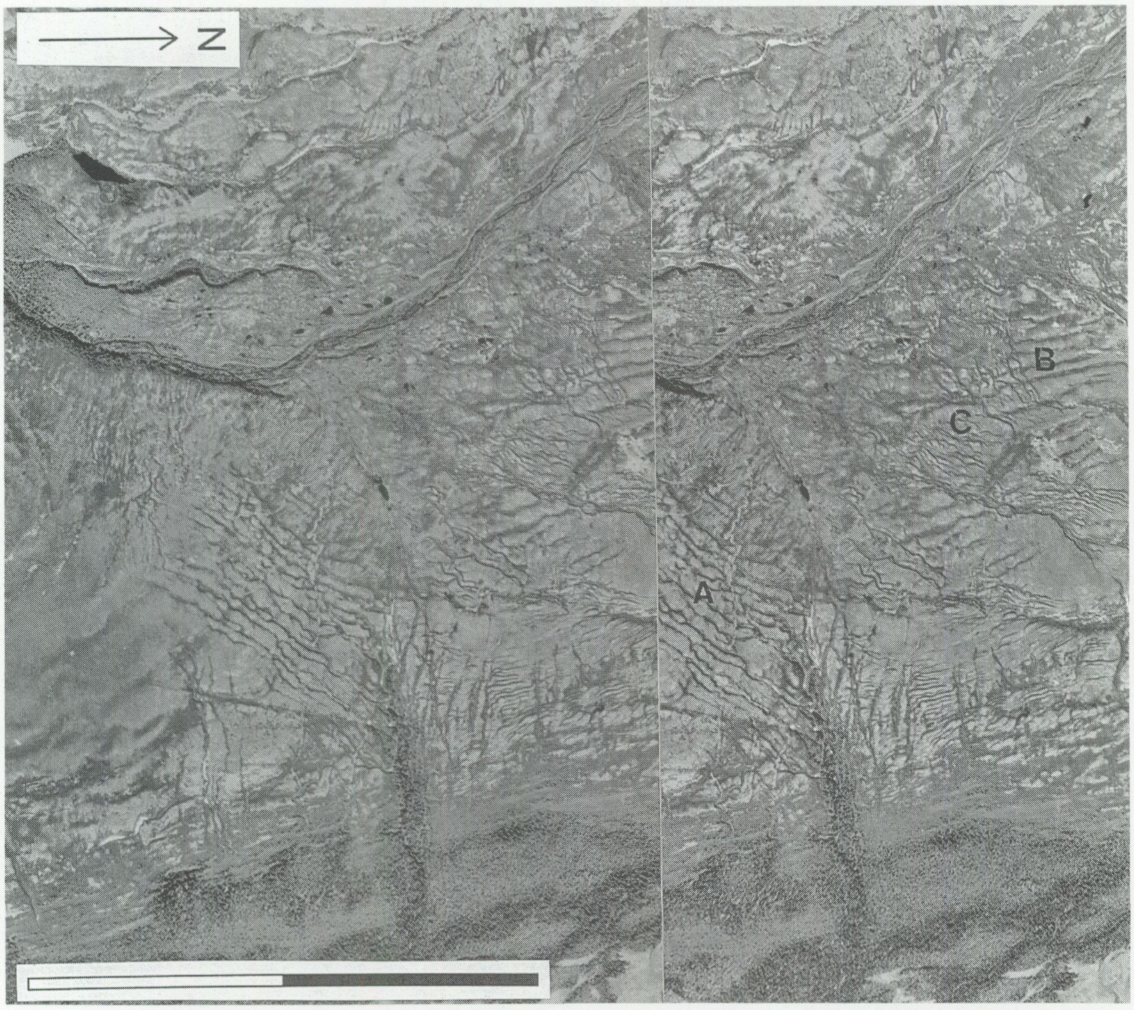


Fig. 10. Stereogram of an area with extensive series of lateral meltwater channels at Mt Fulufjället, western Dalarna. At least three meltwater channel systems of different age are present in this area. A – channels sloping towards the north-east, B – channels sloping towards the south, and C – channels sloping towards south to south-southwest. The channels of system C are cross-cutting those of system B, and are interpreted to represent the last deglaciation. The channel systems A and B do not cross-cut each other, but as they reflect ice surface slopes at opposite direction, they are interpreted to date from two separate (pre-Late Weichselian) deglaciations. Scale bar is 2 km.

(ii) The detailed morphology of the channels. Channels that pre-date the last deglaciation often have a subdued and degraded appearance. Mass-wasting processes acting on the channel walls may create small enclosed basins along the channel floor, a feature that is very rarely seen in channels formed during the last deglaciation.

(iii) The compatibility of channels with prevalent models of the Late Weichselian deglaciation (J. Lundqvist 1994; Kleman et al. in press). The ice-surface slope direction indicated by some channel systems is clearly in conflict with current models of the last deglaciation, based on stratigraphy and other glacial geomorphological data, and must therefore be attributed to one or more earlier deglaciation(s).

The accuracy of the distribution of meltwater channels as shown in Figure 11 may vary over the mapped area. In areas above the tree-limit, glacial meltwater channels are easily mapped and few errors are anticipated. Medium and large sized channels (>5–10 m deep) can also be accurately mapped in forested regions, while smaller channels are often obscured by tree-cover, resulting in an under-representation of these channels in interior parts of the study area. However, because the symbols do not show position and direction of individual channels, but rather of a series of channels, this under-representation is not likely to influence the general pattern in Figure 11.

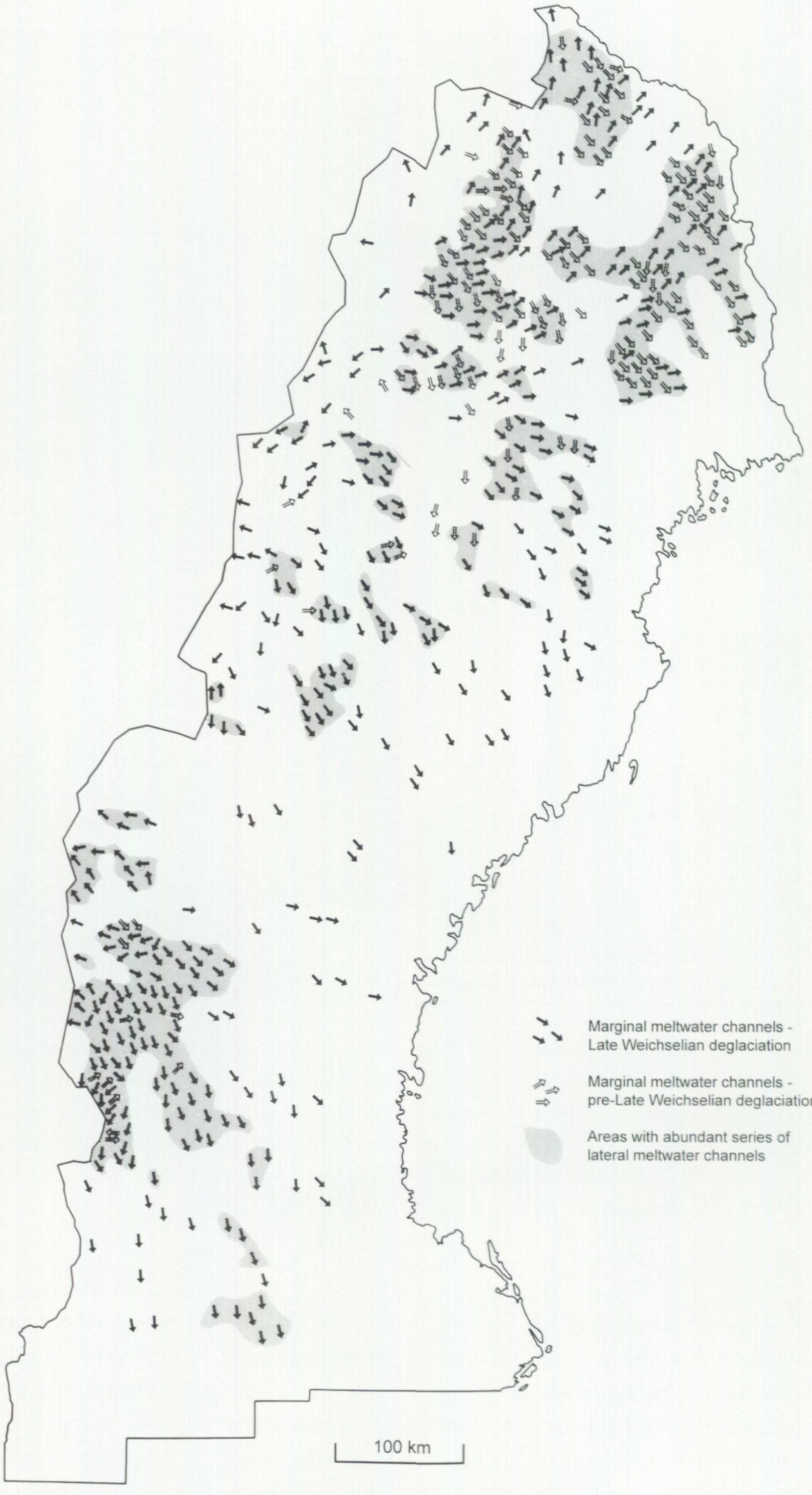


Fig. 11. Distribution of lateral meltwater channels in central and northern Sweden. The arrows mark the ice flow (ice-surface slope) direction during channel formation, as interpreted with respect to channel morphology and local slope-aspect and angle. This reconstruction was made from a 1:250,000 base map of Sweden with 25 m elevation contours. The shaded areas mark zones with numerous marginal meltwater channel systems, interpreted to be areas where a considerable part of the glacial meltwater drainage took place on the glacier surface rather than subglacially.

Glacial geomorphology regions

To be able to describe efficiently the glacial geomorphology in the study area, the study area is subdivided into different regions (Fig. 12), each with more or less internally homogeneous landform assemblages. These regions to some extent correspond with the large-scale relief, such that many of the bedrock geomorphology regions of northern and central Sweden (Rudberg 1960) are also associated with a specific assemblage of glacial landforms. The borders between the different regions presented here are usually not very distinct, and the regions sometimes overlap. Still, subdivision of the study area serves an important purpose, helping to discriminate landform assemblages of different ages and appearances. The glacial geomorphology regions presented here differ in many respects from the classification presented by J. Lundqvist (1981). This is mainly because Lundqvist based his zonation on moraine morphology alone, whereas the classification in this work also includes the distribution of meltwater channels and eskers.

The mountain region

This region constitutes the central and western part of the mountain range (Region 1 in Fig. 12). The surficial geology is dominated by exposed bedrock or only thin cover of glacial drift. Therefore, the glacial geomorphology is dominated by large-scale bedrock landforms such as cirques, U-shaped valleys, glacial troughs, roches moutonnées, and steep glacial facets. Some of these landforms have a formation history that spans over millions of years (e.g., Rudberg 1988; Kleman & Stroeven 1997).

Glacial lineations are found in many parts of the mountain region (except in the most alpine areas such as the Sarek and Kebnekaise mountains) and are mostly present as a light fluting/striation in thin drift cover on flat uplands and on valley floors. Some lower areas in the western part of the mountain region, such as Padjelanta, the western Torne Träsk area, and west-central Jämtland, display evidence of heavy glacial erosion and scouring. In some of these areas it is also common to find large-scale lineations of the crag-and-tail type. Ribbed moraines and end moraines are less common in the mountain region. The ribbed moraines are almost exclusively confined to the mountains of southern Lappland and southern Jämtland/Härjedalen. In the northern Lappland mountains, ribbed moraines are only found at a few locations, such as Abisko, Sälka, and Nikkaluokta. Early-Holocene end moraines are occasionally found throughout this region. Some of these have a morphological resemblance to De Geer moraines, and were probably formed by ice fronts calving in ice-dammed lakes (e.g., in the Bunnerfjällen area; Borgström 1979). Other end moraines occur as a series of lobate moraines crossing valley floors in high relief terrain, such as in Stor-Stensdalen and in the Härjångån valley. There are also a few examples of single lobate moraines at the lower end of valleys, such as in the southwestern part of the Staika massif (Fig. 7).

