Middle and Late Pleistocene stratigraphy, chronology and glacial history in Finnmark, North Norway

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The Pleistocene superficial deposits in Finnmark, North Norway, were investigated in about 250 excavations and drillings during the period 1980-1990. Based on this regional background data six localities on Finnmarksvidda and two localities on Varangerhalvøya were selected for more detailed stratigraphic work. This paper presents results from the key localities Vuolgamasjohka, Vuoddasjavri and Sargejohka between Kautokeino and Karasjok on Finnmarksvidda, and additional data from the Karasjok area (Balučohka, Gamehisjohka and Buddasnjarga), and along the eastern coast of Finnmark on Varangerhalvøya (Komagelva and Leirelva).

Pre-Quaternary weathered bedrock characterises the subsurface in many topographical depressions on eastern Finnmarksvidda, for example at Sargejohka. Weathered bedrock is also recorded in some plateau areas in the same region. The Pleistocene stratigraphy in Finnmark extends from at least 300 ka ago to the present. It includes paleosols, waterlain sediments and tills from at least seven glaciations during the last three major glacial 100 ka cycles. The glaciations shifted between configurations with ice-centres located inland south and southeast of Finnmarksvidda (Fennoscandian ice-sheet configuration) and with ice-centres in the mountain range in the west (Scandinavian ice-sheet configuration).

TL and OSL dates from Finnmarksvidda, and additional dates from other inland areas of Fennoscandia, group in intervals which approximately correspond with speleothem-growth periods from caves in Nordland (Lauritzen 1991), and also with low ice-volume signals reflected by oxygen isotope ratios from deep sea sediments (see front cover). Interglacial beds from the Bavtajohka Interglacial in the Sargejohka placer gold field on Finnmarksvidda have been TL- and OSL-dated to c. 250-260 ka B.P. This suggests a correlation with parts of Oxygen Isotope Stages 8 and 7, and with the Salthølene (200-240 ka B.P.) speleothem Chronozone defined in Nordland, North Norway. Below the Bavtajohka Interglacial beds are two tills with intercalated and underlying waterlain sediments, the older of which may reach back in time to before 300 ka B.P.

A red-yellow soil profile at Sargejohka is thought to be a podzol that derived from the last interglacial, and a soil of this type may indicate a warm, perhaps 2-3 °C warmer than today, and relatively wet interglacial climate. At Buddasnjarga (Karasjok), oxidation and possibly rubification in a remarkably thick paleosol developed in an assumed Late Saalian fine-grained till, indicates a pedogenic process during an Eemian climate with an annual mean temperature significantly higher than during the postglacial optimum.

Although only a sparse pollen content is found in the beds, the stratigraphy at Vuoddasjavri, which is one of the key localities on Finnmarksvidda, seems to include sediments from at least two interglacials and four interstadials separated by till beds. The total thickness of the drift deposits at this locality is measured to about 57 m based on refraction seismics and drilling. The last interglacial (Eemian), as suggested by TL dates and pollen concentration, is represented by waterlain fluvial and glaciofluvial sediments from 10 to 30 m below ground surface. The upper c. 15 m of the stratigraphy is known from sections excavated in two steps, and this stratigraphy includes glaciofluvial - fluvial deposits from the Late Saalian - Eemian - Early Weichselian, and an overlying Early Weichselian till below glaciofluvial outwash beds from the deglaciation prior to the Eiravarri Interstadial (c. 100 ka B.P.). Above that is a sequence of three tills, separated by a c. 0.1-0.3 m thick glaciofluvial and colluvial sand, assumed to represent the deglaciation prior to the Sargejohka Interstadial (c.35->45 ka B.P.).

Stratigraphies and ^{14}C-AMS dates from two localities in the eastern coastal part of Finnmark, on Varangerhalvøya, suggest either that the ice-margin retreated to the coast of eastern Finnmark prior to c. 17.3 ka B.P. (uncalibrated age) after the Late Weichselian maximum (LWM), or that the ice-advance across Varangerhalvøya towards LWM-position occurred after c. 16.4 ka B.P. The dates, as they appear, have obviously important implications for the glacial history during the Late Weichselian also in the Barents Sea region adjacent to the Norwegian coast, but contamination of the samples by old as well as young carbon should be carefully considered before any conclusions are finally reached.

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Contents

Introduction

During the last two decades the Quaternary stratigraphy of Finnmark county, mainly from Finnmarksvidda, has been investigated and reported by the senior author and co-workers in a number of articles and maps (Hamborg 1982, Olsen 1982, Olsen & Hamborg 1983, 1984, Olsen 1984, Often & Olsen 1986, Olsen et al. 1987, Olsen 1987, 1988, 1989a, b, c, Often et al. 1990, Olsen et al. 1990, Olsen & Selvik 1990, Larsen et al. 1991, Olsen 1993b, Lyså & Corner 1994, Olsen 1995a, b, Olsen et al. 1996, Olsen & Selvik 1995). The oldest of these publications have been dealing mainly with the last interglacial - glacial cycle (e.g. Olsen & Hamborg 1983, 1984), while the youngest have also reported evidence of events significantly older than the last interglacial (Olsen 1993b, 1995a,b). It is now due time to gather all information, new as well as old, and to give a joint report based on all Quaternary stratigraphical data from Finnmark. To do this, we find it necessary to simplify by describing a few key localities from Finnmarksvidda. The most important of these will be the locality at Vuolgamasjohka that includes beds from the last interglacial - glacial cycle, and the localities at Vuoddasjavri and Sargejohka that both include beds from the last two interglacial - glacial cycles. The first locality has recently been thoroughly described by Lyså & Corner (1994) and it will therefore be dealt with only briefly here, while the last two localities will be described in more detail.

This report will also present some new stratigraphical data and ^{14}C-AMS dates from the coastal area of Finnmark that suggest either a very early deglaciation and retreat of the ice-margin from the Late Weichselian maximum position on the shelf of the Barents Sea adjacent to Finnmark, or a very late Late Weichselian maximum advance stage. It is our hope with the present paper to shed some new light on the

Middle and Late Pleistocene history of this northernmost part of Fennoscandia.

The investigation of the Quaternary stratigraphy in Finnmark includes the largest number of luminescence (TL and OSL) dates used so far in any Quaternary project in Norway; and this project was also the first to use the TL dating technique on feldspar grains from Pleistocene sediments in Norway (Olsen et al. 1983). Luminescence dating is therefore more thoroughly described here than the other methods used in this paper.

The senior author has written most of the manuscript, and the co-authors have contributed by improving parts of the text and by carrying out and being responsible for the luminescence dating (V. Mejdahl) and the pollen analyses (S. F. Selvik), respectively.

In this paper the abbreviation ka, meaning kilo anno (1000 years), is used synonymously with ka B.P. if not otherwise mentioned or made implicit in the text.

Physiography and geology

The physiography of the county of Finnmark in northern Norway is characterised by low pre-Caledonian plateaus 300-400 m a.s.l. and coastal mountains that form a part of the Caledonian orogenic belt. The major plateau, Finnmarksvidda, is situated in the inland area, while some less extensive plateaus are situated in the north and northeast (Fig.1). The highest summits in the mountains reach up to 1204 m a.s.l. in the northwest and no more than 700-800 m a.s.l. in the east.

The climate in Finnmark today varies from

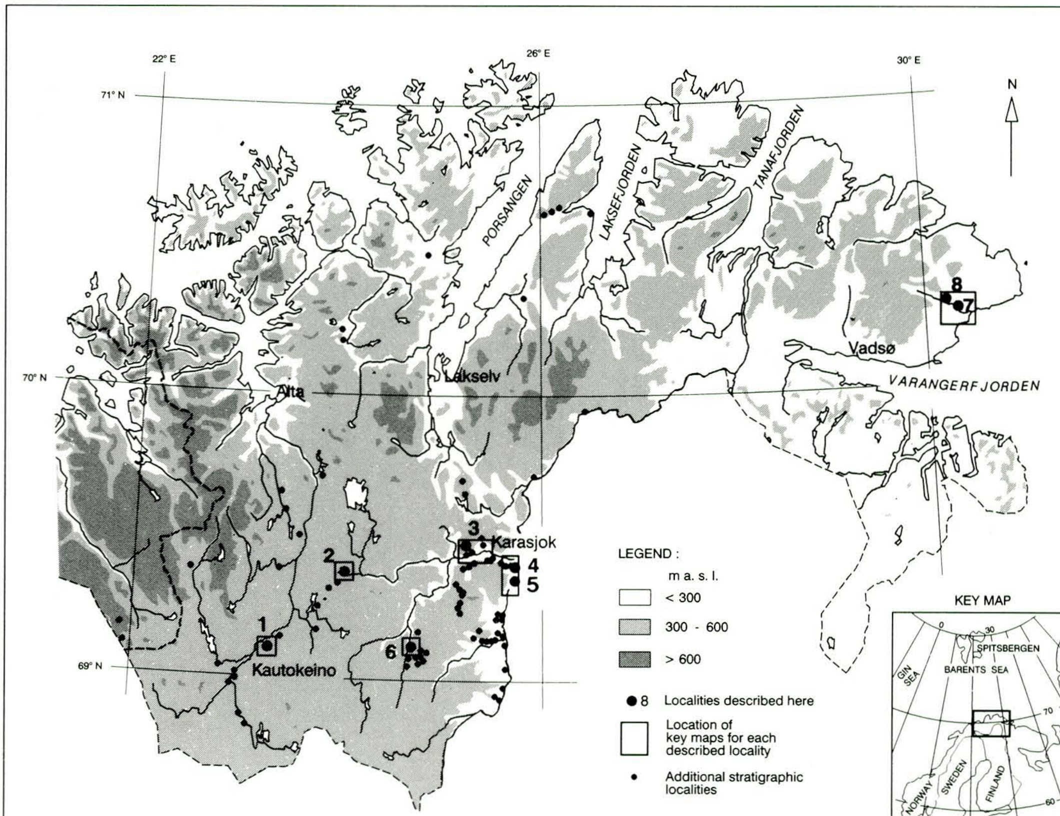


Fig. 1. Topography of Finnmark county, northern Norway, and map of the studied stratigraphic localities (dots). The selected localities described in this paper are numbered and indicated by large dots: 1= Vuolgamasjohka, 2= Vuoddasjavri, 3=Balučohka, 4= Gamehisjohka, 5= Buddasnjarga, 6= Sargejohka, 7= Komagelva, and 8= Leirelva. The areal extension of the key map for each described locality is framed. The numbering of the localities is based on the succession of columns in the correlation diagram in Fig.34.

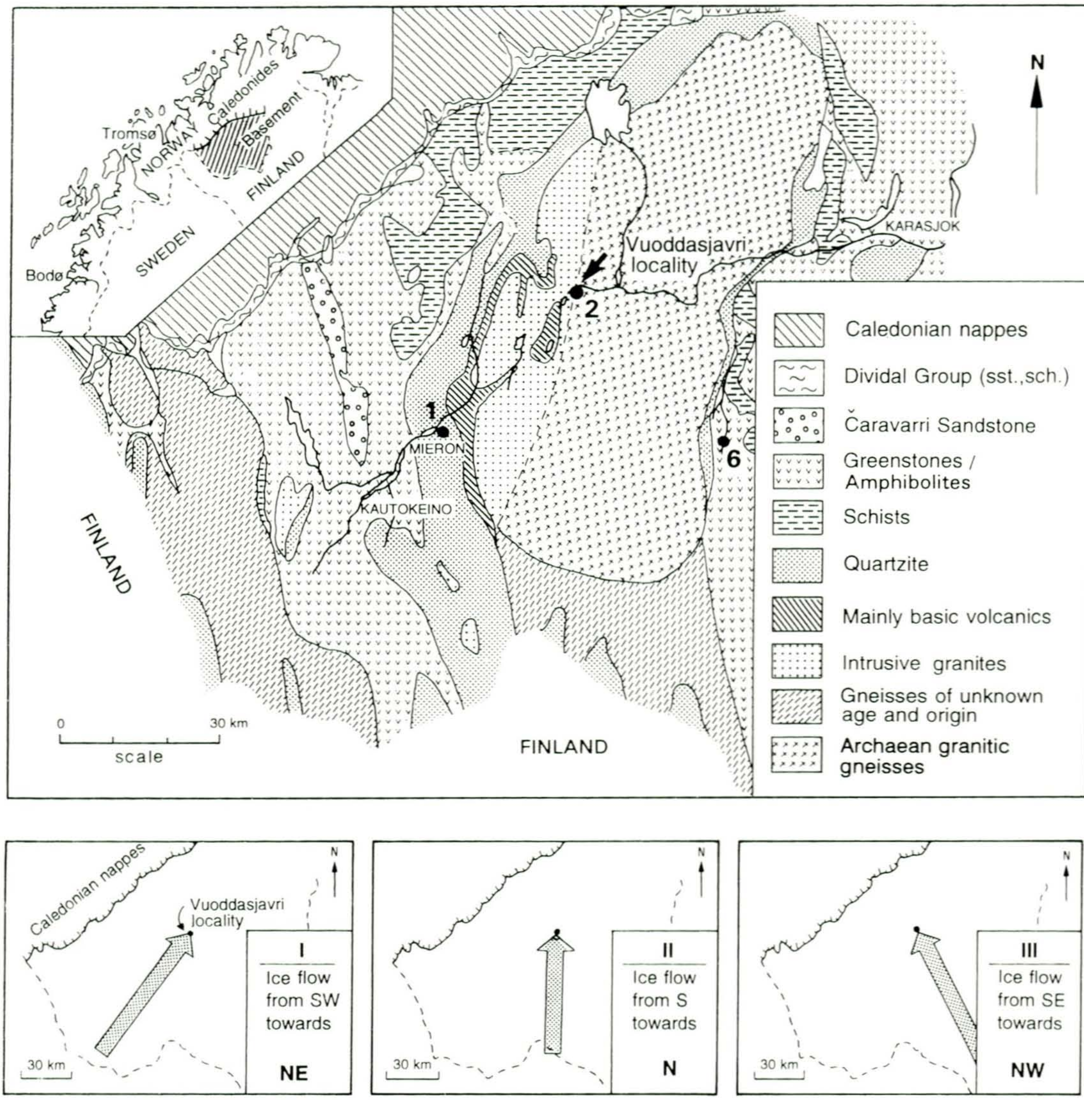


Fig. 2. Outline of the bedrock geology on Finnmarksvidda; and the expected rock distribution of till clasts at Vuoddasjavri, central Finnmarksvidda, during various ice-flow events (small maps: I, II and III). Major rock groups for ice-flow event I, II and III, respectively: I - Granites, basic volcanics, quartzites and greenstones; II - Granitic gneisses and granites; and III - Granitic gneisses and amphibolites. Minor groups: I - Gneisses and other rocks; II - Basic volcanics, gneisses, quartzites and other rocks; and III - Quartzites, gneisses and other rocks. Content of reddish granites and syenites after transport along the different routes: III > II > I, and I ≤ 3-5% (empiric values from young tills). 1, 2 & 6: Localities shown in Fig.1.

oceanic to relatively dry subarctic conditions in the coastal region to dry subarctic continental conditions on Finnmarksvidda. Some small ice-caps exist in the high mountains in the northwest. The precipitation in the coastal region is c. 500-700 mm per year while the mean annual temperature is close to 0°C. The comparative numbers for Finnmarksvidda (Kautokeino) are 300 mm and -2°C, respectively.

The bedrock of Finnmarksvidda may be roughly described from west to east in terms of three major zones (Fig.2). The dominant rocks in the west, starting in the southwest and moving northeast, are gneisses and granites, greenstones, amphibolites, diabases, diverse volcanites, and quartzites. The middle bedrock zone consists mainly of granitic gneisses situated in a huge N-S elongated dome structure. The eastern bedrock zone is dominated by amphibolites, komatiites, migmatites and other gneisses, granulites and quartzites. Red sandstone, which is commonly found in drift deposits on eastern Finnmarksvidda, is not observed in bedrock to the south or east of the mountain range area in the north and west, where it occurs for example in the Dividal Group or in similar formations.

The bedrock on Finnmarksvidda is commonly weathered to a depth of several metres below the drift deposit - bedrock interface in the east (e.g. the Sargejohka area), while it is significantly less weathered in the west. The common presence of kaolinite in the weathered material suggests a pre-Quaternary age (Olsen 1993b).

About 45% of the thick and continuous cover of Quaternary drift deposits in Norway is located in Finnmark (Thoresen 1990). Most of this is located on Finnmarksvidda and in the smaller plateaus in the north and northeast. The major and most common ice movement directions in Finnmark have been towards the north and northwest in the western areas and to the north and northeast in eastern districts (Olsen et al. 1987, Olsen 1988). This means that the major Quaternary ice centres that affected Finnmark were situated in the inland area south of Finnmark, somewhere close to the Gulf of Bothnia. Depending on the location of the ice-divide and ice-dome areas, the ice-sheets may be regarded as either Scandinavian (with ice-domes near the mountains) or Fennoscandian (with ice-domes located far east of the mountains). It is most likely that the major glaciations have been of Fennoscandian type, as was the case during the Late Weichselian.

Extensive fields with large drumlins, some of them more than 1-2 km in length, characterise the western part of Finnmarksvidda, while more scattered drumlins of various sizes are located in the other parts of Finnmark. The drumlins vary from old, complex, multi-stage ones to single-stage drumlins from the last deglaciation period.

Ice-marginal moraines are mainly located in the coastal and fjord-valley areas, and they date to the deglaciation period some 15,000 to c. 9,900 years B.P. (Marthinussen 1960, 1962, 1974, Sollid et al. 1973, Olsen et al. 1996).

Glaciofluvial deposits commonly occur within or adjacent to the ice-marginal moraine zones mentioned above, or they may be grouped together with hummocky moraines in 1-3 km wide belts or zones which are elongated roughly N-S. These are located mainly on Finnmarksvidda and they are thought to derive mainly from the last deglaciation. However, different ice flow indicators combined with stratigraphical evidence also suggest a multi-stage origin for some of these deposits (Olsen et al. 1987).

Methods

Fieldwork

The fieldwork was accomplished by airphoto interpretation and subsequent studies of natural sections along rivers and gullies, and man-made sections along roads and in gravel pits. In addition a number of machine dug excavations and some 50 drillings were carried out at chosen sites for gold prospecting or particularly for the regional studies. The Quaternary stratigraphy has been studied at all such sites at about 200 localities in Finnmark. Most of these are located on Finnmarksvidda, which covers an area of c. 10,000 km^2 or the southernmost c. 20% of Finnmark county. The fieldwork was organised and carried out with the first author in charge. A variable number of people have participated each year during the decade of fieldwork (1980-1990). All together some 25 geologists and students have taken part in these studies (Olsen, *in press*).

Standard procedures for till stratigraphical studies have been followed in most cases (Olsen & Hamborg 1983, 1984, Olsen 1988). These methods include measurements of striation on clasts and bedrock, clast fabric analyses, stonecounts, pebble roundness analyses, and estimation of overall grain-size distribution, compactness, sediment colour, bedding planes and tectonic structures. Sediment samples have also been taken for more detailed grain-size distribution analyses, geochemical analyses and X-ray diffractometry in particular beds.

Our research has benefited greatly both geologically and financially through a cooperation with other projects in this area. Particularly the Nordkalott Project 1980-1986 (Hirvas et al. 1988), a collaborative resource mapping programme for northern Fennoscandia carried out by the Nordic Geological Surveys, has provided much important geological basic information of significant value for our studies. On the local scene, the research involved in looking for the sources of the placer gold at Sargejohka (Olsen 1984, Often & Olsen 1986, Often et al. 1990) has contributed *much to our field studies.*

Radiocarbon dating

The radiocarbon datings used are AMS (Accelerator Mass Spectrometry) dates performed mainly at the R.J. Van de Graaff Laboratorium (University of Utrecht) by K. van der Borg. In addition, some AMS dates have been carried out at the Tandem Accelerator Laboratory of the University of Uppsala by G. Possnert. All the dates are listed in Table 1.

The ^{13}C-values have been measured for the Utrecht dates in each case, while these values for the Uppsala dates have only been set at the standard value of -25‰ (compared to PDB) for the organic fraction of terrestrial sediments. We have used the measured ^{13}C-values to estimate the eventuality of contamination by C from carbonate rocks, and we have concluded that all the measured values are too low to indicate a contamination of this kind (Table 1). However, we also realise that we cannot exclude such contamination in general, for instance contamination by C from old soils, with this method.

The preliminary calibration of ^{14}C-years to calendar years with the use of U/Th datings to estimate the calendar years for ages above 10 ka, as reported by Bard et al. (1990), may need more extensive testing before it can be universally accepted. However, as we in some cases compare ages given by other dating methods, we have included the calibrated numbers for the radiocarbon dates in Table 1.

TABLE 1. Radiocarbon - AMS dates of various Quaternary geological samples from Finnmark. Ages are given as uncalibrated and calibrated to calendar years, respectively.

Field no.	*Sample no.*	*Locality*	*Analyzed fraction/* material	*Del-13* per mill.	*Loss on ignition*	*Age yrs. BP* ^{14}C-AMS	*Calibrated* age
229-86	Ua 318	Vuoddasjavri	INS, plant remains		2.1 %	13,780 ± 195	16,520 ± 260
199-86	" 319	Sargejohka	---------"---------		1.2 %	35,100 ± 1600	
35-84	" 320	-----"-----	SOL, humus		1.2 %	7240 ± 240	8000 ± 240
28-84	" 321	Marevæjskaidi	SOL, humus		1.2 %	6050 ± 240	6770 ± 450
	UtC 1392	Sargejohka	wood/plant remains	-28.2		>45,000	
	" 1428	Gamehisjohka	---------"---------	-27.9		>50,000	
9-85	" 1791	Vollneset	INS, plant remains	-26.0		4650 ± 70	5380 ± 80
"	" 1792	-----"-----	SOL, -"-	-26.0		5180 ± 60	5945 ± 45
5-85	" 1793	Fauskeelva	INS, organic C	-26.8	0.9 %	6250 ± 80	7120 ± 100
"	" 1794	-----"-----	SOL, -"-	-26.5		5370 ± 60	6155 ± 115
501-89	" 1795	Komagelva	INS, -"-	-27.8	1.4 %	16,420 ± 190	19,345 ± 255
"	" 1796	-----"-----	SOL, -"-	-27.3		15,370 ± 140	18,290 ± 160
507-89	" 1797	Leirelva	INS, -"-	-26.6	2.1 %	15,010 ± 160	17,925 ± 185
"	" 1798	-----"-----	SOL, -"-	-25.9		10,550 ± 100	12,470 ± 130
512-89	" 1799	-----"-----	INS, -"-	-25.7	4.1 %	17,290 ± 170	20,530 ± 310
"	" 1800	-----"-----	SOL, -"-	-23.5		17,110 ± 160	20,275 ± 305
4-250891	" 1966	Reinøya	plant remains	-25.0		3540 ± 70	3800 ± 100
1-220891	" 1967	Hopsfjorden	shell	-1.6		recent	
1-090891	" 1968	Vadsø	--"--	2.4		3350 ± 60	3575 ± 105
1-170891	" *1969*	*Skånsvikdalen*	--"--	*0*		*3840 ± 70*	*4245 ± 155*
90.0041	" 2219	Komagelva	organic C	-26.0	1.7 %	8420 ± 100	9380 ± 110

Luminescence (TL and OSL) dating

Introduction

In the present study some 54 sub-samples of a total of 29 main samples (each of 1-2 kg or more) from Finnmark, mainly Finnmarksvidda, were dated by luminescence methods. These include thermoluminescence (TL) and optically stimulated luminescence (OSL). The work began in 1982 and continued with additional samples each year up to 1994. This period has been one of rapid progress in luminescence dating; therefore, several different procedures have been used over the years. We have not differentiated in the tables between results produced according to different procedures, but it is possible to do this if we consult with the laboratory journals. Some differentiation between results may, though, be read from the tables, because the dating techniques have progressed over the years and the laboratory numbers of the samples include, as the first two digits, the year when each sample was analysed for the first time. The methods now used at the Nordic Dating Laboratory have been described recently by Mejdahl & Christiansen (1994). A comprehensive account of TL dating methods may be found in Aitken (1985) and a survey of progress in OSL dating has been given by Aitken (1994).

The basis of luminescence dating

TL and OSL have the common basis that certain minerals including quartz and feldspars are able to absorb and accumulate radiation energy when they are exposed to e.g. alpha, beta and gamma radiation from radioactive materials in their surroundings. If the minerals are heated to 500°C or exposed to light, the stored energy will be released and emitted as a blue-violet signal called luminescence. The signal is called TL if the energy is released by heat and OSL if the release is by light. The main difference between the two methods is thus the way in which the stored energy is released.

Application of luminescence methods for dating

Application of luminescence methods for dating requires that a zeroing event has taken place which has reduced the stored latent signal to zero (or almost to zero) at the time of interest. Zeroing by heat, e.g. firing of pottery, leads to archaeological applications (dating of pottery, bricks, burnt stones, etc.) while zeroing by exposure to light (called bleaching), which will take place when a sediment is exposed to sunlight during transport in nature, enables the dating of this transport/sedimentation event. However, if the exposure to light is too little during the last sedimentation event, then the luminescence signal may reflect an inherited zeroing event from a previous transport and sedimentation event. This will be dealt with later.

After zeroing, a fresh accumulation of radiative energy begins and, provided that the intensity of the irradiation is constant, the radiation dose absorbed (called paleodose) *will be proportional to the time elapsed since the zeroing event took place.* This time period (the age) is given by the following equation:

$$Age = \frac{Paleodose}{Annual\ dose} = \frac{P}{D} \qquad (1)$$

The different methods used at the Nordic Dating Laboratory in the period 1983-1993 for determining P and D are reviewed briefly below.

Annual dose

The annual dose experienced by the mineral grains consists of several components including environmental gamma plus cosmic radiation, external beta radiation, internal beta radiation in K-feldspars from potassium and rubidium in the crystal lattice and a small alpha-dose contribution from uranium and thorium embedded in the crystals. Because we use a grain size of 0.1-0.3 mm (coarse grains) the effect of external alpha radiation can be eliminated.

Gamma plus cosmic radiation

In most cases these components were measured in the field using a sodium iodide scintillation counter. When this was not feasible, the radioelements were measured in the laboratory by means of gamma spectrometry. *The K, U and Th concentration values* were converted to annual dose using conversion factors from Nambi & Aitken (1986) and a cosmic-ray dose of 0.15 Gy/ka was added.

Beta radiation

Originally, external beta radiation was measured by a TL-dosimetry technique using a $CaSO_4$:Mn phosphor (Mejdahl 1978). In 1988 this method was replaced by a much simpler method based on direct counting of beta particles using a GM multicounter system developed at Risø (Bøtter-Jensen & Mejdahl 1988).

The internal beta dose-rate component was determined by measuring the K content of the mineral grains. In the beginning, K concentrations were measured by means of atomic absorption, but in 1985 a technique was developed based on beta counting using the multicounter system mentioned above (Bøtter-Jensen & Mejdahl 1985). The contribution from rubidium was estimated by assuming a fixed ratio of Rb to K (Mejdahl 1987).

Alpha radiation

Finally, there is a small, but not negligible alpha dose contribution from U and Th embedded in the grains. In the beginning of the period discussed here we neglected this contribution, but from 1987 we measured the U content of the grains by delayed neutron counting and estimated the Th content by assuming a linear relationship between the U and Th contents (Mejdahl 1987). Unfortunately, the unit for delayed neutron counting was closed down in 1991. Since then we have used an estimated value for the U content, usually 0.2 ppm. In the conversion from U and Th concentration to annual dose we have used alpha effectiveness factors of 0.1 for quartz and 0.2 for feldspars. The beta dose contribution from U and Th is negligible.

The uncertainties associated with annual dose measurements have been discussed by Mejdahl (1990a). A total uncertainty of 3.7% at the one sigma level was estimated.

Paleodose measurement

TL dating of sediments at our laboratory was taken up in 1982 and the first results were published by Kronborg (1983). The technique used was the added-dose method (Aitken 1985) incorporating a residual value obtained by exposing a set of samples to a sunlamp for 20 hours. Because the residual value obtained by this long exposure might be smaller than the actual residual value in the minerals at the time of deposition, the paleodose (and the age) was probably overestimated in some cases. In cases when the signal vs. added-dose curve was not linear, the curve was approximated by an exponential function.

Mejdahl (1985) proposed a 'partial bleach' method based on regeneration combined with a plateau criteria. This method is applicable also for sediments for which the signal has not been totally bleached, and we have used it in recent years. The lamp used for laboratory bleaching was a specially selected fluorescent lamp, Philips TL05.

Paleodose determination by means of OSL was taken up in 1991 using infrared light (IR) from an array of diodes for stimulation of the luminescence signal (Bøtter-Jensen et al. 1991). The resulting signal is called IRSL (infrared stimulated luminescence). Shortly after, Bøtter-Jensen & Duller (1992) developed a halogen lamp based unit that enabled exposure of samples to green light with a resulting 'green light stimulated luminescence' (GLSL). Green light works with both quartz and feldspar while IR only affects feldspar. Both units can be attached to the automated TL apparatus developed by Bøtter-Jensen (1988).

Very recently, a new OSL method has been developed (Mejdahl & Bøtter-Jensen 1994) which is called SARA (single aliquot, regeneration, added dose) based on single aliquot measurements (Duller 1991). Major advantages of the SARA method are that it has a high precision and can be applied to very small samples.

The measurement uncertainty in paleodose determination is around 5%. However, we usually state a total uncertainty of about 10% for the age to take account of possible dose rate variations with time, e.g. because of movements of the groundwater table.

TABLE 2.1:TL and OSL dates from coastal Finnmark (5) and Finnmarksvidda (49). Additional dates from adjacent inland areas in northern and central Fennoscandia (52 dates from various publications) are shown in Appendix C, p. 111.
Age corrections are given according to the equation: y = 1.35x + 0.7, where x is the given age and y the corrected age (see text for further explanation). All ages are given in ka (= 1000 years).

Dates of samples from Finnmark (Olsen 1988, and unpublished data)

Risø no.	Field no.	Material	TL-age (ka)	Corr.age (ka)	OSL-age (ka)	Corr.age (ka)	Corr.age average (ka)	Locality/ comments
R-823820a	TL 13	sand	41 ± 5	56 ± 6				Kautokeino gravel pit
— « — b	TL 13	—»—	37 ± 5	51 ± 6				—»—
R-823801	20-81	sand	74 ±7	101 ± 10				—»—
R-863804a	TL1-85	sand	91 ± 10	124 ± 10				—»—
— « — b	TL1-85	—»—	88 ± 10	121 ± 10				—»—
R-823802	23-81	sand	< 324 ± 30	< 438 ± 40				—»—
R-823803	24-81	sand	< 411 ± 40	< 556 ± 50				—»—
R-823807	TL1-82	sand	< 389 ± 40	< 526 ± 50				—»—
R-823809	TL3-82	sand	< 300 ± 30	< 406 ± 40				—»—
R-823804	LO31-81	sand	< 459 ± 50	< 620 ± 60				Vuoddasjavri
R-863801a	LO31-81	—»—	156 ± 15	211 ± 20				—»—
— « — b	LO31-81	—»—	170 ± 20	230 ± 25				—»—
— « — c	LO31-81	—»—	156 ± 20	211 ± 25				—»—
— « — d	LO31-81	—»—	160 ± 20	217 ± 25	320 ± 40	433 ± 44	325 ± 40	—»—
R-863805a	TL230-86	—»—	179 ± 20	242 ± 25				—»—
— « — b	TL230-86	—»—	156 ± 15	211 ± 20	173 ± 20	234 ± 25	223 ± 20	—»—
R-823805	LO32-81	s-gravel	< 252 ± 25	< 341 ± 40				—»—
R-863802a	LO32-81	—»—	114 ± 10	155 ± 15				—»—
— « — b	LO32-81	—»—	126 ± 10	171 ± 20				—»—
— « — c	LO32-81	—»—	134 ± 20	182 ± 25				—»—
— « — d	LO32-81	—»—	123 ± 20	167 ± 25				—»—
R-823806	LO34-81	sand	< 358 ± 40	< 484 ± 50				—»—
R-863803a	LO34-81	—»—	176 ± 20	238 ± 25	159 ± 16	215 ± 20	227 ± 20	—»—
— « — b	LO34-81	—»—	210 ± 20	284 ± 25				—»—
— « — c	LO34-81	—»—	183 ± 30	248 ± 40				—»—
— « — d	LO34-81	—»—	180 ± 30	244 ± 40	180 ± 20	244 ± 25	244 ± 35	—»—
R-913805	TL6-89	sand, E	178 ± 20	241 ± 25	349 ± 30	472 ± 40	357 ± 35	—»—
R-823816	TL15-82	sand	< 292 ± 30	< 395 ± 40				Vuoskujavri
R-823817	TL10-82	sand	96 ± 10	130 ± 15				Vuolgamasjohka
R-823818	TL11-82	sand	69 ± 10	94 ± 10				—»—
R-823819	TL12-82	sand	103 ± 10	140 ± 15				—»—
R-913806	TL1-88	sand, C_1	194 ± 20	263 ± 25	359 ± 30	485 ± 40	374 ± 35	—»—
R-913807	TL2-88	sand, C_1	171 ± 20	232 ± 25	211 ± 20	286 ± 25	259 ± 25	—»—
R-893801a	TL1-89	sand, G_1-G_2	195 ± 30	264 ± 40				Sargejohka
R-893801	BH16-88	sand, G_1- G_2	197 ± 20	267 ± 25				—»—
R-913801	TL2-89	silt, G_2			210 ± 20	284 ± 25		—»—
R-913802a	TL3-89	sand,G_3	189 ± 20	256 ± 25				—»—
R-913803	TL4-89	sand, I	145 ± 15	196 ± 20	225 ± 20	304 ± 25	250 ± 25	—»—
R-913804	TL5-89	sand, E	200 ± 20	271 ± 30	231 ± 20	313 ± 25	292 ± 25	—»—
R-933801	TL9-89	g-sand, C			17 ± 2[1]	17 ± 2		Komagelva
R-933802a	TL8-89	sand, D			123 ± 10[1]	167 ± 15		—»—
R-933802b	TL8-89	sand, D			117 ± 10[1]	159 ± 15		—»—
R-943801	TL10-89	s-silt, C	26 ± 3	36 ± 3	26 ± 3	36 ± 3		Leirelva
R-943802	TL11-89	g-sand, D			370 ± 40	500 ± 55		—»—

[1]) SARA, IRSL

Continuation in App. C, p. 111

Luminescence dating results

The dating results were based primarily on TL, but in a few cases OSL was used as well. The OSL method was the added-dose, multiple sample method using IR or green light for stimulation. Ages larger than 16 ka (uncorrected) were corrected mainly for the shallow trap effect (Shlukov et al. 1993) using the procedure derived by Mejdahl et al. (1992):

$$Y = 1.35X + 0.7 \qquad (2)$$

where Y is the corrected and X the uncorrected age in ka. The correction coefficient 1.35 is empirically based on comparison mainly with established oxygen isotope correlated chronologies from Greenland and parts of Scandinavia.

The necessity for age corrections, as in our approach, is best founded for high ages (ages above 80-100 ka). It is uncertain whether significant underestimation of ages normally occurs for low ages, but in this paper we have chosen to use the same correction (2) for all age intervals.

All results are assembled in four tables (2.1, 2.2, 3 and 4) given below. Tables 2.1 and 2.2 give a summary of the dating results, included corrected ages for all dates. Dates determined by the use of old and new methods are generally thought to be compatible with each other, but the majority of the old method dates (those with 82-numbers) could not be estimated more precisely than by indicating their maximum ages (e.g. Table 2.2). Table 3 contains results pertaining to annual dose measurements (water content, grain size, K and U contents in the grains, dose rates from gamma and cosmic radiation (called env.), beta dose rate and total effective dose rate). Table 4 presents results relevant for the determination of paleodose (laboratory bleaching time, residual value, plateau length, paleodose and TL age (uncorrected)).

Additional general remarks

The samples were kept in watertight black plastic bags after extraction. The water content (W%) given in the tables is the water content of the samples as received expressed as percentage of dry weight. This content was in most cases assumed to be representative for the sample during its burial history. In some cases ages have been calculated assuming different water contents (e.g. Olsen 1988).

Severe underestimates of ages of samples from Eemian and Early Weichselian deposits in Denmark have recently been reported (Kronborg & Mejdahl 1989). Ages of 80-90 ka for typical Eemian deposits with an expected age around 125 ka were encountered. The same result was obtai-

TABLE 2.2. Luminescence dates for feldspar samples from Finnmark. Dates are listed in sequence, and additional information are given in Tables 3 and 4.

Lab. no.	Field no.	TL age (ka)	OSL age (ka)	TL/OSL age[1] corrected (ka)
R-823801[2]	20-81	74 ± 7		101 ± 10
R-823802	23-81	< 324 ± 30		< 438 ± 40
R-823803	24-81	< 411 ± 40		< 556 ± 50
R-823804	LO31-81	< 459 ± 50		< 620 ± 60
R-823805	LO32-81	< 252 ± 25		< 341 ± 40
R-823806	LO34-81	< 358 ± 40		< 484 ± 50
R-823807	TL 1-82	< 389 ± 40		< 526 ± 50
R-823809	TL 3-82	< 300 ± 30		< 406 ± 40
R-823816	TL15-82	< 292 ± 30		< 395 ± 40
R-823817	TL10-82	96 ± 10		130 ± 15
R-823818	TL11-82	69 ± 10		94 ± 10
R-823819	TL12-82	103 ± 10		140 ± 15
R-823820	TL13	41 ± 5		56 ± 6
R-863801	LO31-81	156 ± 15		211 ± 20
R-863802	LO32-81	126 ± 10		171 ± 20
R-863803	LO34-81	176 ± 20	159 ± 16	227 ± 20
R-863804b	TL 1-85	88 ± 10		121 ± 10
R-863805	230-86TL	156 ± 15	173 ± 20	223 ± 20
R-893801	BH16-88	197 ± 20		267 ± 25
R-913802b	TL 3-89	108 ± 10		147 ± 15
R-913803	TL 4-89	145 ± 15		196 ± 20
R-913804	TL 5-89	200 ± 20		271 ± 30
R-913805	TL 6-89	178 ± 20		241 ± 25
R-913806	TL 1-88	194 ± 20		263 ± 25
R-913807	TL 2-88	171 ± 20		232 ± 25
R-933801	Komagelva[3]		17 ± 2	17 ± 2
R-933802b	Komagelva[4]		117 ± 10	159 ± 15
R-933802a	— « —		123 ± 10	167 ±15
R-943801	Leirelva[5]	26 ± 3	26 ± 3	36 ± 3
R-943802	Leirelva[6]		370 ± 40	500 ± 55

Notes
LO= Lars Olsen

[1] In cases when an OSL date was available, the average of TL and OSL dates was used. Dates older than 20 ka (uncorrected) were corrected for the «shallow trap» effect by means of the equation (Mejdahl et al. 1992):
$$Y = 1.35X + 0.70$$
where X is the uncorrected and Y the corrected age in ka.

[2] The age of samples having laboratory numbers that begin with 82 may be overestimated because a long laboratory bleach (sunlamp, 20h) was used to obtain a residual signal.

[3] Depth 3 m [4] Depth 5 m [5] Depth 1.2 m [6] Depth 5 m

TABLE 3. Dose rate data for feldspar samples from Finnmark.

Lab. no.	W (%)	Grain size (µm)	K (%)	U (ppm)	Dose rate (Gy/ka) Env.	Beta	Total
R-823801	Nat[1]	100-300	8.2	0.0	0.78	1.34	2.41
R-823802	-	100-300	7.5	0.0	0.83	1.71	2.98
R-823803	-	100-300	8.6	0.0	0.89	1.71	3.10
R-823804	-	100-300	9.4	0.0	0.70	1.43	2.68
R-823805	-	100-300	9.8	0.0	1.15	2.33	4.05
R-823806	-	100-300	8.1	0.0	0.75	1.55	2.77
R-823807	-	100-300	3.9	0.0	1.07	1.72	3.02
R-823809	-	100-300	2.7	0.0	0.66	1.02	1.84
R-823816	-	100-300	12.1	0.14	1.00	1.48	3.02
R-823817	-	100-300	13.2	0.12	1.00	1.55	3.15
R-823818	-	100-300	12.4	0.05	0.80	1.40	2.77
R-823820	-	100-300	12.3	0.06	0.96	1.34	2.88
R-823820	-	100-300	12.9	0.10	0.96	1.45	3.00
R-863801	1.0	100-300	12.4	0.06	0.70	1.68	3.19
R-863802	0.0	100-300	11.8	0.20	1.15	2.70	4.15
R-863803	14.4	100-300	12.3	0.08	0.75	1.66	3.24
R-863804b	18.6	100-300	11.3	0.12	0.78	1.47	2.86
R-863805	8.8	100-300	11.3	0.10	0.75	1.67	3.04
R-893801	15.0	106-180	13.1	0.06	0.86	1.44	2.69
R-913801	16.7	90-180	12.4	0.10	0.60	2.95	3.59
R-913802b	15.7	90-250	10.8	0.20	0.80	2.00	3.19
R-913803	2.4	106-300	11.8	0.20	0.80	1.60	3.25
R-913804	21.1	106-212	11.7	0.20	0.80	1.53	2.77
R-913805	4.0	106-300	11.1	0.20	0.80	1.78	3.33
R-913806	14.0	106-300	10.6	0.20	0.80	1.30	2.76
R-913807	1.6	106-300	9.4	0.20	0.80	1.74	3.21
R-933801	5.0	90-212	0.2	0.20	0.60	0.59	1.34
R-933802b	5.0	150-300	0.0	0.20	0.60	0.14	0.87
R-943801	12.3	150-300	9.9	0.20	1.32	2.54	4.29
R-943802	1.6	106-300	0.0	0.20	0.26	0.11	0.51

Notes

[1] When the dosimetry technique was used for measuring annual beta doses the water content was not measured because the samples were sealed with their natural water content during the measurement.

[2] W(%) is the water content of the samples as received.
K(%) is the potassium content of feldspar grains.
U(ppm) is the uranium content of feldspar grains.
Beta is the infinite-matrix beta dose rate.
Total is the total dose experienced by the grains from gamma + cosmic radiation, external and internal (K + Rb) beta radiation and internalalpha radiation (an alpha effectiveness factor of 0.2 was assumed). The measurement error (one sigma) is around 5% (Mejdahl 1990).

TABLE 4. TL dates and related data for feldspar samples from Finnmark.

Lab. no.	Bl. time (h)	Res(%)	Plateau (°C)	Paleodose (Gy)	TL age (ka)
R-823801	20	0	280-480	179	74 ± 7
R-823802	20	0	280-350	<967	<324 ± 30
R-823803	20	0	280-360	<1274	<411 ± 40
R-823804	20	0	280-350	<1230	<459 ± 50
R-823805	20	0	365-425	<1022	<252 ± 25
R-823806	20	0	300-360	<993	<358 ± 40
R-823807	20	0	280-440	<1175	<389 ± 40
R-823809	20	0	290-380	<552	<300 ± 30
R-823816	20	0	no plateau	<882	<292 ± 30
R-823817	20	0	– « –	303	96 ± 10
R-823818	20	0	– « –	190	69 ± 10
R-823819	2	0	– « –	296	103 ± 10
R-823820	1	19	290-440	123	41 ± 5
R-863801	1.5	32	330-410	499	156 ± 15
R-863802	0.3	24	400-500	522	126 ± 10
R-863803	9	21	300-400	569	176 ± 20
R-863804b	8	5	280-500	252	88 ± 10
R-863805	18	13	330-430	474	156 ± 15
R-893801	1	13	330-430	530	197 ± 20
R-913802b	20	2	310-470	345	108 ± 10
R-913803	0.7	27	320-400	471	145 ± 15
R-913804	0.3	41	380-450	556	201 ± 20
R-913805	10	5	no plateau	592	178 ± 20
R-913806	10	5	300-450	535	194 ± 20
R-913807	10	7	370-480	494	171 ± 20
R-933801	-	-	-	23	17 ± 2[1]
R-933802b	-	-	-	102	117 ± 10[1]
R-943801	-	39	320-440	109	26 ± 3[1]
R-943802	-	-	-	189	370 ± 40[1]

Notes

[1] Obtained by the OSL method SARA using IRSL (Mejdahl & Bøtter-Jensen 1994); there was too little material for TL.

[2] Bl. time is laboratory bleaching time using the Philips TL05 fluorescent lamp. Res(%) is the residual level after bleaching as percentage of the natural level. Plateau is maximum range over which the standard deviation of the paleodose is less than 5%.
P is paleodose. The uncertainty as determined from repeated measurements is around 6%.

ned with optically stimulated luminescence (Mejdahl, unpublished). A small part of the underestimate, perhaps 10 ka for ages around 100 ka, might be ascribed to thermal fading (Mejdahl 1988, 1989). Previously higher water contents may also explain some of the underestimate, perhaps another 5-10 ka for ages around 100 ka. These factors, together with the more significant shallow trap effect, are thought to constitute the main part of the underestimation that is corrected for by applying the age correction equation (2).

To use and evaluate luminescence dates it is important to realise the difference between the precision of the analyses and the empirically based conclusion of underestimation of given ages. The former, which is thought to be ± 5%, or ± 10% if fluctuations of the groundwater table are taken into account, is based on the dating technique and may thus be improved only if the luminescence dating methods are improved. The latter, on the other hand, is mainly based on comparisons with other dating methods, and it is very likely that better age estimates eventually will be achieved through a development of the correction equation (2) as other dating methods are improved and further comparisons with these are made.

In this work we have adopted the idea of Olsen (1988) of preservation of the TL-signal signature from a former zeroing event more or less unaffected by a younger redepositional event with little exposure to light. This may, in fact, be a normal situation for most fluvial and glaciofluvial environments because material in suspension seems to reduce a significant portion of the light penetration even at low flow rates (e.g. Gemmell 1985). The distribution of TL dates may therefore very well reflect the ages of older ice-free intervals (or zeroing events), although the samples may have been taken from younger stratigraphical levels. We will return to this under the discussion on page 76 by comparing with other dating methods, for example speleothem growth periods (ice-free periods) from caves in Nordland (Lauritzen 1991).

Geomagnetic measurements

A paleomagnetic investigation of samples from the Sargejohka stratigraphy has been performed by Løvlie & Ellingsen (1993). Field sampling was carried out by pushing/hammering short, cylindrical tubes into the semi-consolidated sediments.

The results of this investigation demonstrate that the 'sample-push' may affect coarse-grained sediments as well as fine-grained, and it is recommended that paleomagnetic samples of coarse-grained sediments should be collected by carefully carving out proper shapes using a knife, and subsequently conveying the sediment to proper boxes for transportation and measurements.

TABLE 5.1. Pollen, spores and other microfossils in sub-till sediments from some localities on Finnmarksvidda, Northern Norway.

Analysis: P.U. Sandvik 1988 and S. F. Selvik 1991-1992				
Microfossils	Vuolgamasjohka I, sample no. 811661, 811664 and 811665	Áskal, sample no. 821213	Balucohka, sample no. 870401	Vuolgamasjohka no. 870442
Pinus	1	4	4	1
Betula	25	31	42	5
Alnus	4		2	1
Juniperus	1	1		
Corylus			4	
Ulmus	1	1		1
Asteraceae achillea t.	2			
Ranunculaceae			2	
Thalictrum			1	
Urtica/Humulus/ Cannabis t.		2		
Rosaceae	2			
Artemisia			6	
Lamiaceae			1	
Cyperaceae	5	1		
Rumex	4			
Caryophyllaceae	1			
Poaceae	21	5	34	
Ericales	4		3	
Empetrum	2			
Unidentified incl. deteriorated pollen	11	5	65	
Polypodiaceae	32	1	5	
Huperzia selago	1		1	
Lycop. clavatum	2			
L. annotinum	12			
L. sp.	2		1	
Sphagnum		1		
Pediastrum	9			2
Charcoal			1	
Pollen sum	84	48	166	8
Pollen concentration (p. grains/cm^3)	20-57	15	865	210

TABLE 5.2. Pollen and spores in the Vuoddasjavri deposits.

Analyses: S.F. Selvik 1991-92 x, xx and xxx (most frequent) indicate relative frequencies of the pollen types										
Microfossils	Unit M	Unit tL	Unit K	Unit tJ	Unit I	Unit tH	Unit G2	Unit G1	Unit E	Unit tD
Pinus			x			x	x			
Betula	x	xx	xxx	x	x	xxx	xxx			x
Alnus		x	xx				x			
Juniperus						x	x			
Tilia									x	
Asteraceae			x							x
Rumex			x				x			
Caryophyllaceae		x								
Poaceae		x	xx	x			xx	x	x	
Ericales	x									
Unidentified incl. deteriorated pollen		xxx	xx	x			xxx	x		x
Polypodiaceae		x	x				xx	x	x	x
Sphagnum			x							
Max. pollen concentration (p. grains/cm^3)	50	200	950	200	50	200	1500	100	60	150

Pollen analysis

Pollen analysis has been performed on samples from sediments below and between till units, and on some selected samples from tills (Tables 5.1 & 5.2, and Figs.15, 35 and 36). The samples were treated with HF and acetolysis as described in Fægri & Iversen (1989). *Lycopodium* tablets were added to allow absolute pollen analysis (Stockmarr 1972). The pollen analysis was carried out by S. F. Selvik, except some initial samples that were analysed by P. U. Sandvik.

The pollen concentration ranges from less than 100 pollen grains /cm^3 in some of the samples to almost $3x10^5$ pollen grains /cm^3 in others. The highest concentrations are found in samples of gyttja from interglacial and interstadial beds at Sargejohka. Due to variable preservation, the frequency of unidentified pollen grains also varies, but it is commonly less than 5%.

TABLE 6. Insect and macro plant data from Sargejohka; analysed by G. Lemdahl, 1991. Sample 1/91 is from c. 4.2 m depth in the reworked material indicated in Figs.24A,B. Sample 2/91 is from the uppermost part of unit G2 at c. 7.1 m depth in excavation 3-89 (Fig.20).

