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Pleistocene stratigraphy of Finnish Lapland

by Heikki Hirvas

Geologian tutkimuskeskus
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PLEISTOCENE STRATIGRAPHY OF FINNISH LAPLAND

by

HEIKKI HIRVAS

with 75 figures, 9 tables in the text and 2 appendices

ACADEMIC DISSERTATION

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In the course of the research project on the glacial stratigraphy of Finnish Lapland in 1972—1977 some 1 400 test pits were dug with a tractor excavator; about 400 of them intersected the entire Quaternary cover and 114 ended in weathered bedrock. The average depth of the study pits was 3.8 m, the deepest ones reaching 8—11 m. Some 2 200 fabric analyses and 1 360 stone counts were made from the pits, and 11 500 stratigraphically controlled samples were taken for laboratory tests.

Six stages of ice flow, or glaciation, differing in direction and corresponding from youngest to oldest till beds I to VI, have been established in Finnish Lapland. The three youngest till beds are interpreted as having deposited during the Weichselian glaciation; the others earlier.

Since 1973, more than a hundred new observations of subtill organic deposits have been made in Lapland, most of them in the course of systematic drilling by the Geochemistry Department of the Geological Survey of Finland. Forty-nine deposits have been studied so far. On the basis of their pollen spectra, 39 findings are interpreted as interglacial and 10 as interstadial. Twenty-four deposits are gyttja, 20 peat and five diatomite or diatom gyttja. The thickness of the deposits ranges from a few centimetres to 2.5 m. All except one of the findings studied are in central Lapland, where preglacial weathered bedrock is most common. The weathering is dated back to the Tertiary.

Till bed I was deposited during deglaciation. The Peräpohjola interstadial deposits underlying till bed II represent the Maaselkä interstadial and are correlated with the early Weichselian interstadial deposits in Jämtland, Sweden, and in Brørup, Denmark. Organic deposits indisputably younger than the Peräpohjola interstadial have not been encountered in northern Finland. The interglacial deposits underlying till bed III form the Tepsankumpu interglacial and are correlated with the interglacial deposit at Leveäniemi, northern Sweden, and further with Eemian and Mikulino deposits. Bed IV, which is overlain by till bed III and/or interglacial deposits, is interpreted as having deposited during the Saale glaciation.

The peat deposits overlain by till bed IV at Naakenavaara, Kittilä, are attributed to the Naakenavaara interglacial and are tentatively correlated with the Holstein-Likhvin interglacial. Thus far, it has not been possible to date the older till beds, V and VI. At Rautuvaara the tills are separated by sorted waterlain sediments.

Key words: glacial geology, stratigraphy, till, pit sections, borehole sections, glaciation, interglacial environment, Quaternary, Pleistocene, Eemian, Weichselian, Saalian, Holsteinian, Lapland, Finland

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INTRODUCTION

The study area (Fig. 1) of northern Finland, or Finnish Lapland as it is often called, lies at the northern margin of the Fennoscandian glaciation area, east and south of the Scandinavian mountain range. As the study area covers all of northernmost Finland, with the southern boundary at latitude 66° 20', it is largely located north of the Arctic Circle (cf. Fig. 5). The area is about 78 000 km² in size,

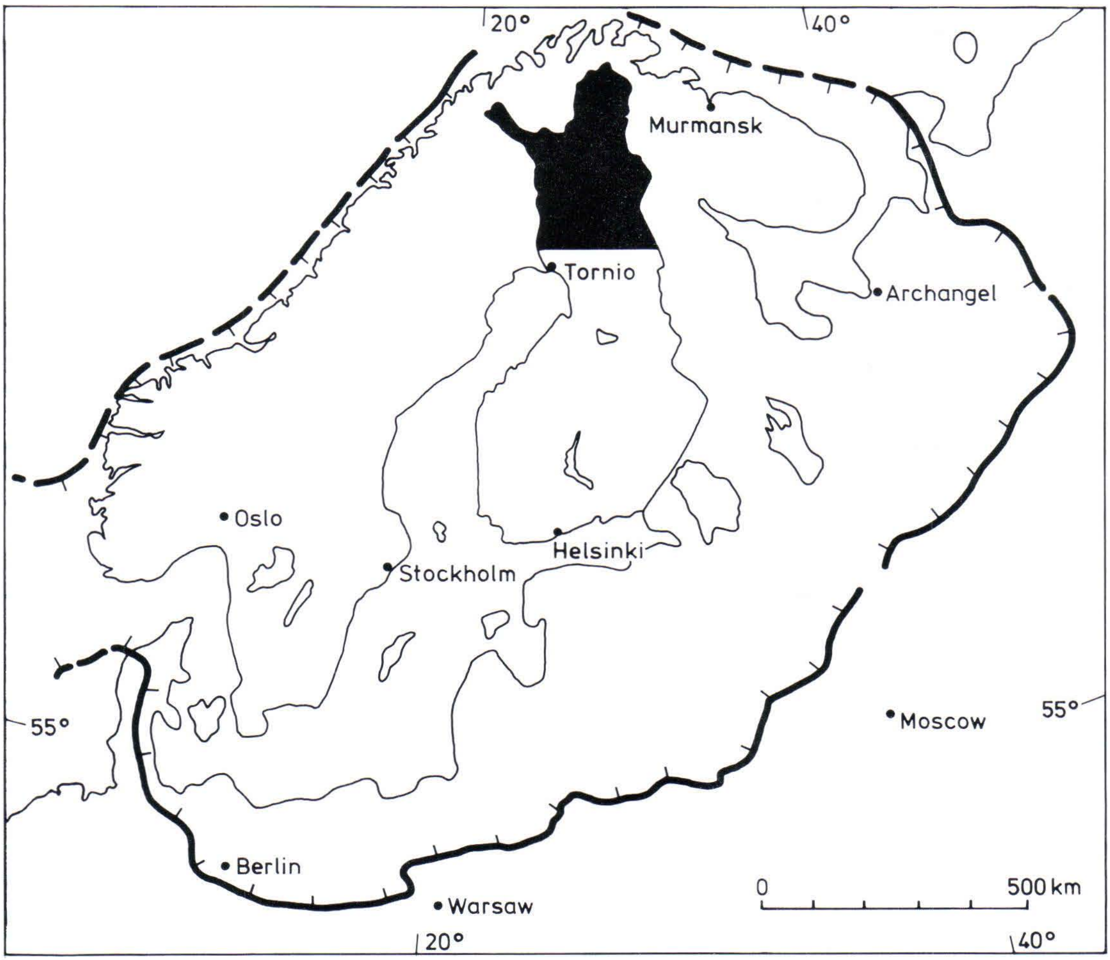

Fig. 1. The study area (black) within the region covered by the Scandinavian ice sheet and the maximum extent of Weichselian glaciation.

which is about a quarter of that of the whole of Finland. Being part of the central area of glaciations, or ice divide zone, the area has repeatedly been affected by very weak glacial erosion (Penttilä 1963, Kujansuu 1967), as attested by the widespread occurrences of preglacial weathered bedrock and the thinness of the Quaternary deposits. The mean thickness of the overburden in northern Finland is only 5.9 m (Mäkinen 1975).

Glacial stratigraphical studies have a long tradition in Finland. The earliest observations of superimposed till beds and deposits of sorted sediments overlain by till were made in southern and central Finland back in the late 1800s (Korpela 1969 and the references). Soon after, observations were made in northern Finland, too. In the early 1900s Rosberg described a sequence from the valley of the River Lutto, where the weathered bedrock was overlain by two till beds with glaciofluvial sand between them (Rosberg 1908). The superimposed till beds were attributed either to deposition during metachronous glaciation stages or to oscillation of the front of the continental ice sheet.

The sediments overlain by till were interpreted variously as interglacial or interstadial, as having been covered with till deposited by the oscillating ice front or as subglacial accumulations. By 1949 only four such cases had been recorded from the present study area (Aurola 1949).

From observations made earlier in Sweden (Högbom 1893, 1913, Munthe 1904, Erikson 1912), Tanner came to the conclusion that the whole of Fennoscandia, Finnish Lapland included, had experienced an ice-free stage in the course of the last glaciation (Tanner 1930).

The vigorous building activity that followed the Second World War, above all the construction of hydroelectric power plants, resulted in the excavation of deep earth cuttings, some of which exposed intriguing new features of Quaternary stratigraphy. The general mapping of Quaternary deposits in northern Finland that got under way in 1960 also produced much new data on stratigraphy. Some of the most interesting features were the till-covered eskers and other glaciofluvial deposits that are so common in central and western Lapland (Kujansuu 1967).

Having found organic deposits below till, Korpela (preliminary report 1962) was able to demonstrate that some of the subtill deposits of sorted sediments in Peräpohjola were interstadial (Korpela 1969). The pollen assemblages of the deposits are dominated by birch. According to Korpela (1969), about 45 000 years ago, during the last glaciation, Peräpohjola experienced an ice-free stage when the climate was subarctic and thus somewhat colder than it is at present. He named this substage the Peräpohjola interstadial.

Intensified geological mapping and research brought more interstadial deposits with organic matter to light in the early 1970s. Tree and coal fragments in a soil profile from Vuotso, central Lapland, were dated to 42 000 ± 2 000 yr BP (Su-153) (Kujansuu 1972a). At Marrasjärvi, western Lapland, a till-covered esker was studied where the interstadial organic matter intermixed with the basal till layer was dated to over 55 000 yr BP (Su-236—237 and 263—266) (Kujansuu 1975).

Finds of subtill organic deposits with micro-fossils also provided evidence of a climate warmer than the present one. Ilvonen (1973) reported an extensive diatomite, diatom gyttja and peat deposit in Sokli, eastern Lapland, where the microfossils were totally different from those of interstadial flora. The deposit is characterized by pine-dominated pollen assemblages that also contains pollen of thermophilous plants (*Corylus, Carpinus* etc.). The diatom gyttja was dated to over 39 400 yr BP (Birm. 278) and to 32 830 $^{+1\,460}_{-1\,240}$ yr BP (Birm. 279). The peat was dated three times to 46 000 $^{+9\,000}_{-4\,000}$ yr BP (Hel-348) and twice to over 45 000 yr BP (Hel-147 and Hel-349). As the pollen assemblages differed from those of the Peräpohjola deposits, but resembled those of the Eemian deposits, the deposits were interpreted as interglacial (Ilvonen 1973).

Tanskanen (1975) described a subtill peat deposit from Pyssyselkä, central Lapland, which also differs from the Peräpohjola interstadial in pollen composition. In the upper part *Pinus* is dominant (65 %) and in the lower part *Betula* (66 %), both layers being over 55 000 yr BP in age (Su-311 and Su-312).

The intensified exploration of the 1970s and systematic geological mapping and research called for more detailed information about Quaternary deposits in Lapland. This was needed primarily to boost the search for ore floats but also to aid the planning of geochemical till sampling, when it could be used to help determine the direction of sampling lines and the depth of sampling. Commissioned and financed by the North Finland Ore Geological Committee of the Ministry of Trade and Industry, a five-year till study was undertaken in northern Finland in 1972—76 with the main objective of establishing the Quaternary stratigraphy, the flow directions of the continental ice sheet and the transport distance of till.

The study was continued in 1977 by the Geological Survey of Finland, and the most troublesome and complex areas, most of them in the extensive ice divide area of central Lapland, were revised. Since then, checking and supplementary sampling have been carried out every year, chiefly at the sites of subtill deposits and extensive excavations.

The basic material for the present study was collected during 1972—1977 but the task of supplementing it went on until the summer of 1989. The findings have been published in a number of reports and papers (e.g. Kujansuu 1976, Hirvas & Tynni 1976, Hirvas et al. 1976, Hirvas 1977, Hirvas et al. 1977, Hirvas & Kujansuu 1979, Hirvas & Kujansuu 1981, Hirvas et al. 1981, Hirvas 1981, Hirvas 1983, Hirvas & Nenonen 1987). The present monograph gives a detailed description of the data together with an interpretation of the Pleistocene history of Finnish Lapland.

Only a few new subtill organic occurrences have been discovered in Lapland since the most active period of field work of the project and geochemical sampling of the Geochemistry Department. These include the Kauvonkangas interstadial peat deposit at Tervola, southwestern Lapland (Mäkinen 1979), a large *Larix* trunk in a till covered valley train deposit at Vuotso, central Lapland (Mäkinen 1982), and fossil ice wedges with some organic material in a till-covered glaciofluvial delta at Orajärvi, Pello, western Lapland (Mäkinen 1985). These occurrences are dealt with in the chapter Correlation and dating of the Pleistocene stratigraphy in Finnish Lapland.

DESCRIPTION OF THE STUDY AREA

Relief

Except for the far northwest, northern Finland is a rather flat and gently undulating peneplain, dissected by river valleys. Only a few chains of higher fells, solitary erosion remnants and horst-like hills rise above the general level (Tanner 1938). Fracture lines, often tens of kilometres long, divide the bedrock into blocks.

The elevation of the peneplain in the northeast and southwest of the area is 100—200 m a.s.l. Only in river valleys, e.g. of the Tenojoki, Pulmankijoki, Näätämöjoki, Kemijoki, Ounasjoki and Tornionjoki, are there places where the elevation is under 100 m a.s.l.. With the exception of the fells, which regularly attain heights of over 400 m a.s.l., the elevation throughout most of the area is within the range 200—400 m a.s.l. (Fig. 2).

The Saariselkä-Marasto fell area, the Enontekiö mountain area and the Enontekiö uplands (Granö 1952), where the highest peaks rise up to 500—700 m, extend as an almost unbroken fell region from northern Sodankylä on Finland's eastern border to northern Enontekiö in the west. In the northwesternmost part of the fell region, where the fringes of the Scandinavian mountain range extend into Finland, the highest summits reach elevations exceeding 1 000 m. Finland's highest point, Halti,

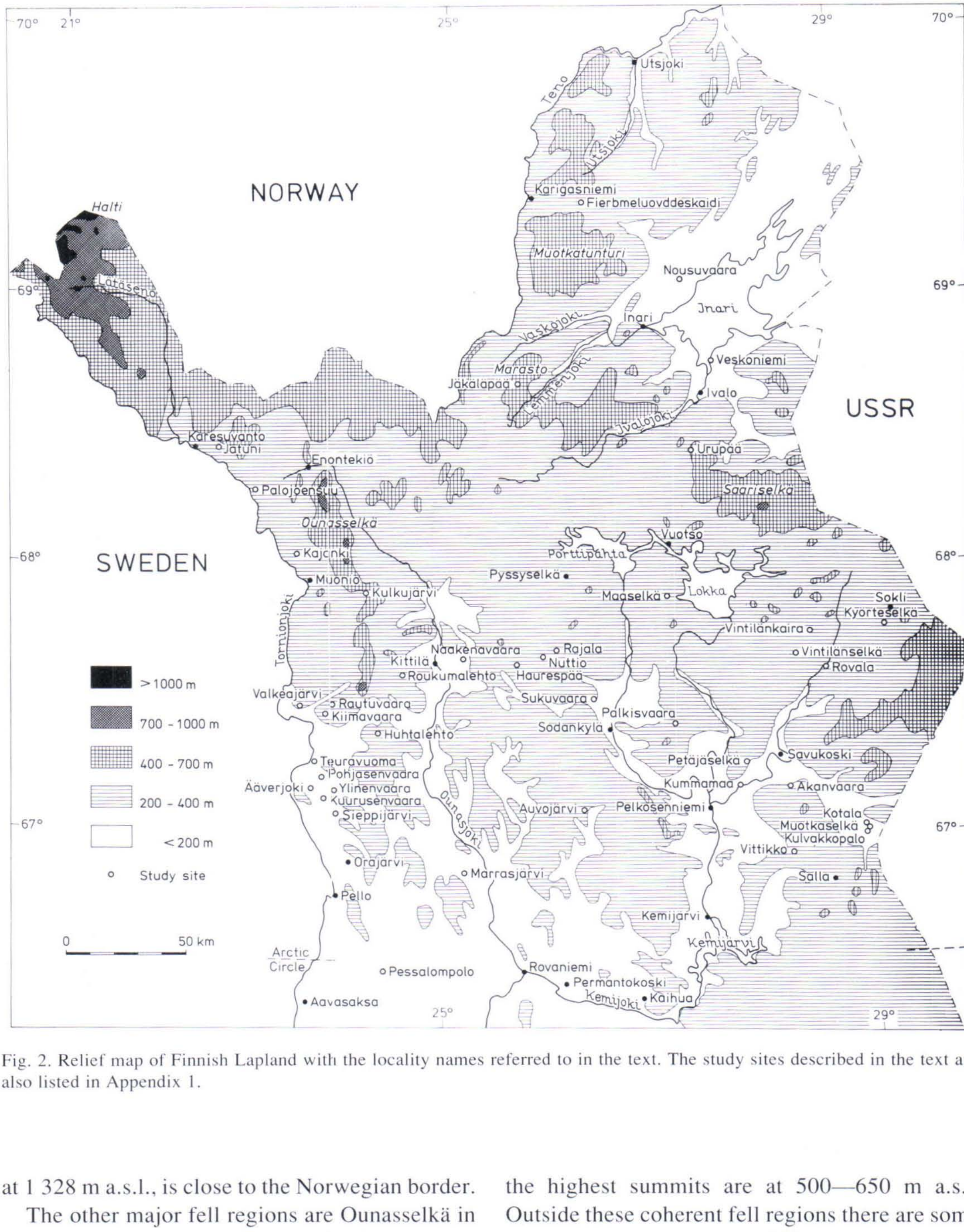

Fig. 2. Relief map of Finnish Lapland with the locality names referred to in the text. The study sites described in the text are also listed in Appendix 1.

at 1 328 m a.s.l., is close to the Norwegian border.

The other major fell regions are Ounasselkä in western Lapland, where the summits rise to 700—800 m, the Muotkatunturi-Teno district in northern Lapland and the eastern Lapland fell area, where the highest summits are at 500—650 m a.s.l. Outside these coherent fell regions there are some solitary erosion remnant fells at elevations of 400—580 m a.s.l. rising 160—370 m above their surroundings.

From the main water divide at Maanselkä the peneplain slopes gently southwards. According to Kujansuu (1967), the gradient is 1.3 m/km in western Lapland and, according to Mikkola (1932), about 1 m/km in the drainage area of the River Kemijoki in central Lapland. To the north of the water divide the gradient is markedly steeper. For example, from Saariselkä to the basin of Lake Inarinjärvi the elevation drops from about 450 m to 120 m over a distance of some 30—40 km, i.e. 10 m/km.

Excluding the fell regions, which are mostly high mountainous country with elevations varying within a range of over 200 m (Granö 1952), the variation in relative height is rather small. The variation is at its greatest in the northwesternmost part of Enontekiö, in the area of the nappe of the Scandinavian mountain range, where it may be up to 300—600 m, and in the Ounasselkä fell region, where the fells rise 400—500 m above their surroundings. The bulk of central Lapland is hillock or hill country, the variation in elevation being 10—20 m and 20—50 m, respectively.

The erosion remnant fells and horst-like hills rising above the peneplain are usually quartzite, which effectively resists chemical and mechanical weathering; less often they are granites or amphibolites (Tanner 1938). Quartzite and amphibolite fells such as Ounasselkä are good examples of the difference in erosion resistance between rock types. The flattest, deeply eroded areas are composed of schists, mica schist, phyllite and greenstone.

Bedrock

Excluding the northwesternmost corner, where a Palaeozoic Caledonian nappe is thrust for 10—20 km over Cambrian sediments (Tanner 1938, Hausen 1942), the bedrock in the study area is Precambrian. Its general features are shown on the map in Figure 3. The bedrock, which is composed of granitoids, volcanics and schists, is often broken into rubble owing to intense mechanical weathering, with the result that boulder deposits predominate over fresh and unfractured bedrock. Talus formations abound in northwesternmost Lapland, particularly on the lower slopes of the Caledonian nappe.

Quaternary sediments cover most of northern Finland, and bedrock crops out mainly in the areas of high relief or when exposed by glaciofluvial or fluvial erosion. The bedrock controls the relief to such an extent that all the major morphological features can be attributed to it. The relief of the bedrock is due to differences in erosion resistivity between the rock types and/or tectonic factors (Mikkola 1932, Tanner 1938, Niini 1964, 1967).

In many places the bedrock is composed of clearly defined units. Use can be made of this in studying the provenance and transport distance of glacial sediments, till in particular. The studies undertaken by the author and his coworkers in different parts of Lapland have been reported elsewhere (Hirvas et al. 1977 and Hirvas 1977) and will be referred to in so far as they contribute to the determination of glacial transport directions.

Preglacial weathered bedrock

In situ occurrences of weathered bedrock are distinctive features of Lapland's bedrock. They vary greatly in appearance and degree of weathering, in places resembling aggregate, shingle or sand and in places silt or clay. The appearance of the weathered bedrock probably

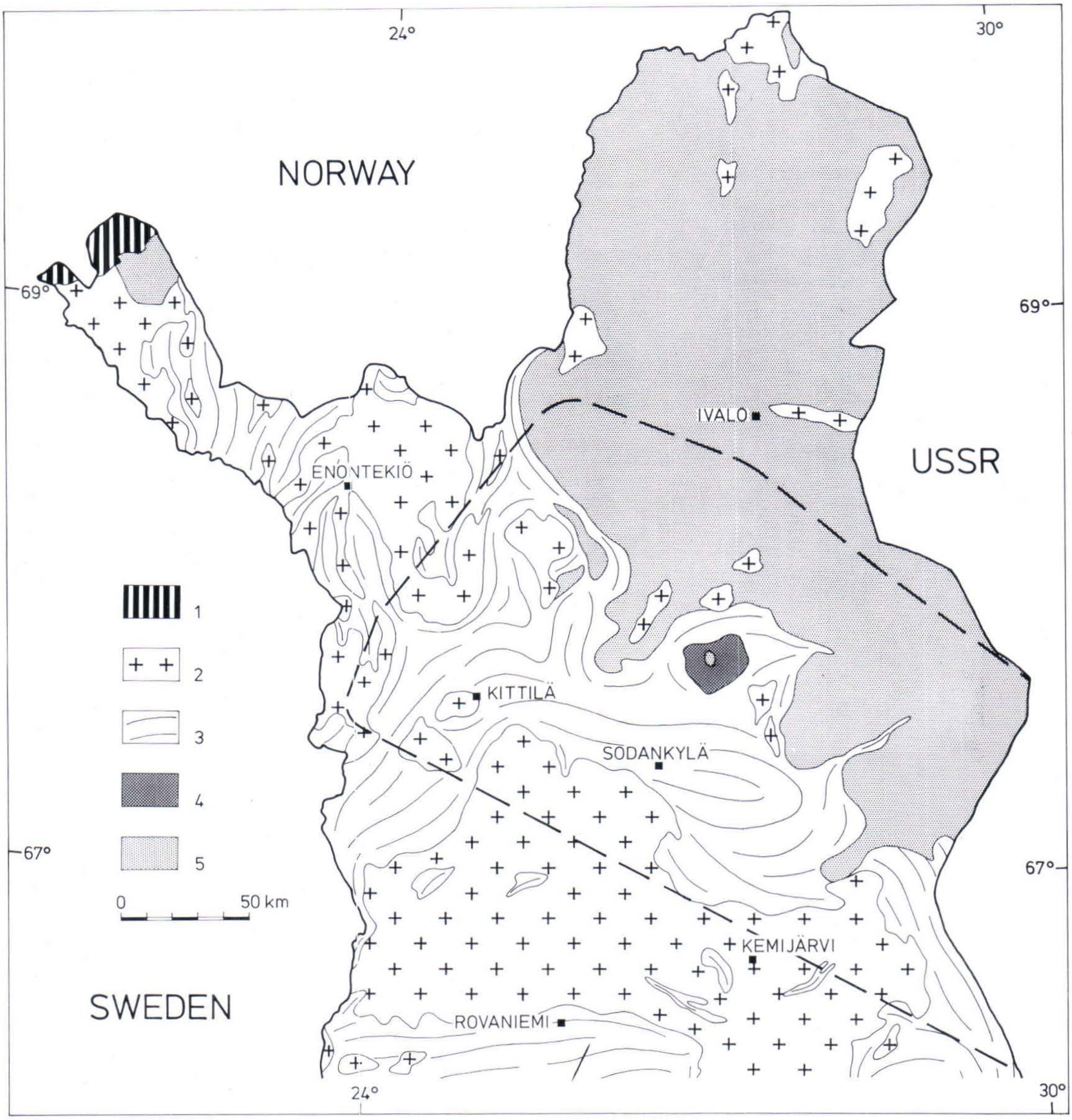

Fig. 3. Distribution of preglacial weathered bedrock in Finnish Lapland after Hirvas (1983). The occurrences of weathered bedrock are common in the area outlined with a dashed line. Pre-Quaternary rocks after Simonen (1980): 1, Caledonidic rocks; 2, Svecokarelidic plutonic rocks; 3, Svecokarelidic schists; 4, Presvecokarelian layered mafic intrusion; 5, Presvecokarelidic basement (schists, basement gneisses and granulites).

depends on the grain size of the parent rock and the degree of weathering (Fig. 4). The material is often quite loose and much easier to dig and drill than the overlying till.

The weathering products are mixed with till to a varying degree, thus demonstrating that weathering took place before the glaciations. The high abundance of clay minerals in the weathering products indicates that they formed when the climate was warmer than it is at present. The

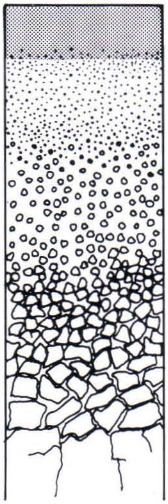

Fig. 4. A schematic section of weathered bedrock in Lapland.

minerals in the cavities of some placer gold nuggets found in northern Lapland resemble products of lateritic weathering (Saarnisto & Tamminen 1987).

Weathered bedrock is also common in eastern Lapland, where the presence of marine diatoms in a secondary position suggests that this part of the country was covered by the sea in early Tertiary times (Hirvas & Tynni 1976 and Tynni 1982). Thus, the weathering of the bedrock can be dated to the late Tertiary.

There is a visible difference in the nature of the weathered bedrock underlying glacial sediments in different parts of the study area. The grain size composition of the weathered bedrock very often resembles that of till (Fig. 18). In western Lapland it is coarse-grained and fragmented, but in eastern Lapland it also contains fine, even clayey, material. This is probably due to the fact that in the west glacial erosion has exposed somewhat deeper levels than elsewhere.

The chemical composition of the gravelly weathered bedrock, 'grus', differs little from that of the fresh bedrock (e.g. Lestinen 1980, Saarnisto & Tamminen 1987), although the former has lost its consistency altogether. In places the weathered bedrock occurrences have undergone intense chemical weathering and contain kaolinite and other clay minerals (Tanner 1938 and J. Hyyppä 1977).

The thickness of the weathered bedrock varies substantially, being only a few metres in most places but tens of metres in others (cf. Sederholm 1913). At their thickest, the occurrences may measure over 50 m (Sederholm 1913) or even 100 m (Virkkala 1955).

Weathered bedrock was reached in 114 study pits excavated in a 150 km wide zone trending northwest-southeast over a distance of 220—300 km in Finland (cf. Kujansuu 1972b). In this zone weathered bedrock occurs fairly commonly, and was observed in over half of the study pits that reached bedrock. In this zone the weathered bedrock does not occur merely in depressions protected from glacial erosion but also at different elevations, even on fell summits. For example at Urupää and Jäkäläpää in the Saariselkä-Marasto fell area, loose grus-weathered granulite is overlain by a 1.5—2 m thick till layer at elevations of 363 m and 470 m, respectively.

The occurrences of weathered bedrock are not related to rock type (Fig. 3), and have been met in almost all the major lithologies in northern Finland, from the most readily eroding black schist and granite to the most resistant quartzites and amphibolites.

Outside the coherent zone, only random occurrences of weathered bedrock were encountered. These are located mainly in depressions and fracture zones protected from glacial erosion. The weathered bedrock does not form a continuous crust, and almost fresh, hard rock is sometimes found in the immediate vicinity of thick weatherings. The abundance of weathered bedrock shows that glacial erosion was rather weak and that the macrolandforms have retained their preglacial aspect.

The weathered bedrock has a definite preference for the ice divide of central Lapland. In contrast then to claims made in other glaciation models (e.g. Flint 1971, Sugden & John 1976 and Hughes 1981), glacial erosion was exceptionally weak in the central area of the continental ice sheet.

Quaternary deposits

The bulk of the study area is supra-aquatic, the highest shore line being at elevations in the range 170—220 m a.s.l. (E. Hyyppä 1966). Basal till is the predominant type of Quaternary deposit (e.g. Kujansuu & Niemelä 1984), covering the bedrock as a veneer that is at its thinnest (0—2 m) on the summits of fells and hills, and thickest (2—>7 m) in river valleys and other low-lying places (cf. Kujansuu 1967). However, the thickness varies greatly, even in adjacent areas. For example, over large areas in the ice divide zone the till blanket is only about one metre thick, whereas in protected depressions in the same areas it may be as much as 20 m.

The thickest till cover (over 22 metres) recorded from the pits was encountered in a drumlin. The mean thickness of the Quaternary deposits in Finnish Lapland is 5.9 metres (Mäkinen 1975). This figure is based on a large volume of drill data.

Stream-lined landforms oriented by the continental ice sheet (drumlins and fluted moraine surfaces) are most abundant in the north and south of the study area. Drumlin fields proper are encountered in only two areas: around Inari-Utsjoki in northernmost Lapland and southeast of Kemijärvi. However, smaller fluted moraine surfaces abound, particularly at Enontekiö in northwesternmost Lapland, and in southern and western Lapland. These forms are almost completely unknown in central Lapland and the fell region of eastern Lapland or then they occur only here and there and are very poorly developed.

Extensive fields of hummocky moraine deposited during deglaciation occur mainly in the north and south of the study area; central Lapland is almost devoid of such deposits.

The till cover tends to be markedly thicker in hummocky moraines, drumlins and fluting ridges than in flat basal till areas, and only seldom could the till be penetrated with pits.

Sorted sediments, which are largely of glaciofluvial origin, occur as eskers, deltas, sandurs and ice marginal formations. The glaciofluvial sediments are fairly evenly distributed throughout the study area, although the most extensive esker chains are located at Enontekiö in northwestern Lapland. In central Lapland, north of Sodankylä, there is a fairly sizable area devoid of eskers. Marked fluvial deposits occur only in river valleys, in areas where glaciofluvial sediments have been transported and redeposited by fluvial activity.

As most of the area is above the highest shore line, littoral deposits and fine-grained bottom sediments are rare. The majority were deposited in ice-dammed glacial lakes, and marine sediments occur mainly in the extensive river valleys in the south of the study area and in the Inari basin in the north. Eolian deposits occur mainly in connection with large glaciofluvial formations, e.g. at Enontekiö and Inari.

The peatland cover in the study area is considerable, ranging from 10 % to over 60 %. The proportion of peatlands is lowest at Enontekiö in northwestern Lapland and in the Inari-Utsjoki area (10—20 %), and highest (over 60 %) west and southwest of Rovaniemi. In most of central Lapland, peatlands account for 50—60 % of the land area.

Excluding the fields of hummocky moraines and drumlins and the major esker chains, Quaternary deposits have done little to mould the landforms. Their main effect has been to smooth the substrate forms, fill depressions and cover small-scale roughnesses of bedrock.

Although glacial morphology mainly reflects deposits of the last glaciation, older glacial relief is still discernible in places. For example, in central Lapland drumlins dated to the Early Weichselian substage differ in orientation, by up to 120°, from the last late-glacial flutings on top of them. Both orientations are evident as positive relief in the landscape (Hirvas et al. 1986 a, b).

MATERIAL AND METHODS

General

The project to clarify the Pleistocene stratigraphy of northern Finland was implemented by systematically studying some 1 400 pits dug by tractor excavator (Fig. 5).

The till stratigraphy described in this paper is largely based on flow stages of the continental ice sheet, i.e. on glaciation stages. The construction of the flow stages and stratigraphy was prompted by the observation that, within a small area, till beds in a given stratigraphic position often exhibit the same fabric and similar physical properties, whereas those in a different stratigraphic position differ markedly. This led to the working hypothesis that the different till beds in each pit can be distinguished on the basis of fabric and other physical and chemical properties (colour, clast content, grain size distribution, texture, compactness, rock type composition, trace metal composition) and that till beds in different areas can be correlated with each other if a dense enough network of study pits is established (Hirvas et al. 1977).

Figures 6 and 7 illustrate the application of the hypothesis. Figure 6 shows how the till beds in adjacent study pits were correlated with the aid of fabric and other physical properties. Six study pits were excavated at Maaselkä, Sodankylä, along a west-east trending line about 7 km long, the average distance between pits being 1.2 km. The younger till bed overlying the sorted minerogenic sediments, and, in pit 4, a gyttja (organic mud) deposit, is brown fissile sandy till. The older till bed below the sorted interlayers in pits 5 and 6 is structureless bluish grey, sandy-silty till. It is clearly more stony than the younger till, and the stones are markedly bigger.

The stones of the younger till in pits 1—5 have the same, very distinct fabric with an almost western orientation maximum of 250°—260° (the direction from which the glacier depositing the till flowed). In pit 6 the younger till is either unoriented, i.e. without a distinct orientation maximum, or it exhibits what is known as transverse orientation. The older tills in pits 5 and 6 all have the same, distinct orientation with a maximum at 350°.

The flow directions of the glacier that deposited these two tills were affirmed with the aid of metachronous cross striae in adjacent areas and oriented moraine landforms (fluting and drumlins). Stratigraphic interpretation at the study pits was facilitated by the occurrence of deposits of sorted sediments between the younger till and the other till units. The *in situ* gyttja on the bottom of pit 4 made it possible to date the ice-free substage (cf. Fig. 51).

Figure 7 shows how the fabric of a till bed in a certain stratigraphic position produces a clear and logical glacial flow pattern within the framework of a larger area and thus permits the glacial flow stages to be constructed. The figure gives the outcome of fabric analyses of five beds of basal till resting on glaciofluvial formations in western Lapland. At the sites, subtill glaciofluvial formations A and B lie north of the ice divide zone of the last glaciation, C is located in the zone and D and E lie south of it (cf. Fig. 21). In the ice divide zone the last glacier flowed from west to east, north of it to north-northeast and south of it to southeast.

About 400 of the study pits intersected the Quaternary sediments completely, and 114 terminated in weathered bedrock. Most of the pits were dug along roads, the first ones at intervals of 1—2 km.

As the field team's proficiency grew, the spacing could be increased, and the final pits were excavated at 10—20 km intervals, with 2—4 pits at each site. The pits were dug in different parts of a formation: on top, on the proximal and distal slopes, etc., to acquire as full and representative a picture as possible of the stratigraphy, glacial erosion, overburden distribution and till fabric.

Most of the study pits were 2—5 m deep. The deepest ones (8—11 m) were dug by deepening

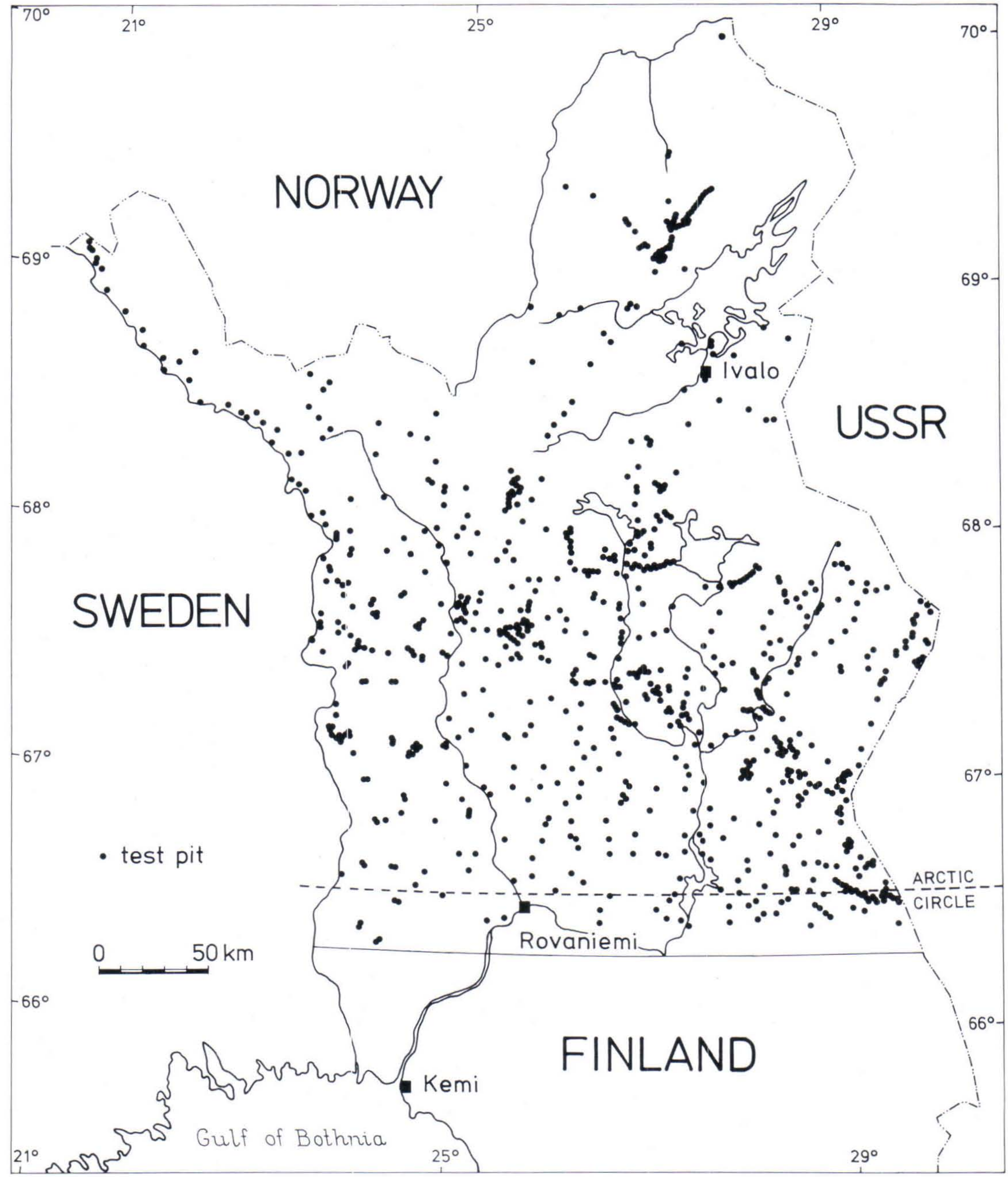

Fig. 5. Network of 1400 test pits. Adjacent replicate pits (2—4) marked with a single dot. Trackless wilderness shows up clearly on the map (dotless areas).

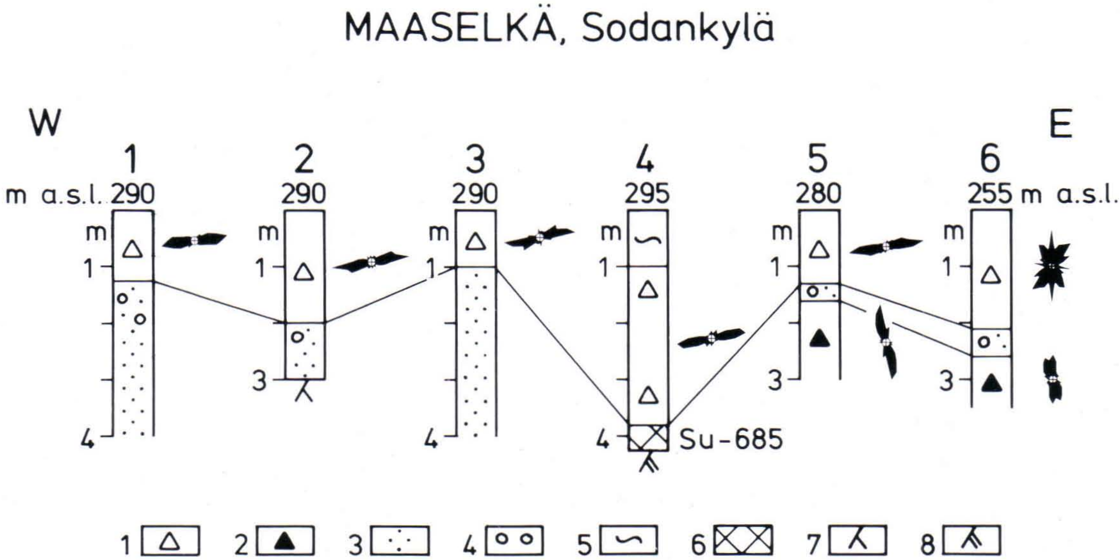

Fig. 6. An example of how till beds are correlated on the basis of fabric (rose diagrams) and other physical properties at Maaselkä, Sodankylä. 1. Younger till bed; 2. Older till bed; 3. Sand; 4. Gravel; 5. Postglacial peat; 6. Subtill gyttja; 7. Bedrock; 8. Weathered bedrock. The pollen diagram and the radiocarbon date of the gyttja exposed at the bottom of study pit 4 are shown in Figure 51.

existing till cuttings. The 22 m high and 700 m long earth cutting at the Rautuvaara mine open pit is the most complete and best studied of the targets. The mean depth of all the study pits is 3.8 m.

At each pit a detailed stratigraphic description was made, the structure of the sediments was recorded, the fabric at different depths was analysed, and samples were taken for granulometric and trace metal analyses. The interesting layers, lenses and so on were sampled for special investigations, e.g. microfossil, humus and roundness studies. Stone counts were made in selected pits to determine the petrography of the till. About 2 200 fabric analyses and 1 360 stone counts were made, and 12 000 samples were taken for laboratory determinations. All original field observations and analyses as well as laboratory analyses are kept in the archives of the Geological Survey of Finland. The study sites described in the text and their map coordinates are listed in Appendix 1.

The test pit grid was made with a tractor excavator as this offered both efficiency and high mobility. It also had several advantages over the previous manual spadework:

1) The study pits could be excavated at sites from which information was needed; no longer was it necessary to rely on the few existing deep till cuttings, which were only too often in hummocky moraines and drumlins of less interest for the present study.
2) The study pits could be excavated much more quickly and in almost any number. If the correlation of subareas or pit groups proved difficult, it was easy to return to the site and make the network of pits more dense.
3) The study pits could be as wide and deep as desired, and observations could be made from non-sliding till walls. Thus the range of data was extended, as a more reliable record could be made of the till properties, clast content, size of clasts, structures, etc.
4) The properties of till and the changes in them could be observed both vertically and horizontally, thus permitting representative

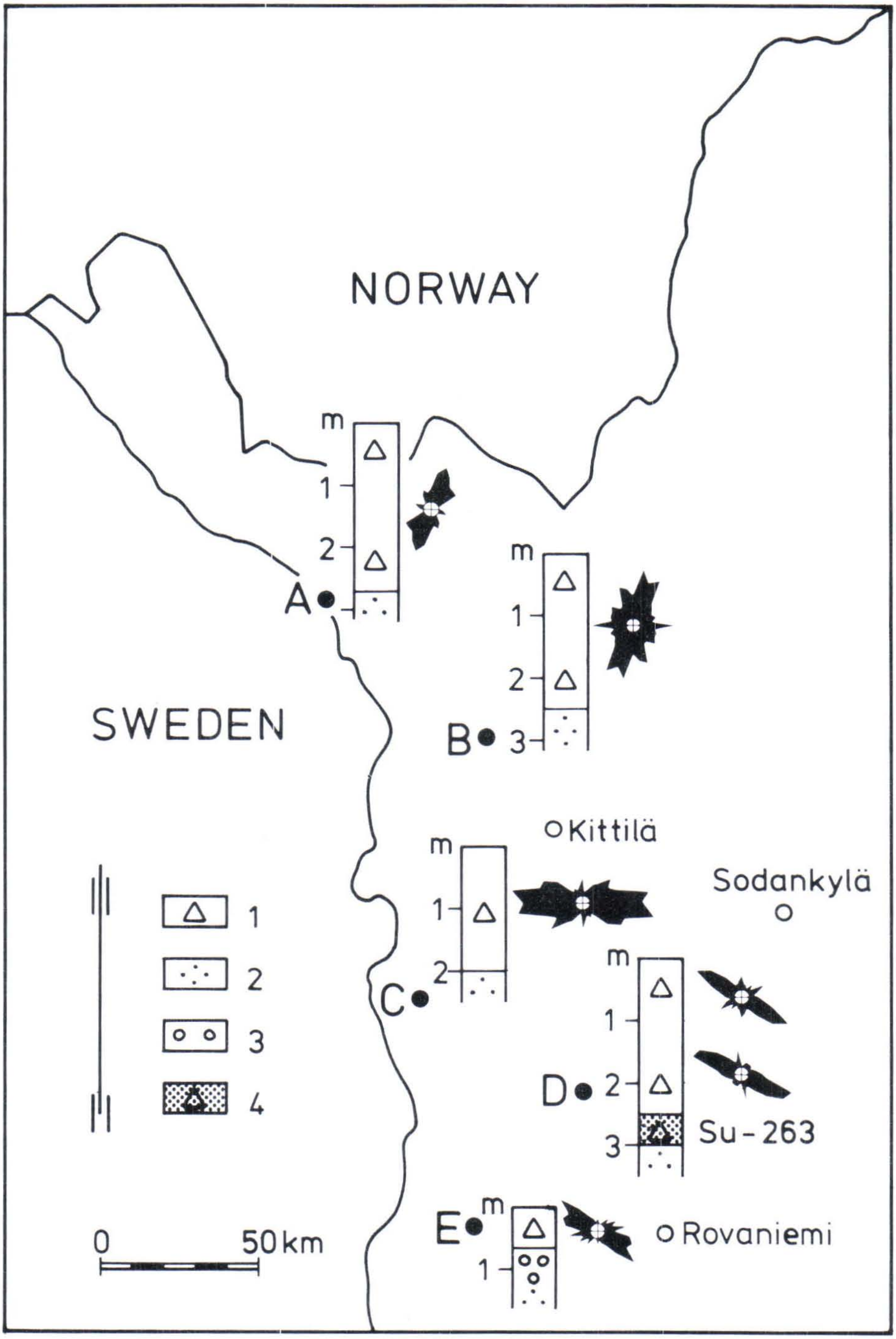

Fig. 7. An example of how the glacial flow stages in western Lapland are constructed. Targets are subtill glaciofluvial formations. The till cover ranges from 0.6 to 3 m. Targets A and B lie north of the ice divide zone of the last glaciation, C is in the ice divide zone, and D and E are south of it (cf. Fig. 21). The fabrics (rose diagrams) of the topmost till bed covering the glaciofluvial formations exhibit a distinct glacial flow pattern. A, Palojoensuu, Enontekiö; B, Kulkujärvi, Kittilä; C, Sieppijärvi, Kolari; D, Marrasjärvi, Rovaniemi rural municipality; E, Pessalompolo, Ylitornio. 1, Covering till; 2, Sand; 3, Gravel; 4, Organic matter intermixed with till. Radiocarbon date (Su-263) over 55 000 yr BP (Heikkinen 1975, Kujansuu 1975).

sampling and fabric analyses with different methods and for different purposes.

5) The systematic excavation rapidly produced volumes of tangible new data on the distribution of overburden, and on stratigraphy and layer thickness. This continuously accumulating collection of data could be put to immediate use in the planning and control of future pitting.

The systematic till sampling with a light-weight percussion drill unit started by the Geochemistry Department of the Geological Survey of Finland in the early 1970s produced as a byproduct useful new information about the Quaternary stratigraphy of northern Finland. In particular it revealed a great number of subtill organic deposits that would otherwise have been inaccessible, as they invariably lay in depressions under present-day mires, i.e. in areas where building, earth moving and research had been avoided.

Continuous sample cores were taken with the percussion drill at sites where subtill organic deposits had been found. The most interesting and promising targets were then exposed with a heavy crawler excavator. Thus the stratigraphic position of the organic deposits could be established (Fig. 8) and representative samples taken for microfossil and radiocarbon determinations. In this way simultaneous geochemical mapping and till stratigraphic studies supported and supplemented each other.

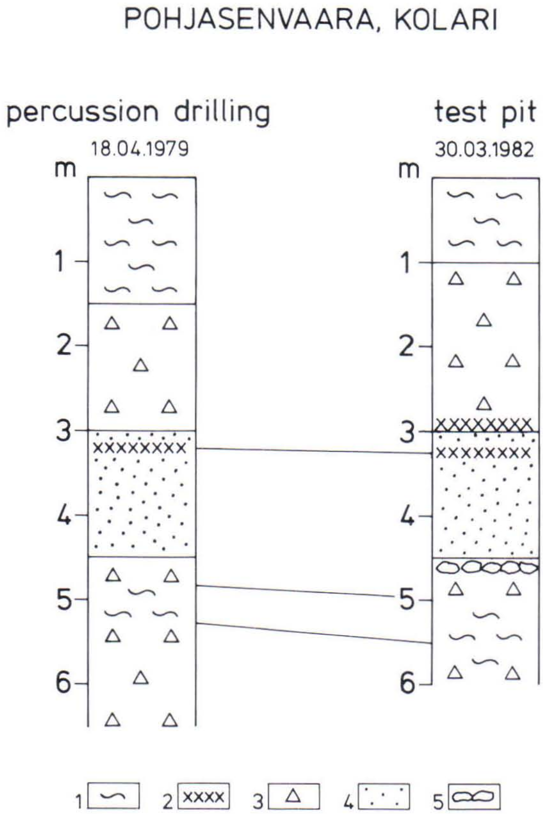

Fig. 8. Comparison of stratigraphies based on percussion drilling and observations made from a test pit at Pohjasenvaara, Kolari, indicates that, in favorable cases, the small samples obtained by drilling provide good material for stratigraphical interpretation. 1, peat; 2, gyttja; 3, till; 4. sand; 5, boulder pavement.

Aerial photo-interpretation

Aerial photo-interpretation was used in planning the field work and in determining the flow directions of the continental ice sheet. The scale of the aerial photos was from 1:20 000 to 1:60 000, most commonly 1:30 000. Quaternary deposits were delineated and classified on the aerial photos to ensure that the study pits were dug at the sites most suitable for observations and sampling. To this end, the till formations were classified as follows: ground moraine, drumlins, fluting ridges, hummocky moraines.

The flow directions of the continental ice sheet were determined on the aerial photos from streamlined moraines, drumlins and fluting. By comparing these data with observations of flow directions made in the field it was possible to apply the findings of aerial photo-interpretation to flow stage maps, particularly when they were being compiled for trackless areas.

In some areas, in the ice divide zone in central Lapland in particular, the aerial photos revealed landscape orientation elements caused by two ice

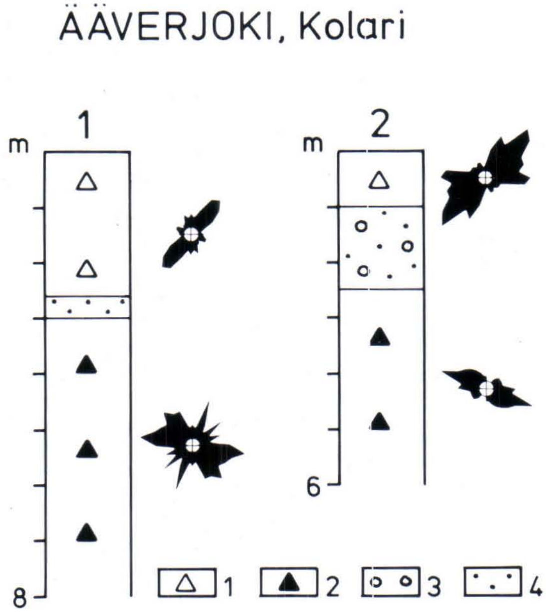

Fig. 9. Lithostratigraphy and fabrics in test pits dug into two drumlin ridges at Ääverjoki, Kolari. The fabric of the lower till bed, 290°—300°, is the same as that of the drumlins (290°). The fabric of the upper till bed, 220°—230°, is the same as the orientation of the fluting shown by the aerial photos. In both pits there is a thin layer of gravel and/or sand between the till beds. 1, upper till bed; 2, lower till bed; 3, gravel; 4, sand.

flows of different direction. As these elements represent different glacial stages they record the directions of two metachronous glacial flows. For example, at Ääverjoki, Kolari, in western Lapland, the larger drumlin-like ridges have an orientation of 290°—300°, whereas the weaker fluting orientation is 210°—220°. Two study pits were excavated here in moraine ridges trending 290°. In both of them (Fig. 9) the thin topmost layer is clast-poor, loosely packed basal till with an orientation of 220°—230°, which is the same as that of the fluting as deduced from aerial photos. The younger till is underlain by a compact basal till with more and bigger clasts. The orientation of the basal till is 290°—300°, i.e. the same as that of the drumlins. In both pits the tills are separated by a thin layer of sorted sediments.

Glacigenic erosion features

The data on glacigenic erosion features collected in the course of field work were supplemented with information gleaned from various archives (e.g. Geological Survey of Finland, Outokumpu Oy, Rautaruukki Oy) and publications (e.g. Tanner 1915, Penttilä 1963, Kujansuu 1967, Korpela 1969).

Owing to the dearth of outcrops in the study area due to its supra-aquatic position and to the intensity of frost weathering, glacigenic erosion features (striation, roches moutonnées, erosion facettes, etc.) are rather scarce. Thus such features play a considerably less important role in determinations of the flow directions and stages of the continental ice sheet than they do farther south.

