The deglaciation in the eastern part of the Weichselian ice divide in Finnish Lapland

by

Peter Johansson

Geological Survey of Finland
Rovaniemi 1995

Cover photo Peter Johansson 1989: Paratiisikuru (freely translated Paradise Gorge) in the fell area of Saariselkä.

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with 42 figures, four papers and one appended map

ACADEMIC DISSERTATION

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Quaternary landforms in central Lapland were identified by a combination of aerial photograph interpretation and stratigraphical studies. The area is characterized by weak glacial erosion and deposition, as demonstrated by the occurrence of five till units of different ages along with at least three subglacial meltwater systems (systems A, B and C, from youngest to oldest). A picture of the movements of the ice sheet before the last deglaciation was created on the basis of the two oldest till units and the erosional and depositional landforms connected with meltwater systems B and C.

During the Late Weichselian deglaciation, the ice divide crossed the area in an E-W direction. The history of the deglaciation was studied by combining results obtained from the till stratigraphy and glacial hydrography. At the first stage the ice sheet was still markedly thick and the margin lay outside the area studied here. The younger till unit was being deposited at its base. At the second stage the subglacial meltwater networks (A systems) were formed, the direction of glacial flow altered to coincide with that of the meltwater systems and the youngest till unit was deposited. The action of the subglacial meltwater was erosional at first, forming channels and gorges, but closer to the edge of the ice sheet deposition dominated, forming the youngest eskers, which were left without any till cover. At the third stage the ice margin consisted of small lobes, the local ice flow occurring in which no longer influenced the directions of the subglacial meltwater systems. At the fourth and last stage the proglacial, lateral, marginal and extramarginal landforms were produced. These, together with the ice lakes dammed up at the ice margin with their various stages and corresponding spillways are indications of the dynamics of the ice sheet and the mechanism by which its margin retreated.

It is estimated that the ice margin reached the NE and SE corners of the area at about the same time, approximately 9 500 BP. In the northern part it receded towards the SSW, and the lateral drainage channels suggest that the rate of recession was 130-170 m per year. In the southern part the retreat took place towards the WNW, at approximately 120-190 m per year. The ice sheet was active almost throughout the deglaciation, so that extensive stagnation and disintegration of the ice margin occurred only in the ice-divide area, before the ice sheet finally disappeared from the western part of the area around 9 100 BP.

Key words (GeoRef Thesaurus, AGI): glacial geology, till, stratigraphy, glaciofluvial features, subglacial environment, meltwater channels, glacial lakes, ice divides, glaciation, deglaciation, Quaternary, Weichselian, Saariselkä, Lap-land, Finland

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CONTENTS

PREFACE

The thesis includes the following previously published papers:

I Johansson, P. 1988. Deglaciation pattern and ice-dammed lakes along the Saariselkä mountain range in northeastern Finland. Boreas 17, 541-552.

II Johansson, P. 1993. Glacial lake development and ice-lake types in the Koilliskaira area, northeastern Finland. In: Aber, J. S.(ed.) Glaciotectonics and mapping glacial deposits. Proceedings of theINQUA commission on formation and properties of glacial deposits. Regina: Canadian Plains Research Center. 274-285.

III Johansson, P. 1994. The subglacially engorged eskers in the Lutto river basin, northeastern Finnish Lapland. In: Warren, W. P. & Croot D. G. (eds.) Formation and deformation of glacial deposits. Rotterdam: A. A. Balkema, 89-94.

IV Johansson, P. & Kujansuu, R. 1995. Observation on three subglacial drainage systems of different age in Savukoski, Eastern Finnish Lapland. In: Autio, S. (ed.) Geological Survey of Finland, Current Research 1993-1994, Special Paper 20, 83-93.

TERMINOLOGY

For the sake of clarity, some Finnish terms occurring in the geographic names and otherwise in this paper are listed below together with their English equivalents or explanations.

tunturi = fell
vaara = forest-clad hill
pää = fell or felltop
kaira = wilderness area
selkä = ridge
joki = river
järvi = lake
harju = esker
rinneharju = engorged esker, chute esker

kuru = gorge
satulakuru = col channel
marginaalinen uoma = marginal channel
extramarginaalinen uoma = extramarginal channel
proglasiaalinen uoma = proglacial channel
nielu-uoma = subglacial chute
lieveuoma = lateral drainage channel
laskukynnys = threshold point
lasku-uoma = spillway

INTRODUCTION

The area discussed here is located in north-eastern Finland and consists of the central and eastern parts of Lapland, the northernmost province of Finland. The area borders on Russia in the east. The area was situated in the north-central part of the Fennoscandian continental ice sheet during the Late-Weichselian glaciation and the flow centre of the ice and the ice divide occupied the middle of the area during the melting or deglaciation stage (Fig. 1). The location of the ice divide had considerable influence on the movements of the continental ice sheet, on the progress of deglaciation and on the glaciomorphological features of the area, and for this reason the deglaciation and related processes in the ice-divide zone constitute a special case com-

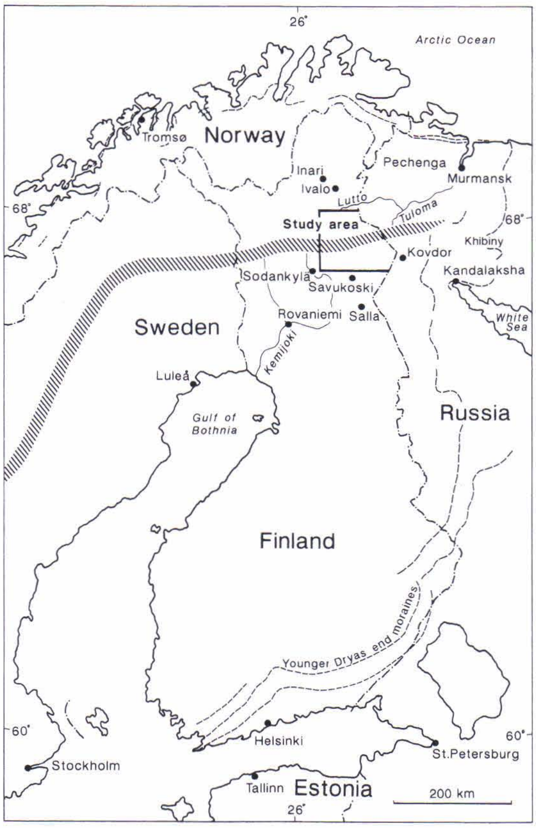

Fig. 1. Location of the area studied. The Younger Dryas marginal formations are indicated by broken lines and the ice divide during the last phase of the deglaciation by shading.

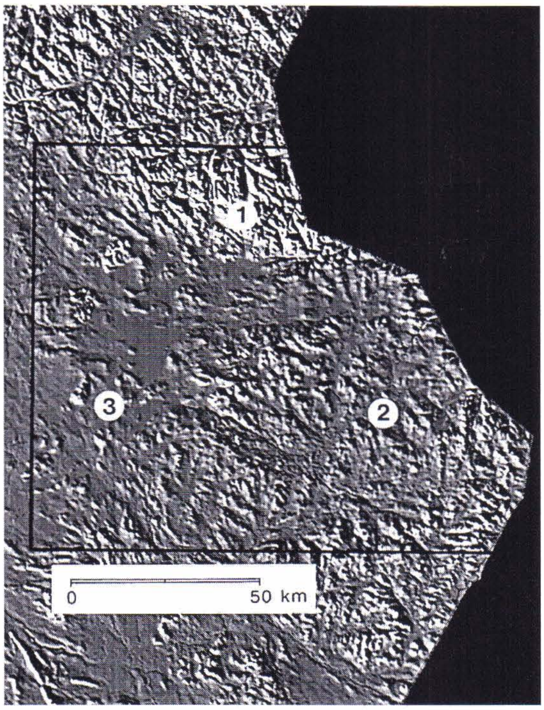

Fig. 2. Relief map of the area based on the elevation model data. 1 = Saariselkä fell region, 2 = central and southern area, dominated by fells and hills, 3 = Sompio lowlands.

pared with other areas once covered by the Fennoscandian ice sheet.

Physiographically the area may be divided into three parts: the fell area of Saariselkä in the north, the fells and hills of the central and southern part, and the Sompio lowlands in the west and southwest (Fig. 2). The rounded fell tops of Saariselkä generally reach an altitude of 500-550 metres, while Sokosti, the highest fell, rises to 718 metres. Tectonic fault lines tens of kilometres long divide the bedrock into blocks of various sizes, which are best displayed by the Saariselkä fell massifs and the valleys between them. Other fells with an altitude of over 500 metres exist in the area stretching from Kemihaara via Tuntsa to Sorsatunturit. The main watershed, separating the waterway systems discharging into the Arctic Ocean from those discharging into the Gulf of Bothnia, runs from Saariselkä to Tuntsa.

From Saariselkä south, the land slopes downwards in the form of a gently undulating peneplain crossed by river valleys. Altitudes are of the order of 200-300 metres a.s.l., and the area is characterized by forest-clad hills, river valleys and deep gorges. In the southwest, the Sompio area, the terrain turns into a swampy lowland crossed by river valleys and with scattered hills and fells in the centre, the highest of which is Koitelainen. The Sompio area, which was earlier covered by the most extensive peatlands in Finland, is nowadays partly beneath the Lokka Reservoir.

The bedrock and its influence on relief

The bedrock of the area consists mainly of Precambrian crystalline rock types (Fig. 3), the oldest of which are the highly metamorphosed and partly migmatized quartz-feldspar gneisses, approximately 2.6-2.9 billion years in age, mica gneisses of sedimentary origin, volcanogenic amphibolites, ultramafic rocks, and the granitoids surrounding them (Juopperi

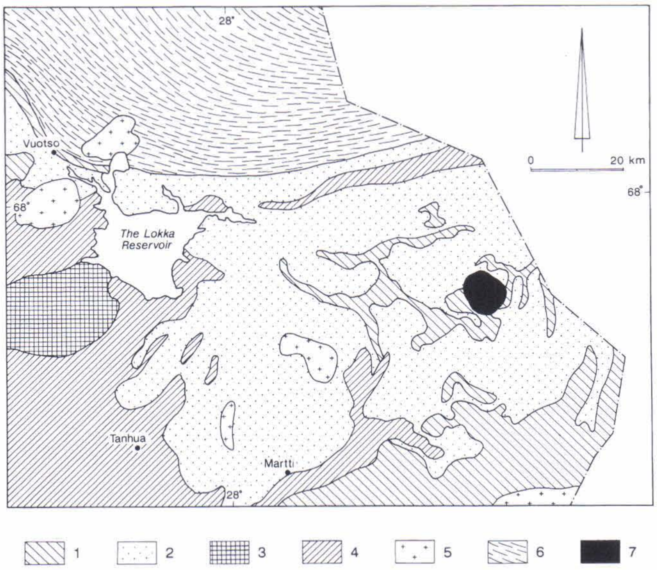

Fig. 3. Bedrock map of the area. 1 = Archean metavolcanics and metasediments, 2 = Archean granitoids, 3 = Koitelainen layered intrusion, 4 = Proterozoic metavolcanics and metasediments, 5 = Proterozoic granites, 6 = granulite, 7 = Sokli carbonatite. Compiled by Juopperi (1994) after Mikkola (1937).

1994). The rock types as such do not seem to have any significant influence on the relief, since the fells and hills in the region, e.g. the fell belt between Sorsatunturi and Sauoiva near the Russian border, consist of various rock types. Instead the morphology would seem to be controlled by structural features in the bedrock, such as schistosity, crush belts and tectonic movements. The rugged profile of Korvatunturi, for example, is a consequence of the gentle northern dip of the mica gneiss (Mikkola 1937 and 1941).

The bedrock in the western part of the area consists of metasediments and metavolcanics belonging to the greenstone belt of central Lapland, and of mafic and ultramafic rocks that have intruded into them. This area, which is fairly even as a whole, has ranges of quartzite hills and fells projecting from it south-east of Lokka (Vuoltistunturi and Kokkotunturi) and east of Tanhua (the Pyörreselkä-Siyliövaara range). Parts of the mafic layered intrusions located in the area, i.e. Koitelainen, Keivitsa, Satovaara and Särkivaara (Mutanen 1989), rise above the surrounding area in the form of residual mountains. Several chromite layers and deposits of gold, vanadium and platinum group elements have been found in Koitelainen in recent years, and large low-grade deposits of nickel, copper, gold and platinum group elements in Keivitsa (op. cit.).

The rock types of Saariselkä, in the northern part of the area, belong to the granulite zone of Lapland. This arcuate zone extends from Finnmark, Norway, across the northern part of the area and into Russia. Granulite is a highly schistose rock type which was formed during the Svecokarelidic orogeny approximately 1.9 billion years ago. It originally consisted of volcanic ashes and lavas which had been deposited as sediments on the sea bed and had later undergone a high degree of metamorphism during the folding process (Meriläinen 1976). The granites of Nattaset and Riestovaara, which intruded into the granulite and granitic gneiss approximately 1.7 billion years ago, form a fell area which rises conspicuously above its surroundings (Front et al. 1989).

The youngest rock type in the area is the Sokli carbonatite, approximately 360 million years old. This is a round massif about 5 km in diameter surrounded by a 2-3 km wide fenitic alteration zone. The carbonatite, which has been eroded deeper than the surrounding area, contains phosphorous minerals such as apatite and francolite, and rare elements, e.g. niobium (Vartiainen 1980).

The Saariselkä fells were formed by block movements related to the new orogeny of the Scandinavian mountain range during the Tertiary, approx. 30-50 million years ago (Mikkola 1932). As a result, the roots of the former fold mountains rose above their surroundings in the form of horsts, with large rifts and fracture zone valleys forming in all directions at the margins of the blocks, the most distinctive directions being NW-SE and SW-NE. According to the interpretation of Niini (1964), the vertical fault running eastwards from Sompiojärvi marks the southern limit of the block movements. The uplift gave rise to pronounced erosion, which lowered the fells and smoothed over the originally sharp, angular features of the valleys.

Weathered bedrock

The mechanically fractured and chemically altered rock known in Finnish as 'rapakallio' is widespread in the depressions and lowlands of the central and western parts of the area (cf. Hirvas 1991), being mostly covered by a till unit 1-3 m in thickness. The consistency of the weathered rock, which may be clayey or sandy, depends mainly on the degree of alteration and on the rock type. Block weathering is the term used to denote weathering of the rock surface into angular fragments. According to Hyyppä (1983) it has not been possible to determine exactly when the weathering occurred, but pronounced weathering is known to have taken place as early as during the Paleozoic and Mesozoic eras, while the climate was also favourable for weathering during the Tertiary, approximately 25-50 million years ago. The fact that weathered rock is common in the gently undulating areas south of Saariselkä proves that the considerable block movements that took place in Saariselkä itself did not reach this area, and that erosion has been minor from the Tertiary onwards.

Quaternary geological history and the ice divide

Numerous observations of deposits predating the last glaciation have been made in central Lapland, and it has been possible to date some of the lowermost till units as pre-Weichselian, since organogenic deposits found between these units have been classified on palynological evidence and OSL (optically stimulated luminescence) dates as deriving from the Eemian interglacial (Kujansuu 1972, Mäkinen 1982, Hirvas 1991, Kujansuu and Eriksson 1995). The Eemian is said by Mangerud (1991) to correspond to oxygen isotope stage 5e (130-117 ka), and the pollen flora of the organogenic deposits suggests that the climate in central Lapland at that time was approximately similar to that of today or slightly warmer (Donner 1995). Central Lapland was covered by ice for at least part of the Early Weichselian substage, and the climate during the ice-free periods, e.g. the Peräpohjola interstadial, was colder than today and a tundra vegetation prevailed (Korpela 1969, Hirvas 1991). The climate became colder during the early Middle Weichselian, about 74 000 BP (oxygen isotope stage 4, Mangerud 1991), and the area was covered by continental ice sheets, after which it remained glaciated for most of the Middle and Late Weichselian.

The zone identified as having contained the ice divide stretches across the central and southern part of the area. This constituted the centre of ice flow and the divide during a number of the more recent glaciations and is characterized by weak glacial erosion and deposition, so that it possesses few parallel moraines or striations. The weakness of the glacial action is also reflected by the common occurrence of weathered rock, glaciofluvial landforms dating from before the last glaciation, and tor landforms, e.g. at Nattaset and Riestovaara. The occurrence of old Quaternary deposits, and especially the concentration of sorted and organogenic intercalations found between them, provides probably the most reliable proof of the weakness of glacial erosion and deposition in the ice-divide zone.

The centre of ice flow during the last deglaciation was located in the middle of the area, so that an ice divide was formed approximately along the line Koitelainen-Lokka-Sorvortantunturi. From there the ice sheet spread out towards its margins in a fan-like manner. At the end of the deglaciation, when the ice margin had receded to the ice divide itself, great variations occurred in the direction of ice flow.

Earlier findings and the aim of this research

The first research into the glaciations and the flow of the continental ice sheet in northeastern Finland were published in the late 19th century (Rosberg 1891, 1893), and Rosberg's work (1908) on the Tulomajoki valley was the first study of the deglaciation in the area. The account provided by Tanner (1915) of the Quaternary geological history of Fennoscandia stood out in its time as the most extensive and thorough study of the glacial geology of northern Finland, and its detailed local descriptions still serve as a basis for research. Tanner describes the directions of flow of the ice sheet and the retreat of its margin, and in this sense may be said to have been the first to describe the ice divide that ran across central Lapland. Tanner's work also includes detailed descriptions of the occurrence of ice-dammed lakes and of their history.

Glaciofluvial landforms, both erosional and depositional, have been studied in northern Finland by Mikkola (1932), Virkkala (1955) and Kurimo (1978 and 1979), while ice-dammed lakes and their distribution in the area near Lake Inari have been described by Synge (1969) and corresponding examples in eastern Finland by Kilpi (1937) and Hyvärinen (1971). Information on areas in Finland formerly covered by ice lakes has been compiled in the form of a map by Eronen and Haila (1981). Equivalent Quaternary terrains exist in Sweden, Norway and Canada, too. Extensive areas which were once covered by ice-dammed lakes have been identified in Sweden, chiefly in the province of Jämtland (Högbom 1892; Lundqvist 1969, 1973; Borgström 1989). The major investigation into Swedish ice lakes and their typology is that of Lundqvist (1972). Research into the large ice-dammed lakes of central Canada, such as the Agassiz Ice Lake, has been published by Christiansen (1979), Teller and Clayton (1983) and Karrow and Calkin (1985).

The mapping of the Quaternary geology to a scale of 1:400 000 that was begun in northern Finland in the 1960's involved the use of stereoscopic aerial photos, as also did the individual studies of Penttilä (1963), Kujansuu (1967) and Piirola (1967, 1982), and this method enabled a more detailed classification to be made of the erosional and depositional landforms caused by the ice sheet itself and by its meltwater streams, thus leading to a closer examination of the deglaciation history of the ice-dammed lakes and the ice sheet in the ice-divide zone of northern Finland. Studies of the glacial morphology of the comparable region of Sweden were carried out mainly by Mannerfelt (1945), Hoppe (1952, 1959), Fromm (1965), Lundqvist (1969, 1979), Minell (1979) and Rodhe (1988), while analogous work has been done in Canada by Shilts (1981), Bouchard (1989) and others and on the Kola Peninsula in Russia by Nikonov (1964), for example.

The outcome of the investigations into the till stratigraphy of Northern Fennoscandia carried out by Korpela (1969), Lundqvist (1971), Hirvas et al. (1977), Aario and Forsström (1979), Evzerov and Koshechkin (1981), Saarnisto and Peltoniemi (1984), Hirvas and Nenonen (1987), Lagerbäck and Robertsson (1988), Olsen (1988) and Hirvas (1991) has been the designation of a number of glacial stages and their corresponding till units, between which sorted or organogenic intercalations can be found. The results of this work have been gathered together in the map of Quaternary stratigraphy of the region produced by the Nordkalott Project (Hamborg et al. 1986). These stratigraphic findings as their connections with the stratigraphy of Northern Europe as a whole are reviewed by Donner (1995). On the other hand, there are certain observations of till units associated with stages in the glaciation and of eskers which predate the last glaciation (Kujansuu 1975, Mäkinen 1985) that have made the glacial stratigraphy more complicated and at the same time have increased the need for further research in central Lapland, and especially in the ice-divide zone, an area in which the erosional and depositional action of the ice sheet was only slight.

The collection of material for this present research commenced in 1985, when the Geological Survey of Finland started its mapping of the Quaternary geology of the Vuotso-Kopsusjärvi area to a scale of 1:50 000 and related investigations (Johansson & Mäkinen 1989). The mapping continued in the Saariselkä area during the years 1986-1988, and information on the deglaciation of that fell region was collected in conjunction with it (Johansson 1990). A map of the Quaternary geology of the Koilliskaira area (the Urho Kekkonen National Park and the Sompio Nature Reserve) on a scale of 1:100 000 with explanations was also published (Johansson & Mäkinen 1994), and more information was gathered on the ice-divide zone and the area to the south of it in 1993-1995.

The aim was to form an overall picture of the action of the ice sheet, its dynamics and the retreat of its margin in the area where the ice divide was located during the melting of the ice, and thereby to be able to compare the action and dynamics of the ice sheet within the ice-divide area and outside it. A picture of the paleohydrography of the area was created by combining evidence from the erosional and depositional landforms caused by meltwater from the ice. A further aim was to clarify impressions of the occurrence of subglacial esker chains and till units and of their age differences. The main focus of the present work, however, is on the melting of the ice from the last glaciation and on the related paleohydrography, which serves as a basis for describing this. By combining information on the altitudes and age relations of the spillways, the directions of water flow and the history of the ice-dammed lakes, a detailed picture was obtained of the melting of the continental ice sheet and of the retreat of its margin in the area.

METHODS

For identification of depositional landforms and interpretation of their formation, aerial photo interpretation was combined with studies of the Quaternary stratigraphy. Interpretation of aerial photos yielded the information necessary in order to focus the field checks and further studies on interesting and problematic areas. In the aerial photo interpretation Old Delft and Wild APT2 stereoscopes were used. When studied under the stereoscope, differences in elevation are exaggerated, which is helpful in the interpretation of landforms. Black-and-white photos to a scale of 1:31 000 were available for the whole study area. In addition, colour infrared or false colour images to a scale of 1:30 000 were available for most of the area. The interpretation of black-and-white photos is above all the interpretation of depositional landforms, in which the size, shape, location and greytone yield information on the behaviour of the ice sheet and on the properties of the deposits. In colour infrared images, the blue-sensitive layer of the film has been replaced by an infrared-blue sensitive layer. In colour infrared images the green of plants is represented by red. The advantage, compared with black-and-white pictures, is that differences in moisture in the terrain cause distinct colour contrasts. Contrasts in vegetation as well as variations in the amount of chlorophyll are also clearly distinguished in the form of various shades of red. The vegetation is of indirect significance in the identification of superficial sediments and landforms, because various types of vegetation represent various sediment types with their characteristic capacities to retain water.

For the field checks samples of the deposits were taken by spade, percussion drill and hydraulic soil-sampling drill. Information on the stratigraphic sequence of the surficial deposits was obtained from existing cuts, from excavator pits, and from ground radar loggings. In cuts and walls of excavated pits the stratigraphic till units were distinguished by study of their physical properties, such as grain-size distribution, compactness, colour, clast content, clast size and roundness of clasts. The grain-size distribution was studied by the laser diffraction method in the laboratory of the Regional Office for Northern Finland of the Geological Survey of Finland. Directions of ice flow were determined by measuring striations and performing conventional till fabric analyses, analyses that included measurement of the direction of inclination and lithological analyses. The ice flow directions are given in the form of compass readings so that, e.g. a flow from west to east is referred to as 270°. Ground-penetrating radar was used to provide information on the stratigraphic sequence and thicknesses of the layers, including those lying beyond the depth range of excavators, and more particularly for studying till-covered sorted deposits. The mapping data were digitized by the FINGIS program to form a file from which the maps presented here, including the appended map, could be produced.