Sample	Material and comments
1/91	Diamicton with reworked organic material in the basal part of the youngest regional till. The organics are thought to represent the Sargejohka interstadial. - Very little insect remains. Remains of gnats (? Culicidae), and one fragment of an unspecified spider. Abundance of brown mosses, mushroom *(Cenococcum geophilum)*, and buds of willow *(Salix)*, etc.
2/91	Gyttja silt from the Bavtajohka interglacial beds. - Four spider taxa, and three other insect taxa recorded. The species represent an arctic to subarctic fauna. Abundance of brown mosses, tree-birch *(Betula alba)*, mushroom, and remains of leaves of birch, willow and other plants. Also represented, but in minor amount are dwarf birch *(Betula nana)*, white mosses *(Sphagnum)*, and pondweeds (*Potamogeton* sp.).

Macroscopic plant remains

The content of macroscopic plant remains has been examined in samples from sediments at Sargejohka (Table 6), and at Gamehisjohka (Fig.1). Some of the largest pieces of plant remains were picked out, cleaned and studied preliminarily in the field, and subsequently re-examined in the laboratory. These include fossil remains and imprints of leaves from tree-birch *(Betula alba)* and willows *(Salix)*, and pieces of wood possibly from the same type of plants.

Insect remains

The content of insect remains has been examined in two samples from sediments at Sargejohka (Table 6). It shows, at least

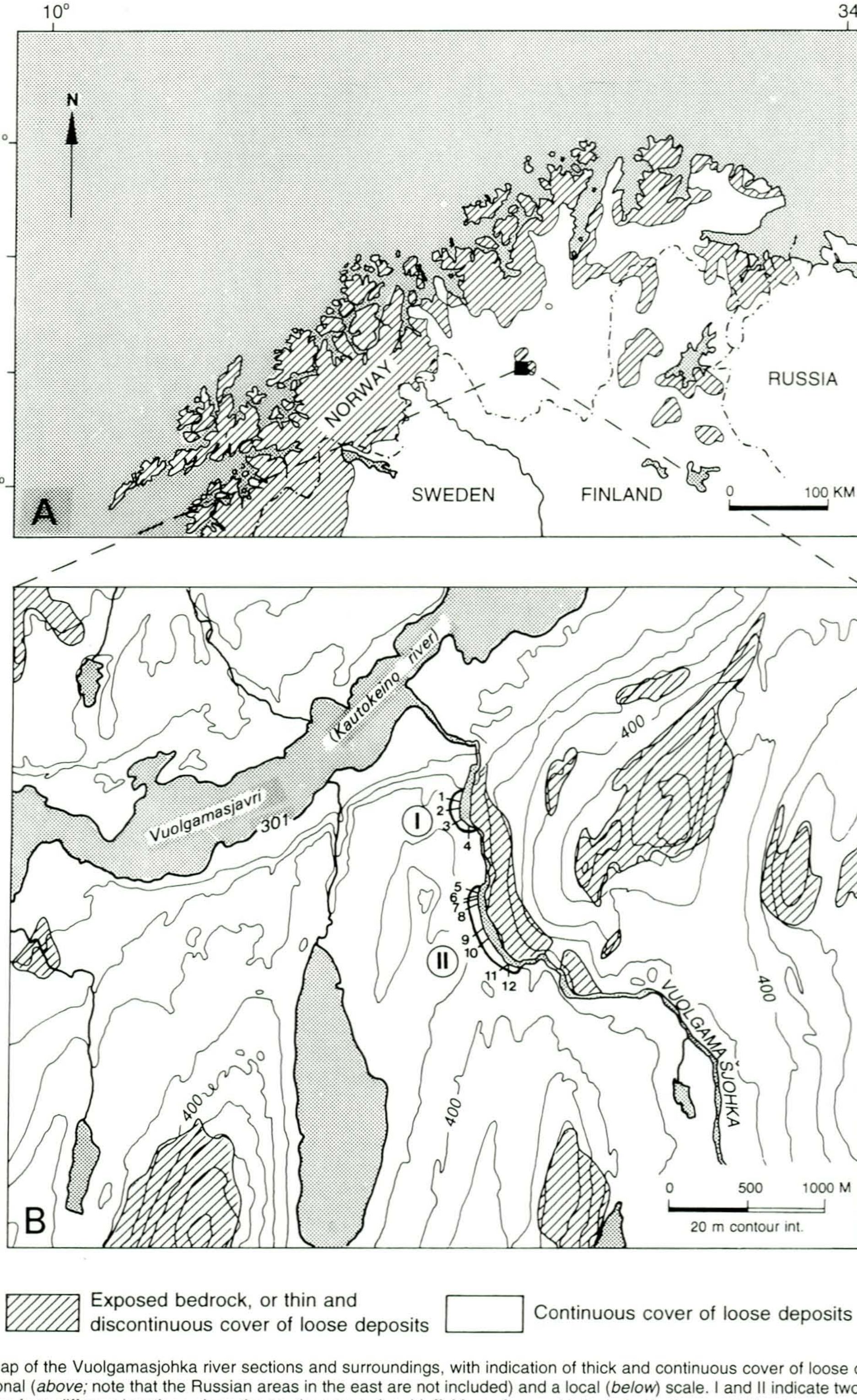


Fig. 3. Map of the Vuolgamasjohka river sections and surroundings, with indication of thick and continuous cover of loose deposits in a regional (*above;* note that the Russian areas in the east are not included) and a local (*below*) scale. I and II indicate two groups of sections from different locations along the southwestern river bluff. Most of group I is included in the vegetation-free zone of Fig.4.

for one of the samples, a poor insect assemblage indicating a subarctic climate in accordance with the pollen content (G. Lemdahl, pers.comm. 1991).

Finnmarksvidda

Stratigraphy of key localities

Vuolgamasjohka (1)

All known major stratigraphic depositional units of the Late Pleistocene of Finnmarksvidda are represented in the deposits along the river Vuolgamasjohka (Figs.3 & 4). The succession in 12 sections along a profile of 1300 m length and about 50 m height (Figs.3-5) is separated into three till sequences by intercalated waterlain sediments. The fourth and lowermost till sequence is assumed to be of Late Saalian age.

The stratigraphical units have been given informal names by Olsen (1988); these are, starting at the top (Fig.5F): Kautokeino Till, Sand C1 (correlated with the Sargejohka interstadial), Vuoddasjavri Till, Eiravarri ('interstadial') Sand, Gardejohka Till, Vuolgamasjohka ('interglacial') Sand, and Mieron Till.

The waterlain sediments are mainly glaciofluvial outwash material deposited in connection with retreating ice, and thus representing initial parts of ice-free periods. However, there also exist fluviolacustrine horizons, e.g. in section 3, cut 3a on top of the lowermost thick gravel and sand sequence (Vuolgamasjohka Sand, J1; Figs.5B, D & F). The sedimentology and sedimentary structures of the two thickest sediment sequences in the northern group of sections (I in Fig.3) have been described in detail by Lyså & Corner (1994), and their conclusions with regard to the general depositional history are in accordance with those of Olsen (1988). In addition, they provide various data on glaciotectonic structures which indicate that the Vuolgamasjohka Sand was at least partly unfrozen, and that the Eiravarri Sand was largely frozen during deposition of the subsequent overlying tills.

Fig. 4. Photo of the western part of the Vuolgamasjohka river bluff (view towards the NNW). Scale: two persons in the middle and upper part of the vegetation-free zone on the slope. The section is about 50 m high and it includes deposits spanning the major glacial - deglacial events during the Late Saalian - Eemian - Weichselian period.

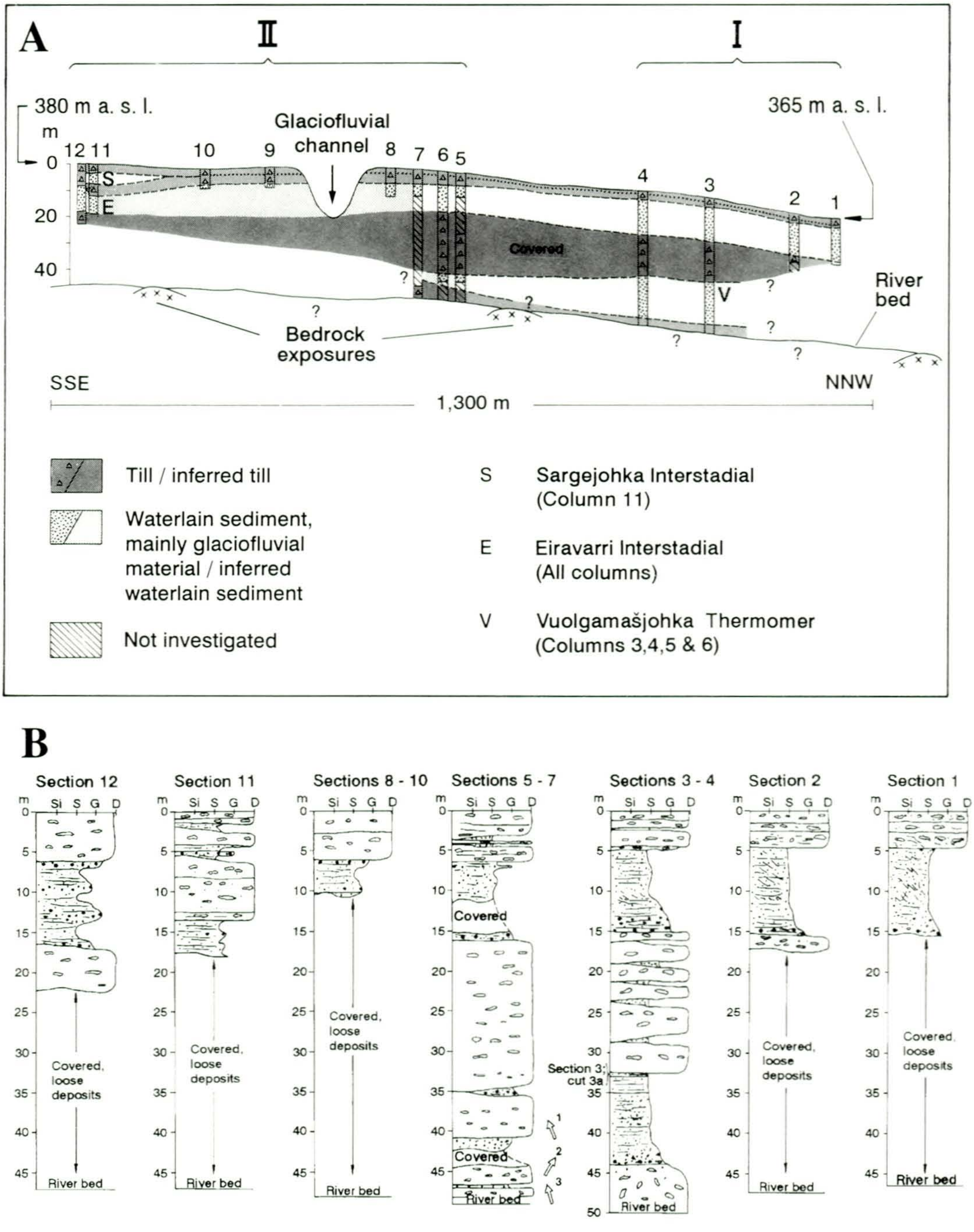
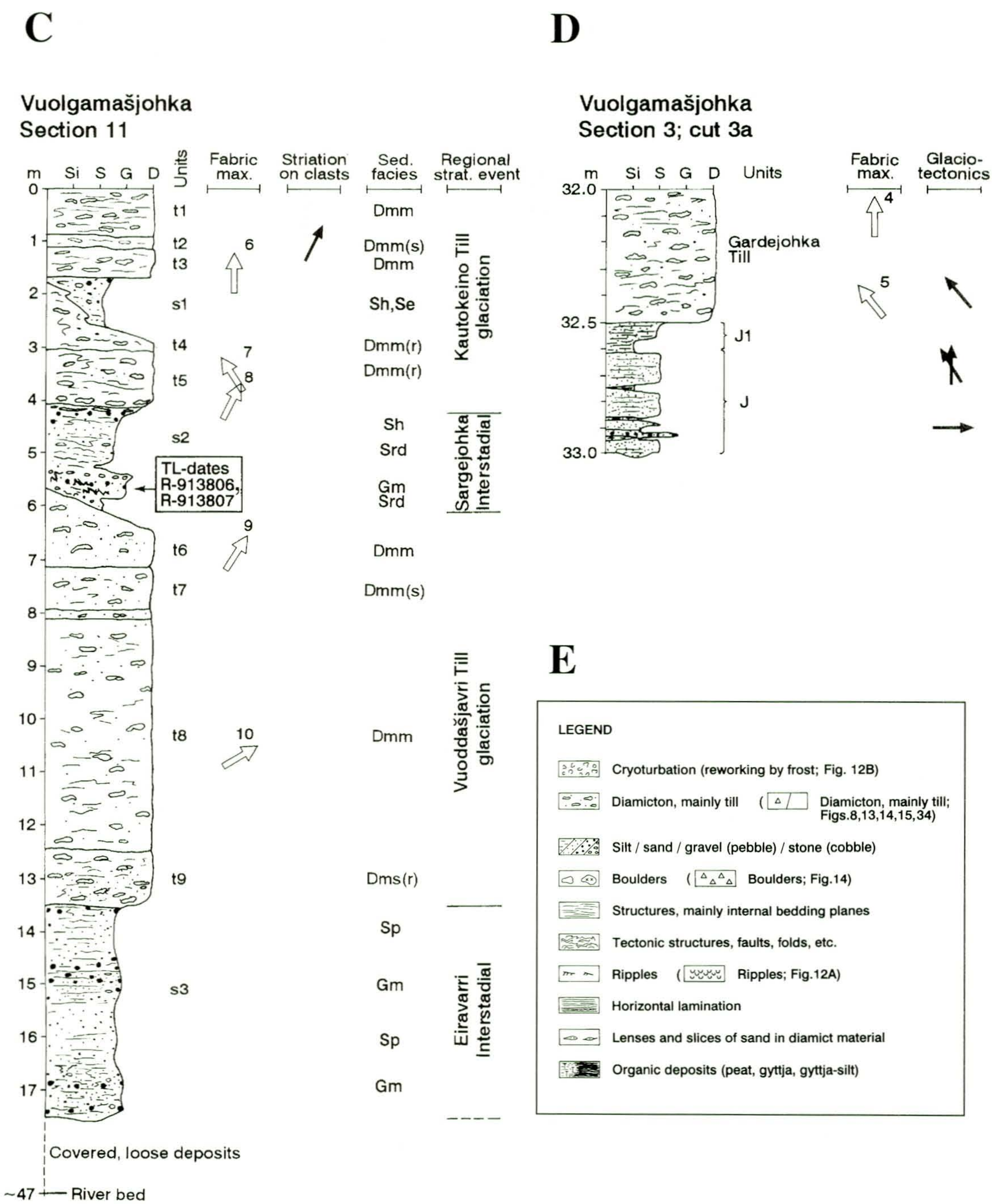
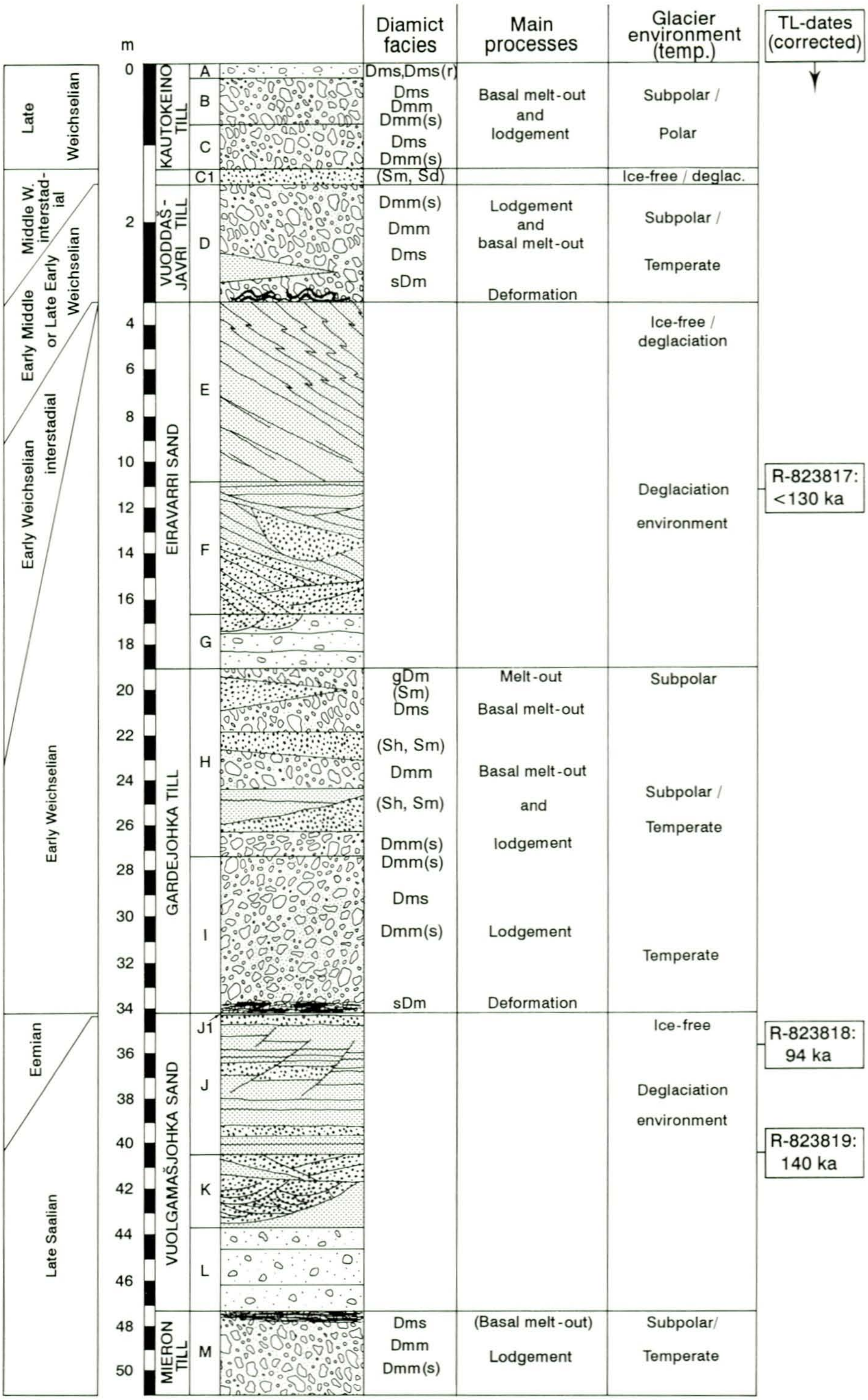


Fig. 5. Profile and studied sections along the Vuolgamasjohka river; A) profile *(above)* and B) simplified logs of sections 1-12 *(below)*, and C)-D) simplified logs of selected and enlarged parts of sections 11 and 3. E) Explanation of symbols used in Figs. 5A-F, and partly in Figs. 8, 10, 12A-B, 20, 21, 24A, 28, 32, 38 and 40. Units t and s combined with a number, as in t1 or s1, indicate informally named local units of till and sand, respectively. Units tA, tB, tC, tD, E and tF indicate regionally correlated units in the western Finnmarksvidda area. The correlations follow the stratigraphic framework defined by Olsen & Hamborg 1983, 1984 and Olsen 1988. The sedimentary diamict lithofacies are according to Table 7, while the monomict lithofacies follow the more standardised F, S and G denotations for fines (silt, clay, mud), sand and gravel, as commonly used in publications (e.g. Miall 1978, 1985); for more details see figure captions to Figs.10 & 12. F) The generalised stratigraphy at Vuolgamasjohka (after Olsen et al. 1990).


C
Vuolgamašjohka
Section 11
m Si S G D
Units
Fabric max.
Striation on clasts
Sed. facies
Regional strat. event
t1 Dmm
t2 6 Dmm(s)
t3 Dmm
s1 Sh,Se
t4 7 Dmm(r)
t5 8 Dmm(r)
Kautokeino Till glaciation
Sh
s2 Srd
TL-dates R-913806, R-913807
Gm
Srd
Sargejohka Interstadial
t6 9 Dmm
t7 Dmm(s)
t8 10 Dmm
Vuoddašjavri Till glaciation
t9 Dms(r)
Sp
s3 Gm
Sp
Gm
Eiravarri Interstadial
Covered, loose deposits
~47 River bed
D
Vuolgamašjohka
Section 3; cut 3a
m Si S G D Units
Fabric max.
Glacio-tectonics
32.0
32.5
33.0
Gardejohka Till
J1
J
4
5
E
LEGEND
Cryoturbation (reworking by frost; Fig. 12B)
Diamicton, mainly till (Diamicton, mainly till; Figs.8,13,14,15,34)
Silt / sand / gravel (pebble) / stone (cobble)
Boulders (Boulders; Fig.14)
Structures, mainly internal bedding planes
Tectonic structures, faults, folds, etc.
Ripples (Ripples; Fig.12A)
Horizontal lamination
Lenses and slices of sand in diamict material
Organic deposits (peat, gyttja, gyttja-silt)

F


m
Diamict facies
Main processes
Glacier environment (temp.)
TL-dates (corrected)
Late Weichselian
Middle W. interstadial
Early Middle or Late Early Weichselian
Early Weichselian interstadial
Early Weichselian
Eemian
Late Saalian
KAUTOKEINO TILL
VUODDAŠ-JAVRI TILL
EIRAVARRI SAND
GARDEJOHKA TILL
VUOLGAMAŠJOHKA SAND
MIERON TILL
A
B
C
C1
D
E
F
G
H
I
J1
J
K
L
M
Dms,Dms(r)
Dms
Dmm
Dmm(s)
Dms
Dmm(s)
(Sm, Sd)
Dmm(s)
Dmm
Dms
sDm
gDm
(Sm)
Dms
(Sh, Sm)
Dmm
(Sh, Sm)
Dmm(s)
Dmm(s)
Dms
Dmm(s)
sDm
Dms
Dmm
Dmm(s)
Basal melt-out and lodgement
Lodgement and basal melt-out
Deformation
Melt-out
Basal melt-out
Basal melt-out and lodgement
Lodgement
Deformation
(Basal melt-out)
Lodgement
Subpolar / Polar
Ice-free / deglac.
Subpolar / Temperate
Ice-free / deglaciation
Deglaciation environment
Subpolar
Subpolar / Temperate
Temperate
Ice-free
Deglaciation environment
Subpolar/ Temperate
R-823817: <130 ka
R-823818: 94 ka
R-823819: 140 ka

The oldest ice-free period represented is named **Vuolgamasjohka Thermomer**, and it is thought to correlate with the Late Saalian deglaciation and the Eemian. This correlation is based on eleven luminescence dates with an average age of 146 ka for the corresponding deglaciation sediments (Vuolgamasjohka Sand), with two of the dates coming from these sediments at Vuolgamasjohka (Table 2.1: corrected ages of R-823818, R-823819), and on lithostratigraphic correlation of the younger tills with those in northern Finland (Olsen 1988).

Sample R-823818 is taken from the upper part of the Vuolgamasjohka Sand where the sediments are strongly oxidised and subsequently glaciotectonised. We think that these events may have caused some reduction of previously stored radiation in the sand grains, and consequently the age of 94 ± 10 ka (corrected; Table 2.1) of this sample is probably significantly too low for the unit. We will return to this matter, with another example of inferred underestimation of an age based on luminescence dating, later in this paper (p. 50).

The younger waterlain sediments represent Weichselian interstadials, named **Eiravarri** and **Sargejohka Interstadial,** respectively. The former is TL-dated to about 100 ka (Olsen 1988), and therefore of Early Weichselian age. It is correlated with the Peräpohjola interstadial in northern Finland and the Jämtland interstadial in Sweden (Olsen 1988). The Sargejohka interstadial is represented by a complex colluvium originating from glaciofluvial - debris flow - fluvial material, as revealed in section 11 in the easternmost part of the Vuolgamasjohka stratigraphy (Olsen, unpublished material; and Fig.5C). The pollen contents with supposedly mainly redeposited pollen, and TL/OSL ages >200 ka (R-913806, R-913807, Table 2.1; note the good zeroing of these dates, 5-7% residual doses; Table 4), indicate a mixture of components just as would be expected from the complex depositional history associated with these sediments. However, the interstadial is inferred to be of Middle to late Early Weichselian

TABLE 7. Sedimentary diamict lithofacies. Mainly after Eyles et al. (1983). Modifications partly after Lyså & Corner (1994).

Code	Facies description	Interpretation
Dcs	Clast supported diamicton, stratified, occurrence often in combination with S-, G-, sDm-, gDm-, and Dms-facies	Ablation melt-out till and poorly sorted glaciofluvial debris flow/debris fall material
Dmm	Matrix supported, massive, normal silty-sandy composition. Variable clast fabric from random to strong parallel or occasionally transverse	Till or debris flow deposits (and also some glaciomarine sediments)
Dmm(s)	Dmm with dense internal shearing, often with strong parallel clast fabric	Lodgement till
Dmm(r)	Dmm with evidence of resedimentation, often medium strong to strong parallel clast fabric	Mainly lodgement and basal melt-out till
Dms	Matrix supported, stratified diamicton, with sand lenses and linings around clasts. Medium to relatively strong parallel clast fabric, transverse fabric may occur in some areas	Mainly basal melt-out till, but often combined with intervening or alternating zones of lodgement till
Dms(r)	Dms with evidence of resedimentation, for instance with rafts of deformed sand/silt/clay laminae and abundant silt/clay stringers and rip-up clasts. Clast fabric variable from random to fairly strong	Mainly basal melt-out, but often combined with zones of lodgement till
sDm	Sand-enriched matrix supported diamicton, mainly massive, but occasionally heterogeneous or stratified	Tillised sediment/deformation till containing sand eroded from local substrate; and melt-out till
gDm	Gravel-enriched matrix supported diamicton, mainly massive, but occasionally heterogeneous or stratified	Mainly melt-out till, but in some cases possibly also tillised sediment or deformation till with gravel eroded from local substrate

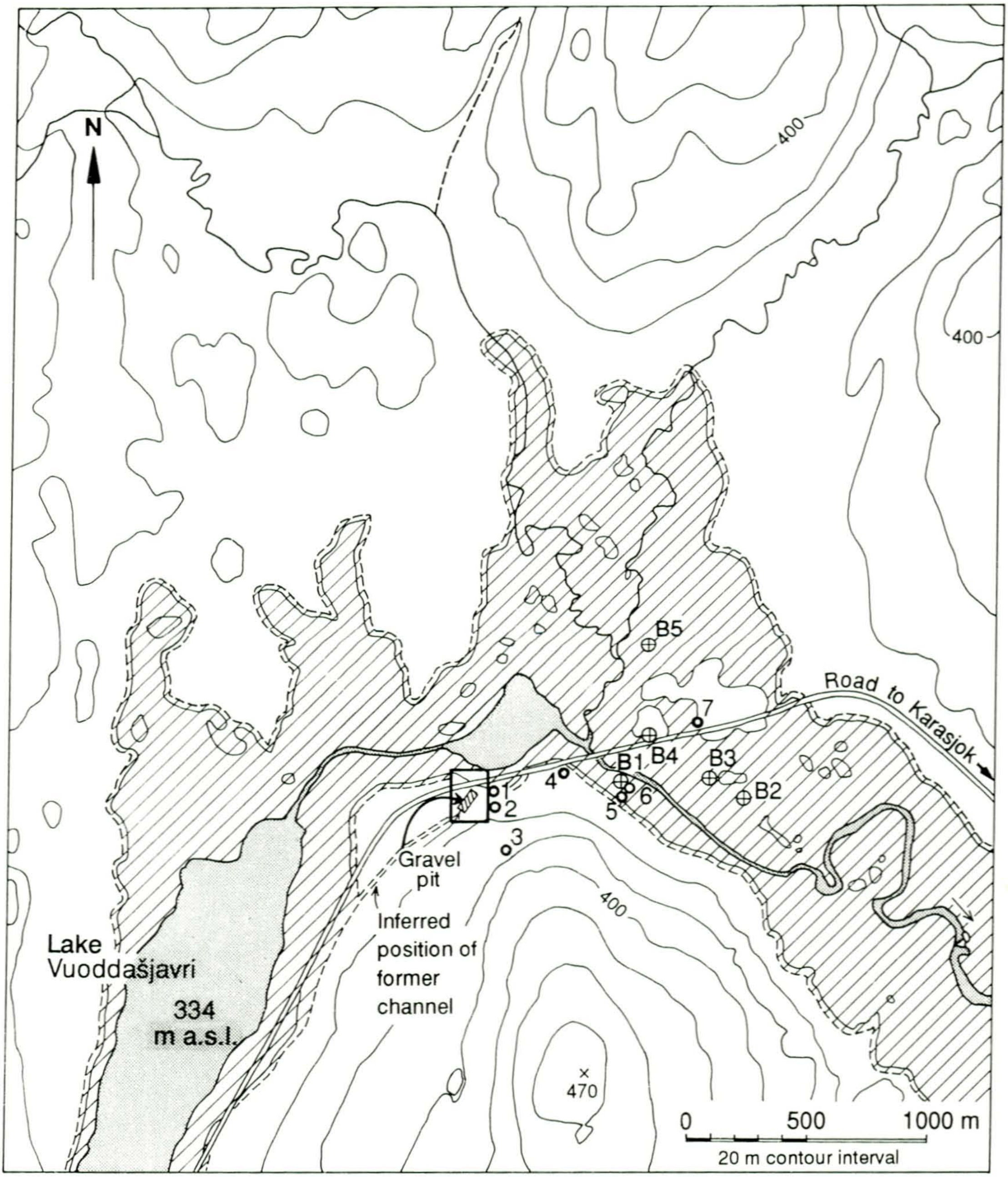


Fig. 6. Map of the Vuoddasjavri locality area with studied sections (circles 1-7) and drilling points (B1-B5) indicated. Areal extension of the former 'Vuoddasjavri' lake during deposition of unit G is indicated by the dashed line (water-level approximately 345 m a.s.l., or slightly higher). The location of the Vuoddasjavri locality is indicated in Fig.2.

age, based on information from other localities with two ^{14}C-AMS and two TL dates with apparent ages, and on correlation with the Tärendö interstadial in northern Sweden (Lagerbäck & Robertsson 1988, Olsen 1988, unpublished data, Larsen et al. 1991).

Vuoddasjavri (2)

The stratigraphy at Vuoddasjavri (Figs.6-15) is recorded in a gravel pit and is supported and extended by several excavations and drillings closely spaced and within a distance of a few hundred metres. New information together with a reconsideration of the previous data supports the interpretation of the stratigraphy as given by Olsen & Hamborg (1983, 1984) and Olsen (1987), and contradicts one of the interpretations and correlations made by Olsen (1988). We will return to this point in the description and discussion.

Description. The total thickness of the drift deposits at this locality is 40-60 m, as indicated by drillings and refraction seismics (Mauring 1989; and Olsen, unpublished material). The stratigraphy below 15 m depth is known from percussion drilling and drillings with continuous mixed bulk-sampling at 0.5 m intervals. Possible important details that only continuous core-sampling can provide may therefore be lacking in the present data. In addition, although the main units have probably been recorded, it should be noted that none of the samples from the very important stratigraphical 'interglacial' levels between 22 and 29 m depth (Figs.8 and 15) and also between 38.5 and 46 m depth were recovered satisfactorily. No sediment or pollen analyses are therefore available from these intervals.

The local bedrock consists of quartz-mica gneiss and mica gneiss, possibly with bands of granitic or granodioritic composition. The bedrock is slightly weathered and there is a small amount of kaolinite present.

Unit M

This is the lowermost unit resting directly on bedrock. It is 1.0-1.5 m thick and consists mainly of brown to brownish-grey sand and gravel (Fig.8). The petrography of the fine gravel fraction (4-8 mm) indicates that 87-100% of the material is of local derivation. Unit M may have a glaciofluvial or fluvial origin.

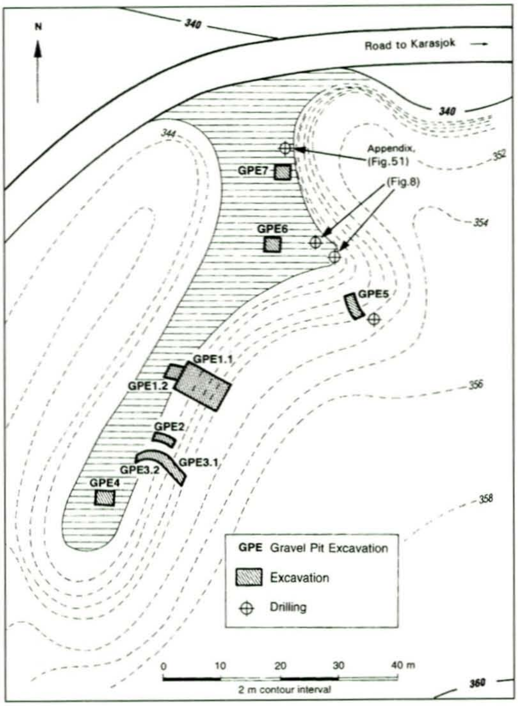


Fig. 7. Sketch of the former Vuoddasjavri gravel pit (year 1981), with approximate elevation contours every second metre indicated.

Unit tL

Above the gravel and sand beds (unit M) is the unit tL that consists of brown to brownish-grey till. This unit is about 3 m thick and its clast petrography, with up to c. 35% amphibolites and c. 0.5% komatiites, both classified as 'Greenstones' on the map (Fig.2), indicates a transport from the southeast where the bedrock consists of similar rock-types not farther than 40-50 km from Vuoddasjavri. Up to c. 16% of reddish granites also supports a transport from relatively closely situated source rocks to the southeast or south. Both amphibolitic and granitic source rocks may also be found in the southwest but we think that the lack, within till tL, of massive amphibolites and greenstones that dominate within the

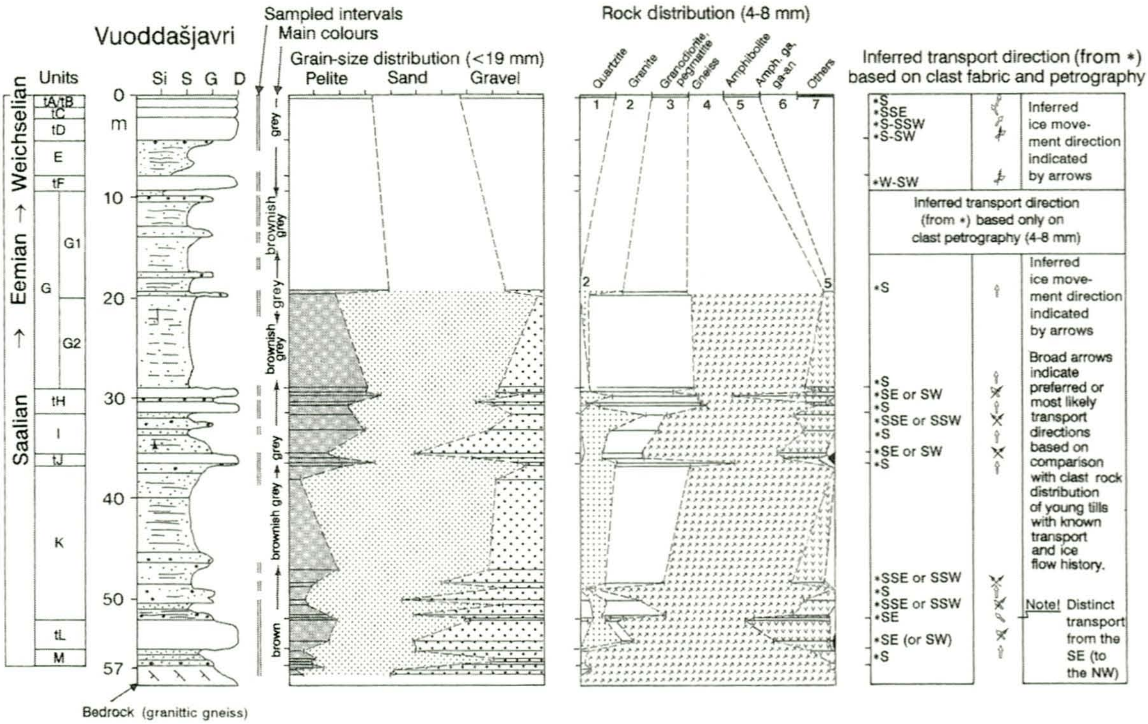


Fig. 8. Generalised stratigraphy at Vuoddasjavri with grain-size data and rock distribution of the gravel size fraction indicated. Only the analyses of samples from drillings in pre-Weichselian strata are included here. For analyses from younger levels we refer to previous publications (e.g. Olsen & Hamborg 1983). Note the predominant trend of ice flows towards the N and NE in the young (Weichselian) tills above 10 m depth, and the more common ice flows towards the N and NW in older (Saalian) tills below this depth.

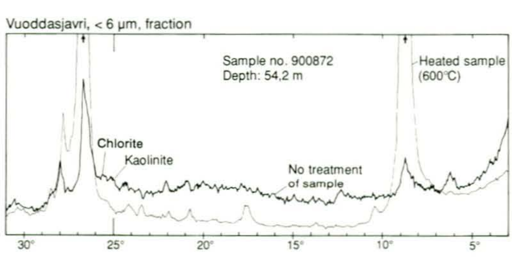


Fig. 9. XRD-diagram from till tL. Traces of kaolinite are thought to be represented on the curve (thick line), for example at the 25.1° reading. The kaolinite signal disappeared (as expected) after heating (thin curve line), while the top at the 25.4- 25.6° reading remained to a certain extent after heating, indicating that chlorite is also present in this sample.

amphibolitic source areas in the southwest, and the very long distance of at least 80-100 km to reddish granites in bedrock in the southwest, do not favour a southwestern provenance for this till.

Some inferred local weathered material occurs in this till, as shown by traces of kaolinite (Fig.9). This is thought to derive from previous or subsequent pedogenic processes.

Unit K

Unit K consists of a lower gravelly part and an upper part wherein sand predominates

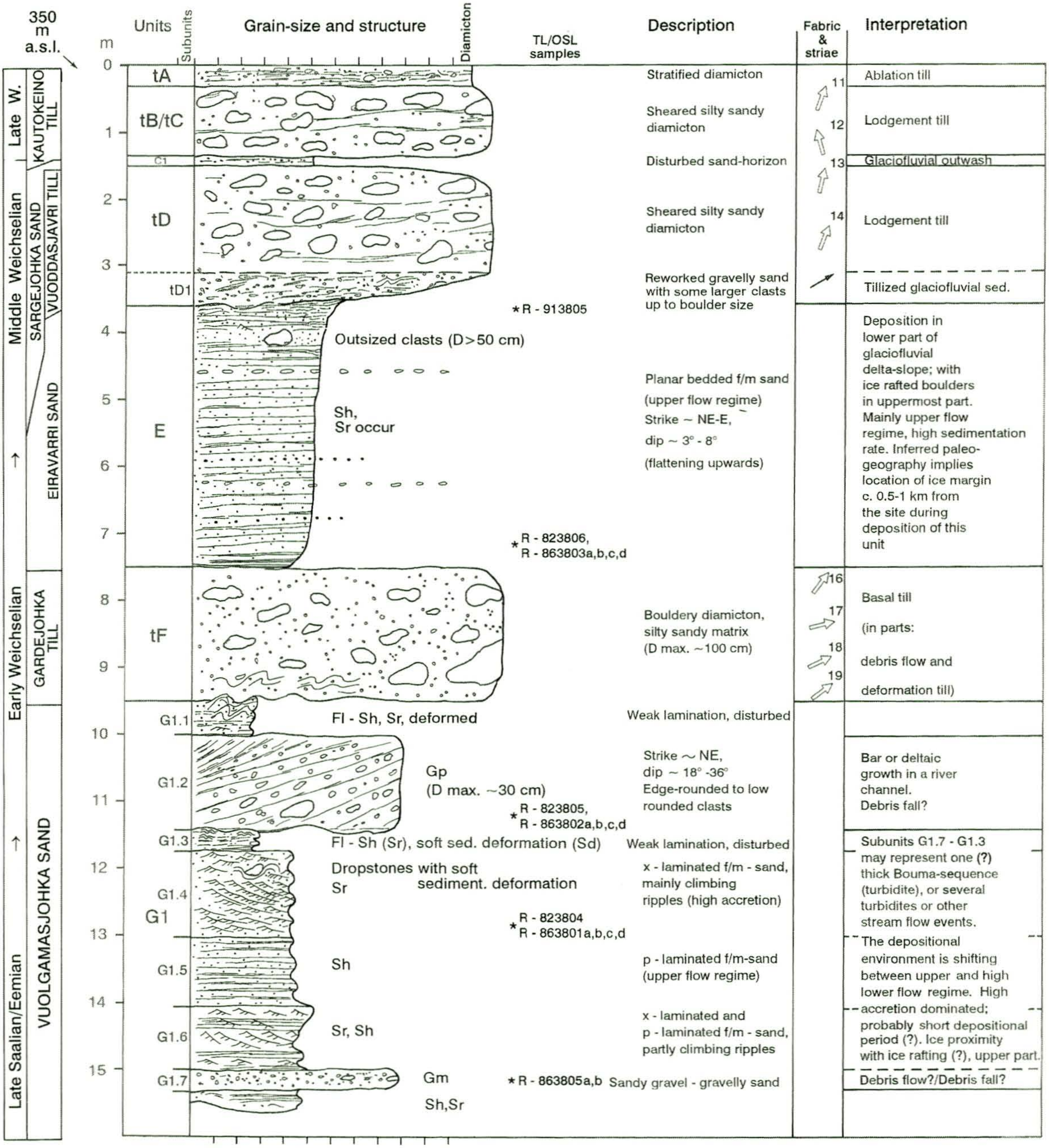
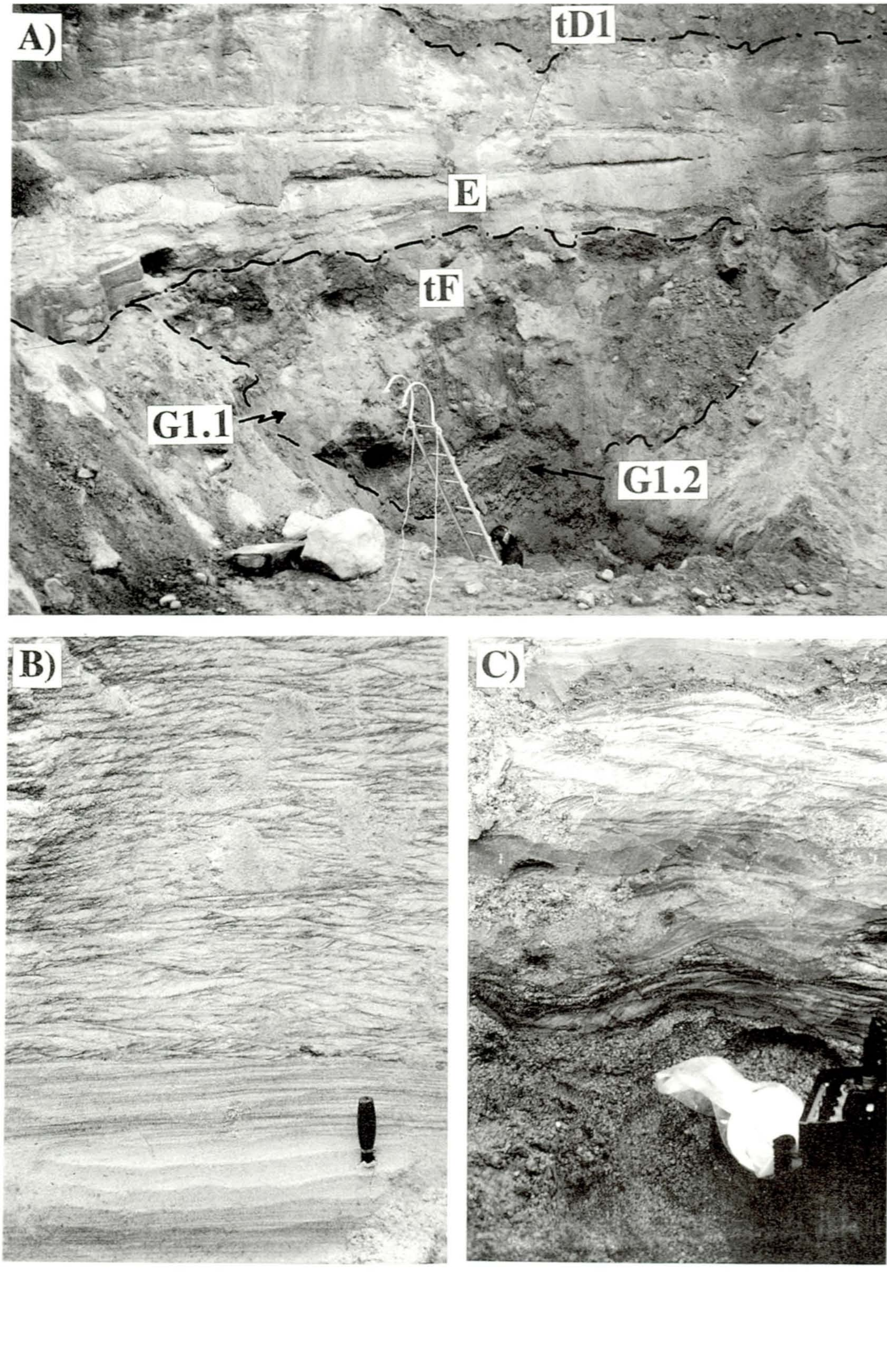
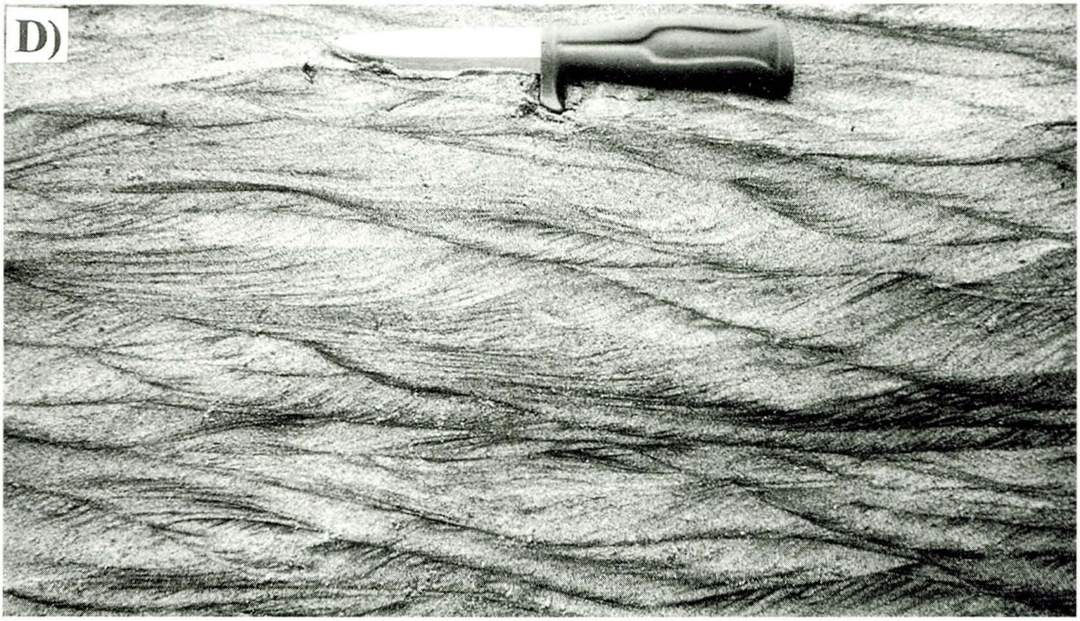


Fig. 10. Simplified log of the upper part of the Vuoddasjavri stratigraphy. Sample positions of TL dates with reference numbers are indicated (cf. Table 2.1). The log is mainly based on section GPE 1.1 (Fig.7). Clast fabrics are indicated with open broad arrows; the numbers refer to the analyses shown in Schmidt's net contour diagrams in the Appendix. The thin arrow in the basal part of till tD indicates the striation direction recorded on till boulders. North is up in the figure.