The most valuable were the few observations of cross striation, or rather striae differing in orientation, on different erosion facettes of a single roche moutonnée, as these permitted the relative ages of the striae to be determined. The data were compared and correlated with the fabric analyses of till beds and with the results of aerial photo-interpretation. They were also useful for compiling flow stage maps and checking the interpretation of the till stratigraphy. The orientations of the glacigenic erosion features are shown in Figure 10 (cf. Hirvas et al. 1986 b).

The clustering of striae in the environment of Kittilä is due to the intensity of exploration and research activities in that area. The reason for the occurrence of striae in apparently opposite directions in adjacent areas is that the orientations were usually measured on small outcrops, and the glacial flow direction could not always be deduced

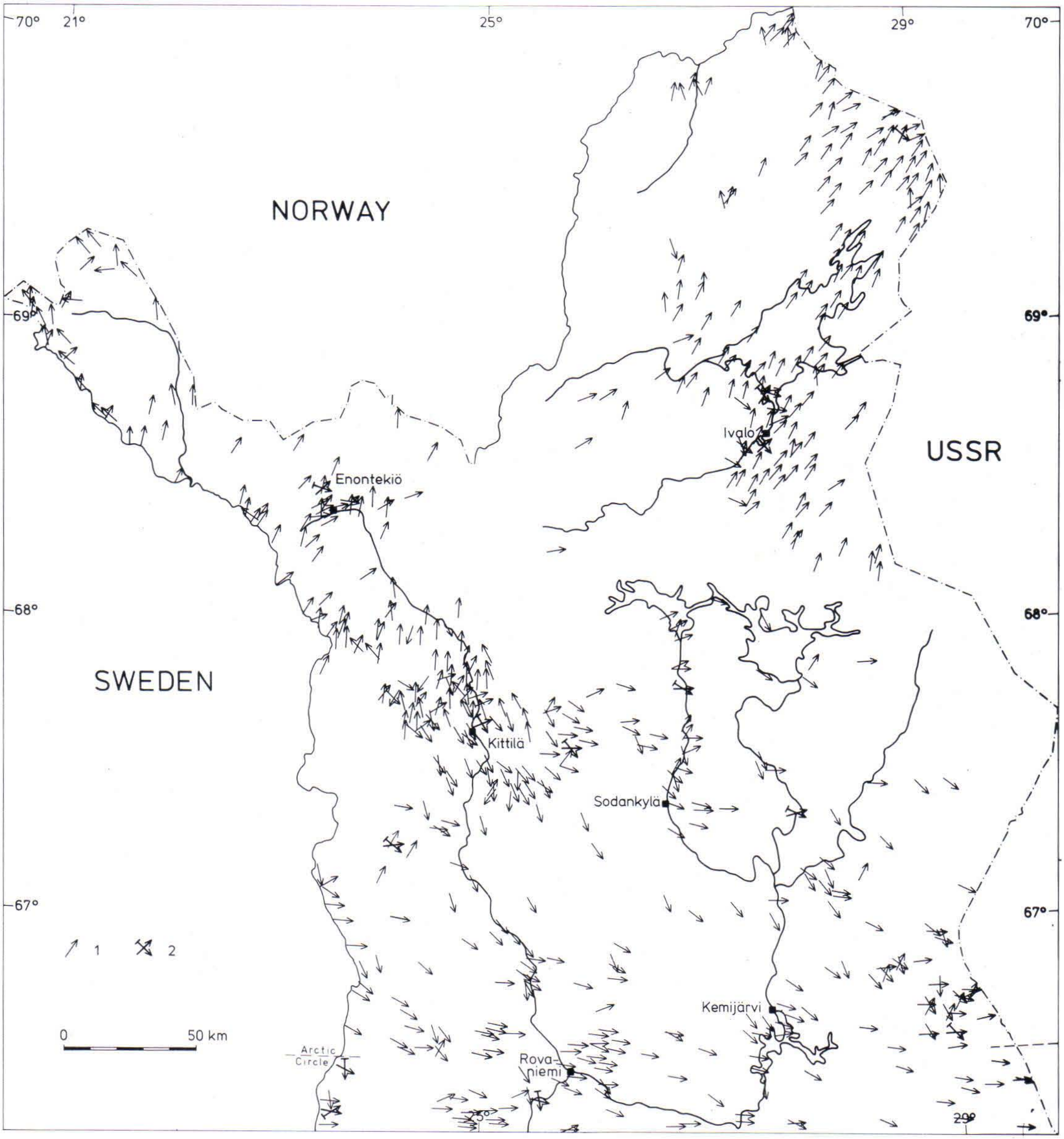

Fig. 10. Striations in the study area. 1, striation; 2, cross striation (arrow with cross bar = older striation). Collected from various sources, see text.

from the form of the roche moutonnée. As a result the interpretation of glacial flow directions is influenced by the opinion held by individual researchers on glacial geological history in the area.

The scarcity of outcrops suitable for striae observations and the discrepancies in interpretations of existing data emphasize the importance of till fabric analyses in studies of glacial flow directions, particularly in central Lapland, where the fluctuations in flow direction have been exceptionally high.

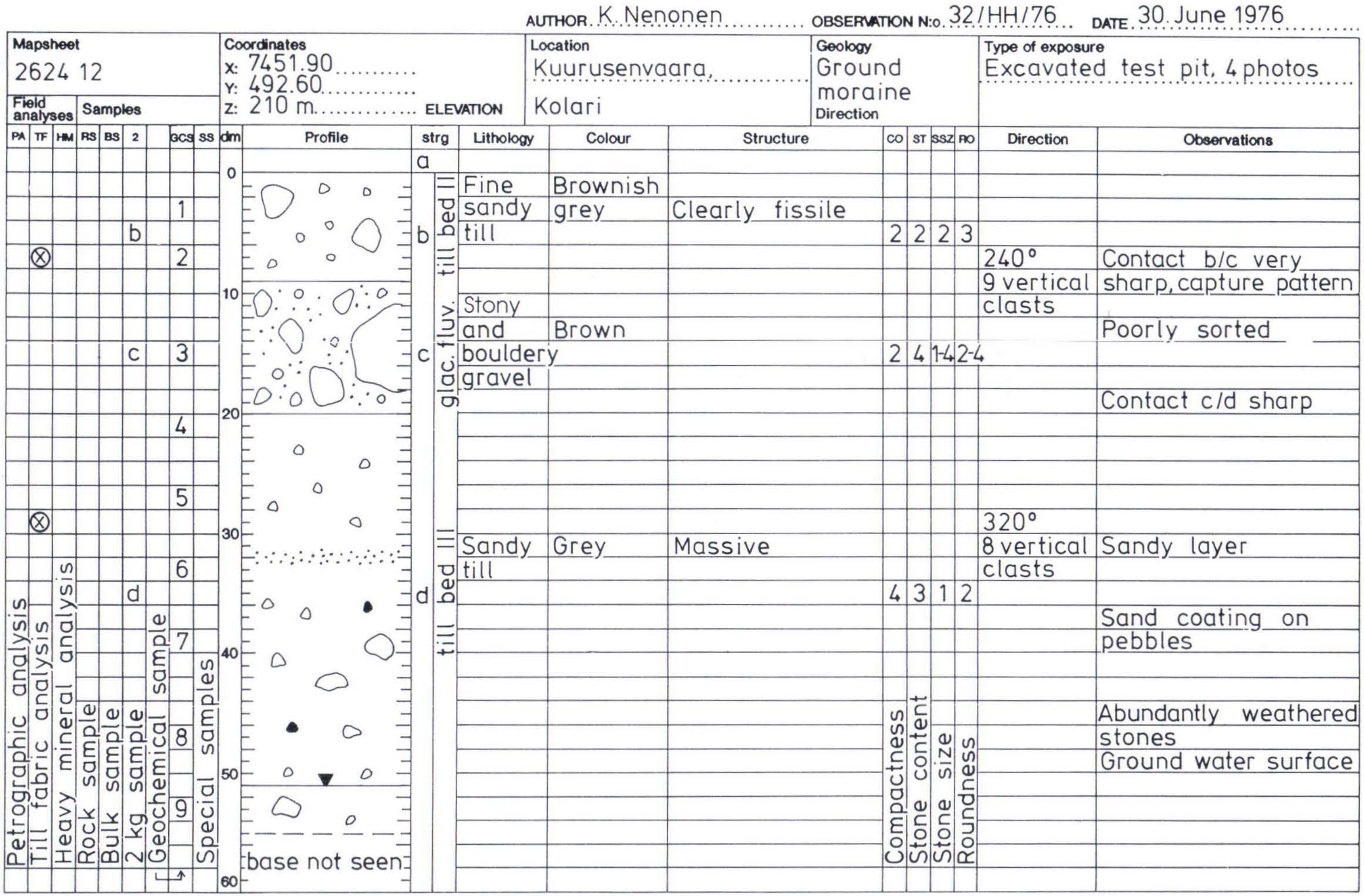

Fig. 11. Observation form for recording stratigraphic data from test pits. A typical example of stratigraphy in western Lapland. The test pit has two till beds (II and III) deposited by continental ice flowing in two different directions with about 1 m of stony and bouldery poorly sorted glaciofluvial gravel between them.

The high scatter in striae directions is due to the striae having been carved during metachronous glacial flow stages. In areas of rough relief the glacial flow followed topographic macrostructures, at least when the ice sheet was melting and the glacial lobes flowed in widely divergent directions at the same time.

Physical properties of till

An observation form (Fig. 11) was designed to standardize and simplify the recording of field data and to ensure that all necessary observations were recorded. The field analyses made and the samples taken were recorded to the left of the profile drawing, and the analytical data and physical properties of the layer units were marked to the right.

As not all till properties can be described with numerical laboratory data, photographic standards were prepared to make these properties mutually comparable. These include structure, clast content, and the average size and roundness of clasts in the >2 cm fraction retained on the sieve. The properties were classified on a five degree scale, on which 1 refers to the lowest and 5 to the highest degree of the property. The compactness and moisture content of till were classified using the same 5-degree scale (Hirvas et al. 1977). The properties were classified as follows:

clast content, the abundance of clasts (>2 cm) in till visually estimated

1 = none
2 = few
3 = normal
4 = high
5 = very high

clast size, the predominant size of the clasts in till

1 = pebbles, 2—6 cm
2 = cobbles, 6—20 cm
3 = small boulders, 20—60 cm
4 = boulders, 60—200 cm
5 = large boulders, over 200 cm

roundness, roundness of clasts visually estimated from the most eroded side

1 = non-eroded, sharp-edged, angular, clearly fractured surfaces typical of the rock type
2 = slightly eroded, slightly worn at edges, angular, fractured surfaces still clearly visible and typical of the rock type
3 = eroded, edges eroded and rounded, original shape of clast still recognizable
4 = rounded, original shape difficult to define,
5 = highly rounded, original shape unrecognisable

compactness

1 = very loose
2 = loose
3 = normal
4 = compact
5 = very compact, concrete-like

moisture content

1 = dry, dusty and friable
2 = fresh, slightly staining
3 = moist, staining
4 = wet, muddy
5 = water-logged, often below the groundwater table, quaking and soaked with water.

Descriptive terms were used for the till structure: massive, fissile, layered and deformed (various capture patterns, faults, folds, disturbances, etc.).

All the till units were sampled, and their grain sizes were determined with sieving and areometry.

Colorimetric humus determinations were made on the organic matter of the till beds and their layers with an E 1009 (Metrohm) spectrocolorimeter. The purpose was to establish whether the colour of the dark-brown 10—30 cm thick and strongly fissile layers common in till, particularly in central Lapland, was due to their unusually high humus content. Humus data were also used in selecting the layers for microfossil determinations.

Till fabric analyses

Macrofabric (conventional fabric)

The mineral matter in till tends to assume an orientation either parallel or perpendicular to glacial flow, as demonstrated by numerous studies, starting with that of Holmes (1941). Till fabric was one of the stratigraphic classification parameters used to distinguish between till beds. Altogether 1 300 conventional fabric analyses were made from all the till units distinguished. As a rule the orientation of 100 elongated clasts in till was determined, and the results were presented as a rose diagram. If the till fabric was very well developed, the orientation was determined for only 50 stones. This procedure was adopted when it became clear that the rose diagrams of the well-oriented tills based on 50 and 100 stones were very similar (Fig. 12). In unoriented till the increase in sample size did not improve the picture of the till fabric; if the till does not show a significant fabric after 100 clasts have been measured it will not do so after 200 stones either. The till must then be considered unoriented (Hirvas et al. 1977).

The orientation of elongated stones was not measured if their major axis deviated by more than 30° from the horizontal; the stones were then recorded as vertical. In the basal till the number of elongated stones measured for orientation and recorded as vertical was from 0 to 230 per 100 stones measured and accepted: in 40.8 % of the cases there were from 0 to 5 vertical stones, in 23.6 % 6 to 10 and in 13.4 % 11 to 15, i.e. in 77.8 % of

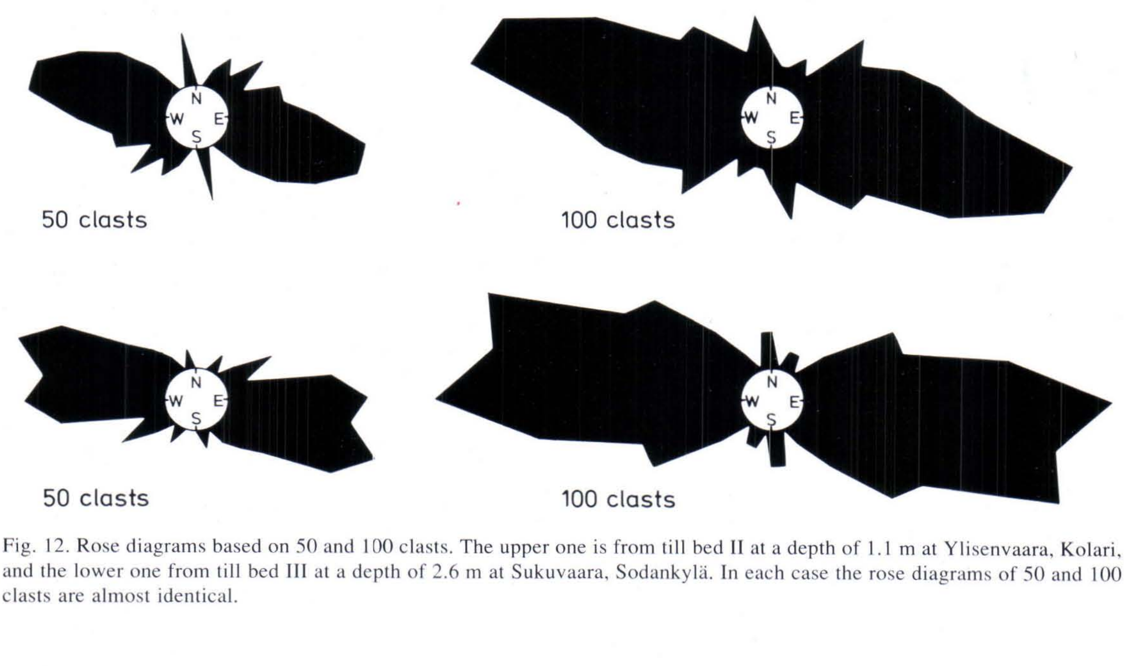

Fig. 12. Rose diagrams based on 50 and 100 clasts. The upper one is from till bed II at a depth of 1.1 m at Ylisenvaara, Kolari, and the lower one from till bed III at a depth of 2.6 m at Sukuvaara, Sodankylä. In each case the rose diagrams of 50 and 100 clasts are almost identical.

Table 1. Proportion of vertical clasts (inclined at over 30°) in fabric analyses.

Number of vertical stones	Till beds*											
	Surficial		I		II		III		Older tills		Total	
	Σ	%	Σ	%	Σ	%	Σ	%	Σ	%	Σ	%
0— 5	70	30.0	22	52.5	307	41.5	100	47.5	15	45.5	514	40.8
6— 10	57	24.5	9	21.4	176	23.8	48	22.9	8	24.2	298	23.6
11— 15	36	15.5	3	7.1	97	13.1	30	14.3	2	6.1	168	13.4
16— 20	20	8.6	2	4.8	59	8.0	21	10.0	5	15.2	107	8.5
21— 25	12	5.2	3	7.1	32	4.3	4	1.9	3	9.0	54	4.3
26— 30	10	4.3	—	—	18	2.4	2	1.0	—	—	30	2.4
**31— 50	15	6.4	3	7.1	32	4.3	5	2.4	—	—	55	4.4
51—100	11	4.7	—	—	14	1.9	—	—	—	—	25	2.0
101—200	1	0.4	—	—	5	0.7	—	—	—	—	6	0.5
> 200	1	0.4	—	—	—	—	—	—	—	—	1	0.1
S total	233	00.0	42	100.0	740	100.0	210	100.0	33	100.0	1258	100.0

* See chapter Stratigraphy
** Note change in scale

the cases there were fewer than 16 vertical stones per 100 oriented stones (Table 1), indicating that the majority of the stones in the basal till are in an almost horizontal position (cf. Andrews & Smith 1970). If the proportion of vertical stones is markedly higher, the reliability of fabric analysis as an indicator of glacial flow direction is impaired. The exceptionally high number of vertical stones is then probably due to a disturbing factor effective during or after the deposition of till, such as glaciotectonic disturbance, partial reorientation, a large boulder or frost action. Then, the till fabric may not indicate the glacial flow direction but the direction of a disturbance or structure deviating from it.

The reliability of the fabric analyses was tested by asking several people to make the analysis at the same site. The results were compatible. The reliability of the method for indicating glacial flow direction was tested by comparing the fabric analyses with the orientation of the striae on the bedrock under the till (Fig. 13) and the longitudinal directions of drumlins and fluting ridges (Fig. 9). The glacial flow directions given by all methods were compatible.

The fabric analyses were always made on a sufficiently big (min. 0.5 x 1.0 m) horizontal base 'fabric analysis table'. The most common clast size was 0.5—10 cm with the 2—6 cm fraction predominating. Within this fraction no differences were noted in orientations between clasts of different size. Whenever possible the fabric analyses were made at a depth of at least one metre, to eliminate the disturbance in orientation caused by frost, and from the central part of the till bed. Exceptionally thick till beds were submitted to several fabric analyses at different depths; as a rule, the orientation maxima were then the same or differed by only 10°—20° (Hirvas et al. 1977).

The orientation of a clast was measured to within five degrees, but the result was expressed in full tens of degrees as the analysts tended to round their readings to the nearest ten. The fabric analyses were not corrected for declination, which is about N5°W in Lapland and varies by only 1°—2° over the area. The fabric analyses were plotted as rose diagrams, and the orientation maxima were marked on map bases (e.g. Fig. 21) with the observation site in the centre of the orientation bar.

The bulk of the basal till in the study area is highly or moderately oriented. In 184 of the 1 258 fabric analyses made (14.6 %), the clasts did not have any clear orientation maximum, and the basal till was interpreted as unoriented (Table 2). An

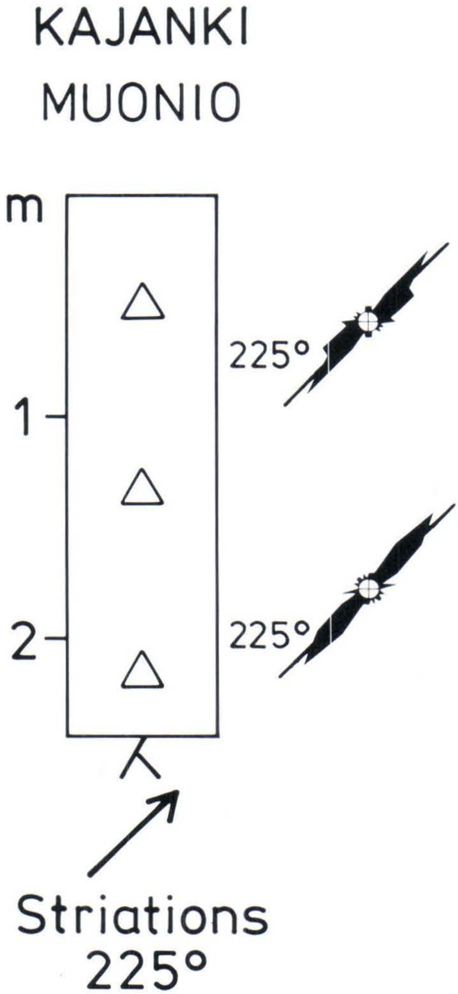

Fig. 13. Comparison between fabric analyses and the striations on the bedrock on which the till rests at Kajanki, Muonio. The clasts in till bed II are highly oriented and in the same direction as the striae on the surface of quartzite under the till bed.

increase in the abundance and size of clasts in till is often accompanied by a decrease in orientation degree (cf. MacClintoc & Dreimanis 1964). When the clast content was 4—5, some of the clasts were oriented perpendicular to the glacial flow direction. Distinct transversal orientation, however, was also observed in many places in basal till of normal clast content (cf. Boulton 1971).

The fabrics of the various till beds showed clear differences. Orientation was best developed in tills

Table 2. Statistics of fabric analyses

Till bed*	Number of analyses	Unoriented	
		N	%
Surficial	233	32	13.7
I	42	3	7.1
II	740	104	14.1
III	210	36	17.4
Older tills	33	9	30.3
Σ total	1258	184	14.6

* See chapter Stratigraphy

deposited during deglaciation, at a time when the continental ice sheet was readvancing and oscillating (cf. Saarnisto & Peltoniemi 1984), and least developed in the oldest till beds. The proportion of unoriented tills in 'the oscillation tills' (till bed I) was a mere 7.1 % and in the older tills 30.3 % (Table 2). One reason for the poorly developed orientation in the older tills is that the fabric analyses often had to be made on the bottom of study pits, from the upper parts of the till beds, where the orientation may have been disturbed by later glacier flow.

In some cases it was noted that a younger glacier flow had reoriented or disturbed the fabric of the upper part of an older till bed (cf. Virkkala 1960, Korpela 1969). Hence efforts should always be made to perform the fabric analyses on the central or lower parts of the till beds. Solifluction is also known to reorient the clasts in till. As a rule, the reorientation is very distinct because almost all the clasts are parallel to the slope gradient. As solifluction even occurs on slopes of surprisingly low angle its impact must be taken into account when interpreting the fabric analysis data.

Disturbing factors notwithstanding, fabric analysis, when carefully executed and correctly interpreted, is a reliable and effective way of determining the flow direction of a continental ice sheet and a very useful instrument in till stratigraphic studies. As the method is statistical, the reliability of the outcome improves as the number of fabric analyses increases (cf. G. Lundqvist 1948, Glen et al. 1957). Maximum benefit is obtained from fabric analyses of various tills when the results are tied to and correlated with the glacial flow direction elements, glacial striations, drumlins, fluting, etc., recorded from adjacent areas (Figs. 9 and 13).

Microfabric and magnetic fabric

The fabric of the fine till fraction was studied by taking 760 oriented till samples. The samples were hardened with araldite (Araldit GY 257, hardener Ciba HY 951), and then made into polished sections (4.5 cm). The orientation of 50—100 elongated grains in the sections was measured under a stereomicroscope, and the results were plotted in rose diagrams. The reliability of the method was tested by taking micro-orientation samples from till beds that had been submitted to conventional fabric analyses. The samples were taken from the same level as that at which the fabric analysis had been made and from the same till bed at small vertical intervals. The orientation results of the samples differ somewhat from each other and from the fabric analysis data. The microfabric orientation rose is generally broader. When the sample is large enough, say, about 10 oriented till samples and 500—1 000 recorded directions of elongated grains, the picture of the glacial flow direction seems to be fairly reliable. However, it takes much longer to carry out that many microfabric analyses than to make a couple of fabric analyses in the field.

Figure 14 shows the results of a fabric analysis and 11 micro-orientation analyses from the same fabric analysis table. In eight of the micro-orientation samples the orientation is either the same as or deviates by 10°—25° from the fabric analysis; in one sample the deviation is 40° and in two samples the orientation is clearly transversal (cf. Seifert 1954, Evenson 1970, 1971).

The fabric of the fine till fraction was also studied with the aid of the anisotropy of magnetic susceptibility, i.e. basal till was submitted to magnetic fabric analyses. In his measurements of the anisotropy of susceptibility, Fuller (1962) had noticed that the magnetic substance in till was oriented parallel to glacial flow. The fabric of the magnetic substance in till was later studied by Boulton (1971), Gravenor and Stupavsky (1976). In connection with the present study, magnetic fabric analysis was used and developed by R. Puranen (1976, 1977a,b). The fabric of the magnetic substance in till usually coincides with that of the sand grains and clasts in till. Figure 15 illustrates the till fabric measured with three different techniques: conventional fabric analysis, microfabric analysis and magnetic fabric analysis. The results are fairly compatible, the deviation being a mere 10°.

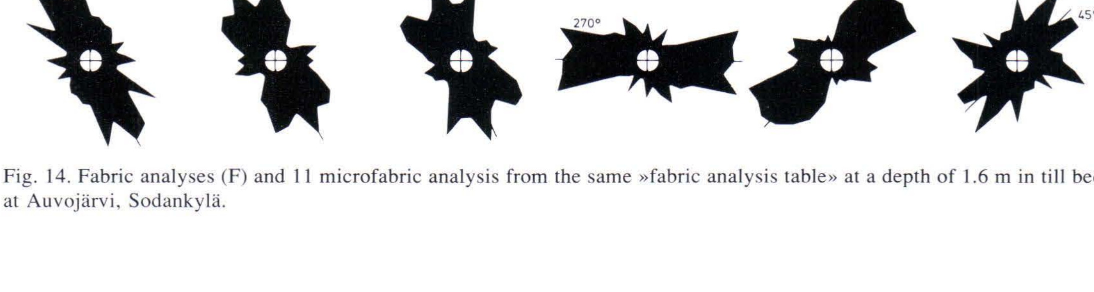

Fig. 14. Fabric analyses (F) and 11 microfabric analysis from the same »fabric analysis table» at a depth of 1.6 m in till bed II at Auvojärvi, Sodankylä.

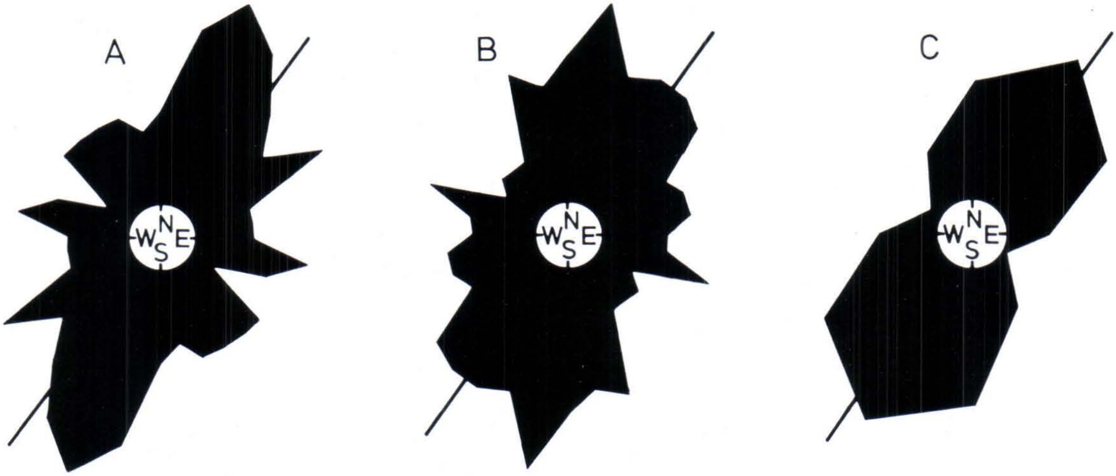

Fig. 15. Conventional fabric analysis (A), microfabric analysis (B) and magnetic fabric analysis (C) from Palojoensuu, Enontekiö. The data are from a small fluting ridge from the same fabric analysis table at a depth of 2.4 m. Bars indicate the direction of the fluting ridge (215°).

Petrographic and geochemical analyses of till

Use was made of petrographic and geochemical analyses of till to 1) distinguish between till beds, 2) to verify the till transport direction and 3) to determine till transport distance. About 1 360 petrographic till analyses were made in selected pits from the 0.2—0.6 cm, 0.6—2 cm, 2—6 cm, 6—20 cm and 20—60 cm fractions, usually from the 6—20 cm fraction. The results show that the percentage of rock types in the different fractions did not differ significantly from each other (e.g. Hirvas et al. 1977, cf. Perttunen 1977).

The difference in rock type composition between the till beds is usually clear, although not great, as varying amounts of the younger till derive from till deposited earlier.

Samples were collected for the geochemical analyses of till from all the study pits. They were taken at 0.5 m vertical intervals or from each till unit if thinner than that. The samples, 6 500 in all, were analysed by AAS at the Rovaniemi laboratory of the Geochemistry Department of the Geological Survey of Finland. A fraction of —0.062 mm was sieved from the samples and analysed for Co, Cr, Cu, Mn, Ni, Pb and Zn.

Pollen and diatom analyses

The microfossil determinations were made at the Department of Quaternary Geology of the Geological Survey of Finland. The pollen analyses were made by Brita Eriksson, Dr Risto Tynni, Kalevi Hokkanen and Liisa Ikonen, and the diatom analyses by Dr Tuulikki Grönlund and Dr Risto Tynni. The sequence at Naakenavaara, Kittilä, was studied for macrofossils by Carl-Göran Stén and Dr Marjatta Aalto (Department of Botany, University of Helsinki).

For the pollen analyses the samples containing mineral matter were treated with cold HF (Müller

1953) and boiled in 10 % KOH. Peats and samples low in mineral matter were boiled in KOH and, if necessary, decanted and/or sieved. Glycerine was used as the medium for the slides, which were studied under a Wild M20 microscope.

For the diatom slides the samples were boiled in 10 % H_2O_2 to eliminate organic substances. The colloidal fines were removed by bringing them into suspension, and the procedure was repeated until all fine fractions had disappeared. The coarser material was removed by decanting. The preparations were fixed with clophen resin and studied under a Leitz SM research microscope. The diatoms were analysed at 1 000 X magnification, and at least 500 diatom frustules were counted for each sample whenever possible.

Radiocarbon analyses

The radiocarbon analyses were made by Tuovi Kankainen and the late A. Heikkinen at the radiocarbon dating laboratory of the Geological Survey of Finland (Su). In the early stages of this work it was generally believed that the finite dates of about 40 000—50 000 yr BP obtained from the subtill organic sediments were the correct ages of, for instance, the Peräpohjola Interstadial of Korpela (1969, see also Lundqvist and Mook 1981). Therefore, in this study, too, the radiocarbon method was applied extensively to date the subtill organic material in Lapland.

As the work proceeded, however, it became evident that contamination is a real problem for old geological samples and that the dates of 40 000—50 000 yr BP should be considered as minimum dates only. The dates in this study are ^{14}C ages according to the radio-carbon dating convention (Stuiver & Polach 1977), i.e. the ages are given with a $\pm 1\sigma$ (68 %) confidence interval. For samples with an activity of less than two standard deviations (2σ), a minimum age (marked with >) is given. These samples are older than the given minimum age at the 95 % confidence level. All dates should be understood as minimum ones. The radiocarbon dates are listed in Table 9.

STRATIGRAPHY

General

As mentioned previously the till stratigraphy of northern Finland presented in this paper is based on flow stages of the continental ice sheet, i.e. on glaciation stages. Thus, over a large area the till bed deposited by the youngest western glacier flow is underlain by an older till bed deposited by the northwestern flow. This again is underlain by till deposited by the southwestern flow.

The till beds deposited by different glaciations are marked from youngest to oldest with the Roman numerals I—VI. This is contrary to general international practice in stratigraphic studies, which present the deposits from oldest to youngest. Our system was introduced on purely practical grounds. At the start of the study, the Quaternary stratigraphy of northern Finland was very poorly known, and no information was available about the number of glacial stages that had deposited till beds there. It is conceivable, even likely, that follow-up studies will reveal even older tills in northern Finland than those described here.

The till beds, and interstadial and interglacial deposits are not named after their type localities in this work, because comparable observations were often made at many sites and over large areas. Moreover, the majority of the typical sequences were exposed only in the walls of study pits or in drill profiles and are thus not visible except when re-excavated and re-drilled. The key sections are described and correlated at the end of this chapter.

In this context the term till bed refers to all the till that deposited during one glaciation. Hence a till bed may be composed of till deposited during both the advance and retreat of the continental ice sheet. The exception is till bed I, which is named as a separate bed even though it refers only to the basal till that was deposited during the last deglaciation stage in the course of readvance, oscillation or, at least, reactivation of the ice front. In general, the till beds were deposited as basal till. In some places, however, a till bed may contain units of various types such as basal till, surficial till and ablation till (cf. Rautuvaara till bed IV, Fig. 39).

The till beds are often composed of several smaller stratigraphic units which here are called layers. Units smaller than layers are described as bands, stripes or lenses. The term till unit is used when it was not possible to distinguish between various till beds and the layers of a single bed. This often happens in the interpretation of drill profiles.

As a till bed may consist of several smaller layers differing radically in physical properties, tills cannot be classified as separate beds merely on the basis of a single property such as colour, fabric, rock type composition or trace metal content. The colour as well as the trace metal content of a till bed may be totally different above and below the groundwater table. The orientation of clasts within a single till bed may also vary, as the clasts may exceptionally assume a diagonal or transversal orientation in relation to glacier flow. Similarly, the rock type composition may vary markedly from one part or layer of a till bed to another. The lower part may contain abundant clasts of local bedrock, or alternatively redeposited long-transported material deriving from an underlying older till bed or glaciofluvial deposit.

For the above reasons, a wide range of different methods were used to discriminate between till beds and to ensure the accuracy of the stratigraphic interpretation. Every effort was made to ascertain which of the till units in the stratigraphic sequence were variants of the same till bed and which were till beds of different age deposited during metachronous glacial phases.

The same research methods and classification specifications were used to distinguish till beds in study pits and to correlate till beds of adjacent areas.

As the till stratigraphy is largely based on different flow stages of the continental ice sheet or glaciation stages, special emphasis was laid on determining the flow directions with different methods. The division of till into beds is based on fabric and other physical properties measured in the field. The stratigraphic interpretation made in the field was checked later with the aid of trace element, grain size and other laboratory determinations.

The stony erosion surfaces, or boulder pavements, that often occur between till beds and deposits of sorted sediments made it easier to distinguish between till beds in study pits and to correlate beds in different areas. The till beds could be dated on the basis of the organic deposits between them.

Description of till beds

The topmost till was deposited during the latest stage of deglaciation. The youngest glacier flow stage, which affected the whole of Finnish Lapland, is known as flow stage II. Till bed II, which deposited during this stage, is frequently uppermost in the study area. However, the melting of the continental ice sheet did not proceed smoothly throughout the study area, but was

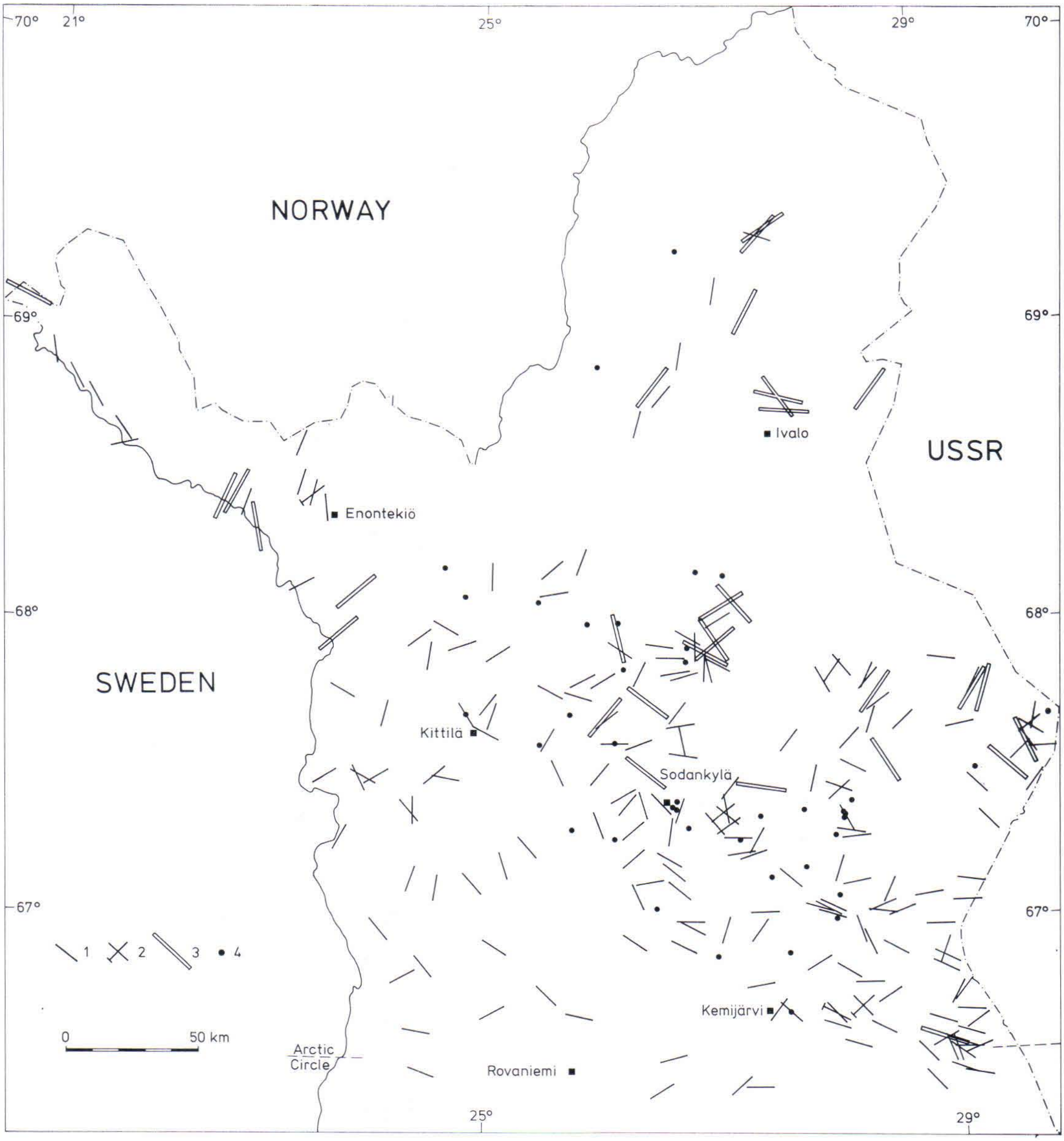

Fig. 16. Orientation maxima of the fabric analyses of surficial till and till bed I. 1, orientation of surficial till; 2, orientation of surficial till at various depths (the lower one with a cross bar); 3, orientation of till bed I; 4, fabric analysis from surficial till, no clear orientation maximum.

interrupted by oscillations of the ice front and ice lobes in the area already free from ice. These small-scale, local oscillations during deglaciation of stage II are named flow stage I, and the tills deposited then, till bed I. The origin of the topmost till unit was often difficult to establish because its uppermost layer could be either a basal till (till bed I or II), supraglacial till deposited during deglaciation or a surface layer of till redeposited by solifluction or loosened and reworked by frost, seepage waters, podzolization and tree roots. Therefore, only those tills that were interpreted as basal till younger than till bed II on the basis of their stratigraphic position, structure, fabric and other properties are classified as till bed I. The other topmost till units that differ from the underlying basal till (till bed II) are named surficial till, which was classified as a separate unit mainly to meet the needs of geochemical till mapping but also because it differs so clearly from the underlying till units in appearance and physical properties and because its importance was not fully understood at the start of the project.

Surficial till

Surficial till was recorded as a separate till unit in 235 study pits. The observations are distributed fairly evenly over the whole study area (Fig. 16), suggesting that in most cases the surficial till is really nothing more than a surface layer of basal till loosened by frost or some other force. In general, the till unit classified as surficial till is rather thin, usually 0.5—1 m, but with a range of 0.3—1.4 m and an average thickness of 0.8 m. Although varying irregularly from one area to another within the above range, the thickness of the unit in adjacent pits tends to be more or less the same. This, too, suggests that it is a surface layer of till deformed by frost, and that its thickness depends on the grain size distribution of the till, vegetation cover or some other factor.

The surficial till grades downwards (Fig. 17) into the underlying basal till without a distinct boundary, whereas the lower contact of till bed I is often sharp and may contain boulder pavements and sorted interlayers.

A characteristic feature of the surficial till is the great variation of material it contains, covering almost the whole spectrum of the classification applied. In places the material is almost stoneless silt or fine silt, in others almost pure gravel or clasts and everything else in between. This can probably be attributed to the great variety of plausible origins for the thin surficial till, ranging from a surface layer of till reworked by frost to supraglacial ablation or flow till. It is even possible that some units interpreted as supraglacial till (in the early stages of the study, in particular) are not really till at all but diamicton, e.g. solifluction deposits that slid down slopes or thin glacial lake sediments impregnated from top to bottom with frost-heaved clasts from the underlying basal till.

Fig. 17. Typical surficial till (S) with some small pebbles at Kummamaa, Pelkosenniemi. The till, which is 0.9 m thick, has a gradual contact with the underlying till bed II.

At its most typical, the material in the surficial till is weakly fissile, loosely compacted fine sandy till poor in small clasts (M_z = 0.132 mm), in which the clay content (-0.002 mm) ranges from 0.5 to

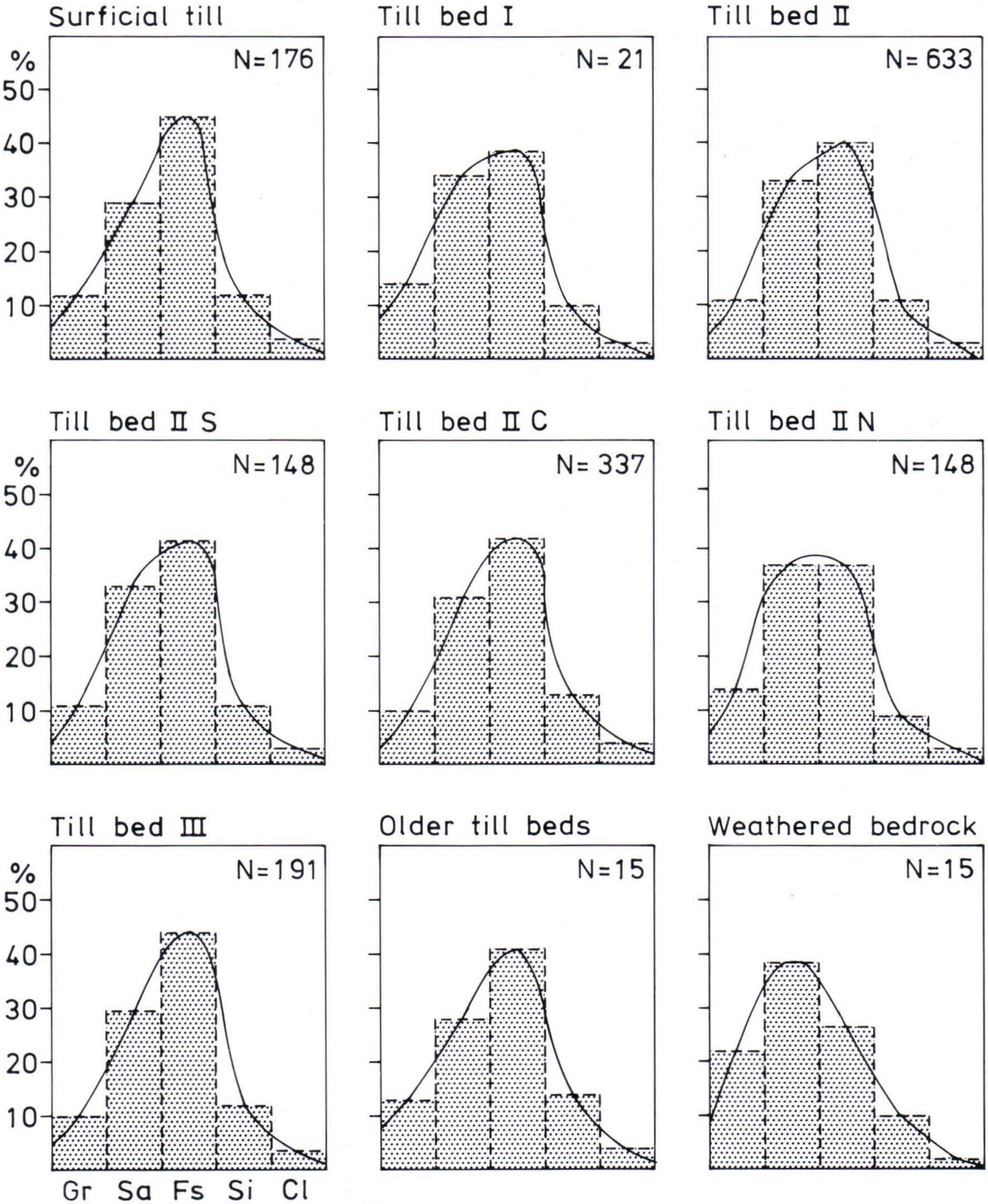

Fig. 18. The average gravel (Gr), sand (Sa), fine sand (Fs), silt (Si) and clay (Cl) contents in different till beds and weathered bedrock. The occurrences of till bed II are divided into three subareas: II S = southern subarea; II C = the ice divide zone; II N = northern subarea.

Table 3. Grain size parameters for the various till beds and weathered bedrock. II S = Southern Lapland, II C = Central Lapland, II N = Northern Lapland. M_z = mean grain size, S.D. = standard deviation, S_o = sorting, S_k = skewness, K_g = kurtosis. For further details, see text.

Till bed	Surficial	I	II	II S	II C	II N	III	Older tills	Weathered bedrock
Number of analyses	176	21	633	148	337	148	191	15	15
Gravel (2—20mm)%	10.2	14.2	11.8	11.4	9.9	14.1	10.4	13.2	22.0
Sand (0.2—2mm)%	29.7	34.2	33.7	33.1	31.1	37.0	29.5	27.8	38.6
Fine sand (0.02—0.2mm)%	44.9	38.5	40.2	41.5	42.2	36.8	44.3	41.3	26.7
Silt (0.002—0.02mm)%	11.7	9.9	10.9	10.8	12.9	9.1	12.3	13.7	10.3
Clay (< 0.002mm)%	3.5	3.1	3.4	3.2	4.0	3.1	3.5	4.0	2.3
M_z (phi)	2.92	2.35	2.71	2.63	2.94	2.25	2.89	2.82	1.68
S.D. (±)	0.80	0.77	0.72	0.72	0.72	0.71	0.69	0.67	1.40
M_z (mm)	0.13	0.20	0.16	0.16	0.13	0.21	0.14	0.14	0.31
S.D. (±)	0.10	0.15	0.11	0.09	0.09	0.15	0.08	0.08	0.60
S_o	2.93	3.05	—	2.97	3.02	3.02	2.95	3.20	2.94
S.D. (±)	0.44	0.44	—	0.31	0.42	0.41	0.41	0.37	0.65
S_k	−0.02	0.03	—	−0.01	0.02	0.03	−0.02	−0.01	0.11
S.D. (±)	0.12	0.10	—	0.12	0.14	0.12	0.12	0.14	0.25
K_g	1.11	1.08	—	1.11	1.11	1.07	1.13	1.10	1.02
S.D. (±)	0.18	0.16	—	0.15	0.17	0.13	0.17	0.16	0.24

14.8 %, the average being 3.5 %. The grain size statistics for the surficial till (176 granulometric analyses), all various till beds and weathered bedrock occurrences are presented in Figure 18 and in Table 3, showing the mean gravel, sand, fine sand, silt and clay abundances, the mean grain size (M_z), sorting (S_o), skewness (S_k) and kurtosis (K_g).

In general, the surficial till is brownish, brown or greyish brown in colour, but only rarely greyish. This is probably because above the groundwater table iron is oxidized and occurs as Fe^{3+} , thus rendering the till brown (cf. Hirvas et al. 1976).

The surficial till is often fissile, individual lamellae being from 0.5 mm to 3 mm thick. The origin of this 'microfissility' has not been established, but the most probable cause is frost action. This concept is corroborated by the fact that similar structures develop on vertical walls of frozen till cuttings in the autumn. Frost susceptibility tests have produced similar structures (Nieminen 1985).

With the exception of the roundness of clasts, the physical properties of the surficial till differ clearly from those of the till beds proper (Fig. 19). The predominant compactness is 2 (mean 2.3), clast content 2 (mean 2.5), clast size 2 (mean 1.7) and roundness 3 (mean 2.9) (Fig. 20).

Altogether 233 fabric analyses were made on surficial till. In 32, or 13.7 %, of them the till was unoriented and without a distinct orientation maximum. This is surprising because even though the fabric analyses were made from close to the ground surface, the material showed the second best orientation of all the till beds. Only the material in till bed I is better oriented (Table 2). The higher abundance of vertical clasts in surficial till than in the other till beds was expected because this layer had repeatedly been submitted to frost action. In 127 fabric analyses on surficial till, i.e. in 54.5 % of the cases, the number of vertical clasts per 100 measured and accepted clasts was 10 or fewer, which is 10—20 percentage points less than in the other till beds (Table 1). The orientation maxima of the surficial till are shown in Figure 16. If these are compared with those of till bed II (Fig. 21), the similarity is striking, suggesting that more often than not the surficial till is uppermost in till bed II.

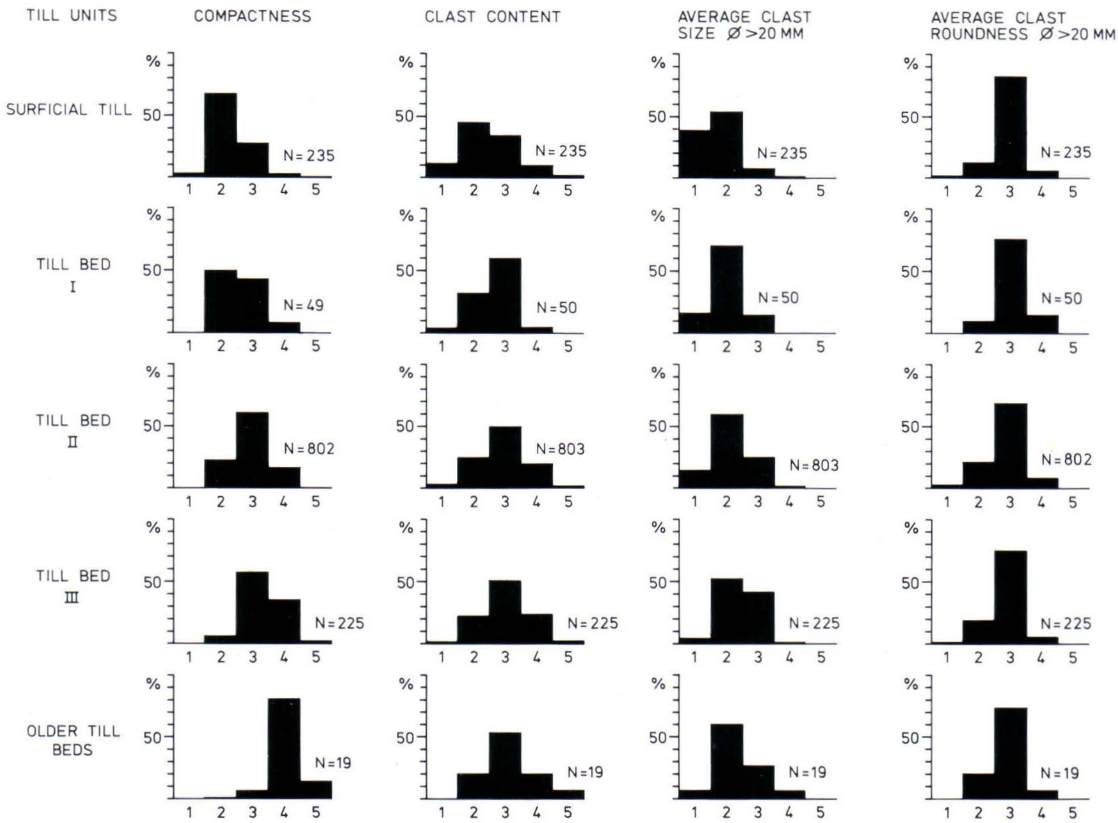

Fig. 19. Histograms showing average compactness, clast content, clast size and clast roundness of different till beds. 1—5 = scale of the property from lowest to highest; N = number of observations.

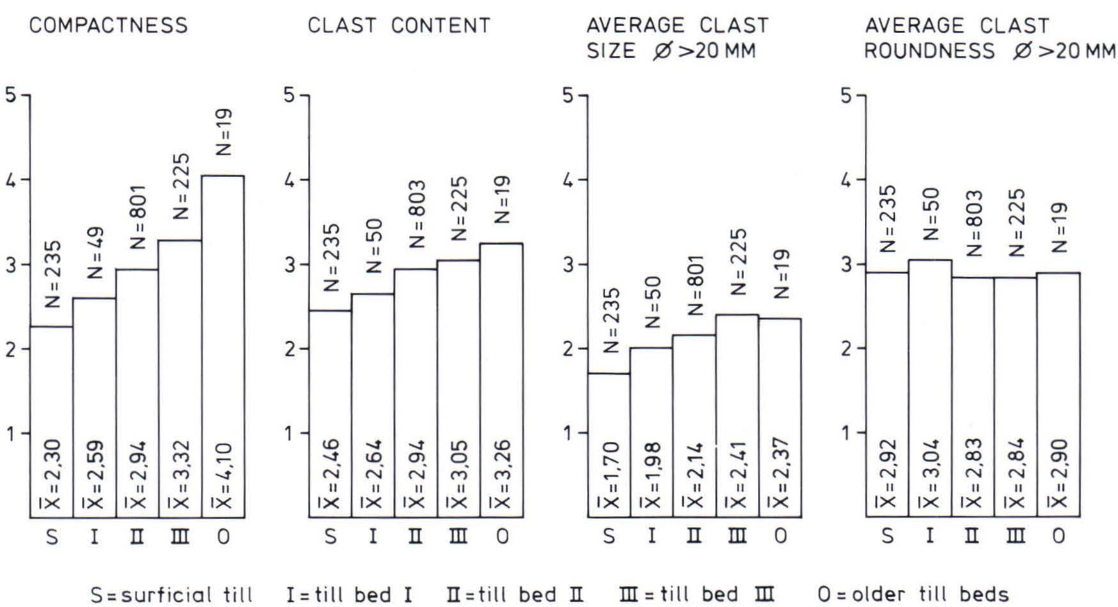

Fig. 20. Average compactness, clast content, clast size and roundness of clasts of the different till beds.