TILL STRATIGRAPHY

In studies of till stratigraphy, the central Lapland ice-divide zone has been found to be an area of numerous till units of different ages. Till fabric analyses have shown that they reflect ice flow stages, corresponding to either different glaciations or flow stages of a single glaciation. According to the till stratigraphy of Hirvas et al. (1977) central Lapland has six till beds of various ages, I-VI, from the youngest to the oldest. Only a few observations exist of till beds IV, V and VI, which represent the Saale or older glaciations (Hirvas 1991). The most common till beds, II and III, also have the best regional coverage. Till bed I and the surficial till were formed during the melting stage of the last glaciation (op.cit.).

By investigations of the till stratigraphy, five commonly occurring till units of various ages have been found in the study area. They are presented in the following table (in brackets the flow direction of the ice that deposited the till unit):

Vuotso-Saariselkä area	Maaselkä-Koitelainen area	Martti-Ruuvaoja area	Corresponding till bed (Hirvas 1991)
		Surficial till (SW-WNW)	Surficial till
Youngest till (SW-WSW)	Youngest till (SW)	Youngest till (WNW-NW)	Till bed I
Younger till (SW)	Younger till (WSW)	Younger till (W)	Till bed II
		'Old Northern' till (N-NNE)	
Oldest till (NW)	Oldest till (NW)	Oldest till (NW)	Till bed III

Oldest till unit

Among the till units found by stratigraphic till studies the oldest one is the basal till, which for the purpose of this study was named the oldest till unit. It consists of massive and fairly compact sandy till (Fig. 4). Its colour is brownish grey, and frequently it contains completely weathered stones and boulders. The oldest till unit was deposited by ice flowing from the direction 300°-330°, apparently during its melting stage, when the ice divide was located in the northern part of the study area, approximately in the Saariselkä fell region (Fig. 5 A). The oldest till unit is equivalent in its physical properties, stratigraphic position and till fabric to till bed III described by Hirvas (1991). Corresponding till units have been found in Vuotso (Kujansuu 1972, Kujansuu and Hyyppä 1995), east of Nattaset (Junnila 1982), in Peurasuvanto (Lestinen 1980), in Maaselkä (Hirvas 1991) and in Keivitsa (Hirvas et al. 1994). In the Koitelainen area (T. Mutanen, oral report) and south of Vuotso, striations in the direction 330° also occur. North of Vuotso, in Härkäselkä, there is a basal till unit, deposited from the direction 270°, which according to Saarnisto and Tamminen (1987) probably belongs to the same stage. The oldest till unit was penetrated only in a few places, and thus much uncertainty is attached to our notions of its thickness. A further till layer was encountered below this oldest unit in the Vuollosvaara area to the east of the Lokka Reservoir which in terms of its till fabric and stratigraphic position may be

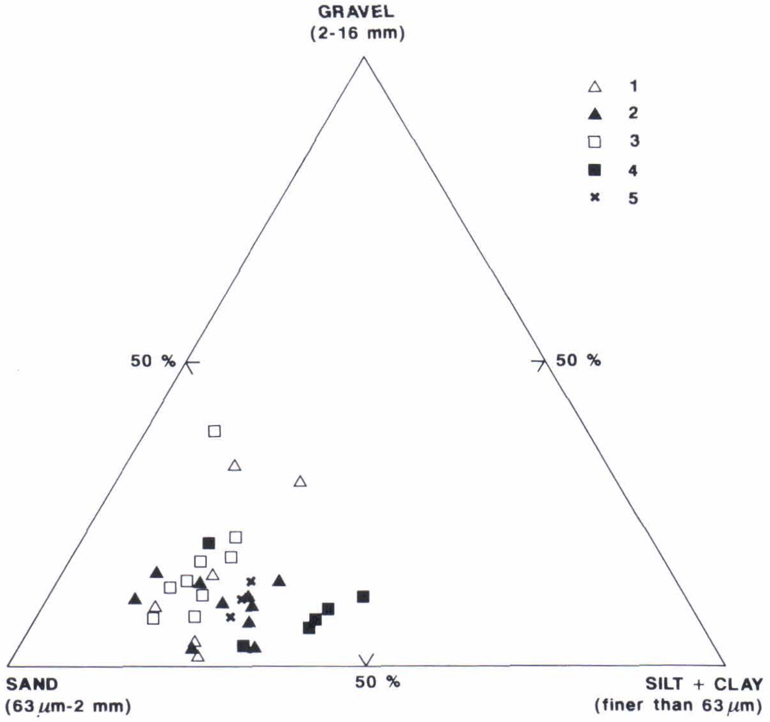

Fig. 4. Ternary diagram of the grain-size distribution of till units in the Martti-Ruuvaoja area. 1 = surficial till, 2 = youngest till unit, 3 = younger till unit, 4 = 'Old Northern' till unit, 5 = oldest till unit.

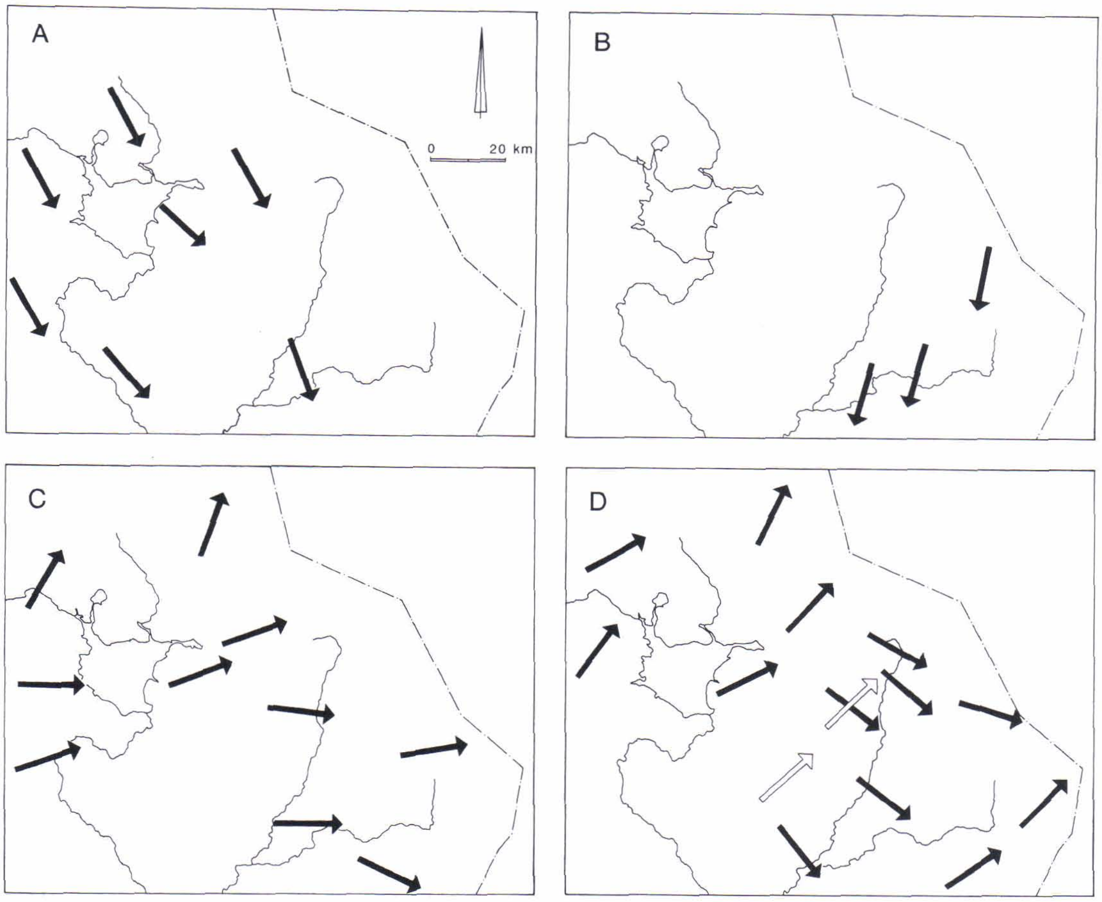

Fig. 5. Directions of ice flow during deposition of the various till units: A = oldest till unit, B = 'Old Northern' till unit, C = younger till unit, D = youngest till unit and surficial till in the Vintilänkaira area (white arrow).

analogous to till bed IV of Hirvas (1991).

The oldest till unit is covered throughout by till deposits of a later date, the contact being visible nearly everywhere in the form of a change in colour or some other physical property. Occasionally there is a distinct contact or a sorted deposit between the till units.

Other landforms related to the NW glaciation stage, or possibly to a still older one, are the col channel of Rumakuru (freely translated: Ugly Gorge) in Laanila (Penttilä 1963), and the col channels of Pirunportti (Devil's Gate) and Keinokuru in the Saariselkä area (Johansson 1990) (Fig. 6). Judging from their locations and directions they cannot have been formed during the melting stage of the last glaciation. The ice sheet has crossed over them, but it has not been able to destroy them or fill them, except for their floors and slopes, which are covered by a thin blanket of till.

The 'Old Northern' till unit

In the area of Martti-Ruuvaoja-Tulppio, a till unit was found that has not been described earlier. Its properties are variable, from a loose, sandy basal till with few stones to a

Fig. 6. Keinokuru in the eastern part of Saariselkä, a meltwater gorge formed before the last glaciation.

compact basal till of homogeneous structure, characterized by a higher than average content of fines (18-44 % Ø < 0.06 mm) (Fig. 4). The till fabric analyses indicate that it was deposited by an ice sheet flowing from between N and NNE (Fig. 5 B). In places this till unit occurs at the ground surface, and so possible earlier observations of it have been classified as surficial till (cf. Hirvas 1991). In this study this till unit is named 'Old Northern'. Its occurrence and relations to other till units and to the various subglacial esker chains of the area will be described later.

Younger till unit

The younger basal till unit was apparently deposited at the end of the last glaciation. At that time an ice divide was formed in the middle of the study area, along the line Koitelainen-Lokka-Sorvortantunturi, where the ice flow and its basal erosion were weak. In the ice-divide area the younger till unit is porous and sandy with small clasts. In the Maaselkä area its thickness is variable, 1-3 m (cf. Hirvas 1991), while the corresponding till unit about 20 km to the south, in the Keivitsa area, is 0.5-1 m, at its thickest 2 m (Hirvas et al. 1994). When the younger till was deposited in the Maaselkä-Keivitsa area the ice was flowing from the direction 230°-260°. South and SE of the ice divide, in the areas of Martti and Ruuvaoja, the direction of ice flow was 260°-280° and in the Sokli area 250°-270° (Fig. 5 C).

North of the ice divide in the Saariselkä-Vuotso area and north of Pihtijoki, the direction of ice flow was to NE or to NNE. The basal erosion and accumulation caused by the ice flow increased with an increasing distance from the ice divide. In the northern part of the study area, in the valleys of Suomujoki and Lutto (in Russian: Lotta), the ice direction was 210°-230°. In the central part of the Saariselkä fell area the ice flow was in the direction 195°-210° and south of Saariselkä, in Vuotso and around Pihtijoki, in the direction 190°-210° (Fig. 5 C). In the area south of Vuotso and in Maaselkä, which were located closest to the ice divide at its northern margin, the dispersion is greatest, with directions ranging 230°-270° (Fig. 5 C). These results are analogous to the results obtained by Penttilä (1963), Kujansuu (1972), Hirvas (1991), Junnila (1982), and Saarnisto and Tamminen (1987) for the ice-flow directions. The striations and shallow flutings that occur in the Saariselkä region (Johansson 1990), and the megaflutings occurring north of the study area, in the Ivalojoki river valley (Väisänen 1994) have the same orientation.

The younger till is looser and on an average it has fewer clasts than the oldest till unit (Fig. 4). It is, however, difficult to distinguish between tills of various ages on the basis of the grain-size distribution, since this property depends especially on the amount of old sediments and weathered rock mixed with the till (cf. Lintinen 1995). The younger till unit is greyish brown, frequently speckled by minor light brown sandy intercalations and lenses. The colour is caused by the oxidation of iron above the groundwater table, but also by the underlying rock type and weathered rock. E.g. east of Nattaset, in the area of Rovaselkä and Pihtijoki, reddish brown basal tills occur. The colour of the tills in Rovaselkä are caused by the reddish colour of the potassium feldspar (microcline) of the Nattaset granite, since the till contains abundant material originating in Nattaset and transported by the ice to Rovaselkä. According to stone counts carried out by Junnila (1982), the clasts of the tills in Rovaselkä consist of Nattaset granite to nearly 100 %.

Youngest till unit

The younger till unit is in the Martti-Ruuvaoja area overlain by a till unit consisting of loose and sandy basal till. On the basis of till fabric analyses it was deposited by an ice sheet flowing from the direction 300°-335° (Fig. 5 D). The ice flow direction is approximately parallel to the subglacial esker chains deposited during the latest deglaciation. The till unit described above is for the purpose of this study named the youngest till unit, and it corresponds partly to till bed I of Hirvas (1991). It was formed at that stage of the deglaciation when the flow of the ice was still active, the subglacial meltwater action strong and the margin of the ice sheet still tens of kilometres away, SE of the village of Martti.

In the Maaselkä-Kuruselkä area the younger till unit is overlain by basal till, which is loose and greyish brown with few clasts. It was deposited when the ice sheet was flowing from the direction 210°-220° and changes gradually without a contact into the underlying younger till unit, which was deposited from the direction 260° (Fig. 5 D). It was probably formed simultaneously with the youngest till unit of the Martti area, since its orientation is equal to that of the esker chains of the latest deglaciation. The ice flow direction seems to have changed towards the end of the deglaciation from western to a more south-western without any distinct changes in the deposition of till. In the vicinity of Vuotso, too, there is a change in ice flow direction from 210° to 240° (Kujansuu & Hyyppä 1995).

Surficial till

Uppermost is a 0.5-1 m thick, sandy and loose layer, the origin of which may be quite variable. It may consist of supraglacial debris, frost-deformed till, till moved by solifluction, or ice-lake sediments containing stones dropped by ice blocks floating in the ice lake. Some of the surficial unit is, however, clearly till, in which the fabric of the clasts reflects the flow direction of the ice.

South and SE of the ice divide the orientations of the surficial till vary between SW and WNW. It was probably deposited at the final stage of the deglaciation, when the flow direction of the ice sheet was no longer necessarily parallel to the direction of the subglacial meltwater systems, but the margin of the ice sheet had turned into lobes and the lobes were flowing in different directions, controlled by the landforms of the terrain. At the bases of the lobes, too, local flow variations occurred. Probably the loose and sandy surficial till presented by Hirvas (1991) corresponds partly to the till unit described above. In the Vintilänkaira area the latest flow stage of the ice sheet, from SW to NE (Fig. 5 D), seems to have been more intensive than the one described earlier, and as a result the surficial till unit deposited in the area is fairly compact and frequently more than a metre thick.

GLACIOFLUVIAL SYSTEMS

Abundant meltwater action was typical during the deglaciation of central Lapland, and the frequently occurring meltwater-related landforms, both erosional and depositional (Appendix) are the best evidence of this. They are classified for the present purposes into subglacially, proglacially, marginally, extramarginally and laterally formed erosional and depositional types depending on how they were formed in relation to the ice sheet and its margin.

Subglacial meltwater systems

Many of the glaciofluvial landforms in the study area were deposited by subglacial meltwater systems inframarginally in a tunnel deep under the ice (cf. Lundqvist 1979). As a contrast to other meltwater-related landforms, the subglacial meltwater landforms are independent of the slopes of the terrain and capable of crossing water divides. This is due to the hydrostatic pressure prevailing in an enclosed conduit. According to Shreve (1972) this pressure is directly proportional to the thickness of the overlying ice and the pressure caused by it. In an open channel, e.g. at the margin of the ice sheet or on top of it, such a pressure could not form.

Subglacial meltwater was formed and started to collect as a thin layer at the base of the ice sheet when the temperature of the ice was at the pressure-melting point, i.e., it was a ‘warm-based glacier’. The meltwater started flowing towards the margin of the ice in the directions of the pressure gradients (Hooke 1989). Meltwater was also formed on the surface of the ice sheet and inside it, from where a part of it penetrated downward along fractures. The meltwater streams finally formed long networks of glacial rivers in the approximate direction of the ice flow, along which the meltwater streamed towards the ice margin. The water-filled conduits widened and narrowed in relation to the contrast in pressure between the meltwater and the ice sheet

(Röthlisberger 1972). Shreve (1985) has stated that already at a depth of 100 m the ice is plastic enough to allow meltwater conduits to open or contract according to the increase or decrease in hydrostatic pressure.

The subglacial meltwater systems are in the study area represented by long, straight-to-sinuous esker chains running across the area (Appendix). The esker chains, which are frequently more than a hundred kilometres long, were hardly formed contemporaneously, but both the erosional and depositional landforms were formed gradually as the ice margin retreated. The chains are dendritic, which is typical of conduits incised in the ice, 'R channels' after Röthlisberger (1972). Walder and Fowler (1994) and Clark and Walder (1994) have presented an alternative model of drainage systems, which comprises widespread, shallow 'canals' incised downward into the till. They have been found to occur in regions of sedimentary rocks, where the ice sheet was flowing on top of a thick bed of deforming sediment (cf. Clark & Walder 1994, Gilbert & Shaw 1994). In the study area the bedrock is crystalline and impermeable, and it is frequently overlain only by a thin, discontinuous till cover. For this reason the meltwater system theory presented by Röthlisberger (1972) was the most probable in the study area. Only in the western part of the area, where the Quaternary deposits along with the weathered rock may form a thick cover on top of the 'hard' bedrock, canals may also have occurred.

Subglacial esker chains include both erosional and depositional landforms. The erosional forms include flat-bottomed basins, and gorges and channels eroded to the bedrock. The most common depositional landforms are esker ridges, single esker hillocks, deltas, and accumulations of sand lacking particular morphological features. Between these, extensive areas may exist with no signs of glaciofluvial action.

Subglacial erosion and related landforms

Under the hydrostatic pressure prevailing in an enclosed conduit, a meltwater stream is able to rise uphill, ascending valley floors and slopes and crossing divides. At divides and passes the meltwater stream seems to have mainly eroded earlier deposits, exposing or incising the bedrock surface. According to Vivian (1970), three types of erosional landforms were formed, depending on the power of the stream and the abrasion it caused: torrential polish on bedrock surfaces, subglacial channels, and gorges. All three types occur in the study area.

The variation of erosion and deposition caused by a subglacial meltwater stream is well illustrated in the glacial hydrography of the Värriötunturi-Sauoiva area, in the eastern part of the study area (Fig. 7). The subglacial meltwater system of Suurkovanselkä-Papuhaara (A4 on Appendix) crossed the orientation of large bedrock landforms in several places. Erosional landforms occur especially at the crest of the divide and on steeply descending slopes. The depositional landforms are located in the flat areas between the divides and on ascending slopes. North of Sauoiva the depositional landforms decrease in size the closer they get to the crest of the divide, where they are replaced by erosional landforms. On the lee side of the divide these gradually become breaches incised deeper and deeper into the bedrock. At their maximum they are 25-30 m deep and approximately equally wide gorges with a V-shaped profile (Figs. 8 and 9 A). They have an irregular long profile with ridges and basins, running downslope for a distance of a few hundreds of metres, until the slope becomes gentle, and in the valley of Papuhaara depositional landforms occur again (Fig. 9 B).

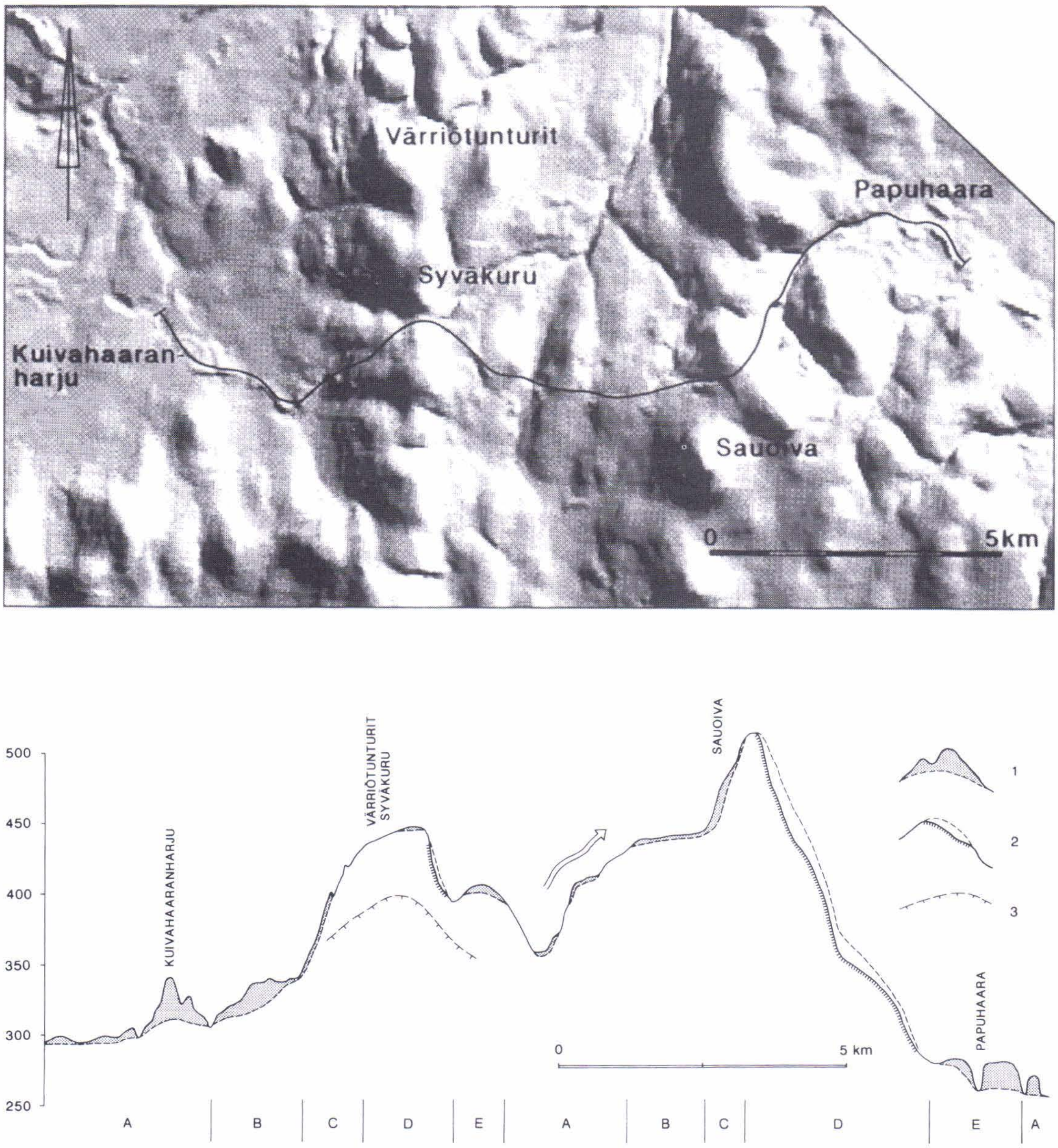

Fig. 7. Longitudinal section of the subglacial meltwater system of Suurkovanselkä-Papuhaara (A 4 in Appendix) with related processes: 1 = depositional landform, 2 = erosional landform, 3 = floor of the Syväkuru gorge. A = Zone of fairly rapid subglacial meltwater flow, resulting in melting in the conduit walls and the formation of sharp-crested eskers. B = Zone of retarded meltwater flow, resulting in abundant deposition at the base of the conduit and the formation of broad-crested, flat eskers. C = Zone of slow meltwater flow, resulting in freezing of the walls of the conduit and the formation of low, even-crested eskers. D = Zone at the crest of a divide and on a descending slope, marked by accelerating meltwater flow and the development of erosional landforms. E = Zone of weakening meltwater flow, marked by abundant deposition at the base of the conduit. The white arrow shows the direction of subglacial meltwater flow. The upper part of the figure shows the course of the meltwater system on a map based on the elevation model data.