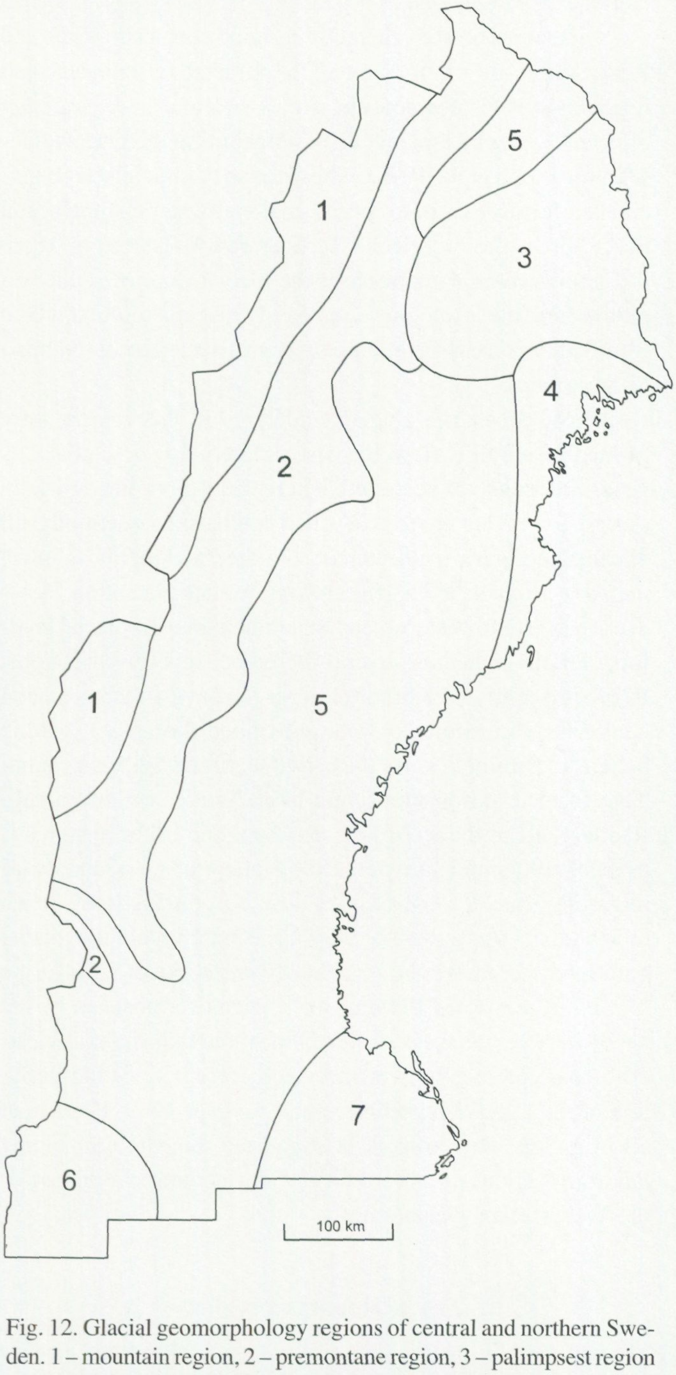


Fig. 12. Glacial geomorphology regions of central and northern Sweden. 1 – mountain region, 2 – premontane region, 3 – palimpsest region of northeast Sweden, 4 – northern coastal region, 5 – interior drumlin region, 6 – southwestern region of exposed bedrock, 7 – southeastern esker and De Geer moraine region.

Eskers and meltwater channels are also common in this region, but they are mostly small and short. The eskers are usually not more than a few kilometres long. The only continuous esker chains over 10 km in length are found in the Laisälven valley in Lappland, and in a few valleys in southern Jämtland/Härjedalen. The meltwater channels in the mountain region rarely occur in large series. Extensive series of lateral meltwater channels are only found in the Jämtland and Härjedalen mountains.

Some areas of high elevation terrain, such as in Sarek and Kebnekaise, are often covered by remnant felsenmeers and residual soils. These deposits are *in situ* and have not been affected by glacial erosion, at least not during the Late Weichselian (cf. Rea et al. 1996). These areas completely lack glacial landforms, except for occasional meltwater channels, and likely retain the pre-glacial Tertiary relief. Therefore, there is a strong vertical zonation of the glacial imprint in this region, where the lower parts are heavily glacially eroded, while some summit areas have scarcely been affected at all (Kleman & Stroeven 1997).

Nearly all of the glacial landforms in this region were formed by ice flow from the east and very few deviating ice-flow directions are recorded. There are a few places where glacial lineations cross at a small angle, but essentially all glacial landforms in the unconsolidated sediments is interpreted to originate from the Late Weichselian glaciation. However, in the southwestern Lappland mountains, the glacial landform record indicates several different ice flow directions. In the proximity of Klimpfjäll, east- and west-facing glacial landforms (lineations, eskers and ribbed moraines) overlap by tens of kilometres. As these two landform systems cannot have formed during one single deglaciation, without a substantial shift in the ice divide position, one of the systems is probably older and partly erased by later erosion of an inward migrating zone of wet-based ice flow. No conclusive evidence on which of the systems is older has been found in the glacial geological data. However, the distribution of landforms formed by eastward flowing ice, indicates a position of the ice divide over the western side of the mountain chain. A westerly ice divide position has not been present since the initiation of the Late Weichselian (e.g., Ljungner 1949; Kleman et al. in press). Therefore, it is suggested that the east-facing landforms in this area were formed during an earlier phase of the Weichselian glaciation.

The premontane region

The topography of the premontane region (Region 2 in Fig. 12) is mostly characterised by glacially deepened and widened river valleys and broad interfluve plateaus. The valleys are often over-deepened and occupied by long and narrow lakes, referred to as "piedmont lakes" (Rudberg 1992). The over-deepening of these valleys, pre-glacial river valleys in origin (Lidmar-Bergström 1996), is likely to be a result of glacial erosion by several ice sheets centred over the mountain range during the late Tertiary and Quaternary (Rudberg 1992; Kleman & Stroeven 1997). Some interfluve areas, especially in the northern part of the region, are relict Tertiary surfaces, with wide and shallow fluvial valleys (Wråk 1908). In the far north, most of the landscape is characterised by rounded hills and wide basins, and shows very limited signs of glacial erosion (Wogelius 1996). Occasionally, I have also found tor remnants, such as in the Golgukjaure area. In the southern part of the premontane region, around Östersund, the relief is lower, and plains and wide basins dominate the large-scale geomorphology.

Glacial lineations, ribbed moraine, and lateral meltwater channels are the most common landforms in the premontane region. In the north, lateral moraines and minor areas of Veiki moraine are also found. The glacial lineations are mostly of fluting-type, and there are only a few large-scale drumlins (mostly along valleys).

The premontane region contains the largest occurrences of ribbed moraines that exist in Sweden. There are vast areas of ribbed moraines occupying the broad basins and plains, especially north of Östersund and in the lake Rogen area. The largest continuous ribbed moraine area, around Hammerdal, is over 50 km in length and covers c. 850 km^2. Ribbed moraines are sometimes superimposed on large glacial lineations, not always aligned with ice flow direction indicated by the ribbed moraine ridges, and are also frequently fluted on their surface. There are also some examples of eskers running through the ribbed moraines.

The most common signs of glacial meltwater in this region are frequent series of lateral meltwater channels. These large series of long lateral channels often occur on slopes of broad interfluves between the piedmont lakes. Eskers are generally rare in this region. Those that exist are mostly small and discontinuous, as in the mountain region, and almost exclusively confined to the deeper valleys. However, within the ribbed moraine areas north of Östersund and in the northernmost part of the region, some eskers are both continuous and reach considerable dimensions.

One of the most characteristic features of the premontane region is the complex pattern of ice flow directions indicated by the glacial geomorphology. Landforms of different orientation are commonly crossing each other or indicate incompatible ice flow directions. There are frequent glacial lineations indicating an ice flow from the NW, underlying all other landforms, and are probably part of a NW-system of drumlins in region 3 (The palimpsest region, Fig. 12) and possibly the NW-drumlins of region 5 (The interior drumlin region, Fig. 12). Overprinted on these landforms are several sets of small-scale glacial lineations with varying directions. Most of the younger lineations belong to the deglaciation, but there are many areas where different sets of fluting and drumlins are crossing each other at both low and high angles. Examples of such areas are Håsjövålen in Härjedalen, the northern Jämtland mountains, Väretsfjället in southern Lappland, and the whole of northern Lappland. It is difficult to sort out age relationships from lineations alone, but frequent cross-cuttings of lateral meltwater channel systems give information on the relative age of the ice flow sets. Examples of such cross-cutting meltwater channels have been given by Rodhe (1988) from Ultevistuottar, and by Kleman et al. (1992) from the Transtrand mountains, and are found in many other places in the premontane region, such as on Råsto and Kuortovaara in northernmost Sweden.

In the northern part of the region, lateral moraines are occasionally found high up on slopes of some major valleys, outlining the surface of eastward draining outlet glaciers from a mountain-centred ice sheet or ice cap. These are previously described by Kleman (1992) and were assigned to a pre-Late Weichselian glaciation. Occasionally, Veiki moraine is found above the lateral moraines, on top of broad interfluves in the northern part of the region. These are often associated with what seems to be thermo-karst features formed during permafrost conditions. Examples of such forms are the Långfjället hollows, described by Borgström (1989), which are interpreted to be thermo-karst features, formed by landslides in the active layer under permafrost conditions. The Veiki moraine in this region, as mentioned earlier, has a slightly different morphology from that in the lowlands of north-central Sweden. It gives the impression of being erosional remnants from slumping and sliding of material around the small plateaus.

The palimpsest region of northeast Sweden

The palimpsest region (Region 3 in Fig. 12) displays a mosaic of glacial and non-glacial landscapes of widely different ages. This is largely a consequence of the cold-based nature of the central part of the Late Weichselian (and possibly earlier) Fennoscandian ice sheet(s). The bedrock geomorphology is characterised by plains with residual hills, that rise 100–200 m above the plains (Rudberg 1960; Lidmar-Bergström 1995). The region is, for the most part, rich in glacial landforms of different age and appearance, comprising at least three different glacial flow systems. These flow systems (set 1–3) each contain a set of directionally consistent glacial landforms, from which a coherent pattern of ice flow can be reconstructed.

Set 1 – Figure 13a. This set of landforms includes large glacial lineations, such as drumlins and crag-and-tails, often with rock-heads or rock-cores. Eskers are present, but are mostly somewhat subdued in morphology. Series of large lateral meltwater channels are also found, especially along the flanks of the drumlins. A marked feature of this set is the consistency of direction. The trend is NW–SE, and the crag-and-tail drumlins show that the ice flow was from the NW. The deviation from this trend of individual landforms is very limited. This set has previously been described by Fagerlind (1981) and Lagerbäck & Robertsson (1988), who assigned it to the first Early Weichselian stadial.

Veiki moraine and terminal moraines are also associated with this set. The terminal moraines are usually accompanied by a 10 km broad zone of Veiki moraine situated proximal of the moraine ridge. The Veiki moraine zone shows a distinct lobate outline, with the largest concentrations of Veiki moraine being located in the interlobate areas. The northernmost lobe, the so-called Lainio-arc, has been known for over a hundred years (Fredholm, 1886), but it was not until the investigations by Lagerbäck (1988a) that it became clear that the Veiki moraine, as well as the other landforms of set 1, belonged to an Early Weichselian deglaciation.

Set 2 – Figure 13b. This set, previously referred to as the "Pajala fan" (Kleman 1992), consists solely of glacial lineations, from faint fluting to small-sized drumlins (Fagerlind 1981; Lagerbäck & Robertsson 1988). The trend of the features is generally from south to north, with a tendency towards a more northeasterly direction in the distal (i.e. northern) part. Striae and till-fabric data (Nordkalott project 1986b) show the direction of ice flow was from the south. In many places the large-scale lineations of set 1 are drumlinised by ice flow from set 2 (Lagerbäck & Robertsson 1988). In some cases the older set 1 drumlins are almost completely reshaped. No meltwater features, such as eskers or meltwater channels, are aligned with this set. This indicates that set 2 was formed far from the ice margin, suggesting it is a non-deglacial landform system.

Set 3 – Figure 13c. Set 3 is the youngest set, overprinting all other glacial features where superposition occurs. This set consists primarily of glacial meltwater channels, found all over the region, appearing both as series of lateral channels and as pro-glacial channels. There are scattered occurrences of faint fluting and in the central parts of the region there are some drawn-out boulder blankets on the lee-side of hills with pre-Late Weichselian boulder fields and talus slopes. Eskers are rare in this system, and those that do occur are small and discontinuous. The orientation of landforms in this set shows a divergent pattern of ice flow eastwards; generally SW–NE in its northern part, W–E in its central part, and NW–SE in its southern part.

The ice-flow directions associated with these three sets, have all been reported and described in previous studies (e.g., Fagerlind 1981; Nordkalott project 1986a–c, Lagerbäck & Robertsson 1988, Kleman 1990, 1992). During the mapping, a possible fourth system of landforms was also found, re-

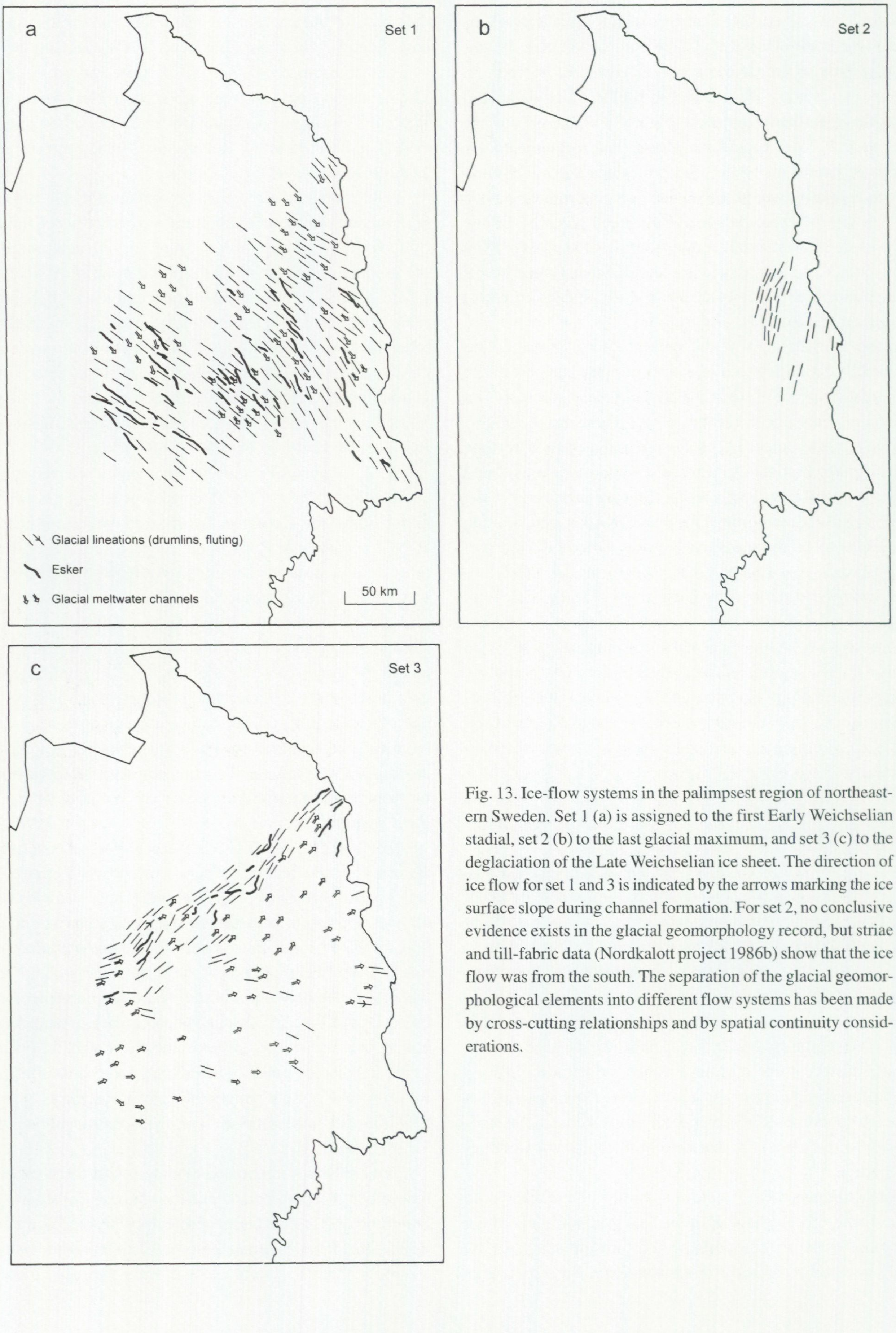


Fig. 13. Ice-flow systems in the palimpsest region of northeastern Sweden. Set 1 (a) is assigned to the first Early Weichselian stadial, set 2 (b) to the last glacial maximum, and set 3 (c) to the deglaciation of the Late Weichselian ice sheet. The direction of ice flow for set 1 and 3 is indicated by the arrows marking the ice surface slope during channel formation. For set 2, no conclusive evidence exists in the glacial geomorphology record, but striae and till-fabric data (Nordkalott project 1986b) show that the ice flow was from the south. The separation of the glacial geomorphological elements into different flow systems has been made by cross-cutting relationships and by spatial continuity considerations.