Till bed I

Till bed I is the youngest till bed, and deposited as a basal till during deglaciation. It occurs only locally, and is interpreted as having deposited in association with the oscillation of the ice front or local ice lobes. Till bed I has been reported from 50 sites, most of them in northern and eastern Lapland and in the Muonio-Karesuvanto areas (Fig. 16). Although rather thin, till bed I is still distinctly thicker than the surficial till, with a range of 0.6—2.3 m, the most common thickness being 1—1.5 m, and the average 1.3 m. The till is structureless (27 cases) or fissile (23 cases). As a rule, the fissile structure is clearly better developed than it is in the surficial till and individual lamellae are often a few millimetres thick.

The till in bed I is markedly more compact than the surficial till and has more and bigger clasts. The predominant compactness is 3 (mean 2.6), clast content 3 (mean 2.6), clast size 2 (mean 2.0) and roundness 3 (mean 3.0) (Fig. 20). It is grey or brown in colour with grey predominating and the shades varying between brownish grey and greenish grey. At its most typical, till I is a rather loosely packed and structureless grey fine sandy till with a normal clast content and small clasts (M_z = 0.196 mm). The average clay content is 3.1 %, the range 1—6.4 %, i.e. the till in bed I is, on average, coarser and its clay content markedly less variable than that in the surficial till. The grain size statistics for till bed I (21 granulometric analyses) are listed in Table 3 and the grain size distribution is shown in Figure 18.

The till in bed I exhibits the best developed fabric and the lowest proportion of vertical clasts of all the till beds. Only three of the 42 fabric analyses made on till bed I lacked a clear orientation maximum (Table 2). The orientation maxima of the analyses are shown in Figure 16. Table 1 lists the proportion of vertical clasts per hundred accepted clasts measured. In 31, or 73.9 % of the fabric analyses from till I, the number of vertical clasts was 10 or fewer.

In contrast to the surficial till, the lower contact of till bed I is usually sharp and the bed contains several layers of sorted sediments. In fact, till bed I could usually only be identified as a separate bed if the lower contact was distinct; if it was not or if it was gradual, till bed I could not be distinguished reliably from till bed II. Consequently, the observations of small, thin till beds deposited by the reactivated ice front during deglaciation (i.e. till bed I) are probably under-represented in the data. Thus till bed I may well occur over a larger area than the present data imply. A good example of the erosional and depositional activity of the continental ice sheet during the deposition of till bed I is visible at Veskoniemi, Inari, where fragments of layered fine sand derived from the underlying 30—40 cm thick slightly deformed fine sand deposits are embedded in the basal parts of till bed I (Fig. 36).

Till bed II

Till bed II is the basal till that occurs almost ubiquitously on the ground surface throughout the study area. In almost all the basal till areas till bed II is the topmost unit (excluding, of course, areas covered by till bed I). Only at nine sites is a till bed older than till bed II uppermost. In each case this is due to glaciofluvial erosion, which wiped off till bed II during the last deglaciation.

As till bed II was encountered in virtually every study pit, its properties are the best known. These are dealt with by considering the ice divide zone of flow stage II and the areas to the north and south of it as subareas. The ice divide zone was delineated with the aid of the fabric analyses made

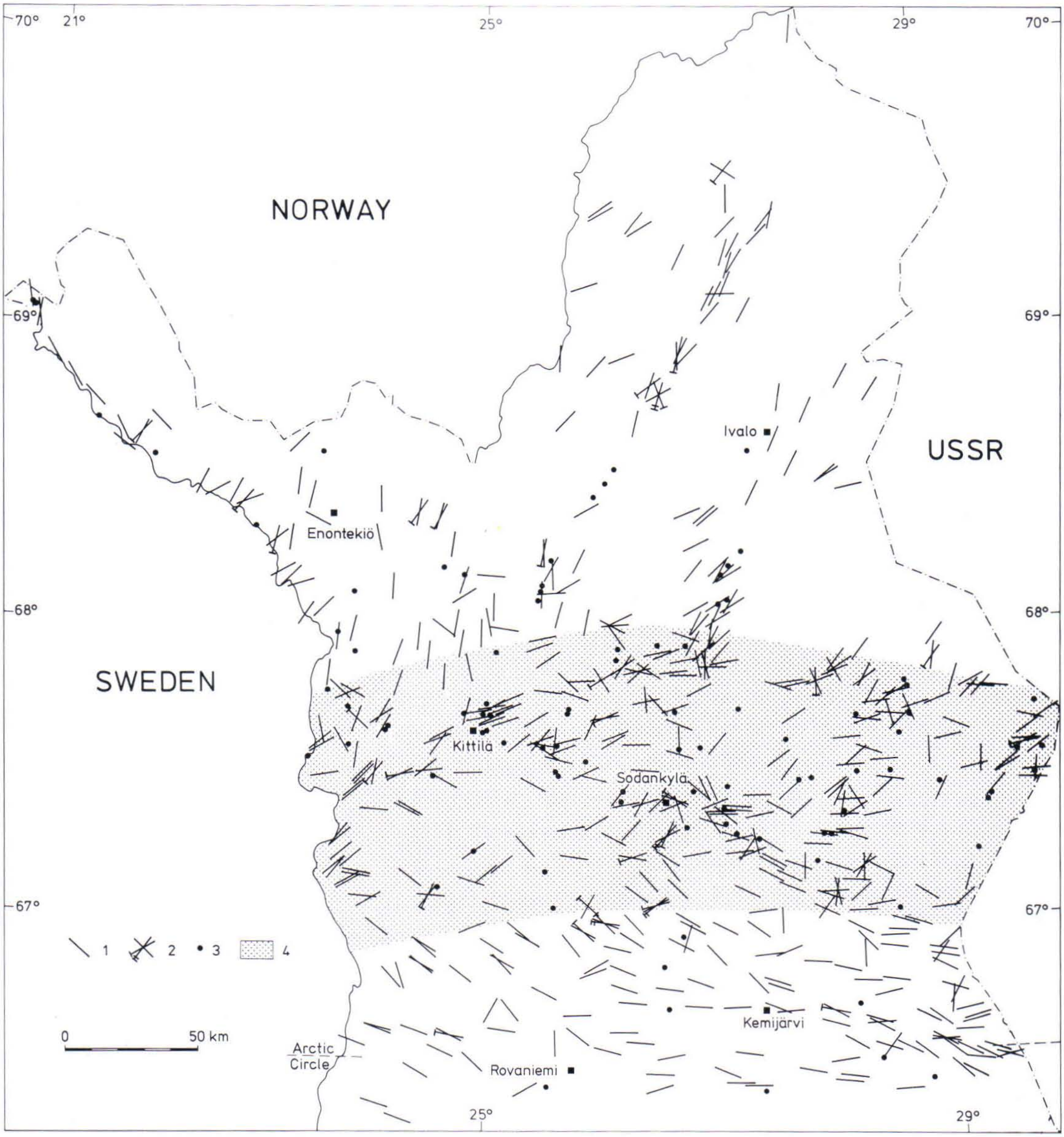

Fig. 21. Fabric analyses of till bed II. 1, orientation maximum of fabric analyses; 2, Orientation maxima at different depths. Fabric analyses from lower depths indicated by a cross bar and those from the lowest depth by a double cross bar; 3, Fabric analysis without a clear maximum; 4, Ice divide zone delineated from fabric analyses.

on till II (Fig. 21) and glacial striation data. In the present context the ice divide zone is the zone with the highest scatter in fabric. North of it the continental ice sheet flowed clearly to the northeast or north during this stage and south of it towards the southeast.

Thickness

Although rather thin in many places, till bed II is usually manifestly thicker than till bed I. Its thickness ranges from 0.3 m to over ten metres, being thinnest in central Lapland and thickest in northern and southern Lapland. The maximum thickness encountered in the pits in the ice divide zone is 5.3 m, whereas north of the zone it is over 10.2 m and south of it 7.3 m. The total thickness of till bed II in the ice divide zone could be established fairly reliably since 80 % of the pits intersected the bed there; the corresponding figure north of the ice divide zone was 59.3 % and south of it 51.7 %. In the ice divide zone the mean thickness of bed II is 1.9 m, north of it 2.5 m and south of it 2.6 m; in other words, the till bed is substantially thinner in the ice divide zone than north and south of it.

The difference in the thickness of till bed II between the ice divide zone and the northern subarea 'proper' is greater still: north of the ice divide zone, between the zone and the Saariselkä-Korsatunturi-Ounastunturi fell chain, there is a zone about 50 km wide in which the thickness and other physical properties of till bed II are very similar to those in the ice divide zone proper. As demonstrated by the occurrences of preglacial weathered bedrock, which are as common here as they are in the ice divide zone, glacial erosion was very weak in this area, too. In the zone south of the fell chain, till bed II is thinner and was intersected by pits even more often (84.7 %) than it was in the ice divide zone. The maximum measured thickness of bed II in the 'intermediate' zone is 4.5 m and the mean thickness a mere 1.8 m. Excluding this zone, till bed II was intersected in the northern subarea in only 41.9 % of the pits and the mean thickness of the bed was 2.9 m, or slightly more than in southern Lapland.

Colour

In the ice divide zone and the 'intermediate' zone in central Lapland, till bed II is often brown, but in northern and southern Lapland it is grey. In the ice divide zone, till bed II occurs in various shades of brown in 61.1 % of the pits, or in 226 out of a total of 370 pits, and in the 'intermediate' zone in 62.5 % of the pits, or in 45 out of a total of 72 pits. In southern Lapland the till in bed II was grey in 115 out of 149 pits, or in 77.2 %, and in northern Lapland in 77 out of 105 pits, or in 73.3 %.

The colour of till often depends entirely on the degree of oxidation of iron and the level of the groundwater table, even to such an extent that the same till above the groundwater table is brown due to Fe^{3+}, but below it grey as the till has retained its original colour. The till may also obtain its colour from the underlying bedrock or redeposited sediments, as in the large greenstone area at Kittilä, where it is often green. In an area of weathered bedrock, where the till may predominantly derive from the underlying weathered bedrock (weathered bedrock till), tills with very unusual colours, varying from brick red to pitch black, are encountered. The tills with fines of redeposited clay and silt frequently show the bluish grey of the original sediment.

Since the colour distribution of till II is so clear, the brown colour of the till in central Lapland can hardly be attributed simply to post-depositional secondary factors such as frost, seepage water or the groundwater table. A more likely cause is weak glacial erosion, as the till in the ice divide zone contains abundant preglacial weathered bedrock material and the continental ice sheet eroded mainly the oxidized surficial parts of the older, earlier deposited sediments. The proportion of the weathered bedrock component in till was studied with the aid of petrographic analyses, geochemical analyses and specific surface area determinations. It has been noted that the specific surface area of till increases sharply in sympathy with the abundance of weathered bedrock material (P. Nieminen, oral comm.).

Structure

In structure, till II varies, being massive, fissile, banded or layered. Most often it is distinctly fissile,

Fig. 22. Fissility typical of till bed II at Teuravuoma, Kolari. Between the lamellae there is often a 0.5 mm thick sand band. The vertical structures are Fe-Mn precipitates developed around plant roots.

individual lamellae ranging from a few millimetres to a few centimetres in thickness (Fig. 22). In the eastern parts of the ice divide zone (in Sodankylä, Pelkosenniemi and Savukoski municipalities), but also to the south of it (e.g. around Kemijärvi), till bed II is characterized by banded layering due to differences in grain size and colour (Fig. 23). The lighter layers are coarser and somewhat richer in the sand fraction, and the darker ones are silty. The basal part of the till bed is then often massive and homogeneous, and only the central part of the bed is banded. Frost, podzolization and seepage waters have frequently obliterated the banded structure on the surface of the till bed (1—1.5 m). However, the orientation of clasts in the till is the same, or almost the same, in different layers, deviating by only 5°—10°. A plausible explanation for this till bed structure is that the homogeneous basal part of the bed was deposited as subglacial lodgement till and the overlying banded till as subglacial melt-out till. Whenever the bands or layers are distinctly thicker (several or tens of centimetres) the till structure is called layered. These tills, too, are most abundant in the ice divide zone.

The till in bed II is clearly more compact (Fig. 20) (mean 2.9) than that in bed I. The clast content (mean 2.9) and the mean clast size (mean 2.1) are also distinctly higher than in till bed I. The roundness of the clasts, however, is slightly lower (mean 2.8). In the subareas the properties of till II vary as follows:

	compact.	clast cont.	clast size	round-ness
Southern subarea	3.0	2.8	2.2	3.0
Ice divide subarea	2.9	2.9	2.0	2.8
Northern subarea	3.1	3.0	2.4	2.7

Grain size

The mean grain size (M_z) of till in the ice divide zone is 0.13, in the northern subarea 0.21 and in the southern subarea 0.16 (Table 3). The corresponding mean clay contents are 4.0, 3.1 and 3.2 %, respectively. In the ice divide zone the clay

Fig. 23. Banded layering in places characteristic of till bed II at Kaihua, Rovaniemi. The basal part of the till bed, which is massive and homogeneous, is interpreted as subglacial lodgement till and the banded till as subglacial melt-out till. See text.

content varies in the range 0.3—15.2 % and in the southern subarea 0.4—10.1 %. In the northern subarea the range is 0.3—12.0 % with the highest clay content (12.0 %) being in the till that rests on weathered bedrock in the intermediate zone. The highest clay content encountered in the northern subarea 'proper' (north of Saariselkä—Enontekiö) is a mere 8.5 %. If the tills of the subareas are pooled, till II is fine sandy till (M_z = 0.16 mm) with a mean clay content of 3.4 %, i.e. on average, it is only slightly finer and richer in clay than bed I.

Regional comparison of till bed II; till fabric

The till in bed II exhibits some interesting differences between subareas. In the ice divide zone it is more loosely packed, and the clasts tend to be smaller than in the southern and northern

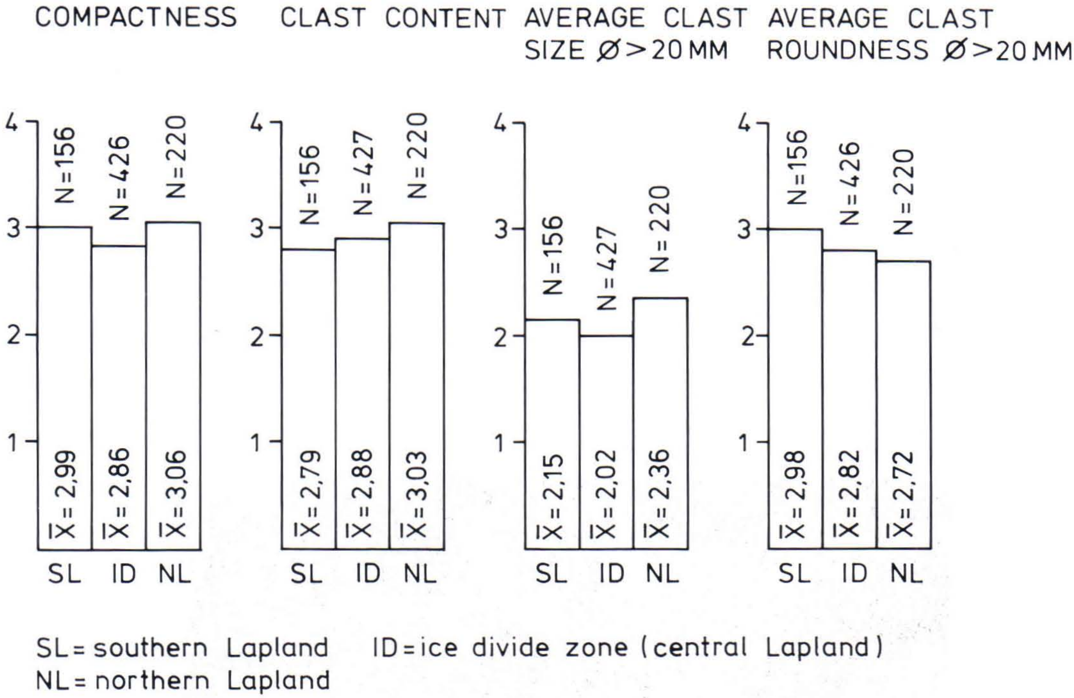

Fig. 24. Average compactness, clast content, clast size and roundness of clasts of till bed II by subareas.

subareas (Fig. 24). It is also finer in grain size and richer in clay, with a larger variation in clay content than in northern and southern Lapland (Table 3). The most likely reason for this is that in the ice divide zone a considerable proportion of till II derives from the underlying weathered bedrock, from its surficial parts in particular (cf. Fig. 4). If the till is composed almost entirely of local weathered bedrock material, but has been transported and deposited by the continental ice sheet, it is called weathered bedrock till. The term weathered bedrock till does not refer to till bed II only, but is a general term applied to all tills rich in weathered bedrock material. It has turned out to be useful in exploration and geochemical investigations and in interpreting the results, as it reveals immediately that the till in question is composed almost entirely of material from local weathered bedrock and that the source of an ore indication found in such a till should be looked for in the immediate vicinity.

The tills of the northern subarea are more compact and richer in clasts than those in the other subareas; on average, the clasts are also bigger and less round. They are distinctly coarser and contain the least clay, and the variation in clay content is the lowest. This is probably due to quarrying by the continental ice sheet, which was very active there, as demonstrated by the numerous drumlins in the area. Seven hundred and forty fabric analyses were made from till bed II, of which 104 (14.1 %) did not show a clear orientation. Most of these unoriented till II occurrences are in the ice divide zone or in the intermediate zone to the north of it (Fig. 21). Till bed II is the second best oriented 'true' till bed after till bed I. In 483 of the fabric analyses (65.3 %) from till bed II the number of vertical clasts per measured and accepted oriented clasts was 10 or fewer, corresponding fairly accurately to the mean of all the fabric analyses (Table 1). The results of the fabric analyses (orientation maxima and unoriented) are shown in

Figure 21. With some exceptions, the fabric analyses made south and north of the ice divide zone indicate the general direction of glacier flow during this glaciation stage fairly consistently. The scatter in directions, however, is high in the ice divide zone, to such an extent that orientations measured from a single stratigraphic unit in adjacent study pits may differ by up to 90°.

Several reasons are postulated for the high scatter in orientation and the lack of orientation in the ice divide zone. One is that more fabric analyses were made here than anywhere else and that some of the till fabrics are 'normal' transversal orientations or were caused by solifluction. But then, even the slightest shifts of the ice divide could have resulted in marked changes in local flow direction. Glacier activity may also have been so weak or the till material so local that a clear orientation parallel to the glacier flow either did not or had no time to develop.

Yet again, due to activation of the ice front, the surficial part of till bed II could sometimes have deposited as till bed I. As clear erosion surfaces or layers of sorted sediments are lacking between

Fig. 25. A sharp contact between till bed II and glaciofluvial sand (esker) at Teuravuoma, Kolari. The till bed is 2 m thick.

the till beds this process has gone unrecognized, and the whole till unit has been considered as till bed II. Thus, the topmost of the fabric analyses made in adjacent study pits from a bed interpreted as a single stratigraphic unit may represent the direction of youngest glacier flow (I) and an analysis from a slightly greater depth, a somewhat older one (II).

Lower and upper contacts of till bed II

As stated above with reference to till bed I, till beds I and II could be distinguished reliably only if the contact between them was sharp or occupied by sorted interlayers. If not, the upper contact of till II is rather ill-defined, and till II grades into surficial till without a distinct boundary. The lower contact of the bed, in contrast, shows great variety, being sharp, gradual or mixed, sometimes displaying distinct erosional surfaces, e.g. boulder pavements, sorted sediments and even organic layers or layers containing organic matter, and sometimes exhibiting glaciotectonic capture patterns with material from older sediments or weathered bedrock in the basal part. Most often the lower contact of the bed is distinct and sharp, the contact zone (mixing zone) being only a few mm or cm thick, in which case the contact can often be delineated by the striking difference in colour. Often the contact is knife-sharp, irrespective of whether the till is in contact with an older till or sorted sediments (Fig. 25). At other sites, particularly if the till bed rests on sorted sediments or weathered bedrock, the mixing zone in the lower part of the bed may be quite thick, 0.5—1 m. If so, the lower part of the bed may be composed almost entirely of reworked underlying sorted sediments or material from weathered bedrock (weathered bedrock till), making accurate determination of the contact difficult.

Origin of till bed II

Till bed II probably deposited for the most part during deglaciation. This supposition is corroborated by the fact that, at Kemijärvi and Enontekiö, the hummocky moraines that deposited during deglaciation are underlain by till bed III, which derives from the previous glaciation. At Kemijärvi, till bed III is covered by an 8.1 m thick hummocky moraine deposit and at Enontekiö by one of 4.7 m. In places, till bed II is composed of two or more units or layers differing in fabric and other properties. This has been seen as evidence that the lower layer probably deposited when the ice sheet was growing, and the upper layer when it was waning. Of course it is always feasible that both layers deposited during the same stage of glaciation with but a slight difference in time and orientation.

Till bed III

Unlike the younger tills, till bed III is fairly regular in appearance and physical properties throughout the study area (Fig. 26). It is almost invariably bluish grey (in 82.4 % of the cases) with only the hues of grey varying, except in the weathered bedrock area, where it is brownish. Observations of till bed III (or the till in the corresponding stratigraphic position) were made in 212 study pits, most of them in central and eastern Lapland. No reliable data on till III were recorded from the northernmost and northwesternmost part of the study area (Fig. 27); either the pits did not penetrate till II or stage II had been so active and powerful that ice had eroded and redeposited most of the pre-existing deposits.

The thickness of the till bed could not be determined reliably, because the excavator could penetrate the whole bed only in 41 (19.3 %) of the total of 212 pits. In 23 pits the till bed rested on bedrock, in 13 pits on sorted sediments and in five pits on older till beds. The recorded thicknesses ranged from less than 0.5 m to over 6 m. It was

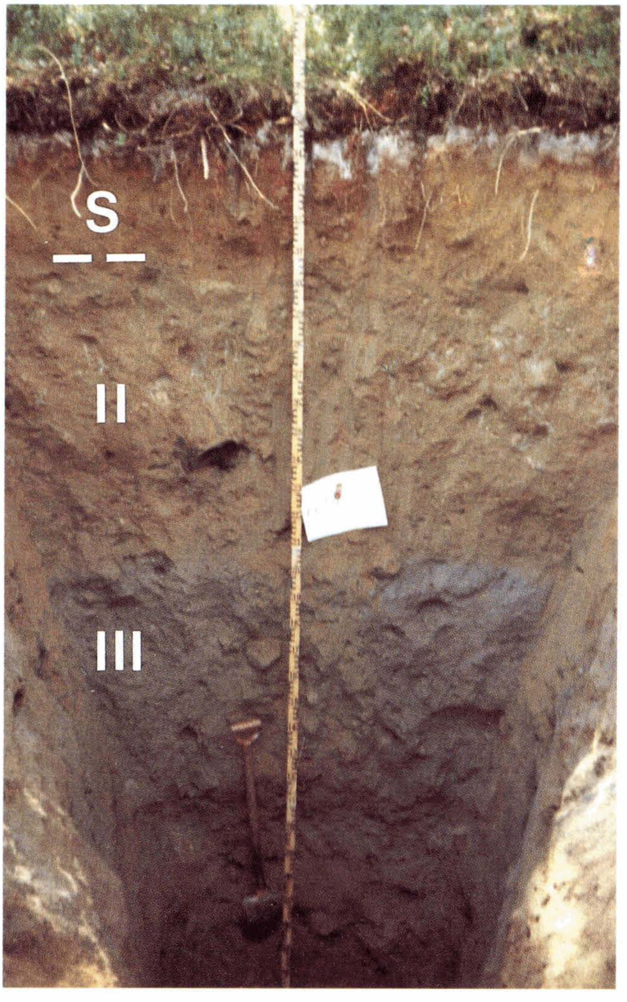

Fig. 26. Surficial till (S) and typical till beds II and III at Huhtalehto, Kolari. The till in bed II is brown and fissile and that in bed III grey and massive. The contact between till beds II and III is sharp whereas that between the surficial till and till bed II is gradual.

noted that in depressions, where the till had been protected from erosion caused by younger glaciations, the bed might be quite thick. However, till bed III is lacking in many places, and the bedrock or weathered bedrock is overlain only by till bed II. This means that either till III was not deposited everywhere or it was glaciofluvially eroded during deglaciation or by the glacial erosion of stage II. The till structure is either massive (54.7 %) or fissile (45.3 %). The fissile structure often becomes more prominent with depth, and the thickness of the lamellae increases, reaching a maximum of 4—5 cm. Small lenses and interlayers of sorted sediments and shear surfaces a few mm thick and containing fines are typical of the till.

In grain size, till III is fine sandy till ($M_z = 0.14$), with a mean clay content of 3.5 % and a range of 0.3—14.2 % (Table 3). It is, on average, slightly finer and richer in clay than till II. The till in bed III is clearly more compact (mean 3.3) and richer

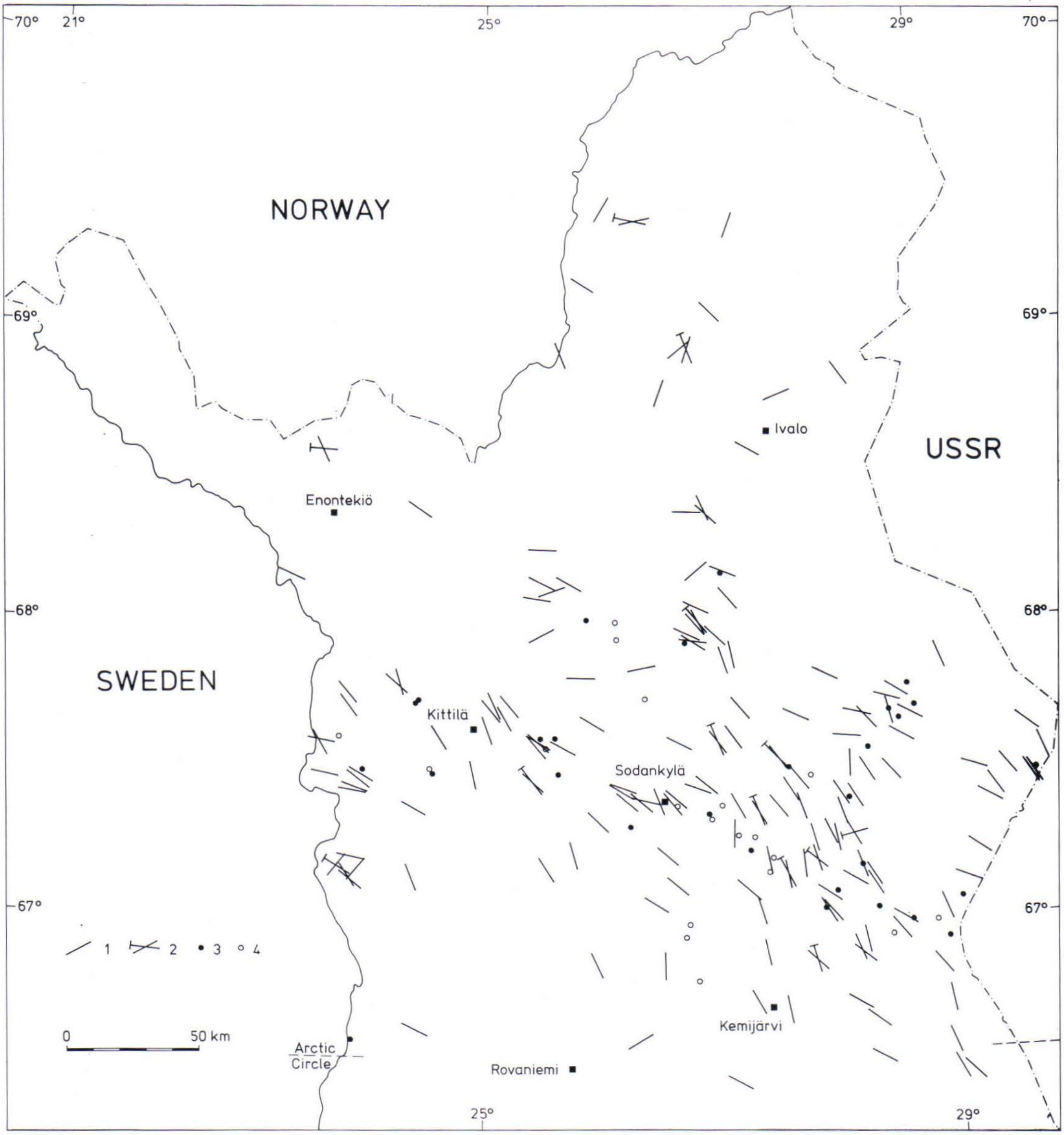

Fig. 27. Fabric analyses of till bed III. 1, Orientation maximum of fabric analysis; 2, Orientation maxima at different depths. Fabric analyses from lower depths indicated by a cross bar; 3, fabric analysis without a clear maximum; 4, observation of till bed III.

in clasts (mean 3.1) than that in bed II (Fig. 20). The clasts are bigger (mean 2.4), but their mean roundness, 2.8, is about the same as that in till bed II. The upper and lower contacts of the till bed vary in type as do those of till bed II. Most often they are both distinct and sharp erosional contacts but with the lower contact being even sharper than the upper one. When the till bed rests on an older till, the lower contact is almost invariably characterized by such a dramatic change in colour and compactness that it shows up clearly, even while the pit is being dug. Two hundred and ten fabric analyses were made from till bed III (Fig. 27), but in 36 of them (17.4 %) the till did not show a distinct orientation maximum (Table 2). The proportion of unoriented tills is markedly higher than in the younger till beds. This can be attributed, at least partly, to the fact that the majority of the fabric analyses had to be made from the surficial part of the till bed on the bottom of a pit, where the orientation of the clasts could have been disturbed by younger glacier flows or ancient frost. Attempts were made to conduct fabric analyses on all the till III occurrences encountered, including those very rich in big clasts, which, had they been younger tills, would not have been analysed.

The results of the fabric analyses suggest that during the glaciation stage that deposited till bed III, the ice divide lay somewhat to the north of where it was during the last glaciation stage, when till bed II was deposited. Fabric analyses from south of the ice divide zone demonstrate clearly that the ice sheet flowed from northwest to southeast during this stage. North of the ice divide, the orientation maxima of till bed III have two directions, which may deviate by up to 90° from each other — one from northwest to southeast and the other from southwest to northeast. Both have been interpreted as real, that is to say, although they reflect the flow directions of a single glaciation they refer to different stages. In some pits the basal part of the till bed exhibits the northwest-southeast orientation, but higher up the southwest-northeast orientation. In other physical properties, the upper and lower parts of the bed may be very similar or differ only slightly from each other.

Both directions are also recorded in the scarce glacial striation in the area, the northwest-southeast striae occuring as older components in the cross striation on bedrock surfaces protected from the younger erosion.

The tills with the northwest-southeast fabric are interpreted as having deposited during the initial stage of glaciation, when the ice sheet was flowing from the Scandinavian mountain range. As the ice sheet gained in thickness and its central area shifted southeastwards the flow in its northern part turned towards the Arctic Ocean.

Older till beds

Older till beds underlying till bed III were encountered in 17 study pits (Fig. 28), most of them in the eastern part of central Lapland. Apart from three pits (the northernmost and the two southernmost), the older till beds are located in the large ice divide zone of stage II, all of them in the area where the occurrences of preglacial weathered bedrock are most common. In general, the older till beds have been encountered only on the bottom of the deepest pits, which were made by deepening existing cuttings. As indicated by their stratigraphic position and fabric and the sorted minerogenic deposits between them (at Naakenavaara also 1.5 m of *in situ* peat, Fig. 65), the older till beds were deposited during at least three different glaciation stages.

Contrary to previous practice (e.g. Hirvas et al. 1976 and Hirvas et al. 1977), the tills older than till bed III are not named as specific beds, with the exception of Rautuvaara open pit and Naakenavaara, but are referred to collectively as older tills or older till beds. This is due to the scarcity of data and to the fact that, apart from Rautuvaara, where there are three superimposed older till beds (Fig. 39), the only places where two superimposed older till beds have been encountered are Naakenavaara (Fig. 37) and Haurespää (Fig. 28), both in Kittilä, and Muotkaselkä in Salla (Fig. 37). In most of the older tills the clasts exhibit a more or less distinct southwest-northeast

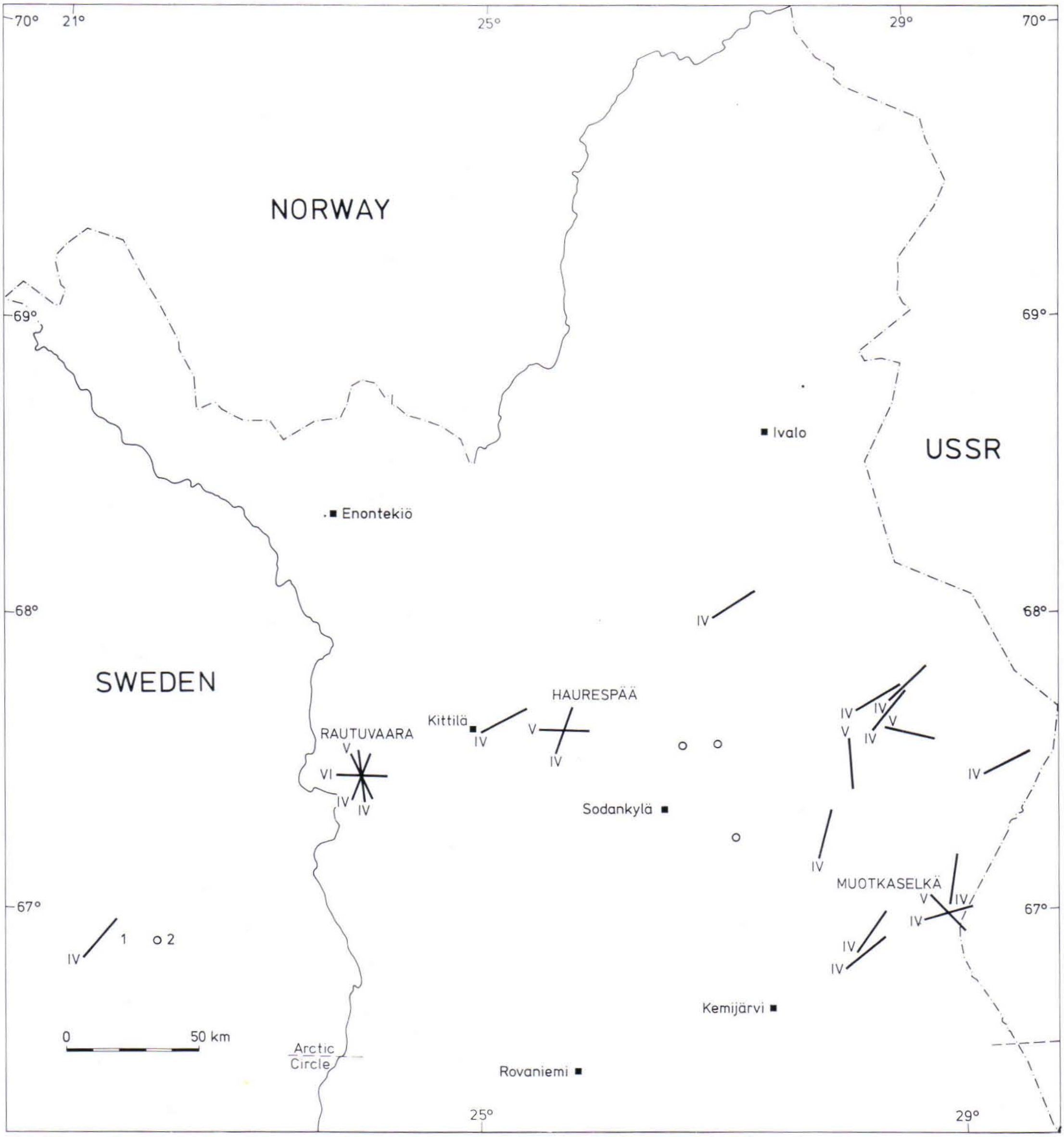

Fig. 28. 1, Fabric analyses of older till beds and their correlation to the till stratigraphy. 2, Observation of an Older till bed.

orientation. Owing to the lack of appropriate tracer lithologies, the only site where stone counts succeeded in unambiguously establishing the flow direction of the ice sheet that deposited the tills with this orientation was Naakenavaara. There, 27 % of the rock types in till bed IV are granite, which could only have been transported from the southwest, from the granite massif lying west and southwest of Kittilä and about 10 km away from Naakenavaara (analysis and oral comm. by P. Rastas, Table 4). The clasts in till IV at Naakenavaara are inclined towards the southwest.

Interpretation of the fabric analyses of the older till beds, or rather the reliability of the interpretation, was hampered by the fact that the analyses often had to be made from the upper part of the till bed, and that stones and boulders were so abundant in the till. It is possible, therefore, that the fabric of the clasts in till does not reflect the direction of glacier flow but, instead, is a transversal or disturbance direction.

Table 4. Petrographic analyses of the tills of the Naakenavaara study site (anal. P. Rastas).

Rock type	Till beds		
	II	III	IV
Granite (Kittilä NW type)	—	35	—
Granite (Kittilä W and SW type)	42	—	27
Quartzite	28	20	34
Mafic volcanic rocks	26	40	20
Diabase	2	4	11
Mica gneiss	—	—	8
Diorite	1	—	—
Monzonite	—	1	—
Jasper	1	—	—
Σ %	100	100	100

The genesis of the older tills is not always clear either, as some structural features may have been obliterated by glacier loading, weathering or younger glacier flows, or then the structures could not be observed over sufficiently large areas on the bottom of the study pits. Some of the older tills may well be ablation or flow tills, in which case the clast fabric does not refer to the direction of glacier flow. At Rautuvaara, at least, till bed IV, which deposited as basal till, is overlain by a veneer of what has been interpreted as very sandy surficial till poor in clasts (Fig. 39). Vittikko in Salla was the only site where the older till with a southwest-northeast orientation could be penetrated down to the bedrock (Fig. 37). As the bedrock, which was medium-grained red granite, did not show any glacial striation, it was not possible to determine the flow direction from the striae either. However, the striation data suggest an old glacier flow from the southwest. At Aavasaksa, in the southwestern corner of the study area, a striation direction of 235°—240° (Fig. 10) was encountered that was older than the prevailing direction, 275°—280°, of the youngest glacier flow. In relation to the younger glacier flow, the older striae are located on the lee-side of a roche moutonnée on their own erosion facets and thus cannot be simply attributed to the ice sheet circumventing an obstacle.

It is quite possible that the older tills did in fact occur more often in the study pits than was realized. At the start of the study, it was assumed that a till bed (IV) older than till bed III had been deposited by a continental ice sheet flowing approximately from the southwest. When a till with this orientation was encountered under till bed III, it was accepted and interpreted as 'old till'. If, however, the till exhibited a fabric more or less identical to that of the overlying till bed (III) and there were no sorted sediments between them, it was not interpreted as a separate older bed but as a layer of bed III that differed from the others merely in physical properties.

The material of the older tills is usually highly compacted (mean 4.1, Fig. 20), and in places as hard as concrete (Fig. 19). The brownish and greyish tills often contain abundant fully weathered clasts that give them an 'old' look (Fig. 29). The brown tills in particular exhibit unusual hues from an intense brown to a yellowish or reddish brown. This is probably due either to the weathering and cementing processes that took place in the tills after their deposition or to the high abundance of material from weathered bedrock. About half of the tills are massive in structure and the other half fissile, often very clearly so. The older tills are richer in clasts (mean 3.3) than the younger ones, but the mean clast size (2.4) and the roundness of the clasts (2.9) are almost the same as in till bed III (Figs. 19 and 20). The roundness of the clasts results from the fact that weathering continued to erode them after deposition.

In grain size the older tills are fine sandy till

Fig. 29. Till bed IV at Rautuvaara, Kolari. The lower part of the bed is brownish grey, intensely fissile, compact, fine sandy till with a low content of small clasts. The bulk of the till derives from underlying sorted sediments. The upper part is brown, compact, sandy till, in places extremely rich in clasts.

(M_z = 0.14 mm). The mean clay content, which is 4.0 %, the range being 1.8—8.7 %, is the highest in any of the till beds. Although the differences in means are not great the data demonstrate that the mean clay content of the till beds persistently increases from the youngest to oldest beds (Table 3).

The upper contact of the older tills, or the boundary with the overlying younger tills, is usually very distinct and sharp, as many properties of the older tills (such as colour, compactness, clast content, structure, degree of weathering and cementing) differ radically from those of the overlying younger tills. The contact is often disclosed by the increasing difficulty, or even impossibility, of digging due to the compactness and high clast content of the till. The older tills also frequently differ from the younger ones in colour.

Thirty-three fabric analyses were made from the older tills (Fig. 28). Their material is distinctly less oriented than that of the younger tills, and nine analyses, or a third, did not show a clear orientation maximum (Table 2). Instead, the number of vertical clasts per 100 accepted clasts measured is approximately the same as in till beds II and III (Table 1). A feature common to the fabric diagrams of the older tills is that the orientation maximum is wider and more scattered than that of the younger till beds. The less distinct fabric of the older tills can obviously be attributed to the factors mentioned above, that is, the high abundance of clasts, the partial reorientation caused by younger glaciations and, above all, the fact that the fabric analyses had to be made from whatever exposed material was available; more appropriate sites, e.g. the central parts of the bed, were out of reach. This is evident at sites where fabric analyses could be made from older tills at various depths. For example, at Vintiläkaira, Savukoski (Fig. 37), the orientation maximum of the fabric analysis from the upper part of the till bed is wide (190°—280°) and incoherent, yet only 0.7 m deeper it is narrow (230°—240°) and very sharp; in both, the orientation maxima of the clasts are the same, i.e. 235°.

The older tills were intersected in only three study pits besides that at Rautuvaara, Kolari. Consequently, the thicknesses of the older till beds are poorly known, and the data mainly refer to the minimum thicknesses. The recorded thicknesses range from 1 to 6.4 m. It is interesting to note that at Rautuvaara, the source of the best bed thickness data, till bed V is the thickest (max. 6.4 m), till bed IV the second thickest (max. 6 m), and till bed III the third, being 'only' 5 m thick (Fig. 39). Also at Naakenavaara (Fig. 37) the older till bed is the thickest. In places till bed IV is 3.8 m thick, whereas the maximum thickness of till beds II and III is about 2 m (cf. chapter on Correlation and dating of the Pleistocene stratigraphy in Finnish Lapland).

ICE FLOW STAGES

Six ice flow stages and their corresponding till beds have been recorded from Lapland. The most recent flow took place during deglaciation. The uppermost till bed in most parts of the study area is called till bed II. It was deposited by the youngest glacier flow that extended over the whole of Finnish Lapland and is named flow stage II. The melting of the continental ice sheet was not, however, continuous throughout the study area, as the area that was already ice-free was affected by oscillations of the ice margin or local ice lobes. These glacier oscillations, local and short in extent, are named **flow stage I** and the tills deposited by them are known collectively as till bed I.

Most observations of local advances of the ice sheet during the last deglaciation were made in northern and eastern Lapland (Fig. 30). The readvancing ice front is attested to by the thin gravel and sand layers and boulder pavements between till beds I and II. East of Sodankylä and southwest of Inari, till bed II contains frost wedges that start on the boulder pavement between till beds I and II. At this stage the ice sheet was already markedly thinner and flowed along depressions in the basement. As the ice front in areas of rough relief was composed of several lobes streaming in different directions, local flow directions may differ substantially from each other. In broad outline, however, the flow directions of the ice sheet during stage I are conformable with those of flow stage II. During flow stage I glacial erosion and deposition were probably very weak, and affected mainly previously deposited formations rather than fresh or weathered bedrock.

During **flow stage II** the glacier flowed approximately from west to east in southern and central Lapland, and to the northeast in northern Lapland (Fig. 31). However, at this stage, too, the flow appears to have conformed to the large-scale morphological features of the bedrock. The ice

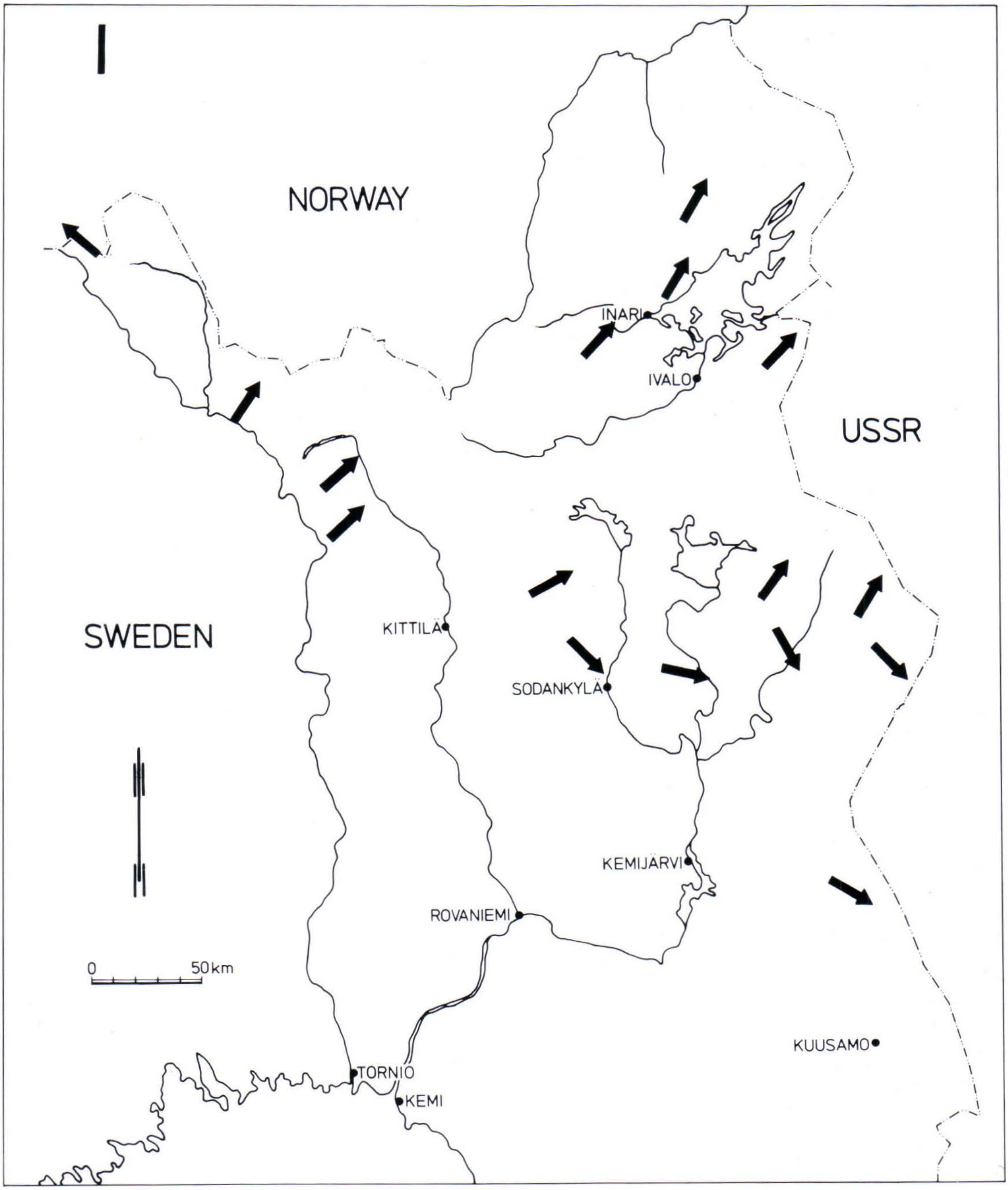

Fig. 30. Flow stage I. The till beds of this stage were deposited during deglaciation as a result of oscillation of the glacier margin or local glacial lobes.

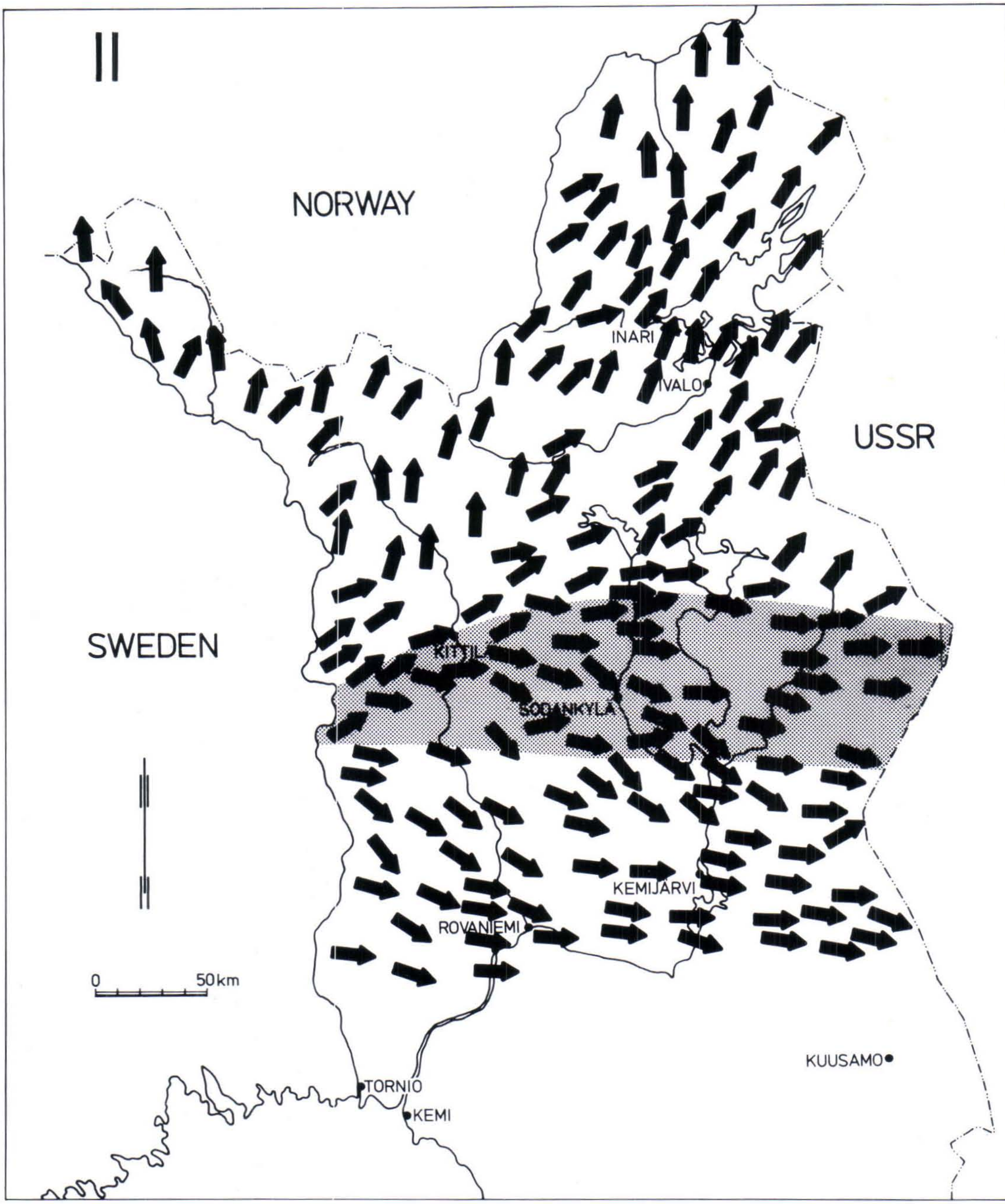

Fig. 31. Flow stage II. The hatched area is the ice divide zone, where the variation in the flow direction of the continental ice was the greatest.

divide was located in central Lapland, in a low-lying, flat area south of the Saariselkä-Marasto fell chain.

It was difficult to determine the directions of ice sheet flow in the ice divide zone. The fabric analyses yielded such discrepant values that orientations measured from the same till bed in adjacent test pits could deviate from each other by as much as 90°. Obviously even the slightest shift in the position of the ice divide can cause a considerable change in local flow directions. The network of glacial striae in central Finnish Lapland, a number of observations of fluted moraine surfaces and the results of stone counts combined with fabric analyses indicate that, on average, the ice sheet flowed eastwards in the ice divide zone.

During this stage the glacier flow was very active outside the ice divide zone, making it easy to determine the flow directions of the continental ice sheet. Most of the striae in the study area and most of the glacial macrolandforms, such as drumlins, flutings and large fields of hummocky moraines, were formed during this stage.