A)
tD1
E
tF
G1.1
G1.2
B)
C)

D)



E)

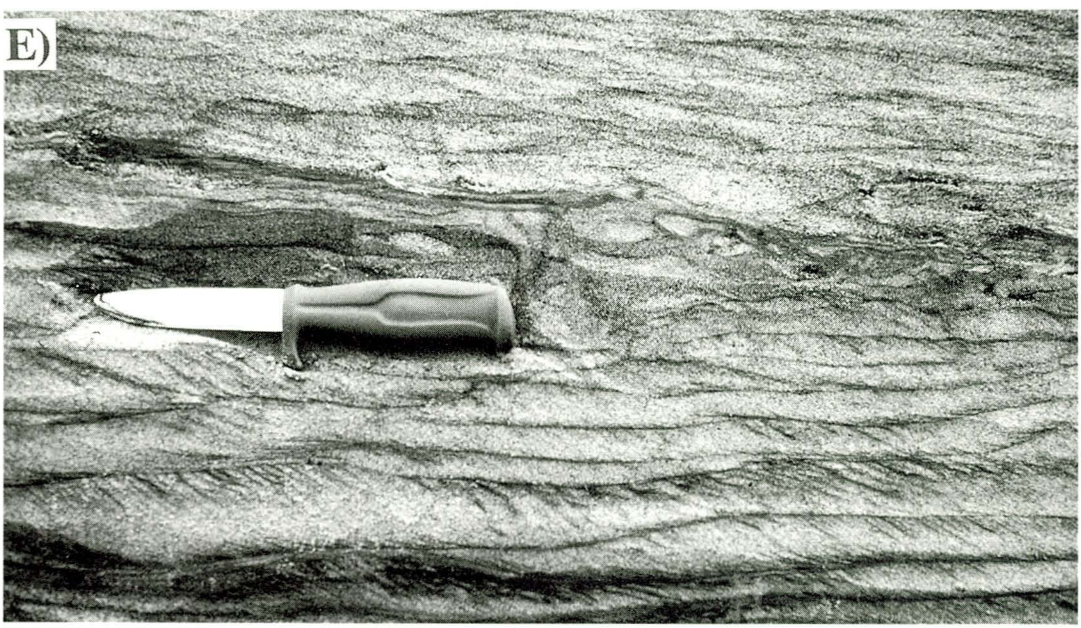
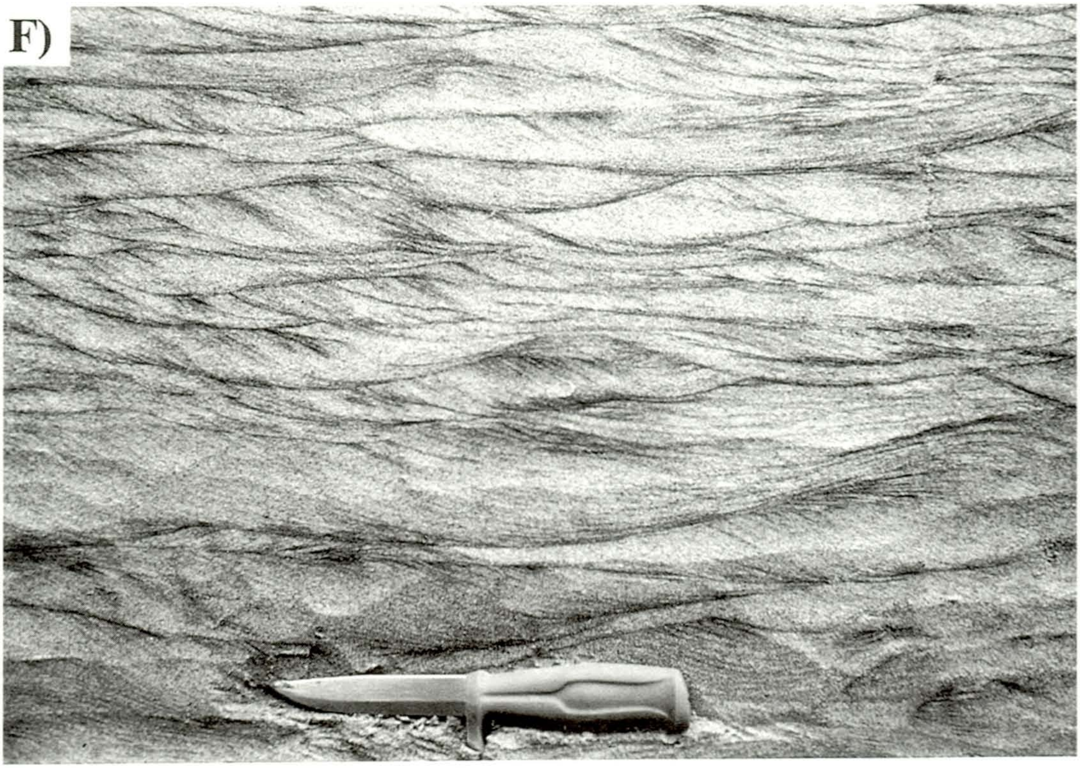
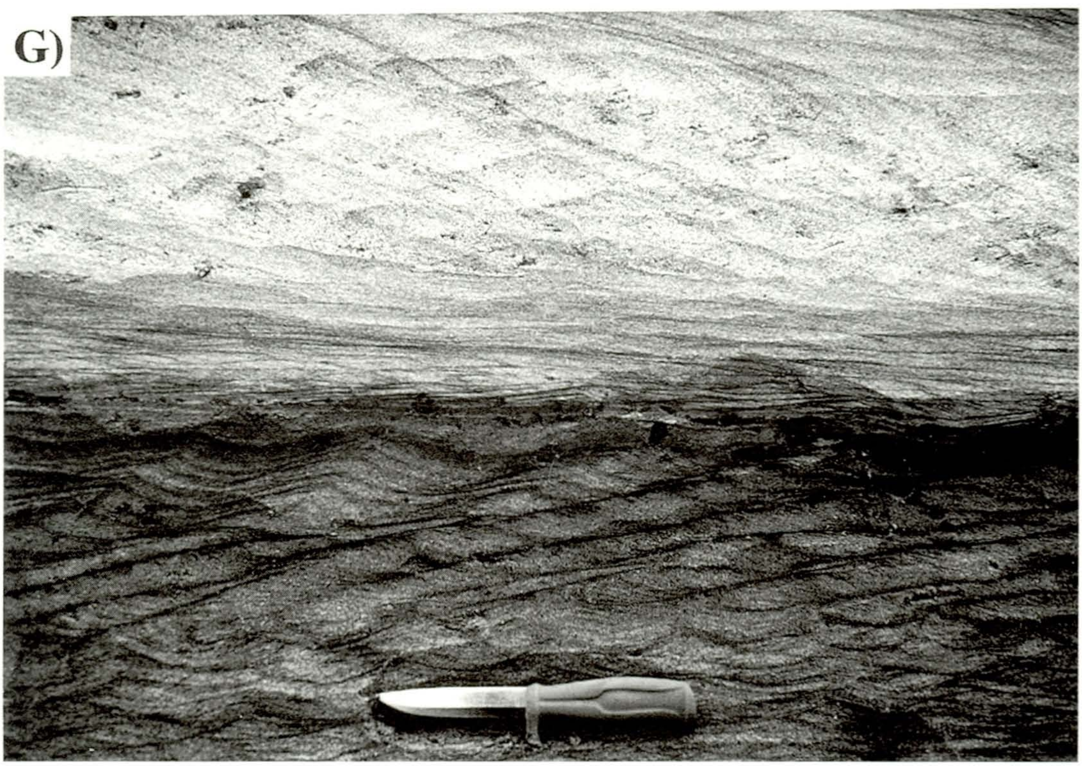


Fig. 11. A) Vuoddasjavri gravel pit; a cut through the sediments in the area where section GPE 1.1 (Fig.7) is described. The following examples of sedimentary facies are from subunits underlying the gravel G1.2 in the lowermost part of the photo; B) Part of cross-laminated subunit G1.4 overlying plane-laminated subunit G1.5; C) Sand G1.6 with various ripple-laminated facies, overlying sandy gravel G1.7 where one of the TL-dating samples was taken. The instrument used for measurement of background radiation in the field may be seen in the lower right part of the photo; D) - G): Further examples of different sand-facies in subunits G1.4 - G1.6, with migration ripples, climbing ripples, wavy bedding, horizontal bedding, etc. D) Unit G1.4: Flow direction to the left, low-angle climbing ripples indicating mainly low aggradation rates (knife c. 20 cm long). E) Unit G1.4: Flow direction to the right, combined-flow ripples (oscillation and current). F) Unit G1.4: Cross-section approx. normal to flow in most of the section, otherwise mainly to the right; current ripples. G) Unit G1.6: Flow direction to the right, climbing ripples with changing angle from low to high in the lower half of the photo, indicating an increasing aggradation rate upwards; changing structures from small-scale ripple lamination and faint flat bedding to large-scale ripples in medium to coarse sand in the upper half of the photo; relatively high flow rates.


F)


G)

(Fig.8). It has a brownish-grey colour and a total thickness of c. 15 m. The lowermost part of the unit is probably glaciofluvial material derived from the same source rocks as till tL, while the upper part has a more local provenance and is thought to be mainly of fluvial origin. The upper part of the unit has a lower fining-upwards trend and an upper coarsening-upwards trend, probably indicating a temporary deeper or more distal channel basin facies.

Unit tJ
This unit is a grey to brownish-grey fine-grained till (Fig.8). Its clast petrography suggests a source area in the southeast, as for till tL. The unit is c. 1.0 m thick.

Unit I
Unit I consists mainly of grey-coloured gravelly and sandy beds, partly with a diamictic character as suggested by the grain-size distributions (Fig.8). The unit is c. 4.0 m thick, and is divided into two parts, each with an overall fining-upwards character; it is probably of mainly glaciofluvial origin. A high content of reddish granites (up to c. 26%) characterises this unit. The provenance area for unit I is therefore thought to be in the southeast - south sector (Fig.2).

Unit tH
Above unit I is a unit, tH, that consists of grey till in two beds separated with a thin gravel horizon (Fig.8). The total thickness of this unit is c. 2.5 m. The clast petrography suggests mainly a southern origin for the till. In the lowermost part of the upper till bed, however, the clast petrography, with up to c. 40% of amphibolites and c. 13% of reddish granites, indicates a more southeasterly origin.

Unit G, subunit G2
Subunit G2 of unit G consists of grey to brownish-grey sand and gravelly sand. The subunit is a c. 9 m thick succession of relatively stable grain-size distribution or a slightly overall coarsening-upwards trend. It represents sedimentation during slightly changing depositional conditions, probably due to local fluvial change in a channel adjacent to a former and more extensive Vuoddasjavri lake which reached up to about 340-345 m a.s.l. (Fig.6). The channel may have been a short-cut channel (chute) between the western and the eastern parts of the drainage system. Alternatively, it may have been the major connecting channel between separate basins in the west and the east. The subunit is therefore thought to be of mainly fluvial origin, although the overall sedimentary environment may perhaps have been of distal glaciofluvial character.

Unit G, subunit G1
The upper part of unit G is here named subunit G1. It consists of a 0.5 m thick, diamictic, gravelly sandy bed below thick beds of mainly sand and gravel in four major alternating gravel - sand successions (Fig.8). The subunit has a grey colour, and it is about 10 m thick. The total thickness of unit G is therefore c. 19 m. The upper half of subunit G1 and the overlying units have been studied in sections, and they are therefore known in more detail than the units below.

The upper part of subunit G1 (Figs.10 & 11) consists of massive or poorly stratified gravelly sand/ sandy gravel (G1.7), planar and cross-bedded sand (G1.6, G1.5 and G1.4), laminated silty sand (G1.3) and foreset-bedded gravel (G1.2), with a planar and cross-bedded silty sand (G1.1) on top. The succession is assumed to represent either a thick turbidite, which is not very likely in this environment, or more conceivably a complex unit of shifting stream channel deposits (G1.7 - G1.3) overlain by a bar or river-bank deposit (G1.2), and with a deeper channel or possible overbank deposit on top (G1.1). This may still represent at least partially ice-free conditions, but the uppermost deeper water environment may be related to the subsequent glacial advance event (till tF).

In places, and in the upper 3-4 m, unit G is affected by glaciotectonic deformation structures. Injections or clastic dykes of diamict material are observed in this zone, e.g. in gravel pit excavation 6 (Fig.12A:f), and they indicate an overall compression direction towards the northeast. The top of this unit reaches c. 10 m above the present lake level (Vuoddasjavri) and its outlet river. The gravel and sand in subunit G1 is interpreted as possible glaciofluvial outwash, but with

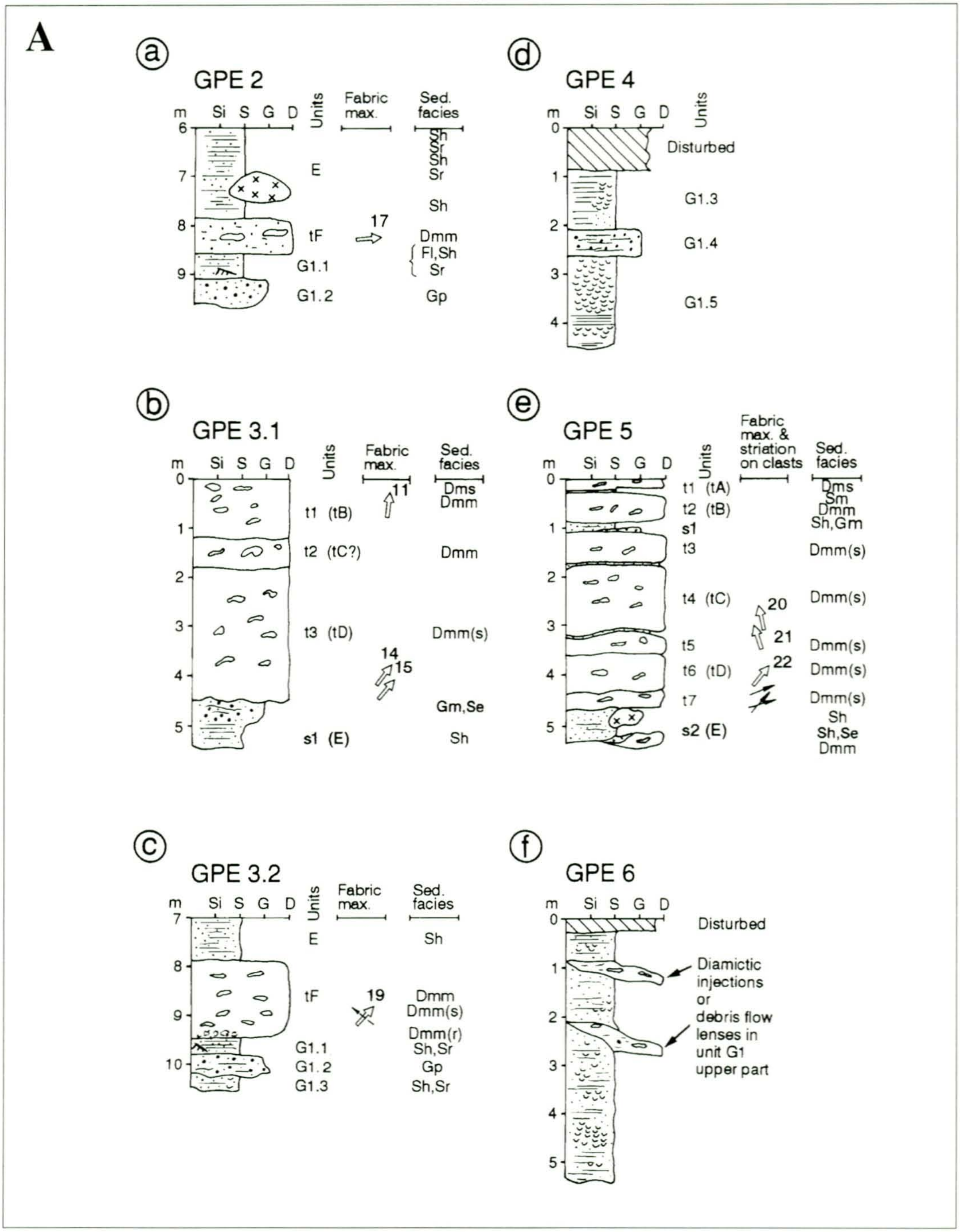
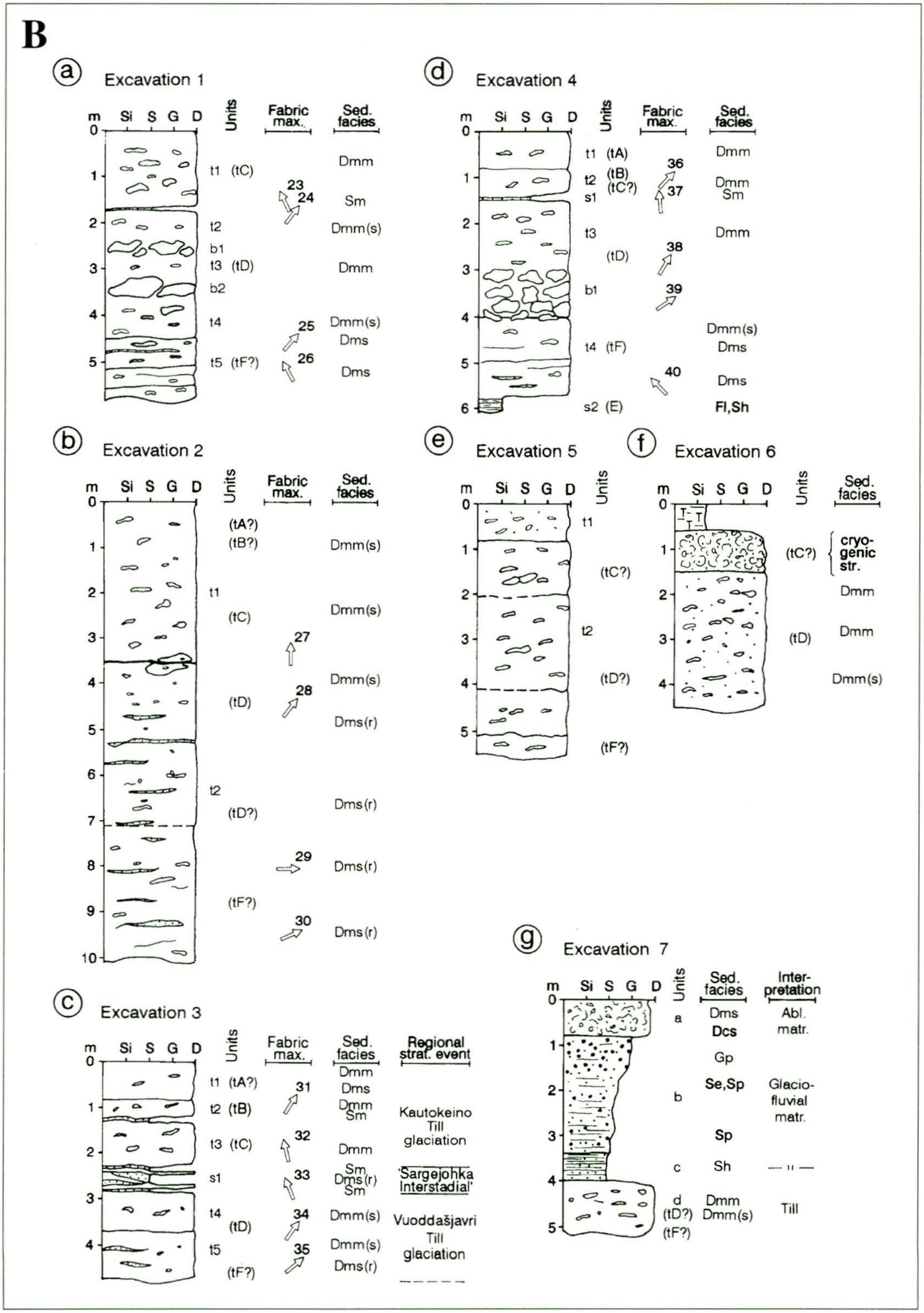


Fig. 12. A) Simplified logs from excavations in the Vuoddasjavri gravel pit (see Fig.7); and B) Logs from nearby excavations (also indicated in Fig.7). Sedimentary diamict lithofacies according to Table 7. Arrows indicate clast fabric and striation, as in Fig.10. The letter symbols of units follow the description given in the figure caption of Fig.5. The sedimentary facies for sorted sediments describes three major grain-size classes, gravel, sand and fines (G, S, F) and several modes of bedding (e.g.: m, massive; t, trough cross-bedded; p, planar (tabular) cross-bedded; r, rippled; h, horizontal laminated; l, fine lamination or very small ripples; e, erosional scours and crude trough cross beds; s, broad shallow scours; d, deformational structures such as faults, folds, etc.).


B
(a) Excavation 1
m Si S G D Units Fabric max. Sed. facies
t1 (tC) Dmm
23
24 Sm
t2 Dmm(s)
b1
t3 (tD) Dmm
b2
t4 25 Dmm(s) Dms
t5 (tF?) 26 Dms
(d) Excavation 4
m Si S G D Units Fabric max. Sed. facies
t1 (tA) Dmm
t2 (tB) (tC?) 36 Dmm
s1 37 Sm
t3 Dmm
(tD) 38
b1 39
t4 (tF) Dmm(s) Dms
40 Dms
s2 (E) Fl,Sh
(b) Excavation 2
m Si S G D Units Fabric max. Sed. facies
(tA?) (tB?) Dmm(s)
t1 (tC) Dmm(s)
27
(tD) 28 Dmm(s) Dms(r)
t2 (tD?) Dms(r)
29 Dms(r)
(tF?) 30 Dms(r)
(e) Excavation 5
m Si S G D Units
t1 (tC?)
t2 (tD?)
(tF?)
(f) Excavation 6
m Si S G D Units Sed. facies
(tC?) cryo-genic str.
Dmm
(tD) Dmm
Dmm(s)
(g) Excavation 7
m Si S G D Units Sed. facies Inter-pretation
a Dms Dcs Abl. matr.
b Gp Se,Sp Sp Glacio-fluvial matr.
c Sh — II —
d (tD?) (tF?) Dmm Dmm(s) Till
(c) Excavation 3
m Si S G D Units Fabric max. Sed. facies Regional strat. event
t1 (tA?) 31 Dmm Dms
t2 (tB) Dmm Sm Kautokeino Till glaciation
t3 (tC) 32 Dmm
s1 33 Sm Dms(r) Sm 'Sargejohka Interstadial'
t4 (tD) 34 Dmm(s) Vuoddašjavri Till glaciation
t5 (tF?) 35 Dmm(s) Dms(r)

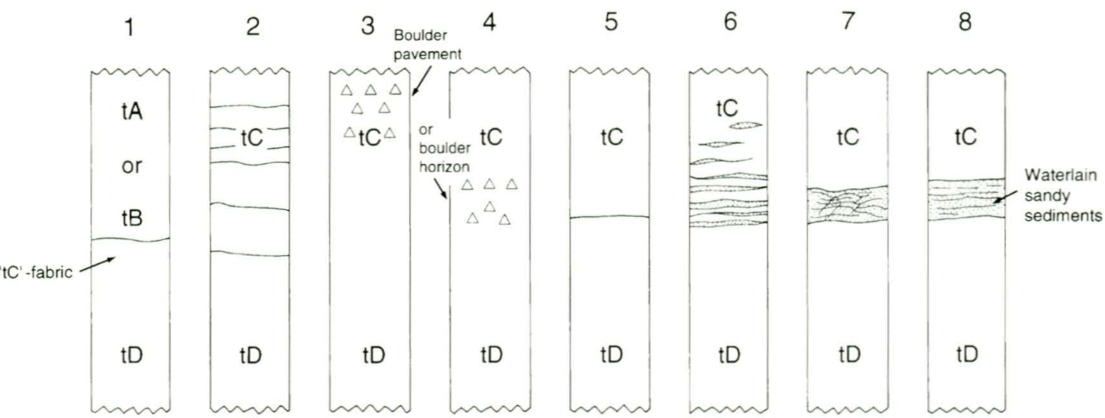


Fig. 13. Sketch of eight different boundary conditions between tills tC and tD occurring at Vuoddasjavri and in adjacent areas (after Olsen 1989a). 1= till tC is missing, removed by erosion and only its characteristic northwesterly clast fabric orientation is preserved and recognised as a reorientation zone in the topmost part of till tD (Olsen & Hamborg 1984); 2= no distinct boundary between tills tC and tD, but rather a transition zone characterised by several thin isolated silt- or sand laminae or subhorizontal clastic dykes; 3= till tC consisting mainly of boulders; 4= a boulder horizon defines the boundary between the tills; 5= the tills are separated by an abrupt, erosional boundary; 6= the lowermost part of till tC is characterised by lenses or bands of sand indicating dislocated parts of underlying waterlain units of sand which are sheared into the till; 7= intermittent glaciotectonically deformed sediments; and finally, 8= tills tC and tD are separated by a weakly deformed unit of waterlain sediments, indicating deposition during a deglaciation environment prior to the last glaciation.

significant parts where a fluvial deposition or redeposition is more likely. Beds containing some pollen occur in the middle and upper parts of the subunit G1, but the highest pollen concentrations are found in subunit G2 (Fig.14). Although some or most of them may be redeposited, these pollen grains indicate at least one period when the glacier was located at some distance from this site. Based on the thickness and the extension of unit G, it is most likely that the pollen originally derived from this unit although it may have been subsequently redeposited within the unit. Thus, the pollen signature implies that an interstadial or interglacial is represented somewhere within unit G. Based on the sediment types we suggest that the optimal ice-free conditions occurred during deposition of subunit G2.

Unit tF

Above unit G is a 1.5-2.0 m thick till, unit tF, in places boulder-rich, which fingers into the underlying sand and gravel towards east-northeast in the north-easternmost part of the locality area. The till is grey, sandy and moderately compacted, and interpreted mainly as a basal till which in places grades into flow-till (debris flow) and 'deformation' till (Fig.10). Stone-counts indicate bedrock sources in the southwest, and fabrics indicate an ice flow towards east-northeast, as also implied by glaciotectonic injections in the underlying unit.

Unit E

The overlying unit E comprises sand and gravel (Fig.10). This unit is up to 6.0 m thick and consists of mainly planar and some cross-bedded sand with a few very thin gravel horizons. Sporadic occurrences of outsized boulders have been recorded. Unit E is assumed to represent glaciofluvial delta slope sediments deposited during an ice retreat phase; and channels were cut into the underlying till tF in places during this event.

Units tA, tB, tC and tD

Above unit E is a 3.5-4.5 thick succession comprising three or four grey-coloured till beds, units tD, tC, tB and tA (Figs.10 and 12; see also Appendix, Fig.51), described by Olsen & Hamborg (1983, 1984) and Olsen (1988). The provenances of these tills may be found somewhere in the quadrant SSE - SW, as suggested by stone-counts and fabric analyses. Between tills tC and tD there is, in places, a glaciotectonised 20-30 cm thick sand horizon (Figs.12 &

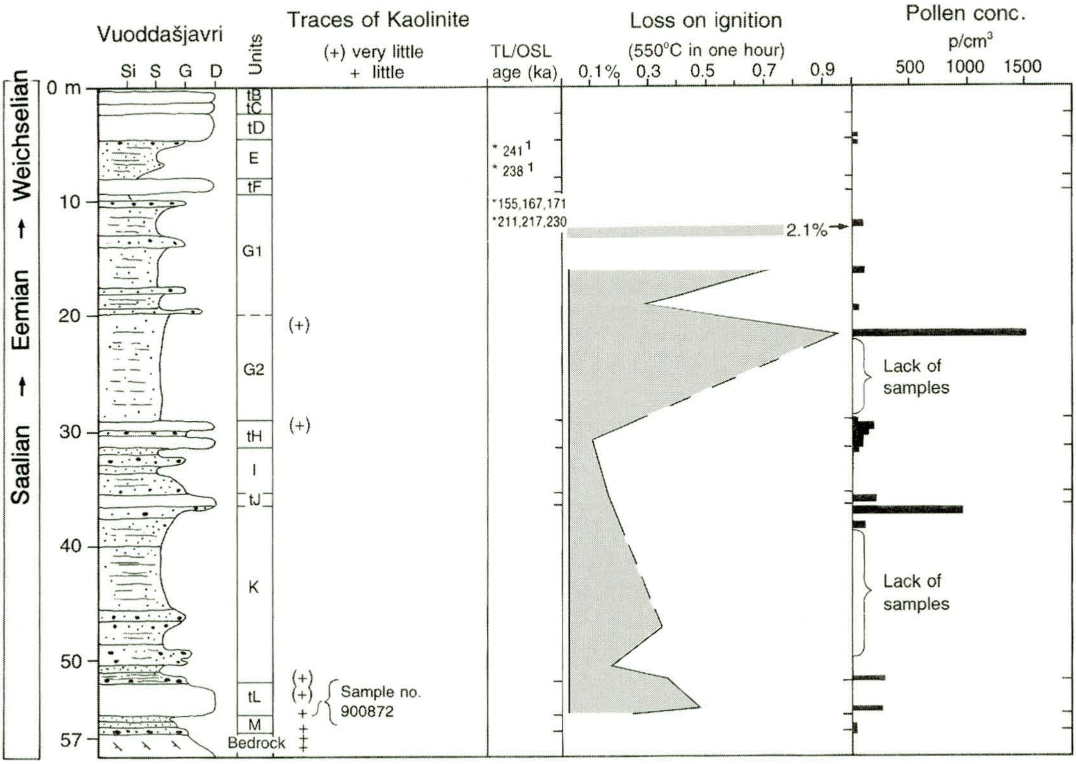


Fig. 14. Traces of kaolinite, TL/OSL dates, pollen-concentrations and loss-on-ignition (maximum organic content) in selected levels at Vuoddasjavri. Sample positions and reference numbers for the TL dates are indicated in Fig.10. [1] Date of reworked material.

13) that is thought to represent the beginning of the Middle or Middle to Early Weichselian Sargejohka Interstadial (Olsen 1988). Unit tD represents the Vuoddasjavri Till, while the overlying glacial deposits represent the Kautokeino Till.

Interpretation and conclusions. The Vuoddasjavri stratigraphy encompasses tills from at least three major Weichselian stadials separated by ice-free periods represented mainly by glaciofluvial gravel and sand. Ice-free conditions with some pedogenic activity at certain levels are normally expected to give a downward enrichment of mobile elements such as Ca, Na, K and Si, due to leaching (Fig.15). Although the sampling density is low in this case, several leaching horizons may possibly be recognised from the distribution of Ca, Na and K. However, the vertical distribution of Si varies often in the opposite direction to the other elements, which may indicate little overall correlation between Si%-changes and pedogenic activity. This is supported by a generally close correlation between Si% and vertical rock distribution of the gravel fraction, except in the upper part of unit K (Figs.8 & 15). The frequent opposite trend of Si distribution as compared with the trends of the other elements indicates that also Ca, Na and K may at least partly be more dependent on the parent rocks than on later weathering. This should be taken as a warning to be more cautious and not to use the elemental distribution uncritically in trying to prove pedogenic activity.

The age assumptions are supported by some TL and OSL dates, although most of the dates suggest reworking and redeposition of sediments from substrate positions (Fig.14, and Table 2.1: 23 analyses of 5 main samples from the Vuoddasjavri sediments). Underlying the Weichselian glacial deposits are beds of gravel and sand alternating with tills. These include three tills of probable Saalian age (Warthe and Dren-

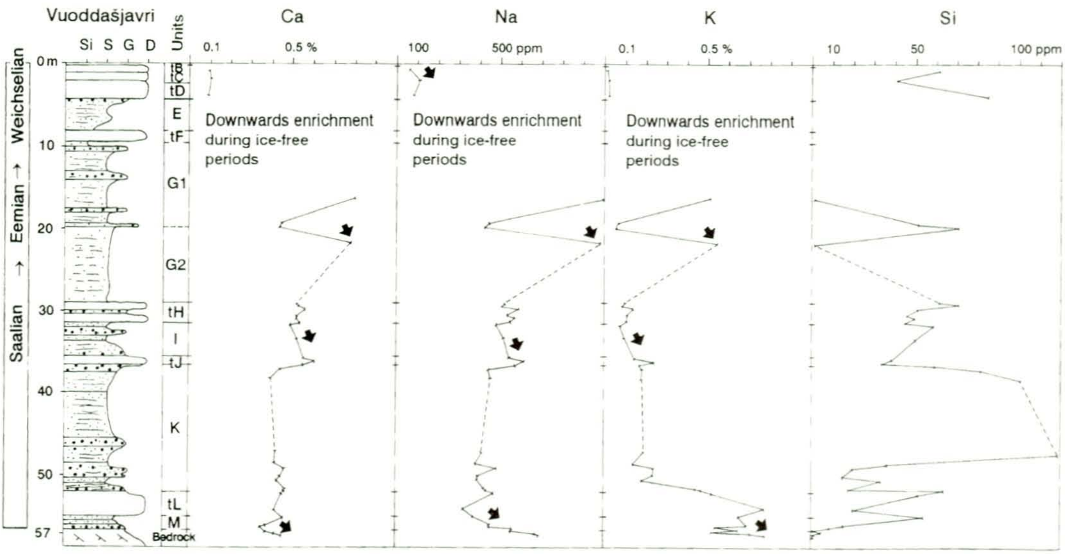


Fig. 15. Selected geochemical data from the Vuoddasjavri stratigraphy. Note the downward enrichment of Ca, Na, and K: i) in the uppermost part of unit G2, ii) in unit I and further into unit tJ, and iii) in unit M with continuation into slightly weathered bedrock. Note also that Si decreases towards the top of unit K despite the corresponding slightly increasing amount of Si-rich rocks in the gravels of unit K (conf. Fig.8). Note and compare also changes from grey to brownish colours as indicated in Fig.8 (left; vertical text).

the?), and waterlain sediments from four pre-Weichselian interglacial and/or interstadial periods.

The provenances of the Weichselian and the pre-Weichselian tills are different. It seems that the bedrock sources for the pre-Weichselian tills are most likely to be found mainly in the south and southeast (Fig.8), while the younger tills contain rock material derived from the south and southwest. One exception to this trend may be the till tC where at least fabric analyses and local transport indicate a more south-southeasterly origin for this particular till (Olsen 1988).

Till tC is correlated with the Weichsel maximum stage, with an ice-divide or domal area situated in Finland somewhere south-southeast of Finnmarksvidda. From these data it is inferred that the pre-Weichselian tills and the Middle to Late Weichselian till tC at Vuoddasjavri mainly represent major glaciations with ice domes or ice divides located far inland. They are therefore indicating truly Fennoscandian ice-sheets in contrast to the Scandinavian ice-sheets that characterised the Early and Middle Weichselian glaciations.

Subunit G1 represents the upper part of Sand E as described by Olsen (1988). However, the revised interpretation of this unit does not accord with the correlation with the Eiravarri interstadial as suggested by Olsen (1988). Unit G as a whole is now thought to represent either parts of or the entire period including the Warthe (late Saale) deglaciation, the last interglacial, and the beginning of the Weichsel glaciation in this area, as suggested by TL and OSL dates from subunit G1 (Fig.14).

Olsen & Hamborg (1983, 1984) correlated the associated ice-free period, unit E, with the Early Weichselian Eiravarri interstadial, while Olsen (1988) named the same unit DD1 and tended to believe that these sediments were deposited during a short ice-retreat and a subsequent advance of the glacier. A lack of associated organic deposits makes it difficult to decide whether unit E represents a part of a full interstadial or only a limited oscillation event. Both possibilities should therefore be considered when discussing the stratigraphy of this area.

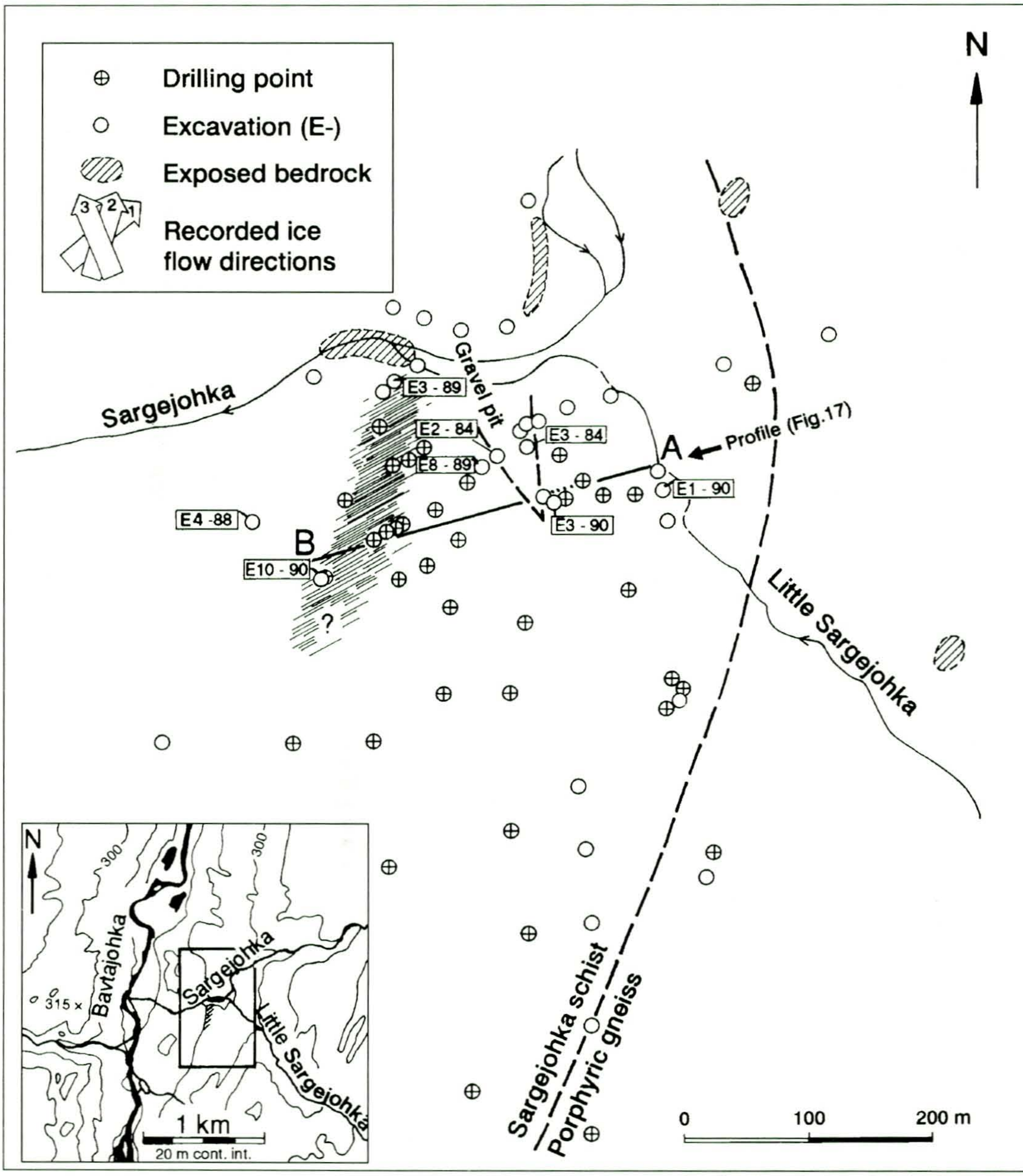


Fig. 16. Map of the Sargejohka locality (6) area with studied sections and drilling points indicated. The minimum areal extension of the buried Bavtajohka Interglacial beds is shaded. The map area is framed in the small-scale map (lower left) where also the Bavtajohka and Sargejohka rivers are indicated; see also framed area of the key map in Fig.1.

Sargejohka (6)

During the course of gold exploration, the 'Sargejohka placer gold field' was mapped by both geophysical and geological methods (Often et al. 1990; and Fig.16). A composite stratigraphy in a profile of 275 m length based on data from excavations and drillings, indicates the presence of at least 5 till units separated by waterlain sediments

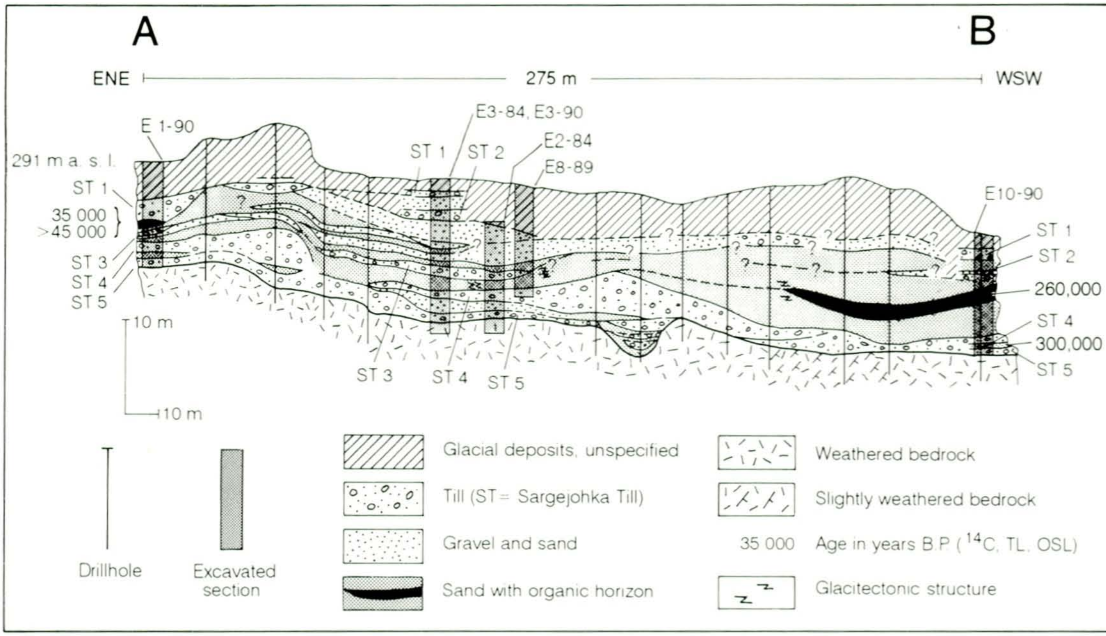


Fig. 17. Composite stratigrapny along one of several profiles through the drift deposits in the Sargejohka area. The profile line is indicated in Fig.16. ST1 - ST5 are described as tB, tD, tF, tH and tJ everywhere else in this article (e.g. Fig. 21).

(Fig.17). The waterlain sediments are mainly glaciofluvial sand and gravel, but the stratigraphy also includes fluvial and fluviolacustrine sediments (Figs.18A and 19). Several paleosols present in the Sargejohka stratigraphy are successively illustrated and briefly mentioned in the following text (Table 8). A more thorough description of the paleosols will be presented in a coming paper (Olsen, in prep.).

Description. The bedrock below the Quaternary drift deposits at Sargejohka is strongly and deeply weathered, in places to at least 30-35 m below the bedrock - drift interface. This is known from drillings and refraction seismic measurements. Kaolinite, a typical clay mineral derived from the weathering of K-feldspar, is present in the weathered bedrock and also in reworked weathered material in the tills (Figs.18B,C).

Unit K

The oldest Quaternary deposit at Sargejohka is a partly tillised gravel bed, unit K, which is resting directly on bedrock. It is less than 0.5 m thick and it was recorded in a c. 15 m deep excavation in 1990 (Fig.20). The petrography of the gravel indicates only c. 10 % of local rocks, and a relatively low clast roundness with slightly more edge-rounded than rounded clasts. The clast rock content and the roundness suggest a relationship to the overlying till, the Sargejohka till tJ (Fig.21). The gravel may be proglacial glaciofluvial outwash from the same glacier that deposited the overlying till, and the age of this glacial event is at least 250-300 ka, as indicated by the TL/OSL dates of younger events in overlying stratigraphies. However, traces of pedogenic activity (p6(?) in Fig.21) are recognised in unit K, and this may have occurred before deposition of the subsequent till (Table 8). If this was the case, then at least parts of unit K are significantly older than till tJ.

Unit tJ

This unit is a fine-grained, compact, lodgement till that normally rests directly on weathered bedrock in the Sargejohka area. The colour of the till is mostly brownish-grey to greenish-grey, with some parts clearly affected by a high content of reddish coloured granites and granite-gneisses. The thickness of the till is generally less than 1.0 m, but a maximum of c. 1.5 m has been recor-

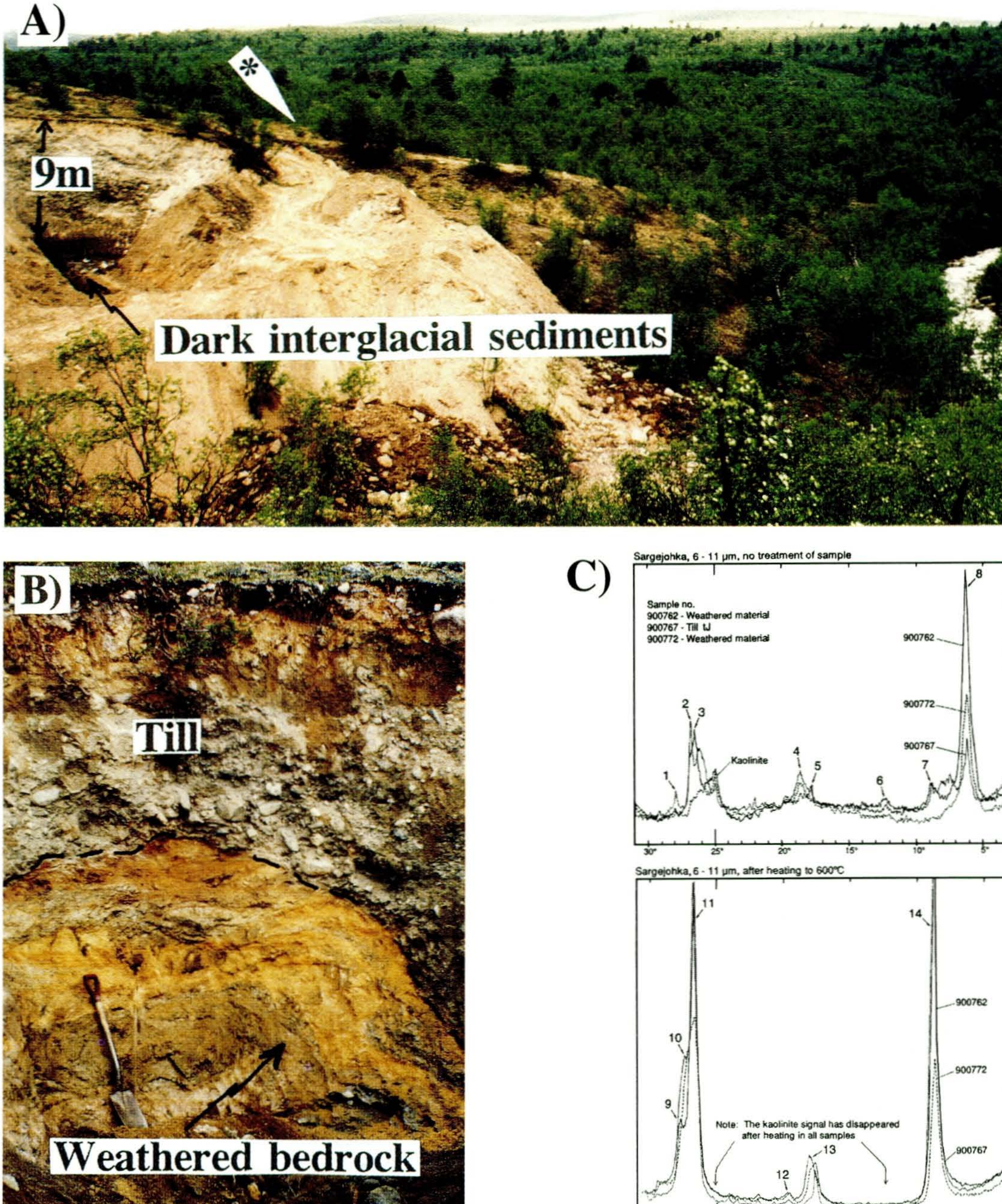


Fig. 18. A) Photo of excavation 3-89 in the complex terrace of glacial and waterlain deposits at Sargejohka. The Bavtajohka interglacial beds appear as a dark-coloured zone about 10 m below ground surface in the section to the left in the photo; B) Photo of weathered bedrock (saprolite) below eroded glacial deposits at the base of the slope of the terrace in the central background of Fig.18A (see asterisk; and E4-88 in Fig.16); and C) XRD data; examples of distribution of clay minerals in tills and weathered bedrock at Sargejohka. The weathering mineral kaolinite occurs in most samples of old glacial deposits from this area. The XRD curves give the following distribution of minerals: Vermiculite/Smectite >> Mica (Muscovite) ≈ Kaolinite = at least 5-10 % > Plagioclase > Quartz, Amphibol, and other minerals. Peaks 1 & 9 = Plag.; 2 & 12 = Quartz; 3, 5, 7, 11, 13 & 14 = Mica; 4 & 8 = Vermiculite/Smectite; 6 = Kaolinite; and 10 = K-fsp.

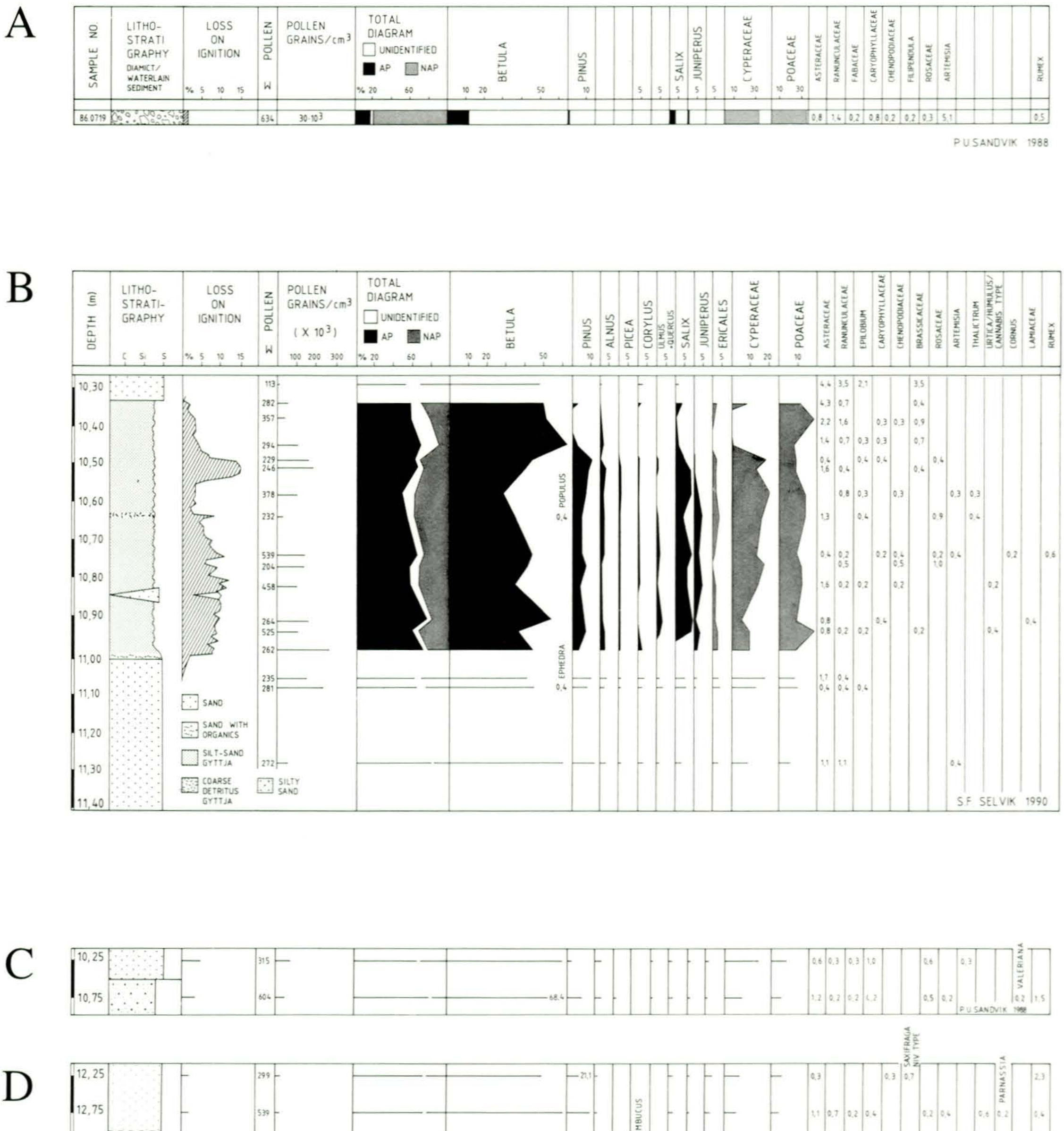


Fig. 19. Pollen diagram representing the Sargejohka Interstadial (A) and the Bavtajohka Interglacial (B,C,D) from gyttja and gyttja silt at Sargejohka. Mainly after Olsen & Selvik 1990. Note: different depth scales in B, C and D. Low frequencies of spores from *Sphagnum* (white mosses), *Selaginella*, *Lycopodium annotinum*, *L. clavatum*, *Huperzia selago* (clubmosses), *Pteridium* and other Polypodiaceae (ferns) were also registered. In addition, the algae *Pediastrum*, *Botryococcus* and some *Scenedesmus*, and scattered pollen grains from *Potamogeton* (pondweeds) were present in the gyttja layer (B, C, D). The location of the samples are: A) from excavation 1-90 (Figs.16 & 24A); B) from a core c. 40-50 m south of excavation 3-89 (Fig.16); C) from a drilling 1 m from the core in B; and D) from a drilling c. 120 m south of the core in B.