ferred to as *set X* below. This set of landforms only consists of meltwater channels and sparse traces of small-scale glacial lineations (Fig. 14). There is no conclusive evidence that the channels and the lineations are associated in age, but due to their directional correlation they will be treated as such. The meltwater channels mostly occur as series of medium sized (100–300 m long, 5–10 m deep) lateral channels, but also as overflow channels in col positions. The direction of ice flow inferred from the channels, and in particular the lateral channel series, corresponds to the trend of the lineations, indicating ice flow from the N or NNE. The meltwater channels are frequently crossing the tails of the large crag-and-tail features of set 1 and the fluting is superimposed on Veiki moraine. Thus, set X is clearly younger than set 1. The presence of an ice flow from the N or NNW is confirmed by striae and till-fabric data from the area (Fig. 14; Fagerlind 1981; Nordkalott project 1986b). According to striae data, set X is older than set 2 and 3, but its relation to set 1 is more elusive. In some cases where cross-cutting occurs in striae data, set X is older than the NW-flow of set 1, in other cases the relation is reversed. Yet, the glacial geomorphology record (meltwater channels crossing drumlins of set 1) indisputably shows that the landforms of set X are younger than set 1.

If set X is truly a deglacial landform set, as indicated by meltwater channels, it must have been formed between the deglaciation of the first Weichselian ice sheet and the last glacial maximum. Unless the Fennoscandian ice sheet underwent a near complete deglaciation during the Middle Weichselian, which seems unlikely (cf. Donner 1996), set X probably belongs to the second Early Weichselian deglaciation. This deglaciation marks the beginning of the Tärendö interstadial (Lagerbäck and Robertsson 1988), presently correlated with the marine oxygen isotope stage 5a (Mangerud 1991). There are also data from northern Finland that support this interpretation. Johansson & Kujansuu (1995) describe three cross-cutting systems of esker chains in the Savukoski area, eastern Finnish Lapland, with NW–SE (oldest), N–S (intermediate), and WNW–ESE (youngest) directions. These are by till stratigraphy assigned to the first Early Weichselian stadial (NW–SE), the second Early Weichselian stadial (N–S), and the Late Weichselian deglaciation (WNW–ESE), respectively. However, no till lineations were found that could be correlated with this ice flow. Sutinen (1992) also describes N–S trending eskers in Finnish Lapland, which he suggests to be of Early Weichselian, or possibly Mid-Weichselian age. Hence, these studies confirm northerly ice-flow directions in this part of Fennoscandia during the second Early Weichselian stadial.

In the northeastern part of the palimpsest region, around Keräntöjärvi, near the border to Finland, there is an area which appears to be more or less unaffected by glacial erosion. No

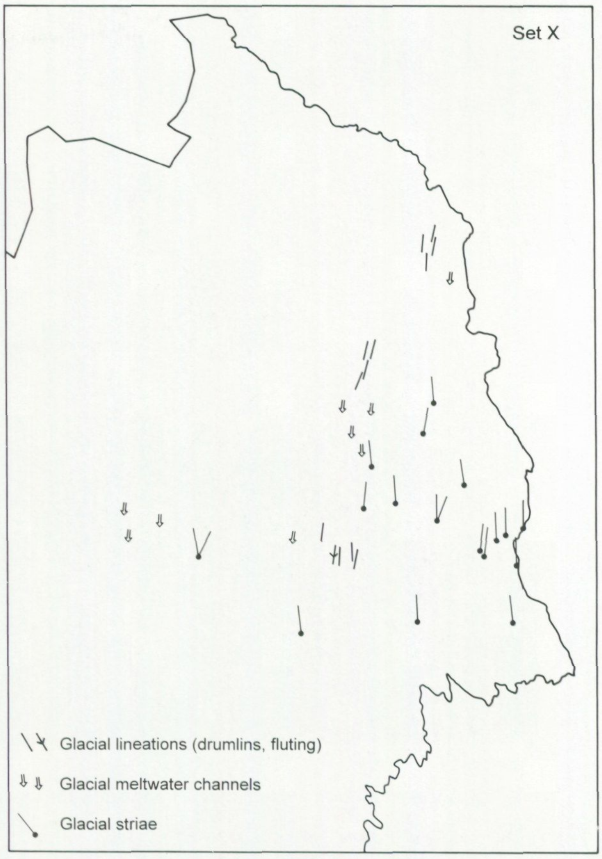


Fig. 14. Ice-flow directional indicators indicating ice flow from the north in the palimpsest region of northeastern Sweden (set X). Striae information has been extracted from the Nordkalott project (1986b). The age of this ice flow cannot conclusively be determined, but the landform record indicates that it is younger than set 1, while the striae record indicates that it is older than set 2 and 3 in Figure 13, i.e. older than the last glacial maximum. Thus, the most likely age for set X is between set 1 and 2, and correlations with data in northern Finland (Johansson & Kujansuu, 1995) indicate that it represents the deglaciation of the second Early Weichselian ice sheet (marking the beginning of the Tärendö interstadial).

glacial landforms are present except for sparse meltwater traces. The landscape is characterised by rounded and symmetrical hills and seems to have been developed under subaerial conditions by fluvial and mass movement processes alone. A few tors are also found in this area (Fig. 15). Drilling through surficial deposits has revealed thin beds of glacial sediments overlying weathered bedrock (Nordkalott project 1986c). The morphology of this area resembles the type of landscape described from an area in northern Finland by Kaitanen (1969, 1989), interpreted to be a relict Tertiary landscape. If the same is true for the area described here, the landscape around Keräntöjärvi may give an indication of the morphology of the pre-glacial landscape in northern Sweden, before the onset of Quaternary glaciation.

Fig. 15. A tor-formation at Naakajärvi in northeastern Sweden.

The northern coastal region

In the northern coastal region (Region 4 in Fig. 12), large crag-and-tail drumlins dominate the glacial geomorphology. The appearance of these is similar to set 1 drumlins of the palimpsest region (3) and the ubiquitous drumlinisation of the interior drumlin region (5). These two drumlinisation zones (the Early Weichselian drumlins to the north and the – presumably – Late Weichselian drumlins to the south), both formed by ice flow from the northwest, overlap in this region. However, it is not possible to see the lateral contact zone between these two sets. Both appearance and orientation of the drumlins are consistent throughout the northern coastal region.

Transverse moraines are also found frequently in the northern coastal region. In the southern area De Geer moraines are common, while ribbed moraines dominate the northern area. There is only a narrow zone, along the Råne River, where the two types of transverse moraines overlap. In this zone, De Geer moraines are superimposed on top of the ribbed moraine ridges and are the younger form, although they both most likely belong to the deglaciation phase of the Late Weichselian. The ribbed moraines in this region were studied by Hoppe (1948, 1952), who named them "Kalixpinnmo ridges" from their internal composition (Kalix till, i.e. glacially disturbed sorted sediments interbedded with stones and boulders). The ridges have also been referred to as Niemisel ridges after their type locality (J. Lundqvist 1981). Later, Hättestrand (1997) argued that these ridges were true Rogen moraine, as their appearance is similar to other Rogen moraines in Sweden.

The De Geer moraines are mostly confined to the plains near the coast, but in the area around Luleå, they extend into the drumlin zone, where the relief is higher (Hoppe 1948). The zone of De Geer moraines may be larger than that shown on the map. Areas of De Geer moraines commonly extend out onto the sea floor, where they protrude above the sea surface in areas of shallow water depth, and are also common on the eastern side of the Bothnian Bay, in Ostrobothnia, Finland. Therefore, it is possible that also large parts of the sea floor is covered by De Geer moraines (T. Andrén, pers. comm. 1997). The De Geer moraines of the southern and central parts of the northern coastal region are similar in appearance to those in south-central Sweden, that is, fairly short and anastomosing. In the area around and to the west of Luleå, the De Geer moraines are much straighter and often very long (1–2 km in length), but are of the same width (25–75 m) as the southern De Geer moraines (Hoppe 1948). The moraines often cross the full width of the valleys between the large

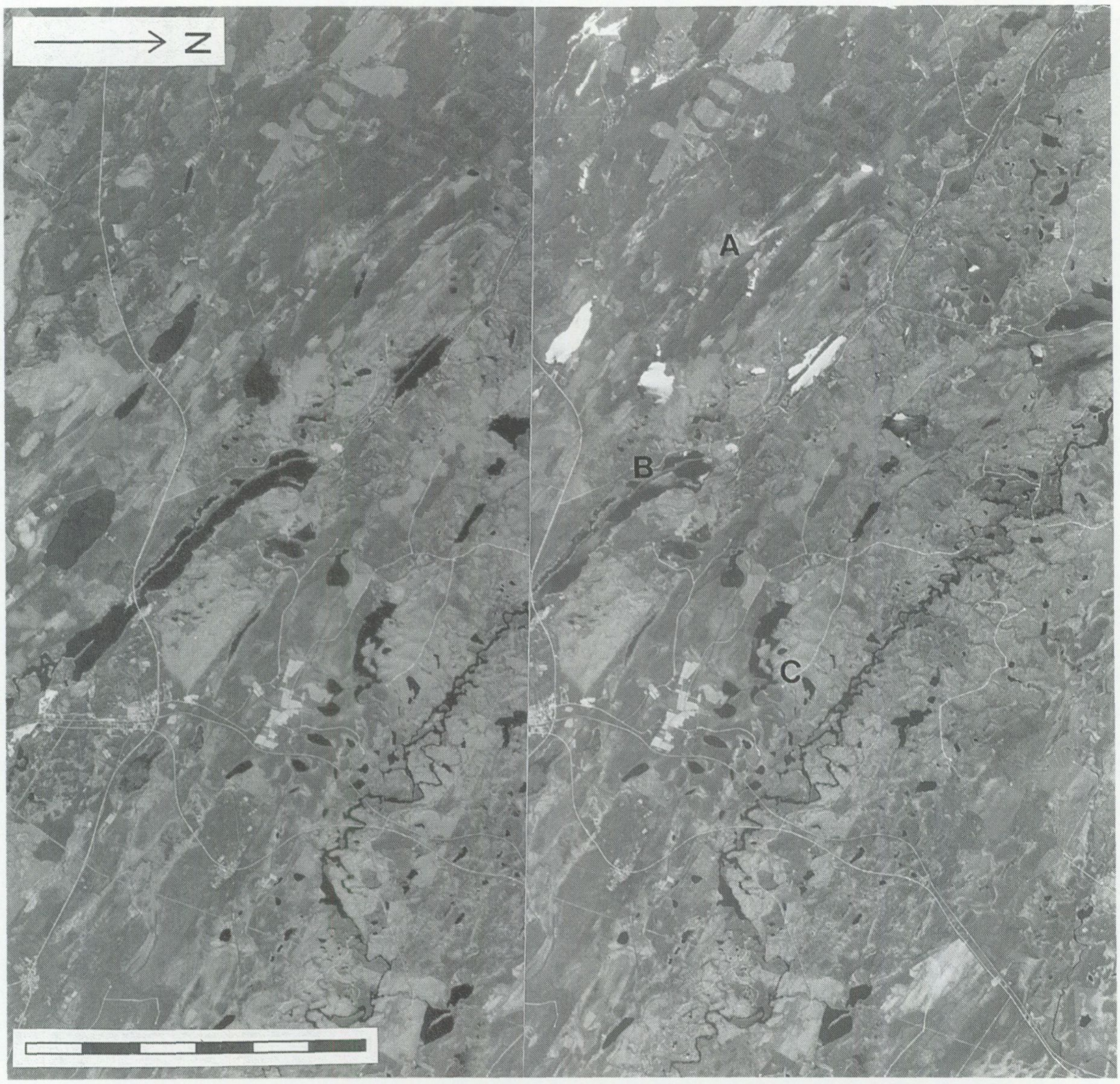


Fig. 16. Stereogram showing the typical glacial landscape of the interior drumlin region in central and northern Sweden, including drumlinisation (A), eskers (B), and ribbed moraine (C) (Långträsk, southwestern Norrbotten). Late-glacial ice flow was from the northwest. Scale bar is 6 km.

crag-and-tail drumlins and resemble the cross-valley moraines described by Andrews & Smithson (1966) from Baffin Island, Canada.