During **flow stage III** (Fig. 32), the ice sheet advanced from northwest to southeast, except in northernmost Lapland, where it streamed towards the NNE and the Arctic Ocean, as it did during flow stage II. At this stage the ice divide was about 50—100 km north of that of stage II, but still south of the Saariselkä-Marasto fell chain. Indications have been found in northern Lapland of a northwest-southeast ice flow older than stage II (cf. Kujansuu 1967). There are some striae with this orientation (Fig. 10), and rounded clasts of Caledonian sedimentary rocks (transported from Norway) have been found west and north of Ivalo. At Jäkäläpää, in the Lemmenjoki gold panning area, about 70 km west of Ivalo, up to 7 % of the rock types in till are sedimentary rocks (5 % sandstones, 2 % shales, anal. P. Pihlaja) transported from Norway.

Numerous other researchers have also made observations on glacial transport from the northwest in northern Lapland. According to Saarnisto and Tamminen (1985), 8.5 % of the rock types are anorthosite in the 6—20 mm fraction of the till bed that underlies till bed II in the Sotajoki area, about 65 km southeast of the only known anorthosite occurrence in Finnish Lapland. The results of stone counts from the northwesternmost corner of the study area, in Enontekiö, where excavations have not confirmed tills older than flow stage II, show that during an earlier stage the glacier flowed from the (west) northwest. The topmost till between Kilpisjärvi and Karesuvanto (till bed I or II) has 1—2 % Caledonian sedimentary rocks and bluish quartzite as shown by stone counts (2—6 cm fraction) (anal. O. Auranen and E. Pulkkinen) (cf. Tanner 1915, Kujansuu 1967).

Till with a northwest-southeast orientation and older than till bed II was encountered in over ten study pits. In two of them the till is overlain by till bed II and a till unit with a southwest orientation (Fig. 27) (cf. chapter Till bed III). This northwest-southeast trending glacier flow in northern Lapland is interpreted as having taken place during the early part of the stage III glaciation while the ice sheet was advancing from the Scandinavian mountain chain (e.g. Tanner 1915, Kujansuu 1967). As the ice cover grew thicker and its centre moved southeastwards the ice sheet started to flow towards the Arctic Ocean, i.e. northeastwards in northern Lapland (cf. J. Lundqvist 1974), but continued flowing southeastwards south of the ice divide zone. In other words, whenever a till bed with a northwest-southeast orientation is immediately below till bed II (and the sorted sediments under it) in northern Lapland, the sequence is interpreted as incomplete, i.e. the till referring to the main phase of flow stage III (with southwest-northeast orientation) is lacking. No minerogenic sorted sediments or distinct erosional contacts were found in northern Lapland between the northwest-southeast and southwest-northeast oriented till beds. This supports the proposition that the till beds were deposited during different stages of the same glaciation.

During stage III, glacier activity was intense, at least in central Lapland, where the rare northwest-southeast trending drumlins and large drumlinoids (up to several kilometres long and a kilometre

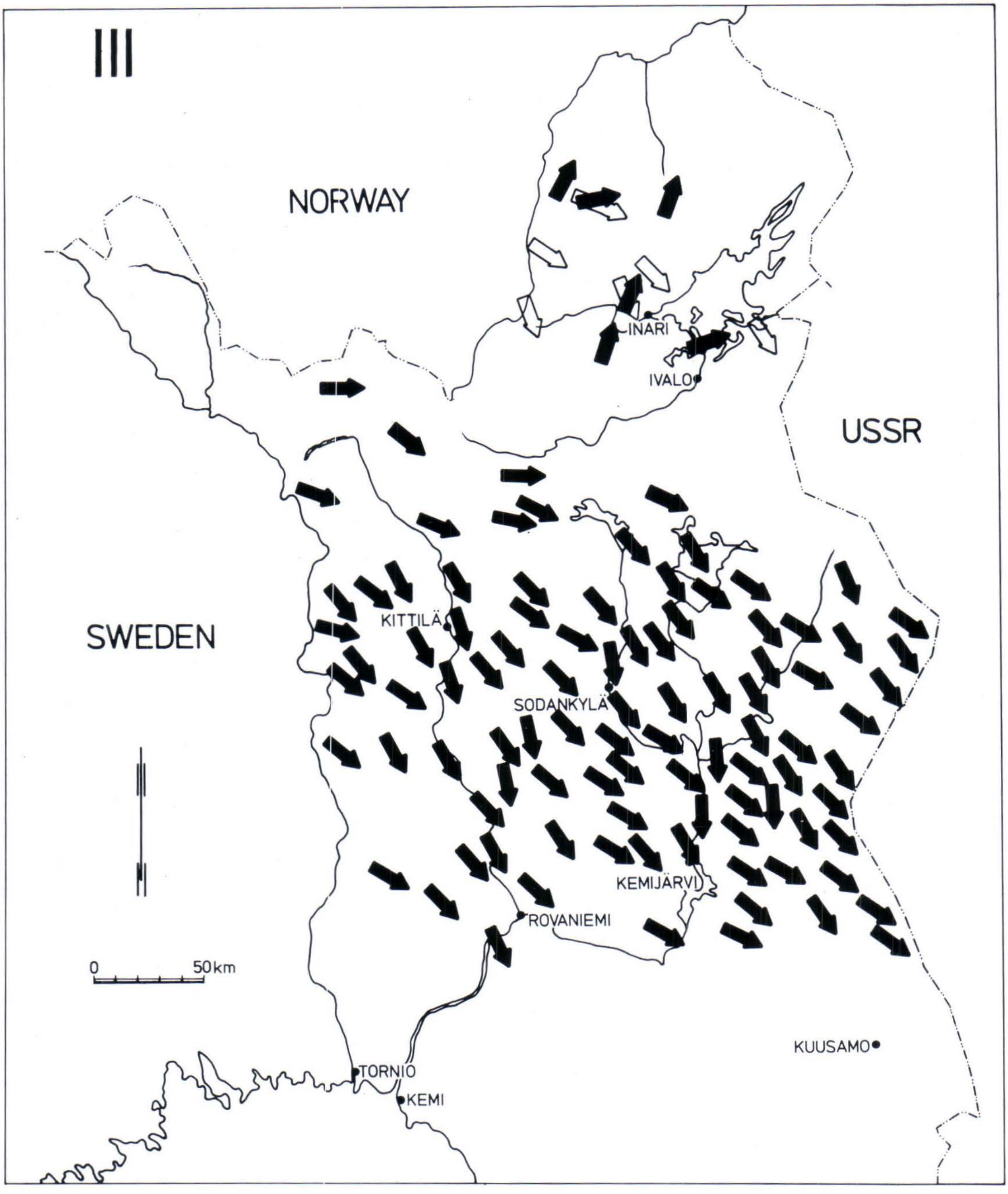

Fig. 32. Flow stage III. Open arrows show the direction of ice flow in northern Lapland during the initial stage of this glaciation.

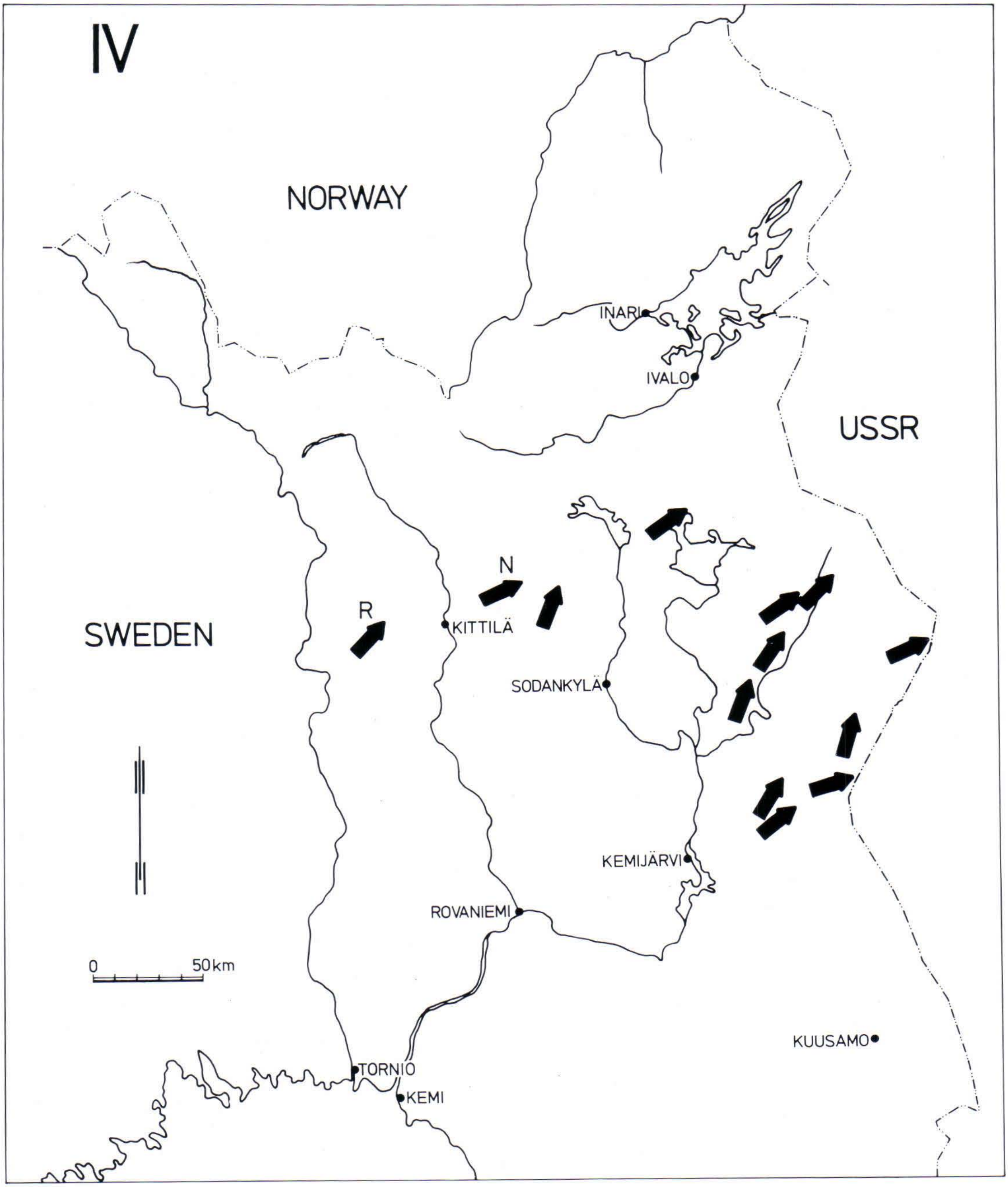

Fig. 33. Flow stage IV. The glacial flow direction during this stage has been confirmed with stone counts only at Naakenavaara, Kittilä (N) and at Rautuvaara, Kolari (R). At other sites the arrows indicate the interpreted direction of glacier flow.

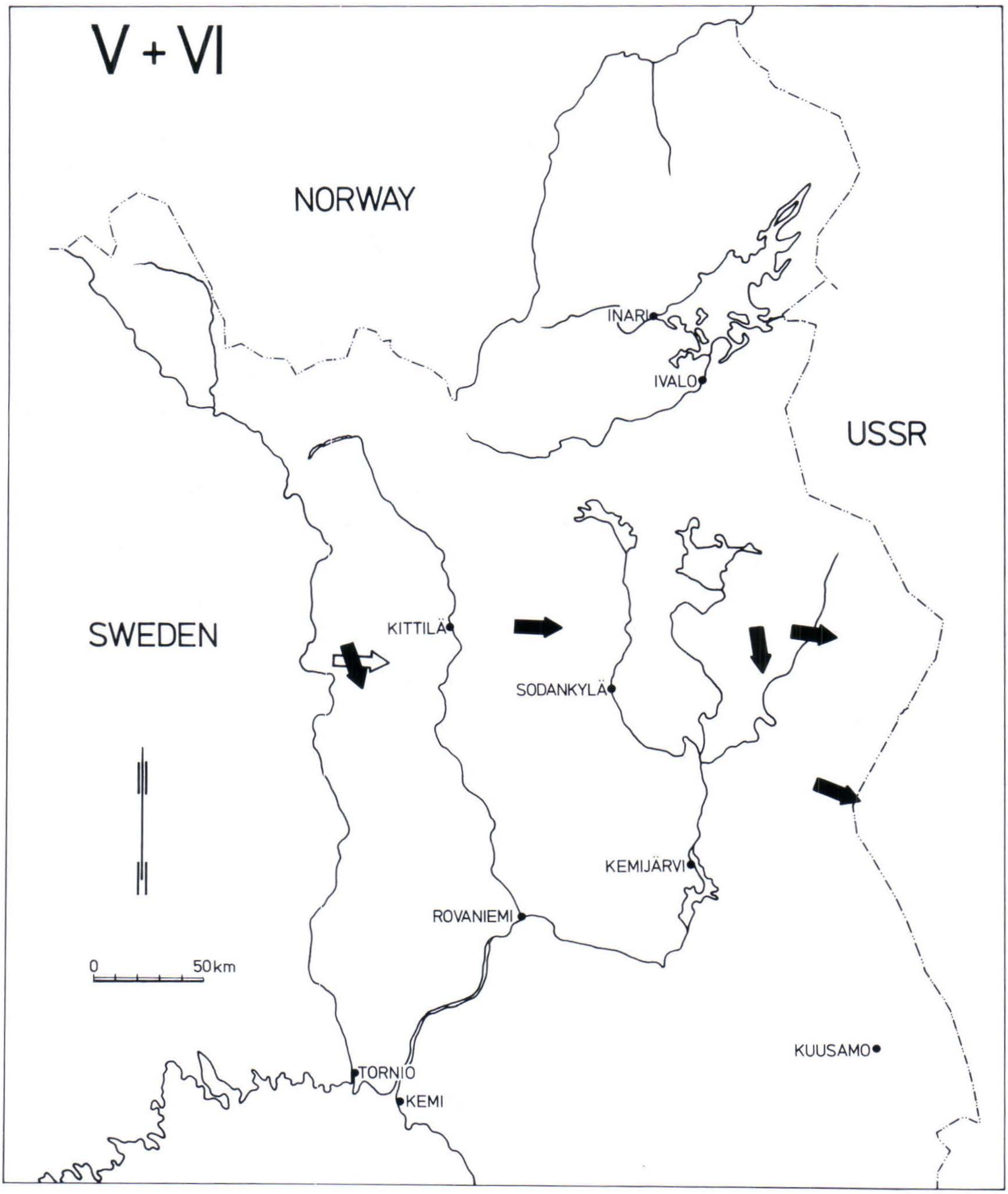

Fig. 34. Flow stages V and VI. From the meagre data available it would seem that during flow stage V the ice sheet flowed in approximately the same direction as during flow stage III. The oldest flow stage, VI, has been observed only at Rautuvaara, Kolari (open arrow).

wide) formed during this flow stage show up distinctly on aerial photos (cf. chapter Aerial photo-interpretation). In contrast, in northern Lapland, some drumlinoids seem to have been formed at the beginning of the glaciation of flow stage III (cf. Kaitanen 1969). East of Karigasniemi, at Fierbeluovdduskaidi, there are WNW-trending drumlinoids. Three study pits were dug into the biggest one. This drumlinoid, which is 5 km long and 1 km wide, exhibits a 290° orientation. The study pits were from 3 to 4.1 m deep and did not reach bedrock. The stratigraphy of the adjacent pits was the same, with the uppermost till bed II typical of the area underlain by till bed III. The thickness of till bed II varied in the range 1.4—2.3 m and its clasts showed an orientation of 220° (two fabric analyses). In the upper part of till bed III the orientation of the clasts was 260° and lower down 285°, or the same as that of the drumlinoids.

Very few till beds older than flow stage III were encountered, the majority of them on the bottom of the deepest cuts. On the basis of fabric analyses they were classified as till beds IV and V. Observations suggest that the ice sheet flowed from WSW to ENE during **flow stage IV** (Fig. 33), and in approximately the same direction as during stage III, or from northwest to southeast, during **stage V** (Fig. 34).

Owing to the scarcity of observational material and the lack of suitable rock types, stone counts could be used at only one site (Naakenavaara, Kittilä) to check the flow direction of the glacier that deposited till bed IV. At Naakenavaara, 27 % of the rock types in till bed IV are granite transported from the southwest (cf. chapter Older till beds and Table 4). The outcome of the stone counts, geochemical analyses and mass-susceptibility determinations from the till bed at Rautuvaara supports (but does not verify) the results of the fabric analyses, implying that the ice sheet that deposited the till bed flowed from the southwest (cf. chapter Geophysical properties of the Rautuvaara tills). According to the fabric analyses, the ice divide was located south and/or southwest of the study area at this stage.

The oldest **flow stage, VI**, was observed reliably at one site only, in a till cut at the Rautuvaara mine. According to four fabric analyses, the glacier flowed from west to east at that stage (Fig. 34).

The observations suggest that in most parts of the study area the ice sheet advanced in approximately the same direction during flow stages II and IV, i.e. from southwest to northeast. Correspondingly, during stages III and V the ice seems to have flowed roughly from northwest to southeast.

PRINCIPLES OF TILL STRATIGRAPHICAL CORRELATION

Key sections

In many places, particularly in central Lapland, the study pits exhibit at least two till beds of different ages (II and III) deposited by glacier flows differing in direction, often with sorted sediments of varying thickness between them. The continental ice sheet that deposited till bed II flowed from the southwest, but that which deposited till bed III from the northwest. The flow directions were confirmed with fabric analyses, stone counts and oriented moraine forms, and tied to cross striation data from the vicinity of the study pits. Till beds II and III are superimposed mainly in central Lapland, in its central and eastern parts in particular, e.g. at Kuurusenvaara in Kolari, Roukumalehto in Kittilä, Nuttio and Palkisvaara in Sodankylä, Vintiläselkä in Savukoski, and Kotala in Salla (Fig. 35). In large parts of central Lapland the differentation of till bed II from till

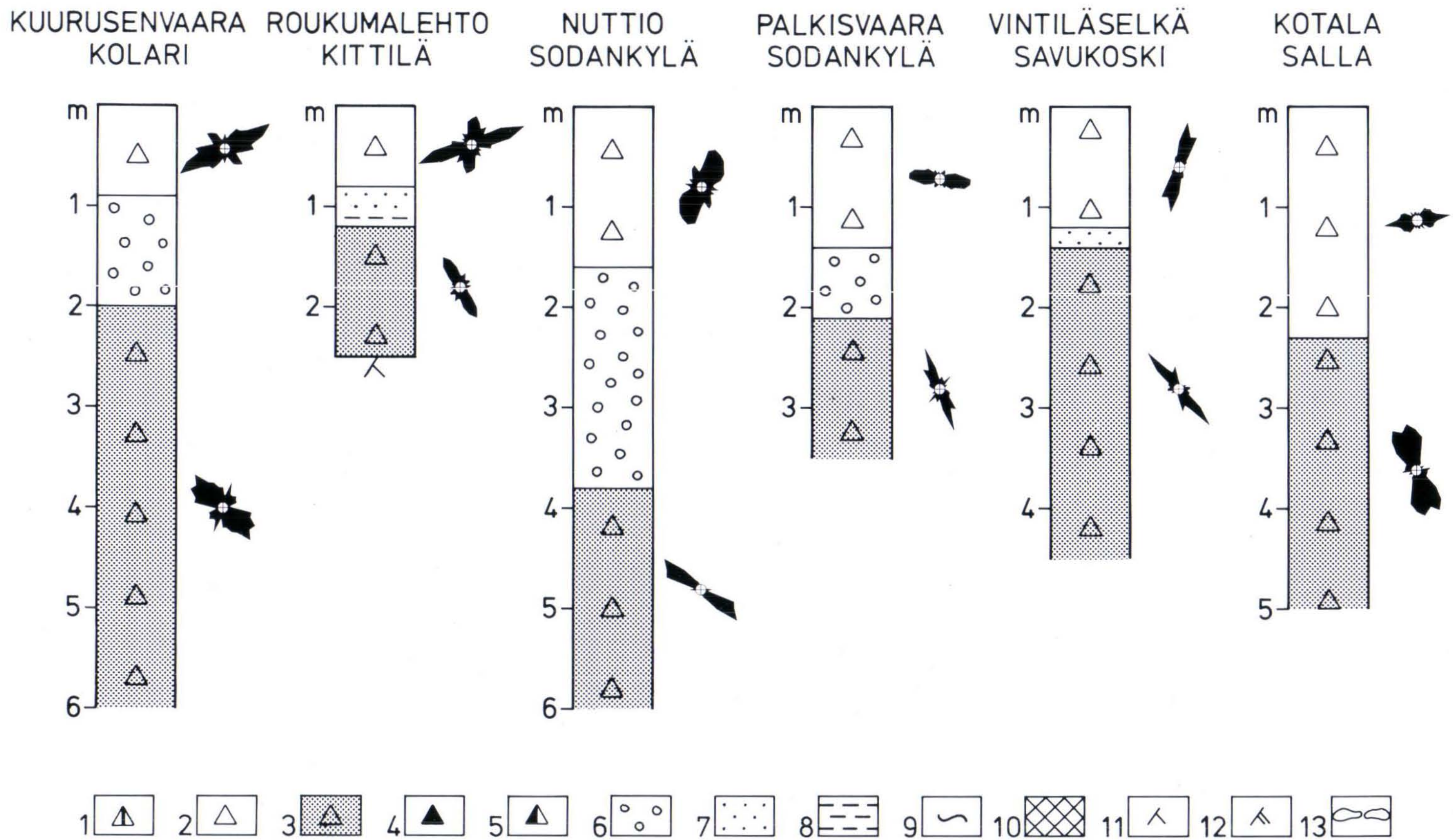

Fig. 35. An example of the stratigraphy typical of central Lapland; till beds II and III were deposited by ice flowing in different directions. With the exception of Kotala, Salla, the till beds are separated by sorted sediments varying in thickness. 1, till bed I; 2, till bed II; 3, till bed III; 4, till bed IV; 5, till bed V; 6, gravel; 7, sand; 8, silt; 9, peat; 10, gyttja; 11, bedrock; 12, weathered bedrock; 13, boulder pavement.

bed III is facilitated by the fact that the flow directions of the ice sheets depositing these beds diverged clearly from each other. With the exception of Kotala, all the sites mentioned above have deposits of sorted sediments, 0.2—2.3 m thick, between the till beds, which make it easier to interpret the stratigraphy. Other aids are the differences in till fabric and physical properties. In the examples given, the fabric of till bed II fluctuates between south-southwest and west-southwest, except at Palkisvaara in Sodankylä, where the macrotopography, the east-west trending fell chains, controlled the glacier flow. Till III exhibits a distinct northwest or north-northwest orientation in all the examples.

Tills II and III also differ from each other in other physical properties. At all the sites mentioned till II is brownish and till III grey. Till II is, on average, less compact and poorer in clasts, which are smaller, than in till III. The mean roundness of the clasts in till II is higher than in till III due to erosion of the rock material in the sorted sediments underlying till II and their redeposition in till II. The mean physical properties of the till beds are as follows:

	Bed II	Bed III
Compactness	2.2	3.5
Clast content	2.7	3.2
Clast size	1.8	2.3
Roundness	3.2	2.7

Apart from Nuttio in Sodankylä, the tills in bed II are fissile, and those in beds III, excluding those at Nuttio and Palkisvaara in Sodankylä, massive. North and south of central Lapland (ice divide zone), it is much more difficult to distinguish till II from till III and also to interpret the till stratigraphy, because the flow directions of the ice sheets that deposited the till beds either differ less from each other or are more or less the same. What is more, glacial activity was markedly more intense there, at least during the last glaciation. Consequently, the beds of till II are substantially thicker and the sorted deposits of the ice-free stage between tills II and III are often totally eroded.

In addition to till beds II and III, which occur almost ubiquitously in central Lapland, younger and older till beds were encountered in some pits. These are interpreted as basal till either overlying till bed II or underlying till bed III. For example at Jatuni in Enontekiö, Nousuvaara and Veskoniemi in Inari, Rajala in Sodankylä, and Kyörteselkä in Savukoski a typical till bed II is overlain by till bed I, which differs from it in physical properties and is interpreted as having deposited as basal till (Fig. 36). With the exception of Jatuni, the till beds are separated by thin layers of gravel and sand. But even at Jatuni the basal part of till bed I contains abundant bands and small lenses of sand that may derive from the sorted sediments on till bed II. Owing to the flow of the ice sheet that deposited till I, the gravel deposit between the till beds in the study pit at Rajala is heavily deformed and 'tillized'. At Veskoniemi in Inari, the layered fine sand between the till beds shows several vertical faults and folds. Fine sand also occurs as cubic bodies in the basal part of till bed I. These features indicate that during a subsequent glacial advance, the sedimentary unit overlying till bed II was subjected to loading, deformation and disruption in the frozen state, thus accounting for its presence as angular blocks within the lower part of till bed I. At the case sites, till bed I is rather thin, from 0.6 to 1.7 m, brownish to greyish in colour and fissile, except at Jatuni. Till bed I is on average less compact (2.6) and poorer in clasts (2.6) than till bed II (compactness 3.2, clast content 3.2). The clasts are approximately the same in size and roundness in both till beds.

Omitting Veskoniemi, Inari, the orientations of clasts in tills I and II are more or less the same or differ by a mere 5°—20°. The similarity in orientation of the clasts in both till beds comes as no surprise, considering that till bed I is interpreted as having been deposited as a result of slight oscillation and reactivation of the ice front during deglaciation. At Veskoniemi, the clasts in till bed I, which in all likelihood show transversal orientation, are oriented approximately perpendicular to the direction of glacier flow.

Tills older than till bed III occur at Naakenavaara, Vintiläkaira, Petäjäselkä, Muotka-

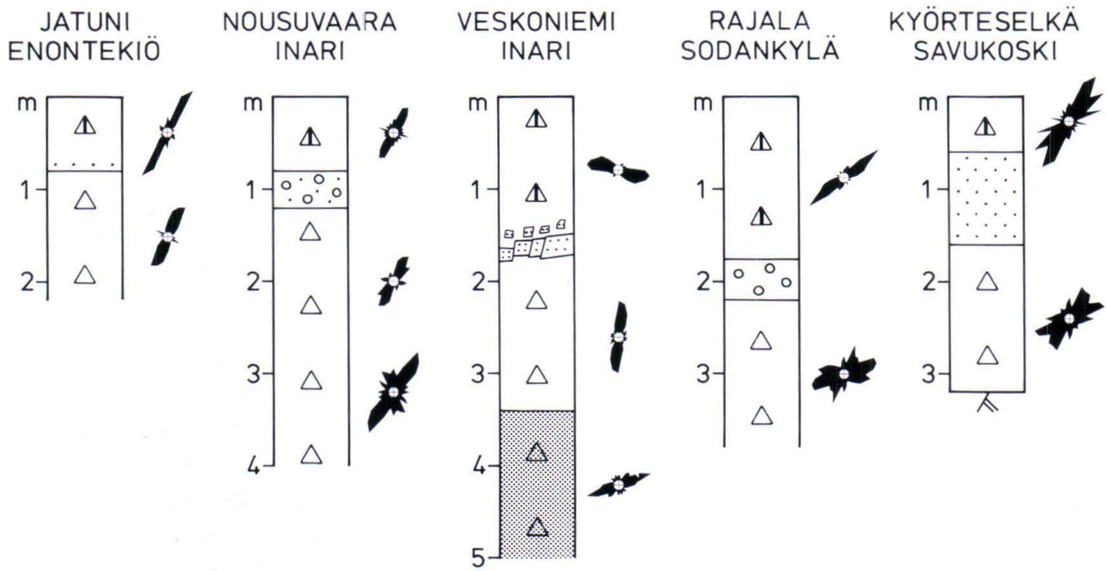

Fig. 36. Owing to oscillation of the ice front, till bed II is overlain here and there by till bed I. Apart from Veskoniemi, Inari, the orientations of the clasts in till beds I and II are almost the same. For explanation of the symbols, see Figure 35.

selkä and Vittikko (Fig. 37). The thickness of the older till beds at these sites ranges from less than one metre to over 5 m. At Naakenavaara, Kittilä, till bed III rests directly on the older till. At Vintiläkaira, there is a clear boulder pavement in the contact between till bed III and the older tills, where the clasts lie flat on the contact surface. At the other sites there are silt or sand deposits of the ice-free stage, from 0.2 to 1.5 m thick, between the typical till III and older tills. The older tills are a compact, fine sandy material from fissile to massive in structure. They are grey, apart from that at Naakenavaara, which is yellowish brown. The most distinct difference between the older and younger tills is their compactness. In till bed II it averages 2.3, in till beds III 3.2 and in the older tills 3.6. In actual fact, the difference is even greater, for at all the sites except Naakenavaara the compactness of the older tills is 4. At Naakenavaara it is only 2, obviously due to the high sand content of the till and because the site is now under a mire and at least from time to time below the groundwater table. Other physical properties of the older tills, such as clast content, size and mean roundness, vary in approximately the same range as those of till bed III. At the sites given as examples, the older tills are fairly well oriented, unlike most of the other older tills. In all the study pits chosen there the older tills underlying till bed III exhibit a roughly southwest-northeast orientation. At Muotkaselkä, till bed III is probably underlain by two older till beds deposited by ice sheets flowing from different directions, or at least by two dissimilar till units. The upper one is 3 m thick and the lower one over 2 m. The units are separated by a discontinuous silt layer up to 20 cm thick. The clasts in the upper till unit have a west-southwest orientation (260°) and those in the lower unit a northwesterly one (320°).

In addition to the orientation of the clasts, the till units differ in rock type composition. The lower unit contains 7 % carbonate rock and skarn clasts, but the upper unit none at all. In other properties the till units are alike, both being grey, massive fine sandy till. The clay content of the upper till unit is 5 % and that of the lower one 3 %. The lower unit is on average poorer in clasts, and the clasts are smaller and more rounded than in the upper one.

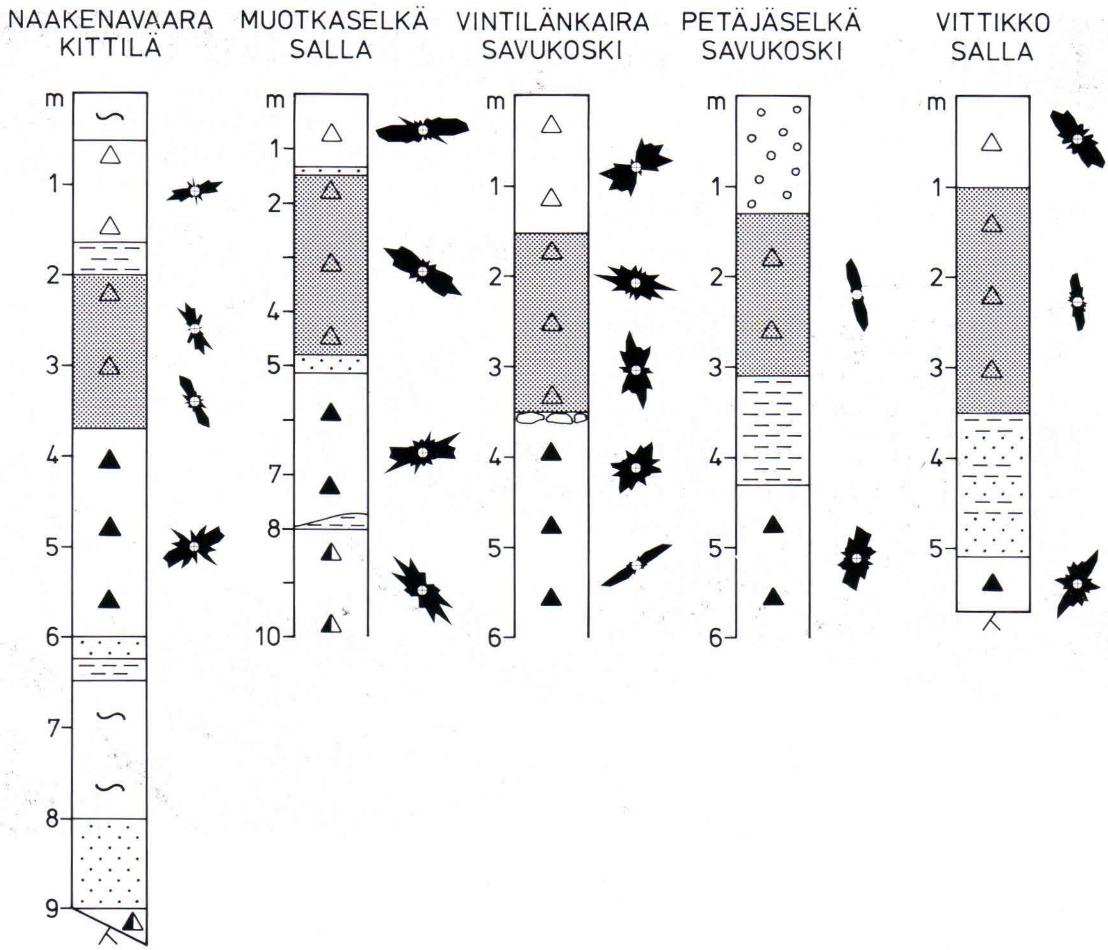

Fig. 37. In central Lapland till bed III is occasionally underlain by 1 or 2 older till beds. For explanation of the symbols, see Figure 35.

Rautuvaara open pit section

The most complete stratigraphy that could be obtained from the study data comes from the till cutting at the open pit of Rautuvaara mine. This mine is located in western central Lapland, in the municipality of Kolari (Fig. 28), on the southeastern flank of a gently sloping hill. As the summit of the hill is at 271 m a.s.l. and the valley of the Niesajoki south of it at 189 m a.s.l., the hill rises 82 m above its environment. The till cutting of the open pit is on the lower slope of the hill at 205—215 m a.s.l. Rautuvaara lies more or less in the middle of the ice divide zone (in a north-south direction) and in the southwestern corner of the area where the preglacial weathered bedrock occurs. In autumn 1974, i.e. in the third year of the research project, Rautaruukki Oy removed about 330 000 m^3 of overburden from above the orebody, thus creating a continuous till cutting, 700 m long and up to 22 m deep (Fig. 38).

At Rautuvaara there are five superimposed till

Fig. 38. The SW wall of the Rautuvaara open pit. The Rautuvaara section is about 700 m long and up to 22 m high. The sorted sediments between till beds III and IV are clearly visible.

beds with clearly divergent physical properties (Fig. 39). The deposits of sorted sediments of the ice-free substages are fairly thick and coherent for Finnish Lapland and facilitated the task of discriminating the till beds and interpreting the stratigraphy (Figs. 38 and 39). Unfortunately, despite a persistent search, no organic deposits were found in the cutting that would have permitted the sequence to be correlated with other subtill organic deposits, the nearest of which are only 2 km south of Rautuvaara. The physical properties of the till beds with their variation ranges are listed in Table 5. Fifty-four granulometric analyses were made from the deposits in the Rautuvaara cutting. However, Figures 40 and 41 give granulometric data only on each significant till unit and deposit of sorted sediments. The samples were selected so as to represent each stratigraphic unit at its most typical.

The topmost till, **bed II**, is of brownish, fissile and loosely packed fine sandy till (Fig. 40 and Table 5), poor in clasts, which are small in size. The mean thickness of the bed is 1 m, but it varies in the range 0.8—2.2 m. The till in bed II is typical of central Lapland, and its appearance and properties correspond to those of till II as recorded from nearby study pits. Fabric analyses from the till bed exhibit two almost perpendicular orientation maxima: at the very base of the till bed the clasts show an orientation of 220°, but higher up of 290°—295° (Fig. 39).

As the orientation of the clasts in the basal part

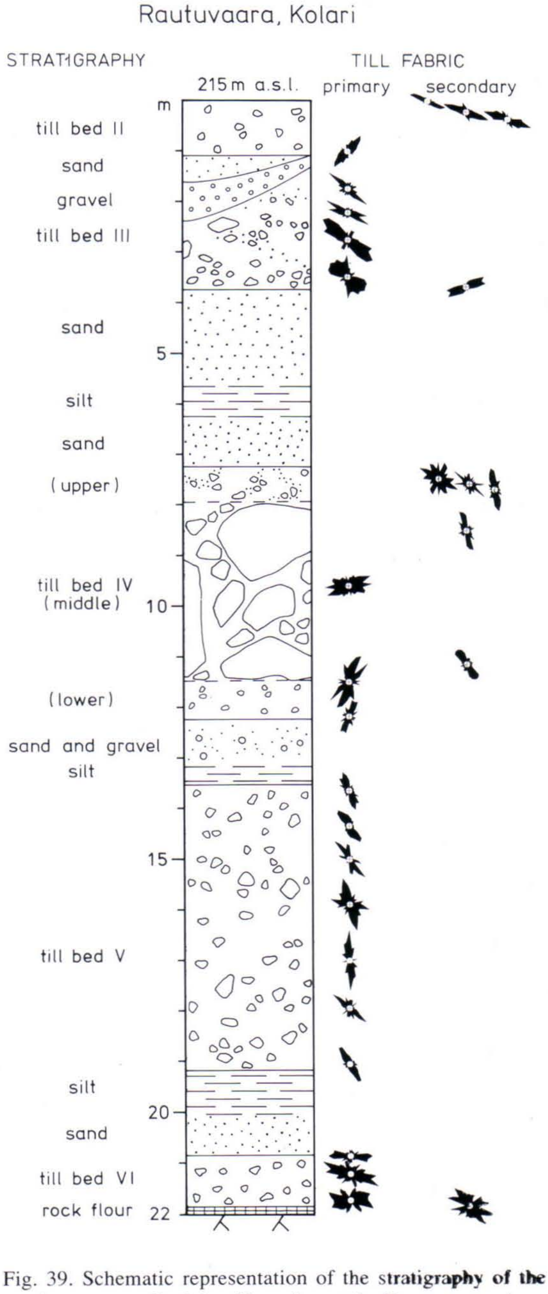

Fig. 39. Schematic representation of the stratigraphy of the southwestern wall of the till section at the Rautuvaara mine.

of the till (220°) is the same as that in the other beds of till II, the stream-lined moraine landforms and the younger glacial striation in the vicinity, it is interpreted as indicating the direction of flow of the ice sheet that deposited the till bed. The very distinct and sharp WNW orientation (290°—295°) shown by the fabric analyses from the upper levels of the till bed is parallel to the slope gradient. It has been attributed to reorientation due to solifluction in the upper parts of the till bed. The almost ideal shape of the orientation roses corroborates the concept of till reorientation (Saarnisto & Peltoniemi 1984). Further support for the concept is provided by a fabric analysis from another cutting made on the same slope 650 m away, where the clasts at a depth of 1 m in till bed II record an orientation of 330°, which is the same as the local slope gradient (Fig. 42).

In the northern and western walls of the cutting, till bed II is underlain for over 100 m by a continuous gravel and sand deposit with an average thickness of 3 m and chiefly composed of poorly sorted and very compact coarse stony and bouldery gravel. In the northern wall of the cutting, the stony gravel is overlain by 1—1.5 m of finer and better sorted gravelly sand (Fig. 41, curve 1). The deposits are interpreted as glaciofluvial.

Till bed III is grey, massive sandy till of normal compaction and with small clasts (Fig. 40). Typical features are the thin sand interlayers, a few centimetres thick, and small sand lenses. The clasts in the till are often surrounded by a thin layer of sand. The sand interlayers and lenses in bed III probably derive from the thick sand deposits that invariably occur under the bed. Owing to the high proportion of redeposited sand, the till bed is heterogeneous, containing both loosely packed (compactness 2) and gravelly (clast size 1) portions. The bed is from 1 to 5.6 m thick. According to four fabric analyses, the ice sheet that deposited the till flowed from WNW, the orientation maxima being in the range 290°—320° (Fig. 39). The clearly contrasting WSW orientation (250°) is obviously a transversal one. In appearance, fabric and other physical properties, till bed III corresponds to the tills in a similar stratigraphic position in the surroundings.

Till bed III is underlain by an almost continuous deposit of sorted sediments up to 4 m thick. Its basal part (0.5—1 m) is highly sorted, stoneless

Table 5. Physical properties of the Rautuvaara till beds.

Till bed	Thickness (m)	Colour	Structure	Compactness	Stone content	Stone size	Roundness
II	0.8—2.2	brown	fissile	2 (3)	2	2	3
III	1.0—5.6	grey	massive (fissile)	3 (2)	3 (2—4)	2 (1)	3
IV upper	0.5—1.5	grey	massive and/or deformed	2	3 (4)	2 (1)	3
IV middle	2.0—4.5	brown	fissile (massive)	4	4 (5)	4	2 (3)
IV lower	0.7—1.5	grey	fissile	4 (2)	2 (4)	1 (2)	3 (2)
V	3.0—6.5	brown/ grey	layered and laminated	4	3—4	2	2 (3)
VI	0.5—2.1	reddish brown, grey	massive	4 (5)	4 (3)	2 (1)	2 (3)

fine sand with current bedding (Fig. 41, curve 4), and its middle part (about 1 m) finely laminated silt (Fig. 41, curve 3). The pairs of light-dark laminae are from 0.5 to 2 mm thick. The upper part of the deposit is well-sorted, cross-bedded fine sand (Fig. 41 and curve 2). In its surficial part a few small unrounded clasts are embedded in fines as is typical of clasts in till. The contact between the finely laminated silt and underlying fine sand is sharp, but that between the silt and overlying fine sand is gradual as the silt gets coarser. The fine sand in the basal part of the sorted sequence is interpreted as glaciofluvial, the overlying finely laminated silt as a glaciolacustrine sediment deposited in deep water under tranquil conditions, and the upper part as a glaciolacustrine littoral deposit or some other littoral deposit.

Three stratigraphic units were distinguished in **till bed IV**. The uppermost unit is grey, loosely packed sandy till (Fig. 40), about a metre (0.5—1.5 m) thick, with small stones. It contains abundant sand lenses and bags and exhibits various disturbance structures; its surficial parts in particular have portions rich in clasts (clast content 4). Three fabric analyses were made from the till unit. Two of them showed the till to be unoriented, without a clear orientation maximum, but the third, made from its basal part, revealed a distinct NNW—SSE orientation. The till unit is thus interpreted as the surficial part of the underlying till bed IV that deposited as basal till. It grades without a sharp contact into the underlying 'proper' till bed IV, which is 2—4.5 m thick. Till bed IV bears no resemblance in either appearance or properties to the younger tills, being brown, compact, sandy till, in places extremely rich in clasts (5) (Fig. 40). The predominant clast size is 4 (ø over 60 cm) with the largest boulders measuring over 2 m in diameter. The stones and boulders are only slightly eroded, and the dominant roundness is 2. The till portions less rich in clasts exhibit a well-developed fissile structure, whereas the portions richest in clasts are massive. According to stone counts (fraction 6—20 cm), 5.1 % of the rock types are local skarns and skarn iron ores, with skarn rocks accounting for 3.4 % and skarn iron ores for 1.7 % (Table 6, analysed by H. Mattila, mining geologist). However, their true proportion in the rock types of the till is markedly higher because many skarn and skarn-iron ore clasts are fully weathered and cannot be counted as they disintegrate when touched. The only other bed where skarn and skarn iron ore rocks were encountered in stone counts was till bed V,

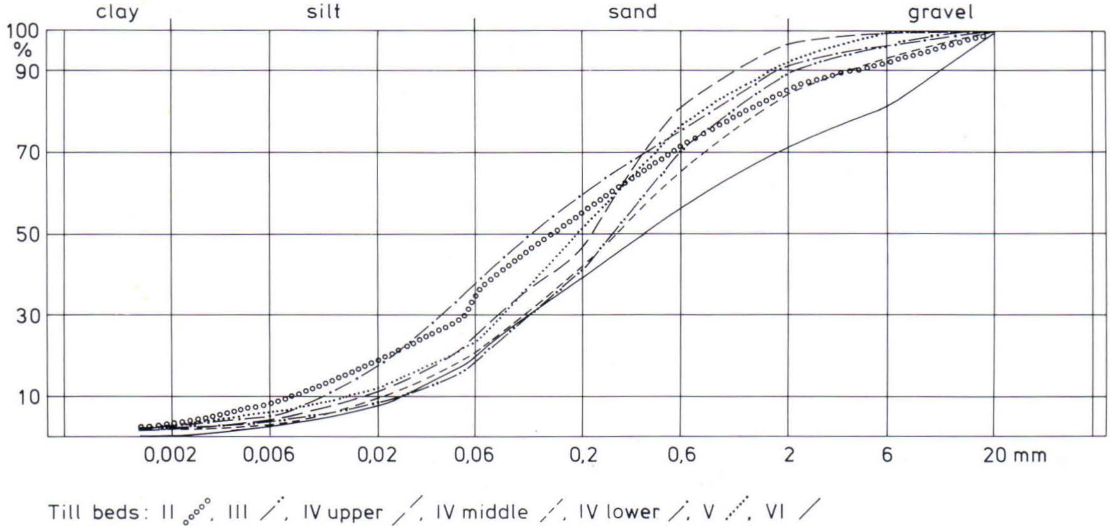

Fig. 40. Granulometric curves of the till beds in the Rautuvaara section.

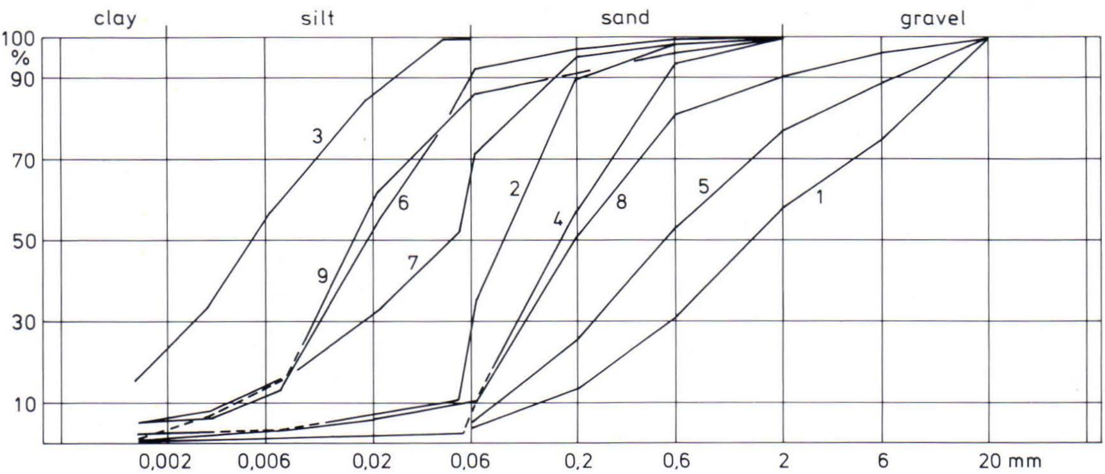

Fig. 41. Granulometric analyses of sorted subtill sediments at Rautuvaara. 1, coarse sand between till beds II and III; 2, upper sand between till beds III and IV; silt between beds III and IV; 4, lower sand between tills III and IV; 5, gravelly sand between till beds IV and V; 6, silt between till beds IV and V; 7, silt between till beds V and VI; 8, sand between till beds V and VI; 9, rock flour below till bed VI.

where their abundance is 0.9 %. They are totally absent from the lowermost till bed (VI), at least in the stone count fraction. The intense brown colour of the till bed is due to the stones, boulders and fine fraction of these weathered skarns and skarn-iron ores.

The flow direction of the ice sheet that deposited the till bed has not been established unambiguously. Owing to the high clast content of the till (4—5) and the big size of the clasts (4) the fabric analyses had to be made adjacent to and/or between large boulders. Consequently, the

Table 6. Petrographic analyses of the tills of the Rautuvaara open pit section (anal. H. Mattila).

Rock type	Till beds				
	II	III	IV (middle)	V	VI
Skarn	—	—	3.4	0.9	—
Skarn iron ore	—	—	1.7	—	—
Monzonite	6.1	3.4	32.2	8.4	24.3
Fine-grained monzonite	0.9	3.4	—	5.6	12.5
Mica gneiss	6.1	2.2	16.9	14.9	3.1
Amphibolite	4.4	—	—	1.9	4.1
Quartzite	21.7	2.2	8.5	24.3	13.5
Hematite ore of Taporova and Suuoja type	0.9	—	—	0.9	—
Granite gneiss	—	1.4	—	0.8	4.1
Syenite	—	3.4	—	0.8	3.1
Granite	40.0	56.8	27.1	28.0	12.6
Aplite	—	2.3	1.7	2.7	4.1
Pegmatite	2.6	1.1	1.7	5.5	13.5
Vein quartz	2.6	—	—	0.8	—
Diorite	1.7	5.6	6.8	4.6	4.1
Gabbro and diabase	9.6	8.0	—	—	1.0
Felsic and intermediate volcanic rocks	3.5	8.0	—	—	—
Greenstone	—	1.1	—	—	—
Greywacke conglomerate	—	1.1	—	—	—
Σ %	100.1	100.0	100.0	100.1	100.0

results of the fabric analyses as indicators of glacier flow direction are questionable, and the divergent orientation maxima are difficult to interpret with any degree of reliability. The till bed was submitted to three fabric analyses, of which two, from the upper and lower parts of the bed, show a clear NNW (345°) — NW (325°) orientation and the third one, from the middle of the bed, a WSW (250°) orientation. In the base of till bed IV there is a unit, about one metre (0.7—1.5 m) thick, of grey intensely fissile, compact (4), fine sandy till with a low content (2) of small (1) clasts (Fig. 40). The contact with the overlying dark brown till rich in big boulders is normally gradual, although exceptions occur (Fig. 29), but the lower contact with the underlying sorted sediments is sharp and erosional.

The till unit is interpreted as a basal part of till IV, the bulk of its material deriving from the underlying deposit of sorted sediments. Two fabric analyses were made from the basal part, both of them indicating a clear SSW orientation (Fig. 39). These fabric analyses are thought to indicate more clearly than any others that the ice sheet that deposited the whole till bed flowed from SSW (200°) to NNE. This interpretation is corroborated by the outcome of the stone count from the till bed mentioned above. At and around Rautuvaara, narrow skarn horizons in the bedrock trend 230° (Hiltunen 1982). Hence the abundance of skarn clasts in till, 3.4 %, seems to favour a glacier flowing approximately parallel to the strike of the skarn horizons rather than perpendicular to them.

Till bed IV is underlain by a deposit of sorted sediments, about one metre (1—1.5 m) thick, that is mainly composed of sand in alternately finer and coarser horizontal layers (Fig. 41, curve 5); only locally is the deposit slightly disturbed and folded. The material is intensely weathered, and the sand has abundant iron precipitates. Occasionally the bed contains small subangular clasts (roundness 2—3) with the 'dirty' silt coating surface typical of clasts in till. In the southern wall of the cutting, below the sand deposit, a thin layer (c. 0.3 m) of silt extends for about 100 m (Fig. 41, curve 6). The silt in the sequence is interpreted as glaciolacustrine and the sand in the upper part as a rapidly deposited littoral formation.

The sorted deposit is underlain by **till bed V**, which is from 3 to 6.5 m thick. The contact of the sorted sediments with the till is sharp. In the upper contact of till bed V there is a grey, roughly 10 cm thick silty precipitation layer that is as hard as concrete (compactness 5). Till bed V is made up of compact (4), fine sandy till (Fig. 40) displaying alternating brown and grey layers, 0.2—1.7 m thick, in which grey tones predominate. The till is fairly homogeneous in all respects except colour as there is little difference between the layers in grain size or other physical properties. The till is fissile, in the upper part of the bed in particular. The clast content is normal to high (3—4) and the predominant clast size is 2. The roundness of clasts varies, being normal (3) in the upper and middle parts of the bed but 2 in the lower part. Orientation is distinct. Seven fabric analyses made at different depths all indicate a clear NW—NNW orientation. The orientation maxima of four fabric analyses were the same or differed by only 10° (325°—335°). According to these fabric data, the glacier flowed from NNW (330°) which differs by only some 20° from the flow direction of the glacier that deposited till bed III.

Till bed V is underlain by 1.5—2 m of compacted (4) silt and fine sand. Between the till and the silt there is a sharp erosional contact. Immediately below till bed V there is a layer of silt, 0.5—1 m thick (Fig. 41, curve 7), that is grey and intensely laminated, with pairs of light-dark laminae from 0.5 to 1 cm thick. The lower part of the silt is brown, and the layering is only barely perceptible. Particularly noticeable in the brown basal part are Fe-Mn precipitates, drop stones of various size, the largest over 20 cm in diameter, and structures caused by these stones. The silt is underlain by 0.5—1 m of reddish, almost stoneless, well-sorted fine sand showing horizontal layering (Fig. 41, curve 8). Sandwiched between the sand and silt in the contact there is a discontinuous layer of stones. The sand is very rich in Fe-Mn precipitates, some of which are 'stone-hard' concretions. The silt, which deposited in a tranquil sedimentation environment, is interpreted as glaciolacustrine, whereas the sand deposit underlying it is in all likelihood glaciofluvial. In contrast to the upper deposits of sorted sediments between the till beds, the lower part of the silt deposit and the fine sand in the basal part are intensely deformed in places. The contact between the fine sand and the underlying till is distinct and sharp.

The oldest **till bed VI**, in the cutting, occurs only in the deepest parts, in bedrock depressions; it is from 0.5 to 2 m thick. The surficial part of the till (0.3 m) is reddish brown and the lower part grey. The till in the upper part of the bed varies, containing abundant gravel and sand portions and being completely cemented by iron hydroxide. This gravelly till is an intense reddish brown and grades without a clear boundary into a grey and more homogeneous till. Deeper down, the till has a banded and layered appearance owing to the presence of narrow layers of coarse gravelly and sandy till cemented by reddish brown iron hydroxide. The till in the bed is of compact, in places extremely compact (5), sandy till (Fig. 40) rich in small (2) clasts (4). The predominant roundness is 2. A characteristic and conspicuous feature of till VI is the high abundance of fully weathered clasts, which, together with the Fe hydroxide precipitates and concretions, make the till look 'old'.