Fig. 8. The subglacially formed gorges of Sauoiva.

The dimensions of the Sauoiva gorges show the enormous erosional force of meltwater in enclosed conduit (Fig. 8). The pressurized flowing water was able to create considerable erosional landforms, even in a very short time, if the underlying rock was already broken (cf. Vivian 1970). The erosion could also continue for a long time in the same place, since the channel cut in the rock offered the meltwater stream an environment better protected from the pressure of the ice and the movements of its base than a channel merely cut in the ice (Nye 1973).

At the divides the erosion seems to have concentrated at the crest, being at its strongest in the upper part of the lee side of the divide. Deposition again occurred in flat areas, on the upstream side of the divide and on gentle downstream slopes. It thus depended on the inclination of the conduit, on the velocity of the meltwater stream in it, and on its transporting capacity, which process was dominating. The power of the stream to erode and transport eroded debris was at its maximum just after the divide, where the stream turned abruptly downward. On uphill slopes the stream was slower, and so the debris transported by the stream was deposited at the base of the conduit (cf. Shreve 1972).

On the Värriötunturi fells it can be seen how the path of a subglacial conduit is independent of the topography of the divide (Figs. 7 and 9). A subglacial conduit crossed the fell range along its southern margin without descending to the floor of the Syväkuru gorge 60 m below, which was formed as early as before the last glaciation (Fig. 10). The path of the subglacial stream can be traced on the slope

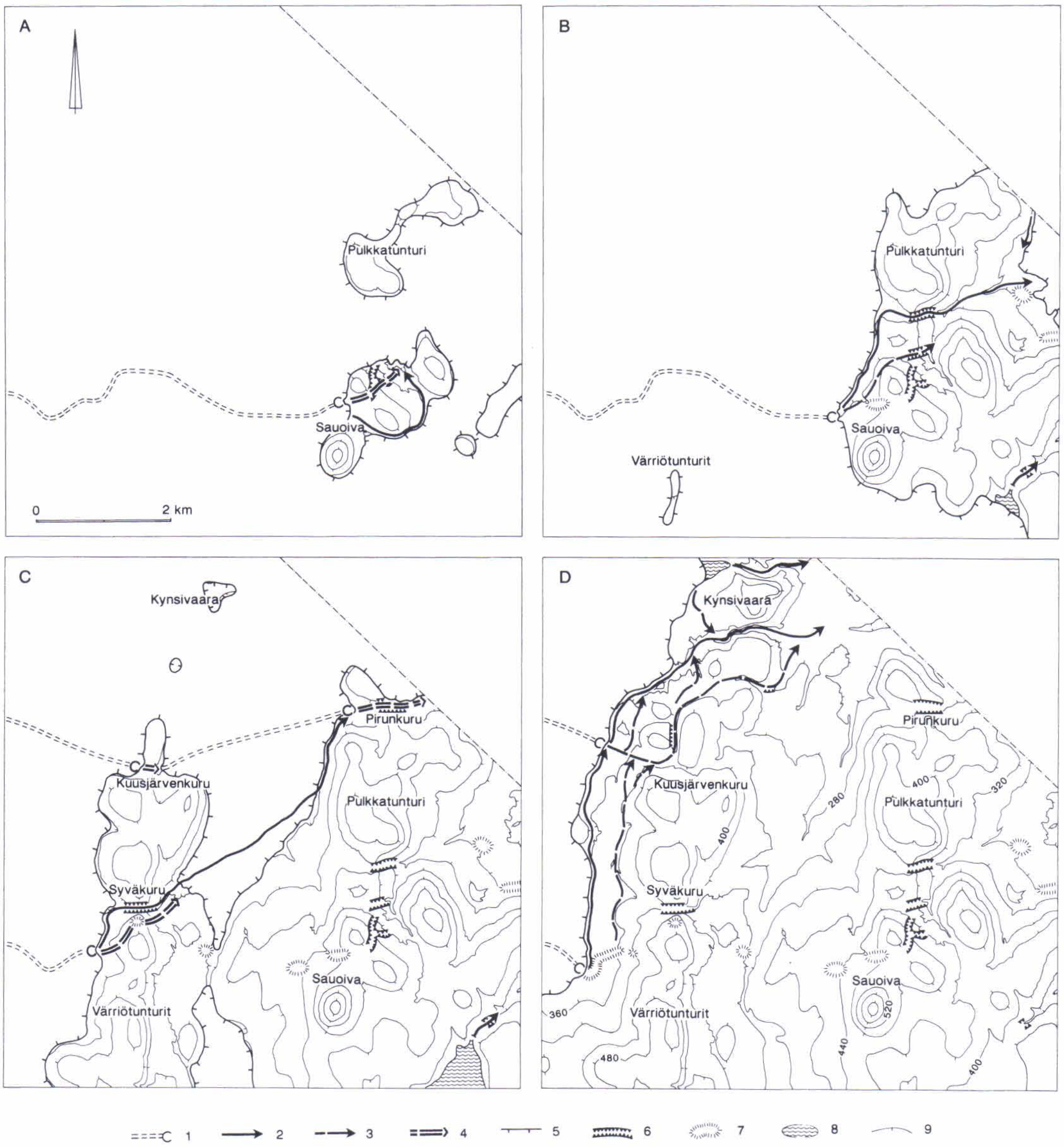

Fig. 9. Glaciohydrographic history of the Värriötunturit-Sauoiva area and disappearance of the glacier (A-D): 1 = subglacial meltwater system and its mouth, 2 = functioning proglacial or marginal channel, 3 = former proglacial or marginal channel, 4 = former subglacial channel, 5 = ice margin, 6 = gorge, 7 = esker, 8 = ice-dammed lake, 9 = contour line.

of the fell in the form of washed bedrock surfaces and low esker hillocks. The meltwater stream did not shift down to the bottom of the gorge until the proglacial stage, when the subglacial conduit at the crest of the fell was broken as the ice became thinner. The proglacial stream followed the floor of the gorge onto the ice located east of the fell, where it probably continued in an open channel to the NE, towards the gorge of Pirunkuru (Fig. 9

Fig. 10. The ancient subglacial Syväkuru gorge, which cuts across the fells of Värriötunturit. Loose debris was washed out from the gorge floor by proglacial meltwater during the final stage of the latest deglaciation.

C). After the thinning of the ice sheet and after its surface had sunk below the bottom of the Syväkuru gorge, the meltwater discharging from its mouth turned to flow marginally along the western slope of the Värriötunturi fells to the north, towards the upper tributaries of Hirvasjoki. Remaining from this stage is a network of deep marginal and extramarginal channels, leading to the north (Fig. 9 D).

On level or gently sloping ground, where the till blanket covering the bedrock is thicker than on the divides and steep slopes, the erosional landforms are flat-bottomed basins and channels, which have been cut into the underlying till or weathered rock. Afterwards they were filled by lakes, ponds or peat deposits. Since the depositional landforms are often located in these channels and basins, as e.g. near the lakes Joutsenjärvi and Naavajärvi, the erosional forms are older than the depositional forms and were formed during the initial stage of the development of the subglacial meltwater system, when the action of the meltwater deep under the ice was mainly erosional (cf. Shreve 1972). In the ice-divide zone the eroded channels formed by the meltwater action are frequently clearly distinguishable, since the base consisted of easily eroded weathered bedrock (Kujansuu & Eriksson 1995). Near the ice margin the power of the stream began to weaken due to decreased ice pressure (cf. Lundqvist 1979). The erosion turned to accumulation and depositional landforms started to form at the base of the conduit quite near its mouth.

Subglacial deposition and related landforms

The most common depositional landforms are long uniform esker ridges, which were deposited on level or gently sloping land. Examples are found in the subglacial esker chain of Suomujoki (A 11) in the Suomujoki valley (Mikkola 1932, Saarnisto 1973, Johansson 1990), in the Sokli esker chain (A 5) in the area between Nuortti and Ainijärvi (Perttunen & Vartiainen 1992), as well as in the Leukkuhamara esker chain (A 1) NW of Ettisselkä and in the area between Vaklivaara and Kemijoki (called Keihäsharjut). The ridges are 5-25 m high and approximately 100-200 m wide. Their slopes are frequently steep, and occasionally they also have sharp crests, e.g. Kuivahaaranharju SE of Ainijärvi, Selkä-Suoniharju south of Leukkuhamaranvaara (Johansson & Kujansuu 1995), and the Tuntsa esker (Fig. 11). In the type of esker deposited on level ground, the variations in grain-size distribution are considerable both horizontally and vertically. The contacts between rhythmically interlayered sand and gravel units are sharp. The variations in grain size were caused by the seasonal changes in velocity and sediment load of the streaming water. The structure is mostly cross-bedded, with the beds dipping in the distal direction and towards the flanks of the esker (Fig. 12). The debris deposited in the eskers originated in the ice surrounding the tunnel, which was flowing from the sides towards the tunnel at the same time as the friction caused by the glacial stream melted the walls of the tunnel. The meltwater stream also eroded the till or glaciofluvial material earlier deposited on the tunnel floor. In many places the erosion apparently reached as far as the underlying rock,

Fig. 11. Sharp-crested esker on the floor of the Tuntsajoki river valley.

which is shown by barren rock at the base of deep esker cuts. On the basis of the structures the debris seems to have been transported and deposited at the crest of the esker and, by the force of the stream, further on obliquely down along the flanks of the esker. According to Röthlisberger (1972) and Shreve (1985), the meltwater stream on level ground strived to shape the cross-section of the subglacial tunnel into a parabolic or semi-circular form, which in an area of thick surficial deposits would be partly underground.

The esker ridges of the most impressive size are in the vicinity of Leukkuhamaranvaara, in Ettisselkä, in the Papuhaara valley and west of the Värriötunturi fells. Many of these are located at the point of the subglacial conduit where the meltwater stream turned in an uphill direction (Fig. 7). The transporting capacity decreased as the stream slowed down, which led to accumulation of the debris carried by the meltwater stream, and so the landforms were built up. Many of the eskers on the proximal side of the divide are flat, occasionally broad-crested landforms, e.g. Nuutamaharju SW of Leukkuhamaranvaara, which belongs to the subglacial esker chain of Leukkuhamara (A1). According to studies by Shreve (1985) of the Katahdin esker system in the USA, the formation of broad-crested and extensive eskers depends on a change in the shape of the tunnel into a low and wide one. It was caused by freezing in the tunnel wall as a consequence of a decrease in stream velocity. Kujansuu (1967) has stated that the esker deposits become better sorted and finer-grained on the upstream side of the divide than in other parts of the subglacial meltwater system. Poorly sorted and mainly coarse-grained deposits formed the esker ridges at the foot of the slope downstream from the divide, where the coarsest debris transported by the stream was the first to accumulate as the velocity of the flow decreased. E.g. in the Muorravaarakanjoki valley the meltwater, which was streaming forcefully down the slope, left behind it a ridge consisting only of round, polished stones and boulders (Rosberg 1891, Johansson 1990).

In the northern part of the study area and north of the study area at Nangujärvi, engorged eskers (Johansson 1994) occur. They

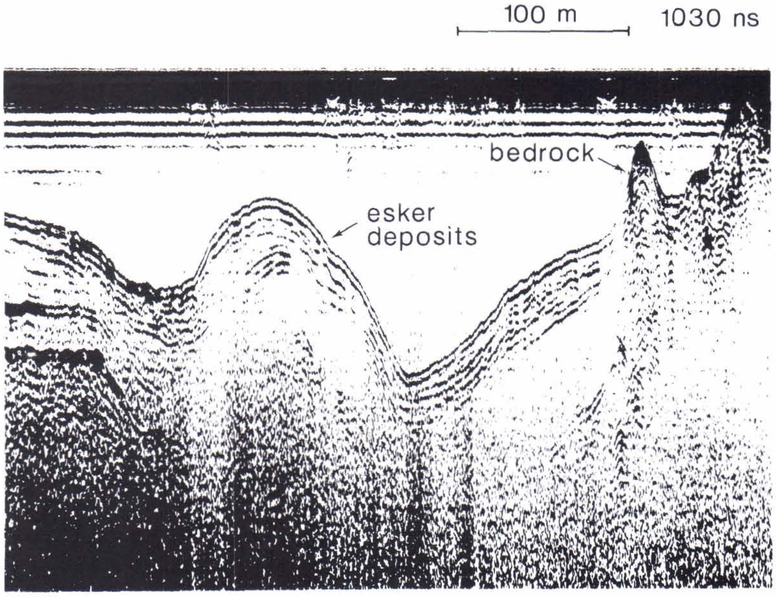

Fig. 12. Ground-penetrating radar image of a cross-section of the Suomu esker on the bottom of the Lake Aittajärvi. Sand and gravel layers slope away from the flanks of the esker. The peaks on the right are caused by the bedrock. The black line in the upper part represents the ice covering the lake.

were formed on the slopes of fells and hills when the meltwater flowing along the ice margin penetrated under the margin in fractured places. In this way a subglacial tunnel was formed, running down the slope. At the base of the tunnel, sand and gravel transported by the meltwater was deposited. The path of the engorged esker with its bends reflects the path of the subglacial tunnel at the base of the ice sheet (Mannerfelt 1945). In Finland, engorged eskers are most frequent in the valleys of Lutto and its tributaries (Johansson 1994), but some observations also exist from the areas of Laanila (Penttilä 1963) and Lemmenjoki (Piirola 1967).

In Saariselkä, there are two esker ridges at Kutturapäät (cf. Penttilä 1963) and Anterimukka, which have been interpreted as formed in open crevasses on the surface of the ice. They are less than a kilometre long, 10-15 m high steep-sided ridges, which are not in connection with the subglacial esker chains proper of the area. Their crests are flat, reflecting the level of the meltwater flowing on the bottom of the crevasse.

Marginal and proglacial landforms

The best developed delta in the area is located west of Kopsusjärvi. It is a part of the Suomu subglacial esker chain (A 11) and was deposited at the mouth of a subglacial conduit at the surface level of the Kopsusjärvi Ice Lake (Johansson 1990, Kujansuu & Hyyppä 1995). Considerably more frequent than the esker deltas are the marginal outwash deltas. While an esker delta was deposited under peaceful conditions during a long time, the marginal outwash delta was formed as the result of a short but forceful discharge of meltwater. The discharge was generally accompanied by a sudden drop in the water level of the ice lake, so that large volumes of water were discharged along the marginal channel to a lower level, frequently to another ice-dammed lake. The debris transported by the water stream accumulated on the shore of the ice lake in the form of a marginal delta. Since the time of deposition was short, the deposits of a marginal outwash delta is poorly sorted, frequently stony gravel. Marginal outwash deltas occur at the southern edge of the Saariselkä fell region, especially on the fell slopes of Siuloiva and Vongoiva (Johansson 1988).

Proglacial depositional and erosional landforms, related to the formation of eskers, occur e.g. in the vicinity of Leukkuhamaranvaara (Fig. 13). When the subglacial meltwater system that deposited the Leukkuhamara esker was broken near Tuorainselkä as a consequence of the thinning of the ice and the retreat of its margin, the meltwater discharging from the mouth of the tunnel turned to flow proglacially into Riikunkuru. The transporting capacity of the proglacial stream was markedly weaker than that of the subglacial one. However, it eroded away a part of the old till-covered Ketsepuhnus esker, depositing it in the form of a delta at the surface level (238 m) of the ice-dammed lake covering the valley of Värriöjoki (Fig. 13 B). There are also delta deposits at the 230 m level, since the proglacial stream of Riikunkuru still continued after the surface level of the Värriöjoki Ice Lake had dropped to the level of the Kemihaara Ice Lake (Fig. 13 C). The channels on the western slope of Tuorainselkä were formed when the meltwater stream had shifted from Riikunkuru to flow marginally towards the ice-dammed lake. These channels end at the surface level of the lake (Fig. 13 D). Proglacially formed erosional and depositional landforms also occur in the vicinity of Kärekeoja south of Kemihaara, and around Joutsenjärvi.

In the valleys of Lutto and Jaurujoki, 0.5-1 km wide and tens of metres thick valley trains occur. They were formed extramargin-

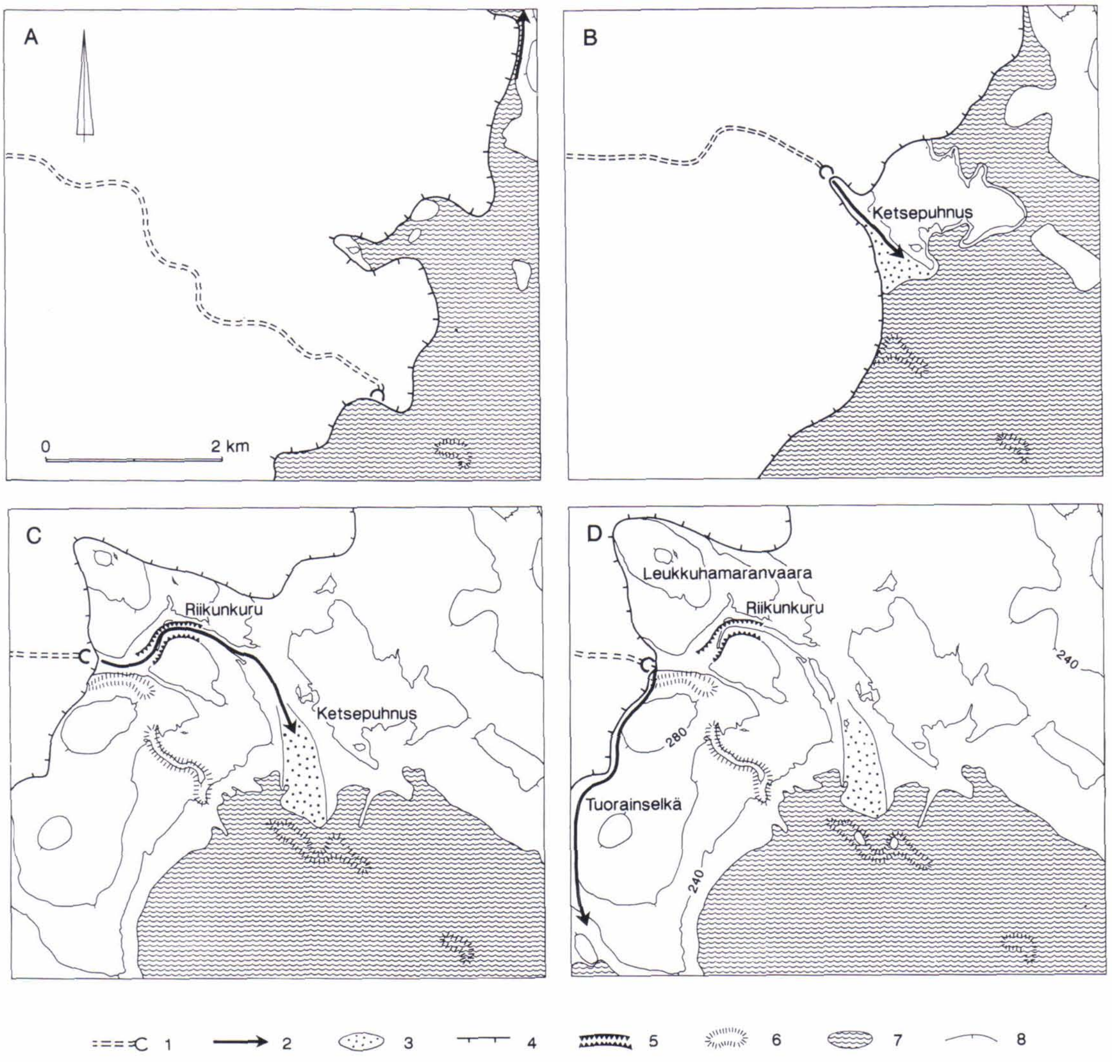

Fig. 13. Subglacial and proglacial meltwater systems of the Leukkuhamara area and the retreat of the ice from the area. 1 = subglacial meltwater system and its mouth, 2 = functioning proglacial or marginal channel, 3 = proglacial delta of Ketsepuhnus, 4 = ice margin, 5 = gorge, 6 = esker, 7 = ice-dammed lake, 8 = contour line.

ally. The valley train of the Jaurujoki valley was deposited in front of the ice margin as it was receding towards SW. This valley train consists of outwash gravel of marginal and extramarginal origin, formed by the sudden discharge of the former ice-dammed lakes south of Saariselkä. Meltwater streaming from the ice later flattened them into valley trains. The Jaurujoki valley train is gently inclined from SW to NE, i.e., in the direction of the meltwater flow. Its surface is smooth with the exception of the postglacial channel of Jaurujoki, 3-4 m deep, in its middle. Investigations by ground-penetrating radar show that the Jaurujoki valley train is 10-20 m thick and its bedding horizontal or slightly inclined in the flow direction (Johansson 1990).

Lateral landforms

The lateral drainage channels were formed when the meltwater flowing on the surface of the ice sheet accumulated at its margin and turned to stream laterally towards the snout of the ice along the ice margin, which was leaning against the slope that was already ice-free. The channels generally occur in groups, running side by side gently sloping down the fell side. The lateral drainage channels are open at both ends, beginning and ending inconspicuously on the slope. They are variable in length, from 100 m to 1 km, and 1-2 m deep.

Lateral drainage channels occur especially in the fell region (Fig. 14), where at the final stage of the deglaciation the ice covered the valley floors while the upper slopes were already ice-free. By using aerial photos and field checks, 66 systems of lateral channels were found in the southern part of the Saariselkä fells. The most representative systems are: a regular system of lateral drainage channels comprising more than 40 in number, one below the other on the southern slope of Vuomapää; a series of approximately a hundred channels on the western slope of Ampupäät (Kujansuu & Hyyppä 1995); and the channel system on Teräväkivenpää (Penttilä 1963).

The surface of the ice lobes was frequently convex, causing the meltwater to accumulate at the margins of the lobes. In the Saariselkä region there are also examples of how meltwater accumulated only along one margin of the lobe, due to the fact that this was in a

Fig. 14. Lateral drainage channels on the slope of Reutupää, a fell in the eastern part of Saariselkä.

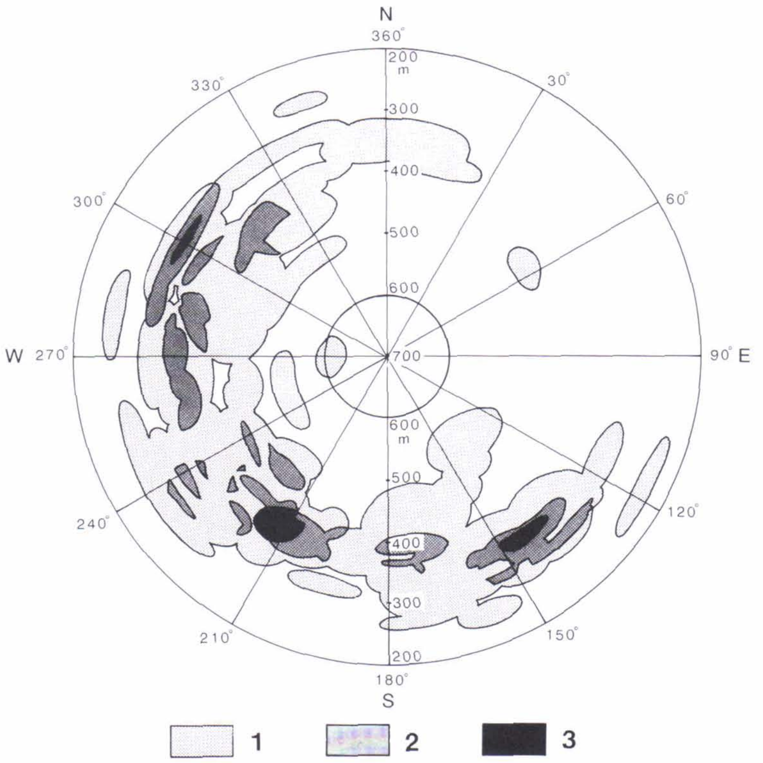

Fig. 15. Distribution of lateral drainage channels on slopes dipping in various directions in relation to the altitude. 1 = one observation, 2 = two observations, 3 = three or more observations. Diagram based on 66 marginal channel systems in various parts of Saariselkä.

position to receive solar radiation while the other margin was in the shade for most of the time. This also had the effect of giving the ice a sloping surface. The majority of the lateral drainage channels in the Saariselkä region are situated on slopes inclined in directions from 120° to 320° between the altitudes of approximately 280 m and 480 m (Fig. 15). Since the margin of the ice was inclined towards the NE, the SE and NW slopes were at the sides of the ice lobes. This is where the deepest lateral drainage channels were formed, since on them the gradient of the ice lobe was at its steepest and the water flow at its strongest. On SW slopes the gradients were gentle and the channels that formed were shallow. On NE slopes lateral drainage channels are lacking, except for one single channel system.