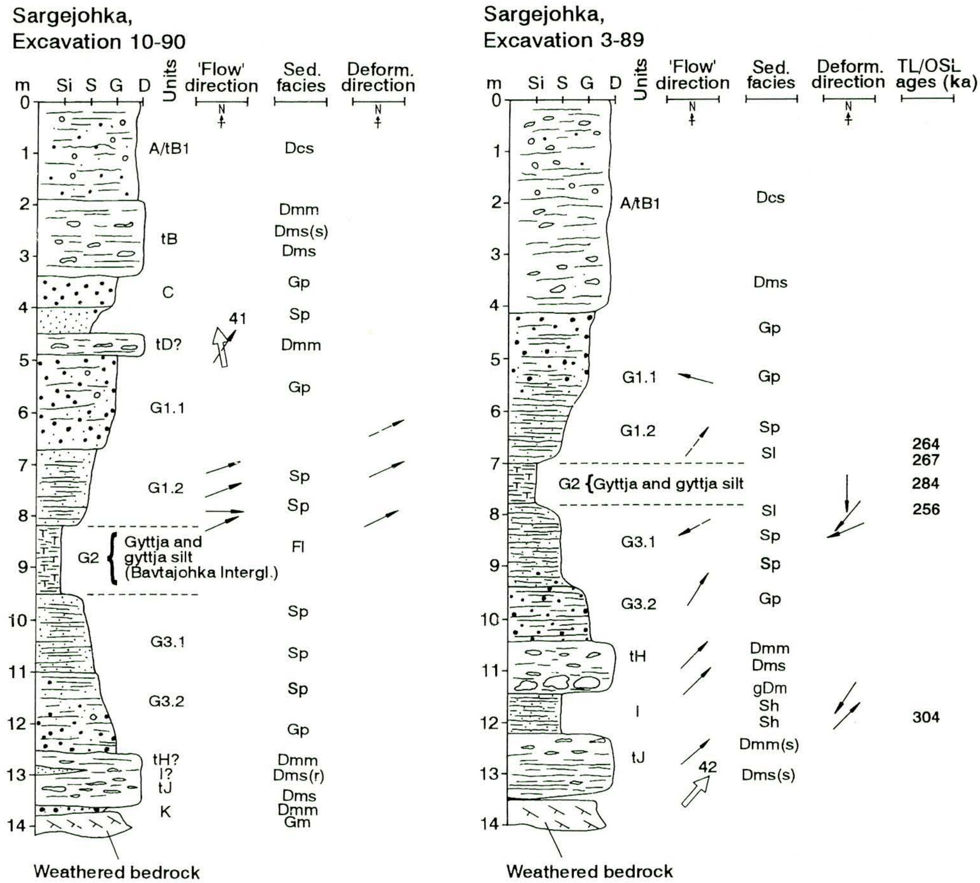


Fig. 20. Simplified logs from main sections in excavations 3-89 and 10-90 at Sargejohka. The maximum thickness of the interglacial gyttja (G2) in excavation 10-90 was measured to 1.6 m, but a mean of 1.3 m is indicated in the log.

ded. The lower part of the till is mainly derived from the local weathered bedrock. The middle and major part of the till had provenance areas located farther away in the south and southwest, while the uppermost part of the till has significant contributions of material with sources in the south and southeast sector.

Between the middle and the upper parts of the till there are lenses or bands of sand in a zone which is up to 0.3 m thick (subunit J2). This zone may indicate a temporary ice-retreat phase within the till tJ - glaciation. Clast fabrics indicate ice movements towards the ENE-NE in the lower part of till tJ and towards the NNW-N in the upper part of this till (Fig.21).

A c. 0.3m thick, dark-coloured, slightly humus-enriched horizon (paleosol p5; Table 8), indicating subsequent pedogenic illuvial processes, is recorded in the uppermost part of the till in the main section of excavation 3-84 (Figs.17,21; and Olsen 1984).

The till is not recorded outside 'the Sargejohka field', except possibly at some localities in adjacent areas on eastern Finnmarksvidda (Olsen, *in press*).

Unit I

This unit is intercalated between tills tJ and tH. In section 3-89 (E3-89; Fig.20) the unit is mainly a sand deposit, while in section 3-84 (E3-84; Figs.16,17 and 21) it is dominated by gravels and pebbles. Unit I is regarded as a coarsening-upward succession, but the coarsest material with pebbles, cobbles and boulders related to the sand in section 3-89 is reworked and redeposited in

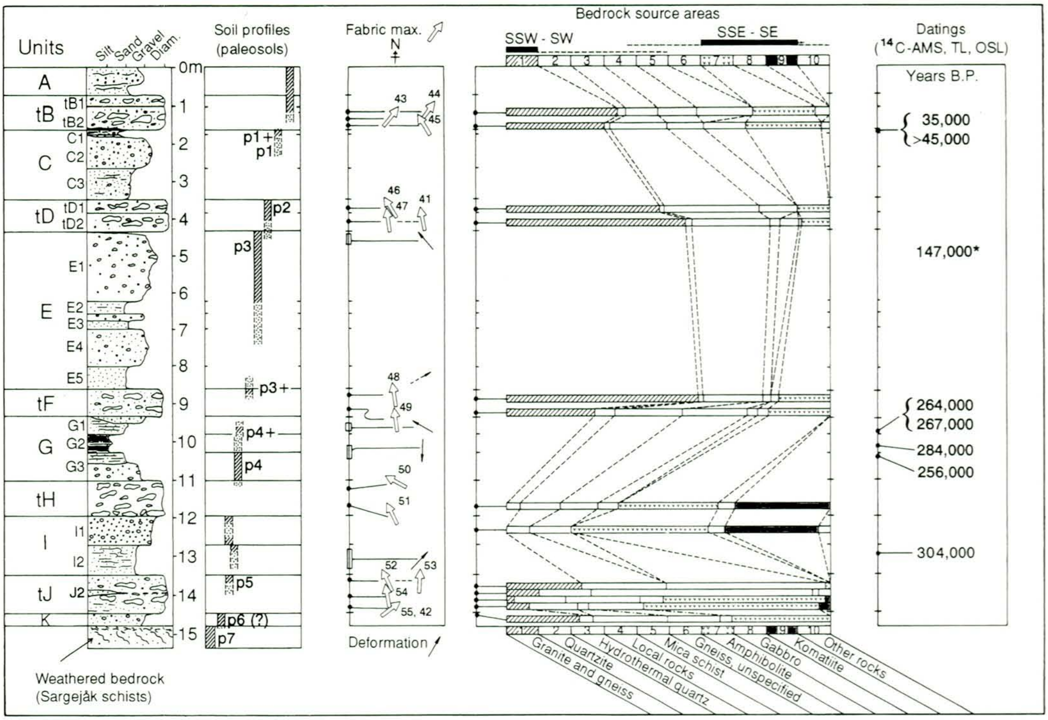


Fig. 21. Generalised stratigraphy at Sargejohka with paleosols recorded in different sections separated only some few metres from each other (see also Table 8). The hatching with cross-lines indicates the most distinct and intensively developed pedogenetic zones, the dots indicate less distinct traces of pedogenetic activity. Some clast fabrics (numbers refer to Schmidt's net contour diagrams in the Appendix), and rock distribution (added to 100%) of the gravel size fraction are also indicated. TL, OSL and ^{14}C-AMS dates are included in the last column.
147,000* - indicates a TL-date of the inferred B-horizon of paleosol p3 which in this case has been developed in the G-unit, in a location where this unit was exposed by river channel erosion during or shortly after deposition of unit E.

the lower part of the overlying till (Fig.20). This follows from the rock distribution, roundness, sorting and location directly overlying the sand of the clasts. The parent rocks of this sand and gravel unit are clearly bipartite, with clasts coming from the southeast in section 3-84 and from the south and southwest in section 3-89.

The southwestern provenance and flow direction of this unit in section 3-89 indicate deposition in a former channel of the Bavtajohka river (Fig.16). However, the relatively high location above the valley bottom suggests a glaciofluvial rather than a fluvial environment.

TL and OSL dating of a sample from this unit has given ages of 196 ± 20 ka and 304 ± 25 ka, respectively (corrected ages; R-913803, Table 2.1). The corrected average age is 250 ± 25 ka.

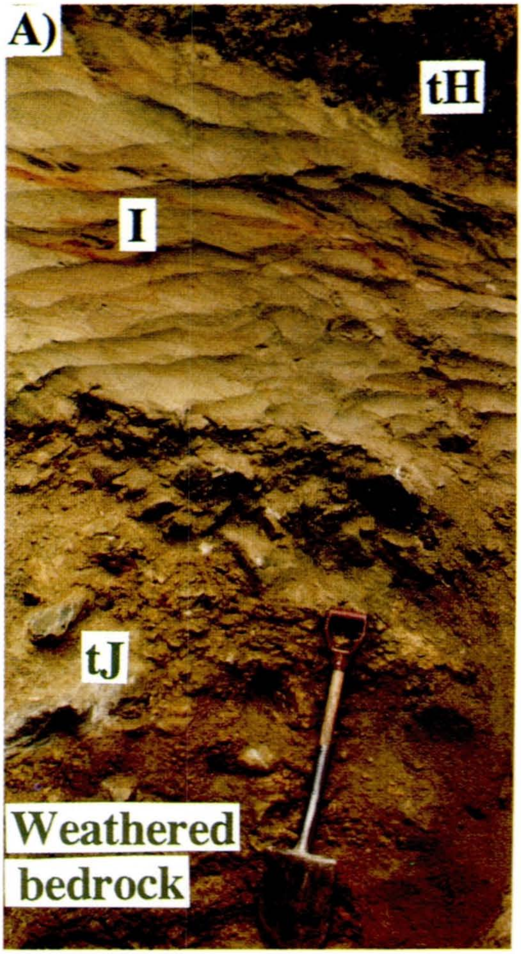
Traces of pedogenetic activity (oxidation, illuviation) are recorded in this unit (Fig.21), but it is not clear whether this is connected with younger events or if the traces represent the uppermost remnants of paleosol p5.

Unit tH

The unit tH is a fine-grained, very compact, lodgement till with parent rocks located mainly in the southeast, as indicated by clast fabrics which imply ice movements mainly towards the northwest. An ice movement prior to or during the initial stages of the till tH event was directed towards the northeast, as suggested by glaciotectonic structures in the underlying sand (Figs.20-22A,B). The amount of local rocks in the till is usually not more than c. 10-15 %. The colour of the till is mainly brown to brow-

TABLE 8. Recorded buried paleosols occurring in the stratigraphy at Sargejohka, Finnmark, Northern Norway. The denotation p1 means paleosol no.1 counted from the present surface soil and downwards. The Tertiary paleosol is named p7, thus meaning paleosol no.7, and as the postglacial soil is not a paleosol, it has no denotation in this system. The + -sign added to some of the paleosol-nos. indicate uncertainty with regard to whether the corresponding soil-related occurrences belong to this or a younger, or possibly represent an additional distinct paleosol.

Paleosol no.	Occurrence/description/climatic signal	Documentation
	Postglacial podzol, developed in the uppermost 1m of loose deposits, for example in lithostratigraphic units A and tB	Photos
p1+	Gyttja-bearing material reworked in the basal part of till tB_2, excavation 1-90. The organics are thought to derive from the same period as paleosol p1	Photos and analyses
p1	A_2 (or E_a), B_s; bleached eluvial horizon overlying B_s-horizon, erosional remnant of paleosol in the topmost part of unit C, excavation 3-90. **Climate**: Probably colder than the present, perhaps as in tundra-areas	Photos and analyses
p2	E_a, B_s, C; well-developed inferred soil profile (brunisol?/inceptisol?) in till tD, excavation 3-90. **Climate**: Probably not much different than the present	Photo and analyses
p3	A_h, E_a, B_s, C; well-developed «red-yellow» humo-ferric podzol in the upper part of unit E, Sargejohka gravel pit; and B/C-horizon with extensive in situ weathering, also in unit E, excavation 3-90. A/B -horizon severely cryoturbated. **Climate**: Warm and wet, probably significantly warmer than the present. Final or subsequent change to arctic tundra	Photos and analyses
p3+	B_2 (B_t or B_s); clayey red to reddish brown oxidation or illuvial horizon in the topmost part of till tF, excavation 3-84. Perhaps a deeper horizon developed during the p3-event (or during the p2-event?), for example by so-called lessivage. **Climate**: Uncertain	No photo; only preliminary analyses
p4+	B_2 (or B_s); illuvial iron oxid horizons in sand within unit G, upper part. These horizons have been glaciotectonised during the subsequent ice advance and deposition of till tF. May be part of a separate paleosol between p4 and p3, or a younger part of the p4-pedogenetic phase (?). **Climate**: Uncertain	Photo
p4	A, E_a, B_s, (B_{Ca}?), C; thick soil profile, probably a podzol with the gyttja horizon G2 as A-horizon in the northern end of the sediment basin for unit G. The bleached eluvial horizon (E_a) occur directly below the gyttja bed. The Bs-horizon includes multiple rusty iron oxid horizons in a more than 2m thick zone. Below that follows a c. 2m thick leached and weathered white residual zone (C). The paleosol is also developed as a «red-yellow» soil profile (podzol?) as recorded in adjacent boreholes and sections, but this may be caused by an «overprinting» of the subsequent p3-pedogenetic phase. **Climate**: Uncertain, but may have been at least as warm (and dry) as the present	Photos and analyses
p5	B_2 (or B_s); illuvial horizon of supposed complex iron-organic compounds in the upper 0.3m of till tJ, excavation 3-84. Resembles postglacial soil developed in similar till located some km to the east. **Climate**: Uncertain, but probably warmer than in tundra areas	Analyses which support the observations
p6 (?)	B_2 (or B_s); illuvial horizon with iron/manganese oxid deposition in unit K, reworked in the basal part of till tJ. Alternatively, the replacement of the illuvial zone may have happened by glaciotectonism during deposition of till tH. If so, the p6-zone may have been developed during the p5-phase and is in that case not a separate paleosol	Field observations
p7	B_1-B_2-B_3, C; fine-grained weathered material in the topmost part of weathered bedrock, below Quaternary loose deposits. Kaolinite occurs in different levels, and amounts in places to contents in percentages, for example in excavation 4-88. Highest values in the weathered material overlying weathered bedrock or reworked in the basal part of the oldest till. Weathered zone at least 30-35 m deep in places. Enrichment of both fine- and coarse-grained gold. **Climate**: Warm, mid-latitude taiga or subtrophical to trophical (Tertiary)	Photos and analyses



nish-grey, but zones with greenish-grey colour are also recorded. The thickness of the till varies from 0.5 m to 5.0 m in the profile indicated in Fig.17 (ST4), but a maximum thickness of c. 7 m has been recorded in a nearby borehole (Often et al. 1990, unpublished report). Till tH is thought to be represented at several localities within a c. 8 km radius south and southeast of the Sargejohka area; and it probably also corresponds to till tL at Vuoddasjavri (p. 21).

Unit G

This unit is subdivided into three subunits, G1, G2 and G3, and it represents a sediment succession which is filling a former channel of the Bavtajohka river. It is assumed to involve depositional environments ranging from glaciofluvial, fluvial, lacustrine,

Fig. 22. A) The lowermost section of excavation 3-89 at Sargejohka. The c. 1 m long spade is standing upon the weathered bedrock surface and it is leaning on the oldest till (tJ). Above till tJ follows the c. 1 m thick glaciotectonised sand I. Overlying sand I is till tH. B) Detail from tectonised sand I, with the boundary-zone between the sand and the overlying till (tH) visible in the upper part of the photo. Deformation directed towards the NE (left on photo). Thin silt-bands penetrate the sand through other sedimentary or deformational structures, thus indicating the youngest deformational events connected with this sand. One of these brownish silt bands may be seen trending from right to left in the level at or just above the lense-protection cap in the photo. According to luminescence dating sand I is about 300 ka old.

fluvial, and back to glaciofluvial. Subunit G3 overlies till tH and represents a fining-upward succession starting with gravels at the base and changing to fluvial basin-laminated sand at the top. Subunit G3 continues upwards into a laminated gyttja silt deposit, subunit G2, of maximum 1.6 m thickness (Figs.18A & 20). The dark-coloured pollen and macrofossil-rich body of gyttja silt is c. 30 m wide and more than 200 m in length (Fig.16). Subunit G2 continues upwards into laminated sand with overlying gravels and sands in an overall coarsening-upward sequence (subunit G1). The total maximum thickness of unit G is c. 11 m (Often et al. 1990).

East of the main channel-filling with the gyttja horizon (Fig.17), the correlative unit is also associated with former channels of the Sargejohka river. This has given rise to more diverse sediments and structures than had the whole unit been related only to a pre-existing Bavtajohka river. The precise correlation between sediment facies is therefore not quite so simple in the actual case, although the overall correlation of the entire unit seems reliable based on the closely spaced excavations and drillings (Fig.16; and Often et al. 1990).

The results of preliminary pollen analyses from the gyttja silt (G2) are shown in Figs. 19B, C and D. The diagram indicates 50-70% AP with a dominance of Betula throughout the subunit at the northern end of the basin (Figs.19B & C), while there are high values of Pinus (> 20%) in samples from the central part of the basin (Fig.19D). Samples from the southern end of the basin are available, but have not yet been analysed for pollen.

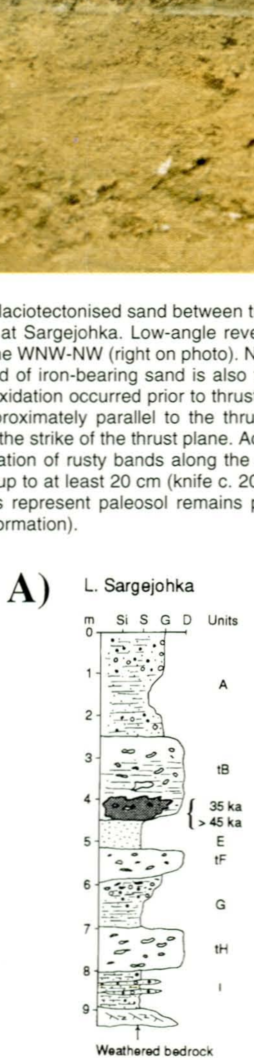
A paleosol with a strongly developed and thick leaching-zone (p4 in Figs. 21, 27 H-J and Table 8) is recognised in subunit G3 in the northern part of the area where the overlying gyttja silt (subunit G2) wedges out. A strong yellow-orange coloured zone in G3 in the southern part of the basin is ascribed to oxidation.

In different parts of the extensive unit G beds at least three different stages of glaciotectonic activity have been recorded, all younger than the gyttja silt horizon or subunit G2. Evidence of the supposed oldest stage of deformation is seen in the central area where folding, reverse faulting and thrusting of rusty horizons (p4+; Table 8) in 0.5-1.0 m thick sand between tills tF and tH indicate an ice movement towards the NW-W. This is an even more 'westerly' direction than that in the overlying till (Figs.21 & 23; and Olsen 1984, unpublished report). The next deformation stage is recorded in the northern part of the area where till tF is missing (section 3-89, Fig.20). There, folding and reverse faulting relate to an ice movement towards the south. This ice movement is thought to be of Early Weichselian age (Olsen 1989b, 1993b), although a Late Saalian age for this event cannot be excluded since it is traced only at the northern end of the gyttja beds (G2) and in the uppermost part of the underlying sediments (G3). The reason why we still think that these glaciotectonic structures may belong to the Weichselian is that only Weichselian tills are found overlying the interglacial beds at the northern end of the sedimentary basin (Fig.20). The youngest deformation stage is recorded in the southwestern part of the area where till tF also is missing, and where the younger till tD(?) rests directly upon deformed subunit G1 sediments (section 10-90, Fig.20). The reverse faulting and thrusting structures in unit G are there considered to be related to an ice movement directed towards the east-northeast. This is much more 'easterly' than the ice movement indicated by clast fabrics and stone-counts in the overlying till which, at least locally, in section 10-90, in fact has a northerly to north-northwesterly preferred clast orientation. There may therefore be a significant time gap between these glacial dynamic events.

Unit tF

This unit is a fine-grained, compact lodgement till. The colour is mostly grey, but zones of brownish-grey and greenish-grey colour are observed (e.g. in section 1-90, Fig.24A). The amount of local rock material is probably slightly greater than in till tH, as indicated by stone-counts (Fig.21), but the major sources of rocks are located more than 2-3 km from this locality in the south and southwestern sector. Fabric analyses indicate ice movements towards the NNW. This signifies a slightly more westward

Fig. 23: Glaciotectonised sand between tills tF and tH from the gravel pit at Sargejohka. Low-angle reverse fault or thrusting towards the WNW-NW (right on photo). Note that the rusty oxidised band of iron-bearing sand is also thrusted, thus indicating that oxidation occurred prior to thrusting. The photo is oriented approximately parallel to the thrusting movement and normal to the strike of the thrust plane. According to the photo, the dislocation of rusty bands along the major thrust plane is therefore up to at least 20 cm (knife c. 20 cm long). The oxidised zones represent paleosol remains p4+ (see Table 8 for further information).



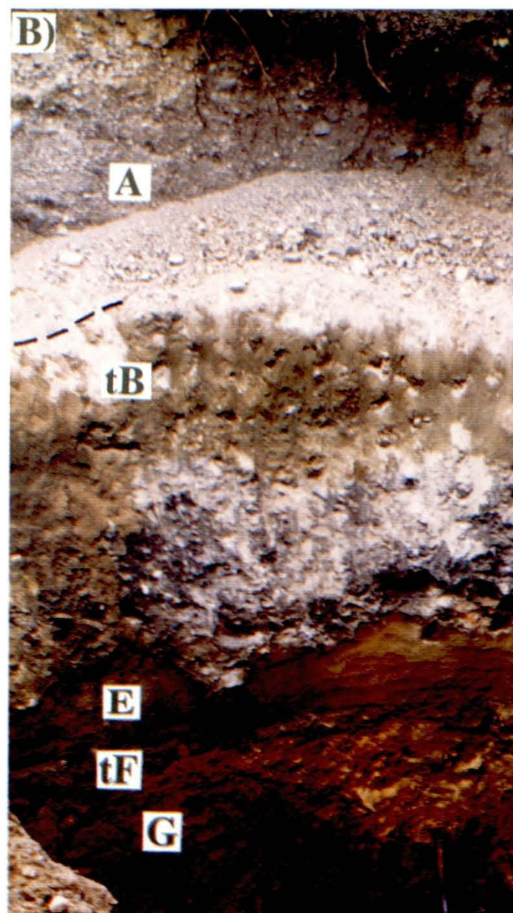


Fig. 24. A) Simplified log and B) photo from the main section of excavation 1-90 at Sargejohka. Note that several stratigraphical units are missing between the dark-coloured organic zone in the middle of the photo and the underlying sand. The part of the section that is included in the photo is indicated on the log.

swing of the ice movement as suggested by the provenances in the S-SSW. An even more westward directed ice movement is apparently related to this glacial event as indicated by glaciotectonic structures in the underlying sand (Figs.23 & 24). The relative age of the deformation compared to that of the till, however, is not precisely known. It may, at least, partly be younger than the till, but a westward directed deformation is not recorded in any of the units younger than G1. Deformation during the initial stages of the till tF event, which has the most comparable directional trend, is therefore more likely. The thickness of the till is 0.3-1.0 m. No till definitely correlative with till tF has been found in any neighbouring locality outside the Sargejohka area. However, we think that correlative tills exist in at least four other localities on Finnmarksvidda (i.e. Vuolgamasjohka, Vuoddasjavri, Gamehisjohka and Buddasnjarga).

A thin, clayey, red to red-brown horizon, which may be a result of younger illuviation through for example lessivage (migration of clay particles) during subsequent pedogenic activity (p3+ in Fig.21 and Table 8), is recognised in the uppermost part of till tF.

Unit E

This unit, which overlies till tF, has an abrupt, erosional lower boundary. The unit consists of three coarsening-upward successions of sand and gravel, and it has an overall upward-coarsening trend (Fig.21). The petrography of the clasts in unit E indicate transport from the south-southwest, probably along a former Bavtajohka river channel. Its location high above the main valley bottom suggests a glaciofluvial origin.

A strongly weathered, easily recognisable paleosol occurs in the uppermost part of unit E (p3 in Figs.21 & 25 and Table 8), and the weathered zone is inferred to represent mainly the B-horizon of a red-yellow soil profile, probably a humo-ferric podzol which is slightly truncated on top. Thus, the humus-enriched A-horizon was mostly, but not entirely eroded and removed during deposition of the overlying till. According to Nortcliff (1984) this kind of soil profile needs a warm and relatively wet climate to develop (Fig.27K). Lenses of a clay layer (subunit E1) representing either a Bt-horizon or the remains of a glaciolacustrine sediment, occur between the diamictic gravelly upper part of unit E and the overlying till (Fig.21). The remains of the clay layer indicate that a process involving transport of clay particles from the A-horizon to the B-horizon may have taken place during the development of the soil profile. This process, which is termed lessivage, is active in subarctic soil development (Tedrow 1963), but also a common process during later stages of brown earth development in more temperate areas (e.g. Nortcliff 1984). However, the thickness of up to 3-4 cm of homogeneous silty clay, and the content of a few specimens of freshwater algae, indicate that the clay lenses most likely derive from glaciolacustrine sediments and not a Bt-horizon. The strong weathering of the clasts (Fig.26) indicates a soil development during a warm climate, probably significantly warmer than today.

Unit E is not only glacially eroded on top, but also glaciotectonically affected. This can be traced through the stretching of some of the weathered clasts in a direction which accords with the subsequent ice movement (Fig.26B). This is also a clear indication of the minimum age of the weathering and of the development of the soil profile (Fig.25A), which thus have to be older than the subsequent till. Another interesting deformation feature is that of a plug or a wedge of the A-Bs horizons consisting mainly of red and black iron and iron-organic complexes, that is 'pressed' at least 70-80 cm downwards into the underlying B-horizon (Figs.25B,C). This feature may be explained either by glaciotectonics or by cryoturbation. We favour the latter and think that it is simply a fossil ice-wedge structure. This interpretation is based partly on its resemblance to previously reported fossil ice-wedges, but more importantly on the location of the wedge structure which is surrounded by characteristic wavy cryoturbation structures (Fig.25A). The age of the cryoturbation is clearly older than unit C because this unit appears to rest undisturbed on unit E in the slope of the central part of the gravel pit where unit tD wedges out. The cryoturbation may also be older than unit tD, but this cannot yet be proven.

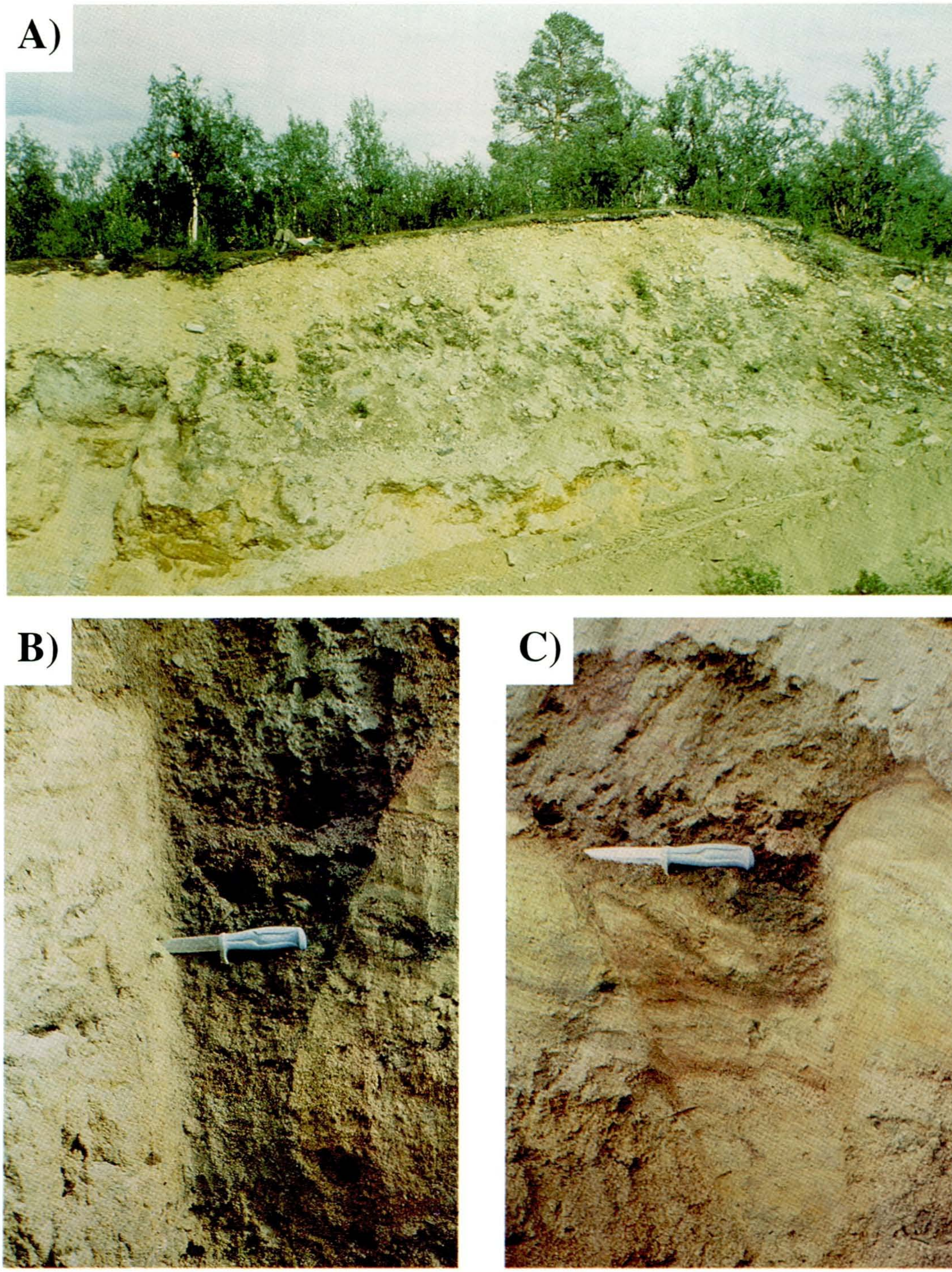


Fig. 25. A) Severely cryoturbated interglacial paleosol (Eemian) at Sargejohka gravel pit (scale: person lying on top of terrace in central part of photo); B) photo of a plug of the A-B horizon which is either glaciotectonically pushed or, more likely, dislocated by cryoturbation downwards into the underlying material, thus representing a kind of ice wedge structure; and C), same as B) but in the opposite direction. Both wedge- or plug-sections are oriented normal to the N-S trending gravel pit wall indicated in Fig. A.

Unit tD

This unit is subdivided into two subunits, tD1 and tD2. The lower subunit tD2 is a compact, sandy, grey to brownish-grey lodgement till. The upper subunit tD1 is a relatively compact, sandy, grey-coloured melt-out till. The latter is probably a till which is derived from a deglaciation period, and it is possibly an ablation till. The relatively compact character may be due to later overloading of sediments and ice-masses. The two tills together probably represent a single glacial stage. Stone-counts in unit tD indicate source rocks located in the south and southwest, while clast fabrics indicate ice movements towards the N-NNW in till tD2, and towards the NNW in till tD1. This means that the ice flow may have been influenced by the Bavtajohka river valley (Fig.16) and turned towards the NNW as it moved over the Sargejohka area. If this was the case, then the associated glacier could not have been very thick as the relief in the area is small. The suggested scenario may, however, have existed during the waxing or waning stages of a much thicker and more extensive glaciation.

A well-developed inferred paleosol is recognised in till tD (p2 in Figs.21 & 27C and Table 8). Although not yet confirmed by specific chemical extraction analyses, as defined for example by FAO (1988), this profile is thought to represent a kind of soil belonging to the inceptisols, according to the soil classification system used in the U.S.A. (Soil Survey Staff 1975, 1992). It may also belong to the brunisolic order, according to the soil classification system used in Canada (Canada Soil Survey Committee, 1978). This soil may have 'overprinted' parts of the paleosol of the underlying unit, thus forming a complex but extremely well-developed soil profile, as for example in the central gravel pit area (Figs.17 & 25). However, the different soil characters (colour and zonation) imply that the paleosols p3 and p2 were developed during different vegetation conditions and climates, and the overprinting is therefore not likely to have been of any major significance.

Unit C

This unit consists of diamictic gravelly sand

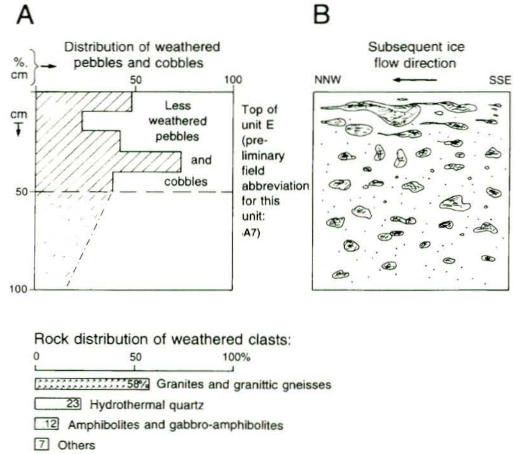


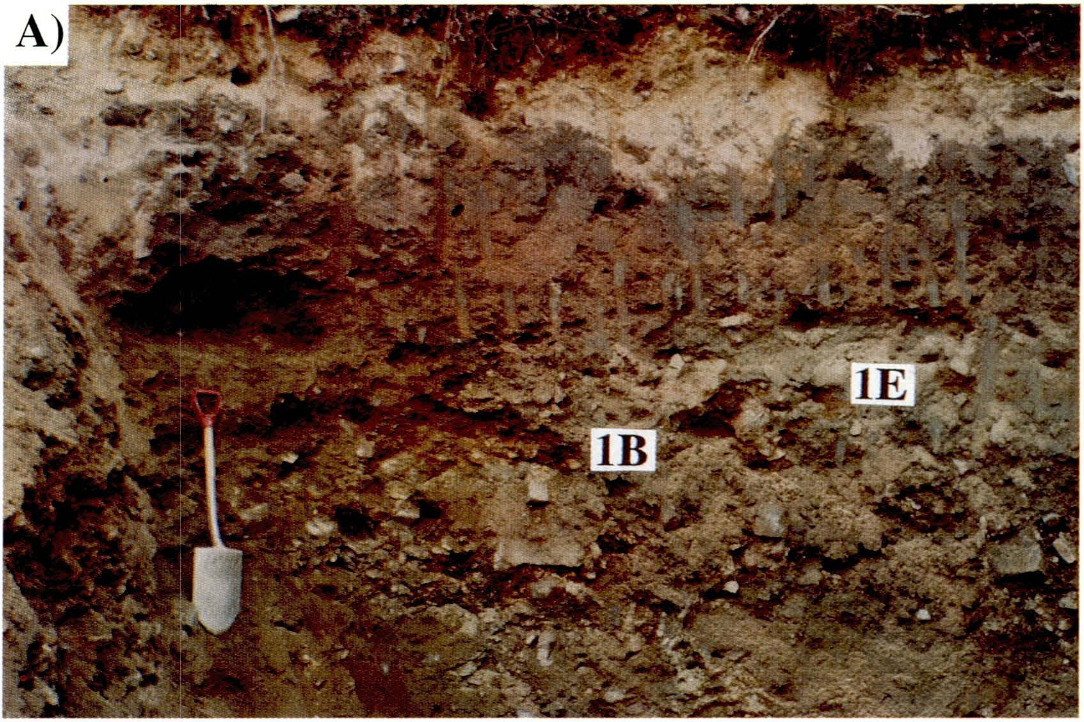
Fig. 26 A) Diagram of distribution of strongly weathered pebbles and cobbles (shaded) in unit E in section 3-90 at Sargejohka; B) Sketch of elongated and smoothly glacially stretched strongly weathered clasts in unit E. The orientation of the section and the associated subsequent ice-flow direction are indicated.

and gravel with pebbles and cobbles in a coarsening-upwards succession (Fig.21). An upper subunit dominated by sand, C1, wedges out between the main part of unit C, subunit C2, and the overlying till. Both subunits are eroded on top. The petrography of the clasts accords with a transport along a pre-existing Bavtajohka river channel, and the high elevation above the main valley bottom suggests a glacial - glaciofluvial environment during deposition. Low clast roundness, with mainly edge-rounded clasts, indicates a very short glaciofluvial transportation for this material. The diamictic character of the main part of unit C may even suggest a partly glacial deposition, perhaps as a melt-out till (gDm-facies, see Table 7).

Remains of the A2/E horizon of a paleosol (p1 in Figs.21 & 27A, see also Fig.27B and Table 8) are recognised in the uppermost part of this unit.

Unit tB

This unit is subdivided into two subunits, tB1 and tB2. Both subunits are tills. The lower till, tB2, is a compact, diffusely 'stratified', grey to brownish-grey basal till. It is


A)
1E
1B


B)


C)
2A
2B

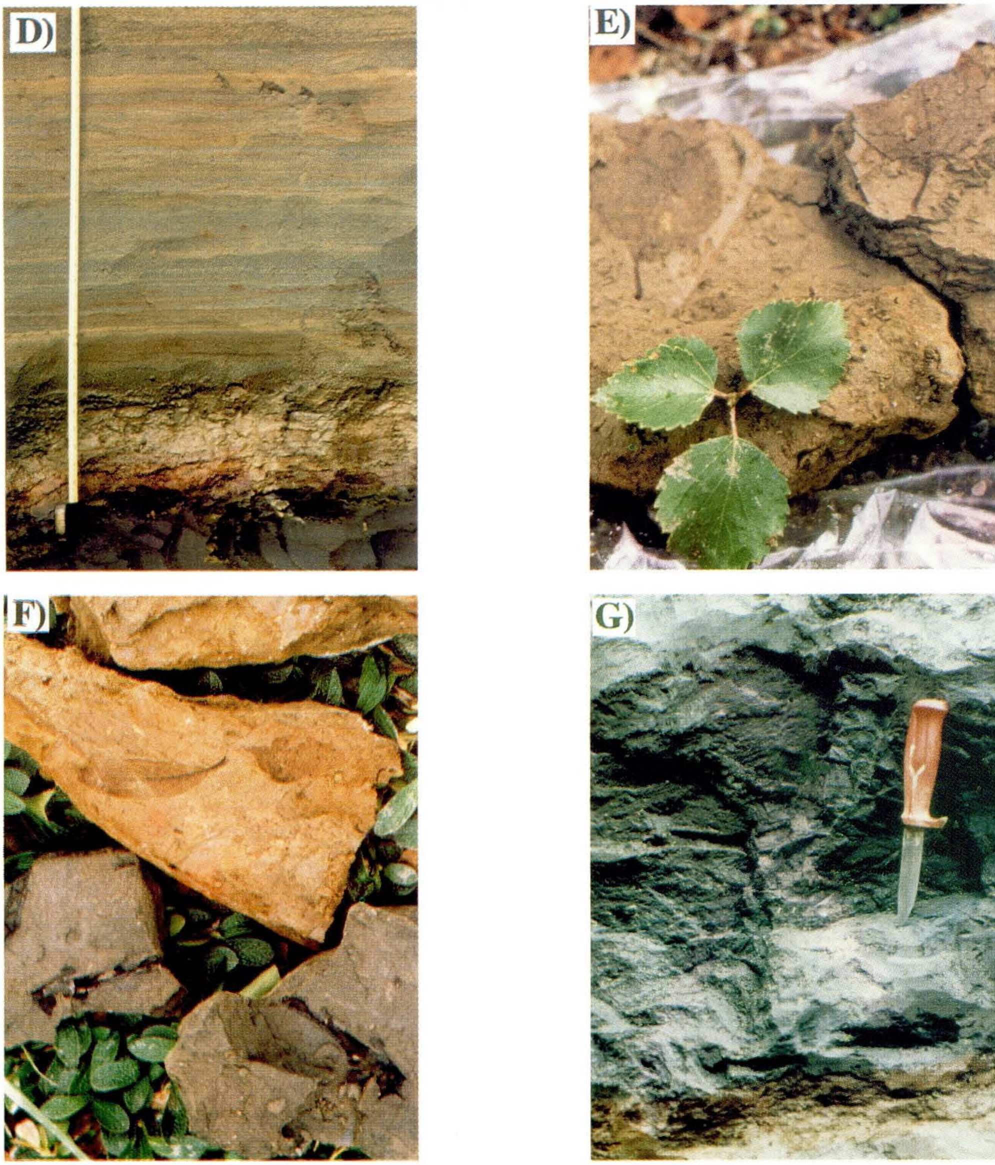
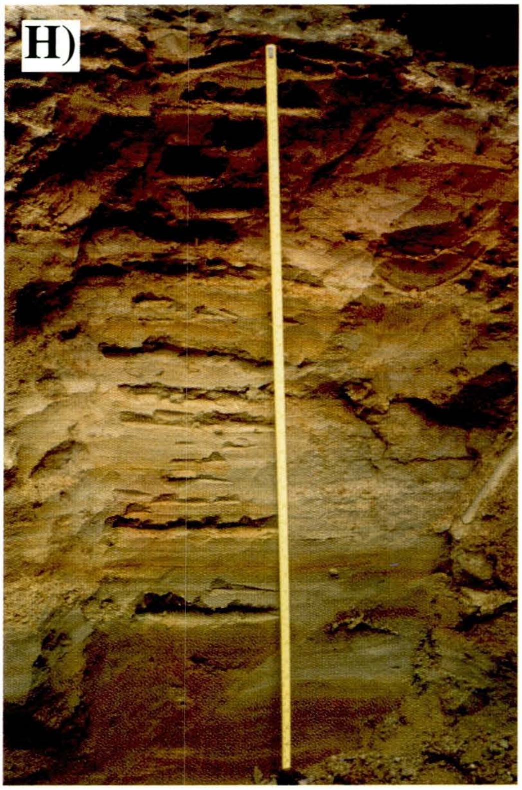
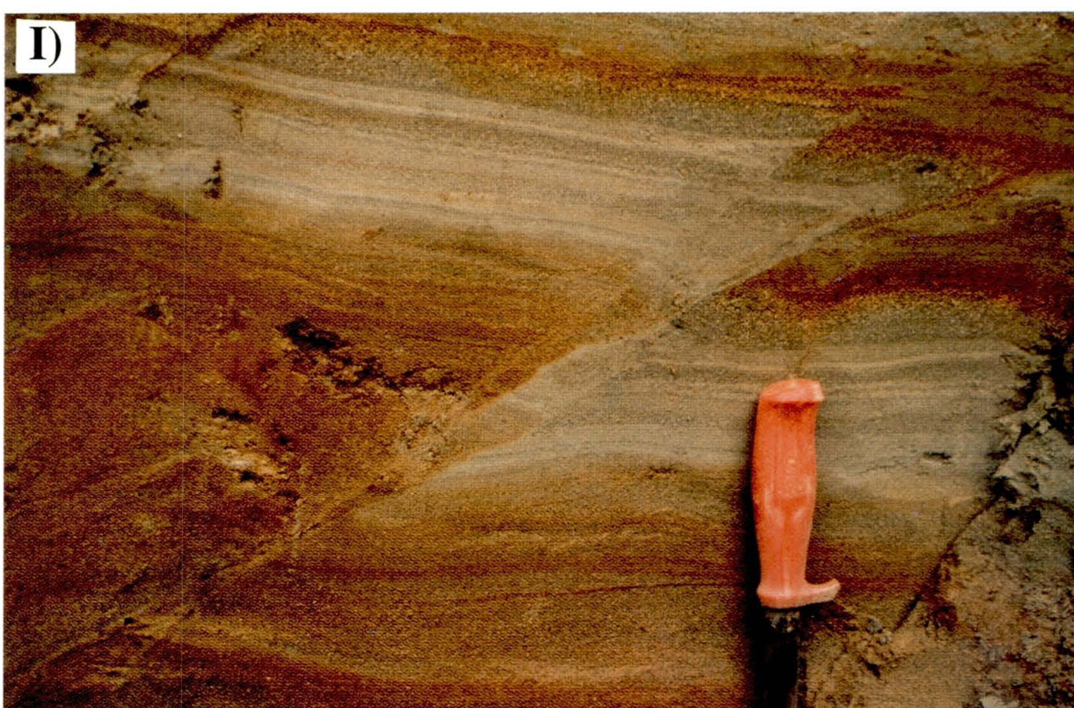


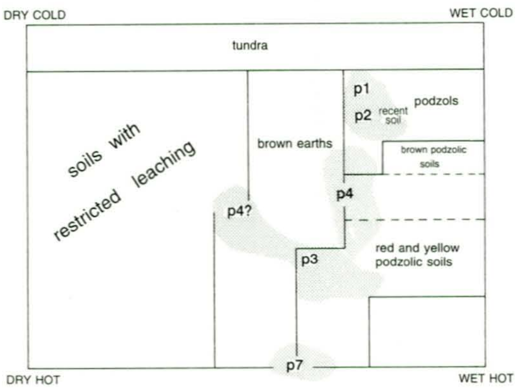
Fig. 27. A) Part of the main section in excavation 3-90 at Sargejohka, with remains of the bleached paleosol p1 visible as a pale grey zone in the middle and right part of the photo. The photographed section includes gravelly diamict C2 with the sandy (and bleached) light grey zone C1 to the right, underlying till tB with gravel and sand (unit A) from the last deglaciation period on top. The postglacial podzol may be recognised in the uppermost 1 m (the spade is c. 1 m long). B) Organic material (intermixed soil A-horizon and gyttja) which is reworked in the basal part of tB2, from section adjacent to excavation 1-90 (see also Fig.24). The organics may also represent paleosol p1, as in Fig.27A (see Table 8 for further information). C) Another section from excavation 3-90, with paleosol p2 visible in the lower part of the photo. The associated organic zone (O-horizon and the uppermost part of the A- horizon) is missing and has probably been eroded during deposition of the overlying sediments. D) Bleaching and oxidation in the laminated sandy and silty sediments overlying the gyttja and gyttja silt deposits representing the Bavtajohka Interglacial. The photo is from the southeastern wall of excavation 3-89, and the topmost part of the gyttja bed is visible in the lowermost part of the photo. The scale is 1.1 m long. E) Sampled slabs of the gyttja beds (G2), with imprints of leaves of tree-birch (*Betula pendula/pubescens*), compared with leaves of a local living tree-birch. F) Sampled slabs of the gyttja deposit, with imprint of leaf of willow (*Salix*). Pieces of deciduous trees (e.g. aspen) have also been reported from these sediments in cores from the middle part of the basin (P.U.Sandvik, pers. comm. 1988). G) Lower part of the gyttja beds overlying sediments where paleosol p4 is developed (see Table 8 for further information). H) Uppermost part of sand G3.1 just below gyttja beds G2. The photo shows a bleached upper zone overlying oxidised and glaciotectonised sand beds. The bleaching and oxidation together with the overlying organic horizon (G2), and the underlying greyish-white pedogenetic horizon (see Fig.27J), represent paleosol p4 (see also Table 8). The scale is 1.1 m long. I) Detail of Fig.27H, with reverse-faulted rusty oxidised zone, and associated deformation movement towards the south (right on photo). J) Lowermost pedogenetic eluvial/illuvial greyish-white zone in the lower part of unit G3, overlying the brown-coloured till tH. The shovel is 1 m long. K) Suggested very tentative positions of the Sargejohka paleosols as outlined in an idealised diagram indicating the relationship between soil and climate (diagram zonation after Nortcliff 1984).


H)


J)


I)

K)



genetically situated somewhere between the lodgement and the melt-out end-members. This till seems to have had a strongly 'erosive' character, for instance as recorded in section 1-90 (Fig.24A). There, the stratigraphical beds corresponding to units C, tD and most of E were removed by erosion during deposition of till tB2. In addition, an up to c. 1 m thick body of dark grey to bluish-grey, organic-bearing diamicton is mixed and redeposited in the basal part of till tB2 (Fig.24B). The organic zone is wedging out, but can be traced over at least 4-5 m in all lateral directions. The aggregate character of this material suggests a more or less bulk deposition. Therefore, if lodgement has been an important process during deposition of till tB2, it cannot have been a grain-by-grain lodgement, but rather a deposition through shearing or thrusting of lenses, sheets and wedges. However, melt-out may equally well explain these structures, and may have been the dominant depositional process. In any case, melt-out has to have been the most important process within the zones of bulk or aggregate character.

The upper part of unit tB, subunit tB1, consists of a grey, relatively loosely compacted, sandy melt-out till. This till was deposited during the last deglaciation; and in places it is overlain by glaciofluvial material (unit A).

Stone-counts in tills tB1 and tB2 indicate provenances in the south-southwest. This does not accord exactly with the clast fabrics in till tB2 (lower part) which indicate an ice flow towards the NNW (Fig.21). The ice movement seems to have been influenced by local features and turned slightly towards the west as it moved across the area, perhaps in a similar manner to that of the till tF ice movement. Clast fabrics in the uppermost part of till tB2, however, and in the basal parts of till tB1 suggest a deposition during ice flow towards the NNE-NE (Fig.21) in accordance with the stone-counts. The latter also accords with the directions of drumlins and the youngest regional striation in the area (Olsen 1989c).