Four fabric analyses from the till suggest that the depositing ice sheet flowed approximately from west to east. Two orientation roses exhibit a distinct westerly (270° and 275°) orientation and one a slightly more WNW orientation (280°). The fabric analysis from the very bottom of the till bed did not show a distinct maximum for the clasts (Fig. 39).

In the deepest part of the cutting, between the till and a rather 'fresh' and unfractured bedrock, there is a coherent layer of banded sediment, 5 cm thick, that extends for at least 50 m. The bands are thin, in general 0.5—1 mm, the maximum being 2—3 mm. The sedimentary layer is of surprisingly uniform thickness over the whole distance. In grain size it is silt (Fig. 41, curve 9). However, it is not entirely homogeneous but contains coarser grains up to 3 mm in diameter. The silt deposit, which is devoid of pollen and diatoms, is interpreted as rock flour. Such occurrences on bedrock are fairly common elsewhere in Lapland, too, although they are usually much thinner, being only a few millimetres thick. They served as a successful indicator of bedrock when digging pits were dug with an excavator, because there are no such layers on boulders, not even on the largest ones.

Geophysical properties of the Rautuvaara tills

Some new and less common research methods — microfabric analyses, magnetic fabric analyses, specific susceptibility and remanence determinations — were used in the Rautuvaara profile to back up and verify the stratigraphic interpretation.

The flow directions of the continental ice sheets were checked with 11 microfabric analyses and 110 magnetic fabric analyses from the till beds at Rautuvaara in addition to fabric analyses (Nenonen 1980). The analytical data acquired with the various methods were more or less compatible, and the orientations statistically consistent (Puranen 1977b, Nenonen 1980).

The magnetic mass susceptibility of till, K (10^9 m^3/kg), varies markedly from one till bed to another (cf. Puranen 1977a). Table 7 shows the variation in mass susceptibility by till bed.

Table 7. Mass susceptibility of different till beds at Rautuvaara.

Till bed	Mean mass suscept.	Range	No. of samples
II	1 480	1 050— 1 750	7
III	2 690	2 500— 3 250	7
IV upper part	2 220	1 950— 2 500	7
IV	19 870	11 000—24 000	7
IV basal part	850	780— 950	7
V	30	25— 50	15

The mass susceptibility measurements were made from oriented till samples from all beds except the lowest (VI), where the till was too compact for oriented samples to be placed in plastic vials. The till beds differ widely in mass susceptibility, the highest values being in till bed IV, where they exceed those in the topmost till bed II by a factor of ten. The high mass susceptibility of till bed IV is probably due to the presence of abundant iron formation material (skarn and magnetite ore). This supposition is corroborated by the stone count data on the till beds, according to which the 6—20 cm fraction of till bed IV has the highest abundance of clasts from the iron formation (cf. Table 6). The high mass susceptibility of till bed IV and the abundance of iron formation clasts are further evidence that the bed was deposited by a glacier flowing from the southwest. The Cu content of the bed is also markedly higher than that of the other till beds in the cutting. In bed IV the Cu content is commonly 300—500 ppm, in beds II and III 50 ppm and in beds V and VI 80—90 ppm (Alfthan et al. 1976). The high Cu abundance of bed IV might be attributed to the Rautuvaara Cu-orebody, which crops out about 1 km southwest of the open pit cutting (Hiltunen 1982).

The mass susceptibility of till bed V is lower than expected. Although the bed lies directly above the ore outcrop in many places, its mean mass susceptibility, measured from 15 samples, is only 30. The value is too low for the till bed to contain magnetite, and hence the material in the till bed resting on the ore outcrop is not of strictly local origin. Remanence determinations from the till beds demonstrate that in the uppermost till beds (II and III) the direction of remanence coincides approximately with the present direction of the Earth's magnetic field but that in the lower beds it deviates from it (Puranen 1977a and Hirvas et al. 1977).

Microfossils of the Rautuvaara sediments

As an exhaustive search did not reveal any organic deposits in the Rautuvaara sequence, attempts were made to date, at least approximately, the till beds and the intervening sorted sediments with the aid of pollen and diatom analyses. However, these also failed, because there was not enough pollen or diatoms for their relative abundances and species to be determined. Till beds IV and V contain some pollen, mostly *Pinus*. A slide made from till bed IV showed three *Carpinus* grains, one *Larix* grain and one *Fagus* grain in addition to the ubiquitous *Alnus* and *Betula* pollen. Apart from *Pinus*, till bed V contains only *Picea* pollen.

Pinus pollen is dominant with some *Alnus* and *Betula* pollen in the fine sand between till beds III and IV and in the silts between beds IV and V, and V and VI. The fine sand underlying till bed III, interpreted as glaciolacustrine or littoral, also contains *Picea* and *Corylus* pollen. Some *Picea* pollen grains and one *Tsuga* grain were encountered in the laminated silt underlying till bed V. Unfractured diatoms were not found in any of the deposits between the till beds; only some fragments of *Pinnularia* sp. were encountered in the silt underlying till bed V. The pollen analyses from the Rautuvaara samples were made by Dr Risto Tynni and the diatom analyses by Dr Tuulikki Grönlund.

The Rautuvaara section supports the overall picture of the flow stages of the continental ice sheet and the till stratigraphy that was pieced together like a jigsaw puzzle from excavator pit data. However, the oldest deposits in the Rautuvaara section were not identified anywhere else for sure. The discrimination of the till beds at Rautuvaara was facilitated not only by the difference in physical properties of the beds but also by the existence of sorted sediments between them. The thickness, continuity, texture and structure of the sorted sediments demonstrate that they are not merely lenses or layers belonging to the internal structure of the till but formations that deposited during ice-free substages. It is also noteworthy that the lithostratigraphy of the sorted deposits exhibits a logical succession from glaciofluvial sediments via glaciolacustrine deposits to littoral deposits.

Regional comparison of Rautuvaara stratigraphy

The Rautuvaara sequence differs clearly from those in the rest of the study area, in thickness of deposits for one thing. The till stratigraphy of the Rautuvaara open pit and the fabric analysis data on the till beds corroborate the concept of till stratigraphy and glacier flow stages and directions in northern Finland compiled from study pits elsewhere. The concept had already been delineated before the Rautuvaara section was studied and not the other way round. The findings from other areas were not adjusted to accommodate the Rautuvaara results; rather the Rautuvaara findings support a concept arrived at from data collected elsewhere.

The orientation of till bed II at Rautuvaara (220°) is the same as that of the fluting and younger glacial striation in the vicinity (cf. Figs. 9—10 and Kujansuu 1967). The orientation of till bed III (290°—320°) parallels that of the older striae and of the drumlins and drumlinoids clearly visible on aerial photos. The orientation of the basal part of till bed IV (200°) which is regarded as the most reliable indicator of the flow direction of the glacier that deposited the till bed, is the same as the dominant orientation of the older tills in central Lapland (Fig. 28). For example, the orientation of the till in a corresponding stratigraphic position at Naakenavaara is 240° (Fig. 37). The older tills with a northwesterly orientation (330°) of till bed V at Rautuvaara were encountered at two sites in the study area: at Rovala in Savukoski and Muotkaselkä in Salla. At Rovala the clasts exhibit a 285° orientation (Fig. 28) and at Muotkaselkä 320° (Figs. 28 and 37). At Muotkaselkä, the older till with a northwesterly fabric is in the same stratigraphic position as till bed V at Rautuvaara, i.e. below till beds II and III and the till bed with a WSW (260°) orientation (till bed IV?) (Fig. 37). The western fabric of till bed VI at Rautuvaara has one counterpart in the older tills, at Haurespää in Kittilä, where a westerly oriented greenish brown till, over 1.6 m thick, occurs under a glaciofluvial limonite conglomerate, about 1.5 m

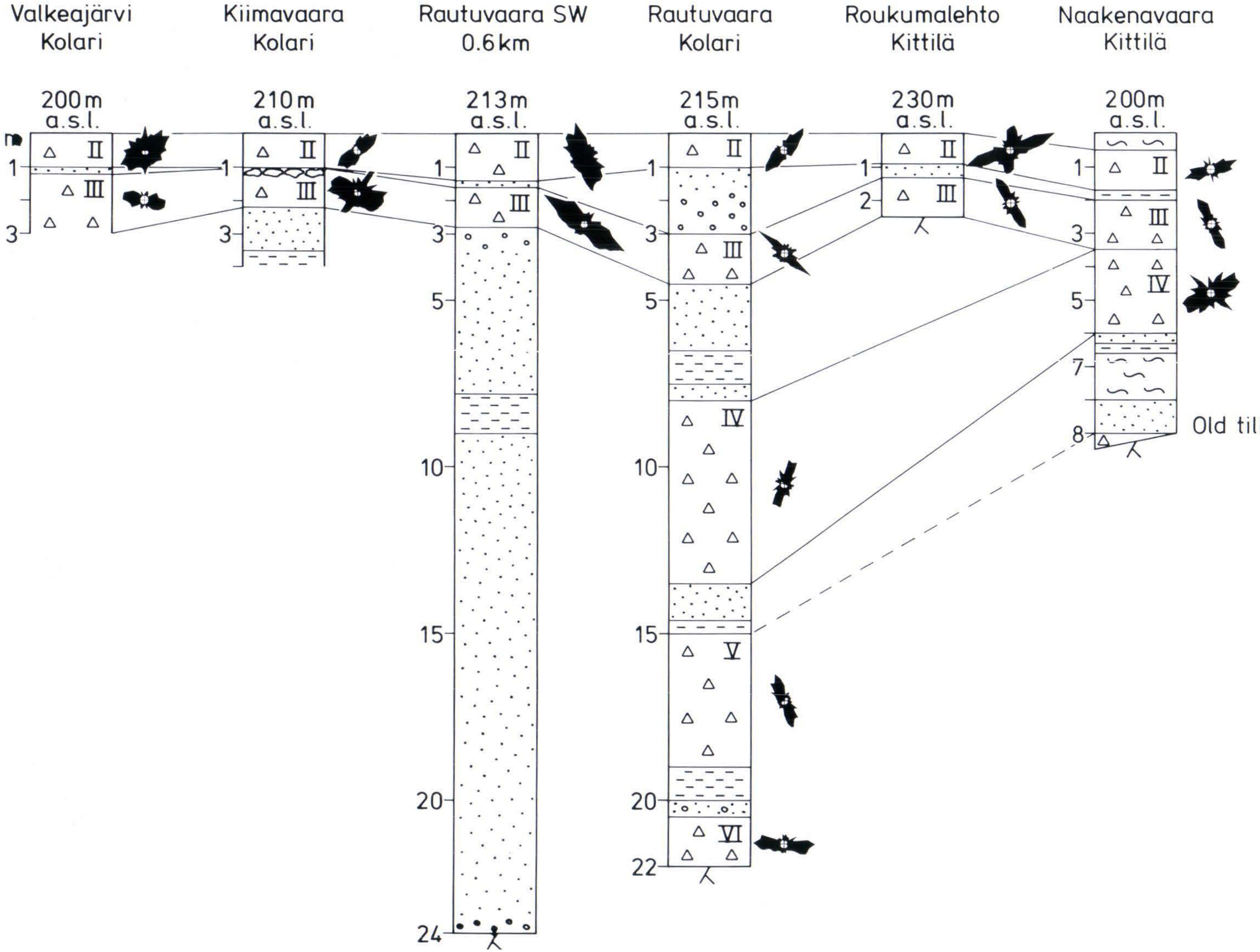

Fig. 42. Correlation of the till stratigraphy of the Rautuvaara open pit section with that of the adjacent area. The fabric analysis from till bed II in the southwest of the Rautuvaara section is interpreted as indicating the direction of solifluction. For symbols see Figure 35 (note that all tills are marked by same symbol).

thick, and a till bed (or unit) with a SSW (200°) orientation (till bed IV?) (Fig. 28). The limonite conglomerate was earlier interpreted as preceding the last glaciation (Korpela 1969) or as interglacial (Kujansuu 1967).

The till stratigraphy of the Rautuvaara open pit and the study pits in the environment are compared in Figure 42. The pits selected lie along a 70 km line trending southwest-northeast from Valkeajärvi in Kolari, to Naakenavaara in Kittilä. Valkeajärvi and Kiimavaara lie southwest of Rautuvaara (14 and 4 km), and Roukumalehto and Naakenavaara northeast of Rautuvaara (34 and 55 km). The nearest site, which is the 24 m deep cutting made for the Rautuvaara mine ventilation shaft, is only 0.6 km southwest of the open pit section. In all these pits, till beds II and III are nearest to the surface, and have an interposing narrow layer of sorted sediments. The only exception is Kiimavaara in Kolari, where this stratigraphic position is occupied by a boulder pavement. In all cases, till bed II is brown and till bed III is grey. Till bed II is of approximately equal thickness in all pits, that is, 0.9—1.4 m. The orientation of the clasts fluctuates between 220° and 250°, being 220°—240° at Rautuvaara and to the southwest of it, and 250° to the northeast. The orientation of the clasts in the Rautuvaara ventilation shaft section (330°) is attributed to the slope gradient and solifluction.

The thickness of till bed III is also surprisingly constant, 1.2—2 m, except at Valkeajärvi, where it is not known. The clasts in till exhibit a clear WNW-NW orientation, being 280°—305° at Rautuvaara and to the southwest of it, and 330° to the northeast. The deposits of sorted sediments underlying till bed III are markedly thicker than those between till beds II and III; in the ventilation shaft section they are as thick as 22 m. At Naakenavaara, till bed III is underlain by a till bed with a WSW orientation that has been correlated with till bed IV at Rautuvaara. The oldest till at Naakenavaara, which occurs only in bedrock hollows, was best correlated with till bed V at Rautuvaara.

The pits selected disclose two contrasting features that mark the till stratigraphy of northern Finland; on the one hand there is the consistency, regularity and continuity of the younger deposits over large areas, and on the other the randomness and great variation of the older ones, even at adjacent sites. Only 600 m apart, the sections of the open pit and the ventilation shaft at Rautuvaara serve as good examples of the sharp difference in stratigraphy. In the open pit section the tills deposited by separate glaciations are dominant, and till bed III is underlain by three till beds differing in age and separated from each other by sorted sediments, whereas in the ventilation shaft section till bed III is underlain only by sorted sediments.

SUBTILL SORTED SEDIMENTS

Subtill sorted sediments were encountered throughout virtually the whole study area (Fig. 43). Sorted sediments underlying till bed I were observed at 20 sites, most of them in northern, central and eastern Lapland. The clustering of occurrences north of Ivalo is at least partly due to the great number of study pits dug close to each other for determining the transport distance of the clasts in till. The sorted deposits underlying till bed I are gravel and sand. The deposits are rather thin, measuring from 0.2 to 1.8 m.

The sorted sediments underlying till bed II are common throughout the study area, and almost ubiquitous in some restricted areas in the ice divide zone. They were encountered in 195 out of 696 study pits (28 %). These deposits are distinctly thicker than those underlying till bed I, ranging from a few tens of centimetres to over 15 metres.

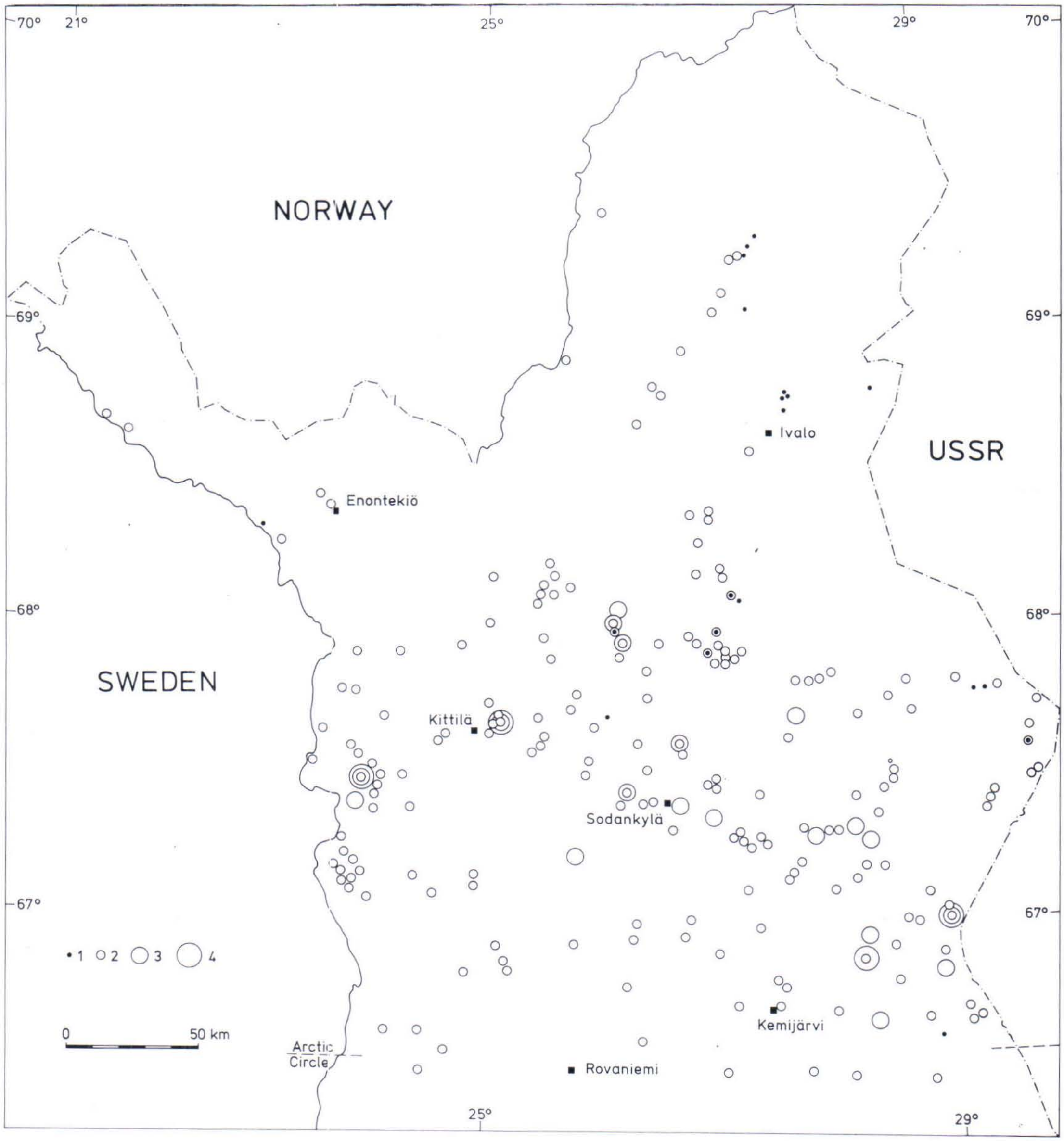

Fig. 43. Map showing the location of the 240 test pits where sorted subtill sediments underlie till beds. Sorted sediments: 1. below till bed I; 2. below till bed II; 3. below till bed III and 4. below older till beds.

Of the 78 granulometric analyses made, 66 (84.6 %) were sand, seven (9.0 %) silt and five (6.4 %) gravel.

Sorted sediments underlying till bed III were encountered in 18 study pits. All are located in the area of weathered bedrock, and the majority of these in the somewhat smaller ice divide zone of central Lapland. The deposits are from 0.3 to 3.5 m thick, except in the Rautuvaara ventilation shaft section, where they are 22 m thick. Thirty-four granulometric analyses were made from the deposits, of which 20 (58.8 %) were sand and 14

(41.2 %) silt, demonstrating that the sediments under till bed III are substantially finer than those under till bed II.

Sorted sediments underlying older tills were met with in three study pits besides the Rautuvaara open pit section. At Kulvakkopalo in Salla, eastern Lapland, there is over 0.2 m of layered fine sand at 8.5 m below the till with a southwest—northeast orientation (till bed IV?). As the deposit was exposed at the very bottom of the pit its total thickness is not known. At Muotkaselkä, Salla, there is a thin (0.3 m at the most) discontinuous silt layer (Fig. 37) between the older tills with SW—NE and NW—SE fabrics (till beds IV and V?). At Naakenavaara in Kittilä, western Lapland, till bed IV is underlain by silt and sand deposits and a very compact peat at a depth of 6—9 m (Fig. 37). Rautuvaara, Muotkaselkä and Naakenavaara are all located in the ice divide zone of central Lapland, and Kulvakkopalo lies in the preglacial weathered bedrock area. Eight granulometric analyses were made from the sorted sediments underlying the older tills: five are sand and three silt. The coarse sand and gravel sediments underlying the tills would appear to be mainly glaciofluvial and to have deposited during both the withdrawal and spreading of the ice sheet. Most of the fine silt sediments, which are more likely glaciolacustrine, were deposited in short-lived glacial lakes, as implied by their thinness, the presence of drop stones and the scarcity of pollen and diatoms. As the pollen grains are often very abraded and only fragments of diatoms are present, the sediments would seem to have been redeposited and washed out from older sediments.

SUBTILL ORGANIC DEPOSITS

In 1973—1980, the Geological Survey of Finland discovered subtill organic deposits or deposits with organic substances at 80 sites in Finnish Lapland. Forty-nine were studied, at least preliminarily, in the course of the present project (Fig. 44 and Table 8). The majority (72) were discovered in conjunction with systematic till coring and sampling undertaken by the Geochemistry Department of the Geological Survey of Finland, seven were encountered in study pits and one was reported by Kock, a local gold prospector. Most of the finds derive from the large ice divide zone of central Lapland. By the end of 1980, the Geochemistry Department had cored till profiles at about 15 000 sites over an area of 14 000 km^2 in central Lapland (oral comm., H. Tanskanen). The coring was extended to as great a depth as feasible, and samples were taken either at 1 m intervals or whenever there was a clear change in penetrability. A subtill deposit was intersected at 72 sites, i.e. one in 200 of the holes (1/208) hit an organic deposit.

Organic deposits were encountered in seven out of 1 400 excavator pits. As one in 200 of the pits also hit a deposit, the rate of discovery was approximately the same at coring and digging sites. However, it should be remembered that the study pits were located throughout the study area, whereas most of the coring sites were in the ice divide zone of central Lapland.

To determine the stratigraphic position of the organic deposit and to collect material for microfossil determinations and radiocarbon dating, continuous cores were taken with a percussion drill (Cobra) at the sites where organic deposits had been found during geochemical sampling. The most interesting and potentially rewarding finds were exposed with a heavy excavator (Fig. 45). Twenty-three of the subtill deposits studied were gyttja, 20 peat, and five diatomite or diatom gyttja. In one pit, the organic matter was so thoroughly intermixed with sand that the deposit had to be classified simply as organic matter. As a rule, the deposits are thin, being from a few centimetres to

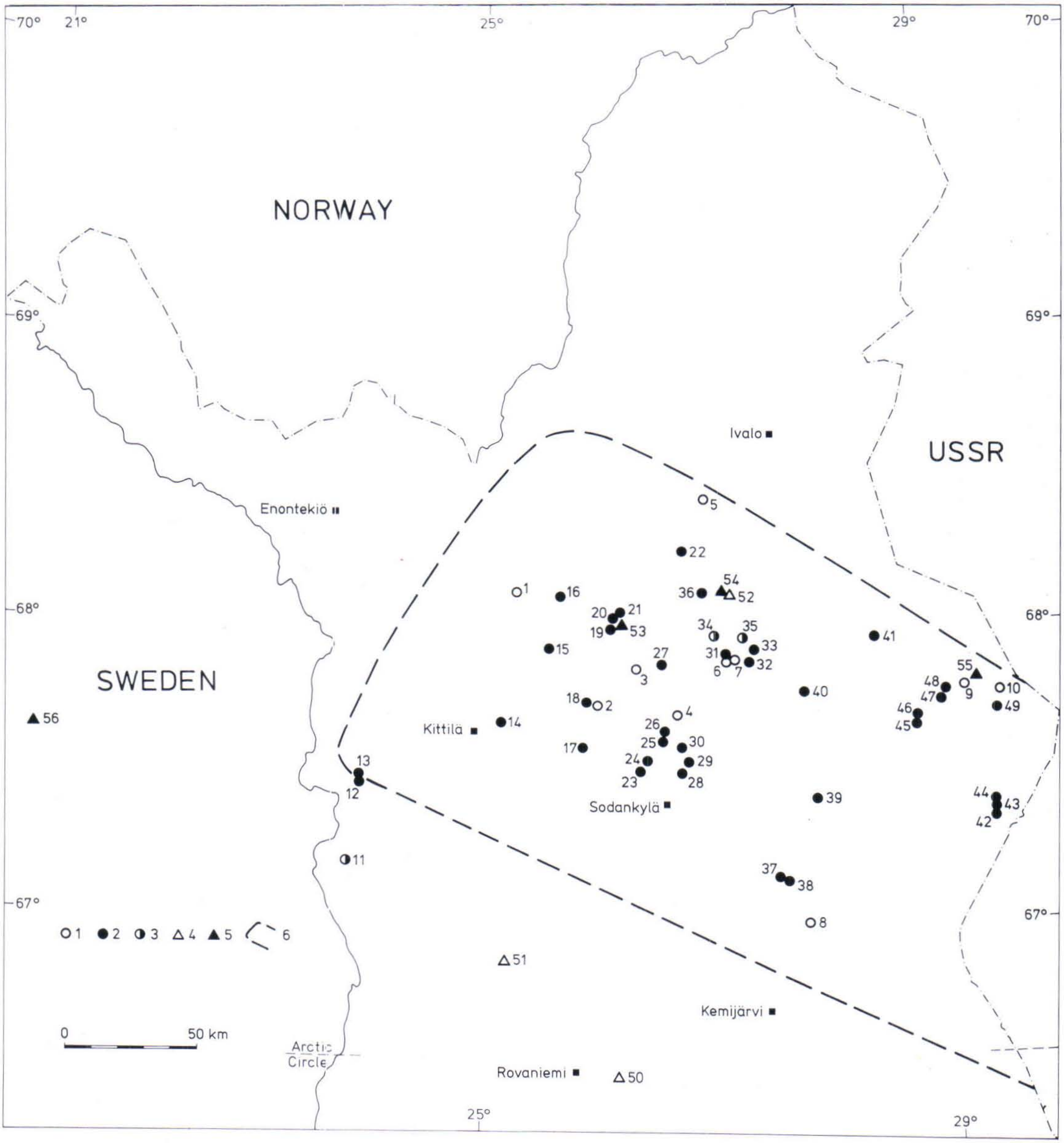

Fig. 44. Location of studied organic subtill deposits in Finnish Lapland. 1. interstadial-type deposit; 2. interglacial-type deposit; 3. organic deposits in different stratigraphic positions, interglacial-type and interstadial-type deposits probably superimposed. 4. an interstadial deposit studied previously; 5. an interglacial deposit studied previously; 6. area where preglacial weathered bedrock is often encountered. Localities studied previously: 50. Permantokoski (Korpela 1969), 51. Marrasjärvi (Kujansuu 1975); 52. Vuotso (Kujansuu 1972a); 53. Pyssyselkä (Tanskanen 1975); 54. Vuotso (Mäkinen 1982); 55. Sokli (Ilvonen 1973); 56. Leveäniemi, Sweden (Lundqvist 1971). The names of the other sites of discovery are listed in Table 8.

a few decimetres in thickness, although there are a few slightly in excess of 2 m. The thickest gyttja deposit, 2.5 m, was encountered at Loukoslampi 1 in Pelkosenniemi, and the thickest peat deposit, 1.5 m, at Naakenavaara in Kittilä. (Fig. 52, localities 37 and 14).

Table 8. List of subtill interstadial and interglacial organic deposits. Numbers refer to Fig. 44. z = m a.s.l.

No. Locality	Map no.	Municipality	x	y	z
INTERSTADIAL-TYPE DEPOSITS					
1. Siukatanjoki	2744 05	Kittilä	7563.68	550.76	260
2. Naakivuoma	3721 10	Sodankylä	7520.42	456.05	290
3. Tunturipäät	3723 05	Sodankylä	7532.00	470.50	300
4. Ilmakkiselkä	3714 09	Sodankylä	7514.36	484.52	210
5. Palsioja	3813 11	Inari	7594.38	497.60	300
6. Maaseljänjänkä	3741 02	Sodankylä	7534.35	502.65	295
7. Maaselkä	3741 02	Sodankylä	7534.63	504.64	295
8. Neulikkoaapa	3642 10	Pelkosenniemi	7535.18	535.40	165
9. Tulppio	4723 01	Savukoski	7521.77	463.86	225
10. Kaulusrovat	4723 04	Savukoski	7524.69	473.05	250
INTERGLACIAL-TYPE DEPOSITS					
11. Pohjasenvaara	2713 10	Kolari	7460.40	493.80	170
12. Sivakkapalo 1.	2713 12	Kolari	7487.17	497.90	200
13. Sivakkapalo 2.	2713 12	Kolari	7488.10	498.00	205
14. Naakenavaara	2734 03	Kittilä	7513.10	547.41	200
15. Tepsankumpu	3721 09	Kittilä	7540.74	443.08	265
16. Pailakainen	3722 07	Kittilä	7559.05	444.12	295
17. Kutuvuoma	3712 11	Sodankylä	7501.95	451.91	230
18. Pomokaira	3721 10	Sodankylä	7520.39	455.67	285
19. Kuorajoki	3723 03	Sodankylä	7547.86	463.66	260
20. Kirakka-aapa	3724 01	Sodankylä	7551.24	466.07	260
21. Laitinrova	3724 01	Sodankylä	7554.01	468.36	250
22. Siikahaara	3724 12	Sodankylä	7576.07	490.32	275
23. Sukuvaara	3714 04	Sodankylä	7493.72	476.48	195
24. Visasaari	3714 04	Sodankylä	7494.26	476.46	200
25. Postoaapa 1.	3714 08	Sodankylä	7506.24	483.31	205
26. Postoaapa 2.	3714 08	Sodankylä	7506.60	483.28	210
27. Korpiselkä	3723 08	Sodankylä	7532.47	480.21	245
28. Sattanen	3714 07	Sodankylä	7493.59	488.70	185
29. Viiankiaapa	3714 10	Sodankylä	7496.53	492.22	195
30. Paloseljänoja	3714 08	Sodankylä	7501.04	486.74	200
31. Pauttisselkä	3741 02	Sodankylä	7537.18	502.43	280
32. Kaitaselkä 2.	3741 05	Sodankylä	7534.30	515.37	240
33. Kaitaselkä 1.	3741 05	Sodankylä	7537.10	515.37	240
34. Lohiaapa	3741 03	Sodankylä	7544.14	501.47	270
35. Kurujoki	3741 06	Sodankylä	7541.66	513.06	245
36. Kultalampi	3724 10	Sodankylä	7559.57	497.57	250
37. Loukoslampi 1.	3642 09	Pelkosenniemi	7450.97	526.09	160
38. Loukoslampi 2.	3642 09	Pelkosenniemi	7450.09	526.57	160
39. Pyörreselkä	3731 12	Savukoski	7482.44	536.36	210
40. Lokka	3741 10	Sodankylä	7524.02	532.48	255
41. Pihtijoki	3743 06	Savukoski	7543.13	559.10	260
42. Naruskajärvi 2.	4713 05	Salla	7478.20	472.88	265
43. Naruskajärvi 1.	4713 05	Salla	7478.25	472.80	265
44. Naruskajärvi 3.	4713 05	Salla	7478.30	472.84	265
45. Lattuna 1.	4712 09	Savukoski	7510.00	446.08	205
46. Lattuna 2.	4712 09	Savukoski	7510.39	446.06	205
47. Sotajoki 1.	4712 12	Savukoski	7518.18	457.26	220
48. Sotajoki 2.	4712 12	Savukoski	7518.21	457.34	220
49. Härkätunturi	4714 06	Savukoski	7513.40	476.63	300

Fig. 45. A heavy excavator exposing a subtill gyttja deposit in April 1980 at Paloseljänoja, Sodankylä, discovered in the course of geochemical coring. The locality is about 1 km from the road, but some research sites were as much as 6—7 km from the nearest road.

Most of the subtill organic deposits lie under mires, i.e. at sites that were already depressions before the last glaciation. This location hampered the studies in many ways. As the deposits are always below the groundwater table, the pits filled rapidly with water and the walls collapsed. To overcome these obstacles the sites were excavated in winter, when the groundwater table was at its lowest. However, in most cases the problems remained. Fabric analyses were usually out of the question and all efforts had to be concentrated on clarifying the lithostratigraphy and taking samples before the pit caved in or filled with water.

The only solution was to excavate duplicate pits in the nearest possible 'hard' till. The lithostratigraphy of the true find site was then correlated as accurately as possible with that in the duplicate. The fabric analyses were made in the duplicate pits whenever it could not be made at the original site of discovery. As the duplicate pits could usually be excavated only a few tens of metres away from the original pit, lithostratigraphic correlation was easy and reliable. Most of the duplicate pits exhibited the same lithostratigraphic units as the original pits. However, their organic deposits tended to be considerably thinner or absent (Fig. 46).

The *in situ* subtill organic sediments were almost invariably overlain by a deposit of sorted sediments varying in thickness (cf. Naakenavaara, Fig. 37). The majority were interpreted as proglacial deposits laid down in spring and summer when the meltwaters at the front of the advancing ice sheet ran into depressions, depositing gravel, sand or silt on the organic deposits. When the ice sheet advanced to the site of the organic deposits,

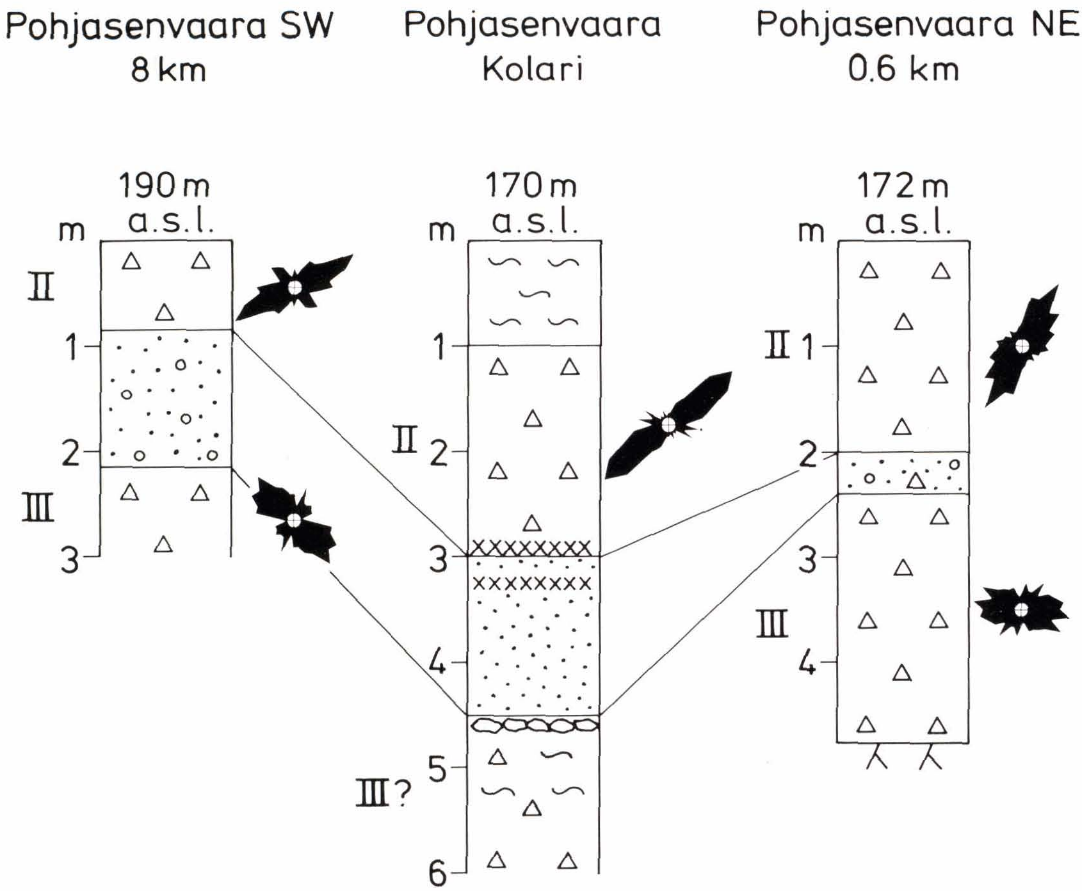

Fig. 46. An example of how the site of discovery of an organic subtill deposit under a present mire is correlated with the nearest exposed moraine ground (Pohjasenvaara NE) and the general stratigraphy (Pohjasenvaara SW). For symbols see Figure 35 (note that all tills are marked by same symbol).

the sorted sediments protected the deposits from glacier erosion. If there were no protective sorted sediments or if glacier erosion was strong, the organic matter was mixed with till either completely or as large lumps.

Classification of the subtill organic sequences

The buried organic deposits found were divided into two groups on the basis of their pollen flora. The interstadial-type deposits are dominated by *Betula*, which often accounts for over 90 % (81.5—99.6 %) of the pollen. The abundance of NAP pollen is high, generally 20—50 % (17—72 %) and comparable to that in Peräpohjola interstadial deposits (Korpela 1969). The deposits of interglacial type contain usually variable amounts of *Pinus* and *Picea* pollen. Also present are pollen of *Betula, Alnus* and the rare deciduous trees *Carpinus* and *Tilia*, and *Corylus*. Ten of the deposits studied are interpreted as interstadial and 39 as interglacial. For pollen diagrams, see Figs. 51, 56—63, 67—68, 70—71, and Appendix 2.

Fig. 47. Interstadial diatomite covered by till bed II at Kaulusrovat, Savukoski (locality 10 in Fig. 44). Diatomite is encountered only in a bedrock depression as an *in situ* deposit 10—20 cm thick. It rests immediately on weathered carbonatite bedrock at a depth of 1.1—1.3 m. Bed II, which overlies the diatomite, is loose, massive, fine sandy till with a few small clasts and 10 % clay fraction. The till is typical weathered bedrock till, greatly resembling the underlying weathered bedrock in appearance and properties.

Interstadial-type deposits

The interstadial-type deposits are fairly evenly distributed throughout the ice divide zone of central Lapland and the area of preglacial weathered bedrock, excluding western central Lapland (Fig. 44). Half of the deposits, that is five, are peat: Siukatanjoki (1), Tunturipäät (3), Ilmakkiselkä (4), Palsioja (5) and Maaseljänjänkä (6); three are gyttja: Naakivuoma (2), Maaselkä (7) and Tulppio (9); and one is diatomite: Kaulusrovat (10). At one site, Neulikkoaapa (8),

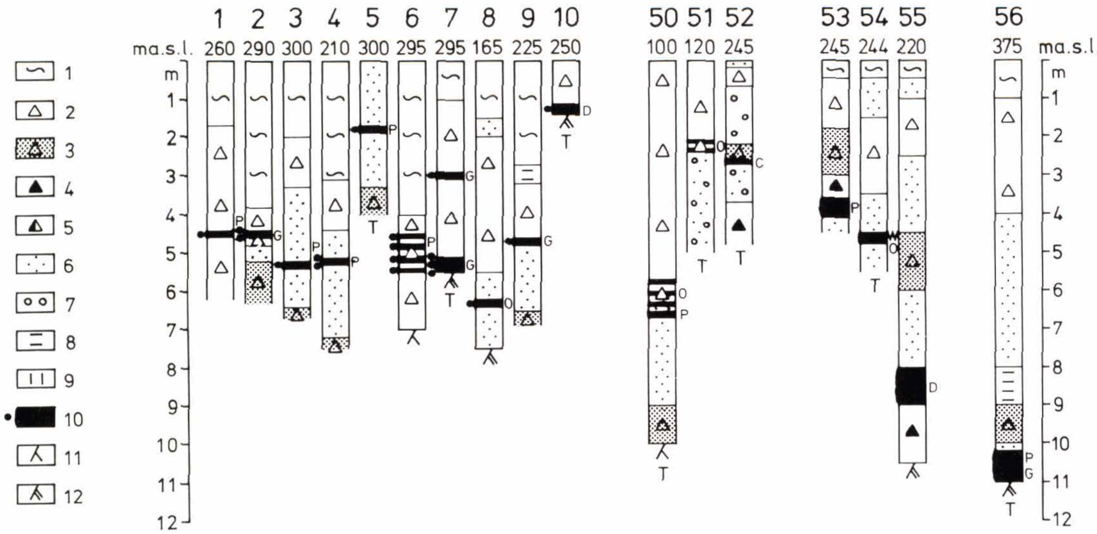

Fig. 48. Stratigraphic positions of the interstadial-type deposits of the present study (columns 1—10), previously studied interstadial deposits (columns 50—52) and interglacial deposits (columns 53—56). Numbers refer to Figure 44 and Table 8. 1. Postglacial peat; 2. upper till bed (in test pits) or till unit (in drill profiles); 3. second till bed or unit; 4. third till bed or unit; 5. fourth till bed or unit; 6. sand; 7. gravel; 8. silt; 9. clay; 10. organic deposit; 11. bedrock; 12. weathered bedrock. P = peat; G = gyttja; D = diatomite; O = organic matter; C = charcoal; W = wood; T = test pit, deposit exposed with an excavator. Dots on the left-hand side of the colums indicate horizons submitted to pollen analysis. At the sites opened with an excavator (1—49) till bed II was uppermost, till bed III was second and till bed IV (Naakenavaara) was third. The fourth till was interpreted as till bed V.

the organic matter was so intermixed with sand that it could not be classified. At Palsioja, Maaselkä and Kaulusrovat the deposits were exposed with an excavator; at other sites the stratigraphy and analytical data are based on samples taken with a Cobra percussion drill. The lower gyttja deposit at Maaselkä and the diatomite at Kaulusrovat (Fig. 47), both exposed by excavator, are in an *in situ* (or almost *in situ)* position. The thin peat deposits at Tunturipäät, Ilmakkiselkä and Palsioja and the organic matter at Neulikkoaapa occur as interlayers in sand and gravel deposits. Intermixed with till are peat at Siukatanjoki and Maaseljänjänkä, and gyttja at Naakivuoma and Tulppio (Figs. 48 and 49).

The interstadial-type organic deposits are invariably thin, ranging from a few centimetres to 0.5 m (Maaselkä, the lower *in situ* gyttja deposit on weathered bedrock). At Maaseljänjänkä the peat in a secondary position is intermixed with till for 0.7 m. Eight deposits (80 %) occur under mires; these were difficult to expose with an excavator and could not be studied in detail. Nine of the deposits are covered by till.

The stratigraphic position of the interstadial-type deposits, which is shown in Figure 48, is as follows:

- *in situ* deposits overlain by only one till bed, which is a typical till bed II in fabric and other physical properties;
- sand and gravel deposits with organic matter as thin interlayers and overlain by only one till bed, which, according to drill profiles, is a typical till bed II;
- organic matter intermixed with till in the till closest to the ground surface.

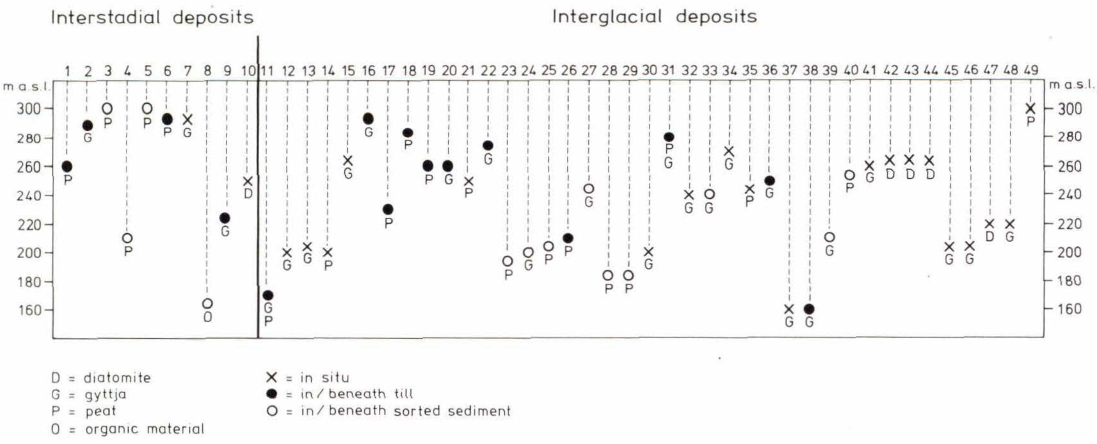

Fig. 49. The elevation of organic subtill deposits. Half of the interstadial deposits are located at elevations of 290—300 m a.s.l., whereas the majority of the interglacial deposits (23) are at 200—260 m a.s.l. The numbers refer to Figure 44 and Table 8.

— thin interstadial-type peat deposit (Palsioja) not covered by till and resting on till bed III in a sand and gravel deposit that extends to the present ground surface. During the last deglaciation stage the site was submitted to intense glaciofluvial erosion that wiped off the youngest till bed (II), as shown by the dense network of meltwater channels. Between and outside the meltwater channels there are occurrences of typical till bed II on the ground surface.

The mean depth of the interstadial-type deposits is 4.3 m, the range being from 1.2 m to 6.3 m (Fig. 48). However, eight deposits were discovered under mires in which the thickest postglacial peat layer was as much as 4 m. The mean thickness of the till or till intermixed with organic matter covering the interstadial deposits is surprisingly low, a mere 2.3 m, the thickness range being 1.0—4.5 m. At five sites (50 %), the till was less than 2 m thick (the mean thickness of till bed II in the ice divide zone is 1.9 m, in northern Lapland 2.5 m and in southern Lapland 2.6 m).

The elevation of the deposits is from 165 to 300 m a.s.l.; half of the deposits lie at 290—300 m a.s.l. (Fig. 49).

The dominant pollen in the deposits is *Betula*, in places accounting for almost 100 %. The proportion of *Betula* pollen in AP pollen ranges from 81.5 to 99.5 % (Fig. 51 and Appendix 2). In over half, or six, of the deposits, *Betula* accounts for over 90 % of the AP pollen. According to the pollen diagrams, the proportion of *Pinus* in AP pollen is between 0 and 16.5 %, and *Pinus* is encountered in every sequence at some depth at least. Most often it accounts for 1—3 % of the pollen, only in three sequences exceeding 10 %.

The abundance of *Picea* pollen is in the range 0—3 %: seven sites lack it altogether and in the other three it accounts for 0.5—3 % of the AP pollen. Apart from two sites (Siukatanjoki and Palsioja), *Alnus* pollen is encountered in all deposits. Its abundance is about the same as that of *Picea*, usually 0.5—1 %, but varying within the range 0.5—4 %. Occasionally *Corylus* pollen (in six deposits 0.5—1 %) and very rarely *Carpinus* pollen (Ilmakkiselkä) are also encountered. NAP pollen accounts for a high proportion of the total, being from 17 to 72 % but most often 20—50 %; only at one site (Tunturipäät) is it less than 20 % and in two sequences (Maaseljänjänkä and Maaselkä) occasionally over 60 %.

Maaselkä interstadial sequence

As the organic deposits interpreted as interstadial are often no more than a few centimetres thick, only one pollen count was made from each. Thus, it was not possible to decipher the evolution of the interstadial vegetation from the study data. The most representative interstadial-type deposit of the study material is that at Maaselkä in Sodankylä (Fig. 44, site 7). It lies under a mire, at an elevation of 295 m a.s.l. Gyttja occurs at two depths, in an *in situ* position on the bottom of the pit and in a secondary position in the overlying till. Immediately on the weathered bedrock, at a depth of 5—5.5 m, there is compact *in situ* gyttja (Fig. 50). The colorimetric humus content in gyttja varies between 15 and 34 %. The gyttja deposit exhibits thin (0.5—2 mm), almost conformable, silt bands that are not genetically related to the sedimentation of the gyttja deposit but were probably formed as a result of glacier load and flow. When the ice sheet flowed over the deposit, eroding its upper part, thin cracks were opened in the frozen gyttja. These were then intruded by high-pressure silt-bearing water from the bottom of the ice sheet. In the duplicate pit a few tens of metres away, the corresponding minerogenic bands are in places composed of 'clear' till with some small clasts. The contact of the gyttja with the overlying till is a sharp, typically erosional contact, and the basal part of the till does not show any signs of gyttja having been mixed with the till, at least not when inspected visually. The gyttja deposit is overlain by 4 m of till and 1 m of postglacial peat. On the basis of its fabric and other physical properties the till is the till II typical of the area, being a fine sandy type poor in clasts (2), which are small in size (2). Since most of the till derives from the local weathered bedrock, the clay content is fairly high, 7 %. In structure the till resembles the tills in the immediate vicinity, showing weakly developed layering due to alternating brownish and greyish layers that differ in grain size and colour, and are from a few centimetres to a few tens of centimetres thick.

The structure is attributed to the process by which the till layers were deposited one on the other at short intervals during the same glaciation stage.

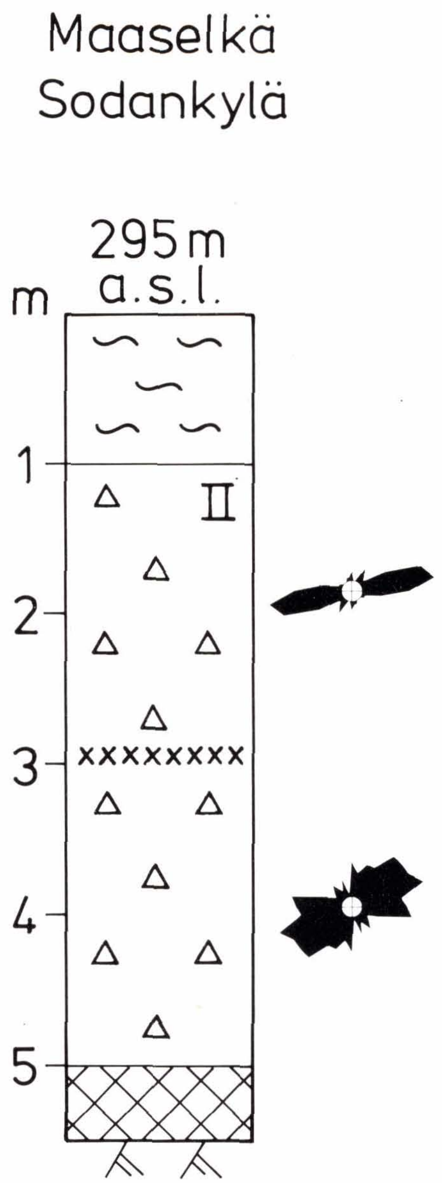

Fig. 50. Schematic stratigraphy of the site where the subtill gyttja was found at Maaselkä, Sodankylä. Two till fabrics from till bed II are also shown. Locality 7 in Figure 44. For symbols see Figure 35.

Approximately in the middle of the till bed, at a depth of 2.8—3 m, gyttja occurs as thin sheets, discontinuous layers or lenses, from a few millimetres to ten centimetres thick. The gyttja sheets are between the till layers rather than in them. In some places they are intensely folded and fractured; in others they occur as coherent, thin and almost unfractured sheets between the till layer over the whole wall of the study pit. Like the gyttja, material from weathered bedrock also occurs as thin sheets between the till layers. These are, however, more numerous than the gyttja layers and occur at various depths.

Fabric analyses were made from the surficial and basal part of the till bed, at depths of 2 m and 3.7 m, respectively. The clasts in till are clearly oriented, with an orientation maximum of 260° for the upper level and 250° for the lower one (Fig. 50), i.e. the same as the direction of the youngest glacier flow in the area or the fabric of till bed II (Figs. 6 and 21).

The gyttja deposit resting on weathered bedrock was submitted to pollen analyses at 5 cm intervals.

The pollen stratigraphy of the Maaselkä gyttja sequence is very constant, being *Betula* dominant from top to bottom; the AP pollen in the bottom and middle parts is almost 100 % *Betula* (Fig. 51). The abundance of *Pinus* pollen in the succession is 0—2 %, except in one sample where it is occasionally 4 %. *Picea* is absent. The abundance of *Alnus* pollen is 0—1 %, the second lowest sample excluded, where it is 4 %. No *Corylus* pollen was encountered in the sequence, with the exception of one grain in the uppermost sample.

The proportion of NAP pollen was from 22 to 72 %, being highest (67 and 72 %) in the basal part of the deposit and 50—58 % at higher levels. There was one exception in the middle of the deposit, where the abundance of NAP pollen was 33 % in one sample (Fig. 51). The gyttja is rich in small wood fragments, which, according to the analyses made by Dr Marjatta Aalto, are *Salix*. The largest fragments are 6.5 cm long and 2 cm thick.

The pollen composition of the gyttja layers in a secondary position in till is similar to that of the lower *in situ* gyttja deposit, except that, in addition to *Betula* (98 %), there is 2 % *Picea* pollen, which is absent from the lower gyttja deposit.

The proportion of NAP pollen is about the same as in the lower gyttja deposit, i.e. 50 %. The gyttja layers in till most probably derive from the same mire basin as the lower *in situ* gyttja deposit, having been transported only a short distance from their site of deposition. Both gyttja deposits exhibit very similar diatom flora and both have a fair number of diatoms but only a few species. These are aerophile or hydrophile species of the genera *Eunotia* and *Pinnularia*, e.g. *Eunotia bigibba*, *Eunotia praerupta* and *Pinnularia borealis*. According to Dr Tuulikki Grönlund, who made the analyses, the diatoms show that the gyttja was deposited under littoral conditions or on wet land, as is also suggested by the abundance of *Salix* fragments in the deposits.