The lateral drainage channels are of great importance in the study of deglaciation, since

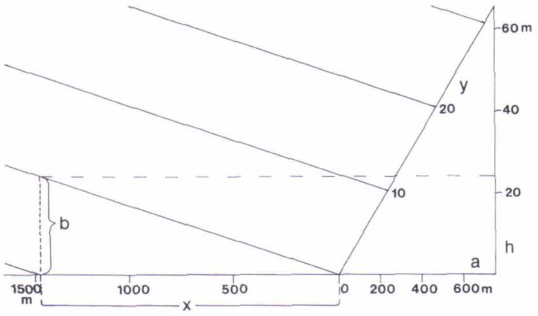

Fig. 16. A diagram showing the distance between lateral drainage channels projected on the horizontal plane allows the annual rate of thinning of the ice sheet and the distance of its retreat to be calculated. a = horizontal length of slope, h = vertical height of slope, y = number of lateral drainage channels on slope, b = thinning of glacier in metres per ten years, x = distance of ice retreat per ten years.

they help construct the position of the ice margin in great detail, which gives a picture of the inclination of the surface of the ice sheet, its gradient and thinning. In favourable places on the fell slopes channel systems comprising several tens of channels were formed, in which the distance between the individual channels remains nearly constant. In these places the channels may have formed as a consequence of the annual thinning of the lateral part of the ice sheet (Penttilä 1963).

According to Kujansuu (1967) the lateral drainage channels are like the varved clays of the subaquatic area: they cannot be directly connected with the annual distance of ice recession, but they do reflect the rate of melting and the gradient of the ice surface. In this study, some of the systems of lateral drainage channels were found to be so regular that on their basis one could calculate the gradient of the ice surface; the annual thinning of the ice sheet; and the rate of recession of its margin (Fig. 16). In these considerable regional variations occur, which are described in more detail in the section on deglaciation. The gradient of the ice sheet was between 1.5 and 3 m : 100 m and its margin thinned approximately 1.2 to 3.5 m per year. The rate of recession of the ice margin varied 70-220 m per year in the various parts of the study area.

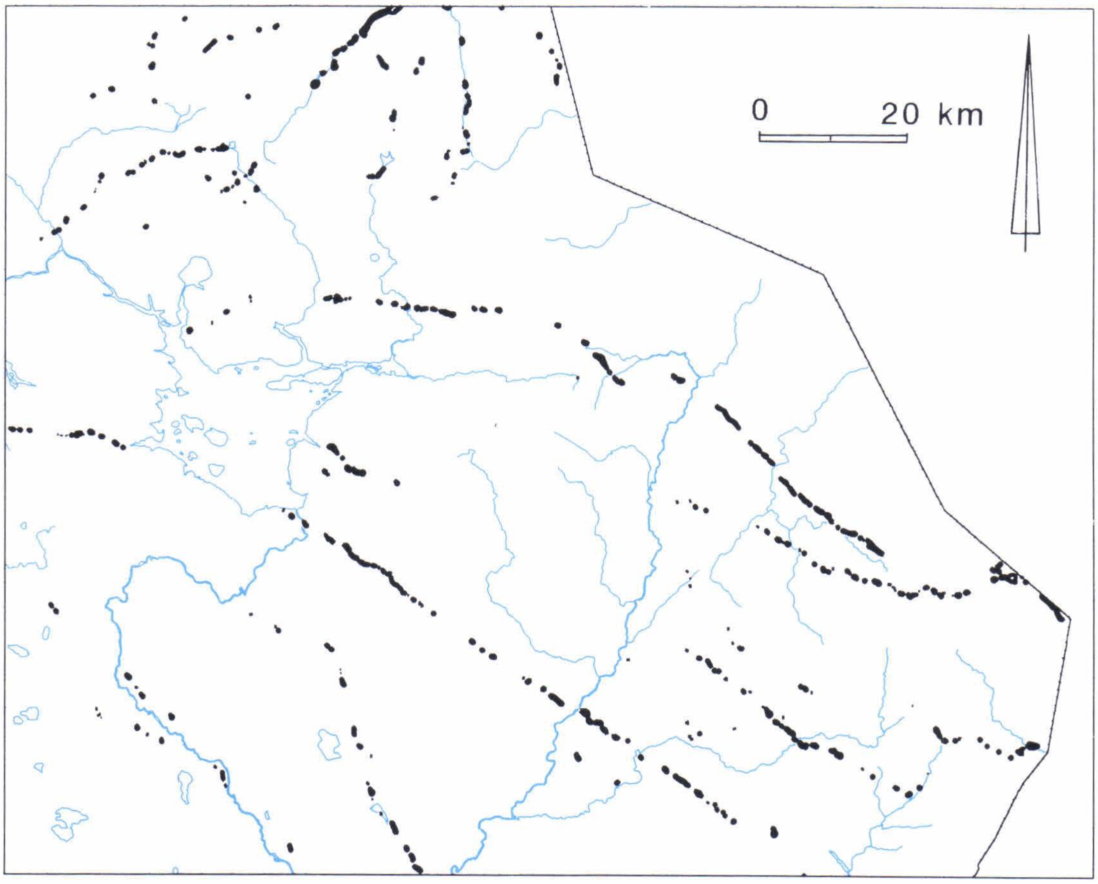

Fig. 17. Subglacial esker chains without till cover.

Directions of flow of the subglacial meltwater systems

By combination of subglacial erosional and depositional landforms, a picture of the subglacial palaeohydrography of the area was obtained (Appendix). In the southern part of the study area, landforms connected with at least three, perhaps even four crossing subglacial meltwater systems were found (Johansson & Kujansuu 1995). They were classified on the basis of the assumed direction of subglacial meltwater flow into: subglacial esker chains without till cover (the A systems of the Appendix); till-covered ones running in a direction N/NNE to S/SSW (B systems of the Appendix); till-covered ones running from NW to SE (C systems); and till-covered ones of variable orientation (D systems).

The esker chains without a till cover begin in the western part of the study area, at the ice divide. The first clear indications of subglacial meltwater action occur outside the arc formed by Lohisarriot-Koitelainen-Moskuvaara. They are minor esker hillocks or channels in the surficial deposits, initially difficult to follow. From there they run in a fan-like pattern (Fig. 17) in the southern and SE part of the area from WNW to ESE (equals the flow direction of the meltwater that deposited the esker). In the central part of the study area they turn to a west-east direction and in the northern part of the study area from SW/SSW to NE/NNE. Farther away from the ice divide the landforms created by the meltwater turn more distinct, reflecting the amount of meltwater and its increase in erosional and depositional capacity. The esker chains without till cover continue both in NE and SE all the way to the marginal formations of the Younger Dryas (Fig. 1) (cf. Niemelä, Ekman & Lukashov 1993).

The total number of esker chains without a till cover is 12 (systems A1-A12, Appendix). They were formed during the latest deglaciation stage. The depositional landforms they include vary in size from over 25 m high gravel and sand ridges to only a few metres high stony and gravelly mounds. In places the eskers are only 2-3 m high, sinuous ridges. They all have distinct features in common, such as steep flanks, and frequently a sharp ridge (Fig. 11). The subglacial erosional forms are also distinct. Frequently the meltwater action has eroded all surficial deposits away from the bedrock.

The esker chains oriented in a northern or NNE direction (B systems) were formed before the last glaciation, and so they were deformed by the following glaciation or glaciations, and covered by tills deposited during these (Fig. 18). Esker chains in a north-south

Fig. 18. Section cut into the till-covered esker of Reutulehto. The till, which is 0.5-0.6 m thick, has a gradual contact with the underlying glaciofluvial gravel and sand deposits.

Fig. 19. Erosional landform produced by a subglacial meltwater system running north-south on the ridge of Tuore-Naavaselkä. The bedrock, eroded by flowing water, is covered almost throughout by a thin layer of basal till formed during the last glaciation.

direction are generally less than 10 m high, and in them an abundance of morphological details have been preserved, such as steep eskers and kettles, contrary to those in a NW-SE direction, in which the ridges are large and discontinuous. Some of the ridges in a NW-SE direction (C systems) are massive, over 25 m high erosional remnants of formerly coherent esker ridges. In the esker chains in a N-S direction the erosional landforms are also visible in the field (Fig. 19), however, frequently covered by younger deposits. The erosional landforms belonging to the systems oriented in a NW direction are today visible in the field only as valleys and depressions in the large-scale morphology. Approximately 9 km south of Leukkuhamaranvaara, in the Kuutsokanharjut esker area, the N-S-oriented esker chain of Kiimaselkä (B1) crosscuts the NW-SE-oriented esker chain of Suomuriniva (C2). This configuration, together with the geomorphological differences described above, leads us to conclude that the N-S-oriented esker chain is younger than the NW-SE-oriented one (Johansson & Kujansuu 1995).

The number of till-covered subglacial esker chains found in a north-south direction is 11 (systems B1-B11, Appendix), and they are somewhat more concentrated than those mentioned before, at intervals of approximately 6-10 km in an extremely limited area between Kitinen and Naruskajärvi (Fig. 20). They are clearly shorter than other esker chains, about 5-15 km long. The longest one (50 km) is that of Kiimaselkä (B1). In the Pihtijoki valley and north of Kemihaara there are subglacial

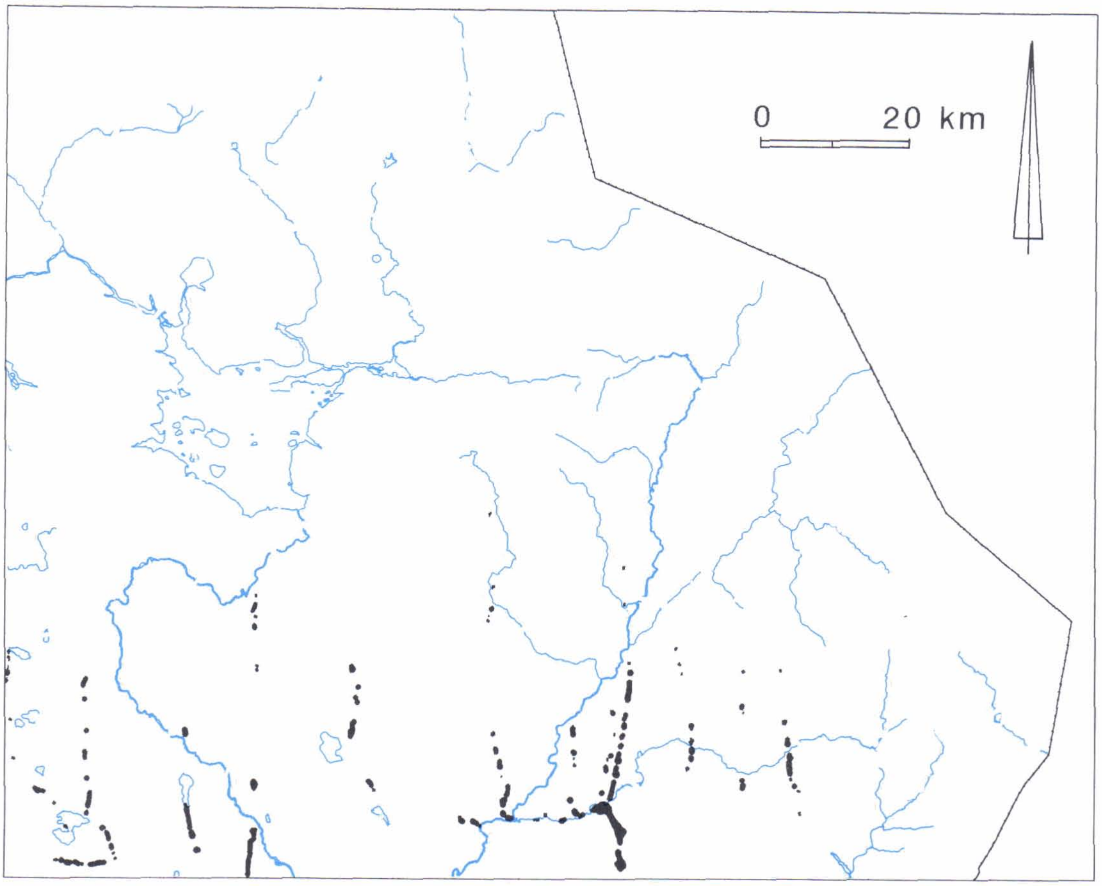

Fig. 20. Subglacial esker chains oriented in a N-S direction.

erosional landforms in a north-south direction, which may be continuations of the esker chains in the same direction. However, no indications of subglacial meltwater activity have been found in the Kemihaara fell region lying in between, and so the connection cannot be shown with certainty.

In connection with the esker chains running in a north-south direction, landforms in a transverse direction (west-east) can also be found. The northernmost of these, Harjusuvannonharjut, is situated on the southern shore of Värriöjoki, 13 km east of Martti. It is a kind of enlargement of an esker, or a landform deposited at the margin of the ice sheet, where three esker chains in the direction north-south join (systems B1, B2 and B3, see Johansson & Kujansuu 1995), possibly also the esker chain coming into Martti from the north (B4). One of the esker chains in a north-south direction, the subglacial esker chain of Kiimaselkä (B1), continues as far as south of Harjusuvannonharjut, terminating in the transverse landform called Niliharju, which runs in an east-west direction and was interpreted by Sutinen (1992) as an Early/Mid-Weichselian marginal formation. The till-covered esker ridge coming from the north from Kelujärvi (B8) in the SW part of the study area, north of Nuolikuru, is joined by the branches coming from the NW from Puolakkavaara and from the west from Palkisvaara.

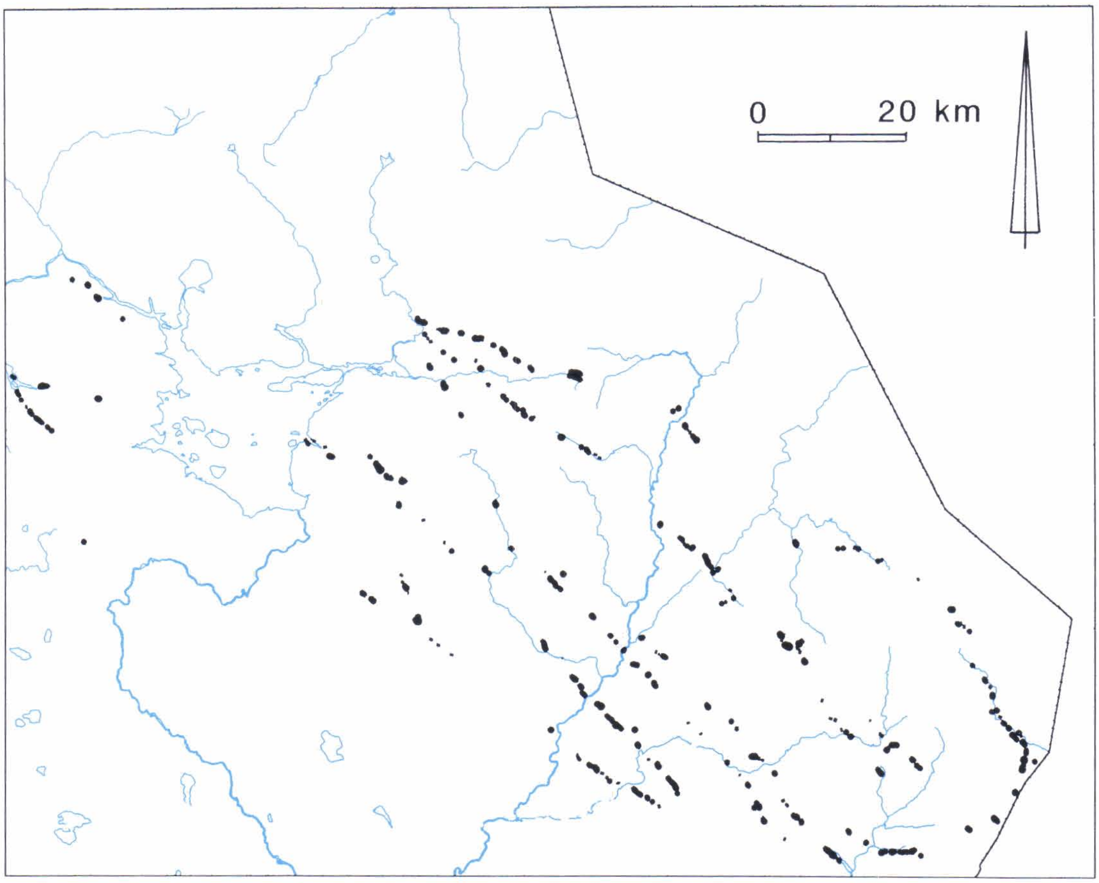

Fig. 21. Subglacial esker chains oriented in a NW-SE direction.

Especially the latter one is nearly transversal in relation to the other branches. It has, however, been found to be an esker and not a marginal formation, and its orientation has been influenced by the high relief of the adjacent hilly areas.

The number of till-covered esker chains in a northwestern direction is seven (systems C1-C7, Appendix). They begin in the western part of the study area with the exception of esker chain C7, which begins as far as 20 km west of the study area. They do not display the fan pattern typical of the esker chains without till cover. They run parallel across the study area for tens, some even for hundreds of kilometres (Fig. 21). They do continue SE of the study area, but information is lacking on their possible continuation in Russia. They are generally situated at a distance of 7-15 km apart which reflects the drainage area of the subglacial tunnel network and equals the average esker frequency in Finland (cf. Punkari 1994).

In the vicinity of Ruuvaoja, two till-covered subglacial esker chains (C3 and C4) run in a NW-SE direction only 2-3 km apart. The fact that two esker chains of a fairly large size exist so close together gives reason to suspect that the meltwater systems are of different ages (Johansson & Kujansuu 1995). In case they had been formed at the same time, one of them would probably had drained the water away from the other one (Röthlisberger 1972).

On the SE side of the Porttipahta reservoir, at Lohijoki, and in the Siella-aapa area there are two till-covered esker chains (D1 and D2), which are very strongly eroded and flattened by the ice. Their orientations differ somewhat from that of the NW-SE esker chains and cross them. It is uncertain whether the two of them are contemporaneous, but apparently they are older than the NW-SE systems. Another unsolved question is the age of the Mäkärä esker (D3) (cf. Kujansuu 1994), which is oriented SW-NE in the NW corner of the study area, and its relation to the other eskers.

Comparison of subglacial esker chains with the till stratigraphy

The till stratigraphy in cuts and test pits excavated in the study area is mostly made up of randomly occurring till units. It is nearly impossible to find a perfect stratigraphic sequence, comprising all five till units described earlier (Fig. 22). The stratigraphic till studies in the area of Suomurinivat (Johansson & Kujansuu 1995) are based on the assumption that the subglacial esker chains formed before the last glaciation in this area should each have a corresponding till unit, deposited from approximately the same direction, since the flow direction of the meltwater systems formed during the latest deglaciation can be correlated with the fabric orientation of the till formed during the same stage. Thus there should exist till units deposited by ice flowing from approximately the same direction as the meltwater flows that deposited the till-covered esker chains from NW and north.

At Suomurinivat the gravel and sand deposits of the esker, which is oriented in a NW-SE direction, are situated between two till units of different ages (Fig. 23). The one below is basal till deposited by ice flowing from the NW (the D till in Johansson & Kujansuu 1995). It is contemporaneous with the esker or older than it, since the subglacial meltwater that deposited the esker have eroded their channel into it. It may be correlated with the oldest till unit of this study. The eskers in a NW-SE direction and the oldest till unit may

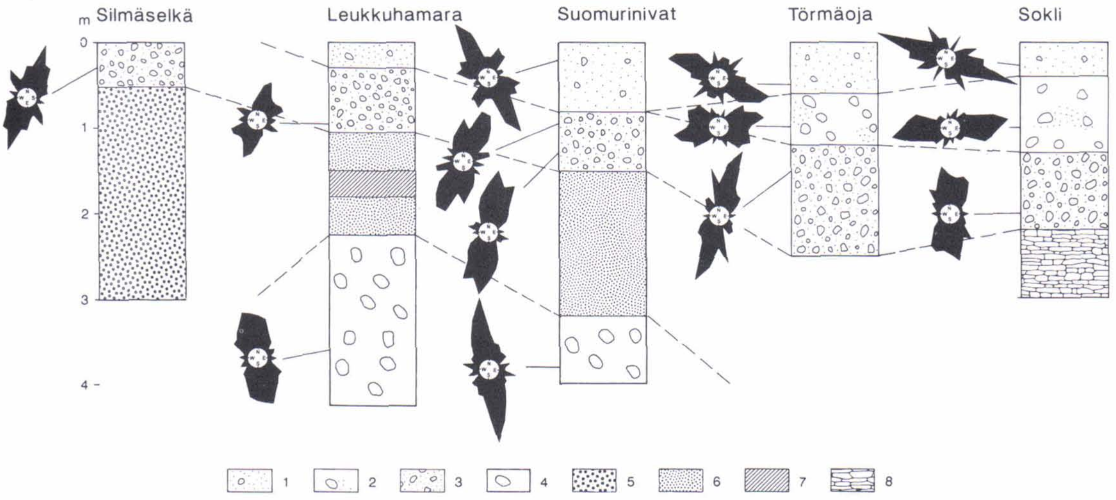

Fig. 22. Compilation of stratigraphic observations in which the 'Old Northern' till unit occurs. 1 = youngest till unit, 2 = younger till unit, 3 = 'Old Northern' till unit, 4 = oldest till unit, 5 = glaciofluvial gravel, 6 = glaciofluvial sand, 7 = silt, 8 = preglacial weathered rock.

Fig. 23. The youngest till unit (a), the 'Old Northern' till unit (b), a sand unit belonging to a NW-SE-oriented esker (c), and the oldest till unit (d) in the wall of an excavator pit at Suomurinivat.

be correlated with the glaciation stage at the end of the Saale glaciation or that during the Early Weichselian, when the ice was flowing from NW to SE.

The till on top of the esker deposits (The B till in Johansson & Kujansuu 1995), i.e., the 'Old Northern', which was deposited by ice flowing from between north and NNE, was formed after the formation of the eskers in a NW-SE direction either contemporaneously with the Kiimaselkä esker, which runs in a north-south direction, or slightly before it. Stratigraphically the 'Old Northern' is situated between the older and the younger till unit, since in the areas of Sokli and Törmäoja it occurs under the younger till unit. The 'Old Northern' till unit and the eskers running north-south have so far been encountered only in the southern and southeastern parts of the study area. The stratigraphic findings at Suomurinivat would seem to support the conclusion reached from the geomorphological observations, that the N-S-oriented subglacial esker chains are younger than the NW-SE-oriented ones. It may be possible to correlate the 'Old Northern' till unit with the north-southern ice flow in the Savukoski area, which was described by Sutinen (1992) and interpreted by him to be Early/Mid-Weichselian.