Interpretation. Till tJ, the oldest till at Sargejohka, is overlying deeply weathered bedrock (or in places, gravel K), and it is assumed to have been deposited during a regional ice movement mainly towards the NE, as indicated both by clast fabrics and by stone-counts. In the uppermost part of the till the ice movement turned to a northerly direction, possibly influenced by the local topography. This suggests that till tJ was deposited during an advance and decay stage of a Scandinavian ice-sheet with ice divide - ice dome areas situated in or close to the mountain chain in the southwest.

The overall upward coarsening trend in the sand and gravel unit I between tills tJ and tH may represent a normal river bed deposit. However, the large rounded boulders in the lowermost part of till tH, which is thought to originally derive from unit I, and the location high above the Bavtajohka valley bottom, are very strongly suggestive of a glaciofluvial environment for unit I. In the sections situated in the western part of the area it is possible that this unit is associated with the ice-retreat stage of the till tJ-glacier; in the eastern part of the area, however, it was probably deposited in a proglacial environment connected to the advance of the till tH-glacier. This assumption is based on changes of sediment facies, lithology and resemblance of the petrography of the clasts to those in the overlying and underlying till in the east and the west, respectively. The ice-free period represented by the sediments of unit I may represent either an interstadial or an interglacial. A subglacial deposition or alternatively, a deposition during an oscillation event, is less likely because of the existence of a probable paleosol developed in the uppermost part of the underlying till in section 3-84 (Fig.21; and Olsen 1984).

Rock content and clast fabrics in till tH indicate a provenance in the southeast and ice movements towards the northwest. This applies for most of the till except the lowermost part where the related ice movements may possibly have been north-northeasterly directed, as suggested by deformation structures in the underlying unit (Fig.21). The associated glacier is likely to have been a Fennoscandian ice-sheet with an ice divide - ice dome area situated mainly in the inland part of northern Finland, far east of the mountains. This seems to be in accordance with most Saalian tills at other localities on Finnmarksvidda, for instance till tL at Vuoddasjavri (Fig.8).

Pollen analysis and fossil imprints of leaves of tree-birch *(Betula pendula/ pubescens)* from the organic gyttja silt horizon in unit G indicate interglacial conditions (Olsen 1989a,b, Olsen & Selvik 1990; and Figs.19B-D). The gyttja silt horizon has previously been correlated with the last interglacial, the Eemian (Olsen 1989a,b, Olsen & Selvik 1990, Larsen et al. 1991), but new information acquired in 1990-91 suggested an older age for this interglacial horizon (Olsen 1993b). The new information is, for one thing, dealing with a slightly truncated *in situ* paleosol, where most of the A and B horizons are preserved in the upper part of the gravelly and sandy diamict unit underlying Sargejohka till tD in the middle part of the Sargejohka profile (Figs.21 & 25A), and TL/OSL dates from the gyttja horizon and the adjacent overlying and underlying sediments (Table 2.1: R-893801a,b, R-913801-R-913804). The strongly weathered paleosol was most likely developed during a significantly warmer climate than today. All known postglacial soil profiles in similar deposits in these areas are much less weathered and much thinner than the Sargejohka paleosol. The youngest period when this paleosol could have been developed is therefore the last interglacial, when the climate during its maximum was warmer than the present. The thick and extensive gyttja horizon must then be even older than the Eemian because there are two sequences of waterlain sediments and one till bed between the gyttja and the overlying interglacial paleosol (Figs.17 & 21). TL and OSL dates of more than 200 ka for the gyttja and the related sediments support this conclusion, and the associated pre-Eemian interglacial has been named **Bavtajohka Interglacial** (Olsen 1993b).

TL dating of the strongly oxidised and glaciotectonised sand subjacent to the gyttja horizon (G2) has yielded two significantly different ages. One date gives an age of 256 ± 25 ka (R-913802a, corrected; Table 2.1) which accords with the other dates of more than 200 ka for the gyttja horizon. The second date gives an age of 147 ± 15 ka (R-913802b, corrected age; Table 2.2) which is significantly lower than all the other dates for the G-unit. The zeroing of this sample is very good as indicated by the extremely low residual dose at only 2% (Table 4). Based on the strong indications of a pre-Eemian age of the gyttja horizon, as argued above, we suggest that the low age and the almost complete zeroing of sample R-913802b may be a result of the strong oxidation and/or the subsequent glaciotectonic deformation. Both these events are significantly younger than the gyttja horizon, and both are expected to have had the ability to reduce previously stored radiation. A similar result and explanation has been mentioned before (see p. 19; Vuolgamasjohka), but more examples of this are necessary before any proper conclusion can be reached about these factors as possible secondary, but significant zeroing mechanisms.

A till related to the east-northeasterly directed ice movement, as indicated by the newly recorded glaciotectonic structures in subunit G1 in section 10-90 (Fig.20), may be lacking in this area. Tills related to such ice movement directions, though, are well represented in adjacent areas (Olsen 1993b, *in press*). Ice movements towards the east-northeast are thought to have occurred in both the first and the second Weichselian major stadials, and the overlying till (tD?) with the associated more northerly ice flow direction may belong to younger stages of either of these stadials.

Another consequence of the new data is that the supposed hiatus between Sargejohka till tB and the underlying deposits, as suggested by the present senior author in Larsen et al. (1991), may be even more complex than thought previously. According to the new data and interpretation the Sargejohka till tD may be the first Weichselian till at this site. As the tills from the first and the second major stadials during the Weichselian in places resemble each other lithologically (Olsen 1988), it is not easy to determine with certainty which one is represented by the Sargejohka till tD. It is therefore not definitely clear if the Eiravarri interstadial postdates or predates this till. However, clast fabrics and stonecounts in till tD favour an age correlation with the first Weichselian stadial, and this suggests a younger 'position' for the Eiravarri interstadial. This is also in accordance with the strongly erosive character of Sargejohka till tB2, as seen in the eastern end of the profile (Fig.17) where the entire till tD has been removed by erosion. Thus, the till that normally dominates the surficial deposits on Finnmarksvidda (Olsen 1988), and which is thought to represent the second Weichselian glaciation, may apparently be lacking here.

On the other hand, the strongly weathered character of the paleosol underlying till tD suggests a warm climate during a long icefree interval. If the Eiravarri interstadial predates till tD, then a long warm Eemian - Early Weichselian interval may associate with the paleosol development. If this happened, then a till from the first Weichselian stadial on Finnmarksvidda is not represented at Sargejohka, and it may never have been deposited there. However, we do not favour the latter hypothesis because a well-developed paleosol (brown earth/-inceptisol/brunisol?) also exists in till tD (Fig.27C), which clearly indicates that a relatively warm interstadial (or interglacial) postdates the till tD glacial event. This warm interval most likely existed prior to the Middle Weichselian, and according to the current (Olsen 1993b) early Middle Weichselian age assignment of the second major glacial event, the age of the Sargejohka till tD should be Early Weichselian.

Organic matter in the non-oxidised reworked sediment in the lower part of the youngest till is ^{14}C-AMS dated to about 35 ka (insoluble fraction; Ua-319, Table 1), which suggests that the youngest till is of Late Weichselian age (Olsen 1988). Macro plant remains from the same mixed organic material are ^{14}C-AMS dated to > 45 ka (UtC-1392, Table 1); this suggests either a long duration of the associated Sargejohka interstadial, or it may suggest a multiple origin for the organics, and perhaps a mixture of organics of different ages. However, there is no support for a mixed origin in the pollen content (Fig.19A), although it should be added that the pollen from interstadials with similar climates and vegetation (as assumed for parts of the Eiravarri and the Sargejohka interstadials) would not be easy, if at all possible to separate. Any young contamination of the ^{14}C-dates through groundwater circulation is not supported by the field data, because the samples were taken within compact and fine-grained material well away from possible oxidation fronts, and there were no observations of plant roots or fissilities in the sediments.

Løvlie & Ellingsen (1993) have performed a paleomagnetic investigation of samples from Sargejohka. They concluded that the occurrence of upward-pointing (negative) inclination trends in till tB2 is strong evidence for anomalous paleomagnetic field conditions, tentatively interpreted to indicate the presence of a paleomagnetic excursion. The age estimate of the till (< 35 ka) suggests that this possible excursion should be the Lake Mungo (30-28 ka) excursion. The till may therefore have been deposited prior to the Weichsel maximum advance less than 25 ka ago.

Conclusions. The Sargejohka stratigraphy encompasses glacial and non-glacial events at least back to 300 ka B.P., as indicated by TL and OSL dates, and it also includes a Tertiary or older weathering prehistory.

The two most significant stratigraphic levels from Sargejohka, in the sense of regional correlations, are thought to be the interglacial paleosol (probably of Eemian age) in the upper part of the stratigraphy (in unit E), and a distinct gyttja silt horizon, up to c. 1.6 m thick, 30 m wide and more than 200 m long, interbedded in one of the glaciofluvial - fluvial sequences, unit G. The pollen and macrofossil content of the latter indicate interglacial conditions, and the associated interglacial is named the Bavtajohka interglacial. TL and OSL dates indicate an age of around 250-260 ka for this interglacial.

One of the most striking and important phenomena in the Sargejohka stratigraphy is the existence of the *in situ* remnants of at least 5-7 buried paleosols at different stratigraphical levels in closely spaced sections (Figs.18B, 21, 22, 25 and 27). This makes the Quaternary terrestrial record at Sargejohka unique in Fennoscandia. The glacial erosion must have been minimal in the Sargejohka area, and this may probably best be explained by prevailing cold-based ice conditions during the glacial stages.

In an idealised model the paleosols may be taken as important signals of previous climates. This is indicated by placing the different paleosols very tentatively in a diagram devised by Nortcliff (1984; Fig.27K). To support these ideas, the geographical distribution of, for example, recent 'red-yellow' podzols should be known in detail. This is probably not so, but as far as we know there has never been found or at least never been reported a postglacial podzol of this type in northernmost Norway. However, it should be added that no careful classification of the Sargejohka paleosols has yet been carried out. More efforts should therefore be made in future studies to determine the precise soil types occurring in this stratigraphy before detailed climatic interpretations are worked out.

It may also be noted that one of the commonly thick Gardejohka or Vuoddasjavri tills from western Finnmarksvidda (Olsen 1988), seems to have been either not deposited at all or totally removed by glacial and/or glaciofluvial erosion from the 'Sargejohka placer gold field'. The lithological similarity between these tills, and other non-conclusive data, has not so far permitted a proper decision as to which till may be lacking here. As Sargejohka now appears to be one of the key localities to understand the regional extension of the Early Weichselian tills and glaciations in northernmost Fennoscandia, the age of the Sargejohka till tD has important consequences for revealing the glacial history in this region.

If the till belongs to the first Weichselian glaciation in Finnmark, then this glaciation may have reached even to the coastal areas, as suggested by Olsen (1988, 1989a,b, 1993b). If the till, on the other hand, belongs to the second Weichselian glaciation, then the ice margin for the first Weichselian glaciation may have ended somewhere on Finnmarksvidda, for example between the Vuoddasjavri and Sargejohka localities. The latter is clearly a minimum version of this (5d) glaciation, but it may correspond better than the maximum version with a suggested ice margin at Pudasjärvi in Finland (Sutinen 1984) and a location proximal to caves not submerged by Early Weichselian glaciers in Nordland, Northern Norway (Lauritzen 1991).

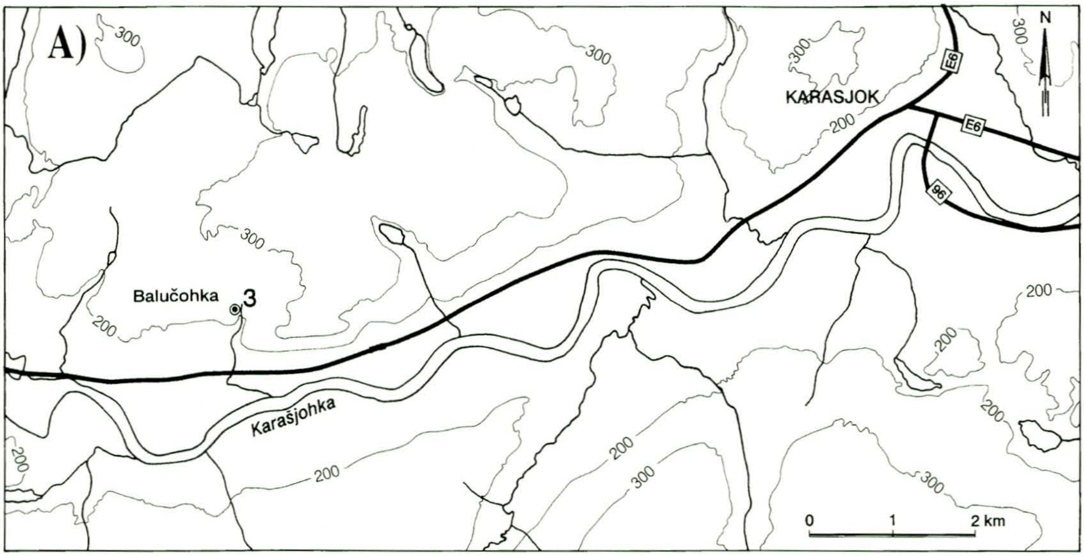
Stratigraphy of other localities

Balučohka (3)

The stratigraphy at Balučohka, c. 9 km west-southwest of Karasjok, involves four different till units tA, tB, tC and tD (Figs. 28A-B), all of them thought to be of Weichselian age. The stratigraphy is known from sections in a c. 5.5 m deep excavation. Pollen has been found in lenses of sand in tills tC and tD (Table 5.1), and based on regional correlation of till tD with the Vuoddasjavri till (Olsen et al. 1990, Olsen *in press*), the pollen and sand-lenses in till tD are thought to derive from reworked Eiravarri interstadial sediments. Such sediments have been found in the vicinity, but their pollen content is unfortunately not known. We refer the pollen and sand-lenses in till tD to the Eiravarri interstadial because there are no observations of older deposits in this area north of the Karasjohka valley (Olsen 1993b, *in press*).

Gamehisjohka (4)

The stratigraphy at Gamehisjohka, close to the border to Finland some 12 km southeast of Karasjok, involves sediments from the last deglaciation, resting on two tills and underlying organic-bearing fluvial sedi-



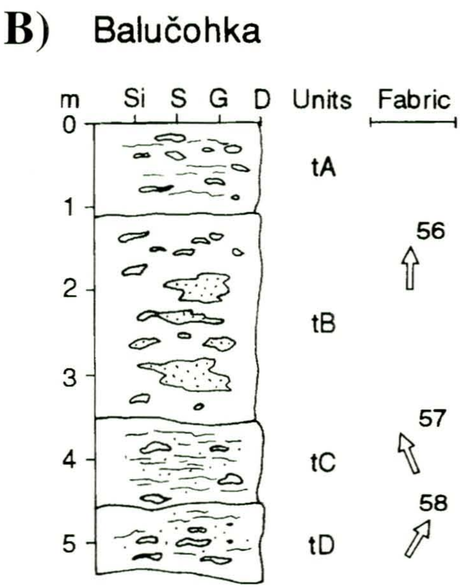


Fig. 28. Location (A) and simplified log (B) of the section at Balučohka. See also Fig.1. Clast fabric numbers refer to analyses shown in the Schmidt's net in the Appendix. Sample no. 870401 is from sand-lenses in till tD (see Table 5.1, p. 12)

ments, which rest on thick fine-grained sediments of supposed lacustrine origin (Figs.29-31). Based on refraction seismic and electrical measurements the total drift thickness is c. 40 m (Mauring & Rønning 1991; Fig.29B). The upper c. 25 m is known from sections and drillings (Figs.30-31).

The upper till tB is mainly of the well known and widely distributed, fine-grained, bluish-grey compact type of till commonly seen in deep inland stratigraphies. Here, it seems to have been deposited mainly during ice flow towards the NNW in the lower parts, as indicated by clast fabrics

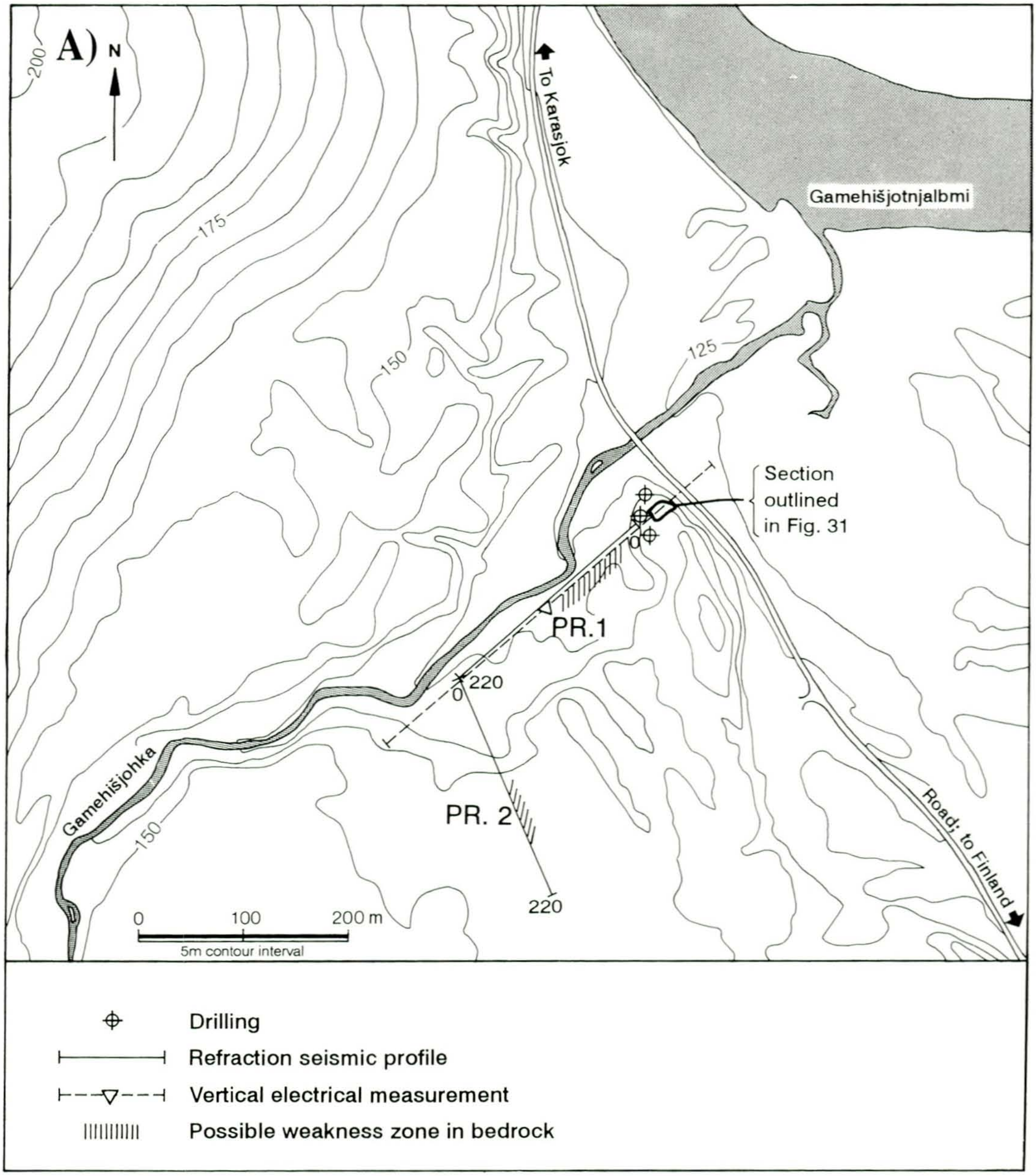
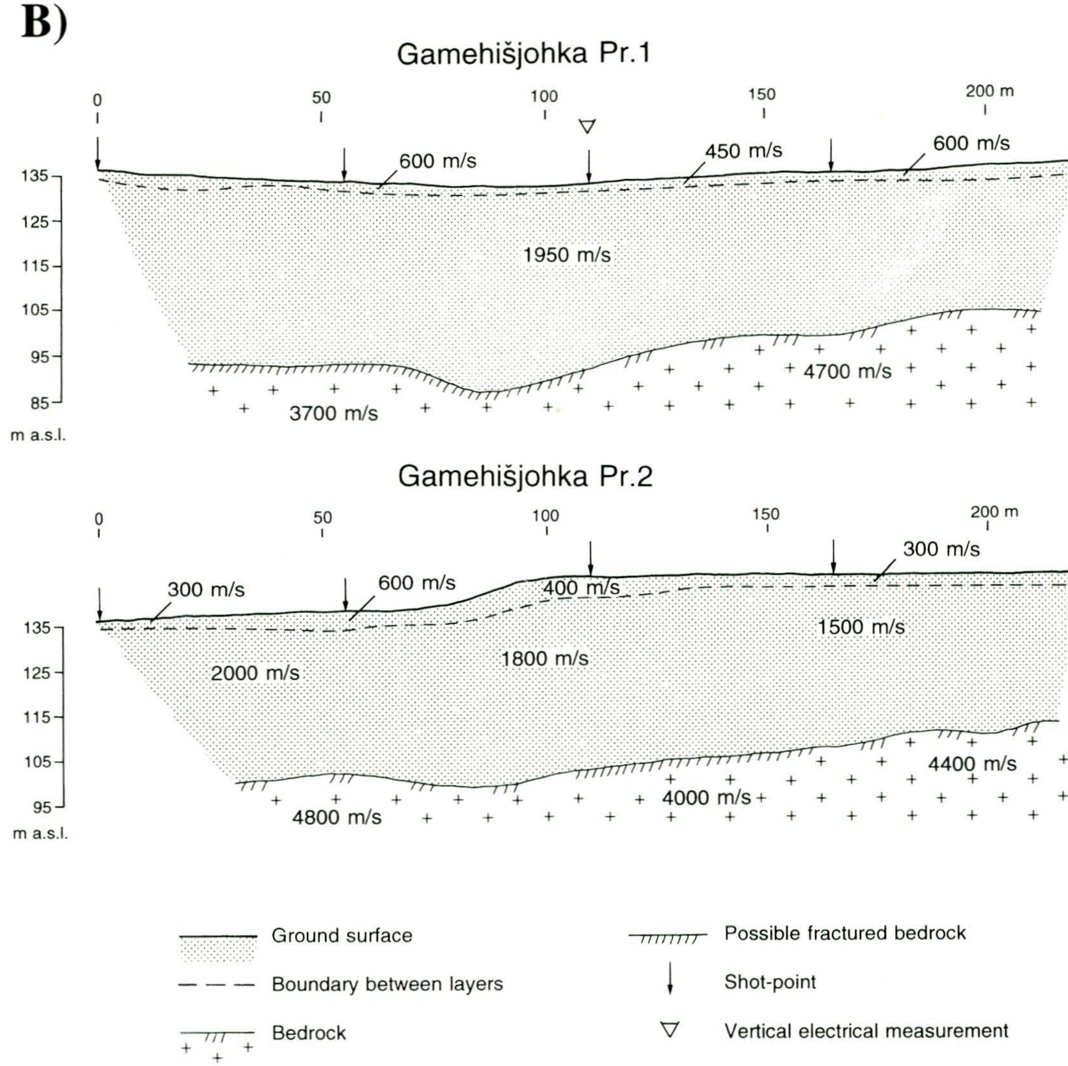


Fig. 29. A) Map of the Gamehisjohka locality with the section, the drilling points and the geophysical profile lines indicated. For location, see Fig.1. B) Refraction seismic profiles 1 and 2 along the lines indicated on the map (A).

(Fig.30). During younger stages the ice movement seems to have turned towards the ENE (striation on till clasts) and later towards NNE. The upper till is eroded on top. This has the implication that only the lowermost part of the brown B-horizon of a paleosol developed in the upper part of this till remains (subunit tB1). That the soil profile is a paleosol and not of postglacial origin is shown by glaciotectonic deformation of



this material, as recorded in the western part of the studied section (Fig.31). The B-horizon is partly injected, folded and sheared into the underlying bluish-grey till, and the tectonic structures indicate a younger ice movement and deformation direction towards the NE-ENE. This observation casts some doubt on the age interpretation of the striation on the till clasts, mentioned above. The striation may have been produced either during the till tB-glaciation, as said before, or during the younger deformational glacial event (Fig.31).

The fine-grained, greenish-grey till tD resembles the lowermost part of till tB. It is not known if the intermittent, loose, gravelly sand C relates to a major deglaciation or only a minor ice retreat event, or even a change of subglacial depositional conditions. A minor local environmental change is perhaps most likely.

The organic-bearing fluvial sediments (subunit E4) contain both pollen and macroplant remains (AMS age > 50 ka; UtC-1428, Table 1).

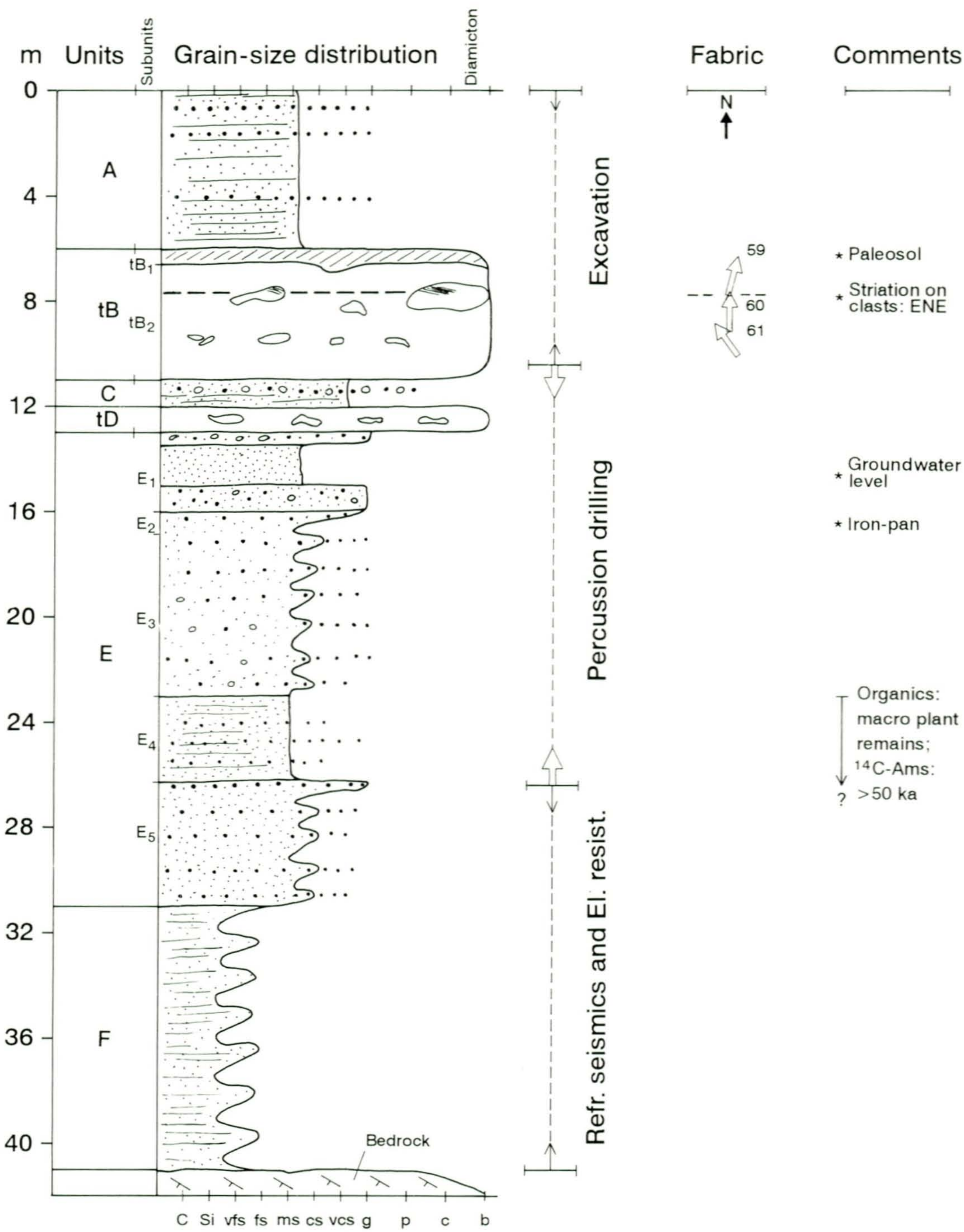


Fig. 30. Simplified log from the section at Gamehisjohka with clast fabrics also indicated.

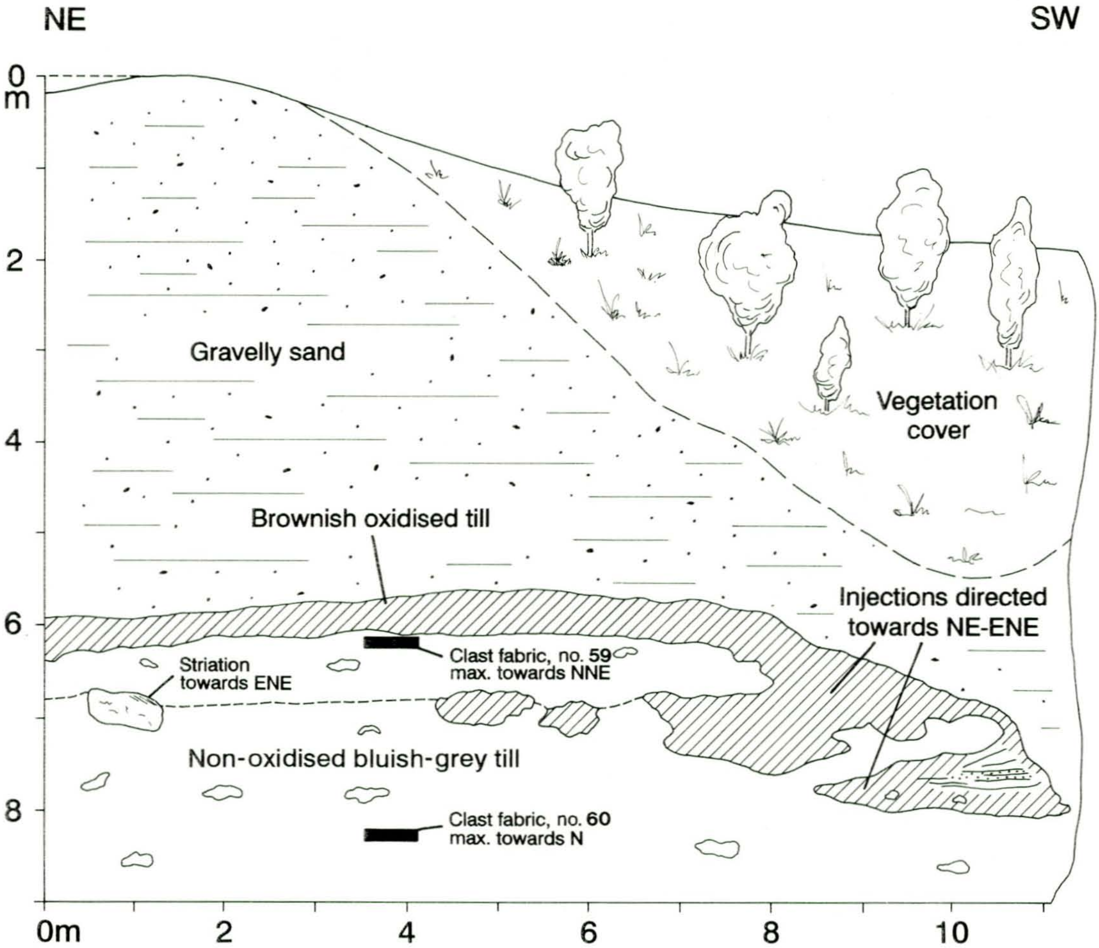


Fig. 31. Outline of the section at Gamehisjohka. The section is indicated on the map in Fig.29A.

Buddasnjarga (5)

The stratigraphy at Buddasnjarga, at the border to Finland about 6 km south of Gamehisjohka, involves one deeply oxidised till overlying glaciofluvial gravel and sand (Figs.32A-B). It is recorded in an erosional ridge which was probably formed during combined glaciofluvial and glacial erosion. The ridge is elongated NE-ENE along the local trend of the Anarjohka river valley, and is situated on the valley bottom no more than 40-50 m from the Anarjohka river. The studied section is c. 10-11 m high and its base is at least 2-3 m above the maximum 'level' of the Anarjohka river. This means that the deposits are dry and are situated well above the average local groundwater level.

The Buddasnjarga till is a compact, fine-grained, bluish-grey lodgement till of a similar lithology to the Gamehisjohka till tB and the main part of the Mieron Till at Vuolgamasjohka. In the studied section the upper 6 m of the till is brown and reddish-brown due to deep oxidation (Fig.33A). This is inferred to represent the B-horizon of a relict soil profile which is slightly eroded on top. The associated A-horizon is apparently missing. Oxidation of the underlying sedi-

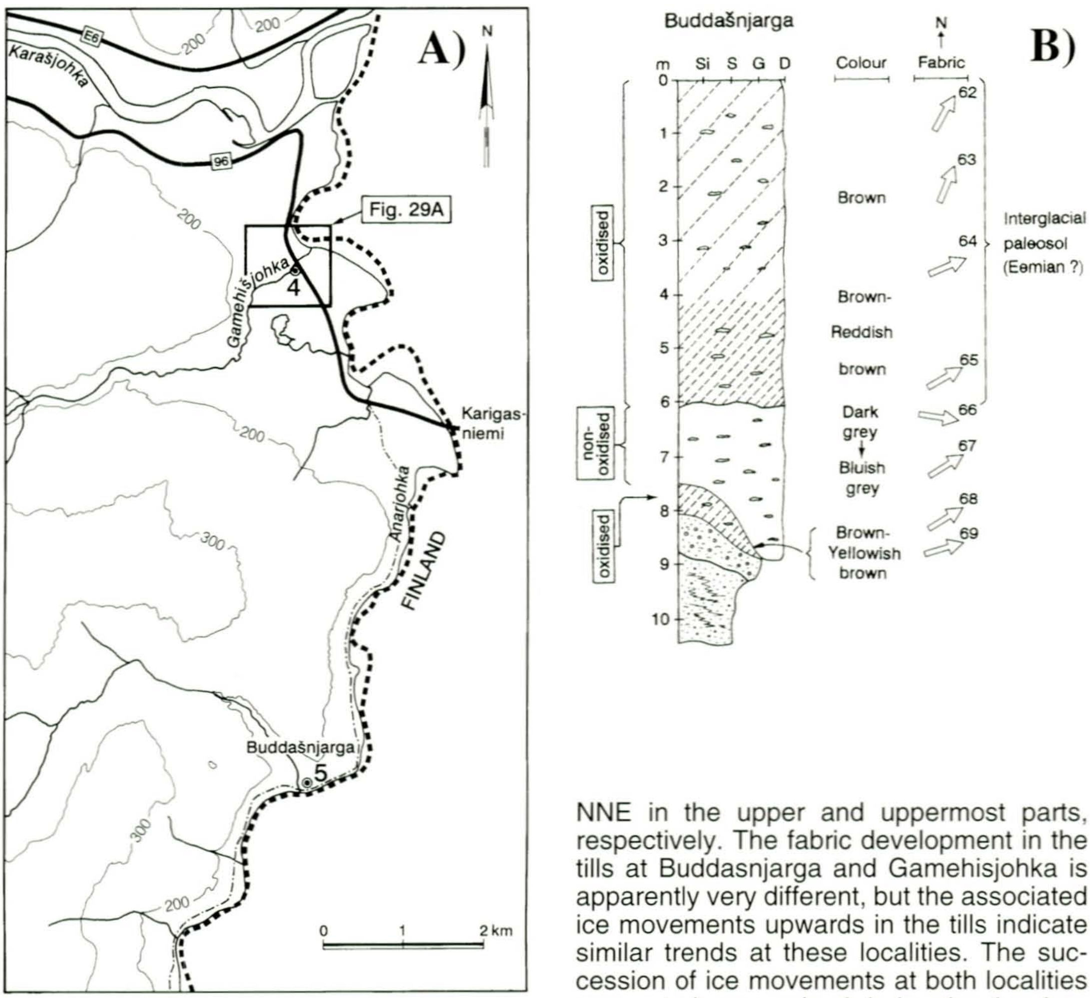


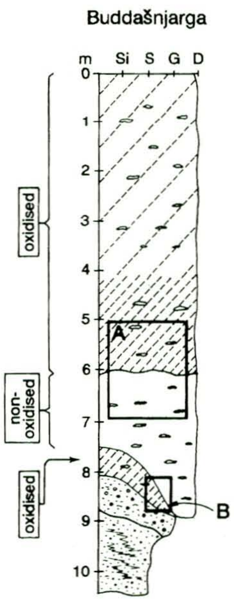
Fig. 32. Location (A) and simplified log (B) of the section at Buddasnjarga with clast fabrics also indicated. Location also shown in Fig.1. Local road along the Anarjohka river is indicated by a dash-dotted line.

ments and in the lower boundary zone of the till is also recognised (Fig.33B).

The Buddasnjarga till is thought to correlate with the bluish-grey till tB at Gamehisjohka where a much more deeply eroded similar brown paleosol is situated on top.

Ice movement directions inferred from clast fabrics are east-northeasterly in the lower part and then turning towards the NE and back to E and ENE upwards in the bluish-grey zone (Fig.32B). In the oxidised zone the associated ice movement seems to have changed from ENE to NE and NE-NNE in the upper and uppermost parts, respectively. The fabric development in the tills at Buddasnjarga and Gamehisjohka is apparently very different, but the associated ice movements upwards in the tills indicate similar trends at these localities. The succession of ice movements at both localities seems to have evolved during the development of a growing glacier with initially topographically dependent movements along the valley, and then turning towards the NNE across the valley during a thicker and less topographically dependent stage. This gives further support to a correlation between the Bavtajohka and Gamehisjohka bluish-grey tills.

Interpretation of climatic implications and glacial history. The inferred, partly 'rubificated' (reddish-brown) lower zone of the soil profile in the till provides clear evidence of a previous much warmer climate than during the present. Such rubifications, if they are in a mature state of development, are known only from temperate areas where the annual mean temperature is at



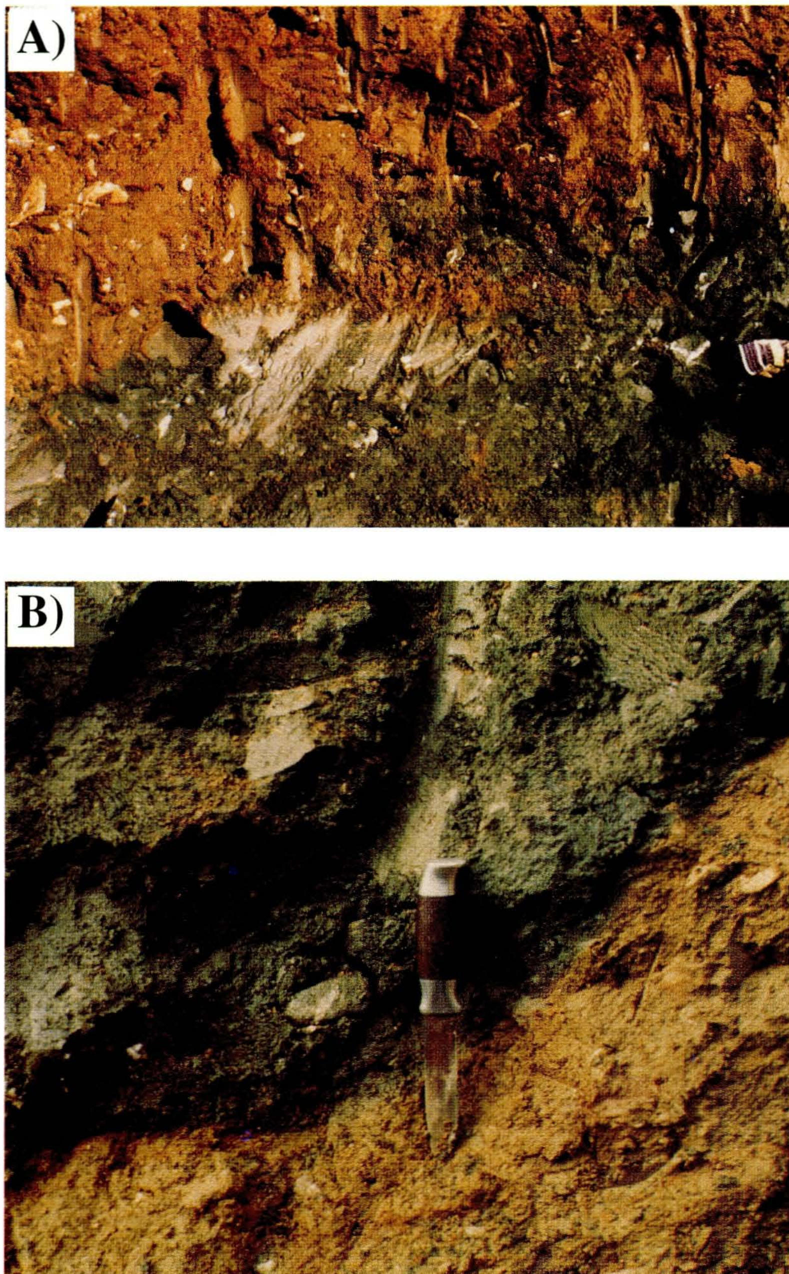


Fig. 33. Photos of oxidation in the till at Buddasnjarga: A) oxidation from percolating surface water, with reddish-brown rusty illuviation or transformation zone overlying non-oxidised bluish-grey till some 5-6 m below surface, and B) 'groundwater oxidation' in the lower boundary zone of the till. Location of photos indicated on the log to the left (see also Fig. 32).

least 7°C and the mean precipitation is more than 500 mm per year (Smith et al. 1987, Tarnocai & Smith 1989). Such climatic conditions in Norway today are found only along the coast of the southernmost part of the country. The mean numbers for temperature and precipitation for Karasjok (close to Buddasnjarga) today are -1.5°C and 340 mm per year, respectively. During the postglacial optimum the mean temperature may have been at most 2-3°C warmer than today. It seems, therefore, safe to claim that the youngest period when this soil profile could have been developed is during the last interglacial, the Eemian. The closest alternatives in time would be the Holsteinian (c. 360-430 ka ago) and the Cromerian (c. 550-600 ka ago) interglacials (e.g. Šibrava 1986). Because of the warm climate needed for this type of pedogenesis, we think that it is most likely that the soil profile is a paleosol from the Eemian, which is commonly thought to be the warmest interval during the last 600 ka (e.g. Sejrup & Knudsen 1993, Eide et al. 1994).

As a consequence of this, the Buddasnjarga till is of at least Late Saalian age. We suggest a Late Saalian age for the till, and based on clast fabrics at Buddasnjarga and Gamehisjohka we conclude, as noted earlier, that the assumed correlative tills have been deposited during a glaciation with initial ice flow along the valley in a northeast to northerly direction. Subsequently, when the ice was thicker, it turned towards the NE-ENE, and then towards the NE-NNE during later stages. The associated ice centres were therefore located in the sector south-southwest of Finnmarksvidda, probably somewhere in the Lapland region of Finland.

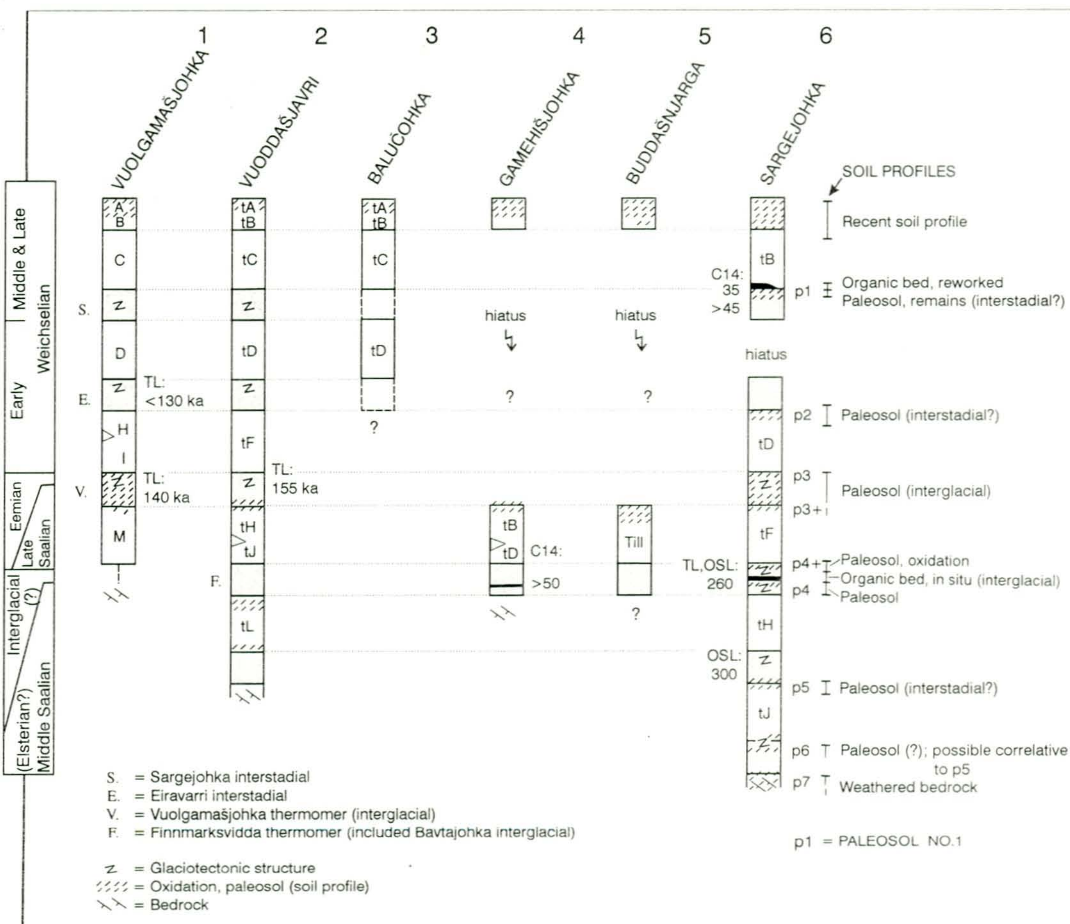


Fig. 34. Correlation diagram for the six described stratigraphies from Finnmarksvidda: at Vuolgamasjohka (1), Vuoddasjavri (2), Balučohka (3), Gamehisjohka (4), Buddasnjarga (5), and at Sargejohka (6). A capital letter with a little t as a prefix indicates a till unit, except at Vuolgamasjohka where only capital letters without prefixes are used for all units in accord with previous publications.

Conclusions. The bluish-grey tills at Buddasnjarga and at Gamehisjohka are assumed to be correlative tills of Late Saalian age. Both tills have remains of a brownish paleosol on top. The paleosol on the Buddasnjarga till has been only slightly eroded, and most of the B-horizon is thought to be preserved. Because a thick zone partly with rubification is inferred to be present in the paleosol, and as this process needs climatic conditions at least as warm as in the southernmost parts of Scandinavia today, we conclude that the paleosol is most likely of Eemian age. It may, however, be older, which also implies an even older age for the till. In any case, the inferred paleosol rubification implies an associated interglacial climate with an annual mean temperature up to 4-5°C (or more) warmer than during the postglacial optimum.

Chronology and correlations

Based on lithostratigraphy, 'counting from the top', TL/OSL dates, ^{14}C dates and stratigraphic relation to paleosols, we suggest the following correlation shown in Fig.34 between the six described localities from Finnmarksvidda. All the main units at Vuolgamasjohka have corresponding units at Vuoddasjavri, and these deposits represent a succession of glacial and deglacial events starting during the Late Saalian and continuing to the end of the Late Weichselian. Proper organic interglacial or interstadial deposits have not been found at either of these two localities. Going eastwards on Finnmarksvidda, the Balučohka stratigraphy is included in the correlation chart (Fig.34) because a pollen specter (Table 5.1: 870401), which was used by Olsen et al. (1990) as a representative from the Early Weichselian Eiravarri interstadial, was taken from this locality.

Remains of a paleosol from a warm interglacial period, probably the last (Eemian) such period, are represented at all the described localities except at Balučohka. Particularly at Gamehisjohka, Buddasnjarga and Sargejohka we think that this paleosol is of utmost importance with regard to stratigraphic correlation. The pre-Weichselian stratigraphic framework of Finnmarksvidda will depend much on the recognition of this marker horizon. This was not properly understood before the last years of the long research period, and as a consequence of this some units were previously thought to be much younger than they have subsequently been shown to be. One of these erroneously young age estimates was that of the interglacial beds at Sargejohka, which we previously thought might correlate with the Eemian (Olsen 1989a,b, Olsen & Selvik 1990). Today we think that these beds are much older, probably corresponding to an interglacial event during isotope stage 8/7, as suggested by the TL and OSL dates (average c. 260 ka).

Based on their stratigraphic position just beneath a till of inferred Late Saalian age, a correlation is suggested between the organic-bearing sediments at Gamehisjohka and the Bavtajohka interglacial beds at Sargejohka.

The correlation between tills tH at Sargejohka and tL at Vuoddasjavri implies that the waterlain deposits of unit K at Vuoddasjavri may correlate with the Bavtajohka interglacial beds.

The till tJ at Sargejohka may be of isotope stage 9 or early stage 8 age (about 300-350 ka ago); if confirmed, this would be the oldest till in the Quaternary stratigraphic framework of Finnmark (Olsen 1993b).