Five of the organic successions interpreted as interstadial contained enough organic matter to permit ^{14}C dating. Both of the gyttja deposits at Maaselkä and the peat deposits at Ilmakkiselkä, Tunturipäät and Palsioja all yielded finite ages in the range 42 200$^{+6\,000}_{-2\,700}$ — 49 000$^{+4\,600}_{-3\,000}$ yr BP (Table 9). Only the peat in the secondary position intermixed with till at Maaseljänjänkä gave an infinite age of over 49 500 yr BP (Su-874) (humus fraction B over 48 000 yr BP).

From their lithostratigraphic position and similar pollen composition the interstadial-type deposits are interpreted as representing one single interstadial substage. The study material did not reveal any organic interstadial deposits in northern Finland younger than the Peräpohjola interstadial, although such deposits have been described from nearby areas in northern Sweden and Norway (e.g. Lagerbäck & Robertsson 1988, Olsen 1989). All the pollen sequences are *Betula* dominant with hardly any changes in pollen composition. The interstadial-type deposits clearly represent a forested, ice-free period in Lapland. Organic deposits indicative of open tundra vegetation are altogether lacking from Finnish Lapland.

In contrast, Lagerbäck and Robertsson (1988) have described an interstadial site with high NAP pollen and sparse tree pollen from Tärendö in

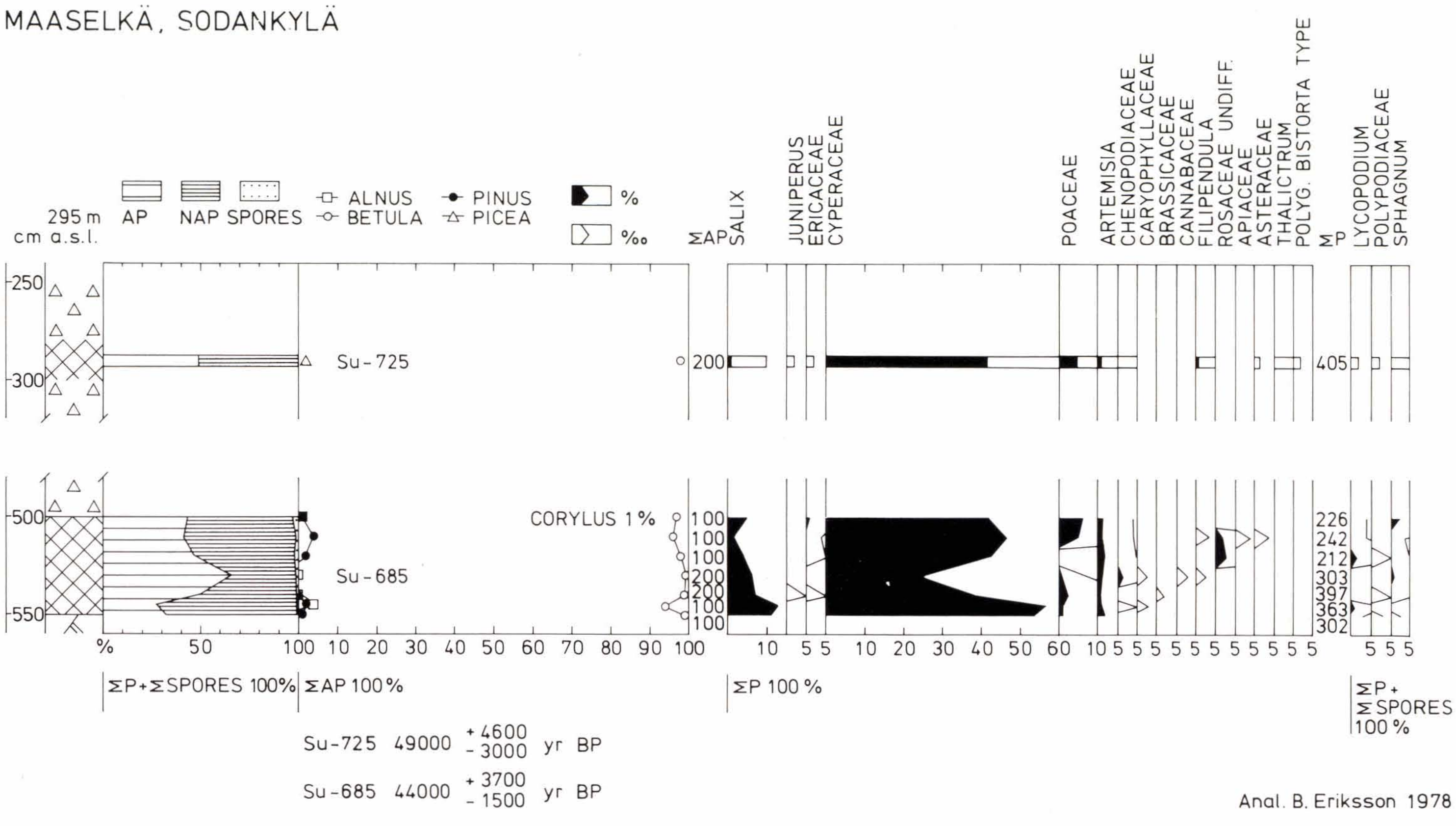

Fig. 51. Pollen diagrams of a gyttja deposit under till bed II and gyttja in the till bed at Maaselkä, Sodankylä, correlated with the Peräpohjola Interstadial on the basis of the high *Betula* values.

Swedish Lapland, indicating tundra vegetation. At Orajärvi, western Finnish Lapland, fossil ice wedges are present on a glaciofluvial delta covered by till, indicating a periglacial tundra climate (Mäkinen 1985). The organic sediment mixed with till filling the wedges contains a *Betula* dominant pollen assemblage. Mäkinen (1985) correlates the fossil ice wedges at Orajärvi with the Peräpohjola Interstadial.

Interglacial-type deposits

Thirty-nine of the 49 sub-till organic deposits studied contain pollen flora that resembles completely or partly the Holocene pollen flora of Lapland. The key feature is the high abundance of *Pinus* pollen, at least at some levels of the sequences studied. On this basis the deposits are interpreted as interglacial in type, and thus they differ from the above monotonous *Betula* dominant interstadial-type deposits.

The pollen diagrams are given in Figs. 56—63, 67—68, 70—71, and in Appendix 2.

The majority of the discoveries are from central and eastern central Lapland, only a few isolated ones being from western Lapland. The deposits are concentrated in Sodankylä municipality, central Lapland, as over half, or 20, of them occur there. Apart from the southwesternmost deposit (Pohjasenvaara) all the deposits are located within the area of preglacial weathered bedrock (Fig. 44): 21 are gyttja, 14 peat and four diatomite or diatom gyttja (Fig. 52). Thirteen deposits were exposed with an excavator and at the sites of the six deepest deposits, Kutuvuoma (17), Pihtijoki (41), Lattuna 1 (45), Lattuna 2 (46), Sotajoki 1 (47) and Sotajoki 2 (48), re-coring and resampling were undertaken with heavy auger equipment. The data on the other successions are based on samples taken with a Cobra percussion drill.

The interglacial-type deposits are located at elevations of 160—300 m a.s.l., with most of them at 200—260 m a.s.l. (Fig. 49); only two are at 290—300 m a.s.l., whereas half of the interstadial deposits are located at this elevation. Thus the interglacial-type deposits seem to favour lower elevations. Their average thickness, which ranges from a few centimetres to 2.5 m, is distinctly greater than that of the interstadial-type deposits. Seventeen deposits exceeded 0.5 m in thickness (the thickest interstadial-type deposit measured 0.5 m), seven of them being 0.5—1 m thick, eight 1.1—2 m thick and two over 2 m thick. Most of the interglacial-type deposits thicker than 0.5 m were fresh-water gyttja (according to diatom analyses); only two were peat (Naakenavaara and Kurujoki) and three fresh-water diatomite (Naruskajärvi 1 and 3 and Sotajoki 1). These deposits, all of which were exposed with an excavator, were found to be or were interpreted as being in an *in situ* position or nearly so. The only exception appears to be Kultalampi.

The interglacial-type deposits lie at distinctly greater depths, on average, than the interstadial-type deposits. Twenty-five of the finds, i.e. two thirds (64 %), are under mires covered with a layer of postglacial peat up to 4.7 m thick (see Fig. 52). The depth to the interglacial-type deposits varies greatly, being 1.5 m at Naruskajärvi 3, and 20 m at Kutuvuoma; the mean depth is 6.8 m (4.3 m for the interstadial-type deposits). The till cover resting on the deposits ranges from 0.4 to 16.5 m in thickness with a mean of 3.4 m (2.4 m for the interstadial-type deposits). The difference between the mean depth to the interglacial-type deposits and the thickness of the overlying till cover is due to the surficial peat and sorted deposits either under or between the till beds and measuring up to 15 m in thickness. The difference in the mean depths to the interstadial-type and interglacial-type deposits has practical implications in that the interstadial-type deposits can be reached with a tractor excavator (digging depth 5 m), whereas the interglacial-type deposits can only be exposed with

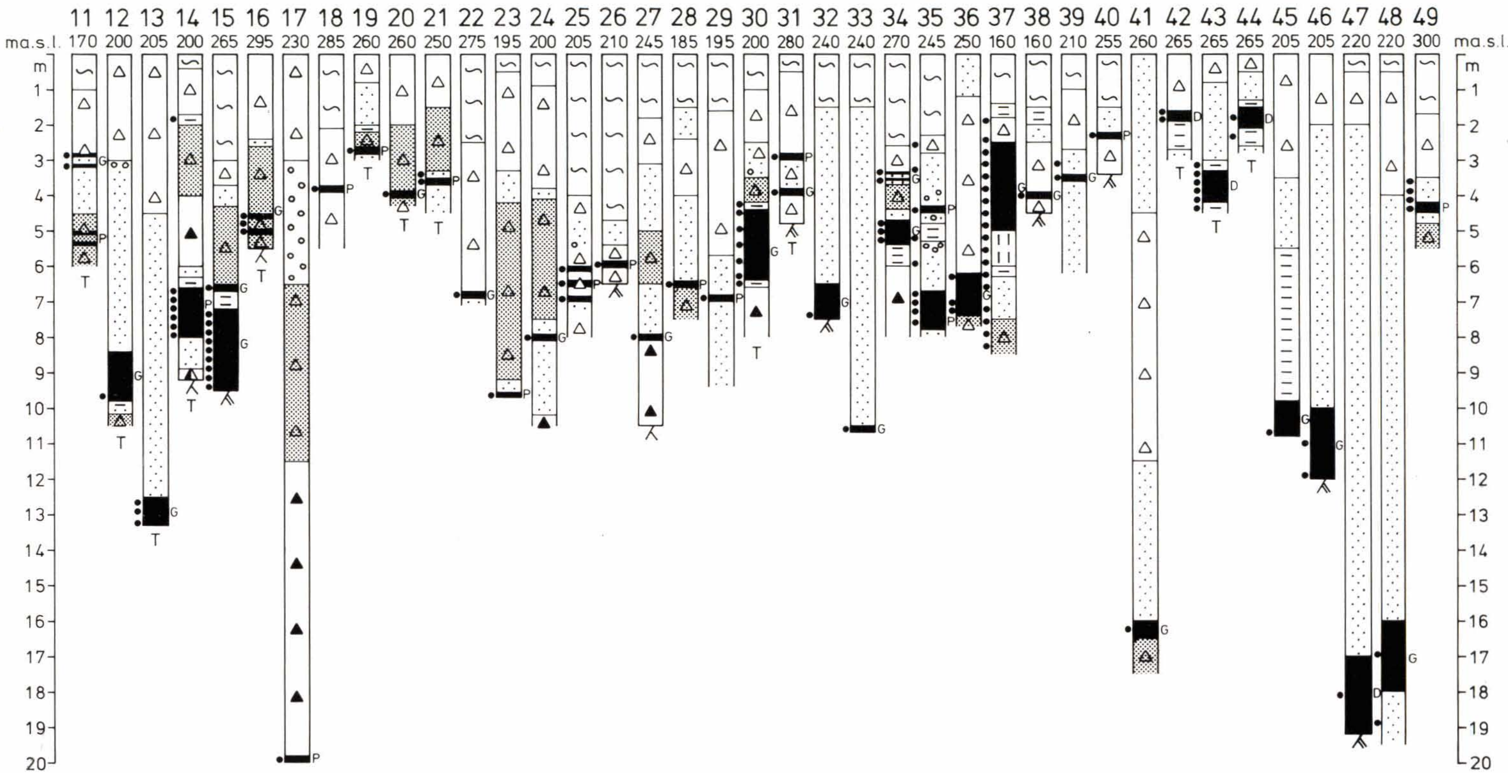

Fig. 52. Stratigraphic positions of the interglacial-type deposits. Symbols are the same as in Figure 48. Numbers refer to Figure 44 and Table 8.

Fig. 53. At Naruskajärvi 2, Salla (locality 42 in Fig. 44), interglacial diatomite (light layers) and diatom gyttja (between the diatomite layers) occur surprisingly close to the ground surface at a depth of 1.6—2.7 m and are covered by only one till bed, i.e. till bed II. As there are no protective sorted sediments between the diatomite and the till, the contact of the diatomite with the till is gradual and the basal part of the till contains abundant diatomite.

heavy crawler excavators, drilling or deep earthworks. The stratigraphic position of the interglacial-type deposits varies, as they may be overlain by one, two or, in some cases, even three till beds (Fig. 52). According to drill profiles, three finds, Kaitaselkä 1 and 2, and Lokka, are covered not by till but by postglacial peat and thick gravel and sand deposits (cf. Mäkinen 1982).

With the exception of the finds exposed by excavator (13), it was difficult to establish the stratigraphic position of the deposits owing to the small size and diameter of the core samples. The results were thus often unreliable, and the till layers were called units rather than beds in the interpretation of drill profiles. The till beds were not easy to distinguish in drill profiles, particularly when they were thin or differed from each other only slightly in physical properties. For example, at Paloselänoja, the drill profile suggested that the gyttja deposit was overlain by only one till unit, about 3 m thick, with a sandy layer in the middle of it. It was not until an excavator pit was dug that a second, 0.7 m thick till unit (till bed III) was found in the pit wall under the sand layer. The stratigraphic position of the interglacial-type deposits was established most reliably at the thirteen excavator-exposed deposits: at six sites the deposit is overlain by only one till bed, typical till bed II: Sivakkapalo 1 (12), Sivakkapalo 2 (13), Naruskajärvi 1 (43), Naruskajärvi 2 (42) (Fig. 53) and Naruskajärvi 3 (44) or is intermixed with it (Pauttisselkä (31)); at another six sites the deposit is under two till beds, probably till bed III: Laitinrova (21) and Paloseljänoja (30) or is intermixed with them: Pohjasenvaara (11), Pailakainen (16), Kuorajoki (19) and Kirakka-aapa (20); and at one site, Naakenavaara (14), the *in situ* peat deposit is overlain by three till beds (II, III and IV) (see Fig. 52).

Nineteen of the interglacial-type deposits are interpreted as lying in an *in situ* position (or almost so); in 16 of them a layer of sorted sediments between the organic deposit and the overlying till has protected the organic deposit from glacier erosion. Eleven of the finds are in till or immediately under it, and nine occur as interlayers in sorted sediments or immediately under them (Figs. 49 and 52). Note that at five sites the coring ended in tightly packed elastic organic deposit: Sivakkapalo 2 (13), Kutuvuoma (17), Sukuvaara (23), Kaitaselkä 1 (33) and Lattuna 1 (45), and at four sites the organic deposit lies immediately on weathered bedrock: Tepsankumpu (15), Kaitaselkä 2 (32), Lattuna 2 (46) and Sotajoki 1 (47) (Fig. 52).

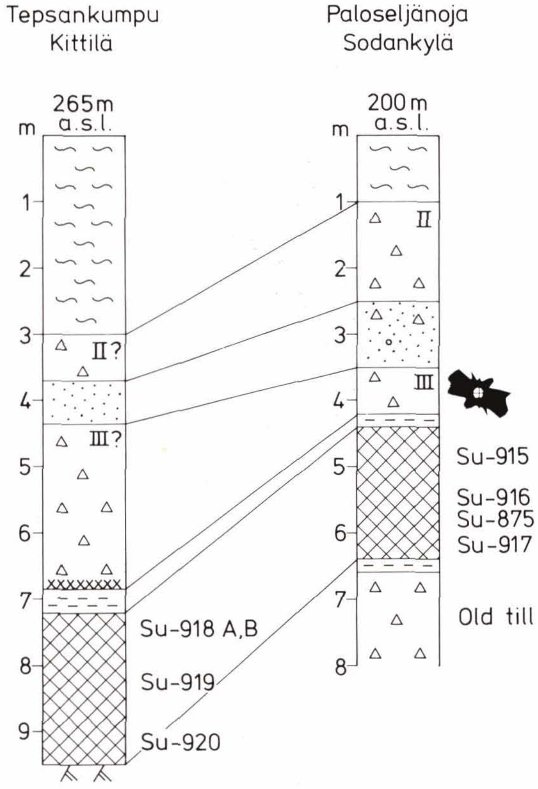

Fig. 54. Stratigraphic positions of the interglacial gyttja deposits at Tepsankumpu, Kittilä and Paloseljänoja, Sodankylä, and correlation of the till stratigraphy of the sites of the deposits. Radiocarbon dates (Su) are shown in Figure 56 (Tepsankumpu) and in Figure 57 (Paloseljänoja) and in Table 9. The till fabric of till bed III at Paloseljänoja is also shown. For symbols see Figure 35 (note that all tills are marked by same symbol).

Tepsankumpu and Paloseljänoja interglacial sequences

Lithostratigraphy

The most complete interglacial-type sequences of the study material are from Tepsankumpu in Kittilä and Paloseljänoja in Sodankylä, where the till is underlain by over 2 m of gyttja. The sites, which are 65 km apart, are under mires in the ice divide zone of central Lapland (Fig. 44, localities 15 and 30). At Tepsankumpu, the postglacial peat is 3 m thick and at Paloseljänoja a mere 1 m. Information about the Tepsankumpu sequence is based on data from percussion drilling. At Paloseljänoja, where the postglacial peat is more shallower, the deposit was exposed with a heavy excavator.

There are three till beds at Paloseljänoja, and the gyttja deposit lies between the two lowermost ones at a depth of 4.35—6.45 m (Figs. 54 and 55). The colorimetric humus content in gyttja varies between 13 and 65 %. The gyttja deposit is underlain and overlain by a thin layer, 10—20 cm thick, of laminated silt. The lamination of the silt under the gyttja is undisturbed, whereas that of the silt overlying the gyttja is deformed by the glacier.

Fig. 55. A gyttja deposit (the brown unit above water level) over 2 m thick under till beds II and III at Paloseljänoja, Sodankylä. Between the gyttja deposit and till bed III there is a grey laminated silt layer, which has protected the gyttja from glacial erosion. As the sites beneath the present-day mires are always very wet, the walls of the pits collapse readily and the pits fill rapidly with water.

Since the layering of the gyttja deposit is completely undeformed, the deposit at Paloseljänoja is obviously *in situ*.

The till under the gyttja deposit is grey, compact (compactness 4), silty till poor in small clasts (clast content and size both 2) and with a clay content of 13 %. The thin till bed (0.8 m) overlying the gyttja and silt deposits is yellowish brown, compact (4), silty till poor in clasts (2) of a small size (1), with 7 % clay. Between the till and the silt there is a typical erosional contact. It is not sharp, however, as the underlying silt is intermixed with the basal till layer in places (Fig. 55). The middle till bed is overlain by a layer of gravel and sand, about 1 m thick, deformed in its upper part. This again is overlain by the third till bed. The contact

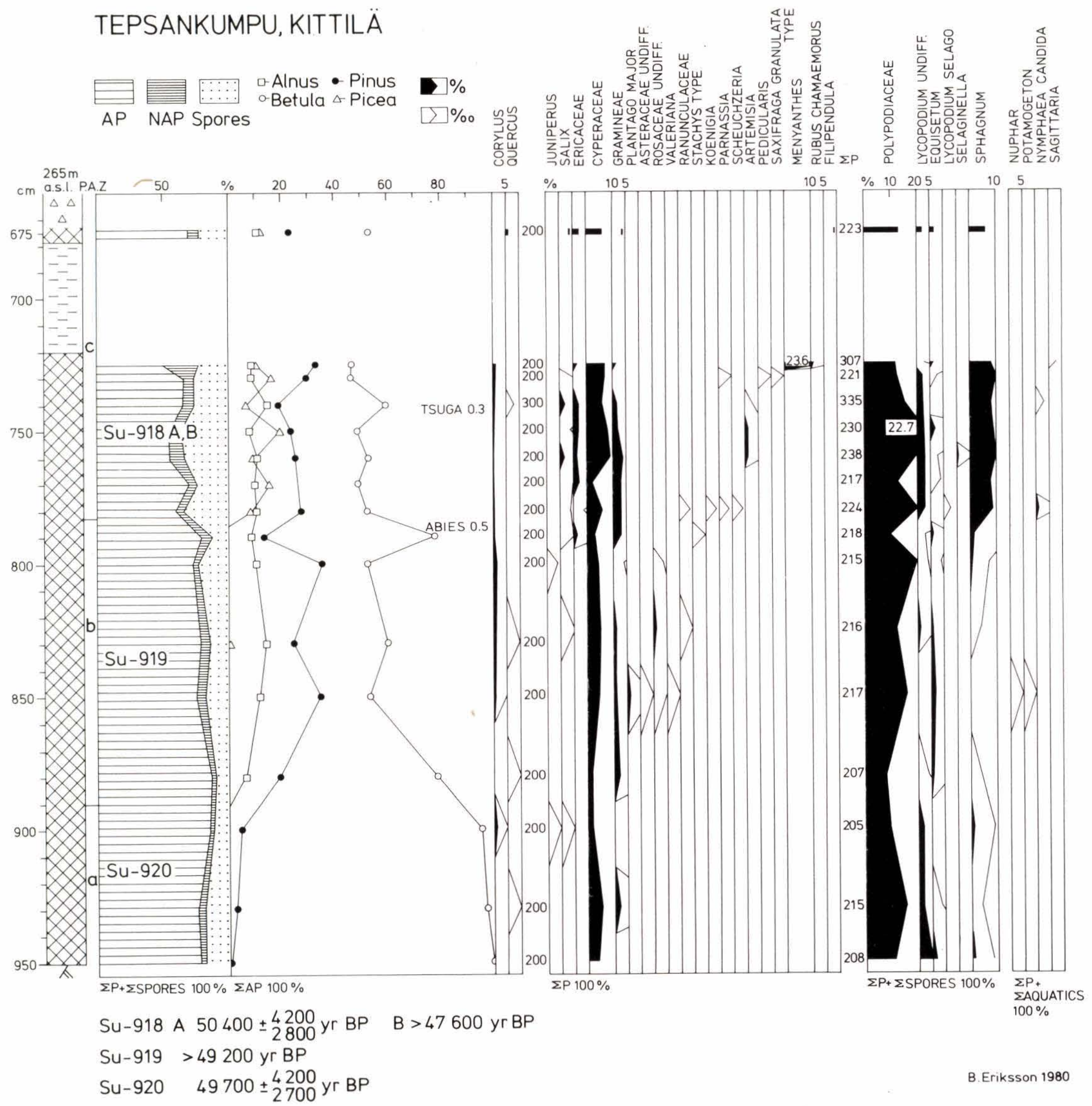

Fig. 56. Pollen diagram of a gyttja deposit over 2 m thick, overlain by two till beds at Tepsankumpu, Kittilä. The gyttja is interpreted as interglacial on the basis of its pollen succession, which resembles that of the Holocene.

between the till bed and the sorted sediments above is gradual, as a considerable amount of sorted material is intermixed with the basal part of the till bed. The uppermost till is grey, loose (2), very sandy and gravelly, and rich in clasts (4), which are well-rounded (4). Much of the material in the till bed probably derived from the underlying sorted sediments.

It was possible to make only one fabric analysis from the till beds. The clasts in the middle till bed show an orientation of 295°, which is the same as the prevailing orientation in till bed III in the area. Owing to its fabric and stratigraphic position, the middle till bed is interpreted as till bed III. From its stratigraphic position the lowest till at Paloseljänoja is interpreted as an older till, and the upper till as till bed II.

Drilling showed that the gyttja deposit at Tepsankumpu rests on weathered bedrock (Fig. 54). The colorimetric humus content in gyttja varies between 10 and 48 %. Here, too, the gyttja deposit is overlain by two till units separated by a layer of sand less than 1 m thick. Both units are grey, fine sandy till (visual estimation) but the lower one is markedly richer in clasts, which are bigger in size than those in the upper one. At Tepsankumpu as at Paloseljänoja the gyttja deposit is overlain by a thin layer of silt which has protected it from glacier erosion.

Pollen stratigraphy of the Tepsankumpu interglacial sequence

The pollen diagram of Tepsankumpu (Fig. 56) can be divided into three local pollen zones:

Te 1 (a) *Betula* pollen zone

The lowest pollen zone is in gyttja on weathered bedrock at a depth of 890—950 cm. *Betula* dominates (>90 %) in AP. *Pinus* is low, 1—5 %. NAP taxa are insignificant.

Te 2 (b) *Betula-Pinus-Alnus* pollen zone

This zone is in gyttja at a depth of 780—890 cm. It is characterized by a sharp rise in the *Alnus* and *Pinus* pollen curves. *Alnus* constitutes c. 10 % of AP, *Pinus* 15 to 30 %, and *Betula* is down to approximately 50 %. A continuous but low, 1—2 %, *Corylus* pollen curve starts in the lower part of the zone. NAP is insignificant.

Te 3 (c) *Picea-Pinus-Betula-Alnus* pollen zone

This zone, which is in gyttja at a depth of 725—780 cm, is characterized by a sharp rise in the *Picea* curve. The curve varies between 8 and 20 %, *Alnus* is fairly constant at c. 10 %, *Pinus* fluctuates between 18 and 35 % and *Betula* accounts for about 50 % of AP taxa. The *Corylus* pollen curve is continuous but low at 1—2 %. *Salix* occurs sporadically, Cyperaceae is higher, 8—9 %, than at lower levels. The Ericaceae and Gramineae curves are almost continuous. This pollen zone is characterized by high *Sphagnum* values (up to 10 % of total pollen). At a depth of 675 cm, a thin gyttja layer exists, separated from the lower gyttja deposit by barren silts. The pollen composition is similar to that of the Tepsankumpu 3 pollen zone.

Pollen stratigraphy of the Paloseljänoja interglacial sequence

The pollen stratigraphy of the Paloseljänoja sequence (Fig. 57) can be divided into two pollen zones:

Pa 1 (c) *Picea-Pinus-Betula-Alnus* pollen zone

The lowest pollen zone is located in gyttja at a depth of 485—640 cm. The lower boundary is at the contact between the pollen-poor silt and the gyttja. The colorimetric humus content in gyttja increases upwards from 16 % to 65 %. The pollen stratigraphy is dominated by *Pinus*, up to 76 %, *Betula* is low at less than 20 %, *Picea* accounts for c. 10 % and *Alnus* for c. 5 %. Cyperaceae values are up to 10 % of total pollen.

Pa 2 (d) *Betula-Salix* pollen zone

The sediment of the uppermost pollen zone is gyttja at 435—485 cm and silt at 430—435 cm. The colorimetric humus content is 13—16 % in the upper part of the gyttja deposit. The pollen

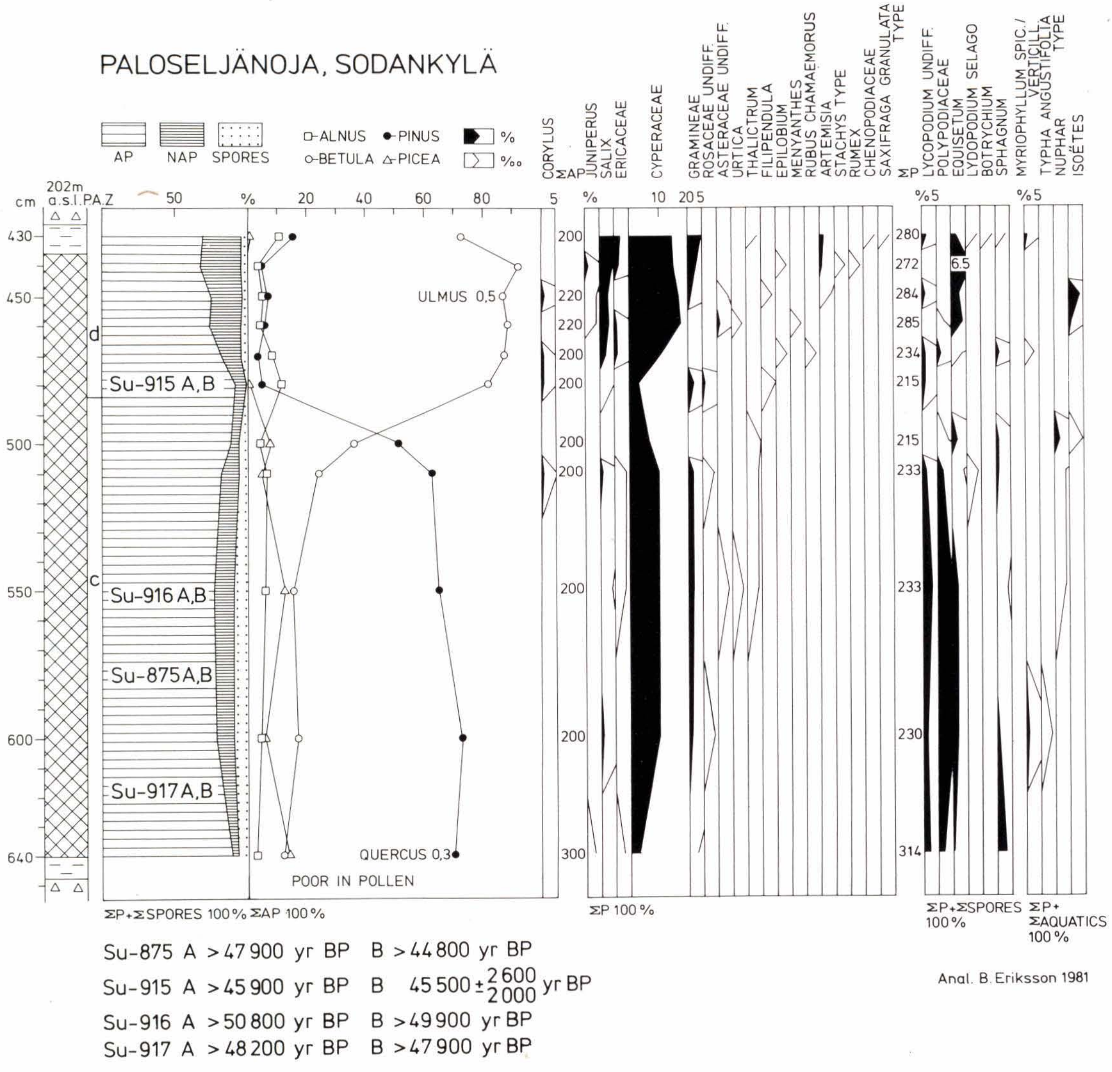

Fig. 57. Pollen diagram of a gyttja deposit over 2 m thick, overlain by two till beds (II and III) at Paloseljänoja, Sodankylä. The gyttja is interpreted as interglacial on the basis of the abundance of *Pinus* and *Picea* pollen and the sporadic occurrence of *Quercus*, *Ulmus* and *Corylus* pollen.

composition is dominated by *Betula*, c. 90 %, *Pinus* declines sharply to less than 10 % and there is an almost complete absence of *Picea*. The *Salix* curve rises from 0 to 6 % and Cyperaceae is higher, up to 18 %, than at lower levels.

Correlation of the Tepsankumpu and Paloseljänoja pollen diagrams

The Tepsankumpu pollen diagram, when compared with the Holocene pollen sequences in central Lapland (e.g. Lappalainen 1970), represents the earlier part of an interglacial vegetation succession. It also represents a fairly long section of the interglacial period, as the pollen stratigraphy covers the evolution from the early *Betula* dominant phase to the *Pinus* dominant phase and, finally, in the upper part, to the *Picea*-dominant phase. In contrast, the Paloseljänoja pollen diagram refers to the later part of an interglacial forest succession characterized first by the presence of *Picea* and then by an almost total absence of it, a decline in *Pinus* and an increase in *Betula* and *Salix*, which indicate a cooler climate.

The diatom analyses made from the Tepsankumpu and Paloseljänoja gyttja deposits also support the above interpretation. The Tepsankumpu sequence starts with alkaliphilous-indifferent diatom flora dominated by *Fragilaria* spp. as dominant species, followed by indifferent-acidophilous flora characterized by *Eunotia* and *Pinnularia* species. The Paloseljänoja sequence, on the other hand, starts with alkaliphilous-indifferent-acidophilous flora dominated by *Eunotia* and *Pinnularia* species and *Aulacoseira italica* subsp. *subarctica*, followed by alkaliphilous flora composed mainly of *Fragilaria* species in the more silty layers higher up. Thus in the Paloseljänoja sequence the lower part of the early interglacial eutrophic phase is missing (e.g. Tolonen 1967).

From their lithostratigraphy and pollen stratigraphy, Tepsankumpu and Paloseljänoja are interpreted as representing the same interglacial period. The *Picea* pollen curves permit pollen zone Te 3 to be correlated with Pa 1. The compiled pollen stratigraphy of both sites most likely covers the whole forested interglacial period, which can be divided into four pollen zones as follows:

Pollen zone	Tepsankumpu	Paloseljänoja
d		Pa 2
c	Te 3	Pa 1
b	Te 2	
a	Te 1	

In the following, the short pollen sequences of other interglacial sediments are first grouped into six types by pollen content and then correlated with the above a, b, c and d interglacial pollen zones.

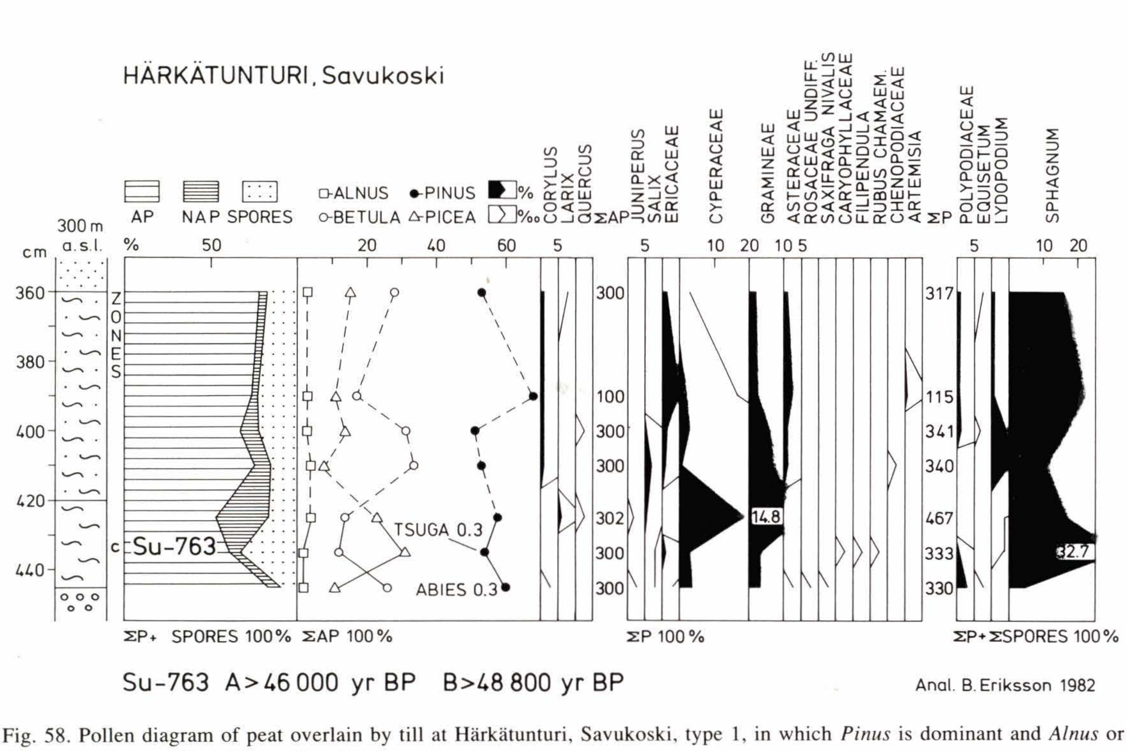

Fig. 58. Pollen diagram of peat overlain by till at Härkätunturi, Savukoski, type 1, in which *Pinus* is dominant and *Alnus* or *Picea* are common (Fig. 44, locality 49).

Types of pollen stratigraphy

Most of the subtill deposits interpreted as interglacial represent only a short, often monotonous, part of the vegetation succession.

Type 1 (Fig. 58) consists of deposits in which *Pinus* is dominant and *Alnus* or *Picea* are common, over 5 %. The abundance of *Pinus* is between 50 and 85 %, that of *Alnus* between 2 and 15 % and that of *Picea* between 5 and 30 %. The deposits usually also contain pollen of *Corylus*, various deciduous trees and *Larix*. Pollen grains of *Abies* and *Tsuga* and spores of *Osmunda* are also frequently encountered.

Type 2 (Fig. 59) consists of deposits where *Betula* dominates and *Alnus* or *Picea* are common, over 5 %. The abundance of *Betula* ranges from 40 % to 60 % and that of *Alnus* and *Picea* from 5 % to 20 %. Pollen grains of *Corylus* and deciduous trees are often present as are those of *Abies*, *Larix* and *Tsuga* and spores of *Osmunda*.

Type 3 (Fig. 60) consists of deposits with a high abundance of *Picea*, up to 40—55 %, and with either *Pinus* or *Betula* dominant. The proportion of *Alnus* is 5—10 %. The deposits also contain pollen of *Corylus*, deciduous trees and *Abies*, the latter in particular. *Tsuga* is encountered occasionally but not *Larix*.

Type 4 (Fig. 61) consists of deposits where *Pinus* is dominant and *Alnus* and *Picea* are rare, less than 5 %. The abundance of *Pinus* ranges from 50 % to 70 %. Some pollen of *Corylus* and deciduous trees are often, and those of *Abies* occasionally, encountered in the deposits of this type.

Type 5 (Fig. 62) consists of deposits where *Betula* is dominant and *Alnus* and *Picea* are rare, no more than 3 %. The proportion of *Betula* is between 60 % and 80 %. Some deposits of this type also contain pollen of *Corylus*, but pollen of deciduous trees and *Abies* occur only occasionally.

Type 6 (Fig. 63) deposits have a very high *Betula* abundance, usually exceeding 90 %. *Alnus, Picea* and *Corylus* are encountered only occasionally. Their pollen assemblage resembles that of interstadial deposits except that the proportion of NAP is low, 3—10 %; in typical Peräpohjola interstadial deposits it is 30—50 % (Korpela 1969, Hirvas & Kujansuu 1979). The type 6 deposits represent either the cold initial or final stage of an interglacial or then they are interstadial.

Correlation of pollen stratigraphies

In the correlation of the deposits it was assumed that the interglacial deposits were formed during the same interglacial. The deposits with a different pollen content were fitted into the pollen zones as follows (Fig. 64).

Type 1: The deposits with dominant *Pinus* and rich in *Alnus* and *Picea* were fitted into zone c.

Type 2: The deposits with dominant *Betula* and rich in *Alnus* were fitted into zone b and those rich in *Picea* and *Alnus* into zone c.

Type 3: The deposits with a high *Picea* abundance and either *Betula* or *Pinus* dominant were fitted into zone c.

Type 4: The deposits with dominant *Pinus* but rare *Alnus* and *Picea* were fitted into zone b.

Type 5: The deposits with dominant *Betula* and rare *Alnus* and *Picea* were fitted into zone d except one deposit that was fitted into zone b.

Type 6: The deposits with over 90 % *Betula* were placed in either zone a or d.

The correlation of the pollen sequences is based on the assumption that the sites refer to the same interglacial stage, a supposition that is mainly based on the lithostratigraphy. The only localities interpreted as representing another interglacial are Naakenavaara and, possibly, Kutuvuoma, which

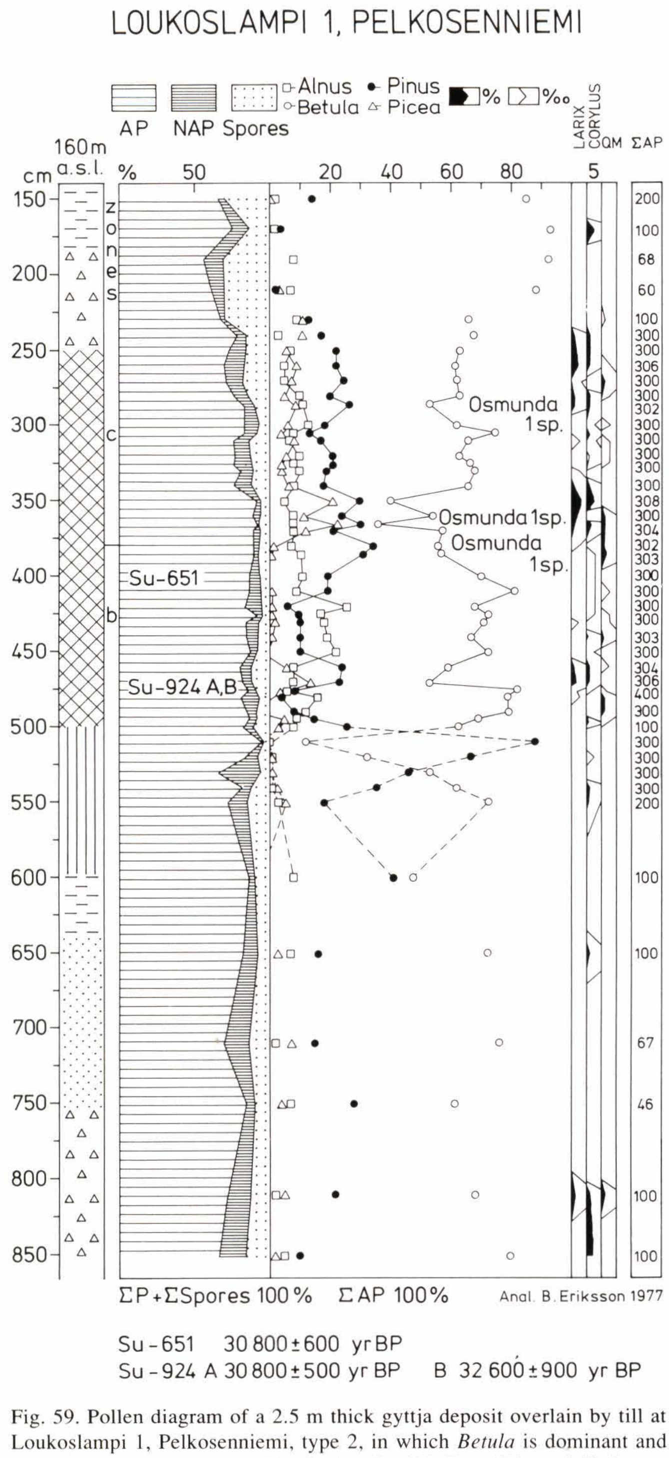

Fig. 59. Pollen diagram of a 2.5 m thick gyttja deposit overlain by till at Loukoslampi 1, Pelkosenniemi, type 2, in which *Betula* is dominant and *Alnus* or *Picea* are common (Fig. 44, locality 37). From Hirvas & Kujansuu 1979 (Fig. 13).

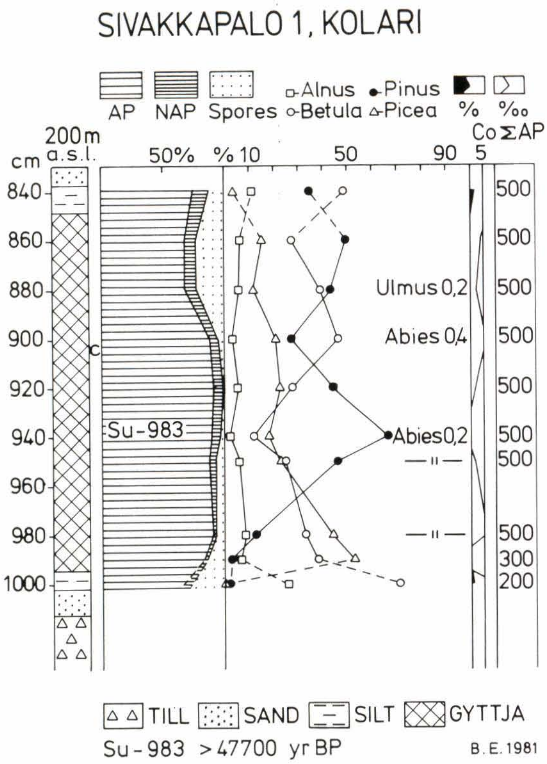

Fig. 60. Pollen diagram of gyttja overlain by till at Sivakkapalo 1, Kolari, type 3, with a high abundance of *Picea* and with either *Pinus* or *Betula* dominant (Fig. 44, locality 12). Modified from Hirvas 1983 (Fig. 4).

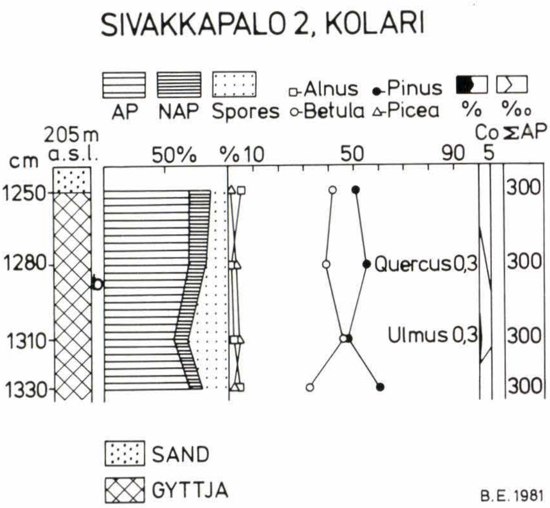

Fig. 61. Pollen diagram of gyttja overlain by till at Sivakkapalo 2, Kolari, type 4, in which *Pinus* is dominant and *Alnus* and *Picea* are rare (Fig. 44, locality 13). Modified from Hirvas 1983 (Fig. 5).

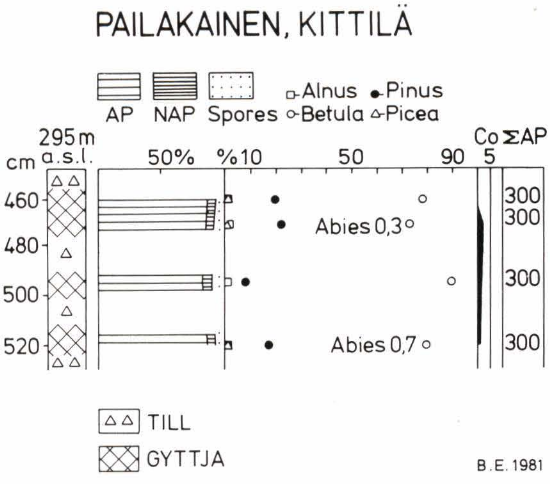

Fig. 62. Pollen diagram of gyttja in till bed III at Pailakainen, Sodankylä, type 5, in which *Betula* is dominant and *Alnus* and *Picea* are rare (Fig. 44, locality 16). Modified from Hirvas 1983 (Fig. 6).

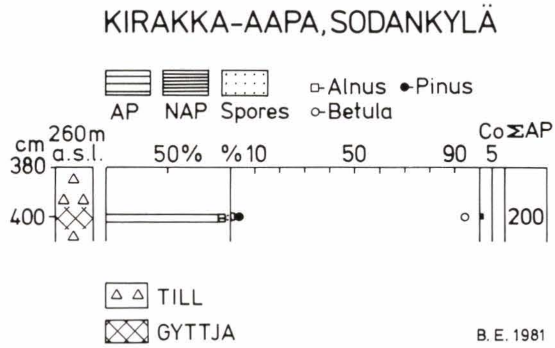

Fig. 63. Pollen diagram of a thin gyttja deposit in till bed III at Kirakka-aapa, Sodankylä, type 6, with a very high *Betula* abundance and only occasional *Alnus*, *Picea* and *Corylus* (Fig. 44, locality 20). Modified from Hirvas 1983 (Fig. 7).

will be dealt with separately. The interglacial deposits are located in central Lapland in an area of very similar forest vegetation. The Holocene pollen sequences are broadly similar throughout the area (e.g. Lappalainen 1970), which is not crossed by any major vegetation boundaries and is part of the northern boreal forest vegetation zone (Ahti et al. 1968).

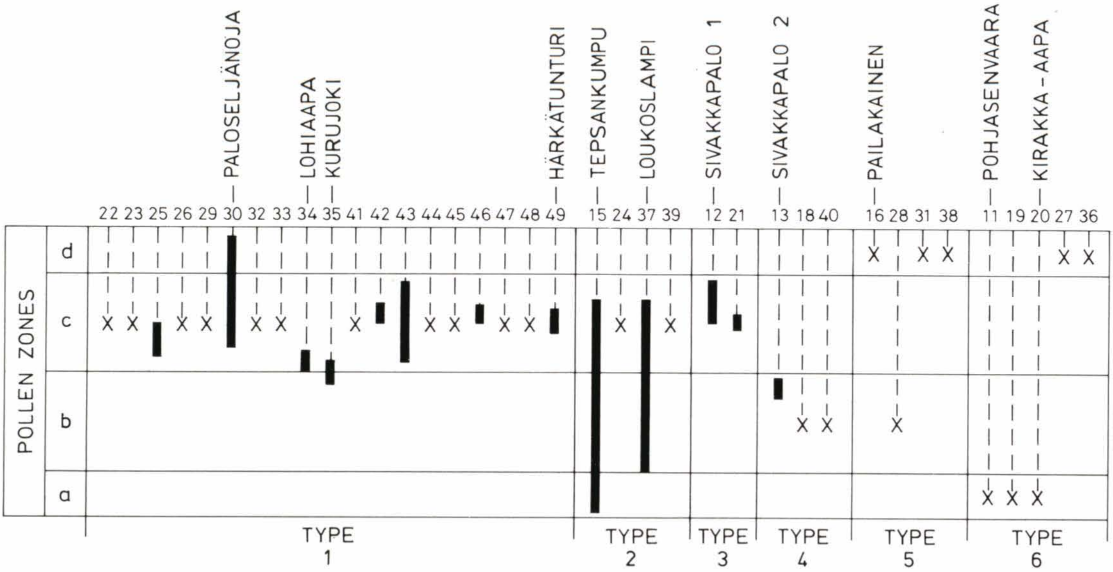

Fig. 64. Correlation of the six types of interglacial pollen sequences and sites in Finnish Lapland. It is presupposed that they all represent the last or Tepsankumpu (Eemian) Interglacial. For details see text.

The present pollen zones, a, b, c and d, are comparable to the zoning of an interglacial, as suggested by Turner and West (1968). Thus, zone a represents the pre-temperate, b the early temperate, c the late-temperate and d the post-temperate substage of an interglacial.

There is no evidence in Lapland of tundra vegetation referring to the beginning of an interglacial or to open tundra vegetation attesting to the beginning of the present (Holocene) interglacial. *Betula* colonized the area as soon as the ice had retreated. Only a short open herb-rich vegetation period is recorded in some pollen diagrams.

The vegetation succession described above is a logical one, closely resembling that reported from the Leveäniemi interglacial deposit in Swedish Lapland (Robertsson 1971, cf. Donner 1983). An interesting difference between Leveäniemi and the deposits discussed is that there are no *Larix, Abies* or *Tsuga* pollen or spores of *Osmunda* at Leveäniemi, whereas in types 1—3 from Finnish Lapland they are almost invariably present. Even so, the interglacial deposits at Leveäniemi and in Finnish Lapland obviously represent the same interglacial period. This study has not taken into account the possibility that the *Larix, Abies* and *Tsuga* pollen may originate from older interglacial deposits.

Radiocarbon datings of subtill sequences

Thirty-one ^{14}C determinations were made from 19 interglacial-type deposits (Table 9). Seven of them are peat (Pohjasenvaara, Naakenavaara, Laitinrova, Postoaapa 2, Pauttisselkä — the organic matter in the upper part of the till, Kurujoki — the lower horizon and Härkätunturi), 10 are gyttja (Sivakkapalo 1, Tepsankumpu — 3 dates, Paloseljänoja — 4 dates, Pauttisselkä — the organic matter in the lower part of the till, Lohiaapa — the lower horizon — 4 dates, Loukoslampi 1—

Table 9. Radiocarbon dates of subtill organic sediments.