It is noteworthy that there are very few eskers in the area around Luleå, although there are large accumulations of glaciofluvial sediments in river valleys (e.g., Fromm 1965). A few esker segments, probably belonging to the last deglaciation, are found in the ribbed moraine zone north of Luleå, but in the area where De Geer moraines occur, eskers are almost completely absent. The lack of eskers in this region is probably due to the presence of cold-based areas to the north and northwest of the coastal region (Lagerbäck 1988a, b; Kleman 1992; Hättestrand 1997; Kleman et al. in press). During the near-frozen basal conditions that must have prevailed just distal of these cold-based zones, subglacial melting and esker formation were probably restricted.

The interior drumlin region

The glacial geomorphology is very consistent throughout the interior drumlin region (Region 5 in Fig. 12), with large-scale glacial lineations in the interfluve areas, eskers following the valley systems, and ribbed moraines occupying many of the wide valleys and basins (Fig. 16).

The region is dominated by undulating hilly terrain in the central and southern parts, and by plains with residual hills in the northern part. This bedrock morphology has important implications also for the glacial geomorphology, as bedrock hills very commonly are cores of large-scale glacial lineations, such as rock-cored drumlins and crag-and-tail drumlins. It is only in areas dominated by exposed bedrock, such as the coastal areas between Hudiksvall and Örnsköldsvik, and in northern Värmland, northwest of Karlstad, that the landscape is less drumlinised.

The morphology of individual lineations varies within the interior drumlin region. The most common type is large crag-and-tail drumlins. These drumlins are normally about 2–4 km long, 500–1000 m wide, and 50–150 m high in their proximal parts, tapering out towards their distal end. Occasionally, they have dimensions up to 10 km in length and 200 m in height. They almost always have a rock head where bedrock is outcropping, while the tails rarely show bedrock outcrops. It is therefore inferred that the tails largely consist of glacial drift. These drumlins are most common in the northern and central part of the region, and are particularly well developed in Västerbotten. Classical fields of symmetrical spoon- or cigar-shaped drumlins without protruding bedrock outcrops are quite rare. However, a few good examples of such fields are found; (i) around Soppero and Karesuando northeast of Kiruna (Hoppe 1951; Wastenson 1970), (ii) in the coastal areas around Umeå (Eklund 1991) and (iii), on the Siljan impact dome southeast of Mora (Yrgård 1982; Ulfstedt 1983).

Ribbed moraines occur commonly in the interior drumlin region. Large areas of well-developed ribbed moraines are found for example near Älvsbyn in Norrbotten, Vindeln in Västerbotten, in the Orsa Finnmark area in Dalarna/Hälsingland, and the Dala sandstone plain in Dalarna. The ribbed moraines are less common in the coastal areas and there is also a sharp limit around latitude 60°30'N, south of which ribbed moraines are absent.

Eskers are common throughout the interior drumlin region. They tend to follow the valleys, although they may occasionally "jump" over to another valley when the angle between valley trend and deglaciation ice-flow direction becomes large. However, in the northern part of the region, northeast of Kiruna, the deglacial ice-flow direction was oblique to the general trend of the river valleys. Here, eskers run more independently of the topography. Other signs of glacial meltwater in this region are scattered meltwater channels. Areas with abundant lateral meltwater channels are found around Arvidsjaur in Lappland and around Borlänge and Ludvika in southern Dalarna.

Around Lycksele and Arvidsjaur, in Lappland, there are two minor occurrences of Veiki moraine. The morphology of these is similar to that of the Veiki moraine in the palimpsest region (Region 3, Fig. 12), but they do not exhibit clear terminal moraines and lobate patterns in their distribution. However, considering their position with respect to the northern occurrences of Veiki moraine, it is possible that the Veiki moraines around Arvidsjaur and Lycksele are remnants of interlobate concentrations, where the actual lobes have been eroded by Late Weichselian ice flow.

Most glacial landforms in this region, except for the Veiki moraine, indicates a coherent pattern of ice flow during the formation, with only minor deviations between individual landforms. Nearly all glacial landforms in the central part of the region were formed by ice flow from the NW, with a ten-

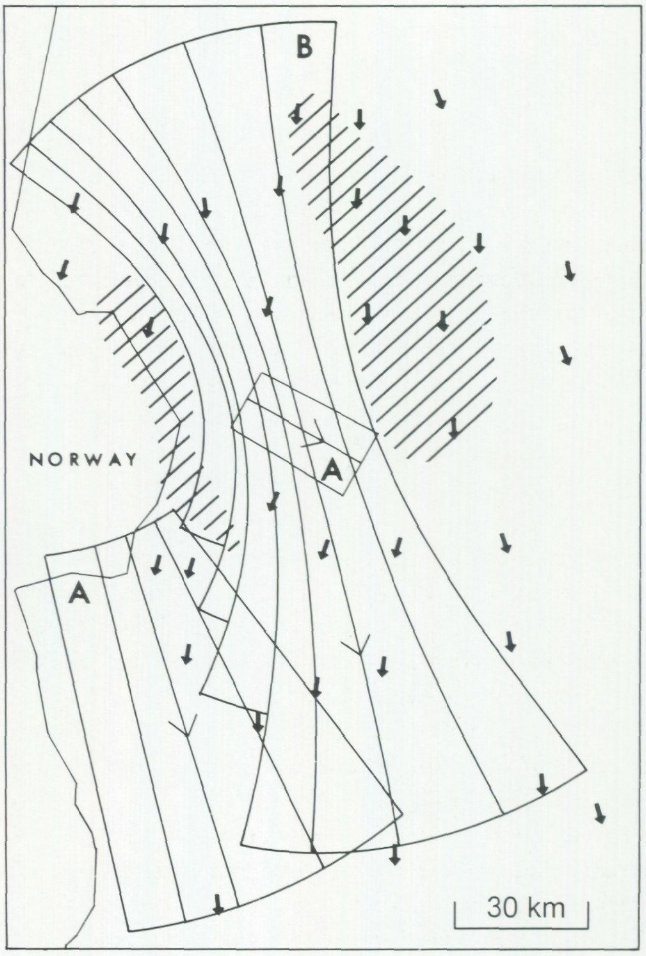


Fig. 17. Cross-cutting ice-flow systems in west-central Sweden. The oldest system (A) consists mainly of glacial lineations, and the intermediate system (B) of glacial lineations and ribbed moraine. Both systems marked with A are interpreted to belong to the same ice-flow event. The arrows mark the last ice flow during the deglaciation, as recorded by striae (G. Lundqvist 1951; Kleman 1990) and eskers. The shaded zones mark uplands that are interpreted to have been entirely or partly cold-based during the deglaciation (Kleman & Borgström 1990, Kleman et al. 1992; Hättestrand 1994).

dency for more northerly directions in the south. In the northernmost part of this region the glacial geomorphology displays a well-defined flow-system towards NE. This pattern reflects the inward retreat of the deglaciating Late Weichselian ice sheet, towards the final ice remnants in eastern part of the mountain range (Kleman et al. in press).

The only major complication to the regular deglaciation pattern occurs in the southwestern part of the region. In northern Värmland and in western Dalarna, there is a system of old glacial lineations formed by ice flow from the NW (A in Fig. 17). Overprinted on this system is a set of drumlins and ribbed moraines which outlines a bottleneck shaped ice-flow system (B in Fig. 17). This system also includes aligned eskers in the southern (distal) part. A third set of ice flow traces, consisting of small eskers, striae and some faint fluting formed by an ice flow from the NNE, overprints the two older flow systems (arrows in Fig. 17). This is the youngest system and represents the deglaciation in this area (G. Lundqvist 1951; Kleman 1990). The geometry of the bottleneck flow system is probably controlled by bed topography and the basal thermal regime of the ice sheet. On either side of the "waist" of this bottleneck, areas of higher altitude (700–1000 m a.s.l.) constrained the ice flow over the sandstone plain (400–500 m a.s.l.). Kleman & Borgström (1990), Kleman et al. (1992) and Hättestrand (1994) have also suggested that these higher-elevation areas were cold-based for most or all of the Late Weichselian stadial. Such bottleneck shaped flow systems are likely to be the result of surges or events of fast outflow of ice during the deglaciation (Kleman & Borgström 1996), and in this case interpreted to be related to a fast inward migration of a wet-based zone into cold-based parts of the ice sheet (Hättestrand 1997; Kleman et al. in press). Thus, the drumlins and ribbed moraines of the Dala sandstone plain are suggested to have formed towards the end of the Late Weichselian, but they are probably related to the deglaciation ice flow only the distal parts of bottleneck flow system.

The southwestern region of exposed bedrock

The surficial geology of this region (Region 6 in Fig. 12) is dominated by exposed bedrock or sometimes thin till cover. The region is also, for most parts, situated below the highest post-glacial shoreline. Therefore, glacial landforms are scarce. There are only patches where glacial lineations occur, mostly in the northern part of the region, and in some of the valleys there are also short discontinuous esker segments. The only landforms that are widespread in the region are De Geer moraines, which are most common on the plains around Karlstad. In addition, a segment of the Younger Dryas end moraine belt crosses the southwestern corner of the mapped area, at Ödskölt and Dals-Ed.

Most glacial lineations in the region were formed by ice flow from the NE, while De Geer moraines mostly run in an E-W direction. This may indicate that lineations were formed earlier during the deglaciation, some distance from the ice margin, when ice flowed out into sea to the west. Later, when the ice margin reached the northern part of lake Vänern, ice flow was more or less N–S (J. Lundqvist 1958). There are also several older lineations in the region, formed by ice flow from the NNW. These, and other similar westerly ice-flow indicators, found at several locations in south-central Sweden, were interpreted by Kleman et al. (in press) to represent ice flow from the growth stage of the Late Weichselian ice sheet (marine oxygen isotope stages 4 and 3).

The southeastern esker and De Geer moraine region

The southeastern part of the map area (Region 7 in Fig. 12) covers parts of the sub-Cambrian peneplain of south-central Sweden. The whole of this region is located below the highest post-glacial shoreline. Upper parts of the terrain are commonly wave-washed, while depressions are infilled by glacial and post-glacial silts and clays. Hence, parts of the original glacial geomorphology has either been subdued or is buried beneath sediments. As a result, this region is not as rich in glacial landforms as the northern part of the country. The most prominent features of this region are the large eskers in the southeastern part of the map area. These eskers, commonly 20–40 m high, sometimes up to 80 m, are continuous for tens or even hundreds of kilometres. An interesting feature is the regular distribution of the six large eskers in the far southeast. They all run roughly N–S and are spaced about 25–30 km apart.

De Geer moraines are often associated with the large esker systems. These moraines are commonly found in a broad zone north of the Younger Dryas end moraine zone (J. Lundqvist 1981). The orientation of De Geer moraines is E–W in general, but fairly large deviations may occur. Most prominently, De Geer moraines tend to bend close to large eskers, depicting the outline of a calving bay around the esker (e.g., Frödin 1916; Bergdahl 1959, 1961; Strömberg 1965). There are deviations in the orientation of De Geer moraines also between the eskers, often related to the local topography.

Other types of morainic features are rare in this region. Glacial lineations, mostly fluting, exist in the area, but are neither well developed nor commonly occurring. Also, the ribbed moraine distribution extends into this region, and a few occurrences of ribbed moraine are found in an area south of Gävle.

The glacial geomorphology record indicates two main ice flow directions in this region. An older set of glacial lineations from the NNW is overprinted by lineations, De Geer

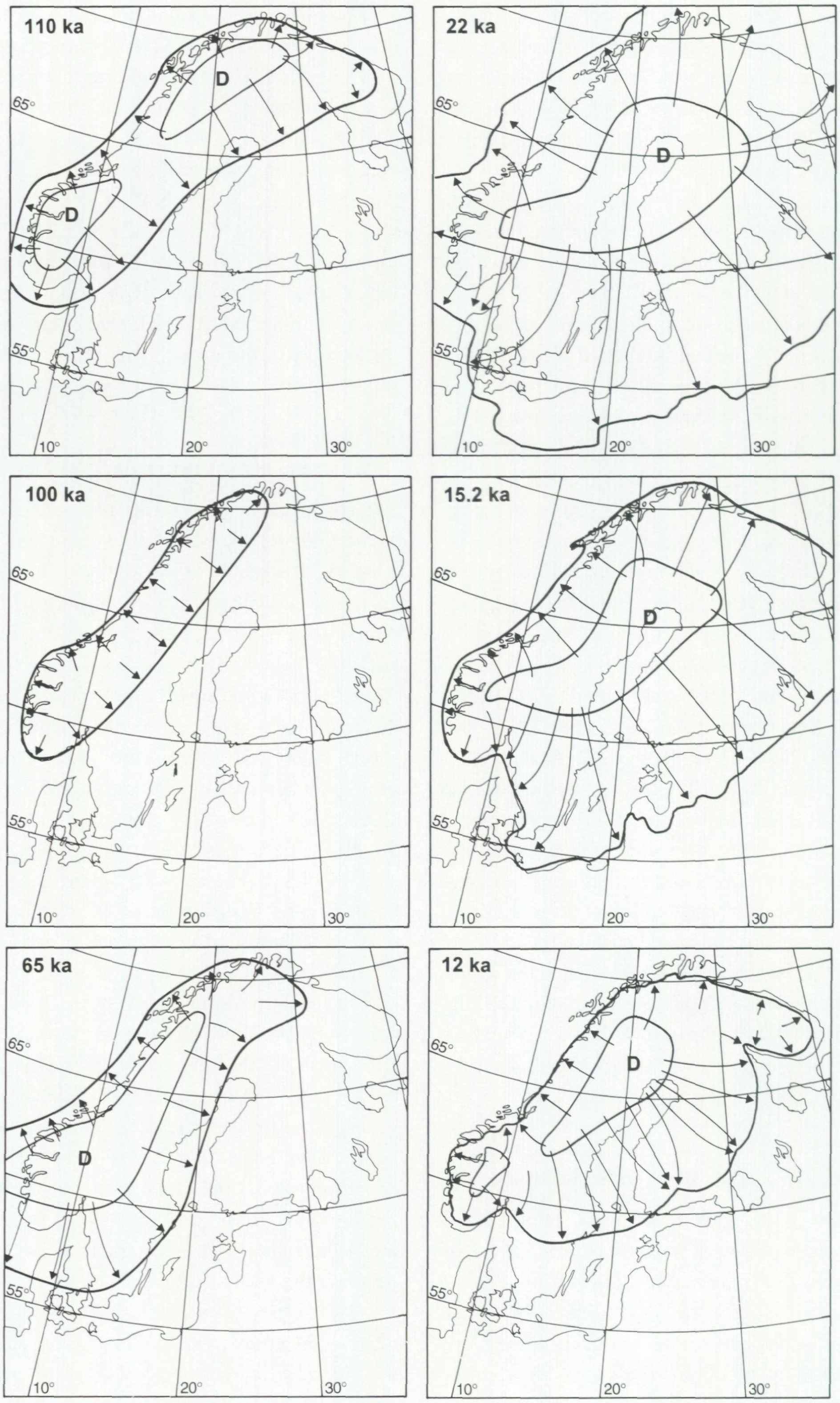


Fig. 18. Ice sheet configurations at six different time slices through the Weichselian glaciation in Fennoscandia. Ages in thousand years B.P. (ka), D – ice dome (from Kleman et al. in press, to be published in the Journal of Glaciology and reproduced with permission of the International Glaciological Society).