Pollen content of sediments

The pollen content of the investigated sediments on Finnmarksvidda is quite variable, as indicated by the pollen concentrations in some samples from the key-localities (Fig.35). Although most of the analysed samples have a very low pollen content, we have found some horizons with a sufficiently high content of pollen to enable us to present representative pollen signatures from two of the major ice-free intervals, namely the Bavtajohka Interglacial and the Sargejohka Interstadial, both represented at Sargejohka. The pollen signatures from two other major ice-free intervals, the Vuolgamasjohka Thermomer (Eemian) and the Eiravarri Interstadial (Brørup-Odderade), are too sparse to be characterised as good representatives. However, we think that as

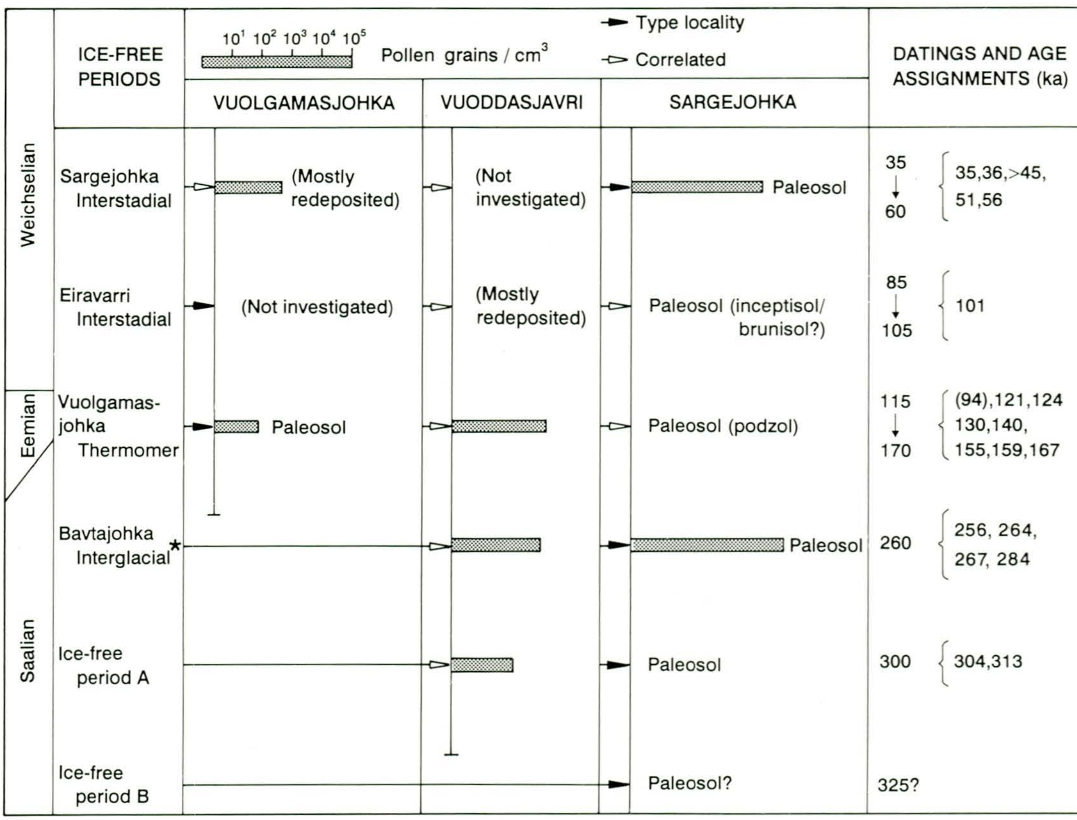


Fig. 35. Pollen concentration from some stratigraphic levels at Vuolgamasjohka, Vuoddasjavri and Sargejohka. *) Note that Bavtajohka interglacial is included as a part of the long ice-free interval named the Finnmarksvidda thermomer (see Fig. 34).

the results reflect some of the vegetative conditions during these intervals, we therefore include them in the following description.

The age estimates of the successively described ice-free intervals are based on the distribution of luminescence dates of samples from sediments on Finnmarksvidda (see curve with TL-maxima on the front cover), which will be dealt with later in this paper.

Finnmarksvidda Thermomer (c.205-285? ka B.P.). This ice-free interval includes the Bavtajohka Interglacial, which is represented by a thick gyttja and gyttja silt horizon at Sargejohka (Fig.17), and supposed correlative fluvial deposits at Vuoddasjavri (sand K; Figs.8 & 14) and at Gamehisjohka (sand E; Fig.30). The pollen diagram from the interglacial gyttja deposit at Sargejohka (unit G2; Fig.19B) indicates a birch-dominated vegetation. High values of more than 20% pines *(Pinus)* in some analyses (Fig. 19D) indicate that also pines grew in the area at least once during the ice-free interval, and the overall vegetation in this area was probably similar to that of the present day.

Vuolgamasjohka Thermomer (c. 115-135 (170?) ka B.P.). This interval, which is assumed to include the last interglacial, is mainly represented by glaciofluvial outwash sediments deposited during the previous (Late Saalian) deglaciation. However, a few thin fluviolacustrine silt laminae on top of the Vuolgamasjohka Sand at Vuolgamasjohka (Figs.3-5), and reworked in the boundary zone to the overlying Gardejohka Till, are thought to derive from a later stage of the thermomer, probably from the first part of the last interglacial. Although the content of pollen is very sparse, the best representation of the pollen that we have found for the Vuolgamasjohka Thermomer is at least partly from these sediments (Table 5.1: 811661, 811664 and 811665). The recorded pollen content indicates (at best) a slightly tree-pollen dominated vegetation with at least 75% birch (of AP), which is far from what would be expected for the optimal Eemian conditions with a local annual mean temperature of up to 5-7°C (?) (p.59 & 61). The assumed correlative fluvial deposits at Vuoddasjavri (sand G) have a higher pollen content (maximum c. 1500 pollen grains/cm^3), and the pollen distribution indicates between 60% and 90% tree-pollen, of which birch constitutes at least 90% (Table 5.2). Although the relative content of tree-pollen in this case may be fairly high, the strong predominance of birches does not accord with the more favourable climatic intervals of the last interglacial. We assume that our pollen records derive mainly from the beginning of the last interglacial and, therefore, a representative pollen signature from a major part of the Eemian is so far lacking in this area.

The Eiravarri Interstadial (c. 85-105 ka B.P.). The pollen record for this interval is represented by one analysis from the boundary zone between the Vuoddasjavri Till and the underlying Eiravarri Interstadial correlative sand at Åskal on western Finnmarksvidda (Olsen & Hamborg 1984), and one analysis from reworked Eiravarri Interstadial correlative sand at Balučohka (Figs.28 & 34; and Table 5.1). Although the pollen content is sparse in sample no. 821213, it is thought to reflect (at best) a tree-dominated vegetation with birch as almost the only tree-species represented. The recorded pollen of pine, elm and juniper may have been either redeposited from older units or transported aerially from remote southern areas. The other pollen sample representative indicates a fairly differentiated vegetation, but with less tree-pollen (sample no. 870401). The analyses may very well derive from different parts of the interstadial.

The Sargejohka Interstadial (c. 35-60 ka B.P.). The pollen record for this interval is mainly from reworked gyttja sediments, intermixed with remains of the A-horizon of a paleosol in the basal zone of the Kautokeino Till correlative unit at Sargejohka (Figs.19A, 21 and 34). The pollen distribution indicates a herb-dominated vegetation with c. 80% NAP, and with grass (Poaceae) and sedges (Cyperaceae) being the most frequently occurring pollen types. Wormwood *(Artemisia)* is present as a characteristic component, amounting to c. 5%. The pollen flora, therefore, indicate a subarctic, tundra-like vegetation, and the climatic conditions during the represented part of this interstadial were probably much less favourable than during the optimum of the supposed relatively warm Early Weichselian Eiravarri Interstadial.

Varangerhalvøya

(The Varanger Peninsula)

Stratigraphy

Komagelva (7)

The stratigraphy in a section in a c.6 m high river bluff along the Komagelva river on the Varanger Peninsula (Figs.36-39A) is described and interpreted. It consists of four main units with a further division into subunits in some of them, based on lithofacies changes (Fig.38). The ground surface on top of the bluff is at c. 55 m a.s.l.

Description. The stratigraphy at Komagelva includes waterlain sediments underlying a till which is covered by silt, sand and a gravelly sandy diamict bed on top.

Unit D

The lowermost part of the Komagelva stratigraphy, unit D (Fig.38), is divided into subunits D1 and D2. The lowermost boundary of the latter is not seen, which implies that the observed thickness of c. 1.5 m of sub-

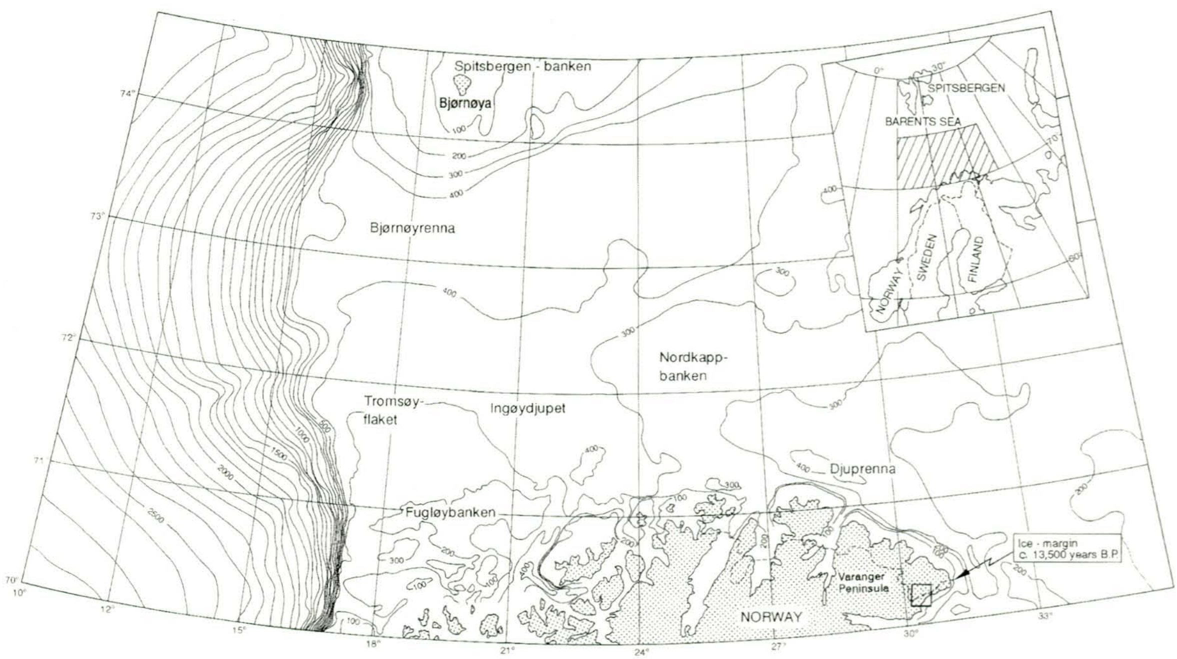


Fig. 36. Location of the Varanger Peninsula and the inferred ice margin position during the Vardø Moraine stage from the last deglaciation c. 13,500 years ago (uncalibrated age). The ice margin position is modified from Sollid et al. (1973) and others, as cited in the main text. The map of Fig.37 is framed.

unit D2 is only a minimum. The subunit is a well sorted, homogeneous, pale greyish-white to yellowish-white sand. The sand is relatively compact due to diagenetic cementation and dry-out effects. It is, however, possible to cut the sand with a spade or a knife for detailed research.

The overlying sand, subunit D1, is about 1 m thick, and is glaciotectonically deformed (Fig.39B). The direction of the glaciotectonic compressive deformation, as inferred from faulting and thrusting structures, is towards the NW-N (Figs.38 & 39B). The tectonised sand seems to be a deformed part of the underlying undisturbed sand. In addition, it contains bands and injections of gravelly material, and clasts of pale greyish-white, well rounded, loosely compacted 'sandstone'. The latter probably derived as fragments from the relatively compact, cemented, underlying sand. These fragments were easily rounded during the fluvial-glaciofluvial transport. Kaolinitic bands or horizons are recorded in the uppermost part of the subunit and along the contact to the overlying gravels (Alnæs & Hillestad 1989). These bands are sheared and stretched out towards the NW-N. The bands commonly have a thickness of 1-3 cm, but one of the bands has a local maximum thickness of c. 0.4 m in the northwestern part of the section. On the southwestern slope of the Komagelva valley we have recorded thick deposits of 'conglomerates' with clasts of the greyish-white sandstone in a similar but loose sandy matrix. These deposits are located in hummocky formations. An alternative explanation for the loose character of the 'sandstone' clasts is that they originated from a strongly and deeply weathered local sandstone. Clasts and slices of kaolinite injected into subunit D1, as well as the (thrusted) kaolinitic bands in the upper part of the subunit, support the latter explanation (Alnæs & Hillestad 1989).

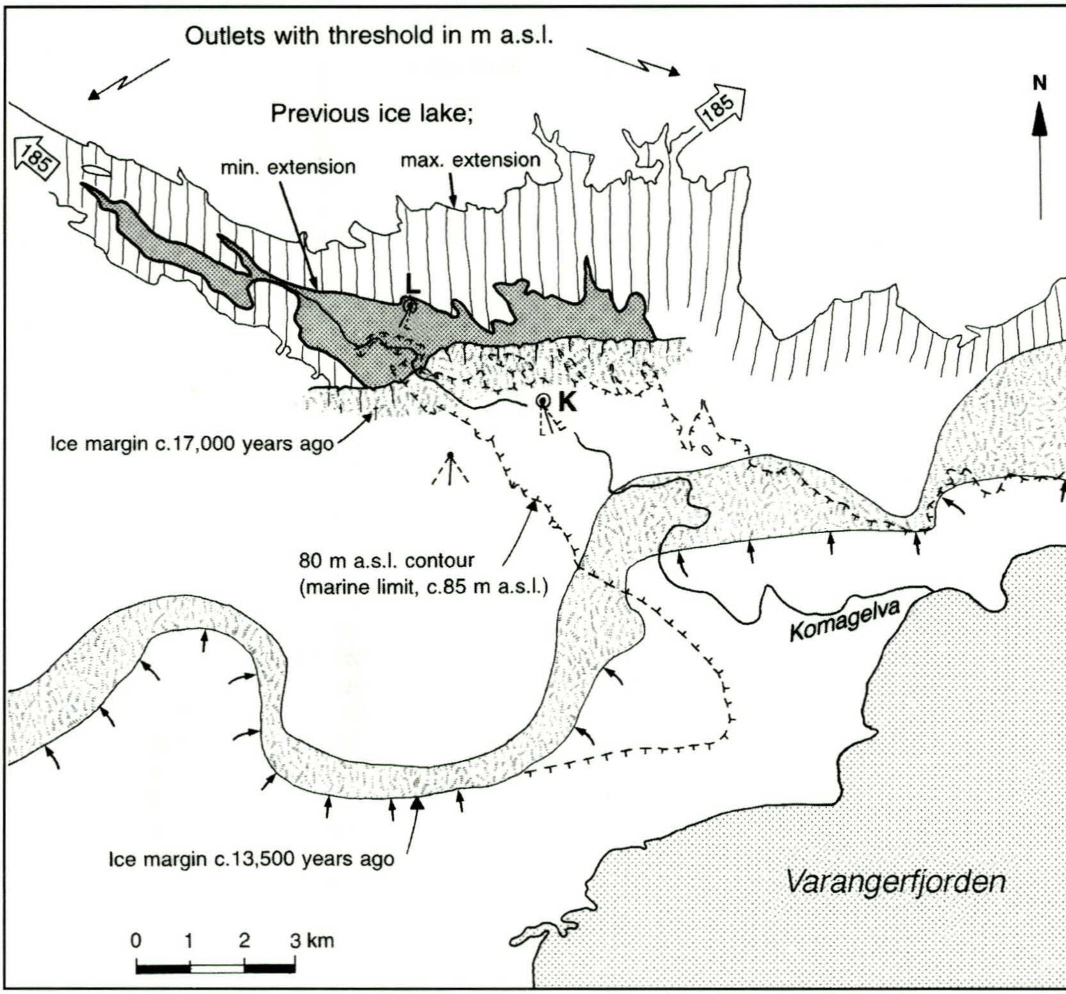


Fig. 37. Map of the Komagelv valley on the Varanger Peninsula, eastern Finnmark, with localities (K= Komagelva; L= Leirelva) indicated. Ice movements as given by clast fabrics and glaciotectonic structures at three localities (L, K and unmarked) are indicated by non-broken and broken arrows, respectively. Arrows with one hatch indicate older directions, and with two hatches the oldest directions. The ice margin position from c. 13,500 years ago corresponds with the Vardø Moraine stage, which has been mapped in detail by Tolgensbakk & Sollid (1981) in the Vardø area some 10-15 km further east, and followed almost continuously to this map area.

Unit C

This unit is a c. 1.5 m thick stony gravel deposit with some lenticular bodies of sand included. The sand lenses are up to 0.2-0.4 m thick and a few metres in width. The clasts are well rounded with an average roundness ('middle roundness') of c. 3.0, and this indicates a high glaciofluvial or a medium to high fluvial roundness as suggested by Olsen (1983a, b). Some edge-rounded boulders are recorded in the lowermost part of the unit. These boulders are thought to have been derived from glacial drift. Clasts of kaolinite-bearing material occur sporadically in all parts of this unit. The gravel deposit was glaciotectonised during an ice flow approximately towards

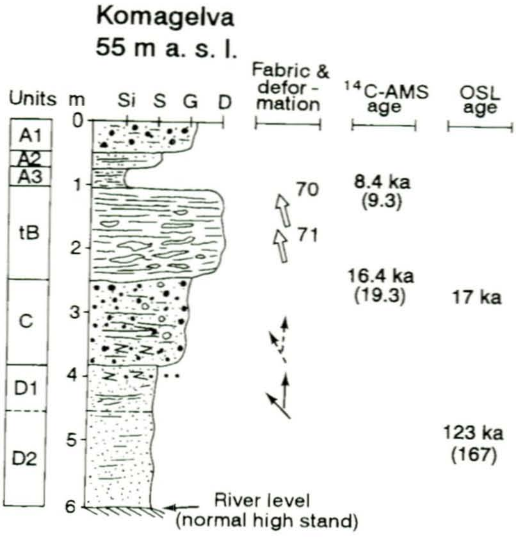


Fig. 38. Simplified log from the studied section at Komagelva, with clast fabric and glaciotectonic deformational direction (normal to fold-axes) also indicated. North is up in the figure. Less distinct deformational directions are indicated with broken arrows. Folds, faults or thrusting structures are indicated with z in the log. Ages given in parentheses are calibrated/corrected (see Tables 1 and 2.1).

the NW-N, as inferred from diffuse folding and thrusting structures (Fig.38).

Unit tB

This unit is a c. 1 m thick, compact, silty lodgement till with a shaly character. It has a dense pattern of vertical and sub-horizontal fissures. The colour is reddish-brown to brown, due to the presence of red sandstones and silty schists. Some rounded and well-rounded pebbles are observed in the basal part of the till. These pebbles are probably eroded from the underlying unit (gravel C). Clast fabrics indicate an ice movement towards the NNW-N (Fig.38).

Unit A

The upper unit at Komagelva is divided into subunits A1, A2 and A3 (Fig.38). Laminated silt and fine sand (A3) overlies till tB. The silt is reddish-brown (caused by red sandstones and silty schists), while the fine sand has a greyish-brown colour. The subunit has a tectonised character, the deformation probably due to either overloading of drift deposits or frost action in the ground. The subsequent overlying material (A2) is a coarsening-upward sequence of fine sand, medium sand and gravelly sand. The uppermost subunit (A1) consists of a sand and gravel diamicton with some cobbles. It is thought to be either a deposit which was dumped or melted out from the last waning ice-masses, for example as rafts from small icebergs, or it may be a debris flow deposit from the postglacial period. Although the ground surface is some 30 m below the marine limit (c. 85 m a.s.l. in this area), there is no clear evidence of reworking in the shore-zone during the early postglacial regression stages. This may suggest a depositional history for this unit, including debris flow activity, well after the last deglaciation in the area.

Interpretation. The lowermost deposit, sand D2, is a well-cemented and well-sorted sand with faint bedding structures. The consolidation is so firm that this sand may be regarded as a very loose 'sandstone', and even non-frozen fragments of it may have survived as smaller clasts during a very brief and non-violent glaciofluvial or fluvial transportation. The sand is thought to be of glaciofluvial or fluvial origin, possibly with some influence of eolian activity. There are no conclusive observations which might suggest a submarine environment for the sand. It may, therefore, have been deposited fluvially in a local basin during a low sea-level stand (lower than 50 m a.s.l.) or glaciofluvially in an ice lake. The precise age of the sand is not known, but two OSL dates suggest an age of c. 117-123 ka (corrected age: 159-167ka) for this unit (Fig.38; and R-933802a,b, Table 2.1). Kaolinitic horizons in the upper part of the overlying tectonised material (subunit D1) may suggest a much higher age for the sand (Tertiary?). However, the kaolinitic zones are dislocated, and they may well have been brought up into a much younger stratigraphic position than they were originally. This implies that the sand may be relatively

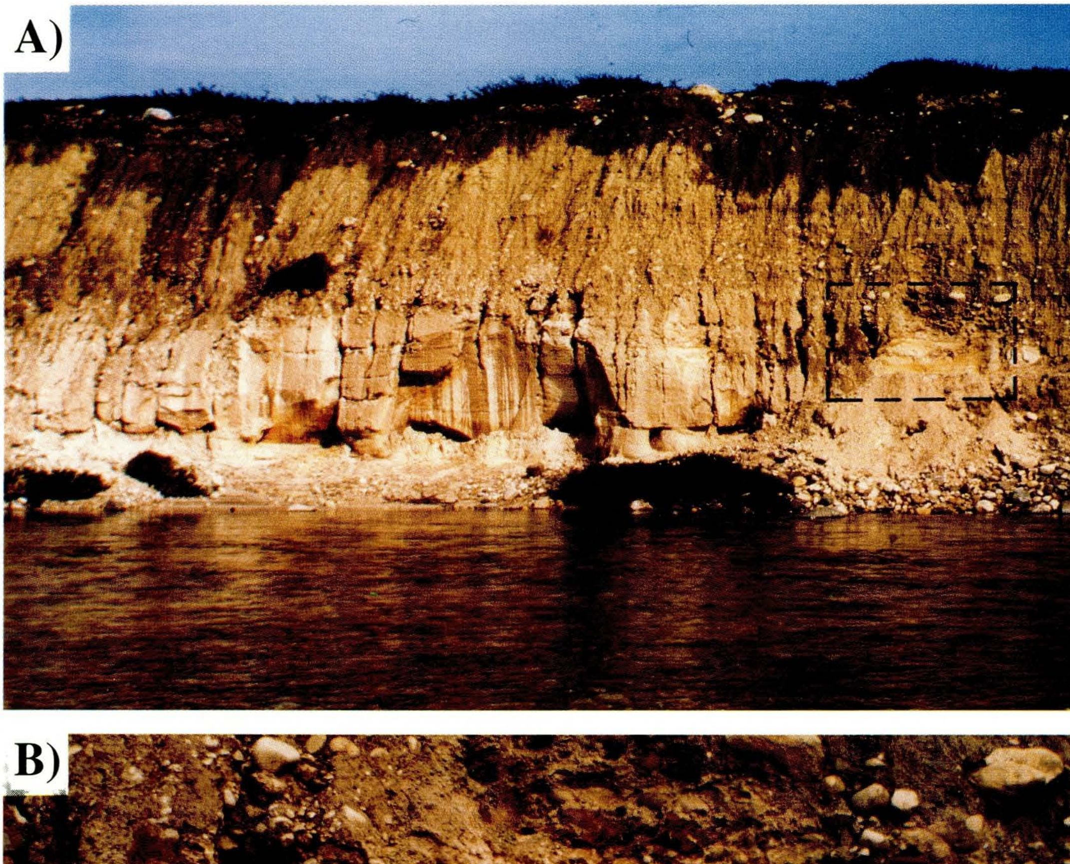


Fig. 39. A) The Komagelv river bluff. Sand D forms the wall in the lower part of the section. B) Close-up of the uppermost part of sand D at Komagelva. The scenario of B is framed in A. The sand was glaciotectonised during ice flow towards the NW (left) and N. The shovel is 1 m long.

young, although the luminescence dates suggest an age significantly older than the dated and inferred Late Weichselian age of the overlying unit. The gravel C consists of both glacially and fluvially derived material. It is thought to have been deposited in a glaciofluvial environment during an event prior to the advance stage of the till tB-glacier. One OSL date from unit C at c. 17 ka and two ^{14}C-AMS dates of reworked organic material in the overlying till (Fig.38; Table 2.1: R-933801; and Table 1: UtC-1795, -1796) support this hypothesis.

The ice flows, as given by glaciotectonic structures and till fabrics, are inferred to have been firstly towards the NNW and then turning in a more northerly direction. Although the locality is located in or 2-3 km proximally to the outer broad zone of the Vardø Moraine stage from the last deglaciation period (Sollid et al. 1973, Marthinussen 1974, Tolgensbakk & Sollid 1981, Follestad 1982), the till tB may still belong to an older glacial event. Because the ice flows associated with till tB and the glaciotectonics of the underlying units indicate the action of an advancing glacier, it may be that none of these units, or at most only the uppermost unit (A), belongs to the last deglaciation, including the Vardø Moraine stage. The suggested lobate configuration of the ice margin upstream in the Komagelva valley during the last deglaciation (Olsen et al. 1996), would not be expected to imply a turning of the ice flow direction towards the north during its final stages. On the contrary, in this area the ice flow would be expected to have maintained a northwesterly direction during the ice retreat phases. In the outermost part of the Komagelva valley, however, the ice flow pattern after the Vardø Moraine stage (Figs. 36 & 37) would have been quite different because of the calving and ice recession in the Varangerfjord area.

Based on ice flow development it is therefore suggested that the till tB was deposited during a previous, regional, ice-advance stage (e.g. Map of Quaternary geology, sheet 5: Ice flow directions, Northern Fennoscandia. Geological Surveys of Finland, Norway and Sweden, 1986).

Leirelva (8)

The stratigraphy in a section in a c. 21 m high river bluff along Leirelva, a tributary of the Komagelva river (Fig.37), is described in four main units overlying weathered sandstone (Fig.40). The ground surface on top of the bluff is located at about 120 m a.s.l. This is c. 35 m above the postglacial marine limit in the area.

Description. The weathered sandstone is strongly fractured and jointed, and many of the apparently coherent zones are also penetrated by fissures. Between the more coherent fragments there are often fine-grained weathered products. The weathered uppermost (c. 1 m) of the sandstone has been strongly affected by pedogenic processes. The material is partly fine-grained, and it has a gradational colour change from grey via greenish-grey to rusty red. The latter resembles the rubification that one finds in soil profiles in temperate areas today. Horizons and lenses of kaolinitic material are also present in the soil profile in the weathered sandstone. The colour of the coherent sandstone fragments varies from grey to pale pink.

Below the weathered zone there is about 5 m of homogeneous reddish and densely fractured sandstone exposed. Slope material covers the lowermost part of the bluff.

The soil profile of the weathered sandstone is not likely to have developed during a Quaternary climate. The 'rubification' suggests a much warmer climate than during the postglacial optimum, but could have been developed during warm interglacial conditions. However, the kaolinitic horizons suggest pre-Quaternary climatic conditions during the pedogenic event.

Unit D

This unit overlies the weathered sandstone and consists of gravel and sand with the latter predominating (Fig.40). The unit is c. 10 m thick and it has an overall fining-upwards trend above the lowermost 1.5 m. The latter is a continuous sand sequence disrupted only by one thin gravel horizon. The gravel clasts consist mainly of pale greyish-white, rounded to well-rounded quartzite. The lowermost sequence of sand, which includes some alternating pale grey and brownish oxidized horizons, has a disturbed character in its upper part. Above this, from 12.5 m to less than 10 m stratigraphic depth, the unit is dominated by gravel. The clasts are almost entirely of the type mentioned above. The upper 6 m of the unit comprises gravel and sand in alternating beds, where the thickness of the latter is increasing markedly upwards. The sand is mainly planar and cross-laminated, of medium grain-size, and includes some fine and very few coarse sand laminae. Clasts of kaolinite-bearing material occur sporadically in all parts of this unit. The uppermost part of unit D has been slightly affected by glaciotectonic deformation (folding) during an inferred ice flow towards the N-NNE (Fig.40).

Unit C

This unit consists mainly of a laminated, brown, clayey silt. The colour is also here caused by the presence of red sandstones and silty schists. The silt is disturbed from top to base, but gradually less downwards, and only some small irregularities at some laminae boundaries are observed in the lowermost parts. In the middle of the unit, folds are thought to indicate glaciotectonic deformation during ice-flow towards the N-NNE (Fig.40). Similar but much more intensive folding in the upper part suggests a deformation during an ice-flow towards the NNE. Silt C has an overall coarsening-upwards trend above the relatively homogeneous lower half of the unit, except for the uppermost few centimetres where the unit again is fine-grained.

Unit tB

This unit consists of a c. 0.3 m thick lower subunit (tB2) of a silty diamicton thought to be a lodgement till, and an upper, few cm thick subunit (tB1) of mostly clayey silt. The latter may indicate deposition mainly by melt-out or undermelt. Both subunit tB1 and the matrix of till tB2 has a brownish colour and resembles the underlying silt lithologi-

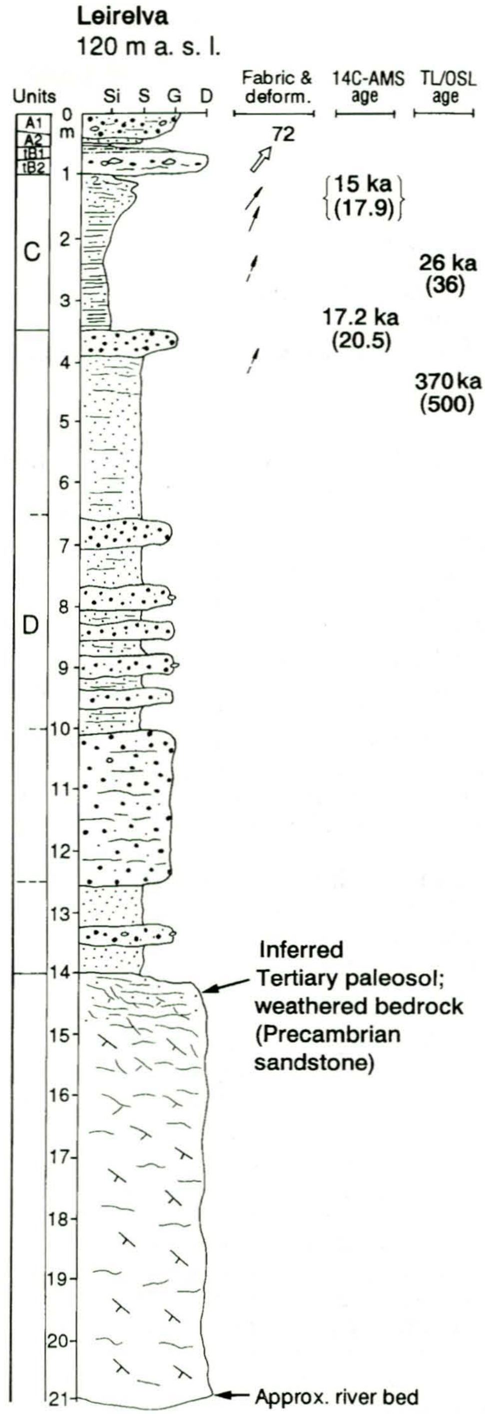


Fig. 40. Simplified log from the studied section at Leirelva, with clast fabric and glaciotectonic deformational directions (normal to fold-axes) also indicated. Ages given in parantheses are calibrated/corrected (see Tables 1 and 2.1).

cally. Clast fabrics in the till indicate an ice flow towards the NNE, in accordance with deformation structures in the underlying sediments.

Unit A

This unit, overlying till tB, consists of a lower, 0.1 m thick, greyish-brown to brown bedded sand (A2) underlying a c. 0.3 m thick subunit (A1) of diamict ablation material. A thin postglacial soil profile is developed in the uppermost part.

Interpretation. The monomict gravel and sand D may correlate either with the polymict gravel C or the monomict sand D at Komagelva. Luminescence dates and ^{14}C-AMS dates from these stratigraphies would seem to reject the former correlation possibility, and at first glance they give apparently no support to the latter correlation possibility either (Figs.38, 40 & 43). However, the background radiation measured for the OSL-dating sample from sand D at Leirelva is reported to be anomalously low. This means that the age estimate of 370 ka (Table 2.1: R-943802) may be far too high for this sediment. It is therefore still quite possible that unit D at Leirelva may correlate with unit D at Komagelva. The tills may correlate with each other as well, and the 'ablation' material on top in both places may derive from the last deglaciation.

The sands in units D at Leirelva and at Komagelva resemble each other lithologically, and the gravel clasts of mainly greyish-white quartzite or sandstone are in both places rounded to well-rounded and commonly strongly weathered.

Greenish-grey horizons with kaolinite in the paleosol in the upper part of the weathered sandstone and in the lowermost part of unit D at Leirelva correspond fairly well with similar horizons in dislocated positions in the boundary zone between units C and D at Komagelva. Another striking resemblance is seen in the occurrence of clasts of kaolinite-bearing material not only in lower parts, but also higher up in unit D here and in unit C at Komagelva.

The horizons and clasts of kaolinite-bearing sandstone are probably deformed flakes and fragments of a pre-glacial paleosol developed in similar weathered arkosic sandstones and reworked weathered products of these sandstones. The remnants of the original paleosol with kaolinite may therefore have a wide distribution within or beneath the glacial drift deposits in this valley.

Rust staining or oxidised brownish zones or horizons in sediments are taken as evidence of terrestrial subaerial conditions (e.g. Boulton 1979, Olsen 1984, 1988). Such horizons are recorded in unit D at Leirelva, and these were later glaciotectonised, suggesting that there existed a subaerial period prior to the subsequent ice phase. We suggest that this may have occurred between the deposition of units D and C, which implies a hiatus between these units at Leirelva. We think that rust staining, as in unit D, would take at least some tens of years to develop in this purely freshwater environment. In a location more likely to be influenced by marine (saltwater) conditions, the rust staining could have developed faster. The glacier that dammed the ice lake where silt C was deposited is thought to have advanced and submerged the site successively, and there was probably no subaerial phase with deep desiccation of the sediments between deposition of silt C and the overlying till. The sediments were probably fully water-saturated during this period, and it would therefore have been difficult to get the necessary and lengthy, relatively dry conditions for the development of rust staining several metres below the ground surface. The deformation of the rust zones most likely occurred during the following ice advance. It is therefore most likely that the suggested subaerial interval occurred between deposition of units D and C, and this is strongly supported by the available dates (Fig.43).

The high elevation above the main valley bottom strongly suggests a glaciofluvial origin for gravel and sand D. It was probably deposited at the margin of an ice-dammed lake, or alternatively during an extremely high sea-level stand (> 100m a.s.l.). The overall fining-upwards trend may indicate a transitional facies change to the overlying laminated glaciolacustrine clayey silt, which was deposited in a lower energy environment, probably in deeper water. However, the inferred subaerial event after deposition of unit D rather suggests a subsequent ice retreat and desiccation of the sediments before the ice again advanced and dammed the ice lake wherein silt C was deposited.

The overall coarsening-upwards trend in unit C, the existence of the overlying till and the glaciotectonic deformation in units C and D are best explained as having been caused by an advancing glacier. The associated ice flows, as inferred from glaciotectonics and till fabric, are mainly towards the N-NNE in the beginning and then towards the NNE. This indicates, in a similar manner to that of the Komagelva stratigraphy, a regional ice advance stage and not a short readvance during deglaciation. The latter would be expected to have resulted in ice flows towards the NW-NNW during later stages, which is not in accordance with the recorded ice flow parameters.

Radiocarbon dates

The glaciolacustrine sediments and the tills at Leirelva and Komagelva (Figs.37-40) have a low but significant organic content. To get a better idea of the chronology of these stratigraphies, AMS dating has been performed on four different samples from these localities (Table 1). The NaOH-insoluble fraction has been dated in each case. In addition, the NaOH-soluble fraction has been dated for three of the samples. The following text will be based on ages not calibrated to calendar years, unless otherwise indicated.

Contamination by young or old carbon may be a severe problem for ^{14}C-dating of sediments (Fig.41a,b). For example, a contribution of ten per cent of modern carbon will cause an infinitely old sediment to be dated at 18 thousand years (Olsson & Possnert 1992). Therefore, using sediment dates we need somehow to evaluate or discuss the probability and size of contamination, at least such from modern sources.

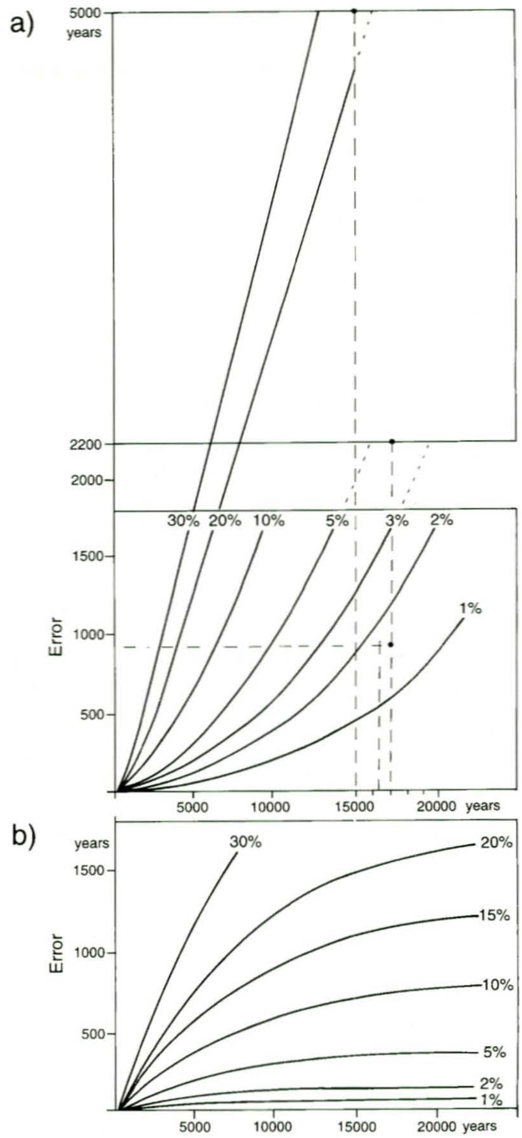


Fig. 41. Radiocarbon age error due to contamination of a) young carbon, and b) old carbon. Examples with main reference to young carbon contamination are discussed in the text. Modified diagram from Olsson (1974).

The dates of both fractions of sample no. 512-89 (UtC-1799,-1800) are very close to each other, and this suggests that both fractions derive from the same carbon sour-

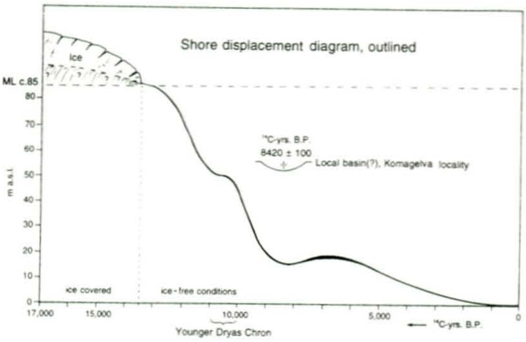


Fig. 42. Shore displacement in the Komagelv valley during postglacial time. The Komagelv locality emerged from the sea during the Younger Dryas Chron. The curve is sketched in outline on the basis of shoreline data taken from Marthinussen (1974) and Sollid et al. (1973). Marine limit (ML) is c. 85 m a.s.l.

ce. This sample is from the clayey silt in the lower part of unit C at Leirelva. The fine-grained and compact sediment has a low permeability, and the downward transport of surface-water to the groundwater has probably drained mainly on top of till tB for some distance until it eventually was able to pass through the compact till tB - silt C sequence, and continue through the more permeable, underlying sandy sediments. The organic content of the fine-grained sediments may therefore have been very well preserved and not contaminated by circulating water.

The same may apply for the reworked fine-grained sediments in till tB at Komagelva. The dated fractions of sample no. 501-89 (UtC-1795,-1796) are, however, not so close as in the case of sample no. 512-89. The results may therefore have been affected by some minor contamination. However, as the age difference between the dated fractions is less than 7%, the dates are still regarded as good age estimates.

Sample no. 507-89 is from the top of the glaciolacustrine sediments at Leirelva. In this zone the sediments are strongly glaciotectonised with fine sand folded together with silt, and this uppermost part of silt C is clearly oxidised from surface-water drainage through the sediments. Down to the same stratigraphical level, but not exactly in the same place as the sample was taken, we observed penetrating root-strings from recent or subrecent plants. Based on these field observations, it is not surprising that the difference between the dates of the two fractions is large (UtC-1797,-1798; Table 1). The age estimate of the soluble fraction is about 30% lower than that of the insoluble fraction. The former has thus apparently been strongly affected by young carbon contamination. It is likely that the insoluble fraction has also been affected, but probably to a much lesser extent. The young carbon contamination may be at least 25% for the soluble fraction (Fig.41a). This follows from an extrapolation of data given by Olsson (1974). If we use the age of 17,200 years given by the dates of sample no. 512-89 (Table 1) as a maximum age of the insoluble fraction of sample no. 507-89, and then put this value into the extended contamination diagram of Olsson (1974), we find that with an age error of 2,200 years (difference between 'maximum' age and given age; Fig.41a) the related percentage of young carbon contamination is c. 4.5 for the insoluble fraction.

If we use the same calculation procedure and maximum age estimate for sample no. 501-89 (Table 1), then we find that the percentage of young carbon contamination of the insoluble fraction of this sample is not more than c. 1.7. Although we realise that the actual dates may be a result of a complex intermixing of several components, young as well as old, we think that the age estimate of the insoluble fraction of sample no. 501-89 may be within a few hundred years of the age of the reworked sediment. This is quite acceptable for our reconstructions and correlations.

The AMS dating of the organic fraction in fluvial(?) silt and sand overlying till tB at Komagelva gives an age of 8,420 ± 100 years (UtC-2219). This is about 4,000 years after the ice retreat from the Komagelva valley and c. 3,000 years after the locality rose above sea-level during sea-level regression in early postglacial time (Fig.42). The silt and sand succession has apparently a fairly low to medium-high permeability, and surface-water would have easily drained through the overlying coarse-grained diamict material, but not quite so easily further through the 'dated' silt and sand sequence. The organic content in the sediment may, however, have originated, at least partly, from water transport along this pathway, or it may be of an older age and subsequently seriously contaminated by young carbon. We have searched for pollen in the sediments, with a negative result, but have not made further attempts to solve this problem. It should be added that with an interpretation of the cover deposit (subunit A1) as a debris flow in a local fluvial basin, and not necessarily glacially related, then the dating result of 8,420 years from subunit A3 may well be close to reality. It may, therefore, be very little affected by contamination.

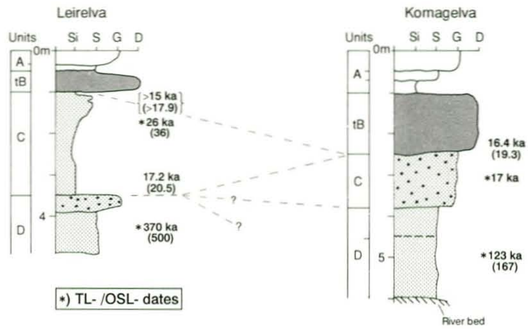


Fig. 43. Correlation diagram for the stratigraphies from the Leirelv and Komagelv localities. Ages given in parantheses are calibrated/corrected (see Tables 1 and 2.1).

Correlation

Based on lithology, stratigraphic relations and AMS dates we correlate the stratigraphies at Leirelva and Komagelva (Fig.43). The uppermost parts of both sections consist of similar sedimentary facies, resembling a typical deglaciation succession from this area: till - glaciolacustrine silt - sand - gravelly diamicton (debris flow and ablation material from ice remnants at ice lake margins). However, only the upper sediments at Leirelva are interpreted as a proper deglaciation succession. At Komagelva, similar sediments (fluvio-lacustrine silt and sand overlain by debris flow deposits) may have been deposited in a local fluvial basin which existed about 3,000 years after the emergence of the locality above sea level during the postglacial period.

We think that there was a subaerial event between the deposition of the glaciofluvial gravel and sand D at Leirelva and the overlying deposits. A subaerial event may also fit in stratigraphically between units D and C at Komagelva. These suggestions are supported by luminescence dates of units D and C (Figs.38,40,43; and Table 2.1: R-943802, R-943801, R-933802a,b, R-933801). It is less likely that there was a significant hiatus between unit C and till tB at Komagelva, and at Leirelva as well. The glaciotectonics in the sediments, the overall coarsening-upwards trend in the glaciolacustrine sediments at Leirelva, and the tills at both localities, are thought to derive from an advancing glacier during a regional phase. The inferred ice-lake in front of the advancing glacier may have existed from c. 17,200 to c. 16,400 yrs. B.P. (Figs. 37 & 44), but because of an inferred minor contamination of the lowest age estimate, together with general considerations of the ice-dammed environment, we think that the duration has been significantly shorter, perhaps less than 100-200 years.

The advancing glacier which tectonised the sediments and deposited the tills at Leirelva and Komagelva was probably not from the final deglaciation, as suggested by Olsen et al. (1996). It is more likely, as we have argued before, that this ice advance was part of a major regional ice advance. We think that this event may correlate with the Late Weichselian maximum ice advance, which ended on the shelf edge in the southwestern Barents Sea area, as also indicated by Olsen (1993a, b). The northerly rather than northeasterly directed ice advance may suggest some influence of ice pressure from the possibly coexisting southeastern Barents Sea and Kara Sea glaciation in the east (e.g. Velichko et al. 1984).

In accordance with our model, the Late Weichselian maximum advance may have occurred c. 16,500 ± 500 ^{14}C-years ago. This is much later than previously thought

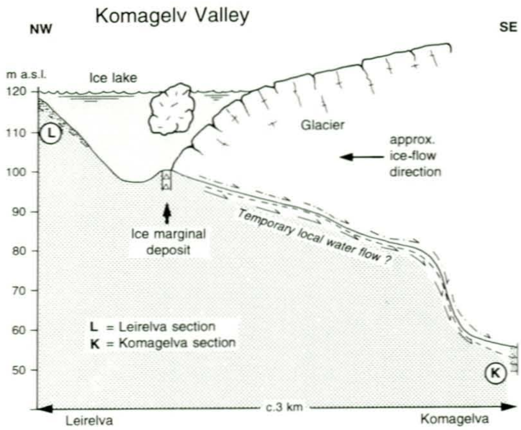


Fig. 44. Sketch of the glacial environmental scenario during the time of existence of the small ice-lake at Leirelva. Possible location of ice-lake margins indicated in Fig.37.

(c. 18,-20,000 years B.P.; e.g. Andersen 1981), but it is actually not in conflict with relevant published shell dates from the shelf area of northern Troms and western Finnmark at c. 70-71°N latitude. If we include all the relevant published radiocarbon dates of samples from the shelf area of Troms and Finnmark and from the island of Andøya, then a Late Weichselian maximum between c. 22,000 and 16,000 years B.P. follows (Vorren et al. 1983, 1990, Alm 1990, 1993, Hald et al. 1990, Møller et al. 1992), and the maximum extension may have been reached during two major ice advances, separated by a significant intermittent ice retreat phase (Vorren et al. 1990).

If such a regional ice advance to the shelf area occurred shortly before 16 ka ago, then the glacial process must have been very much like a surge because of the very narrow time-range available for the entire ice advance-retreat phase across the Norwegian coast at these latitudes (Vorren et al. 1983, 1990, Kverndal and Sollid 1993).

Discussion

Depositional environment of the Weichselian glacial stages

Basal tills constitute the major proportion of till deposits as studied in the sections on Finnmarksvidda. The uppermost ablation till/ debris flow/melt-out till in each glacial formation (deformation/basal till - ablation till/debris flow/melt-out till) is generally less than 0.5-1.0 m thick. Because each glacial formation is usually at least 2-3 m thick, these upper less compacted and normally more coarse-grained parts therefore commonly constitute less than 30% of the volume of the till. The loose coarse-grained tills, which are assumed to derive mainly from deglaciation phases, may, however, dominate the glacial formations in the hummocky moraine landscapes. These are widely distributed but generally concentrated in N-S trending zones on Finnmarksvidda (Olsen 1989a,c, Olsen et al. 1987, 1996). The predominance of basal tills is therefore not so large (perhaps 60-70 %) if we include the hummocky moraines in the total glacial drift volumes of Finnmarksvidda. The distribution of different types of till is different in the coastal areas and in other areas with a much higher relief. There, rockfall materials and debris flows from higher ground have contributed with often coarse-grained materials deposited upon the last melting ice-bodies during deglaciation periods. Along steep valley sides and other slopes these materials were finally deposited as thick ablation material/debris flow/melt-out tills. Such deposits may, at least locally, form the greater part of the glacial formations of these areas.

The basal tills on Finnmarksvidda are commonly homogeneous lodgement tills, but also melt-out tills are widely distributed (Olsen 1988). However, these are the end-members of a continuous variation of basal tills that occur in the area. Both the 'lodgement' and the 'melt-out' processes are probably involved during deposition of most till sheets, and perhaps the most common type of till is situated somewhere between the two mentioned end-members. It has, however, been noted that the pre-Weichselian and Early Weichelian tills are apparently dominated by types closer to the lodgement end-member, while younger tills seem to involve a much larger proportion of melt-out tills (Olsen 1988).

The three major stadials or glacial stages during the Weichselian are represented by three informally named tills (Fig.5F); the Gardejohka Till, the Vuoddasjavri Till and the Kautokeino Till (Olsen 1988). The oldest of these tills, the Gardejohka Till, is represented by both basal till (mostly lodgement till but also melt-out till) and overlying, loose, coarse-grained, deglaciation diamictons. This has been described, for instance, at Vuolgamasjohka (Olsen 1988). The associated glacier must have been temperate with a particularly erosive character. Glaciotectonic structures in the underlying sediment (Vuolgamasjohka Sand) are mainly of soft-sediment deformation types and support the idea of an unfrozen subsurface during the subsequent glacial event (Lyså & Corner 1994).

The glacial stage, represented by the Vuoddasjavri Till, is also thought to have been largely temperate, but perhaps with zones and/or periods when sub-polar ice conditions predominated. The latter is based on the frequently occurring, glaciotectonic, brittle deformation structures in the Eiravarri Sand, indicating frozen ground during deposition of the Vuoddasjavri Till (Lyså & Corner, 1994). The Vuoddasjavri Till is mostly a lodgement till or close to this end-member. In most studied sections, for instance at Vuolgamasjohka and at Vuoddasjavri, the till is commonly eroded in its upper parts and has a sharp upper boundary.