The ridge of Pihtijoki (D4), which is a till-covered glaciofluvial landform, runs WSW-ENE along the eastern shore of the Lokka Reservoir and in the Pihtijoki valley. It is a mostly 500 m to 1 km wide and approximately 25 m high, massive landform. It is joined by a branch from the west. The ridge ends before the national border, and there are no observations of its possible continuation on the Russian side (V. Evzerov, oral communication).

According to Sutinen (1992) the stream that deposited the north-south eskers turned to flow from NE to SW in the Lokka area, and so the till-covered Pihtijoki ridge (Vieriharju) would have been deposited during the same stage by meltwater flowing from ENE to WSW. During this study no evidence was found of a flow from ENE to WSW nor of the connection between the north-southern eskers and the Pihtijoki ridge.

As to its geomorphology, the Pihtijoki ridge may be an esker or an interlobate complex deposited by meltwater flowing from WSW to ENE. In stratigraphic till studies it was found to be older than the esker chains oriented in a NW-SE direction, since the oldest till unit overlies the littoral sand deposits associated with the Pihtijoki ridge, and it is underlain by a till layer with a SW-NE orientation, possibly corresponding to till bed IV of Hirvas (1991). The course of the Pihtijoki ridge crosses that of the Siella-aapa subglacial esker chain (D2), and so they are of different ages, too. The relation of the Pihtijoki ridge to the subglacial esker chains interpreted as the oldest ones (D) remains to be solved. In any case the age of the Pihtijoki ridge is pre-Weichselian, and it was deposited by one of the oldest glaciofluvial systems of the study area.

The till unit occurring on the ground surface in the test pits at Suomurinivat (the A till in Johansson & Kujansuu 1995) is youngest, and it was formed during the latest deglaciation, at the same time as the young eskers running from WNW to ESE in the southern part of the study area. Thus the younger till unit, common in the vicinity of Suomurinivat, equal to till bed II of Hirvas (1991), is totally lacking or too thin to be distinguished. It is probable that the youngest till unit was formed by deformation of the younger till unit during the deglaciation stage, as the ice mixed its clasts, giving the fabric a new orientation.

The till stratigraphy of the Martti-Ruuvaoja area is complicated with its numerous till units, one on top of the other. The glacial erosion and deposition of till varied greatly on a regional scale, which makes it difficult to correlate the till units from one observation site to another. In places the bedrock is covered by one single till unit. In other places the same unit may be totally lacking between other units. The reason that till units older than the last glaciation occur at the surface may also be that the deposition of till during the Mid- and Late Weichselian glaciation was remarkably slight in the ice-divide area. This view is supported by the observations made by Lagerbäck (1988) in northern Sweden and by Kujansuu and Hyyppä (1995) in the Vuotso area.

ICE LAKES

The area concerned here was favourable for the formation of ice-dammed lakes partly for the following reasons. Variations in altitude are considerable over the major part of the area; the main water divide runs across the area, separating the water systems flowing into the Arctic Ocean and the bays of the White Sea from those flowing into the Gulf of Bothnia; and the land surface was inclined towards the margin of the ice sheet that formed the dam. The suitable conditions are not, however, sufficient proof that large ice lakes really existed in the area. In order to dam meltwater, the ice margin had to be intact enough, and the internal pressure of the ice had to exceed the pressure caused by the dammed water (cf. Lundqvist 1972). The ice-lake basin could contain abundant ice blocks and icebergs, which had come loose from the margin of the ice. The ice sheet could also be dynamically passive, meaning that the water escaped from the basin along subglacial or submarginal crevasses and fractures. The ice melted down in place, and blocks of dead ice filled the basin. Thus the proportion of free meltwater was small.

The existence and history of the ice lakes in the area were studied using shore marks, spillways and bottom sediments of ice lakes. By reconstruction of morphological conditions it was possible to draw conclusions regarding the size of individual ice-lake basins and their relations to the receding ice margin.

Shore marks

The shore marks (Fig. 24) are one of the most conclusive indications of the former existence of an open ice-lake basin. The formation of shore marks is influenced especially by the type of surficial deposits, the inclination of the slope, and the length of time during which the water surface of the ice lake stayed at the same level. The position of the shore in relation to the open lake also had great influence. Towards extensive areas of open lake the shores are better developed than in protected places, such as the bays of the lake. According to Lundqvist (1969 and 1972) the best developed shore marks of ice-dammed lakes seems to have been formed rather close to the ice margin.

The shore marks include washed bedrock surfaces, from which the till layer covering the rock has been washed away. These marks occur on the fellslopes, e.g. in the Luirojärvi valley. The surface level of the ice lake is also reflected by the termination of lateral drainage channels on the valley slopes at the same level, as well as by the flat surfaces of the

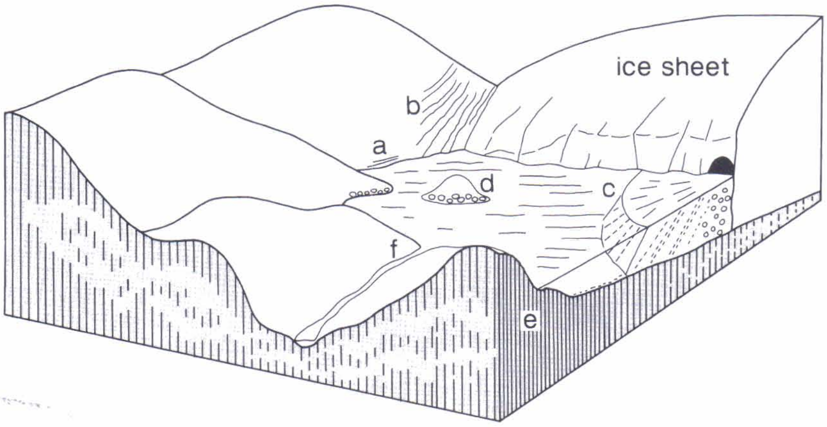

Fig. 24. Types of ancient shorelines and other marks of former ice lakes. a = washed bedrock surface, b = lateral drainage channels terminating at the surface level of the ice lake, c = delta deposited at the surface level of the ice lake, d = stone belt, e = scarp shore, f = spillway with threshold point.

deltas and marginal drainage deltas. The action of waves and surf resulted in scarp shores on esker slopes and boulder belts on till slopes, and in winter the ice pushed up boulder belts or boulder fields (Fig. 25). Indistinct stone belts occur in various parts of the study area, but distinct boulder belts and boulder fields only in the southern part, where the ice-dammed lakes were larger and so the force of the waves and the pack ice in winter was greatest. In the extensive ice-lake basins the shore level reflecting each ice-lake stage may be followed over long distances (Fig. 26). Because the land uplift was stronger in the SW part of the study area than in its NE part, the ancient shorelines are inclined towards

Fig. 25. Littoral boulder belt of the Salla Ice Lake at 237 m a.s.l. on the slope of Puu-Matovaara, 4 km east of the village of Salla.

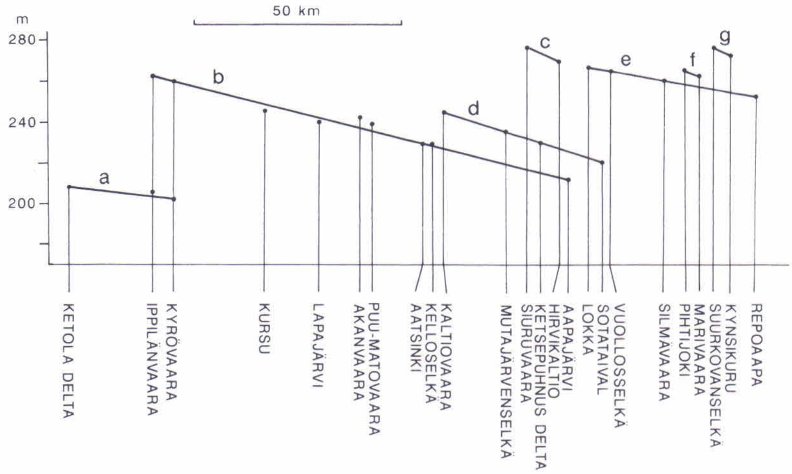

Fig. 26. Distance diagram depicting raised shore levels of the ice-dammed lakes and the Ancylus Lake in Finnish Lapland. For locations of the ice lakes, see Appendix. a = Ancylus Lake, b = Salla Ice Lake, c = Värriöjoki Ice Lake, d = combined ice lakes of Värriöjoki and Kemihaara, e = Posoaapa Ice Lake, f = Pihtijoki Ice Lake, g = Sokli Ice Lake.

NE. Since the land uplift was faster during the beginning of the deglaciation, the shore levels then formed are more strongly inclined than those of later formed ice lakes. Thus the gradient of the ice-lake basins that first became ice-free, i.e., those in the eastern part, such as the Salla Ice Lake, is 0.50-0.55 m/km, growing gentler towards the western part of the area. In the Värriöjoki and Kemihaara ice lakes the gradient is 0.55-0.58 m/km and in the Pososaapa Ice Lake, which was formed at the end of the deglaciation in the area, the gradient is approximately 0.37-0.40 m/km.

Spillways

Spillways are erosional landforms created by strong water streams. Today they are either dry or else the eroding power of the stream flowing on their bottom is in no proportion to their size. On the basis of the shape and dimensions of the spillway, it is possible to get an idea about the strength and duration of the former stream in it. The spillways are not always conclusive evidence of the former existence of ice lakes, because some of them may prove to be of subglacial or submarginal origin, and so the ice lake may never have existed. On the other hand the meltwaters from the ice lake may have flowed across the ice lobe that dammed it or along a crevasse formed within it (cf. Whalley 1971, Röthlisberger 1972), so that no traces of meltwater erosion were left in the terrain. The spillways in the study area are proglacial, marginal or extramarginal.

Erosional landforms that have formed parallel to the slope, frequently perpendicular to the ice margin, part of them typical col channels, are considered to be proglacial origin. The col channels cross ridges that form water divides and are frequently situated at the lowest point of a ridge between two tops. They generally start at the crest of the divide, like the subglacial erosional landforms described above, and terminate in the middle of a descending slope, because the lower part of the slope was still covered by ice. The meltwaters that flowed from the ice lakes formed at the southern edge of the Saariselkä range eroded several col channels between the fells, since the ice sheet lying against the southern edge of the fell range forced the waters to flow across the range. Although the proglacial channels are clearly eroded by running water, the formation of a col channel was also favoured by existing fractures and crush zones in the underlying bedrock. The oldest spillway of the Siuloiva Ice Lake (Tanner 1915, Johansson 1988), a locally 20 m deep col channel which crosses the fell ridge between the tops of Vuomapää and Siuloiva, is a typical proglacial spillway. The spillway of the Tuntsa Ice Lake into the Papuhaara valley is also proglacial. However, it lacks the features typical of a col channel, because the erosion did not start until after the divide, and continued to the lower part of the descending slope.

A spillway could also be formed at a location where subglacial meltwater erosion had taken place earlier. Although the route of the subglacial meltwaters did not always coincide with the lowest points in the terrain, the existing eroded point on the water divide could well be the lowermost route offered to the meltwaters. As the ice sheet melted, the ice lake started to form at the mouth of a subglacial meltwater conduit. The formation of the lake was favoured by strong melting of the ice and by a large volume of meltwater coming from the conduit. Ice lakes that received a subglacial stream also have the most impressive proglacial spillways, such as the old spillway of the Kopsusjärvi Ice Lake south of Kopsusselkä, and the gorge of Kynsikuru, which is situated south of Nuorttitunturi. There are local variations in what part of the erosion occurred as early as subglacially and what part proglacially. As an example there are three closely grouped proglacial spillways north of Kiilopää, the southernmost of which was originally subglacial (Fig. 27). The part played by the subglacial meltwater erosion was certainly more significant than that of the proglacial one, because this gorge served as the spillway of the Kiilopää Ice Lake for only a short time before the next spillway opened, situated on a lower level than the first one.

Marginally formed spillways are erosional landforms formed at the contact between the ice margin and the slope. Although they are situated on the slope like the lateral drainage channels, they can be distinguished on the basis of their considerable size and irregular mode of occurrence. It is evident from the appearance of these spillways that an abundance of meltwaters flowed in them for a short time. E.g. the slopes of the fells Siuloiva and Vongoiva show a number of marginal spillways, one below the other, with a depth from a few metres to ten metres. They were formed as the ice thinned and its margin receded down the slope of the fell. The opening of new spillways under the margin of the ice sheet, below the preceding ones, led to a successive lowering of the water levels in the Siuloiva and Vongoiva ice lakes. Meltwater erosion was at its most marked when the spillway opened and the level of the ice lake dropped to that of the spillway threshold. From that point onwards meltwater erosion weakened, and when a new spillway opened up at a lower level under the ice margin, the former spillway dried out and erosion caused by the water came to an end.

Extramarginally formed spillways were formed outside the margin of the ice sheet. In suitable locations, channels earlier formed marginally or proglacially became extramarginal. The landforms influenced their location more than the position of the ice sheet at the time. In the Saariselkä fell region there are extramarginal spillways in the vicinity of Laanila (Penttilä 1963) and south of the Saariselkä fell range, among the marginal channels on the slopes of Vuomapää (Tanner 1915), Siuloiva and Vongoiva. The Jaurujoki valley is in itself a big extramarginal spillway, which collected the meltwaters flowing in marginal and extramarginal channels south of Saariselkä, leading them eastward to the Tuloma river valley. In the fell region the edges of the spillways are steep and straight, about 5-15 m high (Fig. 28). The floor is 5-20 m wide and mostly smooth. Some of the spillways follow old tectonic valleys and in them the erosion has reached as far as the bedrock. Some canyons south of the fells Vongoiva and Talkkunapää represent an order of magnitude of their own. They are tens of metres deep, formed in fracture zones, and correspond to the meltwater canyons of kursu type in northern Sweden (Rudberg 1949, Olvmo 1989). Although marginal and extramarginal meltwaters were streaming in these canyons, too, their formation was largely controlled by the fracture zones and the preglacial erosion of the bedrock.

In the area between Ruuvaoja and Sotatunturi and in the vicinity of the village of Tanhua, mar-

Fig. 27

Fig. 28. A marginal channel typical of the fell region, on the lower slope of Vongoiva, Saariselkä.

ginal and extramarginal channels occur, which differ from those in the fell region regarding shape and size. They are wider than in the fell region, their floors are smooth and their edges low (Fig. 29). The size and shape of these, too, reflect strong meltwater erosion, which was caused by the waters discharging from the ice lakes. South of Rautuvaara the spillways joined to form a more than 20 m deep extramarginal channel, collecting the waters and leading them to the Nuortti canyon, which for a long time served as an outlet for the ice lakes in the southern and SE parts of the study area. The locally more than tens of metres deep channels oriented north-south in the vicinity of Tanhua served as spillways for the Posoaapa Ice Lake into the Luiro valley.

Ice-lake sediments

The coarsest sediments found on the bottom of the ice-dammed lakes are poorly sorted stony outwash gravels, which were formed from debris transported by running water on the shore of the ice lake at the mouth of a marginal channel. The cause of its deposition could be a catastrophic

Fig. 27. Stereopair showing an aerial view of the terrain north of Kiilopää. The Kiilopää Ice Lake was dammed up in the innermost part of the Kiilo-oja valley during the retreat of the ice sheet (a). Spillways beginning in the ice lake can be observed in the depressions between the fell tops (b-h, in chronological order). The oldest spillway (b) was originally a subglacial channel through which the Kiilopää meltwater system ran. Esker ridges related to it can be seen on the northern slope of Kiilopää (i). Reproduced by courtesy of theFinnish Defence Forces Topographic Service.

Fig. 29. A marginal channel in the Tulppionjoki valley.

water discharge in connection with a rapid drop in the water level of another ice lake at a higher level.

Widespread bottom sediments are found in an ice-lake basin, in which a subglacial river terminated. In addition to the coarse material that accumulated on the bottom and at the mouth of the subglacial river, the meltwater brought with it abundant finegrained sediments, which were deposited on the bottom of the basin where the stream velocity decreased. In the ice lake of Sokli, ice-lake sediments with a thickness from half a metre to five metres (Fig. 30) accumulated on top of the glaciofluvial sand beds. The basal part of the sequence consists of horizontally laminated fine sand, deposited by turbidity currents flowing in a subglacial conduit. While these were deposited, the ice margin and the mouth of the meltwater conduit were still near by. In many places 10-30 cm thick weakly varved or homogenous silt and clay beds were deposited on top of the sands. In the varves, a light 'summer' layer and a darker 'winter' layer can be distinguished. The thickness of a varve is variable, 3-20 mm. The maximum number of varves encountered is approximately 30, generally the number is 5-10. They may represent annual sedimentation, but may also have formed during a short time as a consequence of variations in stream velocity and amount of suspended material (cf. Theakstone 1976). When the varved sediments were formed, the ice margin had receded farther anyway, and the effect of the turbidity currents from the meltwater tunnel had ended. Thus the small number of varves shows anyway that the Sokli Ice Lake was short-lived. A corresponding sequence can be found in the bottom sediments of Luirojärvi (Johansson 1988) and Kopsusjärvi (Kujansuu & Hyyppä 1995).

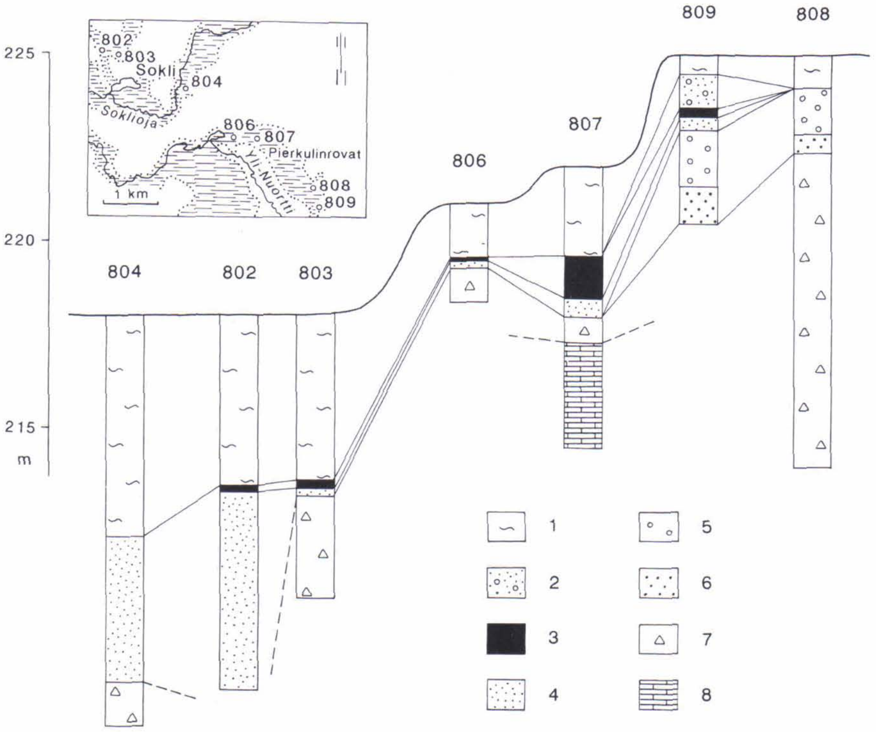

Fig. 30. Distribution of ice-lake sediments in the Sokli area, as determined from drillings. 1 = postglacial peat, 2 = littoral sand and gravel, 3 = weakly graded or homogeneous silt and clay deposited on the bottom of the ice lake, 4 = horizontally laminated fine sand deposited on the bottom of the ice lake, 5 = glaciofluvial gravel, 6 = glaciofluvial sand, 7 = till, and 8 = preglacial weathered rock.

Sand deposits interpreted as littoral were formed at an altitude of approximately 263-265 m., at the shoreline of the Pihtijoki Ice Lake, e.g. adjacent to the Pihtijoki esker, where sufficient amounts of originally glaciofluvial sand was available. Elsewhere littoral deposits are rare, since the shores consisted mainly of till and the ice-lake stages were short-lived, so that they did not have time to form.

Types of ice lakes

The ice lakes in the study area were classified into five types (Johansson 1993).

1: Shallow marginal ice lake or nunatak ice lake lacking bottom sediments.

2: Open ice lake with fairly distinct shore marks but lacking bottom sediments.

3: Open ice lake with fairly distinct shore marks and a thin, frequently less than 20 cm thick bed of bottom sediments.

4: Shallow ice lake with indistinct shore marks and several metres thick bottom sediments.

5: Shallow ice lake with indistinct shore marks and lacking bottom sediments. May have been partly filled with dead-ice blocks.

It is worth noting that many ice lakes could be referred to two or more various types during the stages of its history. Differences between the types were not caused only by outer factors, such as the morphology, the size of the basin and the volume of sediments transported into it, but the relation of the ice-lake basin to the receding ice margin, and the dynamics of the ice sheet also influenced these differences. E.g. ice-lake type 1 existed during the initial stage of the deglaciation, when meltwaters collected around the exposed nunataks. They were possibly supraglacial basins (cf. Liestøl et al. 1980) or transitions between lateral meltwater stream and ponds of stagnant water (Lundqvist 1972). Ice lakes of type 1 existed only in areas of pronounced relief, e.g. the Siuloiva and Vongoiva ice lakes in their early stages, whereas types 2 and 3 were common throughout the area. Type 3 is found especially in places where subglacial meltwater systems occurred, leading to the deposition of fine-grained sediments on the lake bottom. Ice-lake type 5 was common in the centre of the ice divide, e.g. the Posoaapa Ice Lake, because at the final stage of the deglaciation the ice sheet became broken at its margins, so that some of the ice lakes may have turned into fields of dead ice. Ice-lake type 4, of which the Sokli Ice Lake is the only example, differs from the other types on the basis of its thick bottom sediments. Ice lakes of the same type as the Sokli Ice Lake occurred in Sweden over extensive areas (Lundqvist 1972). In addition three other ice-lake types (1, 3 and 5) have their equals in Lundqvist's classification, which comprises a total of seven ice-lake types.

ICE RETREAT PATTERN

The Younger Dryas stadial and deposition of the younger till unit

During the Younger Dryas stadial the margin of the continental ice sheet was situated outside the study area, in northern Norway and in Russia (see Fig. 1). In the north, marginal formations of this stage, named 'the Main sub-stage' by Sollid et al. (1973) are found in the area between Tana and Kirkenes. They may be correlated to the Tromsø-Lyngen marginal formation, which according to the radiocarbon datings originates from the Younger Dryas stadial (Marthinussen 1962). The same marginal formation continues farther on the coast of Petchenga to the Kildin Island NE of Murmansk (Tanner 1930, Nikonov 1964, Evzerov & Kolka 1993). In the central part of the Kola peninsula the position of the margin of the Younger Dryas stadial has not been exactly defined. According to Evzerov and Kolka (1993) the ice margin ran north-south in the central part of the Kola peninsula, east of the Khibiny Mountains. According to Ekman and Iljin (1991) the marginal position of the Younger Dryas stadial continues along the SW shore of the White Sea to the marginal formations of the Rugozero stage in East Karelia. They are related to the Koitere marginal formation and are probably continuations of the Salpausselkä II marginal formations (Rainio 1991). The ridges in a north-south direction in the area between Kovdor and Kandalaksha are part of the marginal formations of the Kalevala stage (Ekman & Iljin 1991), and continue on the Finnish side of the border in the form of the Pielisjärvi marginal formations, which according to Rainio (oral communication) are probably contemporaneous with the Salpausselkä III marginal formation. Between Kovdor and Petchenga no distinct marginal positions can be observed, but apparently the till ridges and hillocks north of the Khibiny Mountains are deposited by the readvance of the Younger Dryas (Ekman & Iljin 1991).