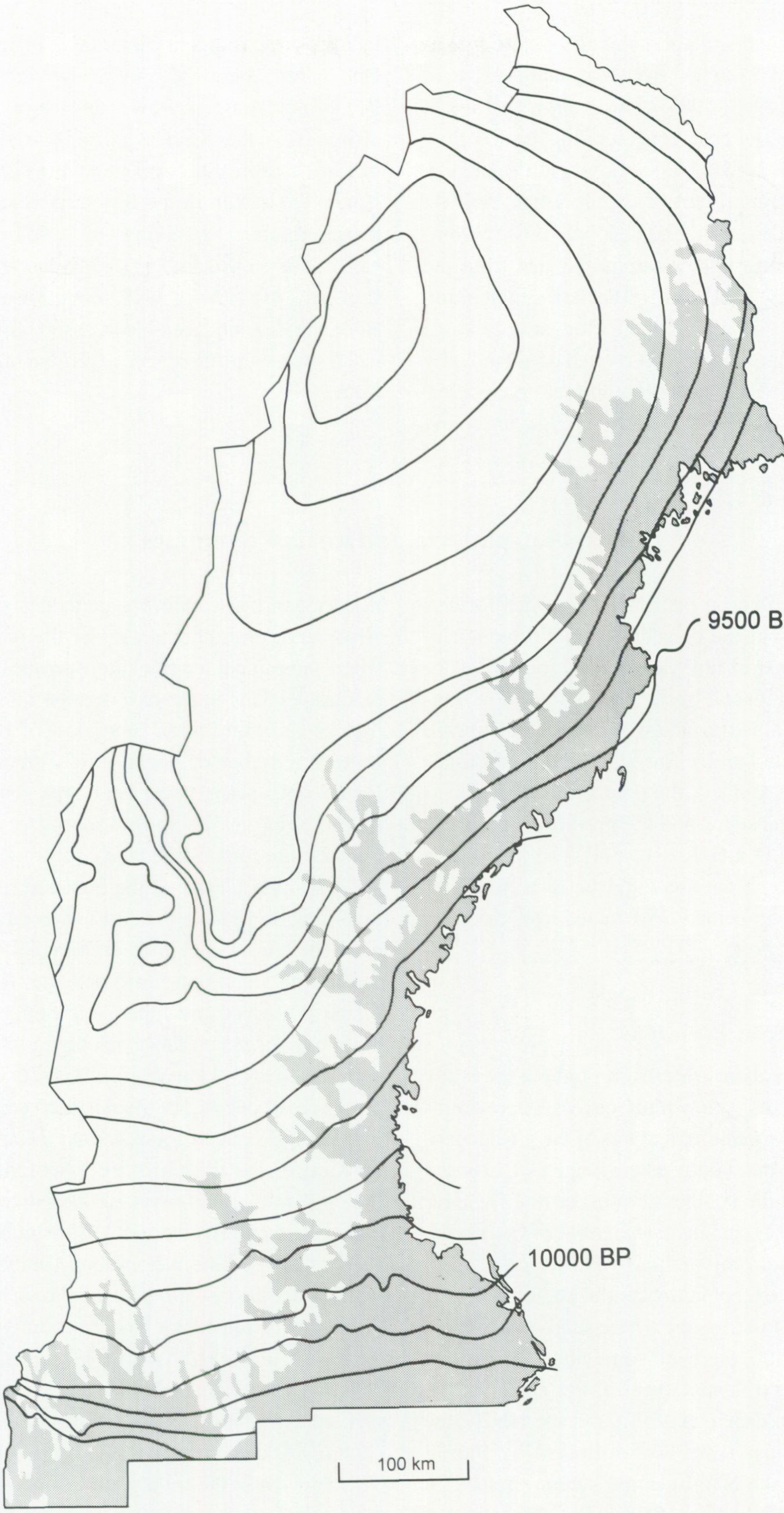


Fig. 19. The deglaciation pattern and the position of the highest post-glacial shore line in central and northern Sweden. Source of information: J. Lundqvist (1994).

moraines, and eskers formed by ice flow with a N to NNE direction. Even though there are not many cross-cutting relationships between the two systems, striae data and clay-varve chronology (Strömberg 1971, 1989) clearly show that the N to NNE-system is the youngest, representing the ice flow during deglaciation. This N to NNE-ice flow is attributed to a large ice lobe in the southern part of the Bothnian Sea (De Geer 1940; Järnefors & Fromm 1960; Hoppe 1961; Strömberg 1971, 1989), draining large quantities of ice from the interior parts of the ice sheet during the last deglaciation (Kleman et al. in press). Likely, this ice flow was to some degree constrained by topography, as it flowed onto land only over the peneplain areas. Further north along the coast, a few striae observations of young northeasterly ice flow are found on the easternmost islands (G. Lundqvist 1963), but no such indicators are found further inland. In the glacial geomorphology record, there are only a few ribbed moraines north of Gävle indicating ice flow from the northeastern sector. It is also possible that the heavy drumlinised terrain south and east of Umeå represents the most proximal part of this late-glacial ice stream in the Bothnian Sea. During the final ice-marginal retreat, a calving bay developed in the Åland Sea, east of region (Strömberg 1971), leading to a shift in the ice flow back to a NW- or NNW-direction along the eastern coast. However, it is not possible to assign any till lineations to this ice flow, as the direction is similar to the earlier ice flow from NNW.

Distribution patterns and ice flow dynamics

In this section, the distribution pattern of each landform is discussed. Also, I will put the distribution and direction of the landforms in a context of the glacial evolution in Fennoscandia through the last glacial cycle. For this purpose, Figures 18 and 19 are included to show; (i) the reconstructed outlines of the Fennoscandian Ice Sheet at six selected times (Kleman et al. in press), and (ii), the course of the deglaciation during the Late Weichselian and the position of the highest post-glacial shoreline (J. Lundqvist 1994). The small-scale maps in the following section, showing the distribution of each landform , contains information extracted from the main map belonging to this report.

Glacial lineations

Glacial lineations are frequent features throughout the study area (Fig. 20). There are only a few limited areas where drumlins and fluting are not dominating features of the glacial geomorphology, such as in the southwestern region of exposed bedrock (6, Fig. 12), in the southeastern esker and De Geer moraine region (7, Fig. 12), and in an area north of Östersund. Large-scale drumlins and crag-and-tails are the most common types of lineations, except in the central and eastern part of the Scandinavian mountain range where small-scale lineations dominate. In addition, there are some lineation swarms that consist of lineations of a specific size. For example, the S–N trending Pajala-fan (Kleman 1992) and the NNE-flow between Gävle and Uppsala are both reflected by fluting swarms alone, whereas the NW-lineation swarm of set 1 in the palimpsest region (set 1, Fig. 13) consists only of large scale drumlins. In these cases, their size is interpreted to reflect the nature of ice flow; sustained wet-based ice flow generates large lineations, while short ice flow-events during near-frozen bed conditions generates small-scale lineations. Also, large drumlinoids may be the only remaining features when subsequent ice flow partly erodes a pre-existing glacial landscape. This is the case for the northernmost part of the interior drumlin region (northeast of Kiruna), covered by a Late Weichselian deglacial flow system. The only remaining features of a pre-existing landscape generated by a NW-flow in this area are large rock-cored crag-and-tail drumlins (Goodwillie unpublished).

A striking feature of the lineation record is the consistent NW-direction present in most of northern and central Sweden. The consistency in itself may not be so remarkable, but there is no significant difference between the NW-drumlins of the preserved pre-Late Weichselian landscape in northeastern Sweden and those belonging to the late-glacial recession landscape to the south. These two drumlin-landscapes are likely to overlap in the northern coastal region, but there is no visible contact zone, as both the appearance and the orientation of the drumlins are essentially the same for both systems. Is there an invisible lateral contact zone where the two systems meet, or do all NW-drumlins belong to a stadial earlier than the Late Weichselian? In the latter case, it is noteworthy that the last ice sheet, as shown by eskers and meltwater channels, must have had essentially the same retreat pattern as earlier ice sheets. Still, I suggest that this was the case, as it appears unlikely that the very large crag-and-tail drumlins, up to 10 km in length and 200 m high, in parts of north-central Sweden, formed solely during the last deglaciation. This is because the time period of NW-flow associated with the deglaciation must have been limited, since the ice-flow direction changed continuously during deglaciation, due to a westward migration of the ice divide (Ljungner 1949; J. Lundqvist 1986; Kleman 1990; Kleman et al. in press).

Fig. 20. Distribution of glacial lineations in central and northern Sweden

At the last glacial maximum, the ice divide of the Fennoscandian Ice Sheet was positioned over the Bothnian Sea. During the first part of the deglaciation, around 22–16 thousand years B.P. (ka), the ice marginal retreat was limited (Andersen 1981) and only minor changes in ice divide position are likely to have occurred. This allows some 6000 years for the shift of the ice divide position, from its easternmost position over the Bothnian Bay, to a final position over the eastern part of the Scandinavian mountain chain. If a more or less continuous migration is assumed, the ice divide reached the western part of the NW-drumlin zone, e.g. around Arjeplog, about 11 ka. This area was deglaciated 9.6 ka (Kleman & Strömberg unpublished), which leaves at most 1400 years of NW-flow during the deglaciation. The time period available for the creation of NW-features is likely to be even shorter, because the ice-flow velocity at the glacier bed, and thereby also the landform-generating activity, is at a minimum beneath the ice divide and increases towards the front. Is it possible for drumlins, several kilometres long and 100–150 m high, to form in such a short time? As there is no modern analogue to such a glacial environment, with migrating ice divides and continuous rapid ice marginal retreat, this question cannot be answered. However, given the vast amounts of glacial sediments accumulated in the tails, it appears that these lineations must have a longer history of formation than what would have been available during the last deglaciation.

Another relevant observation in this discussion is that in areas where the deglaciation pattern deviates from the ordinary NW-flow, the drumlin shape differs from the ordinary. For example, within the deglaciation landscape northeast of Kiruna there are no large crag-and-tail drumlins associated with the northeast trending deglaciation ice flow. Instead, the drumlins are mostly of a smaller cigar-shaped type. The same type of cigar-shaped drumlins are found in the deglaciation morphology around Umeå, where ice flow bends southward into the Bothnian Sea. It is also noteworthy that the distribution of large NW-oriented drumlins extends northwest of the eskers associated with the last deglaciation. Within the mountain range, many NW-oriented drumlins even occur on the western side of the last ice divide, that is, in areas which have not experienced NW ice flow since the onset of the Late Weichselian.

In summary, there are many observations which, in the authors view, indicate that the large NW-drumlins of the interior drumlin region are derived from glacial stages earlier than the Late Weichselian. Based on records of the climatic evolution over the last 3 million years, Kleman & Stroeven (1997) suggested that ice sheets centred over the Scandinavian mountain range was the dominating glaciation mode in Fennoscandia during a total time of ~1.2 million years of the Quaternary. Because the general shape of the mountain chain has not changed during this time, it is likely that these mountain centred ice sheets yielded roughly the same flow patterns. In this perspective, it is suggested that much of the NW-drumlin landscape described here was formed over a large number of glaciations, and that the deglaciation of the last ice sheet only slightly affected their present appearance.

Ribbed moraine

Ribbed moraines are common in much of the mapped area (Fig. 21). They are particularly common along the eastern part of the mountain range and in the coastal areas of northern Sweden. Large areas lacking ribbed moraines are found only in northeasternmost Sweden, south and northwest of Östersund, along parts of the coast, and in the southernmost part of the mapped area. The southern limit of the ribbed moraine distribution is remarkably sharp and runs east–west at about 60º30'N. This boundary is likely to reflect the southern limit of ribbed moraine in Sweden, as no ribbed moraine has been reported from southern Sweden (Hättestrand 1997). The southern boundary does not coincide with any special change in physiography or geology and is therefore likely to reflect a change in the subglacial environment. According to Hättestrand (1997) and Hättestrand & Kleman (in press), ribbed moraines form during the transition from cold- to warm-based conditions under ice sheets. If so, the southern boundary of the ribbed moraine distribution outlines the southern limit of the cold-based central area under the Late Weichselian Fennoscandian ice sheet.