The overlying deposit is either a glaciotectonically deformed gravel and sand (mostly sand) or a till which is representing the Late Weichselian Kautokeino Till. The latter has a lower member which is usually a basal melt-out till, and an upper member which is commonly a lodgement till. The uppermost part of the Kautokeino Till, however, is in most cases a loose coarse-grained diamicton deposited from the last melting ice remnants. In most cases it is the lower melt-out till member that overlies the Vuoddasjavri Till. It is assumed that the frequent occurrence of basal melt-out till in the lower part of the Kautokeino Till and the usually sharp erosional boundary to underlying units, indicate subpolar to polar glacial conditions. We think that the prevailing polar climate which is assumed to have existed prior to the last ice-sheet growth (Lagerbäck 1988, and pers. comm. 1991, 1992), implies permafrost to several metres depth. It is likely that during this period the surface material experienced several cycles of thawing, drying and cryoturbation. This may have produced a very loose surface layer which would have been most easily eroded during the advance and growth of the last ice-sheet. Subsequently, the basal ice-zone with stratified glacial drift was probably frozen to the ground, and this may have lasted for most of the remaining part of the Late Weichselian glaciation. During later stages of the last glaciation, when the ice margin recession had started from the shelf to the coastal areas and the ice sheet became thinner, then the ice conditions changed gradually to a more subpolar-temperate type. The temperature rise downwards in the glacier seems to have happened fast enough in most places to reach the base of the glacier before deglaciation, and thus the glacier finally became wet-based (temperated). This is shown by the youngest ice movement directions indicated by clast fabrics in lodgement tills, striations, drumlins and flutings (Olsen et al. 1987, 1996, Olsen 1988, 1989c).

Several authors have shown that extensive areas in Central Scandinavia and in Central Lapland (northern Sweden and adjacent parts of northern Finland) were covered by a cold-based ice sheet during the entire Late Weichselian glaciation (Lagerbäck 1988, Sollid & Sørbel 1988, Kleman 1992). It is therefore possible that the glacier in very small areas, also on Finnmarksvidda, may have been cold-based and frozen to the ground even as the last ice remnants melted (Olsen 1988). In the southeasternmost part of Finnmarksvidda and adjacent areas of Finland, for example, small areas exist where the youngest ice movement seems to have had only a very weak influence on evolution of the landscape. In these areas the ice may have remained cold-based to a very late stage during the last deglaciation period.

The ages and environments of the ice-free intervals

Distribution of TL and OSL dates

TL and OSL dates of waterlain, mainly glaciofluvial sediments from ice-free intervals in inland areas of Finnmark are given in Table 2.1. The table encompasses 49 analyses from this area, and the ages seem to group into some more or less distinct intervals along the time-axis for the last 350 ka (Figs.45 & 46). To test the apparent clustering of dates, more TL and OSL dates from other inland areas of Fennoscandia (52 analyses; Appendix C, p.111) have been added and are shown in Fig.46.

Several of the dated samples both from Finnmarksvidda and from adjacent inland areas give considerably higher TL and OSL ages than suggested from lithostratigraphy and regional correlations of the sampled units. The luminescence signals from most of these samples, for example R-823801, R-823820 and R-863804b (Table 4), showing good plateaus and good zeroing with 0-19% residual doses, are otherwise similar to those from the dates that coincide with the inferred ages of the sampled units. Therefore, we think that most of the dates with much higher than expected ages may have inherited a previous TL or OSL signal (zeroing) from earlier depositional ice-free events. This means that any TL or OSL date which gives a luminescence signal indicating some kind of previous zeroing of stored radiation may represent an ice-free interval; and a TL or OSL signal from a sediment sample may not always have been influenced by a subsequent reworking or redepositional event (Olsen 1988). In this way of thinking, we may say that despite the fact that half of our dates are much higher than the expected ages of the sampled units, the distribution of all of the dates shows maxima indicating intervals of ice-free conditions with a corresponding minimum extension of the ice-sheet (Fig.46).

Comparison between TL-/OSL-dates and other parameters used for monitoring glacial fluctuations

In a similar way as we think that maxima in the distribution of luminescence dates of sediments from the Fennoscandian inland area indicate minima in glacial extension, Baumann et al. (1995) use records of maxima in ice-rafted detritus (IRD) from well-dated sediment cores from the Norwegian Sea covering the past 150,000 years to indicate maxima in ice-sheet extension. They correlate the continental record of glacier fluctuations in western Norway with these data and conclude that there is a close similarity between the glaciation curve constructed from continental records and the IRD curve.

It is not to be expected that almost completely ice-free conditions in the inland area, as reflected by a TL-maximum, should exist at the same time as the ice-sheet had a large westerly extension, which is a requirement for IRD-production. During the last deglaciation period there was a delay of 1000-3000 years between the last significant IRD-production at the ice margin in the outer coastal areas to almost complete deglaciation of inland areas. In general, a lag in this order between such events may be expected.

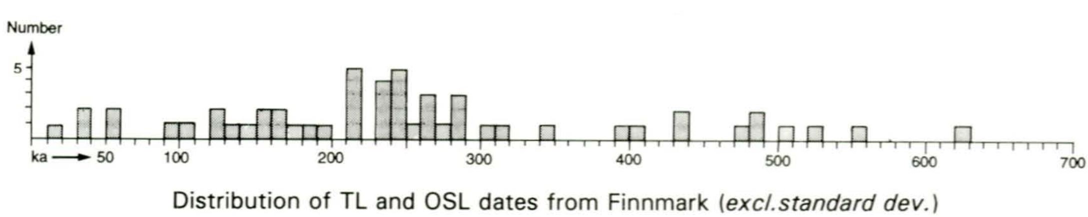


Fig. 45. Distribution of TL and OSL dates from waterlain sediments on Finnmarksvidda (all dates above 40 ka) and from Varangerhalvøya (those lower than 40 ka). Note that standard deviations of dates are excluded in this figure.

TL-maximum 1 peaks at 53-55 ka B.P. for Finnmarksvidda and adjacent inland areas in Fennoscandia (see cover illustration). $CaCO_3$ and ice-rafted detritus (IRD) data from the Norwegian Sea show ice growth with glacial expansion in coastal western Norway from c. 70 ka, and glacial culmination on the continental shelf with subsequent deglaciation at c. 54.5 ka (Baumann et al. 1995). If TL-maximum 1 indicates deglaciation in the inland area in correspondence with this glacial expansion and subsequent deglaciation, then the expected age of this maximum should be closer to 50 ka. It is striking to see that several of the TL-maxima appear to correspond quite closely with the IRD-peaks of Baumann et al. (1995). In addition to TL-maximum 1 at 53-55 ka and the large IRD-peak at 54.5 ka (cover illustration), this applies for the TL-maximum 2 (95-100 ka) and a small IRD-peak at 90-95 ka, TL-maximum 3 (130-133 ka) and a medium IRD-peak at 130 ka and large peak at 124 ka, and finally, the TL-maximum 4 (145-147 ka) and medium IRD-peak at 145 ka and large peak at 140 ka. With a correction coefficient for TL-dates of 1.3 instead of 1.35 which we have used (p.10), there will be a displacement of a few thousand years (2,500-5,000 years) towards lower ages for the TL-maxima. This gives a consequent succession of IRD-peaks followed by TL-maxima for all the mentioned groups of IRD- and TL-maxima indicating a close correspondence between TL-maxima and IRD-peaks. This relationship implies a mutual support between these parameters and emphasises the value of the distribution of both TL-and IRD-peaks as combined monitors for major glacial fluctuations. On the other hand, the discussion above also emphasises the need for further development with minor adjustments of the correction equation of TL-dates.

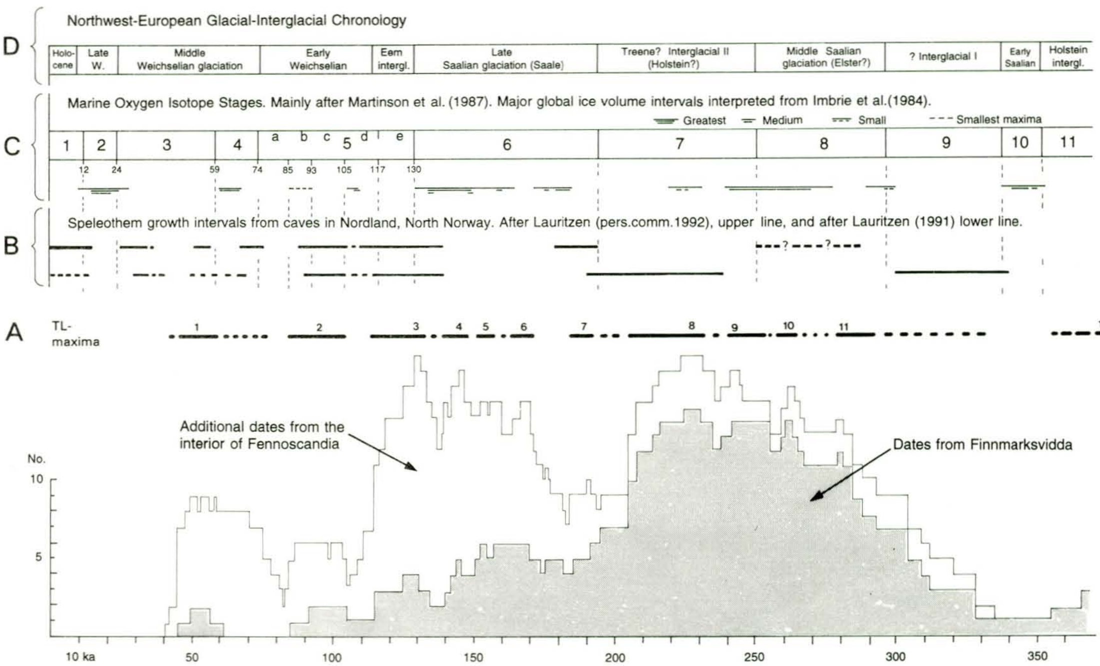


Fig. 46. Distribution of TL and OSL dates mainly from waterlain (and some from windblown) sediments from the inland areas in Fennoscandia, including those from Finnmarksvidda (Fig.45). Standard deviations are included in the figure, and data are taken mainly from published sources (see Table 2.1). The intervals around the peak number of dates are indicated as TL-maxima and numbered from 1 to 12 (A). Speleothem growth periods, as reported by Lauritzen (1991; and pers. comm. 1992), are indicated in the diagram for comparison (B). Oxygen isotope data (C) are taken from Martinson et al. (1987) and Imbrie et al. (1984). The preliminary Glacial - Interglacial chronology which we have used in this work is indicated on the top (D). The most frequently used alternative subdivisions, including the Saalian, the Holsteinian and the Elsterian, are indicated in parentheses. Smoothed curves of A, B and C are indicated on the cover illustration, where also the peaks of ice-rafted detritus (IRD) from the Norwegian Sea for the last 150,000 years are shown (IRD data after Baumann et al. 1995).

Speleothem growth is thought to be a good indicator of ice-free conditions, and therefore we have made a comparison between our TL-intervals and the intervals of U/Th-dated speleothem growth in caves in Nordland (Lauritzen 1991, pers. comm. 1992). It shows a fairly good correspondence for the first, second, third, the seventh to eight and the tenth to eleventh TL-intervals (indicated with horizontal bars at the ages of peak numbers of luminescence dates) counted from the present (Fig.46). Only samples from the inland area are included in Fig.46, and consequently, luminescence dates representing samples from the coastal area (for example R-933801 and R-943801; Tables 2.1 & 2.2) are excluded in this comparison. From the smoothed curves on the cover illustration a close correspondence can be seen between luminescence dates and speleothem growth periods between 130 and 50 ka ago. A TL-interval corresponding to the distinct speleothem growth top at 30-35 ka ago has not yet been found in the inland region. On the other hand, there are no speleothem growth periods corresponding to TL-intervals four, five and six about 140-170 ka ago, and apparently no such periods corresponding to TL-interval nine about 240-250 ka ago either (Fig.46). This may be explained by discontinuous background speleothem data. For example, extensive ice-covered areas may have existed in the mountanous western part of northern Fennoscandia, thus preventing speleothem growth in the investigated caves in Nordland county during these intervals. This is supported by global ice volume data for some, but not all of the intervals, as will be mentioned later. Discontinuity in the speleothem data may also be caused by erosion and removal by fluvial and glaciofluvial subsurface drainage. The lesser correspondence between luminescence intervals and speleothem intervals of higher ages, compared with those of lower ages, may alternatively simply be explained by an error in the luminescence age correction which we have used in this paper. If the correction coefficient is too high, then the error is increasing with increasing age. This may explain the apparently lower correspondence between intervals above c. 140 ka. A different correction coefficient, for example one which varies with age instead of a constant 1.35 for all ages above 16 ka which we have used (p.10), may give a better correspondence between speleothem and luminescence intervals, at least for some age intervals. If U/Th-dates of speleothems are more reliable as age determinations than TL/OSL-dates of glaciofluvial sands, which we do not in fact know, then it is obvious that the luminescence age correction equation has to be studied more carefully, developed further, and consequently, possibly changed in future investigations.

The U/Th, TL and OSL methods evidently have a potential for the dating of ice-free intervals of long duration and simple character. It is more difficult, on the other hand, to evaluate such dates deriving from short, or long and complex ice-free intervals. For instance, within the interval 90-140 ka (Fig.46) there is a record of a glaciation (c. 110 ka) with a till deposited at least in the innermost parts of northern Fennoscandia (Hirvas et al. 1988, Lagerbäck 1988, Olsen 1988). Although there is a minimum at around c. 110 ka, several standard deviations of dates overlap this age as indicated in the generalised TL/OSL - diagram (Fig.46). However, if we exclude the dates from localities outside the area covered by the '110 ka'- glaciation, with ice margins as suggested by Olsen (1988), then at most just one date in the time-interval of 110-115 ka will be left in the diagram. This gives, consequently, a clear minimum at around 110 ka. However, the precision of these methods is not good enough to eliminate all the dates in the glaciated intervals. Statistical overlap would therefore be expected through such intervals during the early Middle Weichselian or older glacial periods. The precision of these methods is probably better compared to the length of the glacial or non-glacial intervals during younger periods, but some statistical overlap of short intermittent intervals are to be expected also here.

A similar approach may apply for the speleothem dates. If we exclude dates from the assumed ice-free areas during the '110 ka'-glaciation, then the speleothems with the continuous growth interval from 140 to 90 ka will be removed from the generalised

U/Th diagram. The dates will still be distributed throughout the 90-140 ka interval, but a non-recorded short interruption in speleothem growth during the assumed short-lived '110 ka' glaciation may now be explained simply by the low statistical precision of the dating method.

If we now compare the luminescence dates with the oxygen isotope record from deep sea sediments (Fig.46), for instance that of Imbrie et al. (1984), then we will see that there appears to be a weak to fairly good correspondence with most stages from 2 to 11. The best correspondence is found for stages 2, first part of 3, parts of 4, 5c, 5d, 5e, first, middle and last part of 6, and finally, parts of 7 (see also cover illustration). In addition, in Fig.45 there are ten TL/OSL dates (all from Finnmarksvidda) of more than 350 ka which correspond with isotope stages 11 to 15; or in terrestrial stratigraphic terms, the restricted older alternative of the European Holsteinian Interglacial (stage 11, after Šibrava 1986) and older chronostratigraphic intervals.

It would appear that the ice volume minimum during stage 5a is not found as a TL-interval, but rather as a clear minimum in the TL-date histogram (Fig.46, and cover illustration). A similar, but opposite trend is recognised for stage 5b. There seems also to be little correspondence between stages 8 and 9 and the distribution of TL-dates. The ice-free events and glacial variations in central northern Fennoscandia may therefore be out of phase with the global ice volumes during stage 9 and the last parts of stages 8 and 5. However, we will emphasise also in this case, that a luminescence age correction coefficient different from the one we have used may give a better correspondence for some age intervals.

The oldest Pleistocene ice-free intervals on Finnmarksvidda

Based on TL and OSL, the ice-free intervals that are represented by *in situ* or reworked sediments on Finnmarksvidda, with the interruption of at least 7, perhaps more than 10 glacial intervals, date from more than 350 ka ago to the present. The oldest interval represented by waterlain sediments below the Sargejohka till tJ is undated (Fig.34), but two possible ages may be suggested. If we compare with the $^{18}O/^{16}O$ record (Fig.46), the two ages, either c. 285 ka or c. 325 ka, particularly the latter, accord well with the other suggested ages and correlations. As there is no proper pollen record from this interval, it may be either of interglacial or interstadial character.

The subsequent ice-free interval, represented by sand and gravel I between Sargejohka till tJ and tH (Figs.21 & 34), is TL and OSL dated to c. 145 and 225 ka (uncorrected ages) or c. 196 and 304 ka (corrected ages, with average age c. 250 ka; R-913803, Table 2.1). Unfortunately, we have no pollen record for this interval either. However, based on the similarity in age estimates for this and the following ice-free interval (which includes the Bavtajohka interglacial), this interval is suggested to be of interstadial character.

The Finnmarksvidda Thermomer (including the Bavtajohka Interglacial)

The ice-free interval following the Sargejohka till tH is named the Finnmarksvidda Thermomer (p. 62) which includes the Bavtajohka interglacial (Figs.21 & 34). TL and OSL dates suggest an age of around 205-285 ka for the entire ice-free interval, and around 250-260 ka for the Bavtajohka Interglacial, and the environment inferred from pollen analysis has optimally been as it is now in this area today; i.e., an interglacial climate and vegetation with an annual mean temperature of about 0°C, a mean July temperature of c. 15°C and an open birch forest with scattered pines. It was probably not quite so climatically favourable in the Bavtajohka interglacial as it was during the last interglacial (Eemian). However, the latter is difficult to evaluate properly because there is no complete pollen record of the last interglacial from sites in the vicinity. The closest, complete, inferred Eemian sites are the Leväniemi locality in northern Sweden (Lundqvist 1971) and the Tepsankumpu locality in northern Finland (Donner et al. 1986), both with definitely warmer pollen-signals than the Bavtajohka interglacial beds. The latter is situated about 150-200 km farther north than these Eemian sites. This may account for some but probably not all of the differences in pollen signature. The differences are slightly greater than what we would expect if the Eemian climatic gradient corresponded perfectly with the present one. Although we don't know if, or by how much the Eemian climatic gradient was different in detail as compared to the present, and despite the fact that we have no complete Eemian pollen record from Finnmarksvidda, we will later in due time be able to argue for a much warmer climate during the Eemian than today, based on pedological evidence.

The Finnmarksvidda Thermomer (included the Bavtajohka interglacial) is thought to be represented by thick beds of glaciofluvial or fluvial sediments also at the Vuoddasjavri, Buddasnjarga and Gamehisjohka localities. At the latter locality the sediments contain several thin organic horizons which probably represent this ice-free period.

It is suggested that the Bavtajohka interglacial corresponds to the Drenthe-Warthe interstadial/interglacial in Germany that has been TL-dated by the dating of corresponding paleosols to the interval 195-240 ka (uncorrected ages; Stremme 1987). It also seems to correspond with oxygen isotope stage 8/7 (Fig.46), and possibly also with the Salthølene speleothem Chronozone from caves in Nordland (Lauritzen 1991, and Fig.46B; U/Th-dating interval from 200-240 ka).

In a thorough study of sediment cores from the GIN sea (Fig.1) north of Iceland, Eide et al.(1994) have found that the warmest climate during the temperate oxygen isotope stages (or 'the superinterglacials') 5, 7, 9 and 11 was reached during stage 5 (5e). The climate during 5e was significantly warmer than the present. During stage 11 the warmest climate was similar to today, while stage 7 was similar or perhaps slightly colder than the present. During stage 9 the climate was relatively cold and should probably not be regarded as a typical interglacial climate. The climatic signal of the Bavtajohka interglacial sediments indicates an optimum similar to today (Fig.19B,C,D), and probably slightly colder than the postglacial optimum (?). Thus, both the TL-/OSL-age and the climatic signal may correspond very well with an early oxygen isotope stage 7 age for this interval.

The first ice-free interval after the Finnmarksvidda Thermomer

The subsequent ice-free interval is represented by double fining-upward successions, unit I, at Vuoddasjavri (Fig.8). This may indicate two, major, gradually decreasing pulses of glaciofluvial outwash during a limited ice-retreat phase, and the associated ice-free interval may be restricted to the coastal areas and northern Finnmarksvidda. Glaciers may still have existed in the inland areas.

The Vuolgamasjohka Thermomer

The following ice-free interval is represented by the thick, overall fining-upward sequence of the Vuolgamasjohka Sand at Vuolgamasjohka (Olsen 1988, and Fig.5B: sections 3-4), and by several coarsening-upward sequences at Vuoddasjavri (unit G; Fig.8) and Sargejohka (unit E; Fig.21). The interval was named the Vuolgamasjohka Thermomer by Olsen (1988) (Fig.34), and it was correlated with the last interglacial, the Eemian *(sensu lato)*, based on two TL dates and correlation of the overlying stratigraphy with that in adjacent areas of Finland. The strongly weathered character of the paleosol developed in unit E at Sargejohka suggests an interglacial environment, which supports a correlation with the Eemian also for this unit. However, it is likely that the Vuolgamasjohka Thermomer includes more than the last interglacial, as the interval started during the Late Saalian deglaciation and continued to the first part of the Weichselian glaciation. Thus, the environment is thought to have changed from arctic to subarctic to warmer than present and back again to arctic conditions during this period.

The beginning of the Vuolgamasjohka Thermomer, as represented by sediments at Vuolgamasjohka and Vuoddasjavri (Fig. 34), and also represented by other corresponding sediments at a few other localities in surrounding areas, is TL and OSL dated to c. 108 ka. This age is an average of eleven dates ranging from 69 to 134 ka (Table 2.1: R-863804a,b; R-863802a,b,c,d; R-823817-823819; and R-933802a,b).These dates are not corrected for a previous higher water content and escape from 'shallow traps'. If we make such corrections then the average will be c. 146 ka, which may be taken as a rough estimate of a Late Saalian deglaciation, thus suggesting an initial stage of the Vuolgamasjohka Thermomer prior to the last interglacial. The range of ages may suggest a duration of the ice-free interval from the Saalian deglaciation, through the last interglacial, and lasting even to the first part of the Weichselian. If the latter is correct, then at least some of the dated sediments are likely to have been misinterpreted as deglaciation sediments, and should rather have originated from proglacial environments existing during the ice advance. Alternatively, the youngest luminescence dates from this interval are too young as they indicate an early Early Weichselian age. We have put forward a hypothesis of secondary zeroing of the luminescence signal due to strong oxidation and subsequent glaciotectonics to explain such underestimated ages, but this hypothesis need more research before it can be confirmed or rejected as the case may be.

In the course of this ice-free period the environment changed to more favourable conditions. However, the poor pollen record from unit G at Vuoddasjavri (p.30) and from subunit J1 on top of the Vuolgamasjohka Sand at Vuolgamasjohka (Olsen 1989a) cannot be interpreted as anything warmer than a birch, shrub and herb-dominated vegetation. The few, warm, tree-pollen grains and types recorded may have been transported by wind from remote areas. The extremely well developed 'red-yellow' soil profile (podzol), and the strongly weathered B/C-horizon of this paleosol in unit E at Sargejohka (Figs.25A, 26A, and Table 8) therefore provide much better arguments for a very warm interval within the Vuolgamasjohka Thermomer. An additional argument for such an interval is provided by another paleosol which is thought to derive from the last interglacial. This paleosol is developed in the till at Buddasnjarga (Figs. 32 & 33), and the oxidation and weathering of this soil profile have reached deeper than in any other similar paleosol in Norway, as far as we know at present. The oxidation depth is also much greater than in any known Norwegian postglacial soil profiles developed in similar material. The soil profile has an overall reddish-brown colour inferred to be caused by the *in situ* production of haematite and other minerals ascribed to oxidation. The process involved is generally called 'rubification', and it is known only from temperate areas with an annual mean temperature of at least 7°C and a mean precipitation of at least 500 mm per year (Smith et al. 1987). Such climatic conditions have not existed on Finnmarksvidda since the last interglacial period. If we have correlated correctly, then this is a strong argument for a very warm interval within the Vuolgamasjohka Thermomer. It also provides important evidence of an Eemian climate that was up to 4-5°C (annual mean temperature) warmer than during the postglacial optimum on Finnmarksvidda. This temperature difference is slightly greater than that between the average air-temperatures of the warm phase of the Eemian and the postglacial optimum, as recently recorded in the summit ice core from Greenland (GRIP Members 1993, Nielsen 1994).

The average Eemian sea-surface temperature in the Kara Sea area was up to c. 4°C warmer than during the present (V.I. Astakhov, pers. comm. 1993). The summer air-temperature above the Norwegian Sea at this latitude (69°N) was, however, according to Sejrup & Larsen (1991), only some two degrees warmer during the Eemian than at the present. Therefore, if the correlation of the paleosol with the Eemian is correct, then the oceanic influence with temperate winters and the continentality with warm summers must have been much stronger during the Eemian than at the present day. This requires a different atmospheric circulation pattern with more winds coming from the west during the Eemian winters and from the south and southeast during the Eemian summers than during the Holocene winters and summers, respectively.

The Eiravarri Interstadial

The first major Weichselian interstadial is represented by the glaciofluvial Eiravarri Sand formation at Vuolgamasjohka. This interval is named the Eiravarri interstadial (Olsen & Hamborg 1983, 1984, Olsen 1988). Although the Eiravarri Sand generally has an abrupt lower boundary, in places the boundary is gradational or transitional into the underlying Gardejohka till. This, and the overall fining-upwards trend in the lower parts of the sand formation, indicates a deposition during deglaciation of the Early Weichselian Gardejohka Till glaciation. A TL date of c. 96 ka (uncorrected) derives from the middle part of the Eiravarri Sand formation (R-823817; Table 2.1).

The last part of the Eiravarri interstadial is thought to be represented by the overall coarsening-upward succession of sand and gravel E at Vuoddasjavri. This unit has an abrupt erosional boundary to the underlying till and a partly transitional, partly erosional boundary to the overlying Vuoddasjavri Till. TL and OSL dates from the lowermost part of unit E give ages of 170-180 ka (uncorrected; R-823805, R-863803a,b,c,d; Table 2.1), or more than 200 ka if corrected according to our procedure. The underlying till tF is eroded and glaciofluvially 'channelised' in the southwestern part of the gravel pit. One channel cuts through the till tF bed and more than three metres into the underlying unit G. Based on these data it is easy to imagine how the sand in the lowermost part of unit E may have originally derived from the underlying unit G, by erosion and redeposition, and thus may explain the extraordinarily high TL/OSL ages attained. The short transport after erosion was probably insufficient to have significantly affected the previous zeroing of the TL/OSL-signals, as also indicated by TL-dating of short-transported glaciofluvial deglaciation sediments from western Finnmarksvidda (Olsen 1988).

Two luminescence dates from the uppermost part of unit E give ages of 178 ka (TL) and 349 ka (OSL), respectively (R-913805, Table 2.1, uncorrected ages), indicating no zeroing of the TL- and OSL-signals during final deposition. The dates may indicate redeposition of previously zeroed sediments of, for example, Middle Saalian or Holsteinian interglacial age (c. 250 - 450 ka), but the TL-date at least is difficult to evaluate precisely because the measurements show no plateau although the residual dose is as low as 5% (R-913805; Table 4).

Based on the theory that a short transport of a sediment in a river with a normal to high flow rate, a high suspension density, and therefore a restricted daylight exposure of the individual grains, does not affect the TL/OSL-signal significantly (p.12, and Olsen 1988), and if we accept the till stratigraphical correlations of Olsen & Hamborg (1983, 1984), then one more TL date may be taken to represent the Eiravarri interstadial. This is from the Kautokeino gravel pit, and the age given is 74 ka uncorrected, or *101 ka corrected (Olsen 1988, and Table* 2.1: R-823801). Therefore, the age of the Eiravarri interstadial, based on two TL dates (R-823801 and R-823817), is c. 74-100 ka with an average of c. 88 ka. If we make corrections for an inferred, previously higher, water content (Olsen 1988) and 'shallow traps' (p.10), then an average close to 115 ka is attained. This age may be regarded as a rough age estimate for the beginning of this ice-free interval, but it may equally well represent a slightly altered age of redeposited, or better, reworked material from thick and closely spaced underlying sediments which were originally deposited and TL-zeroed during the last interglacial.

The sparse and discontinuous pollen record for the *Eiravarri interstadial* suggests a birch, shrub and herb-dominated vegetation, indicating subarctic to subboreal open birch forested conditions. However, if the warmer tree-pollen recorded at Balučohka and Åskal (Table 5.1; p.12) derive from local contemporary living plants and not from older units or remote areas (airborne), then a more favourable climate would have existed during the Eiravarri interstadial.

The Eiravarri interstadial is correlated with the Peräpohjola interstadial in Finland and the Jämtland interstadial in Sweden (Hirvas et al. 1988), and therefore possibly to both the Odderade and the Brørup interstadials in Germany and Denmark, respectively (Olsen 1988, Robertsson 1988). Both these periods are known as warm, wooded interstadials with trees growing at least as far north as the northeasternmost part of Sweden (Robertsson 1988), and therefore probably also in the southern part of Finnmarksvidda. Such climatic conditions together with the added length of these periods may have been important factors in developing such a deep and well-developed soil profile as that occurring in till tD at Sargejohka (p2 in Figs.21, 27C). The recent soil profiles developed in similar diamictons in this area are normally much thinner and not so well developed. The time available during the Holocene may therefore have been significantly too short to have allowed the development of a soil profile like p2 in the postglacial period in this area. If this is correct, then the extension of the Eiravarri interstadial from approximately 10 ka duration as suggested by Olsen (1988), to at least 20 ka (Olsen 1993b), may give the necessary length adjustment to help explain the development of the correlative soil profile.

The Sargejohka Interstadial

The second major Weichselian interstadial, named the Sargejohka interstadial (Olsen 1988), is represented by reworked organic-bearing sediments in the basal part of till tB at Sargejohka (Figs.21 & 24A,B), and waterlain sediments at Vuolgamasjohka (section 11, Fig.5B), at Vuoddasjavri (Figs.12 & 13), and at several other places on Finnmarksvidda (Olsen & Hamborg 1983, 1984, Olsen 1988, *in press*). The age of this interstadial is probably Middle Weichselian, but a complex multi-stage interval with an initial stage as early as the latest part of the Early Weichselian cannot be definitely ruled out for this ice-free period.

The late Early Weichselian period, including the relatively warm Odderade interstadial in the northern part of the European continent, seems to be a part of either the Eiravarri interstadial (Olsen 1993b), or the Sargejohka interstadial (Olsen 1988). The most important argument for a partly Early Weichselian age of the Sargejohka interstadial was a suggested correlation with the Tärendö interstadial in North Sweden, which has been correlated with the late Early Weichselian Odderade interstadial based on a birch, shrub and herb-dominated vegetation and on general lithostratigraphy (Lagerbäck & Robertsson 1988). It has been a kind of 'common sense' to think that such a vegetation, even if the birches were of a shrub-like type, could not have existed during a Middle Weichselian interstadial in the middle and northern parts of Fennoscandia (Mangerud 1991a,b,c). New data from these areas challenge this view. This information comprises both ^{14}C-dates and TL/OSL dates which indicate Middle Weichselian ages of sediments with pollen from birch, shrub and herb-dominated vegetation (Thoresen & Bergersen 1983, Lagerbäck pers. comm. 1991, Rokoengen et al. 1993, Selvik et al. 1993).

The warm oceanic influence of the North Atlantic may have been much more important for areas well away from the Atlantic coasts, and the general atmospheric circulation may have affected the northern areas differently during the Middle Weichselian than previously thought. The suggestion of a N-S climatic gradient close to zero in Scandinavia during parts of the Middle Weichselian, as forwarded by Olsen (1988) and also speculated by Larsen & Sejrup (1990), does in fact seem more realistic today (Olsen 1993a). Based on these considerations we conclude that the late Early Weichselian ice-free events should rather be included in the Eiravarri interstadial. A chronology based on TL dating is not precise enough to exclude such a hypothesis; and at the same time, there is no other information available for us today that serves to reject it.

^{14}C-AMS dates of c. 35 ka on organic-bearing sediment and >45 ka on macrofossils of plant remains from the same complex sediment, represent the Sargejohka interstadial (Olsen 1988, 1989, Larsen et al. 1991; and Table 1: Ua-319, UtC-1392). TL dates of 37 and 41 ka (51 and 56 ka; corrected ages) on reworked sediments, and TL and OSL dates of 26 ka (36 ka, corrected) from glaciolacustrine sediments, are also taken to represent this ice-free interval (Olsen 1988, and Table 2.1: R-823820a,b; R-943801), which therefore seems to be of Middle Weichselian age.

The amount of regional evidence for an almost fully deglaciated Scandinavia during the Middle Weichselian some 30-40 ka ago (Thoresen & Bergersen 1983, Olsen 1988, 1993a, Lagerbäck pers. comm. 1991, Bergersen et al. 1991, Lauritzen 1991, written comm. 1993, Rokoengen et al. 1993) is now so extensive and differentiated that we simply have to accept it. Scandinavia was therefore almost entirely ice-free at least once during the Middle Weichselian. The evidence includes conventional ^{14}C-dates and ^{14}C-AMS dates of plants, animal bones and organic-bearing sediments, U/Th-dates of cave speleothems, and TL/OSL dates of waterlain and windblown sands. The Sargejohka interstadial may either correlate or overlap with this interval. The pollen record from the Sargejohka interstadial indicates a subarctic period with tundra vegetation dominated by herbs, grasses and birches (inferred to be dwarf-birches).

The last major ice advance on Varangerhalvøya and in the southern Barents Sea

Based on lithostratigraphy and AMS dates

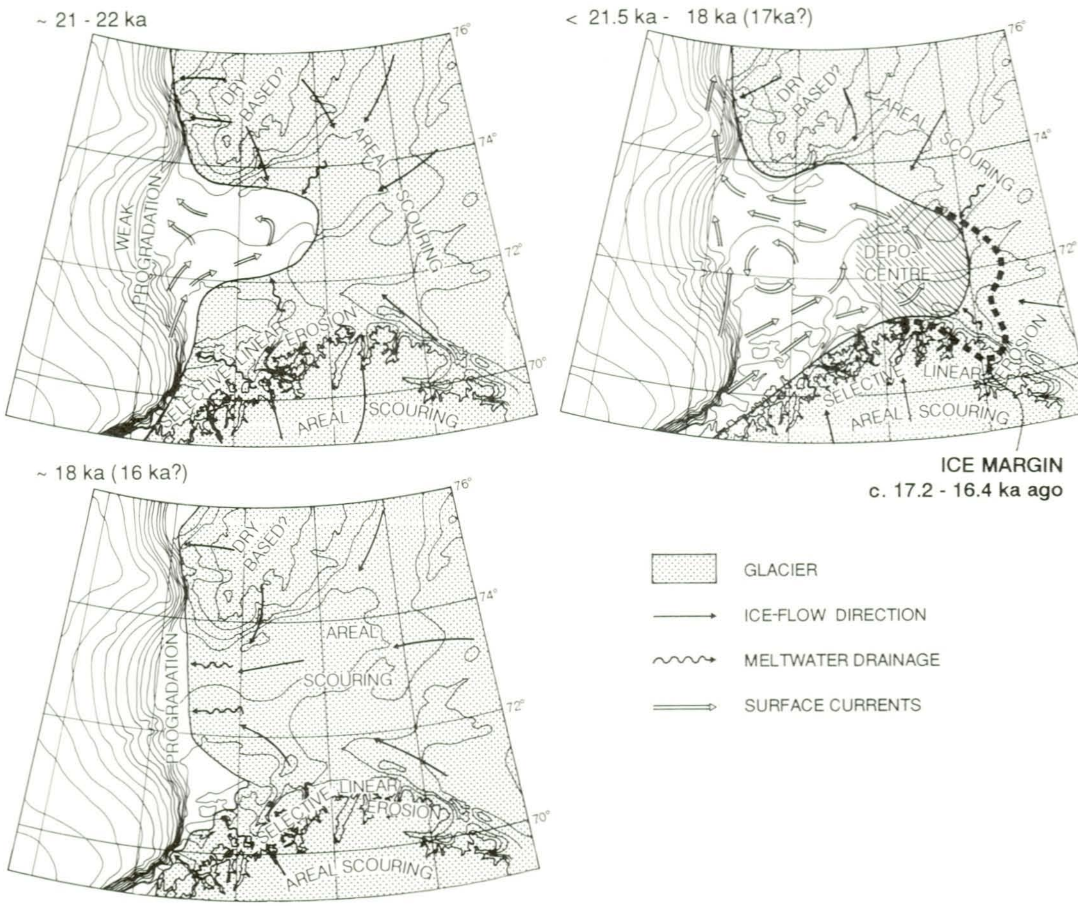


Fig. 47. Maps with sketches of different scenarios indicating the distribution of glacial coverage in the Finnmark and Barents Sea area in the time interval between 21 and 16 ka ago (uncalibrated age). The LWM configuration may have occurred twice during this period, the first maximum stage c. 21 ka and the second possibly c. 16 ka ago. Modified from Vorren et al. (1990).

we conclude that the last ice advance in the Komagelv valley in the eastern part of Varangerhalvøya occurred after c. 16.4 - 17.2 ka B.P. (not calibrated to calendar years). We have argued for a regional rather than a local ice advance during this event, and we have also suggested that this ice advance may even correlate with the Late Weichselian maximum advance. Our hypothesis may either apply as a modification of the two-stage Late Weichselian maximum advance put forward by Vorren et al. (1990), or it may suggest a displacement towards a younger age for a one-stage maximum advance. It is even possible that both scenarios may have existed; for example, the two-stage development in the west and the one-stage advance phase in the east.

The Barents Sea Ice Sheet had its maximum extension after c. 22 ka B.P., as reported by Elverhøi (1993) and Elverhøi et al. (1993). The last ice advance extending to a maximum position on the edge of the shelf of western Svalbard happened probably after 18 ka B.P., as suggested by Mangerud et al. (1992). However, according to Hebbeln (1991, 1992) ice-rafted material in deep-sea sediment cores from the Fram strait between Svalbard and Greenland may indicate that a maximum ice-sheet configuration occurred also just prior to 20 ka B.P. On the southwestern shelf area of Svalbard the maximum advance may have occurred as late as c. 16 ka ago. This follows from high-quality core data reported by Dokken & Hald (1993), and Hald & Dokken (1993).

We think that the lack of ^{14}C-ages in the interval 17-21 ka on samples from the southern Barents Sea area indicates that most of the area was glaciated in this period. On the other hand, if the area were non-glaciated but mainly covered by sea-ice throughout the year during most of this period, it would have been difficult for marine organisms to populate and survive in an environment such as that. This would also explain the apparent time gap in dates.

A warm Atlantic water pulse in the north c. 20 ka ago was first recorded from the distribution of marine organisms (coccoliths) by Gard (1987, 1988), and later confirmed by Hebbeln (1991, 1992) based on a minimum in the distribution of ice-rafted material in deep sea sediment cores from the area between Svalbard and Greenland. This warm water pulse had probably also a significant effect on the sea-water temperature and circulation in the eastern Norwegian Sea and possibly the western Barents Sea area. It is most likely that an embayment of the ice margin developed in the Bjørnøyrenna area during this period (Vorren et al. 1990). This might have occurred either due to calving of a partly grounded marine ice-sheet which may have advanced in the period 22-21 ka ago, or as a result of a rapid melting of an ice shelf or only a more or less continuous cover of sea-ice. In any case, this would imply that there were at least some intervals in which marine organisms were able to invade and survive. This is, however, in contrast to the published record.

There is always a possibility that the geologist may fail to recognise particular stratigraphic levels or not be able to date particular events. On the other hand, the relatively high number of relevant core analyses that are performed and published suggests either that most of the continental shelf off Troms and Finnmark was glaciated during the entire interval between 21 and 17 ka, or alternatively, that the Weichselian maximum advance c. 16 ka ago may have eroded most of the datable material in this area from this interval, and dumped it along the shelf edge. In some areas, for instance in the outer Bjørnøyrenna region and on the adjacent part of the shelf, there are seismic records of large glaciotectonic structures, erosional unconformities and glacially derived debris flows (Sættem 1991, Laberg & Vorren 1992) that may support an idea of substantial erosion during the Weichsel maximum advance over the shelf areas. It is still difficult to accept that the last ice advance onto the shelf should have been able to 'clean' the southern Barents Sea for all 17-21 ka-aged material. We may conclude that although this interval is the longest period (c. 4,000 years) between 45 ka and the present with no dates of shells from these shelf areas (Vorren et al. 1983, 1990, Hald et al. 1990, Elverhøi et al. 1993), the significance of this is not understood. The apparent time gap problem may eventually be shown to be of only statistical origin, such that more samples, analyses and dates may solve the problem by partly filling the time gap.

We suggest that ice, at least sea-ice, covered most of the shelf off Finnmark and adjacent seas in the period between 21 and 18 ka (Fig.47). After 18 ka a rapid ice retreat occurred in Bjørnøyrenna, Nordkappbanken, and Djuprenna adjacent to east Finnmark. The ice retreat seems to correspond with a period when the Komagelv valley on eastern Varangerhalvøya became partly ice-free. However, we have no evidence indicating that the coastal region of northeastern Varangerhalvøya was fully ice-covered during the Weichselian prior to 17 ka B.P.

Subsequently, the Fennoscandian ice sheet advanced over the area, with deposition of basal till at least all over the Komagelv valley. This may have happened as early as 17 ka B.P. The ice advanced probably onto the shelf and it may have reached to the shelf-edge in a Late Weichselian maximum position c. 16 ka ago, possibly as maximum stage no. 2 during the Late Weichselian (no. 1 in western areas, c. 21 ka).

It is quite possible that the eastern part of the Varanger Peninsula was not fully covered by dynamic active ice during the Weichselian before c. 17 ka B.P. This follows from the stratigraphy of several localities in the Komagelv valley, where only one till (of Late Weichselian age) is overlying medium- to unconsolidated weathered sand with remains of a soil profile in its uppermost part, developed during a warm climate (e.g. at Komagelva and Leirelva, pages 63 and 68). If this is correct, then the influence of a possible maximum ice advance about 21 ka ago, and previous Weichselian ice advances as well, had to involve Finnmark mainly west of Varangerhalvøya, while the eastern part of this peninsula was either not fully ice-covered or at least partly covered by cold-based ice with no deposition of till.

The glacial history of Finnmark and adjacent areas in northern Fennoscandia and the SW Barents Sea

Number of glacial cycles. To simplify the further discussion we use a North European stratigraphic and chronological framework (Fig.48) which is compared with a version of the deep-sea Oxygen Isotope Stages after Imbrie et al. (1984). We use the term 'Late' Saalian glaciation for the glacial period which corresponds with isotope stage 6; the 'Middle' Saalian glaciation similarly corresponds with stage 8, and the 'Early' Saalian glaciation corresponds with stage 10. For convenience, and because the older events are not so well correlated in the North European stratigraphy, we name the thermomer between the 'Early' and the 'Middle' Saalian glaciations *Interglacial I*, and the thermomer between the 'Middle' and the 'Late' Saalian glaciations *Interglacial II*. These correspond with isotope stages 9 and 7, respectively. We also assume a correspondence between the Holstein Interglacial and isotope stage 11, as suggested by some authors for this time interval in the Netherlands and North Germany (e.g. Šibrava 1986). On the other hand, we realise that if the Holsteinian is rather of stage 7 age, as inferred by some geologists (e.g. J. Mangerud, pers. comm. 1994), then our 'Middle' and 'Early' Saalian glaciations correspond with the Elsterian glaciations in Germany.

Based on ^{14}C-AMS dates of organic material and organic-bearing sediments, TL and OSL dates of fluvial and glaciofluvial deposits, till stratigraphy, the number of glacial formations and paleosols, we assume that at least three glacial cycles of 100 ka-length are represented by glacial deposits on Finnmarksvidda (Fig.48). We assume that at least seven glaciations within the last three glacial 100 ka-cycles are represented in this area. Using the stratigraphic framework described above we find that the oldest till at Sargejohka (till tJ), which derives from glaciation no. 7, may correspond with an early Middle Saalian or an Early Saalian glacial event. The underlying gravel unit may, therefore, correspond with Interglacial I and isotope stage 9, or perhaps to

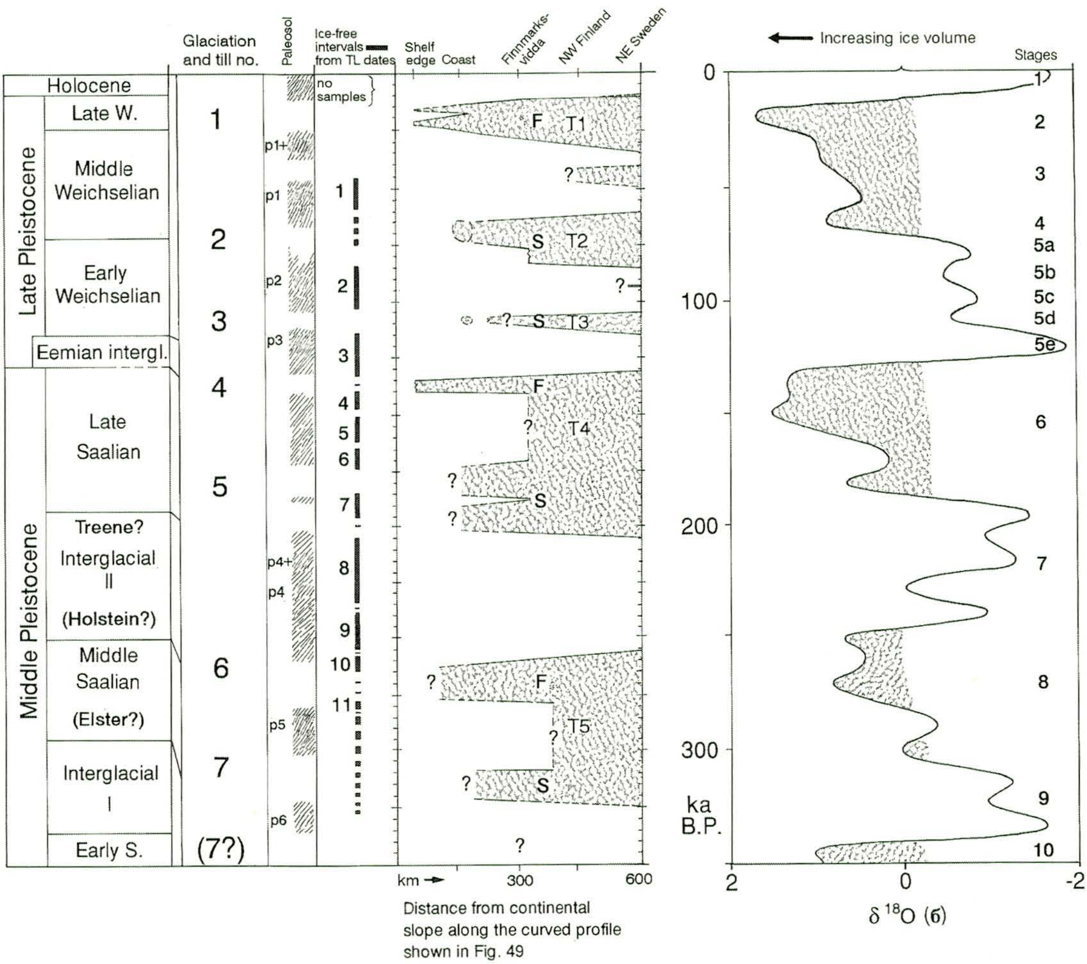


Fig. 48. Glaciation curve for northern Fennoscandia during the last 300 ka. The data from North Finland and North Sweden are taken mainly from Hirvas et al. (1988). For comparison, a stratigraphic framework for Northwest Europe is used in combination with a correlated oxygen isotope chronology, and these data are mainly after Šibrava (1986) for the Middle Pleistocene and after Mangerud (1991) for the Late Pleistocene. The average oxygen isotope curve is from Imbrie et al. (1984). Capital letters F and S in the glaciation curve indicate Fennoscandian and Scandinavian ice sheet configurations as described in the text. T1 - T5 below NW Finland in the glaciation curve profile indicate tills as named in the Finnish stratigraphic framework. Note that tills no. 1 - 3 from North Norway correspond in general with the Finnish tills T1 - T3, while the Norwegian counterparts of the older Finnish tills are thought to be subdivided into more units.

the Holsteinian or stage 11 interval if till tJ is of Early Saalian (stage 10) age.

The TL-intervals appear to be slightly out of phase with the glacial volume minima as indicated by the oxygen isotope curve in Fig.48. This trend seems to be progressively more distinct with increasing age, suggesting that the age correction for the luminescence dates, as mentioned before (p.78), may be too big for high ages. However, to reveal this further both more dates and a further development of the age corrections are required. It is also desirable to find better data for comparative purposes, because the average oxygen isotope data from deep-sea sediments, as used in

Fig.48, cannot be taken as a perfect representation but rather a proxy record of glacial variations in the inland areas of Fennoscandia.

If the Naakenavaara interglacial beds in northern Finland are of Holsteinian age, as suggested by the lithostratigraphy and the rich content of seeds of *Aracites johnstrupii*, which is a peat-forming mire plant that apparently has been extinct in Europe since the Holsteinian (Hirvas 1991), then the number of glacial 100 ka-cycles represented by glacial deposits is at least four in Finland. However, it is not fully clear if the term 'Holsteinian' in this case means the undivided broad interval which corresponds with oxygen isotope stages 7-11, 9-11, the more restricted period corresponding only with stage 7, or stage 11 which we favour. In any case, it is most likely that the stratigraphy in Finland reaches back at least to isotope stage 10 (Finnish till 6; older than Finnish till 5, Fig.48:T5).

If a maximum version of the ice sheets that fed ice streams in Bjørnøyrenna on the Barents Sea shelf existed once, but only once, during each major glacial cycle of the Quaternary, then a number of at least ten major glacial cycles occurred in northern Fennoscandia and the Barents Sea area during the Quaternary. This follows from the existence of ten (?) thick and extensive, seismically mappable, Quaternary depositional units of debris flows located on the continental slope outside the mouth of Bjørnøyrenna, and these are thought to be a result of glacial influence during maximum stages (Laberg & Vorren 1992). The maximum configuration may, however, have occurred more than once during some of the major glacial cycles, for instance during the Late Weichselian (Fig.47), and some of the glacial extentions may not have reached far enough to initiate major debris flows. These factors complicate the counting of glacial cycles. It is therefore even more important to note that at least four of the major glacial cycles appear to be represented by glacial deposits on the mainland in northern Fennoscandia. In the future, drillings may very well reveal even older glacial deposits on land in this area. In our opinion the number of represented major glacial cycles in Fennoscandia is more restricted by current knowledge (or financial resources) than by geology.