No.	Locality	Depth (m)	Material	Sampling method	Lab. No.	Radiocarbon age Fraction A (insoluble)	Radiocarbon age Fraction B (soluble)
INTERSTADIAL-TYPE DEPOSITS							
3.	Tunturipäät	5.2—5.4	Peat	Per. drill.	Su-774	44 600 $^{+1\,700}_{-1\,500}$	41 400 $^{+2\,300}_{-2\,300}$
4.	Ilmakkiselkä	5.1—5.3	Peat	Per. drill.	Su-684	43 500 $^{+3\,700}_{-1\,500}$	
5.	Palsioja	2.0	Peat	Spade	Su-668	42 200 $^{+6\,000}_{-2\,700}$	
6.	Maaseljänjänkä	4.9—5.2	Peat	Per. drill.	Su-874	>49 500	>48 000
7.	Maaselkä	1.8—1.9	Gyttja	Spade	Su-725	49 000 $^{+4\,600}_{-3\,000}$	
»	Maaselkä	4.5—4.8	Gyttja	Spade	Su-685	44 000 $^{+3\,700}_{-1\,500}$	
34.	Lohiaapa	3.1—3.3	Gyttja	Per. drill.	Su-793	45 800 $^{+2\,200}_{-1\,700}$	41 400 $^{+1\,200}_{-1\,200}$
35.	Kurujoki	4.3—4.8	Peat	Per. drill.	Su-508	41 900 $^{+3\,000}_{-3\,000}$	
INTERGLACIAL-TYPE DEPOSITS							
11.	Pohjasenvaara	4.5—5.0	Peat	Spade	Su-1099	47 200 $^{+2\,300}_{-1\,800}$	43 900 $^{+2\,400}_{-1\,800}$
12.	Sivakkapalo 1.	9.0—9.1	Gyttja	Spade	Su-983	>47 700	>46 900
14.	Naakenavaara	6.0—6.5	Peat	Spade	Su-510	>48 700	
15.	Tepsankumpu	7.3—7.7	Gyttja	Per. drill.	Su-918	50 400 $^{+4\,200}_{-2\,800}$	>47 600
»	Tepsankumpu	8.1—8.5	Gyttja	Per. drill.	Su-919	>49 200	
»	Tepsankumpu	8.8—9.5	Gyttja	Per. drill.	Su-920	49 700 $^{+4\,200}_{-2\,700}$	
21.	Laitinrova	3.5—3.7	Peat	Spade	Su-945	>51 700	>49 200
25.	Postoaapa 1.	6.0—6.5	Peat	Per. drill.	Su-513	>48 400	
30.	Paloseljänoja	5.3—6.2	Gyttja	Per. drill.	Su-875	>47 900	>44 800
»	Paloseljänoja	4.8	Gyttja	Spade	Su-915	>45 900	45 500 $^{+2\,600}_{-2\,000}$
»	Paloseljänoja	5.5	Gyttja	Spade	Su-916	>50 800	>49 000
»	Paloseljänoja	6.2	Gyttja	Spade	Su-917	>48 200	>47 900
31.	Pauttisselkä	2.9—3.0	Peat	Per. drill.	Su-686	44 500 $^{+3\,000}_{-2\,000}$	
»	Pauttisselkä	3.0	Peat	Spade	Su-782	48 100 $^{+2\,800}_{-2\,100}$	>49 600
»	Pauttisselkä	3.9	Gyttja	Spade	Su-781	>50 000	>47 300
34.	Lohiaapa	5.1—5.3	Gyttja	Per. drill.	Su-683	>43 000	
»	Lohiaapa	4.7—4.9	Gyttja	Per. drill.	Su-921	47 900 $^{+4\,300}_{-2\,800}$	
»	Lohiaapa	4.9—5.1	Gyttja	Per. drill.	Su-922	>42 100	
»	Lohiaapa	5.2—5.3	Gyttja	Per. drill.	Su-923	46 100 $^{+2\,700}_{-2\,000}$	
35.	Kurujoki	6.9—7.8	Peat	Per. drill.	Su-509	>47 700	
37.	Loukoslampi 1.	3.0—5.0	Gyttja	Per. drill.	Su-651	30 800 $^{+600}_{-600}$	
»	Loukoslampi 1.	4.5—5.0	Gyttja	Per. drill.	Su-924	30 800 $^{+500}_{-500}$	32 600 $^{+900}_{-900}$
39.	Pyörreselkä A	2.9—3.0	Gyttja	Per. drill.	Su-726A	>47 700	
»	Pyörreselkä B	3.5—3.6	Gyttja	Per. drill.	Su-726B	>47 700	
41.	Pihtijoki	16.0—16.5	Gyttja	Auger drill.	Su-773	>50 800	>50 200
43.	Naruskajärvi 1.	3.5—4.2	Diatomite	Spade	Su-687	43 700 $^{+2\,000}_{-1\,400}$	
»	Naruskajärvi 1.	3.6—4.0	Diatomite	Spade	Su-1014	45 700 $^{+3\,000}_{-2\,200}$	44 000 $^{+1\,600}_{-1\,300}$
46.	Lattuna 2.	10.0—11.0	Gyttja	Auger drill.	Su-727	>49 000	
47.	Sotajoki 1.	18.0	Diatomite	Auger drill.	Su-1015	35 800 $^{+700}_{-700}$	>50 300
48.	Sotajoki 2.	16.0—18.0	Gyttja	Auger drill.	Su-728	49 000 $^{+4\,000}_{-3\,000}$	
49.	Härkätunturi	4.2—4.4	Peat	Per. drill.	Su-763	>46 000	>48 800

2 dates, Pyörreselkä — 2 dates, Pihtijoki, Lattuna 2 and Sotajoki 2), and two were diatomite (Naruskajärvi 1—2 dates and Sotajoki 1).

Twenty determinations were made from gyttja, eight from peat and three from diatomite or diatom gyttja.

Unlike the interstadial-type deposits, the interglacial-type deposits almost invariably show infinite ^{14}C ages (Table 9), i.e. the deposits exceed the age that can be reliably dated with the method. Some thicker organic deposits were submitted to several ^{14}C determinations, yielding both finite and infinite ages for the same deposit. For example, four ^{14}C determinations were made from the 0.6 m thick lower gyttja deposit at Lohiaapa, which was intersected by two holes drilled at different times. Two of them gave finite ages (at depths of 4.7—4.9 m and 5.2—5.3 m) and the other two infinite ages (at depths of 4.9—5.1 m and 5.1—5.3 m). Three ^{14}C determinations were made from the over 2 m thick gyttja deposit at Tepsankumpu. Those from the upper and basal parts of the deposit gave finite ages, whilst the one from the middle of the deposit yielded an infinite age. The insoluble fraction A of some samples from three sequences (Tepsankumpu, Pauttiselkä and Sotajoki 1) showed finite ages, whereas the soluble fraction B gave infinite ages.

The sequences at Loukoslampi 1, Naruskajärvi 1, Sotajoki 2 and Pohjasenvaara yielded finite ages only. The gyttja deposit at Loukoslampi was sampled for radiocarbon determinations in winter 1976 and again four years later in winter 1980. The first sample (Su-651) was dated by A. Heikkinen and the second (Su-924) by Tuovi Kankainen; both times the result was the same, 30 800 ± 600 yr BP (Su-651) and 30 800 ± 500 yr BP (Su-924). This cannot be attributed to identical contamination by surficial peat during sampling. The diatomite at Naruskajärvi 1 was submitted to radiocarbon determinations at an interval of five years, Su-687 (A. Heikkinen 1977) and Su-1014 (Tuovi Kankainen 1982). As the diatomite at Naruskajärvi was exposed with an excavator and the samples for dating were taken with a spade from the carefully cleaned wall of the excavator pit, no organic contamination could have entered the samples during the sampling. Fraction B was not analysed the first time, and so the sample, which had been kept in a freezer, was submitted to re-analysis in the course of which both fractions were analysed. All three dates were very similar: Su-687 fraction A 43 700 $^{+2\,000}_{-1\,400}$ yr BP, Su-1014 fraction A 45 700 $^{+3\,000}_{-2\,200}$ yr BP and fraction B 44 000 $^{+1\,600}_{-1\,300}$ yr BP. A sample taken with an auger drill from the gyttja deposit underlying a mire at a depth of 16—18 m at Sotajoki 2 gave an age of 49 000 $^{+4\,000}_{-3\,000}$ yr BP (Su-728). Sotajoki 2 is only about 100 m southwest of Sotajoki 1, where diatom gyttja at the same depth and in the same stratigraphic position yielded an age of 35 800 ± 700 yr BP (fraction A) and an infinite age of over 50 300 yr BP (fraction B) (Su-1015).

As shown by their pollen composition, the organic deposits at Loukoslampi 1, Naruskajärvi 1 and Sotajoki 2 are clearly interglacial in type, containing almost ubiquitous pollen of deciduous trees and *Corylus*. The sequences at Loukoslampi 1 and Naruskajärvi 1 also contain *Larix* pollen and spores of *Osmunda*; the latter occasionally contains *Tsuga* pollen, too. Redating demonstrated that the samples were not contaminated during sampling. However, the high reproducibility of the dates might be attributed to slow contamination, of the subtill organic deposits by substances transported by seepage water and groundwater. At both Loukoslampi 1 and Naruskajärvi 1, the interglacial-type deposits have only a very thin till cover (0.7 and 0.8 m). Moreover, as the till at both sites is very permeable, rich in sand and loosely packed, it is feasible that organic matter has migrated into the deposits causing an age to be too young. At Sotajoki 2, though, the mixing of younger organic substances with the sample to be dated could be ascribed to the drilling technique applied (auger drilling).

The apparent discrepancies between the interpreted interglacial ages and the ^{14}C ages of the samples are probably due to the fact that even a very small amount of younger carbon may result in a finite age (cf. Harkness 1975, Olsson 1986).

The younger organic matter may have been introduced into the samples by intermixing in the course of sampling from tree roots or seepage water and groundwater (cf. Kankainen & Huhta 1986).

The finite dates in the order of 30 000 to 50 000 are interpreted as too young and are attributed to contamination. They are not reasonable in the light of the spread of the continental ice sheet during the Weichselian glaciation and the last interglacial/glacial chronology based on the dates of deep sea sediments (Mangerud in press). The chronology and correlation will be discussed in the chapter Correlation and dating of the Pleistocene stratigraphy in Finnish Lapland.

The Naakenavaara Interglacial

Naakenavaara, Kittilä (Fig. 44, site 14) is located in the extensive ice divide zone of central Lapland. The Naakenavaara deposit is dealt with in this context only to the extent necessary for the stratigraphic interpretation. A more detailed description of its lithostratigraphy, pollen stratigraphy and macrofossil stratigraphy will be given elsewhere (Aalto, et al. *in prep.*). Naakenavaara is the only one of the sites studied where an organic deposit was encountered under till bed IV. The deposit, which is *in situ* peat at a depth of 6.5 m, is up to 1.5 m thick. The find is currently under a forested mire covered with a thin peat layer. The mire is at 200 m a.s.l. The stratigraphy of the deposit is shown in Figure 65.

The Naakenavaara test pit has four superimposed till beds. The oldest till of the sequence is encountered only here and there as thin layers in bedrock depressions at a depth of 9 m. It is greyish, visually estimated sandy till rich in fully weathered clasts in various colours. On the basis of its stratigraphic position, it is »old till», and is a remnant of till bed V or an even older till bed.

The old till is overlain by 1—2 m of glaciofluvial gravel and sand. Resting on them is up to 1.5 m of peat at a depth of 6.5—8 m. In the adjacent test pits the peat deposit is from 0.5 to 1.5 m thick. It is very tightly compressed, so much so that sampling had to be done with a chain saw (Fig. 66). In the basal and surficial parts of the deposit, the ash content of the peat, calculated from dry matter, is 5—6 % and in the middle part only 3 %. The peat is thus not intermixed with mineral matter. The peat deposit is overlain by thin layers (10—30 cm) of laminated silt and sand on which rests till bed IV. Up to 3.8 m thick, this is the thickest

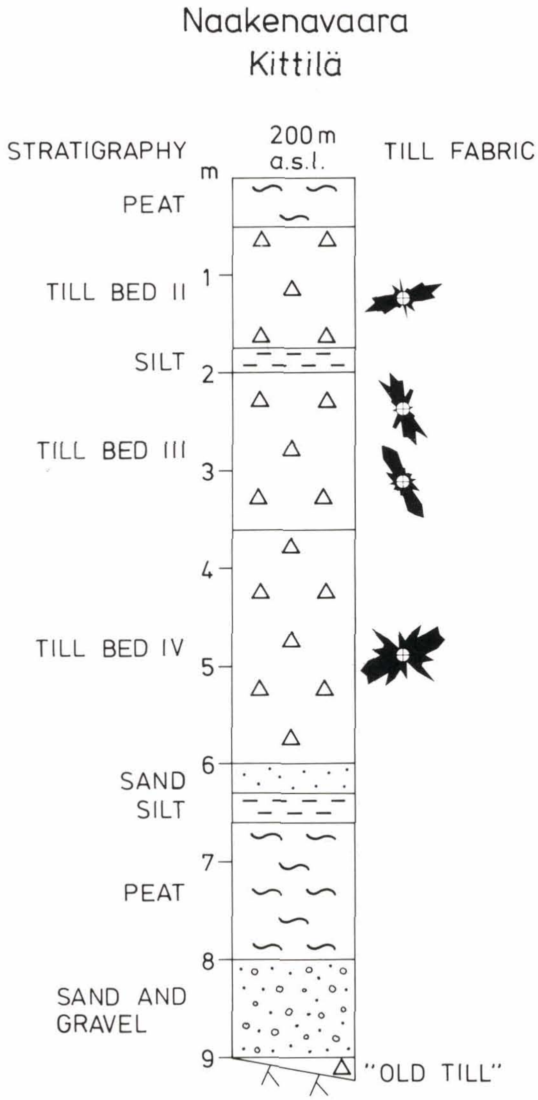

Fig. 65. Stratigraphy and fabric analyses of the Naakenavaara interglacial peat deposit at Kittilä. The flow direction of the ice sheet that deposited till bed IV was established with stone counts. For symbols see Figure 35.

Fig. 66. The subtill peat at Naakenavaara was so tightly compressed and hard that it had to be cut with a chain saw.

till unit of the sequence. The contact between till bed IV and the underlying sand is sharp and erosional.

Till bed IV is a yellowish brown, massive sandy till (clay content 6 %) poor in clasts (content 2) of small size (2). Sand lenses and bands probably deriving from the sorted sediments under the till bed are abundant. The till is surprisingly loosely packed (compactness 2) probably due to the high sand content.

Overlying till bed IV is the third till bed, till bed III. The contact between till beds III and IV is sharp (a typical erosional contact) and gently undulating. Till bed III is from 1 to 2 m thick, grey in its upper part and brownish lower down. It is composed of massive fine sandy till (clay content 2 %). Its compactness is 3 and clast content 4; the clast size is 2 or 3.

Between till bed III and the uppermost bed, till bed II, there is a 30 cm thick layer of varved silt without pollen or diatoms that is interpreted as glacial lake sediment. The upper and lower contacts of the silt are sharp. Till bed II, which is about 1 m thick, contains clearly fewer and smaller clasts and is less compact than till bed III. Till bed II is greyish brown silty till (clay content 7 %) poor

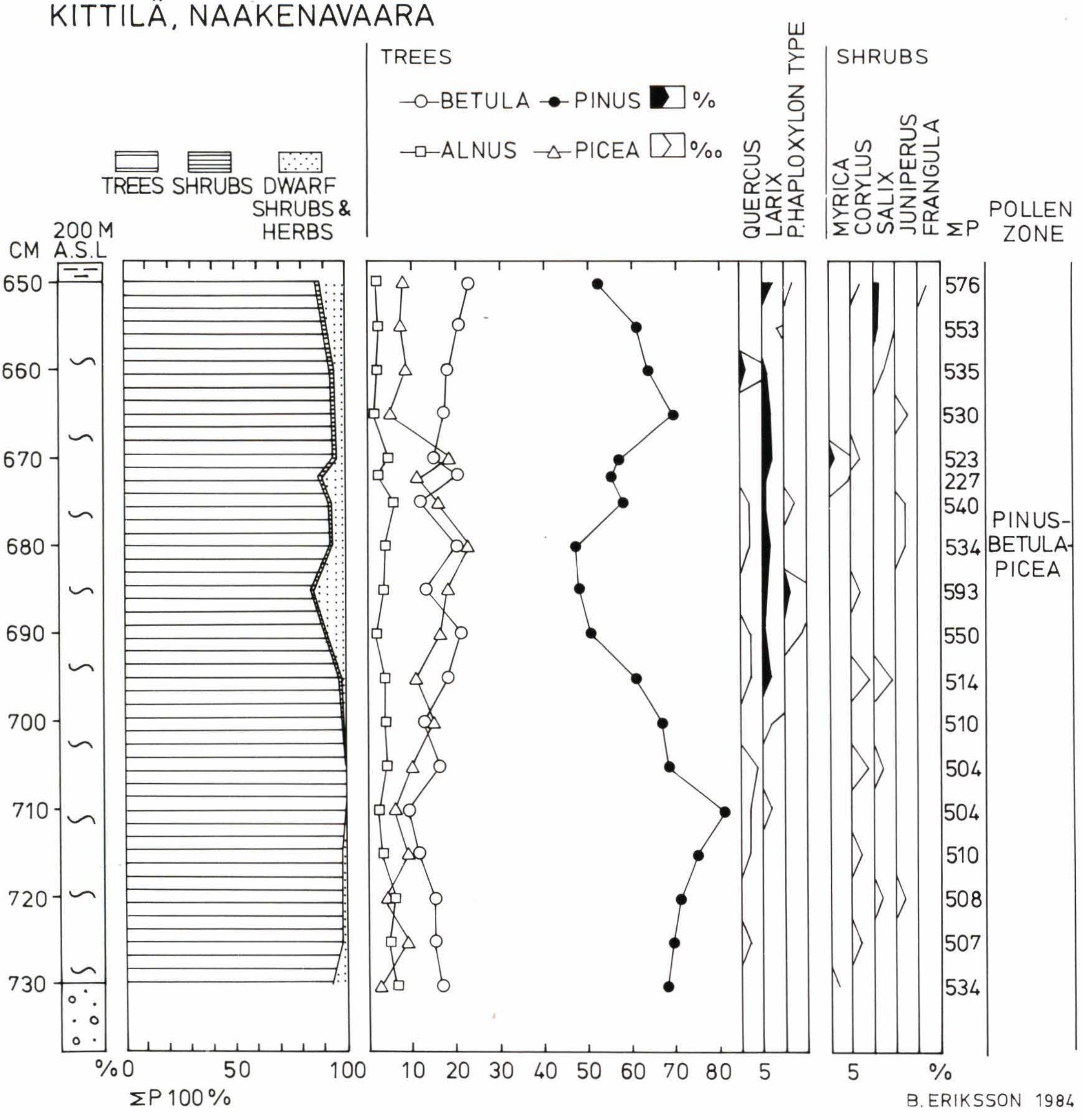

Fig. 67. Pollen diagram of peat overlain by till beds II, III and IV at Naakenavaara, Kittilä. The Naakenavaara peat deposit is correlated with the Holstein-Likhvin interglacial deposits.

in small clasts (clast content and clast size both 2), in places intensely fissile and loosely packed (compactness 2). On the surface and resting on till bed II there is about 0.5 m of postglacial peat. At Naakenavaara the fabrics of till beds IV, III and II correspond to the dominant fabrics of the till beds in the same stratigraphic positions (cf. Fig. 42).

The buried peat deposit underlying till bed IV was submitted to pollen analyses at 5 cm intervals, and 500 arboreal pollen were counted from each sample by Brita Eriksson. The pollen grains were very well preserved. The pollen spectra of all samples are very similar. The *Pinus* curve is high, varyin between 47 % and 81 %. *Picea* fluctuates between 3 % and 22 %, *Betula* between 9 % and 23 %, *Alnus* between 1 % and 6 % and *Larix* between 0.2 % and 2.4 %. The continuous *Larix* pollen curve starts in the middle of the peat deposit, where the *Picea* curve is at its highest (Fig. 67). In addition to *Larix* pollen, a *Larix* cone was found in the peat deposit.

The peat deposit does not show any clear vegetation succession, except that the *Picea* curve rises from 3 % in the basal part to 22 % just above the middle part of the bed, and that *Pinus* correspondingly declines from 67 % on the bottom to 47 % in the middle.

The samples also contained pollen of other coniferous trees besides *Larix* that did not grow in the area during the post-glacial stage.

The *Pinus* pollen curve includes individual pollen grains not from *Pinus sylvestris*, and some pollen of *Pinus haploxylon* were also encountered. The *Picea* pollen curve contains some *Picea omorica* pollen but their abundance is less than 1 %. Some pollen grains of conifers, such as Podocarpidites, Abiespollenites and Zonalapollenites, are considered pre-Quaternary.

Shrub pollen is rare. The only one occurring in an abundance worth mentioning is *Myrica gale* in the upper part of the sequence.

Dwarf shrub pollen is also rare in the sequence, although pollen of the Bruckenthalia-type occur in almost all samples. The abundance of these pollen is less than 1 % except in the lowermost sample, where they amount to 4 %. Recent *Bruckenthalia spiculifolia* grows in the Balkan Peninsula and in the mountains of Romania (Tutin 1972).

Herbaceous plants are rare in the total pollen composition, the main representative being Carex. Spores of pteridophytes are also rare, only one or two spores of *Osmunda* being found in four samples.

At the time the peat was depositing the climate was warmer than it is at present, and conifers were the dominant trees in the area. In broad outline, the vegetation was very similar to what it is now, although there were some species that have not grown in the area during the Holocene. These include *Larix*, a species of the genus Bruckenthalia, *Osmunda* and probably also *Picea omorica*.

The site was a forested mire when the peat deposited, as it is today. Thus, areas that are currently depressions were already depressions a long time ago. The general features of the basement topography have hardly changed at all during the last three, if not more, glaciations, particularly in the ice divide zone of central Lapland.

In terms of dominant trees, the pollen diagram of Naakenavaara is very similar to that of zone c in the interglacial deposit at Leveäniemi in northern Sweden. However, an interesting difference between the two deposits is that the above pollen alien to the current flora have not been found at Leveäniemi. The pollen composition of many other interglacial-type deposits in northern Finland (cf. Fig. 58) is also very similar to that of the Naakenavaara peat deposit. Therefore, it is not possible to date or discriminate between the interglacial deposits in northern Finland merely on the basis of pollen analysis.

Macrofossil determinations have, however, brought to light something really new. The peat deposit at Naakenavaara contains abundant seeds of *Aracites johnstrupii*, which have not been found in any other interglacial or interstadial deposit in northern Finland (Aalto & Hirvas 1987, Hirvas & Eriksson 1988). The species has been encountered in Europe only in Holstein-Likhvin and older interglacial deposits and in Pliocene deposits (Katz et al. 1965, Zinova 1982, Zubakov 1988). *Aracites johnstrupii* is a peat-forming mire plant, about 20—30 cm high, resembling *Menyanthes*.

The seeds of *Aracites johnstrupii* were identified by C-G. Stén at the Geological Survey of Finland in 1976. The determination was verified by Dr Marjatta Aalto in 1984, and finally confirmed in 1986, when Dr Aalto visited Cambridge and was able to compare the seeds from Naakenavaara with the reference samples of Prinemanskaja and Gralevo from the Mikulino deposits.

As the pollen composition in the Naakenavaara peat deposit is clearly interglacial in type, the ice-free stage, which was warmer than the present day, is named the Naakenavaara interglacial. The true age of the peat has not been established, but from its stratigraphic position it can be deduced that the deposit predates the last, or Eemian, interglacial. The pollen diagrams of the Holsteinian interglacial in northwestern Europe are characterized by a preponderance of conifers and poorly developed zonation of the forests. Pollen diagrams of the Holstein stage nearest to Naakenavaara are from Karukülä and Körvekylä in Estonia (Liivrand 1984). Features shared by these sites and Naakenavaara are the high abundance of conifers, pollen of *Larix* and the *Picea omorica* group and spores of *Osmunda*. The Naakenavaara peat deposit contains abundant *Aracites johnstrupii* seeds, which have been encountered in European Quaternary deposits only in those of the Holstein-Likhvin and older interglacials. It would then be most natural to correlate the Naakenavaara interglacial with the Holstein interglacial. It is always possible, of course, that the Naakenavaara interglacial is older still.

In a drill profile at Kutuvuoma, Sodankylä, peat has been found at a depth of 22 m, in a stratigraphic position similar to that at Naakenavaara. There, too, the peat deposit lies below three distinctly different till units (Fig. 52, site 17). On the basis of their physical properties, the two uppermost till units and the 3.5 m thick gravel layer between them can be reliably correlated with till beds II and III and the intervening deposits of the ice-free stage in nearby study pits. A third till unit clearly differing from the upper till begins at a depth of 11.5 m. Between them there is a layer very rich in stones and boulders (boulder pavement?) which was hard to penetrate. Thus, it is plausible that the Kutuvuoma peat deposit is overlain by a till older than till bed III, most likely by till bed IV. The thickness of the peat deposit is unknown, as drilling was stopped at the surficial part of the deposit. The pollen composition in the upper part of the peat deposit is very similar to that at Naakenavaara: 54 % *Pinus*, 37 % *Betula*, 8 % *Picea* and 1 % *Larix*, see Appendix 2. Kutuvuoma lies about 32 km ESE of Naakenavaara (Fig. 44, site 17 and Naakenavaara site 14).

Superimposed subtill organic deposits

Unfortunately, the study material does not include any fully reliable or unambiguous observations of superimposed organic interstadial or interglacial deposits separated by till beds. At three sites, Kurujoki and Lohiaapa in Sodankylä and Pohjasenvaara in Kolari, organic deposits lie at various depths and in different lithostratigraphic positions, and the interstadial and interglacial deposits may be superimposed.

The Kurujoki and Lohiaapa finds, which are 12 km apart (Fig. 44, localities 35 and 34), lie under mires. At Kurujoki, there are subtill gravel, sand and silt deposits interlayered with peat deposits at depths of 4.3—4.5 m and 6.7—8.0 m (Figs. 68 and 69). The Kurujoki find is under a reservoir and could not be exposed with an excavator. The sequence at the site is as follows: on the top there is 2.3 m of postglacial peat underlain by 0.4 m of till, below which there are gravel, sand and silt deposits down to a depth of over 8 m, where the drilling was stopped. The upper peat deposit is 20 cm thick and appears to lie in its original position. It was also encountered in a hole drilled adjacent to the first hole. The pollen composition of the peat deposit (Fig. 68) is typical of Peräpohjola interstadial deposits, with *Betula* at 92—96 % (including *Betula nana*) and NAP at 12—21 %. NAP includes Gramineae, Cyperaceae, Cruciferae, Sparganium, *Sphagnum*, Polypodiae and Rosaceae genera, i.e. the genera which Korpela (1969) described as typical of Peräpohjola interstadial deposits. Radiocarbon dating on the peat deposit (Su-508) gave a finite age of 41 900 ± 3 000 yr BP.

The lower pure peat deposit is 1 m thick. In its upper part (at a depth of 6.7—7.0 m) the peat is intermixed with sand but lower down the peat is unmixed and seems to be undeformed. According

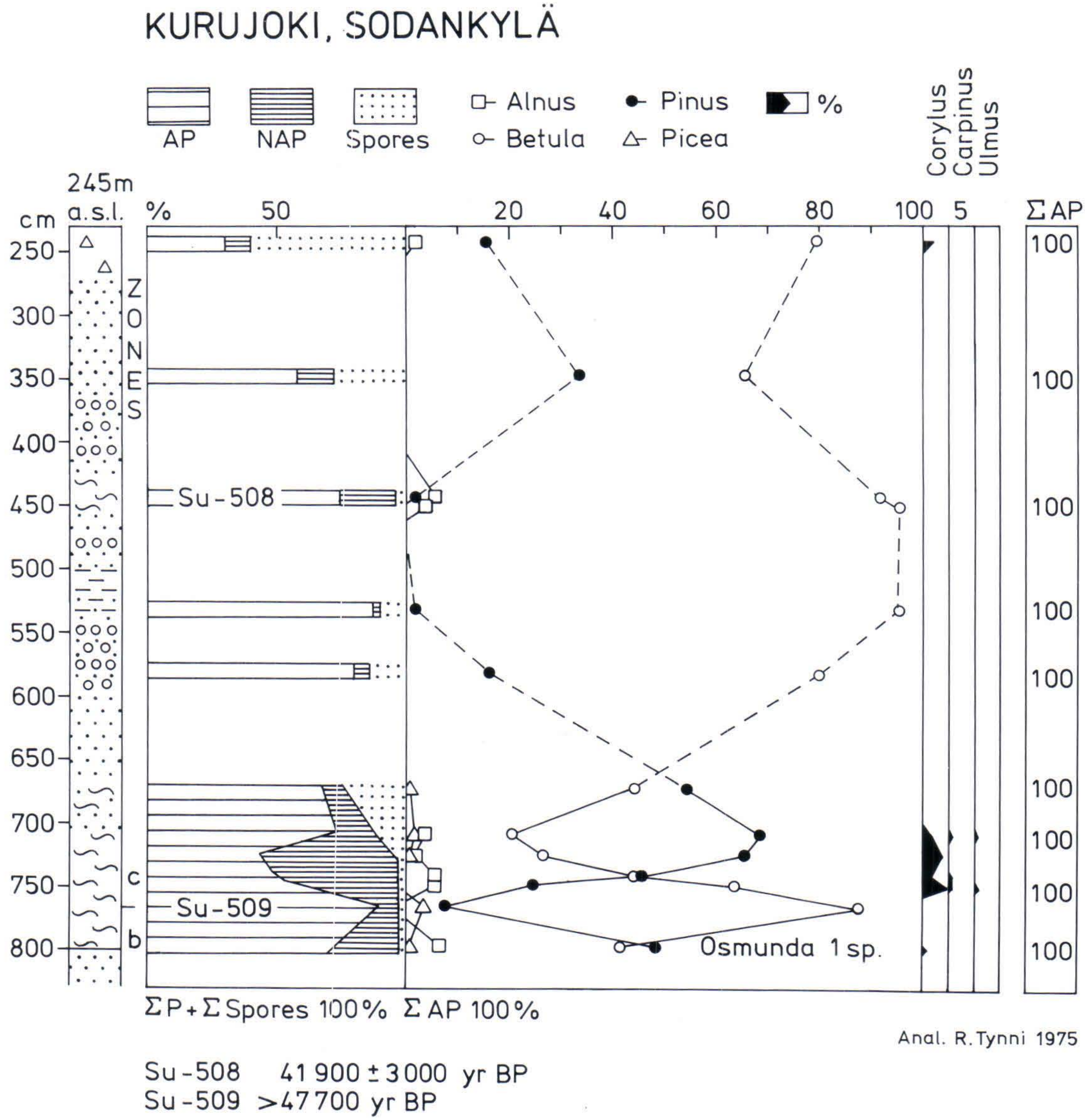

Fig. 68. Pollen diagram of Kurujoki, Sodankylä, where subtill peat occurs in different lithostratigraphic positions. On the basis of the pollen composition, the lower peat deposit is clearly interglacial. The upper peat deposit is interpreted as interstadial. See text.

to its pollen composition, the deposit was formed when the climate was warmer than it is at present. Excluding the lowermost analysis, the pollen contain 46—88 % *Pinus*. *Corylus* values are at their highest, 5 %, in the middle of the deposit; *Alnus*, 4—7 %, and *Picea*, 1—4 %, occur widely throughout the sequence. *Carpinus* and *Ulmus* pollen are met with occasionally at three depths and spores of *Osmunda* in the lowermost sample. The *Alnus* and *Corylus* pollen refer to vegetation of a stage which was relatively humid and warm for northern Finland. The high abundance of

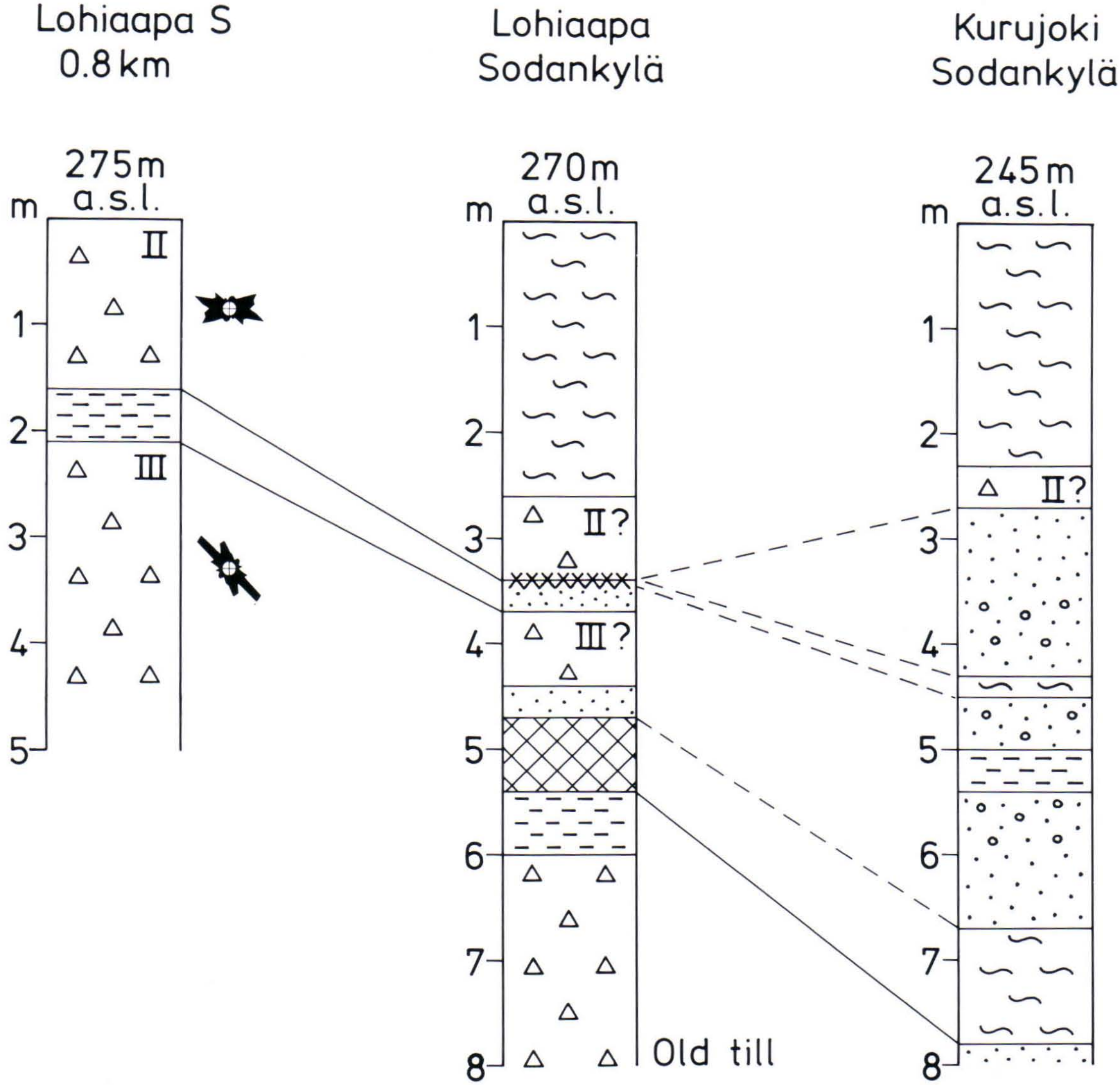

Fig. 69. Stratigraphic positions of the superimposed organic deposits at Lohiaapa and Kurujoki in Sodankylä, and their proposed correlation with each other and with the general till stratigraphy (Lohiaapa S). For symbols see Figure 35.

Corylus together with *Alnus* and *Pinus* represents the climax forest and indicates that the peat deposited during the interglacial climatic optimum. The high NAP values in the middle of the peat deposit are due to the high abundance of Cyperaceae pollen. The ^{14}C age of the peat deposit is over 47 700 years (Su-509).

Although without a till layer of indisputable glacial origin between them, the peat deposits are interpreted as having developed during various ice-free substages, i.e. the upper peat deposit represents an interstadial and the lower one an interglacial. The absence of a till indicating glaciation from between the peat deposits may be due to the fact that the site is only 100 m from the channel of the River Kurujoki. Glacial meltwaters running in the channel during deglaciation or floodwaters of the ice-free stage may have eroded any till that existed between the peat deposits. But then, it is sometimes extremely difficult to identify a till composed of very sandy sorted material when only a small sample is available. Therefore, the existence of till between the peat deposits is not entirely ruled out, especially because the sand overlain by silt at a depth of 5—5.4 m is coarser and less sorted (containing small stones) for a thickness of about 1 m than the sand layer immediately above the peat deposit. Of course it is possible that both the lower and upper peat deposits were formed during the same ice-free substage.

The Lohiaapa sequence (Fig. 44, locality 34) contains gyttja at a depth of 3.4—3.6 m intermixed with the basal part of till and as thin layers in a deformed sand layer under the till and at a depth of 4.7—5.4 m between the sand and silt layers (Fig. 69). The drill cores suggest that the sequence contains three till units differing in appearance and properties and probably referring to three different glaciations. Numerous replicate cores were drilled at the site to obtain enough material from the upper thin gyttja horizon for radiocarbon dating. Almost all these cores exhibited a thin sand layer, from a few cm to 25 cm thick, between the two uppermost till units. Six replicate samples also contained gyttja in the basal part of the till and/or in the underlying sand. The lithostratigraphy of the Lohiaapa sequence is as follows: 2.5 m of postglacial peat underlain by 1 m of grey till rich in silt, 0—0.25 m of deformed sand, less than a metre of grey sandy till, 0.3 m of sand, 0.6 m of gyttja, 0.6 m of silt and 2 m of very compact and clay-rich brown till containing abundant weathered clasts.

A study pit was dug in the nearest exposed till-covered terrain, about 800 m south of the drilling site, to check the lithostratigraphy (Fig. 69). The pit is 5 m deep and shows two till beds (II and III) with a deformed silt layer, less than a metre thick, between them. The upper bed (II) is fine brown sandy till (the colour is due to the oxidation of iron above the groundwater table) with 6 % clay. The lower bed (III) is fine grey sandy till with 1 % clay. The clasts in till bed II show an orientation of 265° and in till bed III of 315°, in accordance with the general orientation of these tills in the area. The lithostratigraphic units in the drill profile and in the study pit seem to correlate with each other fairly well. As both have a silt-rich till unit as the uppermost member underlain by a layer of deformed sand/silt and a unit of sandy till, the upper gyttja horizon at Lohiaapa seems to be under till bed II and the lower gyttja layer under till bed III.

The pollen composition of the upper gyttja layer is interstadial in type with 97 % *Betula* (Fig. 70). *Pinus* accounts for 2 % and *Picea* for 1 % of the pollen. The proportion of NAP is high, 36 %, and is composed mainly of Cyperaceae and Gramineae grains. The ^{14}C dating on the gyttja yielded an age of 45 800 $^{+2\,200}_{-1\,700}$ yr BP (Su-793).

The pollen composition of the lower gyttja deposit is distinctly interglacial in type. *Pinus* has persistently 70 % dominance, and the *Alnus* (3—5 %) and *Picea* (2—5 %) values are fairly constant. *Corylus* and occasionally *Ulmus* pollen are encountered in the middle of the gyttja deposit. The proportion of NAP is low. Four ^{14}C determinations were made from the deposit, of which two gave finite ages and two infinite ages. One infinite age, over 43 000 yr BP, was obtained from the basal part of the original sample (Su-683) and the other, over 42 100 yr BP, from the middle of the replicate sample (Su-922) taken somewhat later (Fig. 70). The stratigraphic position, pollen composition and radiocarbon dates of the Lohiaapa gyttja deposit suggest that the sequence contains both an interstadial and an interglacial organic deposit, and a till between them indicating glaciation. According to this interpretation, the lowermost till beneath the lowermost organic sediment is an old till predating the Weichsel glaciation.

The stratigraphic position of the subtill organic deposits at Pohjasenvaara, Kolari (Fig. 44, locality 11) was confirmed by digging a study pit at the site. The Pohjasenvaara sequence, too, lies under

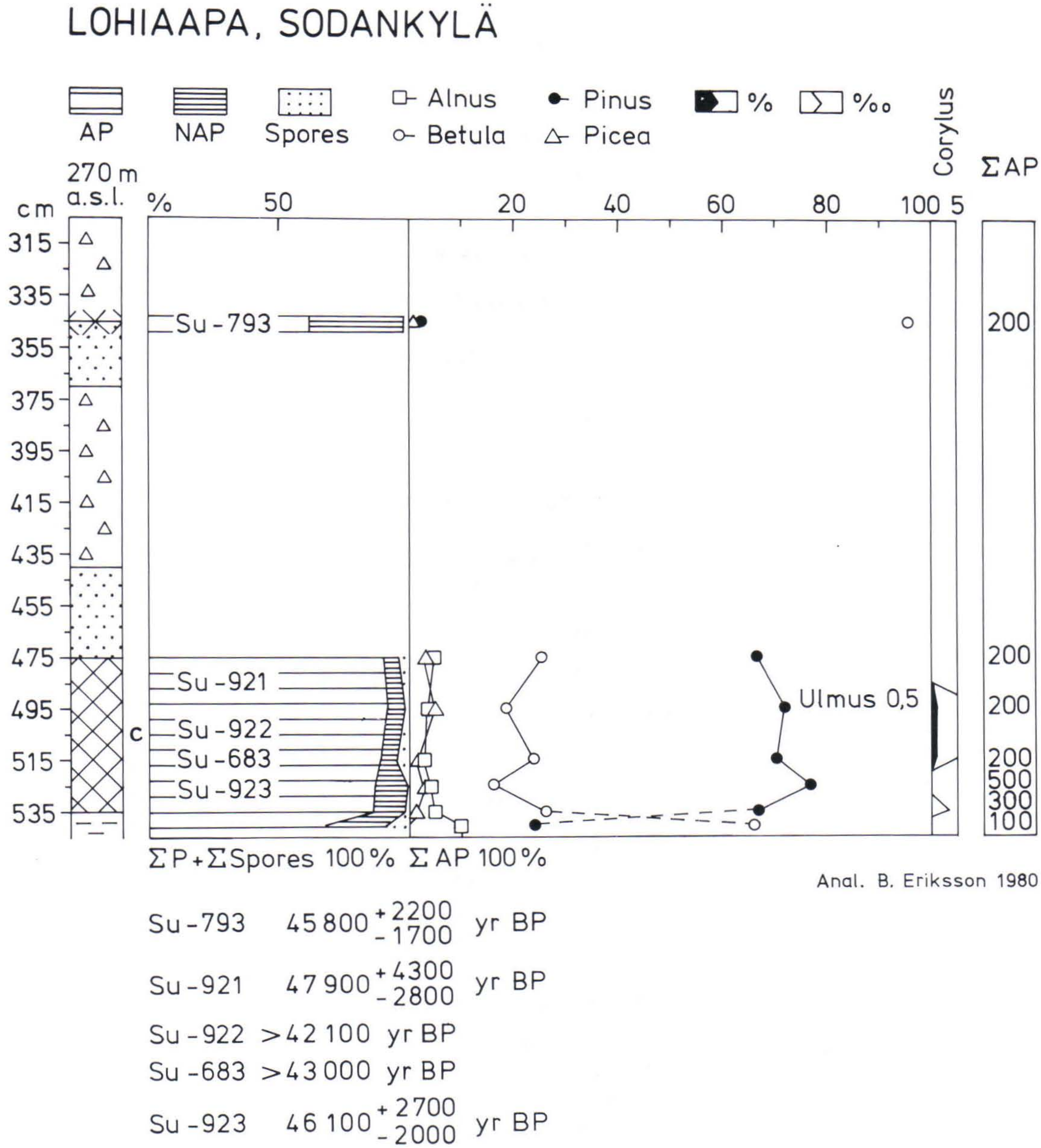

Fig. 70. Pollen diagram of gyttja deposit in different stratigraphic positions at Lohiaapa, Sodankylä. The lower gyttja deposit is interpreted as interglacial and the upper one as interstadial. See text.

a mire. The postglacial peat is underlain by two till beds with 1.5 m of sand, interpreted as a littoral deposit, between them (Figs. 46 and 71). The upper till is the youngest fine sandy till typical of the area and its clasts show the 230° orientation characteristic of till II in the area. The older till is compact (4) and silty. This till could not be submitted to fabric analyses because the walls of the pit continually caved in. Therefore the analyses were made from till in a similar stratigraphic position in a duplicate pit excavated in till 600 m away. The older till showed an orientation of 280°, which is typical of till III in the area (Fig. 46). The above till stratigraphy is very typical of, and often reported from, the immediate vicinity of Pohjasenvaara, where the various flow stages of the continental ice sheet can even be deduced from aerial photographs. The WNW-trending drumlins refer to the older stage of glacier flow and the smaller southwest-trending fluting ridges to the younger stage (cf. Fig. 9).

At Pohjasenvaara organic matter occurs at three depths (Fig. 71): at 4.9—5.5 m, where peat is intermixed with the upper part of an older till, and at 3.1 m and 3.0 m, where there are thin layers of gyttja-banded silt in the upper part of the sand layer between the till beds and in the basal part of the younger till. In the upper part of the older till, peat occurs as small lenses and layers, a few mm to a few cm thick, or completely intermixed with till, in which case the till is almost black. In the sand between the tills, 10 cm from its upper contact, there is a layer of gyttja-banded silt, 0.5—1 cm thick, in which the abundance of organic matter is a mere 8 %. The layer was visible only in one wall of the study pit. In the basal part of the younger till, in the contact of the till with the sand layer, there were some discontinuous layers of gyttja-banded silt, a few mm thick. The pollen composition of all the layers containing organic matter shows *Betula* dominance. In the peat layers of the lower till, *Betula* accounts for 97—99 % of the

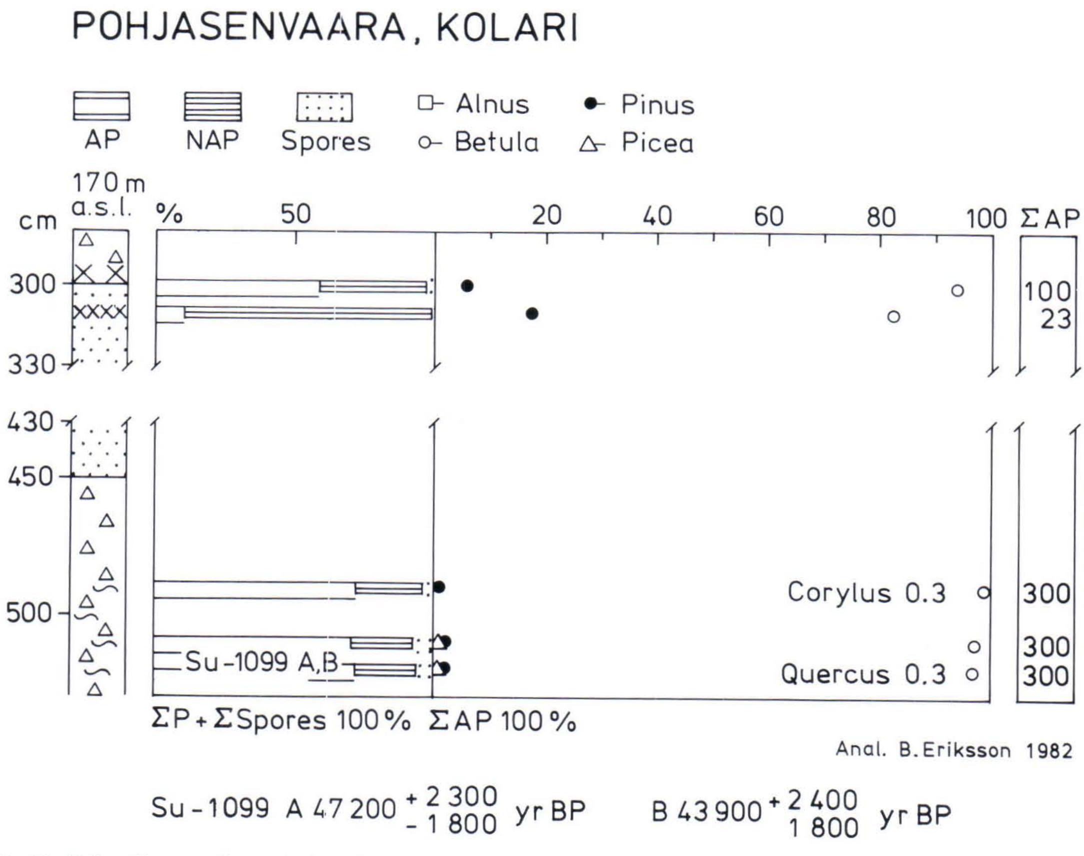

Fig. 71. Pollen diagram of organic deposits at Pohjasenvaara, Kolari.

AP pollen (NAP 21—25 % of total pollen) and in the gyttja- banded silts in the basal part of the upper till for 94 % (NAP 39 %). The pollen assemblage in the gyttja-banded silt in the sand interlayer is composed almost entirely of NAP. Only 23 (10 %) of the total pollen grains counted (236) were AP, of which 19 were *Betula* and four *Pinus*.

The abundance of organic material was high enough for radiocarbon dating only in the lower till. There the peat yielded a finite ^{14}C age of 47 200 $^{+2\,300}_{-1\,800}$ yr BP (fraction A) and 43 900 $^{+2\,400}_{-1\,800}$ yr BP (fraction B) (Su-1099). Despite the finite age and *Betula*-dominant pollen, the peat intermixed with the lower till at Pohjasenvaara is not interpreted as an interstadial-type deposit.

Typical interglacial-type deposits have also yielded finite radiocarbon ages (cf. Loukoslampi 1 and Tepsankumpu sequences). At Pohjasenvaara the deposit where the peat intermixed with till was found is under a mire. Therefore, it is likely that young organic matter transported by seepage water and groundwater had entered the sample. The pollen composition of the peat layers at Pohjasenvaara, including the occasional *Corylus* and *Quercus* pollen grains, is similar to that in zone Te 1 in the Tepsankumpu sequence or in zone Pa 2 in the Paloseljänoja sequence. The proportion of NAP is also lower than in typical interstadial-type deposits. The lithostratigraphic position of the peat layers in the lower till bed (III) corroborates the above interpretation according to which the peat layers were formed during either the cold initial or closing stage of an interglacial. As the thin gyttja-banded silt layers probably derived their material from older deposits through washing and redeposition they cannot be taken as testimony of interstadial deposits younger than the Peräpohjola interstadial.

STRATIGRAPHICAL SCHEME

The stratigraphy is not continous at any site. Therefore the stratigraphy for northern Finland had to be compiled piece by piece, with data from study pits. The pit data were supplemented with drill data acquired from the most appropriate areas, and conversely, the most interesting drilling sites were exposed with a heavy excavator, which allowed the drill data to be linked to the »general» stratigraphy.

The most complete till stratigraphy was exposed at the open pit of the Rautuvaara mine, where a till section, in places 22 m high, shows five superimposed till beds deposited by ice flowing from different directions (till beds II—VI). Between the beds there are coherent and, for Lapland, fairly thick, minerogenic sediments of an ice-free stage (Fig. 39). Unfortunately, no organic layers were found at Rautuvaara, either between or under the tills.

Four superimposed till beds were encountered in two study pits, one at Naakenavaara in Kittilä and one at Muotkaselkä in Salla (Fig. 37). Three superimposed till beds were met with in 16 pits and two superimposed beds in 236 pits. Sorted sediments under or between the till beds were found in 240 pits, and organic sediments in 16 pits.

From this collection of observational data it was concluded that the Quaternary stratigraphy of northern Finland consists of six till beds with sorted and organic sediments of ice-free substages between them (Fig. 72). The three youngest till beds (I—III) are interpreted as having deposited during the Weichselian glaciation, the others (IV—VI) during an earlier glaciation, the Saalian, or even earlier. In almost all ground moraine areas till bed II (or till bed I, cf. Chapter Till bed I) is on the surface. In nine study pits the uppermost till was older than till bed II, in seven of them it was till bed III and in two pits till bed IV (Haurespää, cf. Chapter Older till beds). At all these sites there

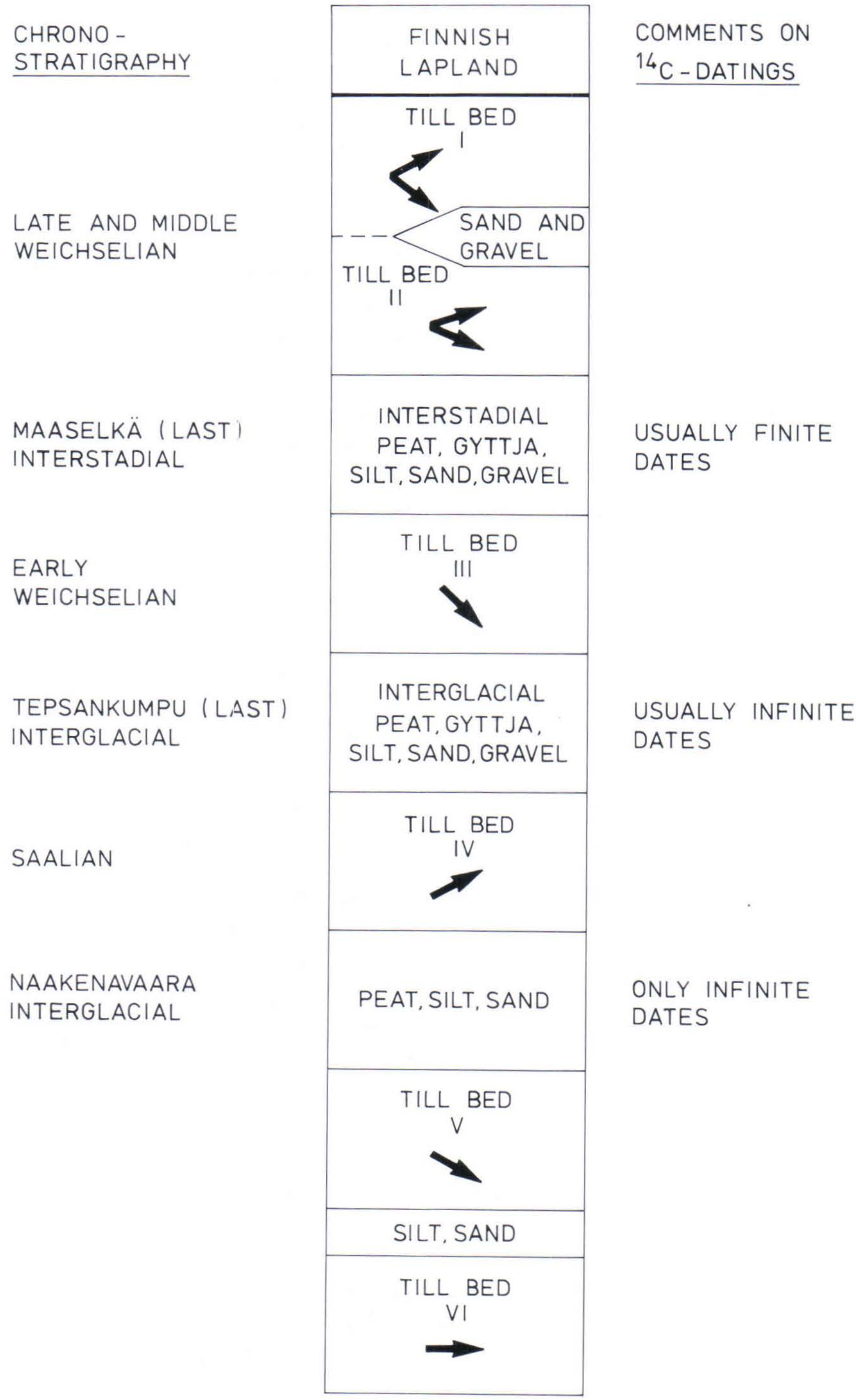

Fig. 72. Till stratigraphy in Finnish Lapland. The arrows indicate the average flow directions of the continental ice sheet in central Lapland during various stages.

are clear indications that glaciofluvial waters eroded the youngest till beds during the last deglaciation.