The direction of ice flow during ribbed moraine formation (inferred from the normal to the ridge orientation) correlates very well with the deglaciation pattern of the Late Weichselian Fennoscandian ice sheet. Even small-scale variations in outline of the retreating ice margin are often reflected in the ribbed moraine direction. Consequently, Hättestrand (1997) and Hättestrand & Kleman (in press) suggested that ribbed moraines generally form during deglaciation close to the ice margin. Only a few ribbed moraines, in the northern part of Sweden, are incompatible with the Late Weichselian deglaciation ice-flow direction. However, these ribbed moraines are an integral part of an Early Weichselian deglaciation system and are thereby the only known examples of pre-Late Weichselian ribbed moraines in Sweden.

Many of the largest and best developed ribbed moraine areas are situated just distally of areas that are interpreted to have been cold-based during most or all of the Late Weichselian (Hättestrand 1997; Hättestrand & Kleman in press; Kleman et al. in press). This is well illustrated in northwestern Dalarna. In the southern part of the bottleneck shaped flow system (B in Fig. 17) there are no ribbed moraines. Northwards they start to show up, many of them strongly drumlinised (Blattnick moraine; Markgren & Lassila 1980). Towards the proximal part of the flow system, ribbed moraines increase

Fig. 21. Distribution of ribbed moraine in central and northern Sweden.

in abundance, becoming more well developed, and are generally non-drumlinised. At the head of the flow-system, large ribbed moraines cover the valley floors, while the upper interfluve areas, such as Långfjället and Städjan–Nipfjället, lack both drumlins and ribbed moraines. These uplands show many signs of having been cold-based during the deglaciation (Borgström 1989; Kleman & Borgström unpublished). This is interpreted to be the result of an inward migrating thawing-bed boundary, at which the ribbed moraines were formed by fracturing of a pre-existing till cover (cf. Hättestrand 1997; Hättestrand & Kleman in press).

De Geer moraines

There are three main areas where De Geer moraines occur in central and northern Sweden; (i) in the Karlstad area around the northern part of Lake Vänern, (ii) on the central Swedish peneplain (around Uppsala and Västerås) and (iii), along the northern coast of the Bothnian Sea, especially around Luleå (Fig. 22).

Because of their formation in association with calving ice fronts, the distribution of De Geer moraines is confined to areas below the highest post-glacial shoreline. However, there are many areas below the highest post-glacial shoreline, such as along the coast from Gävle to Umeå, where no De Geer moraines have been found. This part of the coast is characterised by a high relief and joint-valley landscapes commonly extend out to the coast line (Lidmar-Bergström 1995). In contrast, most De Geer moraines are located in areas in which the morphology is dominated by the sub-Cambrian peneplain. Thus, there seems to be a link between the distribution of De Geer moraines and areas of relatively low relief. One exception is the interior part of the northern coastal region, where De Geer moraines extend into a high-relief area dominated by large crag-and-tail drumlins. In this area De Geer moraines are not confined only to valley floors, as in the southern regions, but commonly occur also on convex surfaces, such as on the tails of the large drumlins. In addition, the detailed morphology of the De Geer moraines differs in this area from the southern regions. In areas (i) and (ii), De Geer moraines are often strongly curved, bent or anastomosing and occasionally split into parallel ridges, while those in area (iii) are mostly long, straight and continuous.

End (and lateral) moraines

This section deals mainly with the distribution of pre-Late Weichselian lateral moraines and early Holocene terminal moraines. Early Weichselian terminal moraines are discussed in association with the Veiki moraine distribution. The total distribution of end and lateral moraines in central and northern Sweden is shown in Figure 23.

There are 10–15 rather small end moraines, or series of end moraines, located within the mountain range which have no connection to any present-day glaciers (e.g., Fig. 7). The moraines occur much lower in altitude than the Little Ice Age moraines in nearby areas and are commonly situated in valleys that have been scoured by wet-based ice flow during the Late Weichselian. Therefore, most of the moraines are interpreted to have formed during the early Holocene, by outlet ice tongues of the waning ice sheet. The moraines are often occurring in series, and are almost exclusively situated in valleys that drained ice westwards during the deglaciation. Although, there are one or two examples of end moraines built by east-facing outlet glaciers in the Kebnekaise-Abisko area (e.g., the Lävasjåkka moraines; Tanner 1914; Melander 1977). The location of individual moraines (Fig. 23) does not appear to coincide with an ice-sheet configuration at a specific time (Fig. 19). Therefore, the formation of these moraines is interpreted to be related to internal changes in ice-sheet dynamics, rather than to climatic factors. Although most of the end moraines are interpreted as early Holocene in origin, there are exceptions. Some end moraines, such as one on the northern side of lake Rautasjaure, west of Kiruna, are overprinted by Late Weichselian deglacial features and must therefore originate from pre-Late Weichselian glaciations.

In many east-facing valleys in the northern part of the mountain range there are lateral moraines along the valley sides. The moraines are often perched high up on the slopes and mostly have a rounded smooth appearance. The slope of the moraines indicates that they were formed by ice tongues draining ice eastwards from an ice sheet that was centred over or west of the high elevation axis of the mountain chain (Kleman 1992). Such an ice sheet configuration is incompatible with the last deglaciation pattern and the lateral moraines must therefore belong to a pre-Late Weichselian glaciation. The moraines have previously been mapped by Kleman (1992) who named them the Torne Träsk–Hornavan ice marginal zone. During the present mapping new lateral moraines have been found, so that this zone can be extended, from northernmost Sweden down to the southern Lappland mountains west of Arjeplog (Fig. 24). A few similar features have also been found in Jämtland and northern Dalarna (Borgström 1983, pers. comm.). In addition, there are also some much larger elongated drift accumulations within the Torne Träsk–Hornavan zone, located in the same topographic position as the lateral moraines. Examples of such accumulations are found along the eastern rim of Ultevistuottar, and in the lower Kaitumjaure valley, where a large drift accumulation is damming the lake Tjuoltajaure.

During the mapping, "moraine ridges of complex origin" (Ulfstedt 1978) were also mapped (these will be referred to as "complex moraines"). The complex moraines occur on the

Fig. 22. Distribution of De Geer moraines in central and northern Sweden.

Fig. 23. Distribution of end- and lateral moraines in central and northern Sweden.

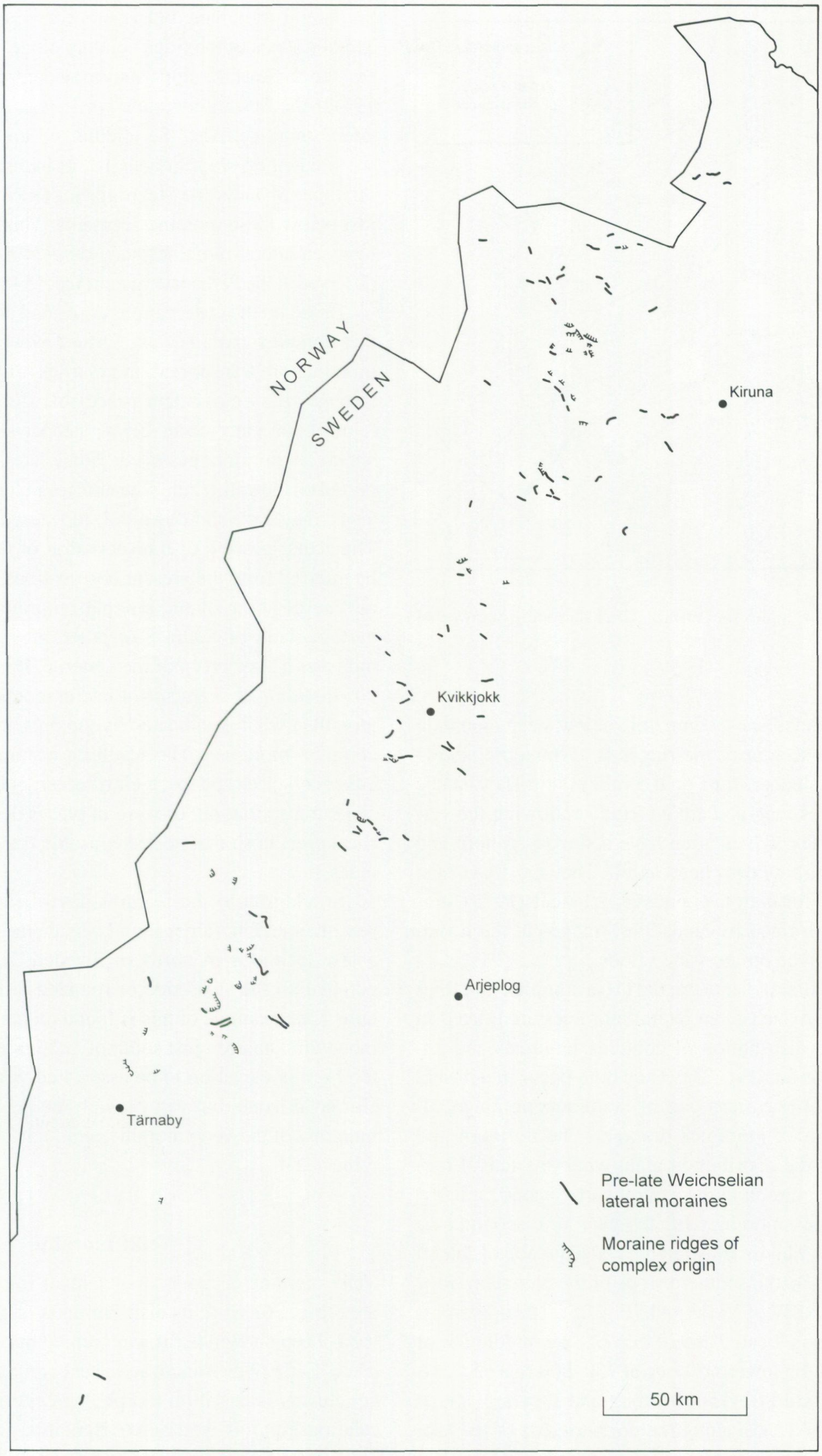


Fig. 24. Pre-Late Weichselian lateral moraines and complex moraines in northwestern Sweden.

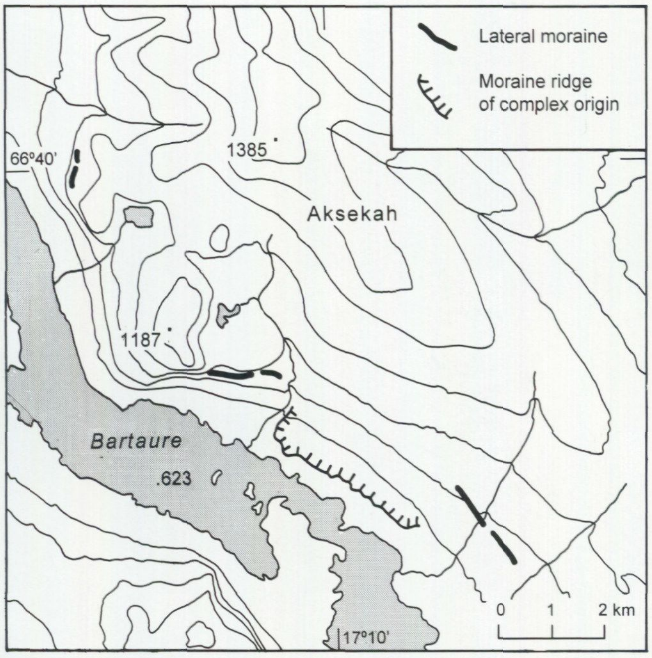


Fig. 25. Lateral and complex moraines at Aksekah, south-southwest of Kvikkjokk.

lower part of valley slopes, commonly below steep mountain faces. The cross-section of the ridges is asymmetric, showing a longer and steeper slope on the valley side. They can be several kilometres long and are generally following the valley orientation. The ridges often have a sinuous pattern and commonly one or both ends bend uphill. They mostly consist of till, but their formation is elusive. Ulfstedt (1978) suggested that they formed by landslides, trapped at the lateral side of an ice tongue on the valley floor.

There are several indications that these complex moraines and the pre-Late Weichselian lateral moraines are related in origin. First, the distribution of complex moraines and lateral moraines overlap (Fig. 24). They both occur in a 50 km wide zone along the eastern part of the mountain range, although the complex moraines dominate the northern and southern part of the distribution area, while the lateral moraines are most common in the central part. Second, at a few locations, complex moraines fill the gaps in discontinuous lateral moraines. This is illustrated by a sequence of lateral moraines located on the southern slope of the mountain ridge Aksekah, 40 km SSW of Kvikkjokk (Fig. 25). The uppermost moraine segment is located at 920 m a.s.l., the middle one at 880 m a.s.l., and the lowermost one at 780–800 m a.s.l. Each of the moraines are 800–1500 m long and they are spread over a distance of 12 km along the northern side of the lake Bartaure. A complex moraine is found between the middle and the lower lateral moraine, but is located about 200 m lower in elevation. The complex moraine ridge is the same size as the lateral moraines, but is more irregular along its length and both ends of the ridge bend up-slope. It can also be noted that the angle of the slope above the complex moraine is about 12° (at the 800 m contour), while it is only 6° at the lower lateral moraine. Also the middle and upper lateral moraines are situated on slopes under 10° in inclination and the break in slope, towards the steep glacial faces below, are located just below these moraine segments. This type of association between lateral moraines and complex moraines can also be observed at the Parka lateral moraine, 15 km SW of Kvikkjokk.