When the Late Weichselian glaciation was at its most extensive, the ice flow center was an ice dome, which was probably situated approximately at the Gulf of Bothnia (Boulton et al. 1985, Bouchard & Salonen 1990). During the

Younger Dryas stadial, at the latest, it had shifted towards the north, changing into an ice divide, which formed a line from the fell region of the western part of the Kola peninsula (Evzerov & Koshechkin 1980, Legkova, Korovkin & Shchukin 1981) via central Lapland southwestward to Sweden, and following the eastern slopes of the Scandinavian mountain range to the central part of southern Norway (Lundqvist 1972, 1986). From the ice divide the ice flowed towards the marginal areas of the continental ice sheet. On the ice divide itself the ice was probably cold-based and static over extensive areas. The ice did not become warm-based until in the marginal zone, which was approximately 100-200 km wide, and then erosion and deposition started at its base. Included in this zone were also Petchenga and the basin of the lake Inarijärvi. In the basin of Inarijärvi the ice was flowing fairly intensively in a SSW-NNE direction, so that the boulder trains formed were narrow and rather short (cf. Salonen 1986). This flow equals flow stage II as described by Hirvas (1991). During that time till bed II was formed, which is common in the area and analogous with the younger till unit of the study area. During the Younger Dryas, the deposition of drumlins also started north and NE of Inarijärvi (Heikkinen & Tikkanen 1979, Ström 1980) and in the central parts of Petchenga (Nikonov 1964). The fields of hummocky moraines and drumlins in Kovdor-Kandalaksha area in the southwestern part of the Kola peninsula (Ekman & Iljin 1991) and the uppermost till unit (Evzerov & Koshechkin 1977) were probably deposited during the same time.

At the end of the Younger Dryas stadial, 10 200-10 300 radiocarbon years BP (Sollid et al. 1973), the ice margin started to recede again. In the north the withdrawal of the margin towards south-SW was rather fast, approximately 100-150 m annually in the Paatsjoki valley at the border between Norway and Russia (Sollid et al. 1973), and 200 m annually in the Inari-Kaamanen area (Seppälä 1980). The oldest ages obtained by radiocarbon dating of mussel shells from the Petchenga river valley are 9120 ± 70 BP (Evzerov & Kolka 1993). Nikonov (1964) estimates that the Lutto valley on the Russian side of the border became ice-free approximately 9500-9800 BP. Southeast of the ice-divide area, in the vicinity of Kandalaksha-Kovdor, the ice margin receded towards the west-northwest (Evzerov & Koshechkin 1977, 1981).

The deposition of the younger till was still continuing during the beginning of the ice recession. Apparently the younger till unit was not formed contemporaneously in the entire study area, but is time-transgressive. The younger till unit in the middle of the ice-divide area was deposited later than the analogous till unit in the northern and SE parts of the study area. The younger till unit was deposited deep in the interior of the marginal zone of the ice sheet at the same rate as the margin was withdrawing towards the ice flow center.

Deglaciation of the Tuntsa area

The ice margin reached Finnish territory in the vicinity of Puitsitunturi and in the Tuntsajoki valley approximately 9500 years ago (cf. Hyvärinen 1973). Before that there was a distinct change in the flow direction of the ice sheet. The glaciofluvial deposits running from NW to SE on the Russian side of the border in the Tuntsajoki valley (Niemelä et al. 1993) become discontinuous and assume a SW-NE orientation in the Auermajoki valley on the Finnish side, turning again to a WNW-ESE direction after about 10-15 km. According to the investigations of the till stratigraphy the same change also occurs in the flow direction of the ice sheet. In the Tuntsa-Naruskajärvi area, the youngest till unit, which was deposited by an ice flowing from SW to NE, overlies the younger till unit, the orientation of which is WNW-ESE. The change in flow direction occurred at a time when the ice was still several hundreds of metres thick and dynamically active, as it is also detectable in the orientation of the esker chains. Thus it was not caused by local movements of the ice margin, which lay further away to the southeast of the area studied here, but rather by the morphology of the area, especially the N-S-oriented fell range of Värriötunturit. It rises more than 200 m above the adjacent area and will have inevitably constituted a transverse obstacle to the ice sheet, influencing the movements of the ice from a very early stage, as the ice tried to circle it.

When the ice sheet had thinned and its mar-

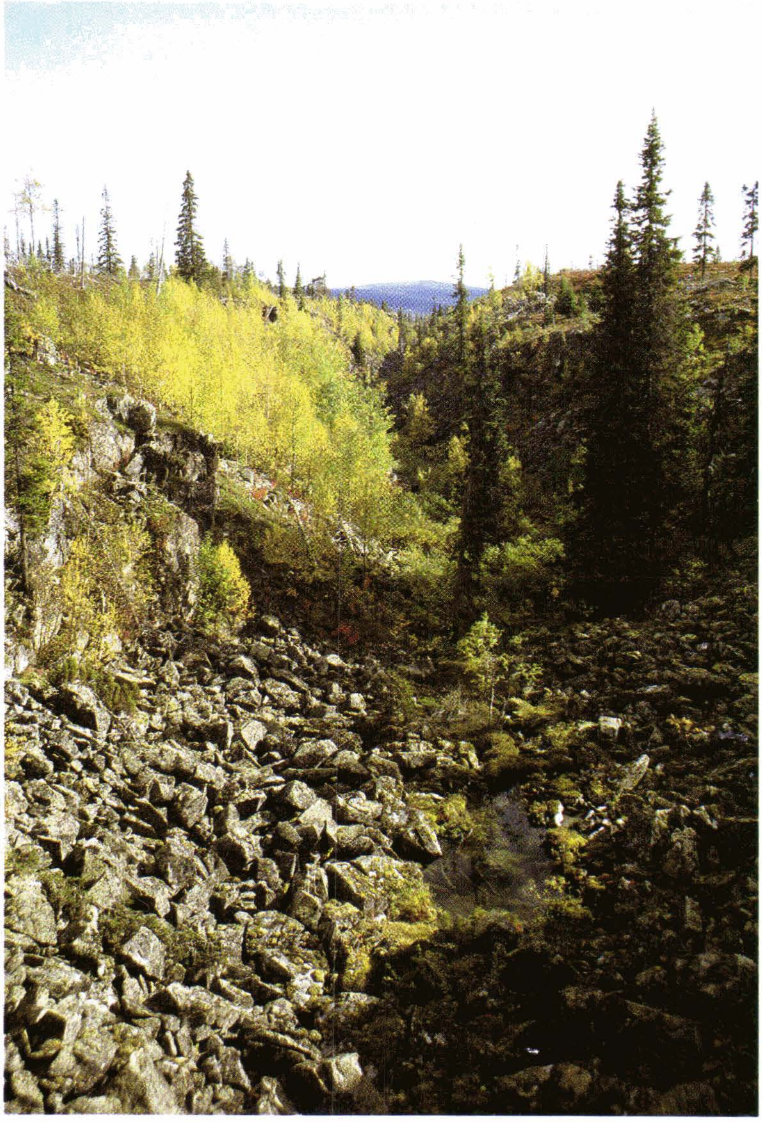

Fig. 31. The proglacial gorge of Nuoluskuru.

gin had reached the area of Tuntsa-Naruskajärvi, it became lobate. It flowed, controlled by depressions in the terrain, from SW to NE. North of Tuntsa, in the area of Sauoiva and Papuhaara, the ice margin receded along the northern edge of Värriötunturit westward. The Tuntsa Ice Lake was dammed in the Peurahaara valley, at a point north of Peuratunturi. At first it discharged across the water divide to the northeast into the river Tulomajoki and along it to the Arctic Ocean. The Tuntsa Ice Lake was of type 2. Due to the shape of the valley, the ice lake did not grow big, and its duration was also short. As the margin of the ice withdrew from the western slope of Peuratunturi, a series of marginally formed spillways were formed, which slope towards the Tuntsajoki valley. Along Tuntsajoki the waters from the ice lake emptied into the White Sea. The subglacial meltwater systems that crossed the fells of Nuolusoiva and Kuskoiva functioned until the ice sheet on the fells became thinner and the conduits were broken. The meltwaters that had discharged from the tunnels continued their flow marginally along the fellslopes and along the bottom of the Nuoluskuru gorge into the Tuntsajoki valley (Fig. 31). The marginal channels formed on the slopes, as well as the lateral drainage channels, indicate that the ice flow was continuously active and that its margin remained intact until the ice sheet wasted down. On the basis of the lateral drainage channels the ice thinned about 2.8-3.2 m a year. Its margin receded only 70-80 m a year. The recession was actually fairly slow compared with the recession in northern Lapland and in Petchenga, mentioned earlier. Observations made south of the Kola Peninsula and in Karelia support the results from the Tuntsa area. This development must have given rise to a colder, more continental climate, so that the deglaciation took place more slowly in the SW part of the Kola Peninsula than on the coast of the Arctic Ocean (Ekman & Iljin 1991).

West of the valleys of Ylä-Naruskajoki and Auermajoki the margin of the ice began to recede uphill and the direction of ice flow altered to WNW-ESE. After the margin reached Värriötunturit, it settled in a nearly north-south direction, leaning on the western slope of Värriötunturit. On the slope of Värriötunturit only a few lateral drainage channels occur, because the meltwater action at the ice margin was minor. The meltwaters streaming from the ice drained either along the southern edge of the fell range via the ice lake dammed at the uppermost tributaries of the rivulet Murhahaaranoja or to the north, where they united with the marginal channels leading from the conduit of the subglacial meltwater system of Suurkovanselkä (A4) to the upper tributaries of the river Hirvasjoki (see Fig. 9).

Early deglaciation or the Saariselkä nunatak phase

During the same time as the ice margin at Tuntsa withdrew towards the west the first felltops in the northern part of Saariselkä appeared in the form of nunataks in the middle of the ice sheet. The deglaciation was at first thinning of the ice, since the ice margin was situated in the NE of the study area, in the basin of the lake Inarijärvi and in the southern part of the Pechenga area. The flutings occurring in various parts of the fell region (Fig. 32) indicate that the ice was actively flowing across the area from SSW towards NNE. There are relatively few subglacial esker chains, and they coincide in direction with the ice flow, although on account of the pronounced relief they frequently follow the fracture zones in the bedrock and the valley floors (Penttilä 1963). During the nunatak stage many of the col channels in the Saariselkä region were also formed, e.g. in the vicinity of Kiilopää and Sokosti-Ukselmapää. The waters flowing in them drained towards north or NE (Fig. 33), in the same direction as the gradient of the ice sheet (Johansson 1990).

Fig. 32. Flutings on the slope of Siliäselkä, north of Lake Luirojärvi.

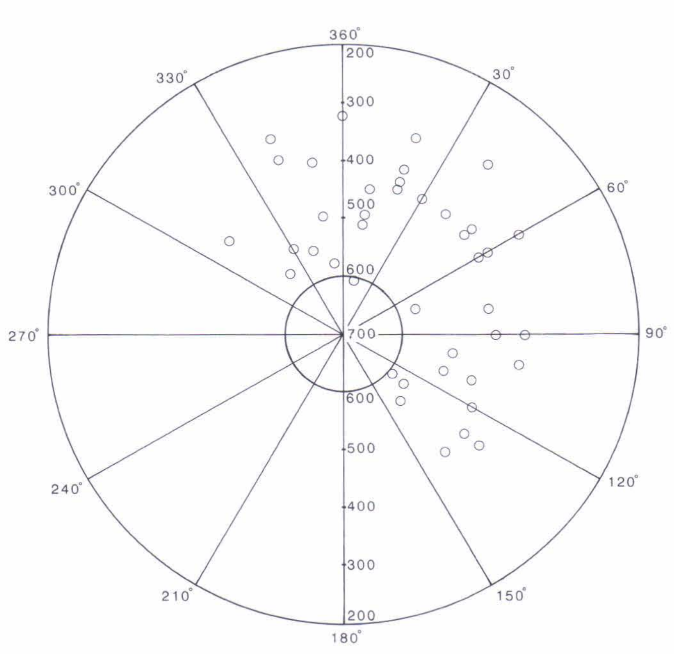

Fig. 33. Orientation of col channels, i.e. directions of ancient meltwater flow in them, relative to altitude.

On the basis of the lateral drainage channels on the upper slopes of the fells the gradient of the ice sheet during the early stage of the deglaciation in the Saariselkä region, i.e., the nunatak stage, was variable, 1.5-2.5 m : 100 m. Similar gradients were also measured in the areas of Inari (Syrilä 1965), western Finnish Lapland (Kujansuu 1967, Abrahamsson 1974) and Finnmark (Sollid et al. 1973).

Deglaciation of the Sokli area

When the ice margin had receded west of the fells of Värriötunturit, damming of meltwaters began in the eastern part of the Ylä-Nuortti valley. This basin, called the Sokli Ice Lake, was at first of ice-lake type 1. It discharged along the proglacial gorge south of Nuorttitunturi into Tulomajoki in the east. Judging from the altitude of the threshold point of the spillway, the water level in the Ylä-Nuortti valley settled at 270 m. As the recession of the ice margin continued, the ice lake expanded to fill the whole valley of Ylä-Nuorttijoki. The subglacial meltwater system of Sokli (A5) terminated in the ice lake. In addition to the esker formed on the bottom of the ice lake, the sand and fine-grained material transported by the meltwaters formed the thickest ice-lake sediments found in the study area. The Sokli Ice Lake is an example of ice-lake type 4 (Johansson 1993). When the ice margin had passed the hill of Pierkulinrovat, the waters of the ice lake started to discharge marginally to the north, first into the canyon of Törmäoja and then, at the final stage, into that of the River Nuortti. The more than 100 m deep canyon of Nuortti had formed in a preglacial fracture zone (Mikkola 1941), and it functioned for a long time as a spillway for the ice lakes in that region. The water drained via Nuortti to the River Tulomajoki and on into the Arctic Ocean.

The history of the Sokli Ice Lake and the stratigraphic till studies in the region give a picture of the deglaciation and glacial action in the area (Fig. 34). At the initial stage of the deglaciation, the ice flow was from the WSW (cf. Ilvonen 1973, Hirvas 1991), depositing the younger till unit. The ice margin was then still outside the study area. At the time when the Sokli esker chain was being formed, the ice flow had already turned towards ESE. At this stage the youngest till unit occurring in the study area was deposited. On the basis of the directions and age relations of the spillways leading to Nuortti, and the till fabric of the youngest till unit, the ice flow direction remained the same until the ice had wasted down. In addition the marginal channels indicate that the ice margin remained coherent and the ice sheet dynamically active to the end.

The Kemihaara and Värriöjoki ice lakes

The most extensive ice lakes in the eastern part of the study area, called the Kemihaara and Värriöjoki ice lakes, were dammed in the valleys of the river Kemijoki and its tributaries Värriöjoki and Siurujoki. The exact size and history of the Kemihaara Ice Lake are unknown, because distinct shore marks are lacking. At the time of the formation of the ice lake the ice margin was divided into two lobes, which is indicated by the directions of the lateral drainage channels in the area. The northern lobe retreated in a NW direction, circling to the north of the Kemihaara fell region, while the southern one retreated in a SW direction, circling the fell region on its south side. If the ice lake was dammed mainly by an ice lobe that had retreated towards NW, the ice lake may have inundated only a narrow

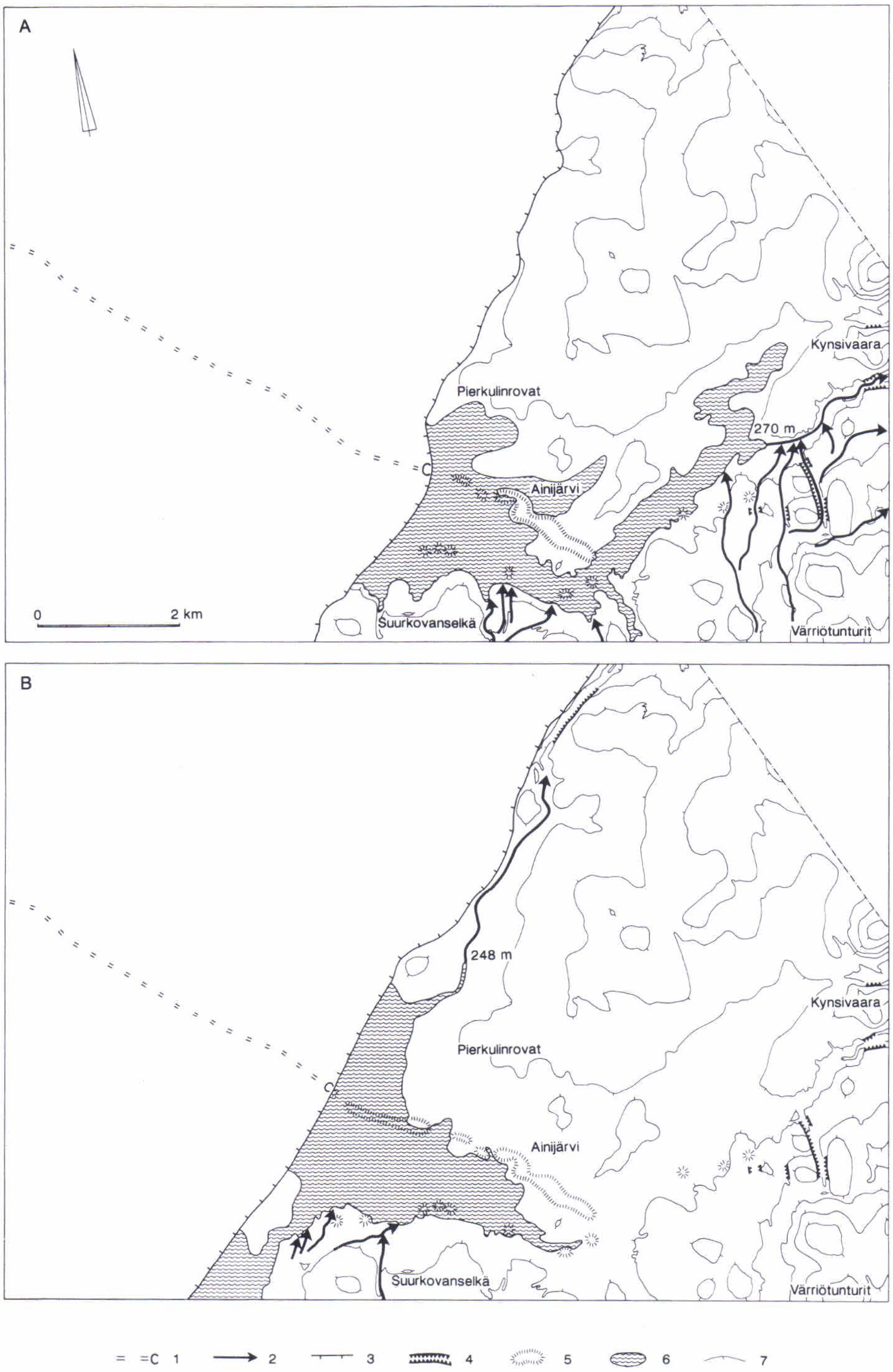

Fig. 34. History of the Sokli Ice Lake. 1 = subglacial meltwater system and its mouth, 2 = functioning proglacial or marginal channel, 3 = ice margin, 4 = gorge, 5 = esker, 6 = ice-dammed lake, 7 = contour line. The figure shows the meltwater channels emptying into the ice lake and terminating at its shore level. The altitude data refer to the threshold that regulated the water level in the ice lake.

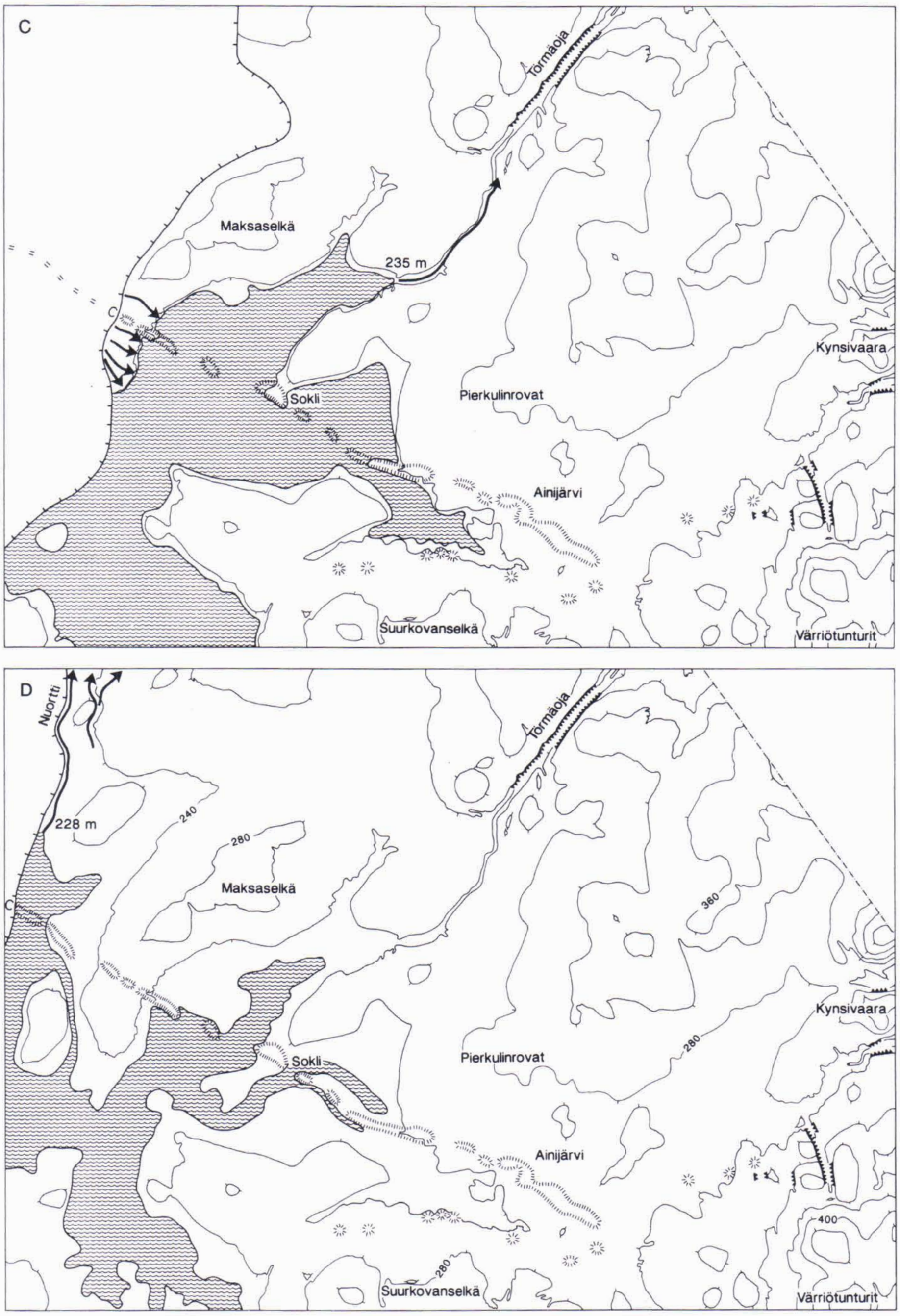
C
Törmäoja
Maksaselkä
235 m
Kynsivaara
Pierkulinrovat
Sokli
Ainijärvi
Suurkovanselkä
Värriötunturit
D
Nuortti
228 m
240
280
Maksaselkä
Törmäoja
360
Kynsivaara
Pierkulinrovat
280
Sokli
Ainijärvi
400
280
Suurkovanselkä
Värriötunturit

Fig. 34

Fig. 35. The littoral boulder belt at 275-278 m a.s.l. on the upper slope of Siuruvaara was formed at the shore level of the Värriöjoki Ice Lake.

strip of the eastern bank of Kemijoki. If the ice lake was mainly dammed by a lobe that had retreated towards SW, the ice lake grew into an extensive but shallow water basin, inundating the valleys of Kemijoki and its uppermost tributaries. The channel leading from north of Kärekelehto to Nuortti served as the first spillway of this ice lake. Its altitude, 248 m, controlled the surface level of the ice lake. Later a new spillway opened on the western slope of Kuttusvaara, causing the surface level to sink to the level of the threshold point at Sotataipale (220 m).