Organic sediments were not encountered between the topmost till beds (I and II). However, thin gravel and sand layers occur between these tills, in northern and eastern Lapland in particular (Fig. 43).

Sorted sediments overlain by till bed II are fairly common throughout the study area (Fig. 43) as are organic sediments, except in northernmost Lapland (Figs. 48 and 52). The sorted sediments are usually gravel and sand. The pollen composition of the organic sediments is either *Betula* or *Pinus* dominant. All the interstadial-type deposits (*Betula* at almost 100 % and high NAP) were encountered

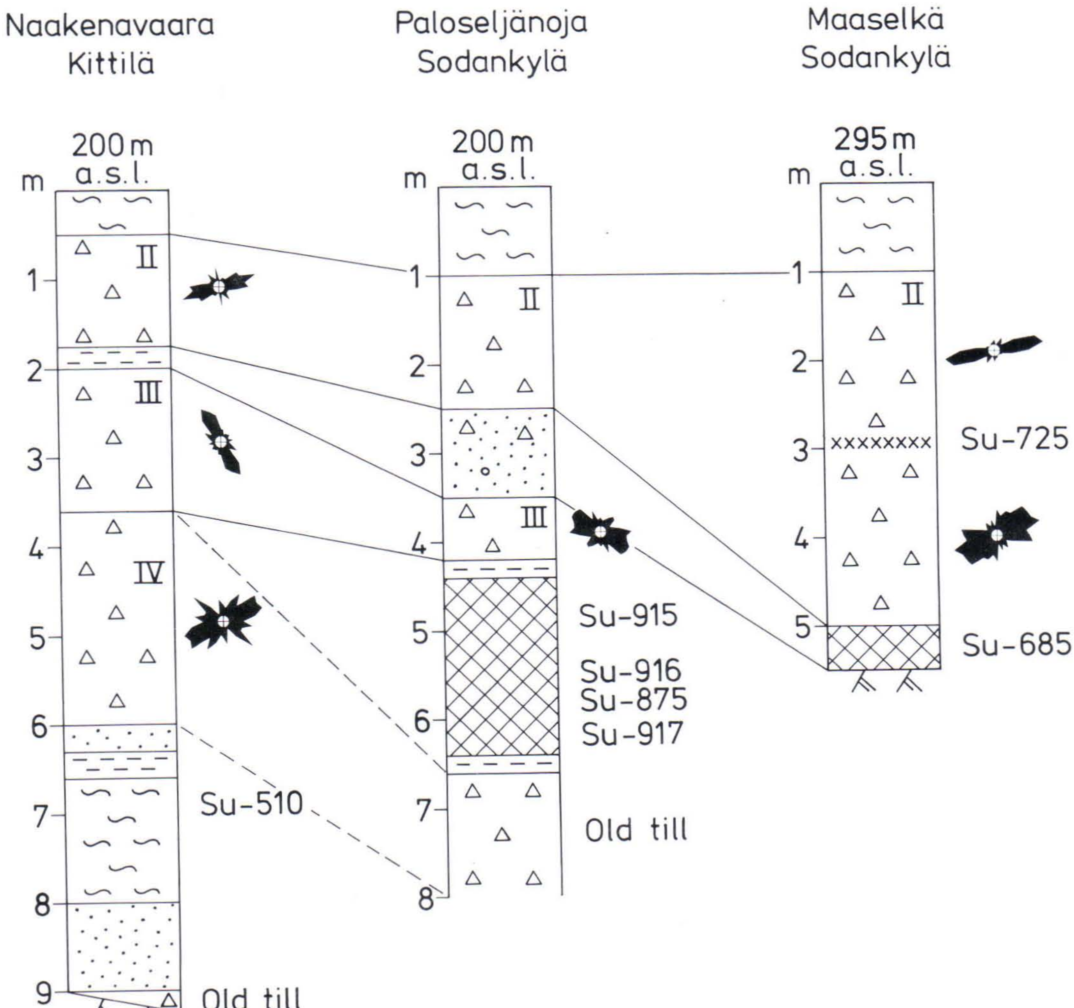

Fig. 73. Stratigraphic positions of the interstadial and interglacial organic deposits and the correlation of the till beds. The interstadial deposits (Maaselkä) lie under one till bed (II). The deposits of the last interglacial (Paloseljänoja) lie under two till beds (II and III) and the interglacial deposits preceding the last interglacial (Naakenavaara) under three till beds (II, III, IV). The till fabrics of these till beds are also shown. The radiocarbon dates are given in Table 9. For symbols see Figure 35.

under till bed II or intermixed with it (Figs. 48 and 73). Excluding one (Maaseljänjänkä), all the radiocarbon determinations from the deposits yielded finite ages in the range 41 900—49 000 yr BP (Table 9). At sites where the pollen composition of the organic sediments under till bed II is interglacial in type (usually *Pinus* dominant with some other thermophilous plants), the stratigraphy is interpreted as incomplete, i.e. till bed III is absent (Hirvas et al. 1981).

The sorted sediments overlain by till bed III are mainly encountered in the large ice divide zone of central Lapland and in eastern Lapland (Fig. 43). Almost half of them (42 %) are silt. The pollen composition of the organic sediments under till bed III or in a corresponding stratigraphic position (drill profiles) is almost invariably distinctly interglacial in type, most often *Pinus* dominant (e.g. Fig. 57). The abundance of *Pinus* pollen is usually 60—70 %, that of *Alnus* 5—15 % and that of *Picea* 5—30 %. With a few exceptions, the radiocarbon determinations indicate an infinite age, i.e. the deposits are clearly too old for dating with the method.

Sorted sediments (sand and silt) overlain by till bed IV were encountered in four study pits in the ice divide zone of central Lapland (Fig. 43). At Naakenavaara (Fig. 44, site 14), the till is underlain by *in situ* peat up to 1.5 m thick (Fig. 73). The pollen composition of the peat deposit is *Pinus* dominant from top to bottom, *Pinus* accounting for 60—70 %, *Picea* for 5—20 % and *Alnus* for about 5 % of the pollen (Fig. 67). The pollen composition of the peat deposit at Naakenavaara is thus very similar to that in most of the interglacial-type deposits under till bed III. However, the peat deposit contains prolific seeds of *Aracites johnstrupii*, a plant which became extinct during the Holsteinian (Likhvinian) interglacial and which has not been found in any other deposit in northern Finland (cf. Chapter The Naakenavaara Interglacial). Radiocarbon dating from the deposit (Su-510) yielded an infinite age of over 48 700 yr BP, as expected.

Sorted sediments underlying till bed V were encountered only at Rautuvaara, where the till bed is underlain by half a metre of laminated silt under which there is about one metre of sand (Fig. 39).

CORRELATION AND DATING OF THE PLEISTOCENE STRATIGRAPHY IN FINNISH LAPLAND

The Pleistocene stratigraphy with its correlation in Lapland is presented in Figure 74. It consists of six till beds often separated by sorted materials of various types. In many places the sedimentary sequence rests on weathered bedrock. Organic sediments, interpreted as interglacial on the basis of their pollen flora, are encountered between till beds IV and V and between beds III and IV. In contrast, the organic deposits between till beds II and III contain pollen flora of a forested interstadial type. No evidence of tundra vegetation was encountered in any of the subtill organic or minerogenic sequences in Lapland, with the possible exception of the Pohjasenvaara site in Kolari.

The organic deposits beneath till bed III (but above till bed IV) are all interpreted as representing the same interglacial. At no site is the whole interglacial sequence present, although that at Tepsankumpu is almost complete, only the upper part being missing. Therefore, the interglacial is named the Tepsankumpu interglacial (cf. Donner et al. 1986), earlier referred to as the Lapponian Interglacial (Hirvas 1983). By compiling several pollen diagrams it was possible to work out the pollen stratigraphy for the whole interglacial.

The forest history starts with *Betula*, which is the only tree at the beginning of the vegetation succession. *Pinus* and *Alnus* arrive almost simultaneously. In some pollen diagrams, e.g. that

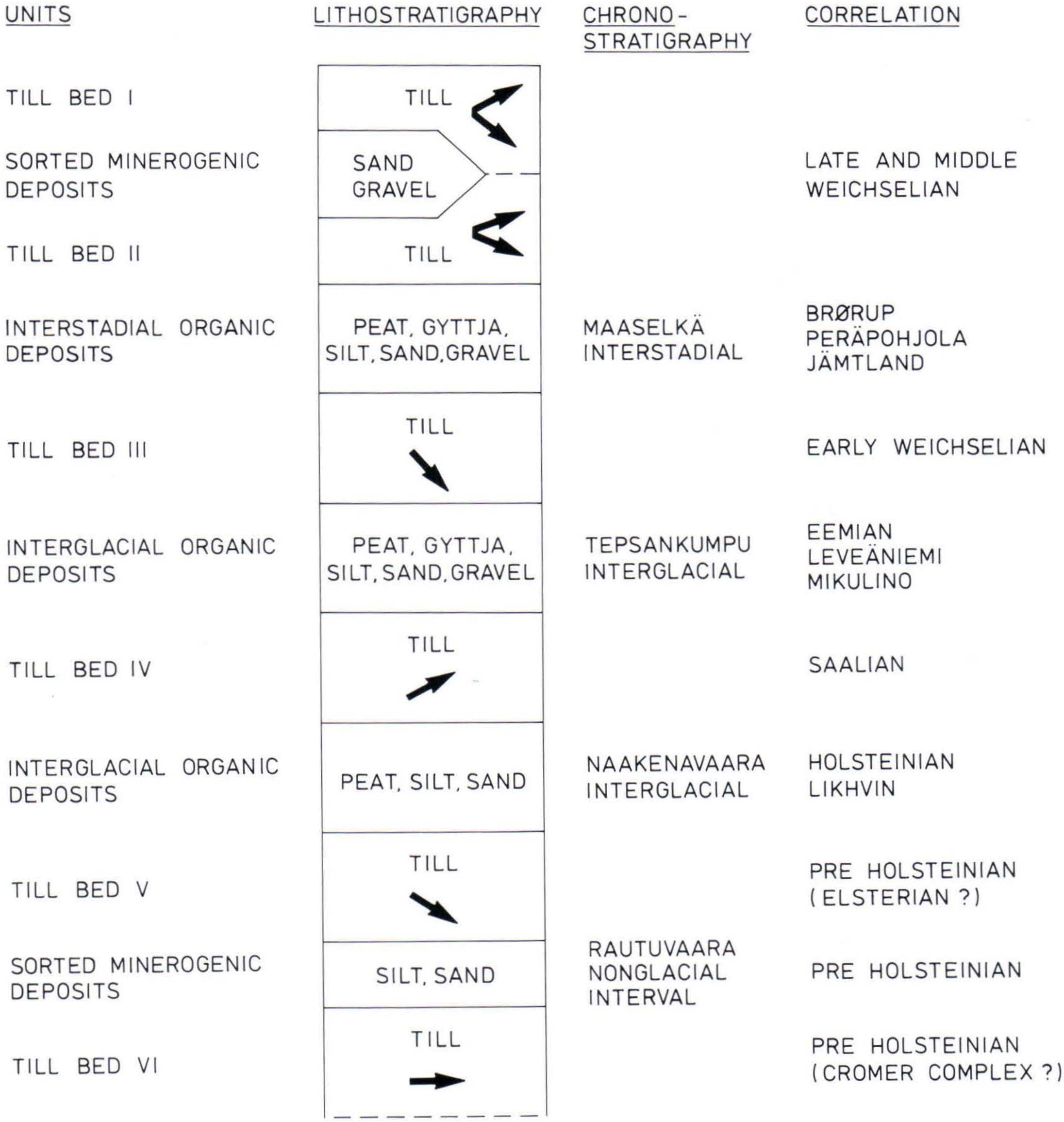

Fig. 74. The Pleistocene stratigraphy with its correlation in Finnish Lapland. The arrows indicate the average flow directions of the continental ice sheet in central Lapland during various stages.

of Tepsankumpu, *Betula* pollen is more abundant than *Pinus* throughout the sequence, whereas in others, e.g. that of Paloseljänoja, *Pinus* is dominant. The same applies to the Holocene pollen diagrams from central Lapland (Lappalainen 1970) and reflects the habitat. During the *Pinus-Alnus* zone *Corylus* appeared, showing much higher values, up to 5 %, than during the Holocene.

The arrival of *Picea* marks a distinct horizon in pollen diagrams, and the period of forest vegetation of the interglacial comes to an end with a clear increase in *Betula* and a decline in *Pinus* and *Picea*.

In many diagrams, *Tsuga*, *Abies*, *Carpinus* and *Larix* pollen occur sporadically as do spores of *Osmunda*. For example, *Abies* is present in nine diagrams from central Lapland and *Larix* in eight, *Carpinus* in seven and *Tsuga* in six; and *Osmunda* spores are present in five pollen diagrams. It is therefore likely that *Larix* grew in Lapland during this interglacial. The plant is usually under-represented in the diagrams because its pollen grains are easily destroyed. The presence of *Larix* is confirmed by a *Larix* trunk found in glaciofluvial sediments in Vuotso. The sediments in which the trunk was buried contain *Pinus* dominant interglacial-type pollen flora, and cones of *Pinus* and *Picea* (Mäkinen 1982).

The forest succession in the interglacial deposits described here is very similar to that in the Holocene, with perhaps the addition of the thermophilous *Corylus*. It is logical to correlate the present 37 interglacial-type sites with the last, or Eemian, interglacial, an interpretation supported also by the abundance of *Corylus* pollen. The Eemian sediments in Lapland are typically covered by two till beds and interstadial sediments. All the interstadial sediments have a very similar *Betula* dominant pollen composition with fairly high NAP. They are interpreted as having deposited during the same interstadial. This Weichselian interstadial was originally named the Peräpohjola interstadial (Korpela 1969) with reference to the region in southern Lapland where the deposits of this interstadial were first found. The name is well-established in the literature. As the most representative site for the present material is Maaselkä, the interstadial could just as well be named the Maaselkä interstadial.

The correlation of the Peräpohjola/Maaselkä interstadial with the Early Weichselian Brørup interstadial is widely accepted (Korpela 1969, Hirvas et al., 1981, Hirvas & Nenonen 1987, Donner 1983) although it is suggested that it may also be correlative with the Odderade interstadial (Forsström 1988). No absolute direct ages are available for the interglacials/ interstadials in Lapland, as they all are beyond the range of reliable ^{14}C dating. In Europe the only forested interstadials are the Early Weichselian Brørup and Odderade interstadials dated at c. 100 and 80 ky BP (Behre & Lade 1986). It is therefore logical to correlate the forested interstadial in Finnish Lapland with them. The stratigraphic properties of the till beds both above and below them suggest that the interstadial sites in Lapland in fact represent only one interstadial. As Mangerud (in press) also points out, if the sites of two different interstadials are grouped together the till fabrics above and/or below the interstadial beds would not be so consistent as they are now. The interglacial (Eemian) and interstadial (Peräpohjola/Maaselkä) deposits are separated by one till bed (III) throughout Lapland, suggesting that this till represents the first major ice sheet advance since the Eemian. As the event was followed by an interstadial period in Lapland, it is quite logical to correlate the period with the Brørup, which was the first, longest and obviously warmest of the early Weichselian interstadials (e.g. Behre & Lade 1986).

There are two localities (Kurujoki and Lohiaapa) where both interglacial and interstadial organic deposits are present within the same sequence. At Lohiaapa the deposits are separated by a till bed, and at Kurujoki sorted sediments occur between the *Pinus*-dominant interglacial and *Betula* dominant interstadial sediments. These localities also corroborate the present correlation.

No evidence of a glaciation between the Brørup and Odderade interstadials has been postulated for Finnish Lapland. In Swedish Lapland, close to the Caledonian mountain range, Lagerbäck and Robertsson (1988, see also Lagerbäck 1988) have identified two interstadials separated by a till bed. They correlate the lower one with the Jämtland/ Brørup interstadial and the upper one (the Tärendö interstadial) with the Odderade. The former was forested and the latter contained elements of tundra vegetation. The extent of the Early Weichselian glaciation in Finland and elsewhere has recently been a matter of debate. As mentioned above, there is no doubt that the ice sheet covered the whole of Finnish Lapland but that it did not extend to southern Finland. Only one Weichselian till unit

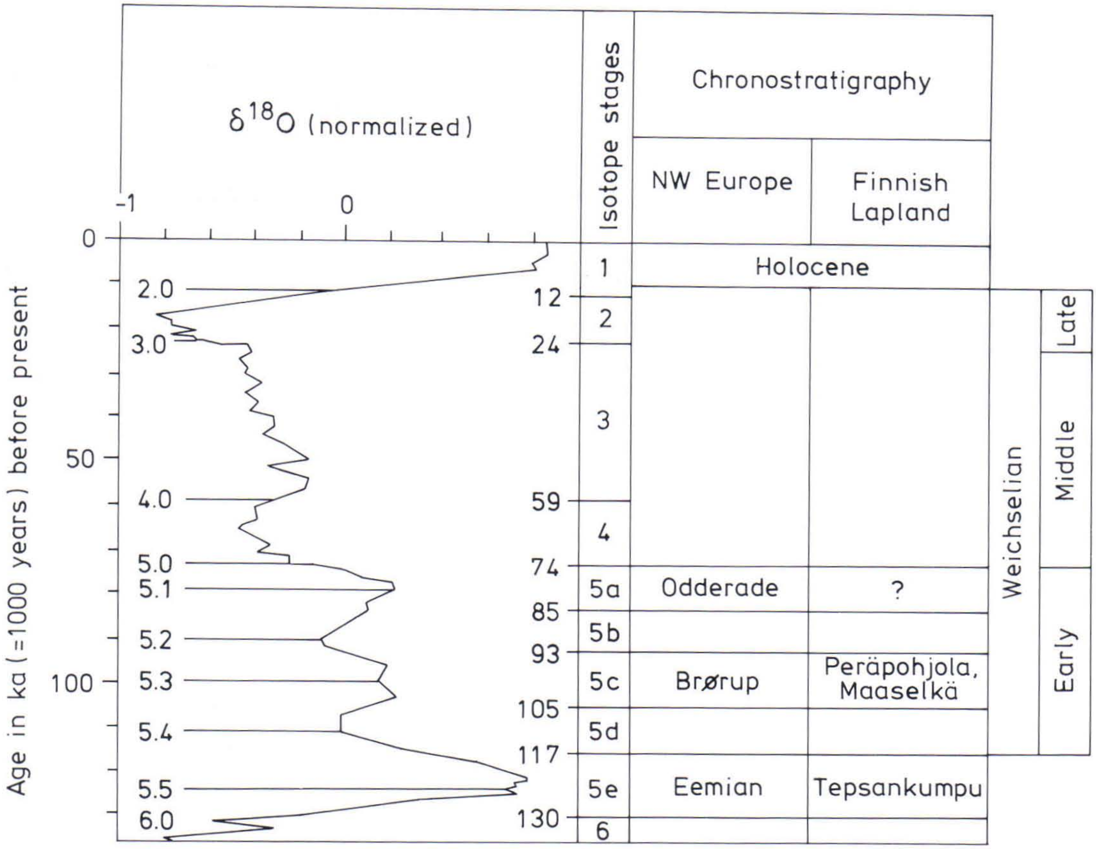

Fig. 75. Chronostratigraphy of the last interglacial/glacial cycle in Finnish Lapland, its suggested correlation with the standard stratigraphy in NW Europe, and marine isotope stages (cf. Mangerud in press).

has been recognized in Ostrobothnia, suggesting that the Early Weichselian ice front was somewhere between southern Lapland and Ostrobothnia (cf. Sutinen 1984, Nenonen 1986, Hirvas & Nenonen 1987). After the Peräpohjola/Maaselkä interstadial the continental ice sheet covered all Lapland until the final deglaciation, which took place 10—9 ky ago (Ignatius et al. 1980).

In Lapland, this major Weichselian glaciation is represented by the widespread till bed II, the more local till bed I and surficial ablation till. The glacial morphology, drumlins, fluting, hummocky moraines and glaciofluvial formations mainly reflect the last glaciation, although the glacial relief of the early Weichsel glaciation/deglaciation is also visible in some places in central Lapland.

The correlation of the last interglacial/glacial events with the deep sea oxygen isotope curve is now well established (Fig. 75) (Mangerud in press), and the chronology of the events predating 40—50 ky, i.e. the range of the radiocarbon method, is based on direct and indirect dating from this curve. These data thus permit absolute dating of events in Finnish Lapland, too.

The last, or Eemian (Tepsankumpu), interglacial (130—117 ky) is correlated with isotope stage 5 e, and the Brørup/Peräpohjola/Maaselkä (105—93 ky) and Odderade (85—74 ky) interstadials are correlated with isotope stages 5 c and 5 a, respectively. The first major Weichselian ice sheet advance in Lapland is correlated with 5 d at about 110 ky. The main Weichselian advance started in Lapland during isotope stage 4 at 74 ky ago.

The above correlation of the stratigraphy with the last interglacial/glacial events in northwestern Europe is compatible with all the data and is, therefore, justified.

Correlation of the interglacial deposits below till bed III (but always above till bed IV) with the last, or Eemian, interglacial leads to the conclusion that the older glacial and non-glacial sediments in Lapland are older than the Eemian. As the pollen stratigraphy of the Naakenavaara interglacial deposit under till bed IV is *Pinus* dominant it cannot be used to distinguish the deposit from the sites of the last interglacial. The Naakenavaara deposit is compressed peat composed almost entirely of remains of *Aracites johnstrupii*, a plant now extinct. The most recent fossil discoveries were made in Belorussia, from deposits representing the Holstein (Likhvin) interglacial. For this reason the Naakenavaara interglacial is here correlated with the Holstein interglacial. It may, of course, be older. The correlation with the Holstein is also supported by the fact that only one till bed (IV) separates the Naakenavaara deposit from the deposits of the last interglacial. This bed may represent the Saalian glaciation *sensu lato*. If it does, Lapland was covered with ice throughout the Saalian glaciation.

Till bed V is thus older than the Naakenavaara interglacial, which is represented by the peat deposit at Naakenavaara (and perhaps also that at Kutuvuoma) and by sorted minerogenic sediments in some places, for example, at Rautuvaara. These sediments are glaciofluvial, glaciolacustrine and littoral in origin. The till bed usually rests directly on till bed V. At Rautuvaara a still older till (VI) lies under till bed V. The till beds are separated by glaciolacustrine silts with dropstones. As till beds V and VI are older than the Holsteinian/ Naakenavaara interglacial, till bed V is possibly of Elsterian age.

The age of till bed VI is not known. It may be only slightly older than till bed V but it may also represent an older glaciation (Cromer complex?). All that can be said with reasonable certainty is that the glacial record in Lapland extends to the Elsterian glaciation. If, however, the Naakenavaara interglacial is older than the Holsteinian, till beds V and VI are also older. Absolute dating of the Naakenavaara deposit is thus of crucial importance. Methods currently in use include thermoluminescence and uranium series dating.

Tertiary diatoms and/or silicoflagellates have been encountered in a secondary position, redeposited in younger sediments, at 11 sites in Finnish Lapland (Tynni 1982). Most of the finds have been made from subtill interglacial-type diatomite or gyttja sediments. As a rule, the diatoms are typical early Tertiary marine forms; late Tertiary fresh-water diatoms (e.g. *Hydrosera trifoliatum* Cleve and *Fragilaria triangulate* Moisseva) have been encountered at only two sites. A big clay slab in a secondary position has been found at Akanvaara, Savukoski, in the eastern part of ice divide zone of central Lapland, which, according to the diatoms (e.g. *Hemiaulus polycystinorum, Trinarcia pileolus* and *Triceratium ventricolusum*), is a marine deposit dated to the early Tertiary (Hirvas & Tynni 1976, Tynni 1982). The clay slab is 0.8 m thick and lies at a depth of 2.6 m on the bottom of till (bed II) close to the surface of the bedrock. The secondary diatoms and, above all, the Akanvaara clay slab demonstrate that deposits dating from the early Tertiary onwards may occur *in situ* in the ice divide zone.

If the above correlation of the pre-Eemian glacial and non-glacial sediments in Lapland with the Saalian glaciation and the Holsteinian interglacial, and probably even the Elsterian glaciation, is correct, it means that the Pleistocene stratigraphy of Lapland covers only some 300 000—500 000 years depending on the correlation (Shackleton & Opdyke 1973) and that the Early Pleistocene and Early Middle Pleistocene glacial deposits are lacking. This interpretation is in accordance with the central European record of only three major Pleistocene glaciations, the Elster, Saale and Weichsel (West 1980, Ehlers 1983). On the other hand, the deep sea record suggests a major glaciation in the Northern Hemisphere beginning 2.4 m.y. ago and some ten glaciations during the last million years (Shackleton & Opdyke 1976, West 1980, Zagwijn 1985). It remains to be seen how extensive the oldest glaciations were and whether they can be recognized and identified in the terrestrial record of Finnish Lapland, where the first glacier advanced over deeply weathered bedrock, which was a »manifesto» of an entirely different Tertiary climate.

SUMMARY

The till stratigraphy of Finnish Lapland has been a subject of study for many years. The earliest descriptions of superimposed till beds of different ages date back to 1908 (Rosberg 1908). However, systematic investigations did not start until the 1970s, when a five-year till research project was launched (Kujansuu 1976, Hirvas et al. 1977). In the course of the project some 1 400 test pits were dug with a tractor excavator; about 400 of them intersected the entire Quaternary cover and 114 ended in weathered bedrock. The average depth of the study pits was 3.8 m, the deepest ones reaching 8—11 m. Some 2 200 fabric analyses and 1 360 stone counts were made from the pits, and 11 500 samples were taken from stratigraphically known locations for laboratory tests.

The till stratigraphy of Finnish Lapland is based on ice flow, or glaciation, stages (Hirvas & Kujansuu 1979). The stratigraphic investigations were prompted by observations that a till in a given stratigraphic position usually exhibits the same preferred orientation over a small area and that the other properties are also more or less constant. This led to the working hypothesis that it would be possible to correlate till beds located in different areas on the basis of fabric and other physical and chemical properties if a sufficiently dense network of study pits were created.

According to the study material, Finnish Lapland has experienced six glacier flow stages differing in direction and there is a till bed corresponding to each stage. From youngest to oldest these till beds are named I—VI. The three youngest till beds are interpreted as having deposited during the Weichsel glaciation, but the others before that. The till stratigraphy is most complete in the vast ice divide zone of central Lapland, where glacial erosion and deposition have been very weak. Nowhere has a continuous stratigraphic column been encountered, although there are some successions of four to five till beds separated by sorted minerogenic sediments (Figs. 37 and 39). The thickness of the youngest till beds increases to the north and south of the ice divide zone.

The most complete example of the stratigraphy is visible in the open pit of Rautuvaara mine, in a till section 22 m high and in places 700 m long. The till beds are easy to distinguish as they are separated by thick, continuous deposits of sorted sediments (Fig. 39). The Rautuvaara section supports the concept of the glacial flow stages and till stratigraphy pieced together from the study pits. At Rautuvaara, the fabric of the till beds is the same as that of the till beds in a corresponding stratigraphic position in the immediate vicinity of the pits. The till beds are often separated from each other by horizons of sorted sediments and in places also by peat, gyttja or diatomite. They are thus easier to recognize and correlate with those in other areas. Most of the organic deposits were found under mires, at sites that were already depressions before the last glaciation. The organic sediments are often overlain by deposits of sorted sediments of varying thickness that have protected them from glacial erosion.

Till bed I was deposited during deglaciation as a result of a re-advance of the ice front. It is not ubiquitous and was encountered at only 50 sites. Till bed II is the youngest till covering the whole study area. Most occurrences of this till bed were probably also deposited during deglaciation. In the ice divide zone of central Lapland the till is usually brown in colour but in northern and southern Lapland it is grey. The till is predominantly (strongly) fissile in structure and, particularly in eastern central Lapland, it exhibits banded layering. Till bed III (Early Weichselian), which is bluish-grey and massive, tends to be very similar in appearance and physical properties throughout the study area. The till bed was encountered at 212 sites. Old tills (preceding the Eemian) were met with at 17 sites, in general only on the bottom of the very deepest pits. The finds are concentrated in the large ice divide zone of central Lapland. The old tills are compact (4—5) and contain abundant weathered clasts. They vary from grey to brown in colour. The colours are usually very intense and may vary markedly with depth, even locally. The old tills are massive to very fissile in structure.

In the —2 cm sieve fraction the till beds differ from each other very little. However, in coarser fractions the differences are more pronounced (clast content and size). In mean grain size (M_z) all the till beds are fine sandy till (Table 3). The material in till bed II is the coarsest (M_z = 0.16 mm) and in till bed III the finest (M_z = 0.14 mm). The mean clay content is lowest (3.1 %) in till bed I and highest (4.0 %) in the old tills. The mean compactness, clast content and clast size of the till beds increase consistently from till bed I to the old tills (Figs. 19 and 20). The only exception is the clast size of till bed III, which is approximately the same as that of the older tills. The increase is clearest in compactness, which rises from 2.6 in till bed I to 4.1 in the old tills. The mean roundness of the clasts is approximately the same in all till beds, varying in the range 2.8—3.0. Roundness is highest in till bed I, which is understandable considering the mode of formation of the till. At the deglaciation stage the ice sheet was already markedly thinner, with oscillations taking place mainly to the low-lying areas poor in outcrops. Consequently, glacier erosion affected the newly deposited till bed II and the overlying glaciofluvial sediments more heavily than the fresh bedrock.

Flow stage I was associated with the last episodes of deglaciation and refers only to oscillation of the ice front or local lobes to the area already free from ice. Therefore, the local directions of flow stage I are approximately parallel to those of **flow stage II,** which is the youngest flow stage covering the whole study area (Figs. 30 and 31). During flow stage II the ice sheet flowed approximately from west to east in southern and central Lapland, and to the northeast in northern Lapland. The ice divide was in central Lapland.

During **flow stage III** (Fig. 32), the ice sheet flowed from northwest to southeast, except in northernmost Lapland, where it flowed towards the north-northeast and the Arctic Ocean. The ice divide of this stage was about one hundred kilometres farther north than during stage II. There are indications in northern Lapland of a northwest-southeast ice flow preceding stage II (Figs. 10 and 27). This flow is interpreted as having taken place at the beginning of glaciation stage III. It is evident that following the Eemian/Tepsankumpu interglacial the continental ice sheet spread to Finnish Lapland from the Scandinavian mountains, whereas after the Peräpohjola/Maaselkä interstadial the glacier formed over wide areas including Finnish Lapland.

Only a very few till beds older than flow stage III were encountered. On the basis of their fabric, they are classified as till beds IV and V. Observations suggest that during **flow stage IV** the ice sheet flowed from WSW to ENE (Fig. 33) and during **flow stage V** in approximately the same direction as during stage III, or from northwest to southeast (Fig. 34). The oldest **flow stage, VI,** was observed reliably at one site only, in a till cutting at the Rautuvaara mine, Kolari. According to four fabric analyses, during that stage the ice sheet flowed from west to east (Fig. 34).

Since 1973, more than a hundred new observations of subtill organic deposits have been made in Lapland, most of them in the course of systematic drilling by the Geochemistry Department of the Geological Survey of Finland. Forty-nine deposits have been studied so far. On the basis of their pollen spectra, 39 findings are interpreted as interglacial and 10 as interstadial. Twenty-four deposits are gyttja, 20 peat and five diatomite or diatomite gyttja. The thickness of the deposits ranges from a few centimetres to 2.5 m. All except one of the findings studied are in central Lapland, where preglacial weathered bedrock is most common. The weathering is dated back to the Tertiary.

No organic deposits have been found between beds I and II, but there are thin beds of gravel or sand between the till beds, especially in some parts of northern and eastern Lapland. The pollen assemblages of the organic sediments overlain by till bed II are dominated by either *Betula* or *Pinus*. In deposits with an interstadial-type *Betula* dominant flora, *Betula* usually accounts for more than 90 % of tree pollen, and NAP, which is also high, often for 30—50 % of total pollen. This flora is nearly identical to that of the Peräpohjola interstadial described by Korpela (1969). Radiocarbon determinations from deposits with a *Betula* dominant flora have almost invariably yielded ages of 42 000—49 000 yr BP, which, however, are regarded as minimum ages only. A type locality for this interstadial is Maaselkä, Sodankylä (the Maaselkä interstadial), where there is a 50 cm thick layer of gyttja with a *Betula* dominant pollen flora (Fig. 51) in a sheltered depression in bedrock overlain by till bed II. It contains over 95 % *Betula* and 1—4 % *Pinus*. The proportion of NAP is high, 40—60 %. Wherever the pollen flora of the organic sediments under till bed II is *Pinus* dominant, the stratigraphy is considered as incomplete, i.e. till bed III is absent, and the pollen is interpreted as interglacial.

The pollen flora of the organic sediments underlying till bed III, or in a corresponding stratigraphic position, is mostly *Pinus* dominant, the proportion of *Pinus* normally being 60—70 %, of *Betula* 10—30 %, of *Alnus* 5—15 % and of *Picea* 5—30 %, as, for instance, at Paloseljänoja, Sodankylä (Fig. 57), where there is approximately 2 m of gyttja *in situ* under till beds II and III. The gyttja is further underlain by more than 1.5 m of basal till. Also underlying till bed III are *Betula* dominant organic deposits with *Corylus* as a rare deciduous element and *Alnus* and *Picea* accounting for 5—20 % of the pollen. At some sites a clear vegetational succession is visible, indicating an extended ice-free period (Fig. 56). A good example is Tepsankumpu, Kittilä, which is the type locality of the Tepsankumpu interglacial.

The organic deposits overlain by till bed III usually contain pollen of *Corylus* and rare deciduous trees but sometimes also of *Larix*, *Abies* and *Tsuga* and spores of *Osmunda*. Most of these deposits evidently originate from the last interglacial, when the climate in Lapland was warmer than it is at present. It has not been possible to date this interglacial, but correlation with the Eemian seems highly feasible.

The non-glacial deposits encountered in excavations under till beds IV and V are all minerogenic except that at Naakenavaara, Kittilä (Fig. 44, site 14), which is the only site where peat was met with under till bed IV (Fig. 65). The peat deposit, which is up to 1.5 m thick, lies in *in situ* at a depth of 6.5 m. The peat is so tightly compressed that samples had to be taken with a chain saw. The pollen spectra of the peat deposit are dominated by *Pinus* from top to base (Fig. 67), the *Pinus* values being 60—70 %, *Betula* 11—20 %, *Picea* 6—21 % and *Alnus* 5 %. The peat deposit does not show any distinct floral succession, except for the rise in the *Picea* curve from 6 % at the base to 21 % at the top, and the corresponding decline in *Betula* from 18 % at the base to 11 % at the top. An interesting feature in the pollen spectra is the continuous curve for *Larix* pollen, which starts at the base of the peat deposit. The *Larix* abundance is highest in the upper part of the deposit, where it ranges from 1.5 % to 2.4 %. A *Larix* cone was also found in the peat deposit. In terms of dominant trees, the pollen diagram of Naakenavaara is very similar to that of zone c in the Leveäniemi interglacial deposit in northern Sweden (Robertsson 1971). The pollen assemblages of many interglacial deposits in northern Finland correlated with the latest, or Eemian, interglacial deposits are also very similar to that of the Naakenavaara peat deposit. The interglacial deposits in northern Finland cannot therefore be dated or distinguished merely on a palynological basis.

Of particular interest was the discovery in the Naakenavaara peat deposit of abundant *Aracites johnstrupii* seeds. This was the first time that these have ever been found in any interglacial or interstadial deposit in northern Finland (Aalto & Hirvas 1987, Hirvas & Eriksson 1988). According to the literature, this species has been encountered in Europe only in deposits of the Holstein-Likhvin interglacial (Katz et al., 1965, Zinova 1982) or older (Zubakov 1988) and in Pliocene deposits (Katz et al., 1965). Only sorted minerogenic sediments were found under till bed V, and as the sediments are invariably poor in pollen and diatoms they have evaded attempts to date them so far.

Central Lapland has turned out to be a very unusual area: Pleistocene sediments rest on bedrock deeply weathered in the Tertiary and covering thousands of square kilometres. Subtill organic deposits, old tills (pre-Eemian), with minerogenic sorted sediments between them, occur almost exclusively in this area, and a large slab of early Tertiary clay deposited in a warm saline sea has been found in till close to the bedrock surface (Hirvas & Tynni 1976, Tynni 1982). The exceptional features of the area can possibly be ascribed to the fact that in the centre of glaciation, glacial erosion and deposition have repeatedly been very weak contrary to some textbook models (e.g. Flint 1971 and Sugden & John 1976). It is, therefore, a highly appropriate area, and may even be the key one, for unravelling the Pleistocene stratigraphy, as older deposits have escaped erosion by younger glaciations, and the till beds are thinner than average, thus permitting the younger ones to be penetrated with an excavator. Another advantage of the central area of glaciation is that only the main stages of glaciation, those of ice-free periods in particular, are recorded there. Consequently, the stratigraphy is clearer and less complicated, as the deposits of short-lived glacial/non-glacial stages typical of the ice-marginal areas are lacking. The dense network of roads in central Lapland also facilitates studies on the Pleistocene stratigraphy. Elsewhere in the Northern Hemisphere the central areas of glaciation are either permafrost or trackless, uninhabited wilderness, or both.

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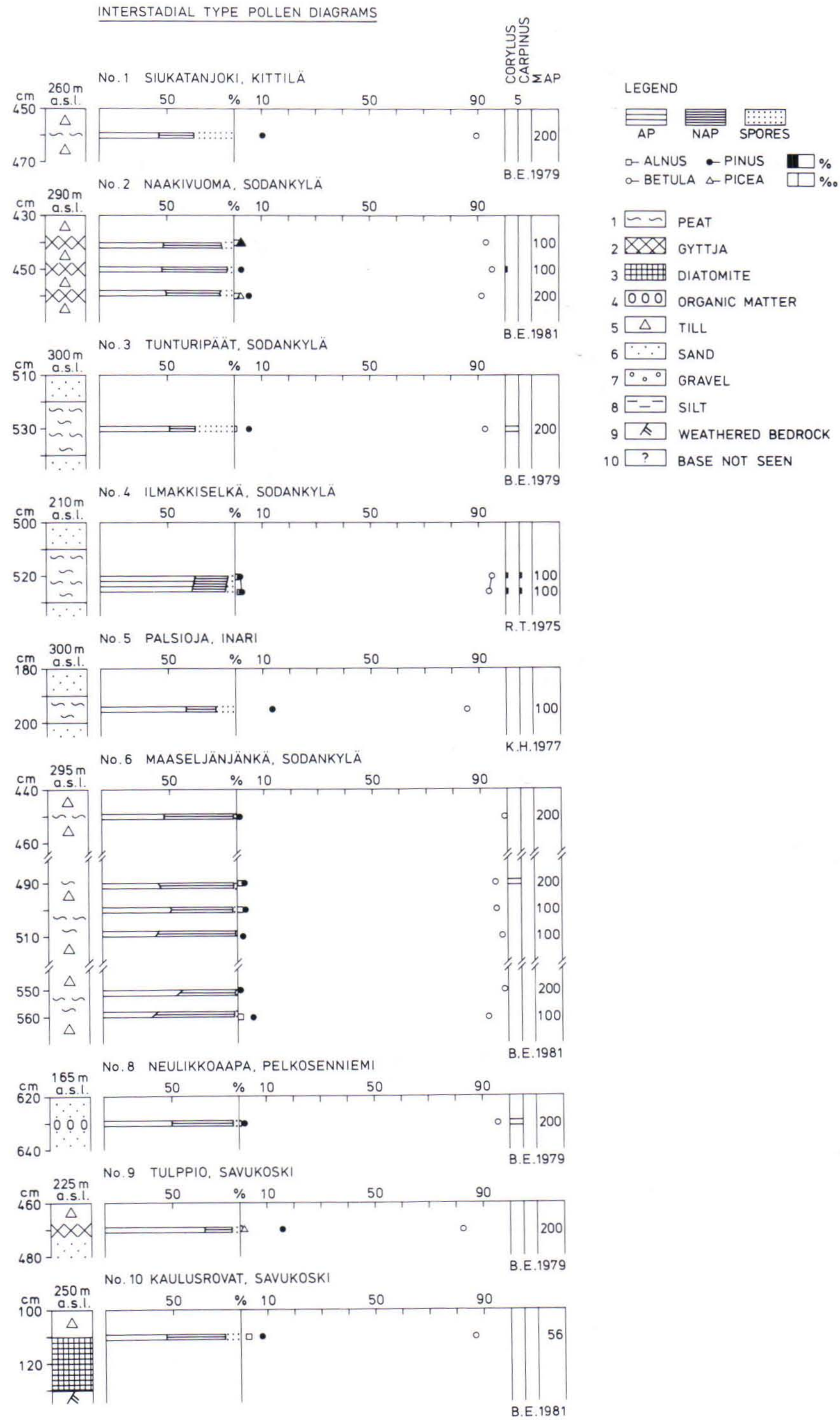
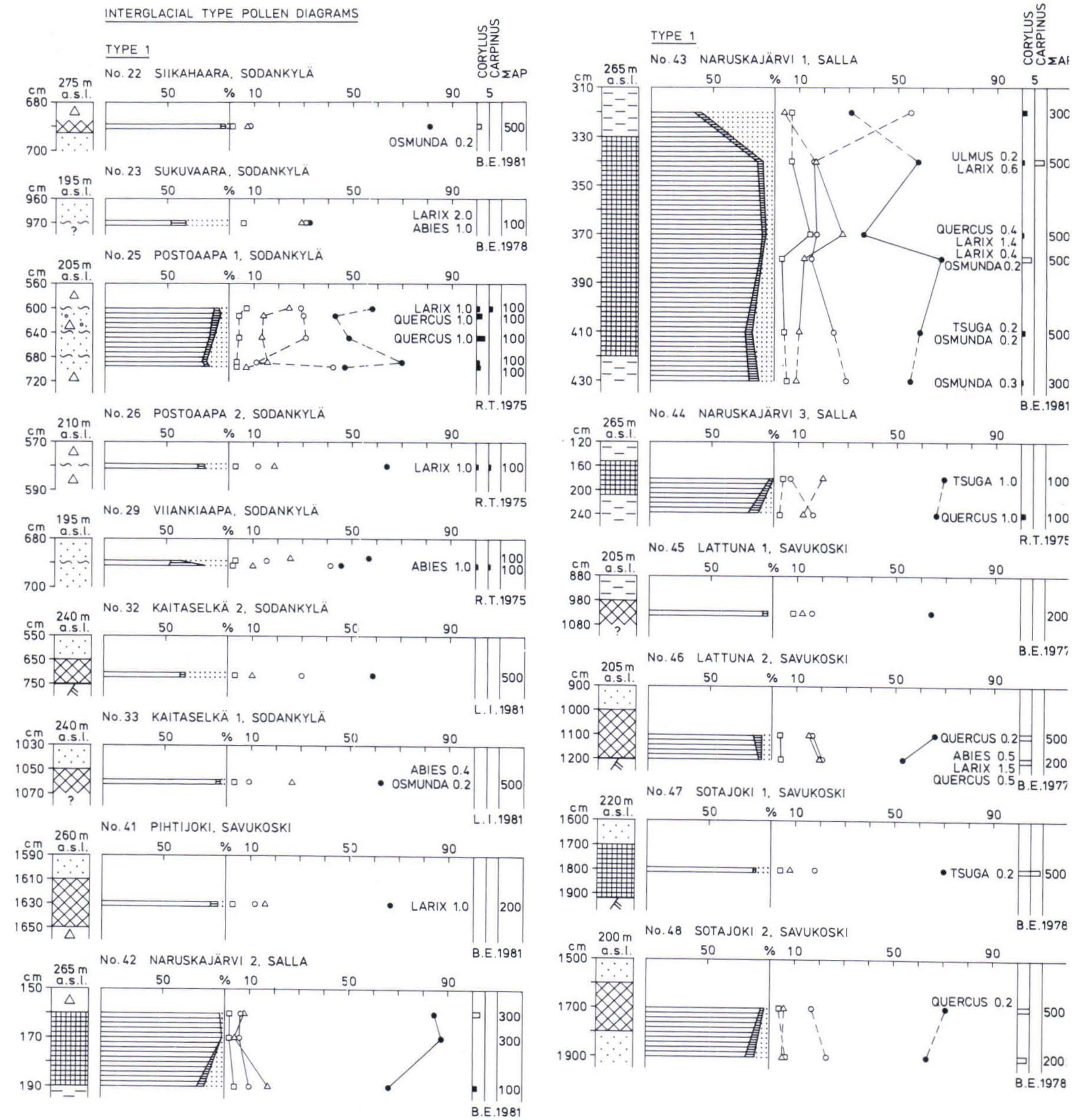
Appendix 1. List of the study sites described in the text. Subtill organic deposits are listed in Table 8. z = m a.s.l.

Locality	Map no.	Municipality	x	y	z
Auvojärvi	3624 02	Sodankylä	7446.52	469.50	223
Fierbmeluovd-deskaidi	3824 06	Utsjoki	7698.42	476.32	280
Haurespää	3712 08	Kittilä	7508.70	445.12	240
Huhtalehto	2731 05	Kolari	7479.00	517.60	240
Jatuni	2811 08	Enontekiö	7595.96	448.98	365
Jäkäläpää	3812 08	Inari	7625.65	449.58	470
Kajanki	2724 07	Muonio	7552.76	480.58	310
Kiimavaara	2713 09	Kolari	7486.64	494.30	212
Kotala	4622 10	Salla	7437.75	459.00	190
Kulkujärvi	2741 05	Kittilä	7536.48	513.48	300
Kulvakkopalo	3643 06	Salla	7423.14	554.92	230
Kummamaa	3642 12	Pelkosenniemi	7456.98	533.76	165
Kuurusenvaara	2624 12	Kolari	7451.90	492.60	210
Kyörteselkä	4723 01	Savukoski	7520.01	468.96	240
Maaselkä	3741 02	Sodankylä	7533.73	502.55	290
Marrasjärvi	2643 06	Rovaniemi	7421.32	550.96	120
Muotkaselkä	4622 10	Salla	7436.33	454.58	204
Naakenavaara	2734 03	Kittilä	7513.10	547.41	200
Nousuvaara	3841 06	Inari	7665.63	515.31	170
Nuttio	3712 12	Sodankylä	7510.15	455.25	225
Palkisvaara	3731 02	Sodankylä	7478.10	508.16	260
Palojoensuu	2724 03	Enontekiö	7579.66	464.50	295
Pessalompolo	2632 08	Ylitornio	7381.95	520.05	106
Petäjäselkä	3733 01	Savukoski	7468.02	540.57	230
Rajala	3714 03	Sodankylä	7512.17	461.10	280
Rautuvaara	2713 12	Kolari	7490.00	497.27	215
Roukumalehto	2732 08	Kittilä	7506.26	525.25	230
Rovala	4712 08	Savukoski	7504.60	442.57	223
Sieppijärvi	2624 12	Kolari	7448.30	499.50	150
Sukuvaara	3714 04	Sodankylä	7491.96	476.08	207
Teuravuoma	2713 07	Kolari	7467.99	488.40	148
Urupää	3831 05	Inari	7596.68	517.35	360
Valkeajärvi	2714 07	Kolari	7490.80	484.04	200
Veskoniemi	3832 09	Inari	7632.70	526.68	130
Vintilänkaira	4712 06	Savukoski	7518.76	438.29	255
Vintiläselkä	3734 06	Savukoski	7512.00	554.43	246
Vittikko	3643 06	Salla	7427.96	555.80	200
Ylinenvaara	2624 12	Kolari	7453.80	497.40	190
Ääverjoki	2624 09	Kolari	7456.60	488.70	150

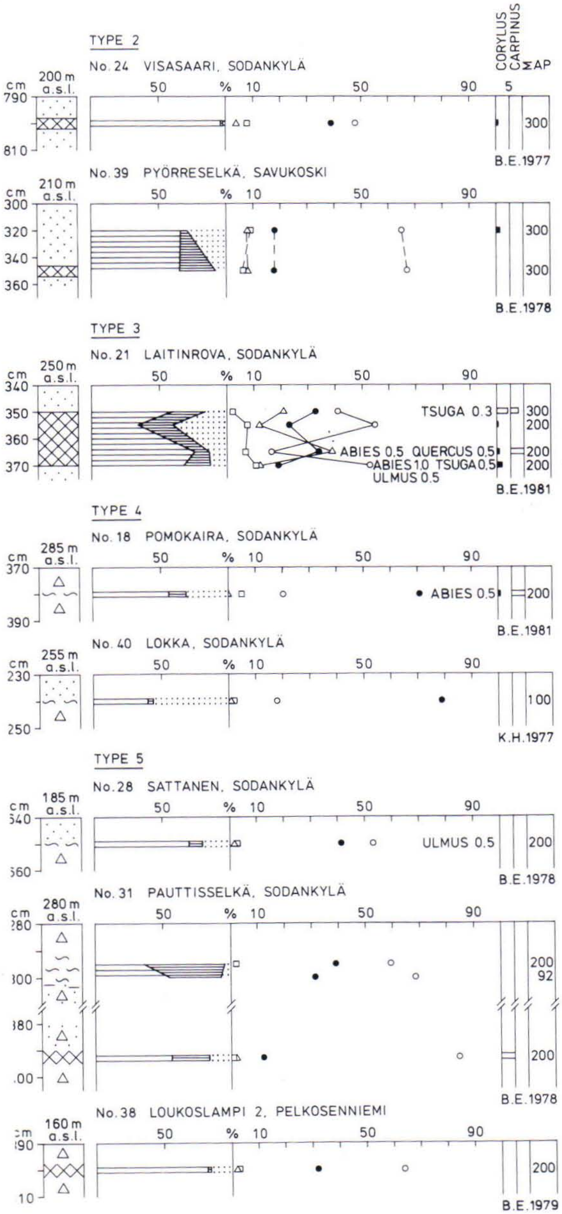
Appendix 2. Pollen diagrams of interstadial and interglacial organic deposits in Lapland. Interstadial type deposits (1—6, 8—10). Interglacial type deposits (type 1: 22, 23, 25, 26, 29, 32, 33, 41—48; type 2: 24, 39; type 3: 21; type 4: 18, 40; type 5: 28, 31, 38; type 6: 19, 27, 36). Kutuvuoma (17), Naakenavaara interglacial?

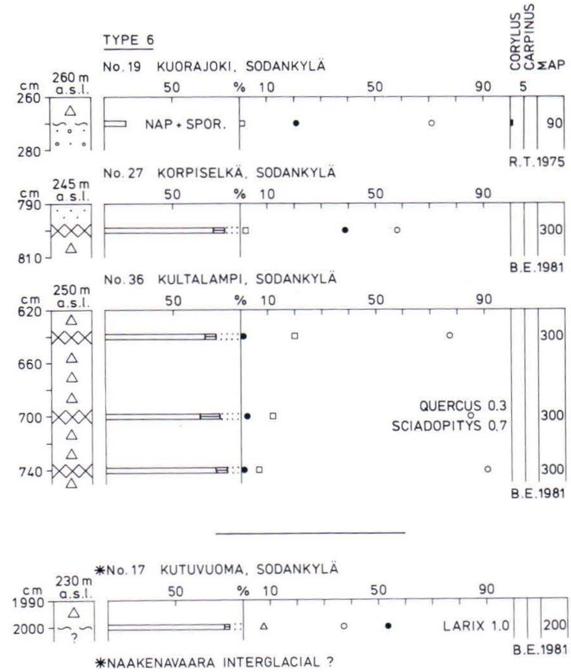


Appendix 2. Cont.



Appendix 2. Cont.





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