Based on the observations described above, it is suggested that complex moraines are formed when sections of lateral moraines are transported, more or less *en masse*, down-slope through mass movement processes. Because complex moraines commonly occur below steeper slopes than those on which lateral moraines occur, some lateral moraines, unsupported on the valley side when the ice that formed them melted away, may have slid down the slope towards the valley floor. The actual process of transportation of the segments cannot be inferred from the present observations, but the very lobate outline of some of the complex moraines (such as on the eastern flank of Södra Storfjället, west-central Lappland), indicates a slow creep of the material. It is also likely that the down-sliding of segments of lateral moraines was more common than what is indicated by the present distribution of the complex moraines. The resulting accumulations may have either collapsed and lost their ridge structure during the down-slope transportation, or were in places destroyed by later ice sheet erosion so that no recognisable traces of them are seen today.

In addition to the features described above, there are a few other end moraines found outside the mountain range. At a few locations in northern Sweden, lateral moraines are perched on the stoss-side of rounded hills and small mountains. One example of this is found on the western side of the mountain Dundret, just south of Gällivare. These are located too high in elevation to be associated with the Torne Träsk–Hornavan zone, but can possibly be related to the terminal moraines of the Veiki moraine, although lacking the Veiki moraine itself.

Veiki moraine

Veiki moraine occupies only a small fraction of the mapped area (Fig. 26). Still, its distribution is of great importance, as it has been shown that it was formed during the deglaciation of an Early Weichselian ice sheet (Lagerbäck 1988a). This conclusion is based on morphological criteria (cross-cutting relationships) as well as stratigraphic evidence (e.g., post-landform deposition of interstadial organic material). The main area of Veiki moraine occurrence is an elongated zone from the river Lainioälven, in northeastern Sweden, to the river

Fig. 26. Distribution of Veiki moraine in central and northern Sweden.

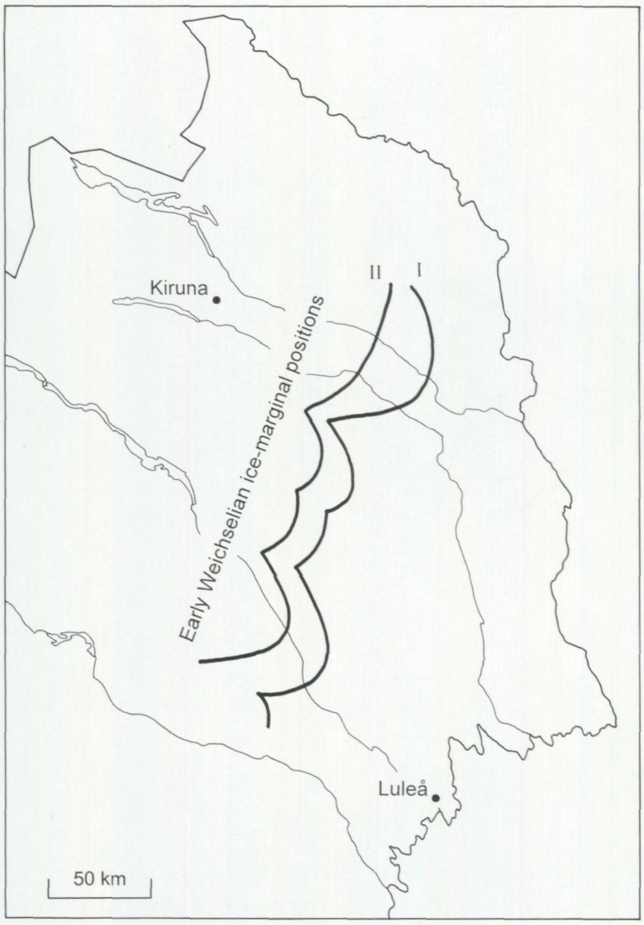


Fig. 27. Inferred outlines of two ice marginal positions during the Early Weichselian, based on the distribution of Veiki moraine and its associated terminal moraines.

Piteälven, at 66°N latitude. Outside this large and nearly continuous belt, there are only minor occurrences of Veiki moraine, primarily around Arvidsjaur and Lycksele, and at a few scattered locations in the eastern part of the mountain range.

As mentioned earlier, the distribution of Veiki moraine, as shown in Figure 26, is more restricted than that shown by Lagerbäck (1988a). One feature that becomes more evident when applying the more strict definition used in this study, is the Veiki moraines outline of 3–4 well defined lobes (Fig. 27). When seen with the associated terminal moraines, it is also clear that the Veiki moraine distribution represents two individual end moraine belts, separated by 15–25 km (I and II in Fig. 27), each featuring well-defined lobes. The outer belt (I) is less continuous than the inner belt (II), but is accompanied by more continuous terminal moraines. These unbroken terminal moraines indicate that Veiki moraine belt I is largely intact, preserved from later ice sheet erosion. One exception from this is the southern lobe of belt I, of which only the lateral sides remain. The central part of this lobe lacks both terminal moraine and Veiki moraine, which was probably eroded by subsequent wet-based ice flow. However, parts of the southern lobe of belt II are still intact, and may show the extent of the inward transgressive wet-based ice flow during the last deglaciation.

The location of the lobes seems to be controlled by the regional bedrock morphology. Deep and glacially widened river valleys (now occupied by lakes) are situated upstream of the two largest lobes (Fig. 27), and the two smaller, central lobes also have river valleys located in their central parts. Therefore, the flow pattern of the ice sheet that formed these end moraine belts, seems to have been influenced by regional topography, with ice flowing down the major river valleys and forming lobes as it reached the lowlands. This flow pattern may be related to large-scale surging in the marginal areas of the ice sheet (cf. Lagerbäck 1988a).

In the northern part of the Veiki moraine zone, terminal moraines indicate that there were not only two major, but also several minor re-advances or interruptions in the retreat of the ice sheet that created the Veiki moraine. Between Junosuando and Skaulo, 3–4 ice marginal positions are indicated by Veiki moraine and terminal moraines (Fig. 28). Lagerbäck (1988a) suggested that more or less all Veiki moraine was formed by areal downwasting of a regionally stagnant ice sheet, possibly following a large-scale surging. However, such an ice sheet stagnation would result in only one terminal moraine. From the distribution of Veiki moraine and terminal moraines, it appears more likely that this landscape was formed during two major re-advances (Fig. 27), interspaced by several ice margin fluctuations (Fig. 28). Also, the distribution of Veiki moraine indicates that stagnation was more local in character, mostly confined to a 5-15 km wide zone inside each ice marginal position.

Lagerbäck (1988a) argued that the same ice sheet created both the Veiki moraine and the NW-landscape (drumlins and eskers) in northeastern Sweden. This was based on the presence of Early Weichselian NW–SE trending eskers within the Veiki moraine. However, I have found only three eskers with this trend overlying Veiki moraine. There are also a few eskers with a SW–NE trend, deriving from the last deglaciation, within the Veiki moraine. Obviously, these are not related to each other, as the Late Weichselian deglaciation eskers are also accompanied by glacial fluting overprinting Veiki moraine (Hoppe 1957; Lagerbäck 1988a). It should also be noted that many of the Early Weichselian eskers disappear when entering the Veiki landscape from the southeast. In addition, the direction of ice flow indicated by the outline of the terminal moraines and the Veiki moraine belts is not entirely aligned with that of the NW-landscape. Especially in the northern part of the Veiki moraine distribution, e.g. at the Lainio arc, NW-drumlins are running obliquely to terminal moraines. These features indicate that Veiki moraine was

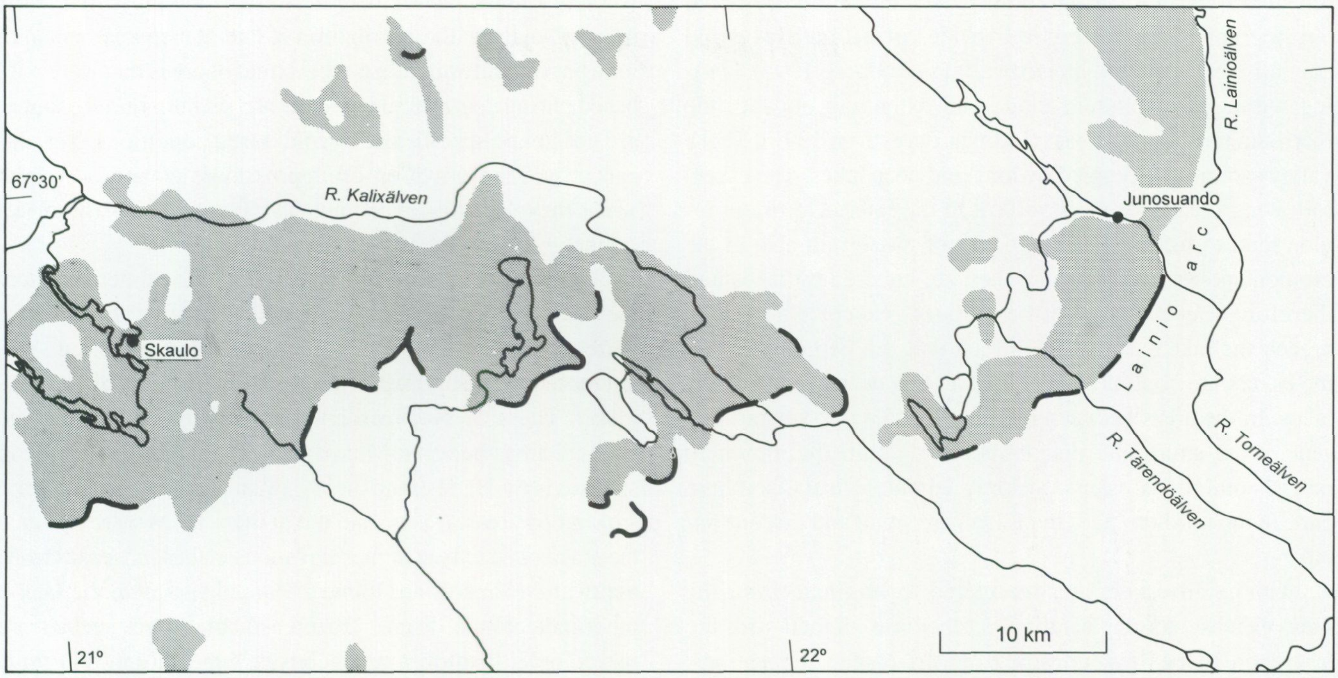


Fig. 28. Early Weichselian Veiki moraine (shaded) and terminal moraines (thick lines) in northeastern Sweden. Inside the Lainio arc, the easternmost Veiki moraine belt, there are at least two well-defined ice marginal positions marked by Veiki moraine and terminal moraines.

formed by an ice sheet with a different configuration, possibly during an advance. Thus, it is argued that from a morphological point of view, Veiki moraine and the NW-landscape cannot be directly linked. Stratigraphical evidence indicates that both the NW landscape and the Veiki moraine date to the Early Weichselian (Lagerbäck 1988a; Lagerbäck & Robertsson 1988), but they may still be separated in time within that period.

There is no clear contact between Veiki moraine in the forested lowland and Veiki moraine in the mountain range. The two types are separated by a more or less Veiki moraine-free zone. There are also morphological and topographical differences between the two types. The Veiki moraine in the mountains generally lacks rim ridges and is only found in higher terrain, such as on plateau interfluves. The Veiki moraine in the mountains shows overprinted faint fluting to some degree, and occurs on surfaces where no subglacial deposition occurred during the Late Weichselian. Therefore, it was most likely formed before the last stadial. However, as the mountain Veiki moraine mostly occurs on surfaces which also lack signs of erosion by the Early Weichselian ice sheets, it may be older. Thus, there is no evidence that the mountain Veiki moraine was formed contemporaneously with the lowland Veiki moraine. They may be related in origin, but this has yet to be proved.

The preservation of Veiki moraine, from the Peräpohjola interstadial until the end of the Late Weichselian, is linked to cold-based conditions of subsequent ice-sheets covering the area (Lagerbäck 1988a). Thus, the present distribution of Veiki moraine gives information of the extent of these cold-based areas. It is most likely that the original distribution extended further towards south-southwest, as the southern lobes of Veiki moraine belt I (Fig. 27) is partly eroded, and considering the position of the Veiki moraine occurrences around Arvidsjaur and Lycksele, which are aligned with a southward extension of belts I and II. However, the westward extent of Veiki moraine in belts I and II probably reflects the original distribution. This is because most of the area between the terminal moraines and the mountain range still displays the Early Weichselian deglaciation landscape and shows only minor signs of erosion of the Late Weichselian Fennoscandian ice sheet. Northeast of the Lainio arc, Veiki moraine is absent. This may reflect the northeastward limit of its formation, but could also be the result of glacial erosion during the Late Weichselian deglaciation.

Eskers

Eskers are common in most of central and northern Sweden (Fig. 29), except for a few areas where the surficial geology is dominated by exposed bedrock (such as in the western part of the mountain range and in the southwestern corner of the map area). Eskers are also generally rare in the premontane region. However, the latter may partly be an artefact of physiography and cartographic presentation. The regional physiography is characterised by wide upland interfluves and glacially reshaped and incised valleys (Rudberg 1992), starting within the mountain range and extending out into the Norrland terrain to the east (Lidmar-Bergström 1996). These valleys are often occupied by long and deep lakes. The eskers following the larger river valleys in the interior drumlin region tend to follow the lowest part of the terrain also in the premontane region, but there they are covered by lakes and therefore, can usually not be mapped, except where they breach the lake surface. Even then it is not certain whether the eskers are continuous features also in deeper parts of the lakes. In the areas between these large valleys eskers are absent or are small and discontinuous. Within the mountain range, continuous eskers are only common in the southern part. In the northern part, the eskers are small and discontinuous.