The ice lake dammed in the Värriöjoki valley was larger and it had a longer lifespan than the one in Kemihaara. It left abundant shore marks and spillways, on the basis of which the size of the ice lake and the retreat of the ice margin may be followed. A notable channel begins at 277 m in the valley south of Verkkomaselkä and leads to the river Ylä-Naruskajoki. The erosion was so marked in this area that it could not have been caused exclusively by the meltwater flowing along the margin of the ice sheet. Since no subglacial meltwater erosion occurred in the valley during the latest deglaciation either, the channel must have been formed by the erosional action of waters discharging from the ice lake dammed in the Värriöjoki valley. The spillway at Verkkomaselkä functioned until the following spillway, leading via Hirvikaltionoja to Nuortti, opened up at the 272 m level. Once this had happened, the water broke through the till-covered Hirvikaltio esker (C5) which crossed the gorge. This rapid meltwater discharge spread the gravel and sand from the esker into extramarginal sandur deposits covering the upper part of Tulppiojoki valley (Fig. 29). The Siuruvaara hill rose in the middle of the ice lake in the form of an isolated island, and the ancient shore marks on its slope, at an altitude of 275-278 m, were formed during this stage of the ice lake (Fig. 35). The ice lake covered an area of more than 400 km^2 and the depth of the water was in places more than 50 m. It represented ice-lake type 2. During the following stage the shore level of the ice lake sank to an altitude of 270 m and soon thereafter to 259 m. The waters drained along marginal and extramarginal spillways that had opened in the area between Ruuvaoja and Sotatunturi, to the threshold point at Sotataipale, and continuing to Nuortti.

The final union of the Kemihaara and Värriöjoki ice lakes occurred at the same time as the meltwaters streaming from the ice margin deposited the Ketsepuhnus proglacial delta (see Fig. 13). The margin of the ice sheet followed the line Mutajärvenselkä-Leukkuhamaranvaara-Ruuvaoja. The area inundated by ice lakes was at its most extensive at this stage, reaching as far as the Kemijoki river valley, to Kuttusoja, and in the Värriöjoki river valley as far as east of Siuruvaara (see Appendix). Due to the land uplift the shore levels of this stage have become inclined from SSW to NNE with a gradient of approximately 0.55-0.58 m/km. The shores rise from the 220 m level in the vicinity of the Sotataipale divide to an altitude of 245 m at the boulder belt on the NW slope of Kaltiovaara. After the recession of the ice margin from Kaltiovaara to the west, the waters from the ice lake that had inundated the valleys of Kemijoki and Värriöjoki discharged into the Salla Ice Lake. The water level sank approximately 20 m. The lower boulder belt at 225 m a.s.l. on the NW slope of Kaltiovaara reflects the water level of the Salla Ice Lake.

The Salla Ice Lake

In the past the Salla Ice Lake inundated extensive areas south of the study area, i.e., in Salla, the southern parts of Savukoski and the eastern parts of Kemijärvi (Fig. 36). The Salla Ice Lake penetrated in the form of a narrow bay along the Kemijoki valley north of Ruuvaoja and into the Värriöjoki valley all the way to the foot of Siuruvaara (see Appendix). Tanner (1915) was the first to suggest the former existence in the area of an extensive ice-dammed lake, which he named the Tenniö Ice Lake. The ice lake described by Tanner covered the northern part of the Salla Ice Lake, which is described in this study. Tanner (1915) also located the spillway of the ice lake in the valley southeast of Aapajärvi in Russia. The ice lake was drained from there into the river Kutsa and into the White Sea, the shore of which was then at a level of 160-165 m (Ekman & Iljin 1991). Hyyppä (1936) continued the investigations of the spillway at Aapajärvi. He obtained as its altitude 211 m, although he mistakenly interpreted it as the spillway through which the waters of the Baltic Ice Lake had drained into the White Sea. Hyvärinen (1973) later proved that the deglaciation of northern Finland did not occur until the Preboreal period, when the Baltic Ice Lake stage was already over.

The lowest shore levels of the Salla Ice Lake on the Finnish side of the border are found at an altitude of 230-235 m in the Kelloselkä-Aatsinki area (Fig. 36) (cf. Hyyppä 1936, Kurimo 1979). Due to the isostatic land uplift the shore levels have become inclined from southwest to northeast with a gradient of 0.50-0.55 m/km. In the vicinity of the village of Salla-Lapajärvi-Akanvaara the altitudes of the shore levels are 237-246 m (Figs. 25, 36 and 37). The westernmost shore levels of the Salla Ice Lake were found in Kyrövaara east of Kemijärvi at an altitude of 260 m, and in

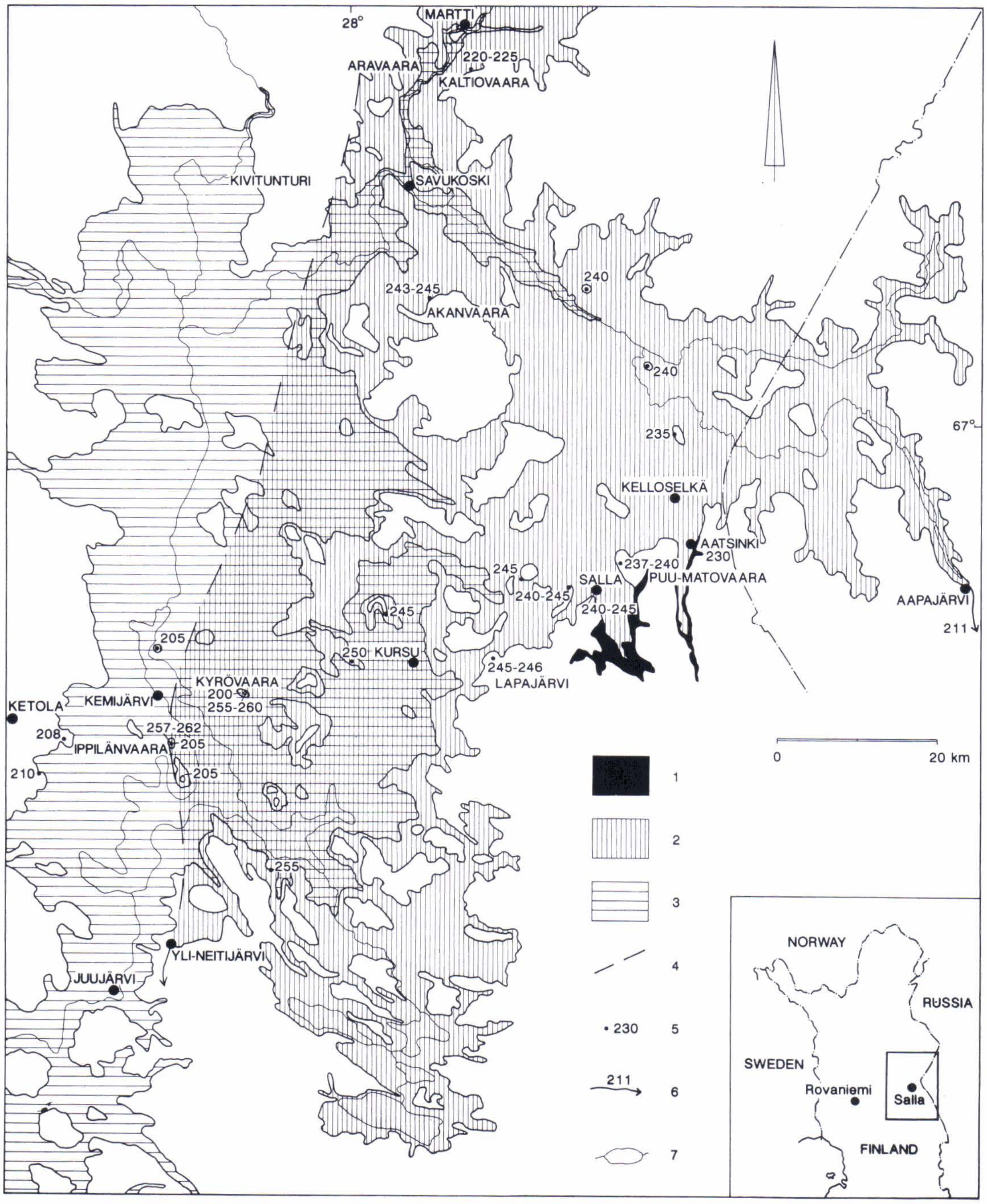

Fig. 36. The Salla Ice Lake. 1 = local ice lakes, 2 = area occupied by the Salla Ice Lake, 3 = area covered by the Ancylus Lake, 4 = assumed position of the ice margin immediately before the rapid lowering of the water level in the Salla Ice Lake, 5 = shore level observation with altitude, 6 = spillway and its height, 7 = present lakes and rivers.

Fig. 37. Boulder shore formed at the surface level of the Salla Ice Lake (244 m a.s.l.) at Tuorelehto, north of Akanvaara.

Ippilänvaara south of Kemijärvi at an altitude of 262 m. They were formed quite close to the ice margin only a short time before the water level of the Salla Ice Lake sank. This happened when a new marginal spillway opened in front of the ice margin at Yli-Neitijärvi, 6 km NE of the village Juujärvi (Figs. 36 and 38). Through it the waters of the Salla Ice Lake drained to the south, to Simojärvi and the Gulf of Bothnia. The waters of the ancient Baltic Sea (during the Ancylus Lake stage) penetrated to the vicinity of Kemijärvi (Fig. 36), where the highest shoreline was formed at an altitude of between 200 and 209 m a.s.l. (Hyyppä 1936, 1966, Kurimo 1977). The Ketola delta west of Kemijärvi is at an altitude of 208 m a.s.l. The Ancylus Lake continued along the Kemijoki river valley, apparently to the vicinity of the village Martti north of Savukoski, at an altitude of approximately 180-185 m. No shore marks were found in the river valley, however.

The youngest till unit in the Martti-Arajärvi area was laid down while the glacier was flowing in a NW-SE direction. At the same time Rogen-type transverse moraines were formed around the lake Arajärvi. The esker chains in this area run approximately in the same direction, although they assume a more NNW-SSE orientation north of the lake. When the surface level of the Salla Ice Lake sank, the ice margin was situated in the area between Kemijärvi and Savukoski in a NNE-SSW direction. At the northern edge of the lake basin the westernmost shore marks of the ice lake are on the slope of Aravaara (cf. Tan-

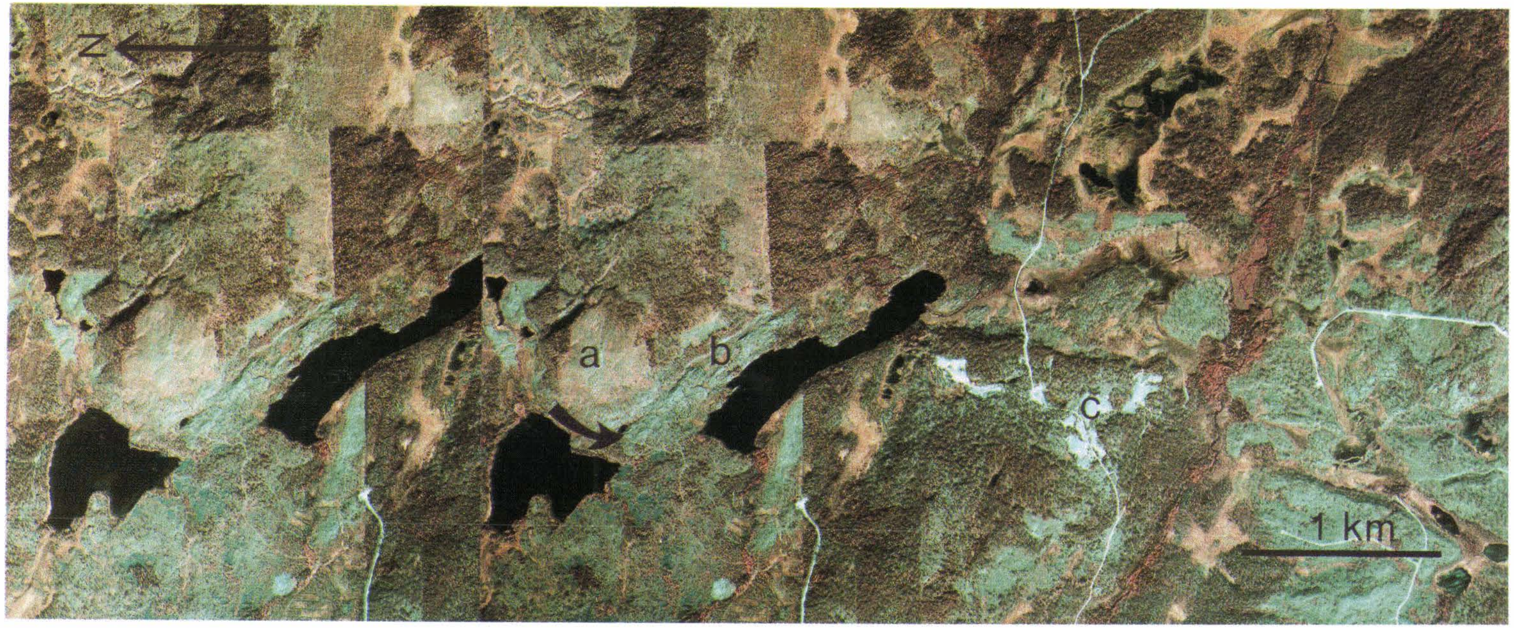

Fig. 38. Colour infrared stereopair showing the spillway of Lake Yli-Neitijärvi, through which the waters of the Salla Ice Lake discharged towards the south, into the Gulf of Bothnia. A spillway opened after the ice margin had withdrawn to the west of the hill (a) shown in the figure. The discharge washed the bedrock (b) bare, seen as pale blue in the figure, and deposited gravel and sand south of the channel (c). Reproduced by courtesy of the Finnish Defence Forces Topographic Service.

ner 1915). West of that, in the vicinity of Kivitunturi, the channels eroded by the marginal streams of the ice sheet continue below the level that corresponds to the surface level of the Salla Ice Lake. This means that the surface level of the ice lake had begun to sink when the ice margin reached Kivitunturi.

Deglaciation of Saariselkä

As the ice sheet grew thinner and its surface sank in the Saariselkä region, the nunataks expanded into vast ice-free fell areas, and the ice flow stagnated. On the distal side of the nunataks, at the ice margin, fractures and crevasses formed (cf. Virkkala 1955), along which the meltwaters penetrated under the ice margin, forming subglacial chutes by erosion or engorged eskers by deposition. In fact the largest number of engorged eskers in Finland are found here, in the Lutto river basin in the northern part of the study area, and at Nangujärvi north of the study area (Johansson 1994). Regarding their morphology and material they have been found to resemble the corresponding depositional landforms described by Mannerfelt (1945). After stagnating the ice sheet apparently became passive and melted down, since no indications have been found of its reactivation and later glacial erosion.

Tanner (1915 and 1936) was the first to suggest that the Arctic Ocean, in the form of a narrow bay, had reached up the valleys of Lutto and Suomujoki all the way to the northern edge of the present study area. Nikonov (1964) mentions finding marine diatoms as high as 120 m a.s.l. in the Lutto river valley in Russia. Considering the influence of the isostatic land uplift on the inclination of the shore levels, the possibility exists that the silt deposits found at a level of 115-125 m by drilling of the banks of Lutto (Johansson 1990) were once deposited in a bay of the Arctic Ocean. Saarnisto (1973) did not find marine diatoms on the Finnish side of the border during his investigations. According to him the valley train in the Lutto river valley is a typical supra-aquatic glaciofluvial formation, which is situated at an altitude of 128-130 m. The marine limit is at a slightly lower level, located on the Russian side of the border. In case a bay of the ocean reached to the Finnish side, it is possible that the meltwater running from the ice sheet stopped the saline water from penetrating upstreams, which would also explain the lack of marine diatoms.

As the retreat of the ice margin continued, the southern edge of the Saariselkä fell region became exposed. The ice was still flowing from SSW to NNE. Its margin was pressing against the fell range, and its flow was led towards NE along the valleys between the felltops. The ice margin became undulated with tens of kilometres long ice lobes penetrating into the valleys of, e.g. Kulasjoki, Suomujoki and Muorravaarakanjoki. On the basis of the lateral drainage channels and the lateral terraces, the edges of the ice lobes were unbroken, although narrow passes had a tendency to obstruct the ice flow. The gradients obtained for the ice lobe surfaces are 3-6 : 100, which is equivalent to the results obtained by Penttilä (1963) and Piirola (1982) from the western parts of Saariselkä. For ice falls formed at the foot of the fell range, the gradient may have been 10-12 : 100 or more. At the terminus of an ice lobe, the ice turned stagnant due to the influence of the underlying topography. The ice lobes probably behaved in the same way as today's valley glaciers (cf. Nye 1952, Østrem et al. 1976 and Sugden & John 1976), although their own accumulation area was replaced by a stream of ice originating in the continuous ice sheet south of Saariselkä. At the end of the ice-lobe stage, stagnant lobes were left on the floors of valleys opening in a northward direction. These lobes became passive and melted down after they lost contact with the continuous ice sheet. The supraglacial material on top of the lobes in the Sarvijoki valley accumulated in crevasses in various directions, and as the ice melted, radial and marginal till and sand ridges were formed on the valley slopes (Figs. 39 and 40). NE of Kiilopää, ringlike or curved hummocky moraines occur. They were apparently formed subglacially as plastic debris was penetrating from underneath into crevasses at the base of the ice. They are similar to the hummocky landforms in Pulju, western Lapland, called Pulju moraines (Kujansuu 1967, Johansson & Nenonen 1991, Aario 1992).

While the margin of the ice sheet was leaning against the southern slope of the Saariselkä fell range, several ice lakes started to form in the depressions between the fells, including the ice lakes of Talkkunapää, Vongoiva, Siuloiva, Hammaskuru, Luirojärvi, Kopsusjärvi, Sompiojärvi, Tankajoki and Kiilopää, in addition to some smaller ice lake basins between them. Their history has been studied by Tanner (1915), Penttilä (1963), Piirola (1982), Johansson (1988, 1990 and 1993) and Kujansuu and Hyyppä (1995). Compared with the ice lakes of Savukoski they were short-lived and small, but since they occupied valleys between fells they became deep, and they contained a considerable volume of water. The first ones were formed as early as when the fell range at the southern edge of Saariselkä was still rising in the form of a row of nunataks in the middle of the ice sheet. They represented ice-lake type 1. The waters dammed at the innermost ends of the valleys between the felltops discharged proglacially across the fell range (Fig. 41) into the Lutto or Anterijoki valley, and finally to the Arctic Ocean. After the ice margin had withdrawn to the southern and southwestern side of the fell range they turned into ice-lake type 2 or 3. At first the Kiilopää Ice Lake (Tanner 1915, Penttilä 1963) discharged across the fell range into the rivers Kulasjoki and Lutto. Later its spillway turned directly into Lutto and later into the Tolosjoki valley. The Tankajoki Ice

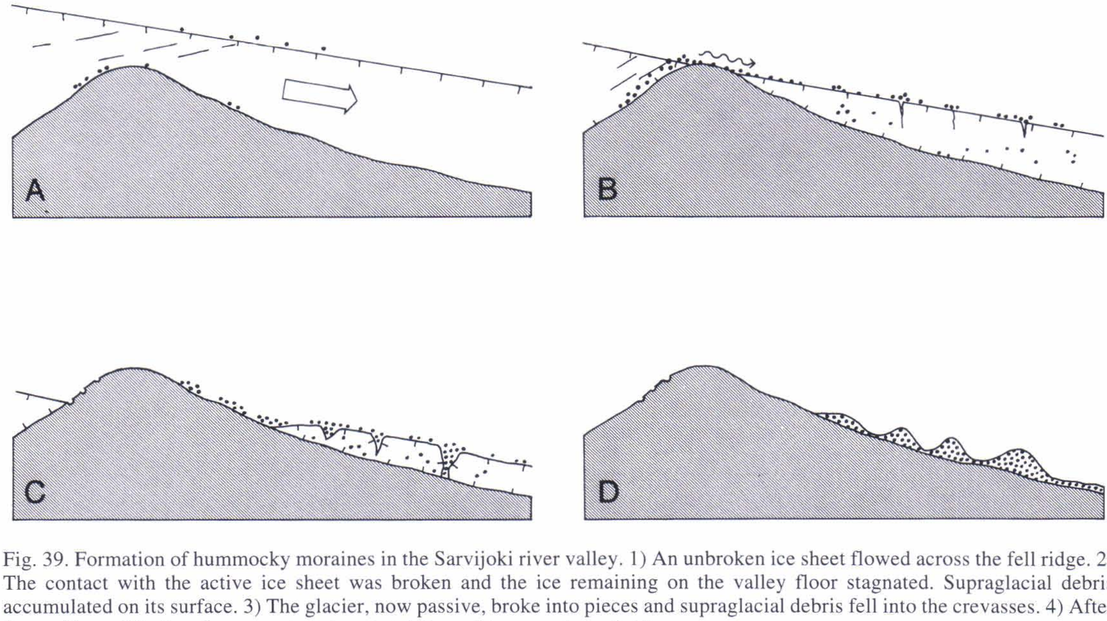

Fig. 39. Formation of hummocky moraines in the Sarvijoki river valley. 1) An unbroken ice sheet flowed across the fell ridge. 2) The contact with the active ice sheet was broken and the ice remaining on the valley floor stagnated. Supraglacial debris accumulated on its surface. 3) The glacier, now passive, broke into pieces and supraglacial debris fell into the crevasses. 4) After the melting of the ice, the supraglacial material formed hummocks and ridges.

Lake discharged along Tolosjoki and later along Sotajoki into the Ivalojoki valley, continuing into the Arctic Ocean (Kujansuu & Hyyppä 1995). For a short time the ice lakes of Luirojärvi and Hammaskuru formed a chain-like basin, from where the waters streamed along the spillway formed by the Paasjoki valley to Lutto (Johansson 1988). The ice lakes of Siuloiva, Vongoiva and Talkkunapäät never united, but the meltwaters were flowing along marginal and extramarginal channels from one ice lake to another and finally into the Jaurujoki valley. Along Jaurujoki the waters continued into the river Tuloma and finally to the Arctic Ocean. The marginal spillways and lateral drainage channels indicate that the ice margin was unbroken. On the basis of the regular set of lateral drainage channels formed on the southern slope of the fell Vuomapää and consisting of more than 40 consecutive channels (Fig. 41), the gradient of the ice sheet was 1.7 : 100, the annual thinning was approximately 2.1 m and the ice margin retreated at a rate of approximately 140 m a year. In the vicinity of Kärpäjärvet and Kaitmitoja SE of Sokosti, the gradient of the ice sheet was 2 : 100, the annual thinning 1.3-1.6 m, and the rate of retreat 130-140 m a year. On the basis of calculations made from various parts of Saariselkä, the retreat of the ice sheet took place on a variable rate of 130-170 m annually.

The surfaces of the ice lakes sank successively and the lakes emptied when the damming ice margin withdrew from the mouth of the valley. The water could also escape through subglacial fractures before the final

Fig. 40. Hummocky moraines in the Sarvijoki river valley. Laterally formed ridges are seen on the slopes and unoriented hummocks on the valley floor.