Almost all eskers are interpreted to originate from the Late Weichselian deglaciation, as they are aligned with the last recorded ice flow (inferred from striae, glacial lineations, and varve chronology; Kleman & Strömberg unpublished). The only exception are eskers of the palimpsest region in northeastern Sweden, where most eskers date back to an early Weichselian deglaciation (Lagerbäck & Robertsson 1988). However, NW-trending eskers within this region have a direction and appearance which is similar to eskers of the Late Weichselian deglaciation landscape in the interior drumlin region. At approximately 66°N latitude, along Lule River, there should be a zone where Early Weichselian eskers are replaced by Late Weichselian eskers. Yet, as with the lineations in this area, there are few morphological differences between the two systems, and it is not possible to define the contact zone from morphological or geographical information alone.

Meltwater channels

The shaded areas in Figure 11 show zones where lateral meltwater channels are commonly found, while the arrows that show the interpreted ice-surface slope direction also includes information from extramarginal channels (e.g., overflow channels). The reason for this is that flights of lateral channels indicate an impermeable ice sheet, most likely related to ice temperatures below the pressure melting point. It is often assumed (Dyke 1993; Sollid & Sørbel 1994) that ubiquitous series of lateral meltwater channels reflect the deglaciation of cold-based parts of former ice sheets. This is not strictly true, as they only show that the surface layer is impermeable, while lower parts of the ice may be at the pressure melting point. However, as lateral channels often occur also in low positions, near valley floors, it is likely that the whole ice mass had temperatures below the pressure melting point. Therefore, the distribution of lateral meltwater channels may provide information on the extent of areas that were cold-based during deglaciation. In contrast, extramarginal channels are not linked specifically to cold-based conditions. Yet, they can provide information on approximate ice surface slopes when they occur as overflow channels in col positions, e.g. drainage channels from ice-dammed lakes.

In general, the distribution of areas with numerous lateral meltwater channels (Fig. 11) agrees well with the extent of frozen bed conditions under the Late Weichselian ice sheet, as reconstructed by Hättestrand (1997) and Kleman et al. (in press). The only major exceptions are two lateral meltwater channel areas between Mora and Västerås, that in the reconstructions by Hättestrand and Kleman et al. are not shown as frozen bed areas. It is possible that these areas were frozen to the glacier bed only at higher elevations in the landscape (where meltwater channels are found). This may explain the lack of other indicators of former frozen bed conditions, such as preserved older landforms and deposits, which are mostly found in lower parts of the terrain. The match between areas with numerous lateral meltwater channel series and areas of reconstructed frozen-bed conditions agrees well with the idea that such drainage patterns are indicative of cold-based conditions during the deglaciation stage (Dyke 1993; Sollid & Sørbel 1994). Therefore, widespread occurrences of lateral meltwater channel systems may be used as a complement to ribbed moraines in surveying the total area that was cold-based under former ice sheets. The distribution of ribbed moraines is interpreted to show the extent of areas that changed from frozen- to thawed-bed conditions during the deglaciation (Hättestrand 1997; Hättestrand & Kleman in press).

The retreat pattern of the Late Weichselian Fennoscandian ice sheet, as indicated by ice surface slope directions in Figure 11, is in general agreement with the most recent reconstruction of the deglaciation (Kleman et al. in press; Kleman & Strömberg unpublished). Especially in the central parts of the mapped area, there is a close correlation. However, there are some deviations along the eastern part of the Scandinavian mountain range. Kleman et al. put the retreating southern tip of the waning ice sheet some 20–30 km farther east than what is indicated by the drainage pattern presented in Figure 11. Their reconstruction is, in the central parts of the glaciation, primarily based on till lineations and glacial lakes. This may account for some of the deviation, as ice flow at the southern tip of the waning ice sheet was strongly divergent and the subglacial landform imprint may therefore be weak and difficult to interpret. However, meltwater channels formed, despite the probably sluggish nature of the ice flow. Therefore, meltwater channels are likely to show the ice-marginal retreat more accurately in these areas. An alterna-

Fig. 29. Distribution of eskers in central and northern Sweden.

tive explanation for this deviation may be that many of the channels in the mountain range, indicating drainage towards the southwest, derive from earlier deglaciations.

The meltwater channels associated with earlier glacial phases (open arrows in Fig. 11) appear to be formed during more than one deglaciation pre-dating the Late Weichselian. In the northern part of Sweden older channels are very consistent in direction and indicate an ice sheet retreating towards the northwestern part of the country. This ice-flow direction correlates well with the retreat of the Early Weichselian ice sheet (Lagerbäck & Robertsson 1988) that formed the northwest-oriented drumlins and eskers in the palimpsest region of northeastern Sweden (Fig. 13a). However, there is a problem in correlating these channels with flow set 1. The well developed series of lateral channels often extend to the valley floor, which indicates an impermeable and probably frozen ice sheet terminus during their formation. This is in conflict with the large-scale drumlins and especially the eskers of this flow system, which indicate a wet-based glacier, actively reshaping the bed during deglaciation. One solution to this problem could be that eskers and drumlins represent one deglaciation and channels represents another. However, there are also flaws in such an explanation. First, the channel pattern as well as the drumlin and esker patterns are very well correlated in direction, and second, the drumlins and eskers are overprinted by at least two other deglaciation systems (set 3 in Fig. 13 and set X in Fig. 14), which leaves no room for another deglaciation in the stratigraphical/climatological record. Rather, it is more likely that this Early Weichselian ice sheet was thoroughly warm based (to account for the drumlins and eskers), but downwasted under permafrost conditions, inducing a frozen ice margin at which marginal channels were formed.

Summary of glaciation history and landscape evolution

In this section, an attempt will be made to summarise the links between the glacial landform record and glaciation history.

Pre-Weichselian glaciations

Much of the large-scale glacial geomorphology in central and northern Sweden is likely to have developed during a large number of separate glaciations that occurred during the Quaternary. The dominating type of glaciation during this time has been elongated ice sheets centred over the Scandinavian mountain range, extending to the interior parts of northern Sweden (Kleman & Stroeven 1997). According to Kleman & Stroeven, this glaciation mode has dominated during ~1.2 of the last 2.7 million years. Landforms that are likely to be associated with this type of glaciation are for example glacial facets in mountainous terrain, rock drumlins, large-scale roches moutonnées (flyggberg), and the long and narrow overdeepened basins occupied by the piedmont lakes. During the last 0.7 million years there have been 3–4 growth periods forming large Fennoscandian ice sheets, similar in magnitude to the Late Weichselian ice sheet (Kleman & Stroeven 1997), with ice divide positions to the east of the mountain range. However large in extent, these ice sheets were apparently not very effective in reshaping their bed, as much of their interior parts were probably cold based during long periods. There are few landforms in central and northern Sweden that can be associated with the full-grown stages of these large ice sheets, apart from the scouring zones in the western part of the mountain range (cf. Kleman & Stroeven 1997).

There are only a few locations were Quaternary sediments of a pre-Weichselian age have been found in the study area (Garcia-Ambrosiani, 1990), and no loose-deposit glacial landforms have been dated to a pre-Eemian age. Yet, it is possible that many of the large-scale glacial lineations of north-central Sweden have a formation history that extends over several glaciations. The large NW-oriented crag-and-tail drumlins in the interior drumlin region are aligned not only with the ice-flow direction of the last deglaciation, but probably also with that of mountain-centred ice sheets and late-glacial configurations of preceding Fennoscandian ice sheets. Also, the NW-oriented drumlins extend into the mountain region, to the west of the last Late Weichselian ice sheet remnants. In summary, it is suggested that much of the NW-drumlin landscape in central and northern Sweden derives from several earlier glaciations, each adding to the final morphology of these features.

The Early Weichselian

The first Early Weichselian ice sheet (EW1), correlated with marine oxygen isotope stage 5d, seems to have been very active in reshaping the glacier bed (Lagerbäck & Robertsson 1988). Very few pre-Weichselian deposits have been found in central and northern Sweden. During the ice-marginal retreat of this ice sheet, large portions of the glacial landscape in northern Sweden were formed, including drumlins, eskers, and lateral meltwater channels, all indicating an ice sheet retreating towards the northwest. Still, there are also areas which seem little affected by glacial processes at all, and where the deglaciation of the EW1 is only represented as series of marginal meltwater channels. These areas (e.g., in the premontane region in northernmost Sweden) were probably also cold-based during the first Weichselian stadial. This indicates an ice sheet frozen to its bed at higher elevation, but thoroughly wet-based in lower parts of the terrain.

The Veiki moraine was assigned by Lagerbäck (1988a) to a regional stagnation during the deglaciation of the EW1. The age assignment is based on biostratigraphical evidence, which firmly supports a Peräpohjola age (the interstadial following the EW1) for the Veiki moraine. However, a few observations presented here indicate that the Veiki moraine was formed by local stagnation in a near-marginal zone, rather than during a regional downwasting of the ice sheet. First, there is a slight mismatch in direction between drumlins and eskers of the NW-landscape and terminal zones of the Veiki moraine. Second, NW-drumlins of the Early Weichselian deglaciation landscape extend, unchanged in appearance, far inside the Veiki moraine zone. Third, the distribution of Veiki moraine and its associated terminal moraines suggests several parallel ice marginal zones, each formed by a separate re-advance or halt in the recession. Therefore, it is possible that the Veiki moraine represents one or several surge-like re-advances, following a substantial, although perhaps not complete, deglaciation of the EW1.

Very little is known of the second Early Weichselian ice sheet (EW2), correlated with isotope stage 5b. So far, there are few suggestions of its extent or flow pattern. It was obviously very inactive with respect to subglacial landform processes, as landforms belonging to the EW1 have been left intact despite later cover by both the EW2 and the Late Weichselian ice sheet. Furthermore, in Sweden, the stratigraphical record indicates two Early Weichselian interstadials (Lagerbäck & Robertsson 1988), while in Finland there is only evidence for a single interstadial (Hirvas 1991). However, Sutinen (1992) and Johansson & Kujansuu (1995) describe N–S trending esker chains from Finnish Lapland, which they tentatively correlate with the second Early Weichselian stadial. It is possible, or even likely, that also the N–S trending glacial lineations and meltwater channels of flow set X in the palimpsest region (Fig. 14) belong to the EW2. However, there is no stratigraphical confirmation of such an interpretation. If true, it indicates an almost completely cold-based ice sheet with a northerly centre of mass. Still, the nature of the EW2 remains an enigmatic issue. Because the Late Weichselian ice sheet was almost completely cold based in the palimpsest area, any landforms from older glacial events should remain nearly intact. Even if set X was formed during this stadial, there must have been more landforms associated with the EW2. It is unlikely that such a large ice sheet could deglaciate without leaving more traces in the landform record than a handful of glacial lineations and meltwater channels.

The Middle and Late Weichselian

There are few recognisable traces in the landform record of the build-up phase of the main Weichselian glaciation (during isotope stage 4; Kleman et al. in press). It is not known whether such landforms ever existed, as much of the pre-existing glacial landscape in central and northern Sweden was eroded and reshaped during the Late Weichselian deglaciation. It is possible that some of the glacial lineations with a northwesterly direction in the southwestern part of the map area belong to this time period (Kleman et al. in press), but that has yet to be proven. It can also be noted that since much of the Early Weichselian deglaciation landscape in northern Sweden remains intact, the Late Weichselian ice sheet must have been cold-based in these areas already during the build-up phase (i.e., ice sheet growth under permafrost conditions).

There are a few glacial landforms in the study area that can be attributed to the maximum stage of the Late Weichselian (isotope stage 2). For example, the northward trending lineation system in the palimpsest region (set 2 in Fig. 13) is probably associated with the last glacial maximum, as it reflects an ice spreading centre over the Bothnian Bay. Also, there are a few lineations just southeast of Östersund that indicate ice flow from an ice divide position to the east of the mountain range. The patchy distribution of these ice-flow traces from the last glacial maximum, especially those in the north, suggest that the core of the ice sheet was mostly frozen to the bed, but had basal temperatures near the pressure melting point.

Most of the glacial landforms (in unconsolidated sediments) of central and northern Sweden was formed during the deglaciation of the Late Weichselian ice sheet. The frozen core area of the ice sheet was successively diminished in size as zones of wet-based ice flow migrated inward towards the ice sheet centre (Kleman et al. in press). During this process the deglacial landscape, typical of the interior of central and northern Sweden, was formed, consisting mainly of glacial lineations, ribbed moraines, and eskers, and in areas below the highest post-glacial shoreline, De Geer moraines. In some areas, the receding ice front caught up with the retreating boundary between frozen and thawed bed conditions, leading to a frozen bed deglaciation. In these areas, the only traces of the deglaciation are meltwater channels, some small discontinuous eskers, and occasional weak fluting.

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Glacial Geomorphology of Central and Northern Sweden

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Geological Survey of Sweden
SGU Ca 85

0 50 100 km

1:1 250 000

Legend

- Large glacial lineations; includes drumlins, rock-cored drumlins and crag-and tail features (sense of ice flow direction known/unknown)
- Small scale glacial lineations; primarily glacial fluting (sense of ice flow direction known/unknown)
- Ribbed moraine; including Rogen moraine (orientation and direction of ridges indicated by symbols; convex side facing the up-glacier direction)
- DeGeer moraines
- End moraine; includes lateral and marginal moraines
- Veiki moraine
- Esker

Note 1. The end moraines include primarily Early-Weichselian terminal moraines associated with the outer limit of Veiki moraine, pre-Late Weichselian lateral moraines in the eastern part of the mountain range, and Early-Holocene terminal morianes on valley floors in the mountain range. Neoglacial moraines are not included.

Note 2. The distribution of DeGeer moraines has been complemented with information from the Geological Survey of Sweden maps, series Ae: 9, 10, 20, 35, 53, 61, 73, 90, 104, 110, 113, 117; series Ak: 1, 2, 3, 5, 14; series Ca: 38.

Mapped by Clas Hättestrand during 1992-1996 by interpretation of black-and-white aerial photographs at scales of 1:60 000 / 1:150 000 and field work.

Projection: Gauss' projection

Base map: The National Atlas of Sweden; Map of Sweden 1:700 000

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