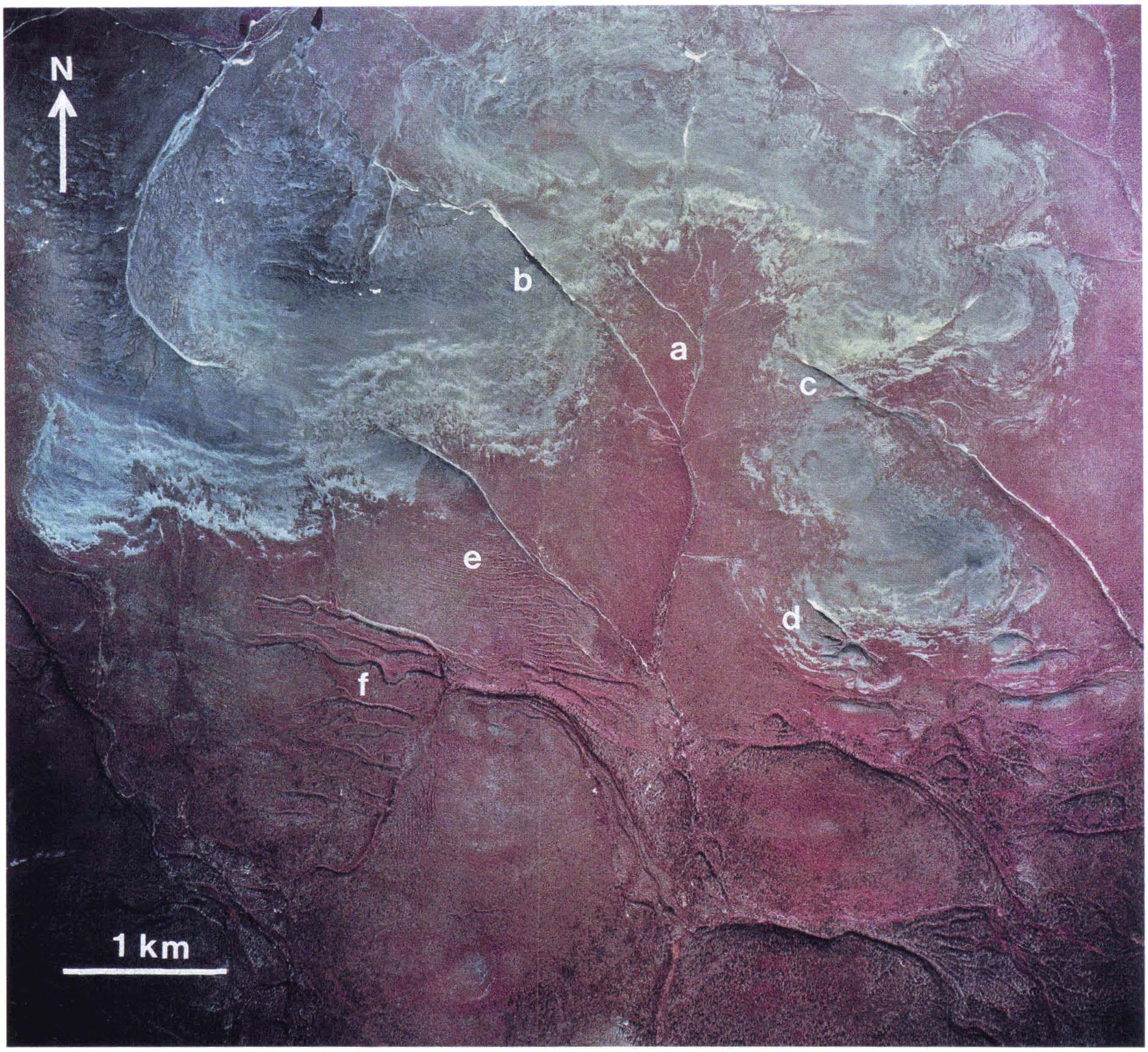

Fig. 41. Colour infrared aerial photo of the southern slope of Vuomapää, Saariselkä. The treeless fell areas are represented in the photo by various shades of blue and the low-lying areas with a forest or shrub vegetation by shades of red. The Siuloiva Ice Lake was dammed up in the closed arcuate valley (a), and the ice margin retreated SSE. The figure shows two proglacial spillways (b and c, in order of age), which led towards the Suomujoki river valley at the initial stages of the ice lake. A series of subsequent marginal spillways (d) can be seen on the southern slope of the fell of Siuloiva, which turned the flow of water from the ice lake into the Jaurujoki river as they formed, causing the ice lake to empty. This left the ice margin resting on the fell slope, and a series of subsequent lateral drainage channels (e) were formed. South of these there are some deeper marginal channels (f) along which the Hammaskuru Ice Lake, located west of the area shown in the photo, discharged towards the Jaurujoki river. Reproduced by courtesy of the Finnish Defence Forces Topographic Service.

wasting down of the ice. This happened especially if the margin of the ice locally became passive, and its damming capacity weakened (cf. Glen 1954). According to the studies made by Liestøl (1956) on valley glaciers, the ice lobe becomes dynamically dead as its thickness decreases to less than 50 m, and its capacity to dam meltwaters disappears. This happened in the ice lobe that dammed the Hammaskuru Ice Lake at its final stage. On the bottom of the ice lake basin there are channels, which did not form until the ice lake had emptied, when the last remaining dead ice melted down. At the final stage the ice lakes of Hammaskuru and Luirojärvi united with the ice lake formed at Repoaapa (Johansson 1988), which is a part of the Posoaapa Ice Lake, formed in the lowlands of Sompio south of Saariselkä (cf. Tanner 1915).

Deglaciation of Vintilänkaira

In the area between Kemijoki and Vintilätunturi the retreat of the ice margin continued westward. Since the ice margin retreated uphill, the meltwaters from it flowed proglacially to the Kemijoki valley. The area was unfavourable for the formation of large ice lakes, with one exception. A short-lived ice lake, which was drained via Sulkarikuru into Kemijoki, was formed in the Suksenaapa area.

The glaciofluvial systems crossing the area, the young ones from WNW, the older ones from NW, are very discontinuous in relation to those in adjacent areas. Especially the old systems are hard to follow. In this area there are only a few minor hillocks of coarse-grained material and a few erosional landforms to be seen in the field. Between them there are long gaps where not a sign of meltwater action has been preserved.

The Vintilänkaira area resembles the ice-divide area in that the subglacially formed meltwater landforms are few. There is one difference, however: In the ice-divide area only the young eskers are discontinuous or locally lacking, while the old till-covered eskers are continuous. In the Vintilänkaira area the esker chains are, regardless of age, discontinuous and hard to follow. Their small number cannot therefore be due to only the stagnation of the ice margin during the latest deglaciation. The reason is probably the erosion caused by an active ice flow. In the Vintilänkaira area as well as in the area stretching NE from there all the way to Kuttusvaarat, it is typical that the surficial till unit is the one deposited by an ice sheet flowing from SW to NE (Fig. 5 D). Its flow direction deviates significantly from those of the esker chains and the youngest till unit. Apparently the active flow of the ice eroded away the earlier formed depositional landforms, at the same time covering the subglacial erosional landform with till. Most of the remaining esker hillocks, such as the Vintilätunturi esker hillocks, consist of very coarse-grained material, and are apparently the core parts remaining from larger esker ridges. They are also located on the NE side of the hills or in NW-SE depressions, where they were best protected from the erosional action of the ice. The surficial till unit, deposited during the flow of the ice sheet, is in this area quite continuous and fairly compact and thick, 0.6-1.5 m, reflecting the intensity of the glacial action.

Except for some proglacial and subglacial gorges, such as the Ettisselkä gorges, the erosional landforms incised by the meltwaters are lateral or marginal. An abundance of well-developed lateral drainage channel systems occur in the vicinity of Vuoltistunturi and Kokkotunturi. On the gentle slope NW of Vuoltistunturi it is possible to distinguish 29 channels, one below the other, running at a distance of about 20-60 m apart. On the basis of the gradient of the channels, the gradient of the ice was approximately 1 - 2 : 100. The ice margin thinned about 2 m annually and retreated about 220 m a year. The lateral drainage channels in the vicinity of Kokkotunturi are situated on steeper slopes. They are at a distance of 10-30 m apart, and on the basis of them the ice margin thinned, depending on the place, 2.1-3.5 m annually and retreated at a rate of 120-190 m a year.

The Kopsusjärvi and Posoaapa ice lakes

The development history of the Kopsusjärvi Ice Lake resembles that of the other ice lakes in the Saariselkä region. At first it discharged its waters proglacially SW of Kopsusselkä into Suomujoki. Its surface level settled at 315 a.s.l., which is reflected by the surface of the Kopsusjärvi delta, a part of the subglacial esker chain of Suomujoki (A 11). As the ice margin had receded to SW of Aitavaara, a new spillway at 310 m opened towards Suomujoki, following the southern slope of Aitavaara. This stage did not last long, however, before the water level sank to 275 m. (Johansson 1990, Kujansuu & Hyyppä 1995). The marginal and lateral channels indicate that the ice margin divided up into two lobes, which circled the Nattaset fells (cf. Kujansuu & Hyyppä 1995). The northern lobe of the ice sheet receded to the valley between Nattaset and Raututunturit. The recession of the southern lobe proceeded towards SW. As the southern lobe withdrew from Tinkiaavankuusikko, the Kopsusjärvi Ice Lake united with the Posoaapa Ice Lake.

The Posoaapa Ice Lake was located in the eastern part of the present Lokka Reservoir, inundating in addition some lowlands in its vicinity (see Appendix). Its surface level was controlled by the Repoaapa spillway, which was situated at 253 m a.s.l. and led to Jaurujoki. As the Kopsusjärvi Ice Lake united with the Posoaapa Ice Lake, its surface level in the Kopsusjoki valley settled at approximately 258 m, which due to the isostatic land uplift corresponds to the altitude of the Repoaapa threshold point. The same ice-lake phase is also represented by the ancient shore lines on the slopes of Vuollosvaara and Silmävaara, at altitudes of 260-264 m a.s.l. (cf. Tanner 1915, Saarinen 1961).

The shore marks in the vicinity of Pihtijoki, at 263-265 m a.s.l., do not fit in with the other shore observations related to the Posoaapa Ice Lake, since they are situated approximately 4 m above the level representing the surface level of this ice lake. Instead, they belong to the Pihtijoki Ice Lake, which occupied the Pihtijoki valley before it united with the Posoaapa Ice Lake. The spillway leading to Kemihaara belonged to the Pihtijoki Ice Lake and not to the Posoaapa Ice Lake as forwarded by Manner and Tervo (1988).

The following spillway of the Posoaapa Ice Lake was not formed until the ice margin had withdrawn from the area between Lokka and Tanhua. Approximately 15 km south of the village of Lokka, on the western slope of Iso Angeevaara, there is a spillway, along which the waters of the ice lake were discharged east of the village of Tanhua into the river Luiro. The threshold point of the spillway is at 254 m a.s.l., and so the surface level of the Posoaapa Ice Lake sank to the 250 m level in the vicinity of Lokka. In the Kopsusjoki valley this corresponds to a level of 238-240 m (today the surface level of the Lokka Reservoir ranges from 240 to 245 m). When the surface of the Posoaapa Ice Lake sank, the ice margin was situated in the northern part of the ice lake in the area between the Silmävaara hill and the Sompionjärvi lake. At Silmävaara the shore marks of the Posoaapa Ice Lake are on a level of 260 m a.s.l., but southeast of Venevaara a channel eroded below this level bears witness to the fact that the water level in the Posoaapa Ice Lake had begun to fall. This channel led from the Sompiojärvi Ice Lake at a level of approximately 256 m a.s.l. into the Posoaapa

Ice Lake. Erosional landforms caused by the discharge of water can be found even below the 250 m level. On the basis of shore marks and the marginal channels between Lokka and Tanhua, the direction of the ice margin was approximately S-N as it ran from Tanhua, west of Lokka to the western side of Silmävaara, where it turned towards NW, to south of Nattaset.

The Posoaapa Ice Lake was of type 5, and the ice bordering onto it was stagnant or passive in places. In depressions, such as Repoaapa and south of Hammaskuru, fields full of ice blocks that had come off the ice sheet were formed, like in extensive areas in central and northern Sweden, according to Lundqvist (1972). Their role was, however, minor. At least the scarp-and-terrace shores of Vuollosvaara and Silmävaara indicate that there was open water in the Posoaapa Ice Lake, and so there was in the area between Lokka and Tanhua, where the ice lake discharged its waters along marginal and extramarginal channels to the south. Here the ice margin was also sufficiently intact to dam a lake.

Deglaciation of the Vuotso-Koitelainen-Keivitsa area

The last area to be exposed from under the ice margin was the Vuotso-Koitelainen-Keivitsa area, which was situated in the western part of the ice divide. Typical of this area are weak erosion and deposition by the ice sheet, the common occurrence of preglacial weathered rock and several till units of different ages, and the occurrence of sorted and organogenic deposits older than the last glaciation (Kujansuu 1972, Mäkinen 1982, Hirvas 1991 and Kujansuu & Eriksson 1995).

Towards the end of the deglaciation there were also considerable variations in the ice flow directions, which is reflected, e.g. by wide boulder fans (Tanner 1915, Salonen 1986). South of Vuotso the ice margin withdrew towards SW and in the Koitelainen - Keivitsa area towards WNW. South of Vuotso in the vicinity of Riestovaara and Sakiaselkä the margin of the receding ice sheet was lobate and continuous. The well-developed system of lateral drainage channels in the valley east of Sakiaselkä reflects clearly how the ice lobe receded along the valley floor towards SSW, whereas in the Koitelainen-Keivitsa area there are only a few channels eroded by meltwater streams, which is partly due to the fact that the ice was dynamically stagnant and its broken margin terminated in the shallow ice lake of Rookkiaapa, which was obviously largely filled with ice blocks. Some of the channels in the ice-divide area may have been created before the last glaciation. The last remnants of the receding ice sheet were probably situated at the western edge of the study area, in the Rookkiaapa-Peurasuvanto area.

The subglacial meltwater action was weak, too. With only one exception there are no subglacial esker chains without a till cover in the western part of the ice-divide area. The exception is the Leukkuhamara esker chain (A 1), which begins west of Maaselkä in a west-eastern direction and is first discontinuous, then turns towards ESE. Till-covered eskers deposited before the last glaciation do, however, occur in the ice-divide area.

The scarcity of eskers on the ice divide is known in Canada, too (Andrews et al. 1985 and Shilts et al. 1987). Several causes have been presented: In the subglacial meltwater systems crossing the area there could be a balance between erosion and deposition, so that the meltwater stream transported all debris forward along the conduit (cf. Brennand 1994). According to Boulton and Hindmarsh (1987) the meltwater could infiltrate into thick deposits and continue its flow there. The latter alternative is hardly possible in the ice-divide area, since the ground underlying a cold-based ice sheet was also frozen to a considerable depth. In this study area the most probable reason for the scarcity of eskers is the dynamic state of the ice sheet. The ice had thinned and over an extensive area it had become stagnant. It was not capable of maintaining extensive subglacial meltwater systems.

Estimation of the time of deglaciation

In the study area, like in most of northern Finland, the deglaciation occurred during the Preboreal time (Hyvärinen 1973). The ice margin probably reached the NE and SE parts of the study area nearly at the same time, approximately 9500 BP, and at that time the oldest ice lakes of the region were also formed (e.g. the Tuntsa Ice Lake) (Fig. 42). The ice margin probably receded to the western part of the study area approximately 9200-9100 BP (Johansson 1988). This is an estimate based on the average rate of recession of the ice sheet as calculated from the lateral drainage channels. A corresponding result was arrived at also by using critically selected radiocarbon ages, by which the recession of the ice margin in Finland has been estimated. According to these, northeastern Finland became ice-free approximately 9100-9500 BP (Ignatius et al. 1980). The exact time for the

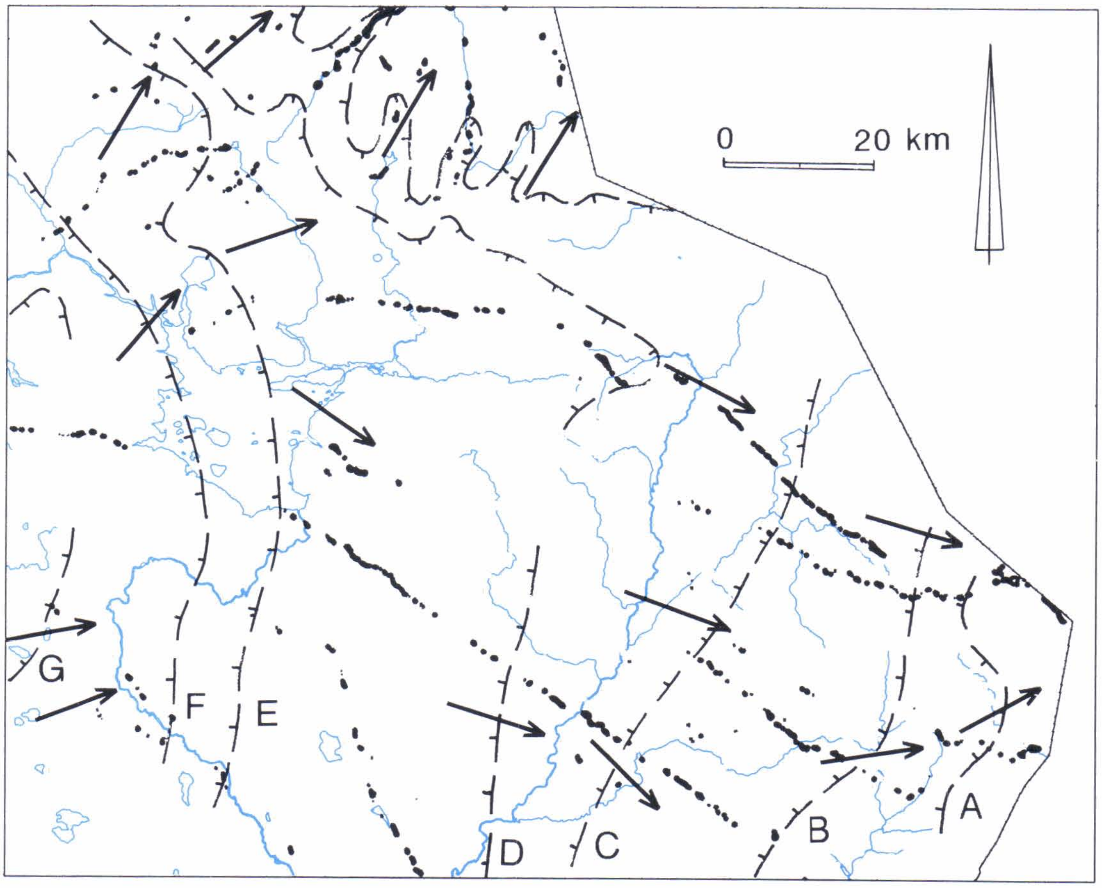

Fig. 42. Map of the retreat of the ice margin (stages A-G) and subglacial esker chains without till cover. The arrows indicate directions of ice flow during deposition of the younger till unit.

disappearance of the ice is impossible to tell. Regarding the pollen studies of the lowermost parts of the postglacial deposits, including their dating, it should be noted that vegetation did not begin to appear until some time after the disappearance of the ice (cf. Sorsa 1965, Saarnisto 1973). On the other hand some so-called over-ages have also been obtained in radiocarbon datings from this area (Vasari 1963, Donner & Jungner 1974).

SUMMARY

In central Finnish Lapland weak glacial erosion and deposition have made possible the preservation of old preglacial weathered rock and till deposits with organogenic intercalations predating the last glaciation. Sizeable till-covered eskers (of C systems), probably of Early Weichselian age, have been found in the area, and the oldest till unit was deposited contemporaneously with these, by ice flowing NW-SE. Some of the older tills and esker chains (D systems and the Pihtijoki ridge) predate these and are apparently of pre-Weichselian age. A new till unit was found in the southern part of the area, deposited by an ice stream running in a N-S direction apparently during the Early or Middle Weichselian. Till-covered esker chains (of B systems) of the same orientation were formed during the deglaciation stage. The morphological features of these eskers are remarkably well preserved, including sharp crests, steep flanks and kettle holes.

At the final stage of the Middle/Late Weichselian glaciation, the icedivide seems to have settled in an east-west direction across Central Lapland. In the ice-divide area proper the basal part of the ice sheet was stagnant, and ice flow, erosion and deposition took place only somewhat further away from the centre of ice flow.

The deglaciation phase and the final disappearance of the Late-Weichselian continental ice sheet were examined by studying the following glacial processes and their resulting landforms: subglacial meltwater action and glaciofluvial hydrography, till stratigraphy and ice flow directions, proglacial, marginal and lateral meltwater action, and the development and typology of ice lakes.

A synthesis of the results was constructed to form a picture of the ice movements, the behaviour of the ice sheet and the retreat and melting of its margin in various parts of the area. The deglaciation was time-transgressive and proceeded in four phases, affecting each of the subareas in turn. The phases were characterized by certain glaciological and geomorphological processes, which resulted in a variety of landforms and deposits. The phase prevailing in a subarea and its duration depended on the location of that area in relation to the ice divide and to the retreating ice margin.

During the first phase the ice sheet covering the area altered gradually from cold-based to warm-based, whereupon the basal parts of the ice sheet in the corresponding zone situated farthest from the ice margin and closest to the ice divide became dynamically active and a movement towards the margins began at the base of the glacier. The ice sheet started to erode its bed and till accumulation began. It was during this phase that the younger till unit, which is widespread in the area, was deposited.

During the second phase, closer to the margin of the ice sheet, meltwater started to collect at the base of the ice sheet, forming a network of tunnels and conduits. Since the hydrostatic pressure in the conduits was high, it was possible for the meltwater to flow uphill and across divides. The subglacial meltwater action was mainly erosional at first, forming depressions, channels and gorges along the path of the conduit. Later, deposition prevailed closer to the ice margin, and it was then that the youngest eskers in the area

were formed. These eskers belonging to A systems differ from the ones deposited earlier in their orientation, morphology and lack of till cover, for example. The orientation of these subglacial esker chains is the same as that of the youngest ice flow.

During the third phase the thinning of the ice sheet continued. The highest fell tops were the first to appear from under the ice to form nunataks, and col channels were formed in the depressions between them as a result of meltwater erosion. The ice flow stagnated on account of the nunataks, and fractures and crevasses were consequently formed at the margin of the ice. The subglacial meltwater streams eroded subglacial chutes and deposited engorged eskers. In areas of high relief such as the Saariselkä region the ice margin became lobate. The movements of the basal parts of the ice sheet were controlled mainly by the topography, and it was at this stage that the surficial till unit was deposited. The direction of the subglacial meltwater systems was no longer influenced by local ice movements.

During the fourth phase the melting margin of the ice sheet reached this area, and the meltwater flowing along the margin gave rise to erosional and depositional landforms. By studying these, information was obtained on the recession of the ice margin. The subglacial meltwater action became proglacial at the mouth of the conduit and diminished significantly in both erosional and depositional power. The landforms produced by marginal and lateral meltwater action, mainly channels, reflect the gradient of the ice sheet and the thinning of its margin. The formation of extensive channel systems also required a continuous ice margin, which again indicates that the ice sheet remained dynamically active until it wasted away. A lack of marginal and lateral channels may indicate that the ice sheet was stagnant or passive, with a discontinuous margin, or one that terminated in an ice lake. The area was indeed favourable for the formation of ice lakes, since the variations in altitude are considerable, the area is crossed by the main watershed, and the ground surface was inclined towards the ice margin that dammed these lakes. The ice lakes may be classified into five types on the basis of their location, size, frequency of shore markers and occurrence of bottom sediments. They also reflect changes in the dynamics of the ice and in the melting of the ice margin. Working from the history of the ice lakes, the variations in their water levels and the changes in their spillways, it is possible to create a picture of the position of the ice margin over extensive areas.

The deglaciation of the area considered here took place around 9 500 - 9 100 BP. The retreat of the ice margin from the position that it occupied during the Younger Dryas stadial started contemporaneously in both the NE and SE. In the northern part of the area the ice sheet receded towards the SSW, and calculations based on lateral drainage channels show that the rate of recession was approximately 130-170 m per year. In the S and SE part the ice margin receded mainly towards the WNW, and the more continental climate meant that the rate of retreat was only approximately 70-80 m per year at first, although it increased to 120-220 m closer to the ice divide. The ice flow seems to have been active almost throughout the deglaciation, and no extensive stagnation or fracturing of the margin took place until it had receded into the ice-divide area.

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