Duration of glacial events. The oldest of the seven glaciations represented on Finnmarksvidda may correspond either to the first part of oxygen stage 8, some 300 ka ago, or to stages 9-10, some 300-350 ka ago (Fig.48). Glaciations nos.1, 2 and 3 occurred during the Weichselian, while nos. 4 and 5 existed during the Late Saalian, no.6 during the Middle Saalian and no.7 during the Middle or Early Saalian glaciations. The Weichselian glacial events 1 and 2 are each suggested to have lasted about 20-25 ka or less (Olsen 1988, 1993a,b), while the duration of glacial event 3 seems to have been about 10 ka based on correlation with a regional glaciation existing during oxygen isotope stage 5d (Olsen 1988). This means that Finnmarksvidda was apparently almost ice-free during approximately half of the Weichselian glacial. However, the durations of the ice-free periods, and therefore also the durations of the glacial events, are uncertain. For instance, the well dated glacial event that occurred c. 40-42 ka ago (uncalibrated age) at the coast of southwestern Norway (Unit I at Skjonghelleren; Larsen et al. 1987) is not reflected by the presence of a till in our model, although a minimum in the distribution of TL-dates is recorded at this age (Figs.45 & 46). If a similar glacial event of significant size happened at around this time in the northernmost part of Norway, then our minimum length of duration of glacial events is probably too small. We assume that the minimum number of luminescence dates at c. 20-30 and 40-50 ka from the coastal area, and at c. 75-85 and 105-115 ka from the inland region, as indicated in Figs.45 and 46 respectively (see also cover illustration), may suggest that glacial events of regional significance occurred at around these times. We also think that such glacial events of very short duration, for example less than 5 ka, may have happened during one or more of the maximum TL-intervals. However, it is much too early to decide if the added length of such non-recorded, but possible glacial events is long enough to have had a major influence on our overall calculations.

The duration of a glacial event is obviously dependent on much more than the ultimate size of the glaciation. The prevailing climatic conditions during glaciation, sensitivity for changing external environmental conditions, and the existing ice volumes prior to new ice growth are all important factors for the duration of any glaciation. For instance, a glacial advance of a given size will reach its ultimate extension much faster if the existing ice volumes in the area prior to ice growth were very large rather than small. Furthermore, the sensitivity of the glacial response to change in the external environmental conditions may change dramatically with the size and location of the glacier.

If we use a careful scientific approach to the problem, we may say that our data suggest a total duration of Weichselian glacial events on Finnmarksvidda to be somewhere between 45 and 90 ka. A duration such as that suggested by the maximum version cannot at present be definitely ruled out, but the distribution of TL-dates (Fig.46) provides strong support for the minimum version or a duration close to that.

The Late Saalian glacial events 4 and 5 may have been of long duration, but this is also uncertain. There is no conclusive stratigraphic evidence of a cold-based, major, late Late Saalian glacial event as a counterpart to the Late Weichselian maximum stage. On the contrary, a thick and massive lodgement till (the Mieron Till) is thought to be the youngest Saalian till on Finnmarksvidda. A thick lodgement till is by no means a strong argument for a long period of deposition. If the sliding velocity were high enough, this till bed may have been deposited within a few thousand years.

A cold-based stage may well exist for a long period without leaving much trace of glacial drift deposits on the ground after the ice retreat (Lagerbäck 1988). If such a cold-based stage occurred during the Late Saalian glaciation on Finnmarksvidda, then a major part of the interval between the Finnmarksvidda Thermomer (Isotope Stages 8-7), including the Bavtajohka Interglacial (c. 250-260 ka B.P.), and the Vuolgamasjohka Thermomer (Saalian deglaciation - Eemian) may have been occupied by glacial events. Although a 'negative proof' is at best an indication, we think that the abrupt, erosive upper boundary of the youngest Saalian till recorded in most sections at all key localities on Finnmarksvidda may conceal a potentially cold-based ice phase. If this actually happened, then the glacier would have had to be almost 'clean' and without glacial drift above the frozen bed and the frozen lodged zone. Because there are normally no traces of intermixed zones with a stratified character overlying the lodgement till facies, we assume that the eventual transformation from warm-based to cold-based glacial conditions occurred relatively abruptly. Alternatively, the lack of stratified tills or ablation tills in most Late Saalian successions on Finnmarksvidda may simply be explained by subsequent glacial/glaciofluvial erosion.

The sand underlying the Late Saalian massive lodgement till tF at Sargejohka must have been frozen during the subsequent ice advance. This is indicated by glacial thrusting and low-angle reverse faulting of the sand (Olsen 1984, unpubl. data). In the most extreme interpretation, an entire sheet of till tF of dimensions c. 50-100 m diameter and 1m thickness may also have been detached and slightly thrusted by glacial movements (Fig.17), and this indicates that at least one thrusting phase follows chronologically after the lodgement phase. It is not known, however, if the local evidence of cold-based glacier zones at Sargejohka has a wider significance, and we will not stress this possibility any further here.

If we examine the distribution of U/Th dates of speleothems from Nordland (Fig.46), then it follows that a long interval with no speleothem growth between 140 and 190 ka supports a long duration of Late Saalian glacial events. A different conclusion follows if we compare this with the distribution of TL dates (Fig.46). In the latter case there is a minimum of dates between 170 and 205 ka, and some minor steps in the frequency diagram which may possibly indicate glacial events at c. 140, 150 and 160 ka B.P. The duration of glacial events during the Late Saalian, as interpreted from the TL dates, may therefore have been about 30-40 ka or less.

The durations of the Middle Saalian and the Middle to Early Saalian glacial events as represented by tills tH and tJ at Sargejohka, are also difficult to estimate. In our model we assume that these glacial events correspond approximately with isotope stages 9-8, and they may therefore have a total duration of maximum c. 50-60 ka. We have then excluded an age of minimum 5-10 ka for the intervening ice-retreat phase represented by gravel and sand I. If we compare with the distribution of TL dates (Figs.45 & 46), we find that dates are lacking in very few intervals between 250 and 360 ka. The suggested maximum version is therefore supported by the TL dates only if we include in our calculations the last part of isotope stage 11, and all of stages 10 and 9 in the 'Middle' Saalian period. Some dates indicate speleothem growth in the interval 240 to 300 ka in caves in North Norway, but these dates have not yet been properly verified (S.E.Lauritzen, pers. comm. 1992). This allows speculations on the existence, and a much longer duration, of the glacial events during isotope stage 8 than indicated by the TL dates (Fig.46). Realising the low precision of TL dates in this time interval, we assume that significant ice volumes may well have existed during most of the isotope stage 8 interval in northern Fennoscandia.

Ice sheet configurations and glacial extensions

The early Middle Saalian glaciation. Till 7. The lowermost till (tJ) at Sargejohka represents a Scandinavian Ice Sheet with ice centres which are assumed to have been located mainly in the SW, close to the Caledonian mountain range. The till represents glacial cycle no. 7 counted from the present, and it is therefore named Till 7. The till is the second till underlying the Bavtajohka Interglacial beds, which are TL/OSL dated to c. 260 ka, and therefore we assume at least an early Middle Saalian or isotope stage 8-9 age for the till. Because of the 'Scandinavian' ice centre configuration during this glacial event, we think that the associated glacial extension may have been restricted to the land areas and probably did not reach far out onto the adjacent continental shelf. The Barents Sea may, however, have been glaciated at this time, and if this was the case, then that ice cover would more likely have been a part of a Barents Sea Ice Sheet than a Scandinavian one.

The paleosol which is developed at the top of till tJ (p5 in Fig.21) may suggest an even older age for this till. It may, for example, correlate with isotope stage 10 which implies that unit K, with the remains of a possible p6-paleosol, may be of Holsteinian (isotope stage 11) age.

The late Middle Saalian glaciation. Till 6. The till directly underlying the Bavtajohka Interglacial beds at Sargejohka (tH) and the correlative till (tL) at Vuoddasjavri represent a Fennoscandian Ice Sheet with ice centres assumed to have been located mainly in the S-SE, in the inland area of Finland far away from the Caledonides. These tills represent glacial cycle no. 6 and the corresponding glacial formation is therefore named Till 6. The age of this till is thought to be late Middle Saalian, and the glacial extension during this stage may have reached far out onto the shelf area, possibly even to the shelf-edge. A corresponding Barents Sea Ice Sheet may well have existed and been in physical contact with this glacier with an ice stream flowing out from the Bjørnøyrenna trench.

The Late Saalian glaciation(s). Tills 5 and 4. Tills tH (4) and tJ (5) at Vuoddasjavri are thought to represent two glacial events separated by a possibly limited ice-retreat phase (Fig.48). The ice retreat may have stopped before all of Finnmarksvidda was deglaciated, and therefore we believe that these glacial events belong to the same major glaciation. The age of this glaciation is older than the Vuolgamasjohka Thermomer (Eemian) and also inferred to be younger than the Bavtajohka Interglacial (Isotope Stage 8/7). It is therefore of Late Saalian age. The lowermost till at Vuolgamasjohka (the Mieron Till), till tF at Sargejohka, and the till beds at Gamehisjohka and Bavtajohka are all inferred to represent the same major Late Saalian glaciation. This glaciation is also thought to have had a major Fennoscandian Ice Sheet configuration with an ice flow pattern as for a full-size ice sheet, similar to that of Weichselian maximum age.

The Early Weichselian glaciation. Till 3. The Gardejohka Till at Vuolgamasjohka (Fig.34) and the correlative till at Vuoddasjavri, and presumably also the till tD at Sargejohka, belong to the first Weichselian glacial cycle after the Eemian on Finnmarksvidda. This is glacial cycle no. 3 from the present and the corresponding till may therefore be named Till 3. It is thought to correlate with Till 3 in the stratigraphic framework of Finland (Hirvas et al. 1988, Olsen 1988). Ice flows during this glacial event started by flowing from mountainous ice centres in the SW and W, and perhaps also in the N. It is thought that additional ice domes subsequently occurred along an E-W trending ice-shed zone in the inland area. These may have influenced the ice flow locally, but we do not think that these ice domes had a major effect on the overall ice flow pattern as suggested by Olsen (1988, 1989a,b).

This glaciation was, erosionally and depositionally, a very powerful event with the production of thick tills and large drumlins in northern Fennoscandia (Hirvas et al. 1988, Lagerbäck 1988, Olsen 1988). It is thought that it had a limited extent to the west, as it has not submerged caves located far inland from the coast around the Arctic Circle in central Nordland. This follows from continuous growth of some speleothems found in these caves, in the interval 140 to 90 ka (Lauritzen 1991). It had also a limited extent to the southeast were it is supposed to have ended in the Pudasjärvi area of Central Finland (Sutinen 1984), and it may not have covered much of the southern parts of Finland (Hirvas & Nenonen 1987). Because of the correlation of younger interstadials with the regional North European Odderade and Brørup interstadials, which are thought to be of isotope stage 5a and 5c age, respectively (e.g. Mangerud 1991a), this glacial event is inferred to be an isotope stage 5d glaciation (Olsen 1988).

Mangerud (1991a,b,c) and Larsen & Sejrup (1990) have shown that the glacial extension of approximately isotope stage 5d age was limited also in the southwestern coastal parts of Norway. No till or other glaciogenic deposits between the Brørup interstadial and the Eemian interglacial sediments at Stenberget (Berglund & Lagerlund 1981) and Margreteberg (Påsse et al. 1988) suggest that the 5d glacier did not reach the southernmost part of Sweden. Actually, it is not known if this glacier reached the southern parts of Sweden at all (Lundqvist 1986). Based on TL dates and lithostratigraphy from Poland, some authors (e.g. Lindner 1984) conclude that a pre-Brørup Weichselian glacier may have reached even to Poland, while others, using similar data, suggest that the first Weichselian ice advance to reach Poland occurred c. 60 ka ago (e.g. Drozdowski & Fedorowicz 1987). The 5d ice extension is not thought to have reached Denmark during this interval (Houmark-Nielsen 1989). We may, therefore, conclude that the southern part of this glacier may, at most, have filled much of the Baltic Sea basin, but it probably did not cover very much of the southern margins of this basin.

The 5d ice extension to the north is not thought to have reached beyond the coastline and onto the shelf area, because the regional ice flow in the northernmost part of Norway has apparently been mostly towards the N-NE; and it did not acquire the NW-N flow direction expected for a similar ice extension to that of the Weichsel maximum. In addition, there is so far no proper record of a till of this age, neither in the eastern part of Finnmark nor in the coastal areas in general. This means that a minimum version of the 5d glaciation in the north would have covered only Finnmarksvidda and ended mainly at the head of the fjords. However, the glacier may have reached even to the Komagelv valley on Varangerhalvøya in the east, where sand D at Komagelva may represent deglaciation sediments from the 5d glaciation (Fig.38). It should, though, be added that OSL dates of sand D at Komagelva and the correlative unit at Leirelva (Fig.43) indicate rather a

Saalian to Eemian age for these sediments. This problem remains to be solved before we can reach any conclusion about the extension of the 5d glacier in the northeast. In addition, if separate ice centres existed in the high coastal mountains in the NW during stage 5d, then the total extension of ice cover may have been larger and the ice flow pattern slightly different than we have stated.

The Middle to Early Weichselian glaciation. Till 2. The Vuoddasjavri Till (Vuolgamasjohka, Vuoddasjavri; Fig.34) represents the second glacial cycle during the Weichselian in Finnmark. It is also the second glacial formation counted from the present, and it may therefore be named Till 2. It correlates with Till 2 in the stratigraphic framework of Finland (Hirvas et al. 1988, Olsen 1988). The Till 2 glacial expansion is thought to have been wide, and the ice margin may have reached to the innermost part of the continental shelf. No proper correlative of this till is found in the easternmost coastal part of Finnmark, and the extension of the corresponding glacier to the east/northeast is therefore unknown. Stratigraphies and dates from the Komagelv valley on Varangerhalvøya suggest, however, that the only Weichselian glacier to have covered this area was of Late Weichselian age (p. 86). Coastal ice domes related to pre-existing local ice caps in the west may have existed during the Till 2 glacial event. However, the main configuration of ice flow pattern is assumed to have been of Scandinavian Ice Sheet type with ice centres located close to the mountains in the SW.

Olsen (1988) suggested that this glaciation was of isotope stage 5b age. However, if the extension of the Eiravarri Interstadial to include both the Brørup Interstadial (stage 5c) and the Odderade Interstadial (stage 5a) is correct (p. 82), then the Till 2 glacial event must be younger than isotope stage 5a. We assume now that the age of this glacial event corresponds with isotope stage 4 (Olsen 1993b; Fig.49), with an ice advance phase possibly already during stage 5a; and we have argued for this by referring to TL/OSL dates and comparisons with stratigraphies in Finland and Sweden, and also taking into account the nearby regional oxygen isotope data from deep-sea cores as published in the literature (p. 79). We have also noted that the Barents Sea Ice Sheet apparently had a major extension over the Svalbard region during isotope stage 4, as indicated by a peak in the amount of ice-rafted material in deep-sea cores west of Svalbard (Hebbeln 1991, 1992). Although the Till 2 glacial expansion of the Scandinavian Ice Sheet appears to be less extensive than the corresponding Barents Sea Ice Sheet, it was most likely the Weichselian glacial event that came closest in extension to the Late Weichselian maximum. This is also demonstrated for the stage 4 glaciation in the southwestern, and possibly also the southern part of the ice sheet (Drozdowski & Fedorowicz 1987, Houmark-Nielsen 1989, Larsen & Sejrup 1990, Strand Petersen 1990, Mangerud 1991a,b,c).

This glaciation may have started the U/Th-clock (by compaction) c. 59 ka before present for the Early Weichselian interstadial peat at Brumunddalen in southeastern Norway (S.E.Lauritzen, pers. comm. 1991), and it may correspond with the Horns stadial with a glacial advance from the N-NE almost to Denmark during the early Middle Weichselian period (Lykke-Andersen & Knudsen 1991). It is even thought that the stage 4 glaciation may have reached farther to the southwest than during the Late Weichselian maximum, and eventually joined up and flowed together with the British Ice Sheet during this period (Larsen & Sejrup 1990).

The Late Weichselian glaciation. Till 1. The Kautokeino Till (Vuolgamasjohka, Vuoddasjavri, Sargejohka, etc.) represents the third (and last) glacial cycle during the Weichselian. This till is the uppermost till formation and is therefore also named Till 1. It correlates with the youngest till in the stratigraphy of Finland (Hirvas et al. 1988, Olsen 1988). The ice flow configuration indicates that this was a typical Fennoscandian type of ice sheet with inland ice centres distributed along an E-W trending ice-shed zone, and with the glacial extension reaching to the edge of the shelf during its maximum advance.

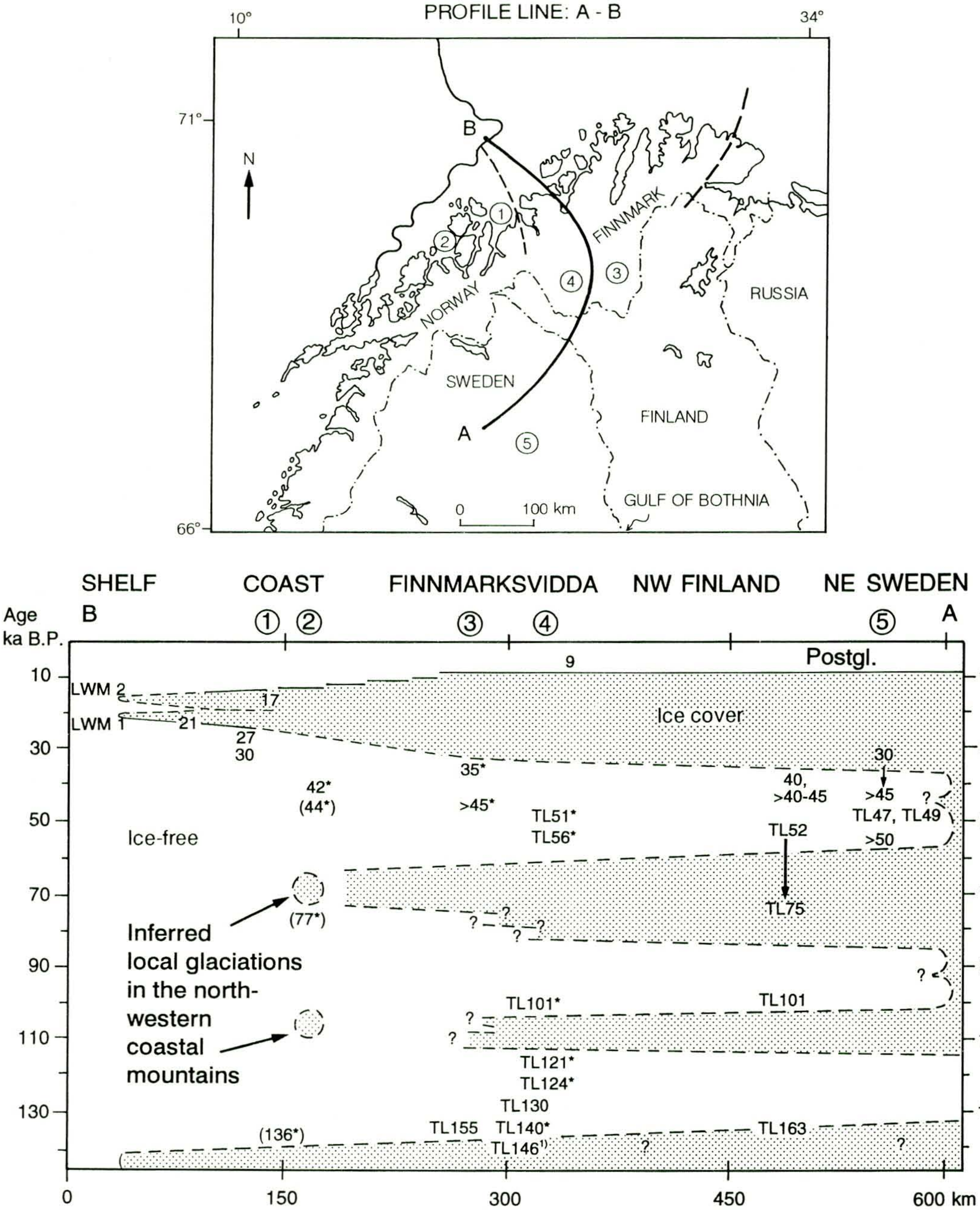


Fig. 49. Glaciation curve for northern Fennoscandia during the Weichselian. Information from groups of localities 1 - 5 are projected onto the curve. Mainly after Olsen (1988, 1993b), and other sources referenced therein. The main curve follows the profile line A - B indicated on the map (*above*). Examples of local deviations of main trends of ice advances and retreats along the profile in the coastal zone are indicated with broken lines in two areas. It is thought that the Late Weichselian maximum advance to the shelf edge was reached at about 21-22 ka in the west (LWM 1). In the east the glacial history seems to have been quite different, with a much later maximum advance phase; note the second LWM peak around 16 ka on the glaciation curve. All luminescence dates are corrected according to the empirically based procedure described in the main text (p. 10). Explanation of symbols:

TL 130 = Thermoluminescence dating with age in ka (thousand years) B.P.;
27 = ^{14}C-dating with age in ka B.P. (amino acid age estimate in parenthesis);
** = Dates of reworked material; and*
$^{1)}$ = Average of several dates.

It is not known if the maximum extension onto the shelf adjacent to Finnmark was reached more than once during the Late Weichselian. Hald et al. (1990) and Vorren et al. (1990) have shown that the maximum extension may have occurred around or shortly after 21 ka (uncalibrated age) before present. We have demonstrated that a glacial advance of probably regional size occurred in the northeasternmost parts of Finnmark after c. 16.5 -17.0 ka ago (Olsen 1993a, b; and Fig.49). This advance may have extended onto the adjacent Barents Sea shelf and may even have reached its maximum position along the shelf-edge. The glacial maximum advance c. 22 ka ago on Andøya (Nordland) farther south (Alm 1990, 1993, Møller et al. 1992) supports the oldest maximum alternative in the Troms - Finnmark region, whereas analyses and dates of deep-sea sediments southwest of Svalbard indicating a late maximum extension of the Barents Ice Sheet (Dokken & Hald 1993) correspond better with the youngest maximum alternative (c. 16 ka ago). We have indicated that both alternatives, resulting in two maxima (c. 21 ka and c. 16 ka), may actually have existed for the Fennoscandian Ice Sheet (Fig.47).

Because of the commonly stratified meltout character of the lowermost till bed in the Kautokeino Till, and the other indications of a corresponding ice-sheet with an initial cold-based phase (glacial thrusting, low-angle reverse faulting, sharply eroded lower boundary), we find it most likely that an intervening interval of geological history between the Kautokeino Till and the underlying Vuoddasjavri Till is missing in our stratigraphic record. We don't know if this represents a hiatus or eventually a major erosional discordance. If an intervening glacial event existed, and it was characterised by an almost entirely cold-based glacier in the northern areas, then very little glacial drift may have been deposited during the retreat of this particular ice sheet. Examples of stratigraphies from NE Sweden and NW Finland recorded during collaboration between the Nordic Geological Surveys (Fig.50) may, indeed, support a hypothesis of intervening glacial events as mentioned earlier. However, as pointed out by Hirvas (1991), the stratigraphy for example at locality no. 21 (Fig.50) in Finland is complex and not easy to interpret, and both organic horizons may represent dislocated/redeposited older units.

TL dates of proglacial sediments in northern Finland may indicate an ice advance between 45 and 38 ka B.P., uncorrected ages, or between 61 and 52 ka B.P., corrected ages (K. Mäkinen in Mejdahl 1990, 1991). It is, therefore, quite possible that a glacial event of regional importance occurred during isotope stage 3 in northern Fennoscandia, and this event may correspond with the significant ice extension in the SW just before 40 ka (uncalibrated age) ago, which is most convincingly demonstrated by glacial submergence of coastal caves in SW Norway (Larsen et al. 1987, 1993). An ice advance at or shortly after 40 ka ago, reaching very close to the northeastern-most tip of Denmark, has also been recorded and reported (Vennebjerg stadial; Lykke-Andersen & Knudsen 1991), and the Mesna till at Lillehammer in SE Norway may belong to this glacial event (Olsen 1985a, b, 1993a). If these correlations are correct, then a glacial extension during isotope stage 3 reached a significantly larger size than that of the Younger Dryas glacial event both in the south and in the west. The corresponding glacial extension in the north is not known, but, although no evidence of this has yet been found, it may at least locally have reached the coastal areas.

The Late Weichselian ice advance crossed the coastline in northern Troms and western Finnmark after 27-30 ka before present (Andreassen et al. 1985). The ice advance phase in the eastern part of Finnmark may have been much later, and one extreme interpretation implies a single ice advance phase after 16.5 - 17.0 ka B.P. (Fig.47). We prefer to think that if this was a major ice advance, then it represents the second rather than the only maximum ice advance during the Late Weichselian. However, the ice advance of about 16.5 ka ago may still have been the only Weichselian glacial event with a total ice cover -at least of a dynamic active ice- in the easternmost coastal part of Finnmark.

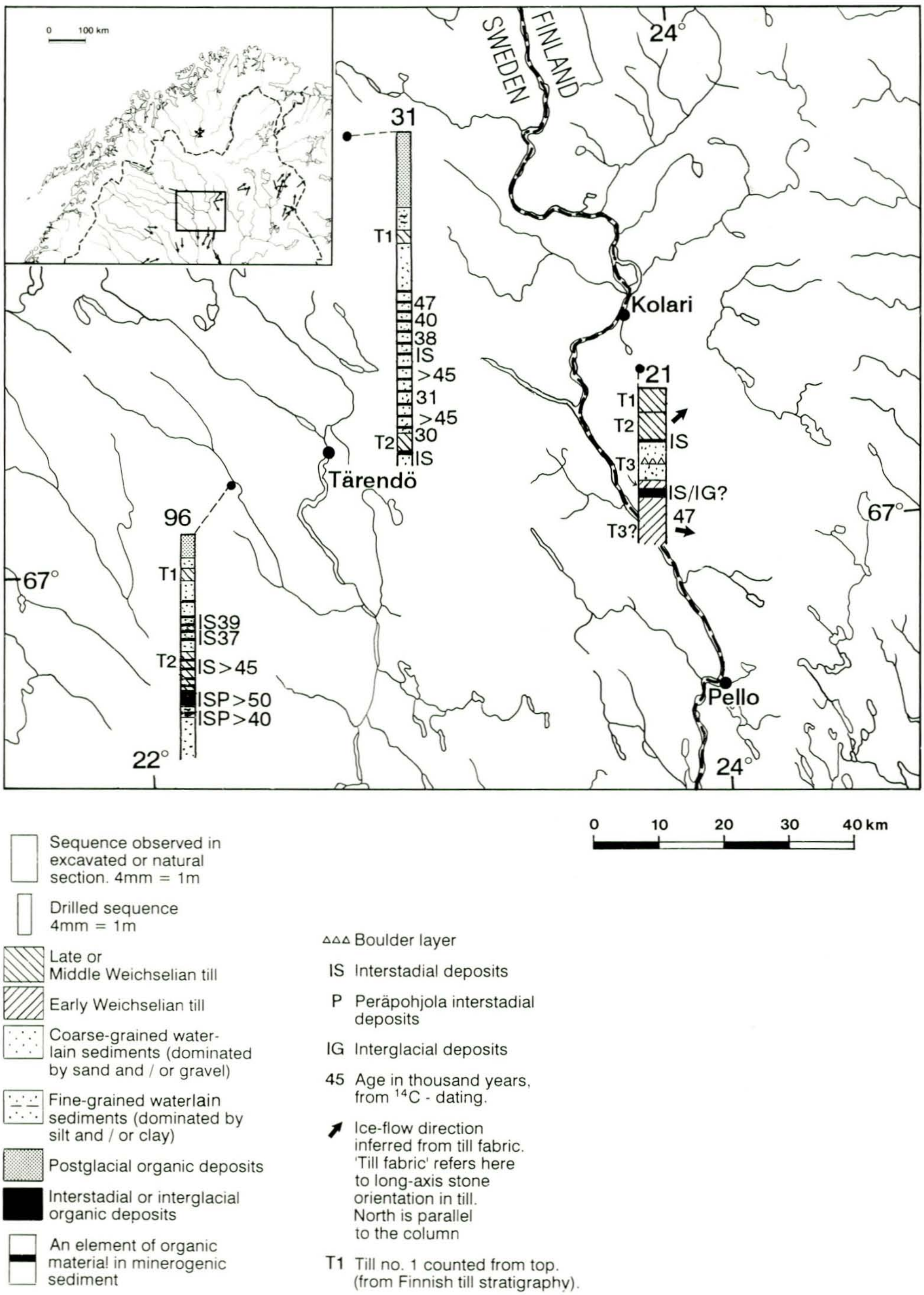


Fig. 50. Simplified logs from sections in North Sweden and North Finland with information on stratigraphies, where tills or other deposits within the Tärendö and Peräpohjola interstadial complexes suggest intervening glacial events. Consequently, there may have been more glacial events than the three major ones during the Weichselian glaciation in northern Fennoscandia. The data are taken from Hirvas et al. (1988) and the maps described therein. Note that Hirvas (1991) has given a different interpretation of the stratigraphy from the site from North Finland (see text for more details).

Orbital forcing of the glaciations. It has been demonstrated that at least three glacial - deglacial cycles of Weichselian age have existed in northern Fennoscandia (Hirvas et al. 1988, Olsen 1988, 1989a,b). The first cycle of this kind occurred shortly after the last interglacial (Eemian) and the last occurred during the Late Weichselian. The age of the second Weichselian glacial cycle is less straightforward; both an Early Weichselian age (Olsen 1988, 1989a,b, Larsen et al. 1991) and a Middle Weichselian age (Olsen 1993b) have been suggested for this cycle. U/Th dates of speleothems from Nordland at c. 66-68°N latitude (Lauritzen 1991) indicate glacial events in three different intervals during the late Early Weichselian and the Middle Weichselian, and these existed during isotope stages 5b-5a, 4 and 3, respectively. TL and OSL dates of sediments from Fennoscandian inland areas (Fig.46) indicate different glacial events during isotope stages 5a-4 and 3. Based on this and the speleothem growth record, we may therefore conclude that there is evidence for more than three glacial cycles of Weichselian age in Fennoscandia.

The total ice volumes of the areas surrounding the North Atlantic - Norwegian Sea margins were much greater during isotope stage 4 than during stages 5a-5b, as indicated by oxygen isotope data from deep-sea cores in this area (Ruddiman 1985). We think that it is unlikely that the Fennoscandian Ice Sheet should have been much out of phase with this more general ice volume signal, and therefore we favour the late Early to Middle Weichselian (stages 5a-4) age alternative for the second major Weichselian glacial cycle in northern Fennoscandia (Fig.49). A limited and much shorter glacial event may, however, have occurred during isotope stage 5b also in central and northern parts of Scandinavia, as it did in western Scandinavia (Larsen & Sejrup 1990, Larsen et al. 1991, Mangerud 1991a,b,c). Although this is not supported by the distribution of TL and OSL dates, it may well correspond with the 'cold' phase or interruption in the more favourable (warm) climatic conditions during the Jämtland Interstadial at Pilgrimstad, as inferred by Robertsson (1988).

The glaciation curve for northern Fennoscandia during the Weichselian glaciation (Fig.49) is similar with regard to the timing of events as that presented by Mangerud & Svendsen (1992) for the Svalbard - Barents Sea region. They discussed orbital forcing of glaciations and found a close correlation between the major glacial events and the c. 41 ka tilt periodicity. Our data indicate that these relationships were not restricted only to the northernmost latitudes (77-80°N), but reached much farther to the south (66-71°N). This accords well with the strong influence imparted by the tilt frequency in the global ice volume signal (Imbrie et al. 1984).

The southern part of the Scandinavian Ice Sheet, at 52-63°N latitudes, fluctuated apparently more frequently than the northern part of the same ice sheet and the Barents Sea Ice Sheet further north. The southern parts were, apparently, to a large extent, driven by the precession cycle of c. 23 ka (Larsen & Sejrup 1990, Mangerud 1991a,b). There is, as yet, no glaciation curve presented for the entire Weichselian in the middle part of Scandinavia west of the watershed, but we expect that the glacial fluctuations in this area may show a transitional pattern between those from the south and those from the north.

Mangerud & Svendsen (1992) explained the differences in glacial response for Svalbard and southern Scandinavia by different consequences arising from a variation of the Atlantic current circulation in combination with insolation variations. They referred to data presented by McIntyre et al. (1976) and Berger & Loutre (1991), respectively. We have shown that the timing, and partly the durations, as well as the extents of the glacial fluctuations in northern Scandinavia are apparently similar to those proposed for Svalbard by Mangerud & Svendsen. It therefore seems that the boundary between differences in glacial responses should perhaps not be placed between Svalbard and Scandinavia, but rather somewhere between the latitudes 63°N and 66°N in Scandinavia. This suggestion is also in accord with the Atlantic current circulation data and the insolation data cited by Mangerud & Svendsen (1992).

The extent of the second Weichselian glacial cycle in northern Fennoscandia is thought to have been limited, with the ice margin located in its maximum position just outside the coast. The ice movement indicators related to this glacial event imply ice movements towards the N-NE over the northernmost parts of Fennoscandia (Olsen 1988, 1989a,b, 1993b). This is not in accord with an ice sheet of wide extension, reaching far out onto the shelf area in the NW. In addition, there are no records with conclusive evidence of glacial deposits on the outer shelf, indicating an extensive glaciation of Middle or Early Weichselian age (Hald et al. 1990, Vorren et al. 1990). This may be different for the Svalbard - Barents Sea Ice Sheet because, as indicated by ice-rafted material in deep sea cores west and northwest of Svalbard (Hebbeln 1991, 1992), the ice advanced probably almost to the shelf-edge during both the second and the last major glacial events on Svalbard. We therefore conclude that the glacial response during the second Weichselian glacial cycle in northern Scandinavia and on Svalbard were mainly in phase, but slightly different in relative size.

Perhaps the postulation of Denton & Hughes (1981) that Arctic ice sheets started to grow from the surface of ice shelves in shallow water is applicable for the second Weichselian glacial event on Svalbard, but not for northern Scandinavia. If this was the case, then the glaciers on Svalbard would have grown faster and probably reached further than those in Scandinavia which expanded only from the land area.

Conclusions

We have, in this paper, described the main features of the Quaternary stratigraphic record of Finnmark county, northern Norway. The depositional environments are inferred from the character of the sediments and the chronology is based on ^{14}C-AMS and TL/OSL dates. Climatic implications are interpreted from pollen distributions, and from the occurrences and preliminarily inferred types of paleosols. Geochemical data on the latter are not dealt with here, but will be presented elsewhere (Olsen, in prep.).

The conclusions may be expressed in separate points as follows:

1) Pre-Quaternary weathered bedrock characterises the subsurface in many topographical depressions on eastern Finnmarksvidda, for instance at Sargejohka where the weathering in places reaches down to c. 30-35 m below the bedrock - drift deposit interface. Both the weathered bedrock and particularly the reworked weathered material contain a significant amount of kaolinite, indicating either a 'mid-latitude' or subtropical to tropical weathering (Figs. 18B,C). The age of the weathering is therefore pre-Quaternary (probably Tertiary).

2) The Quaternary stratigraphy of Finnmark reveals a succession of glacial - deglacial deposits from at least seven glaciations during the last three glacial 100 ka-cycles (Fig.48). The oldest Quaternary deposit recorded on Finnmarksvidda is thought to correspond with or possibly predate Oxygen Isotope Stage 9 (c. 300-340 ka B.P.), as indicated by TL/OSL dating of younger units.

3) At least once during both the Middle Saalian and the Late Saalian glaciations the ice-centres were situated south and southeast of Finnmarksvidda, indicating a Fennoscandian configuration of the ice-sheet. This is a similar situation to that of the Late Weichselian maximum, and this type of ice-sheet configuration is thought to characterise all stages with a maximum ice extension to, or close to, the edge of the continental shelf. We conclude that such a maximum ice-sheet extension is thought to have occurred during the Middle Saalian, the Late Saalian and the Late Weichselian. This accords tentatively with the huge volumes of ice which are thought to have accumulated on a global scale during these glaciations (e.g. Imbrie et al. 1984).

4) The average length of transport of coarse-grained till clasts based on stone-counting (petrography) and roundness analyses is found to be 20-25 km in the western

part of Finnmarksvidda, whereas the comparable transport length for the Karasjok area in the east seems to be c. 5-7 km. The transport length of fine-grained till material is not estimated in this way, but is thought to be of similar magnitude, though probably more variable where, for example, temporary meltwater transportation interferes with the overall glacial transport history. (Olsen, unpubl.)

5) TL and OSL dates from Finnmarksvidda, and additional dates from other inland areas of Fennoscandia (Figs.45 & 46), group into intervals which approximately correspond with speleothem-growth periods from caves in Nordland (Lauritzen 1991), and also with low ice-volume intervals reflected by oxygen isotope ratios in foraminifera in deep-sea sediments. The correspondence in either case is less clear at higher than at lower ages, suggesting that the luminescence correction coefficient of 1.35, which we have used, is possibly too high. The peak values, which may indicate ice-free events with zeroing of the TL/OSL-signal of the dated sediments, give the following intervals: 33-39 ka (only at the coast), 45-62 ka (45-80 ka in adjacent inland areas), 85-105 ka, 115-135 ka, 140-175 ka (represented by three distinct peaks in adjacent inland areas), 185-195 ka (not distinctive on Finnmarksvidda), 205-285 ka (205-235 ka, 240-255 ka, 260-270 ka and 280-285 ka), and possibly one or more intervals between c. 360 and 580 ka B.P. These intervals may indicate periods of minimum ice-volumes in Fennoscandia (Fig.46, and cover illustration).

6) The *Bavtajohka Interglacial* which is represented by a thick and extensive deposit of gyttja and gyttja silt at Sargejohka (Figs.16-19), reveals a pollen signature indicating a local vegetation similar to that of the present day - a birch-dominated forest with scattered pines. This interglacial has been TL/OSL-dated to an average of c. 260 ka B.P., suggesting a possible correlation with the Drenthe - Warthe interstadial/interglacial in Germany (according to Stremme 1987) and with the global Oxygen Isotope Stage 8/7 (last part of 8 and first part of 7).

7) Based on the oxidation and inferred moderate rubification of the very thick relict paleosol developed in the fine-grained till at Buddasnjarga (Figs. 32-33), the associated ice-free interval is considered to have been a warm interglacial, and most likely the Eemian, provided that a strong oceanic influence reached far inland during the winters in this interglacial. Such a paleosol development, in a mature state, implies an annual mean temperature of at least 7°C and a mean annual precipitation of more than 500 mm (Smith et al. 1987). This is at least 4-5°C warmer than during the postglacial optimum in this area. The inferred correlative 'red-yellow' podzol (p3 in Figs.25 & 27K) at Sargejohka indicates also a very warm interglacial climate at this latitude. The pollen record for the *Vuolgamasjohka Thermomer*, which is thought to include the last interglacial, is so far too sparse to allow climatic interpretations of the kind just mentioned. However, the remains of a glaciotectonised paleosol similar as p3 at Sargejohka are also recorded in the uppermost part of the Vuolgamasjohka Sand at Vuolgamasjohka (Olsen, unpublished material). This implies a similar climatic interpretation as that for the Sargejohka 'p3' event.

8) Two major Weichselian interstadials are described, and these are named the *Eiravarri Interstadial* (c. 85-105 ka B.P.) and the *Sargejohka Interstadial* (c. 35-60 ka B.P.). Climatic conditions were probably much more favourable during the optimum of the older of these interstadials. This is inferred from the pollen content (although sparse) from the associated sediments, which suggests that trees were probably growing in or not very far from this area during the Early Weichselian interstadial, but not during the Middle Weichselian interstadial.

9) Orbital forcing is thought to drive glaciations globally, and particularly in northern latitudes, in cycles corresponding to the 41 ka tilt periodicity (Imbrie et al. 1984). The glaciation curve for northern Fennoscandia during the Weichselian glaciation (Fig.49) demonstrates a tentative correlation between the major glacial events and this periodi-

city, similar to that Mangerud & Svendsen (1992) found for the Svalbard - Barents Sea region. *This is in contrast to the southwestern part of the Scandinavian Ice Sheet* where the major glacial events apparently correlate with the 23 ka precession cycles (e.g. Larsen et al. 1991), which accords with the global ice-volume signals of middle latitudes (Imbrie et al. 1984).

10) The existence of *in situ* remnants of 5-7 buried paleosols of different ages (Figs. 18B,C, 21, 23, 24, 25 and 27; and Table 8) makes the Sargejohka stratigraphy unique in Fennoscandia with regard to the apparent preservation potential of a long and very little interrupted terrestrial Quaternary record.

11) A recorded ice advance after 16.5 - 17.0 ka (uncalibrated to calendar years) ago on Varangerhalvøya in the easternmost part of Finnmark may correspond to the Late Weichselian maximum (LWM) extension. It is, however, not known if this would be the only major Late Weichselian ice advance onto the shelf, or perhaps as we think, the second advance after a significant ice-margin retreat prior to 17.3 ka B.P. The latter accords best with the hypothesis of Vorren et al. (1990), where they suggest that the ice margin reached to the shelf-edge twice during the Late Weichselian, first c. 21-22 ka ago and then again, after a significant ice retreat due to massive calving in the Bjørnøyrenna depression, prior to some 18 ka B.P. Nevertheless, we have so far no reports of more than one till overlying Middle to Late Weichselian or older sediments on the Varanger Peninsula; and no meltwater pulse indicating ice retreat of age 17-18 ka seems to exist in high resolution core-data from the northern margin of the Bjørnøyrenna trench (M. Hald, pers. comm. 1995).

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Because this paper is meant for a broader group of readers than only pure Quaternary stratigraphers we have throughout the paper chosen to use the more commonly used terms *Early, Middle* and *Late* for subdivision of time series, although the strictly correct stratigraphical terms in many cases (for events and deposits) would be *Lower, Middle* and *Upper* following international rules of stratigraphic terminology.

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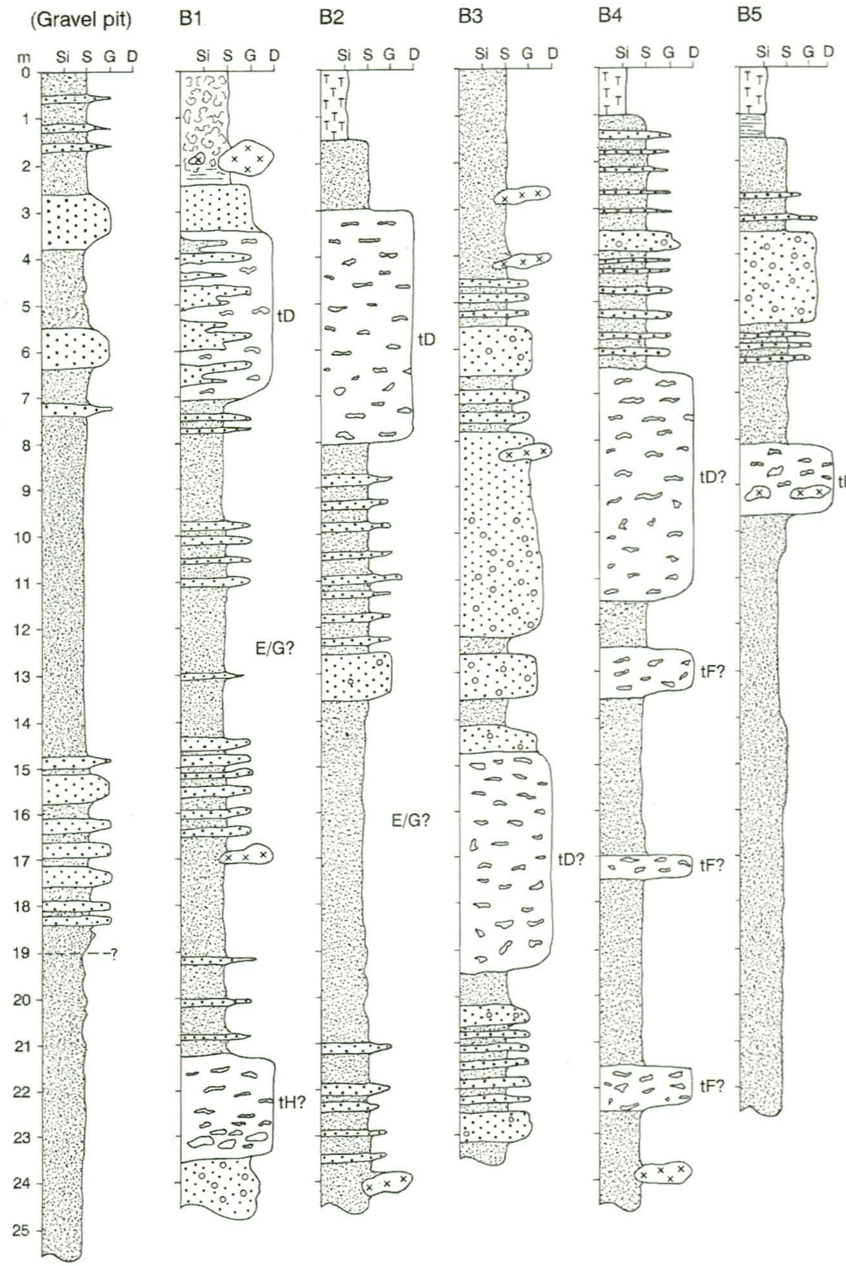
Appendix with additional background data:

A) Fig.51: Simplified logs from drillings within and adjacent to the Vuoddasjavri gravel pit (conf. Figs. 6-7). None of these preliminary drillings reached bedrock.

B) Clast fabric analyses used in this work are here indicated in stereonet-projections (Schmidt's net). Eigenvector pole 1 at 90%, 95% and 99% confidence levels are also indicated. However, the curves of these statistical parametres are in most cases difficult to see because of the high density of frequency contours. The number of measured clasts in each analysis varies, but the majority of analyses include at least 30-34 long-axis measurements. The inferred ice flow direction based on each fabric analysis is used and indicated with an arrow and the corresponding analysis no. in the illustrations (Figs.).

C) Table 2.1. (p.9), continuation.

A



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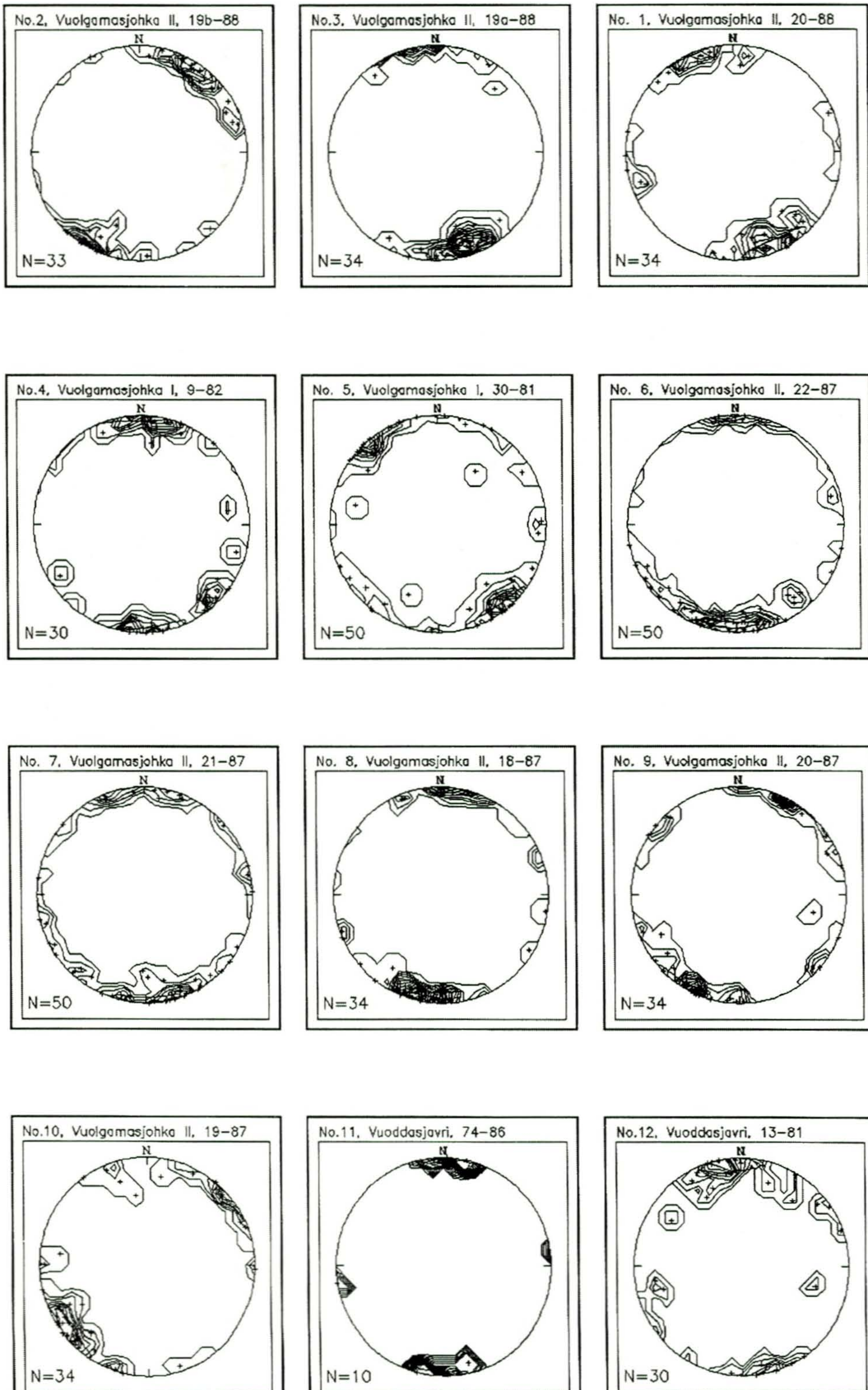
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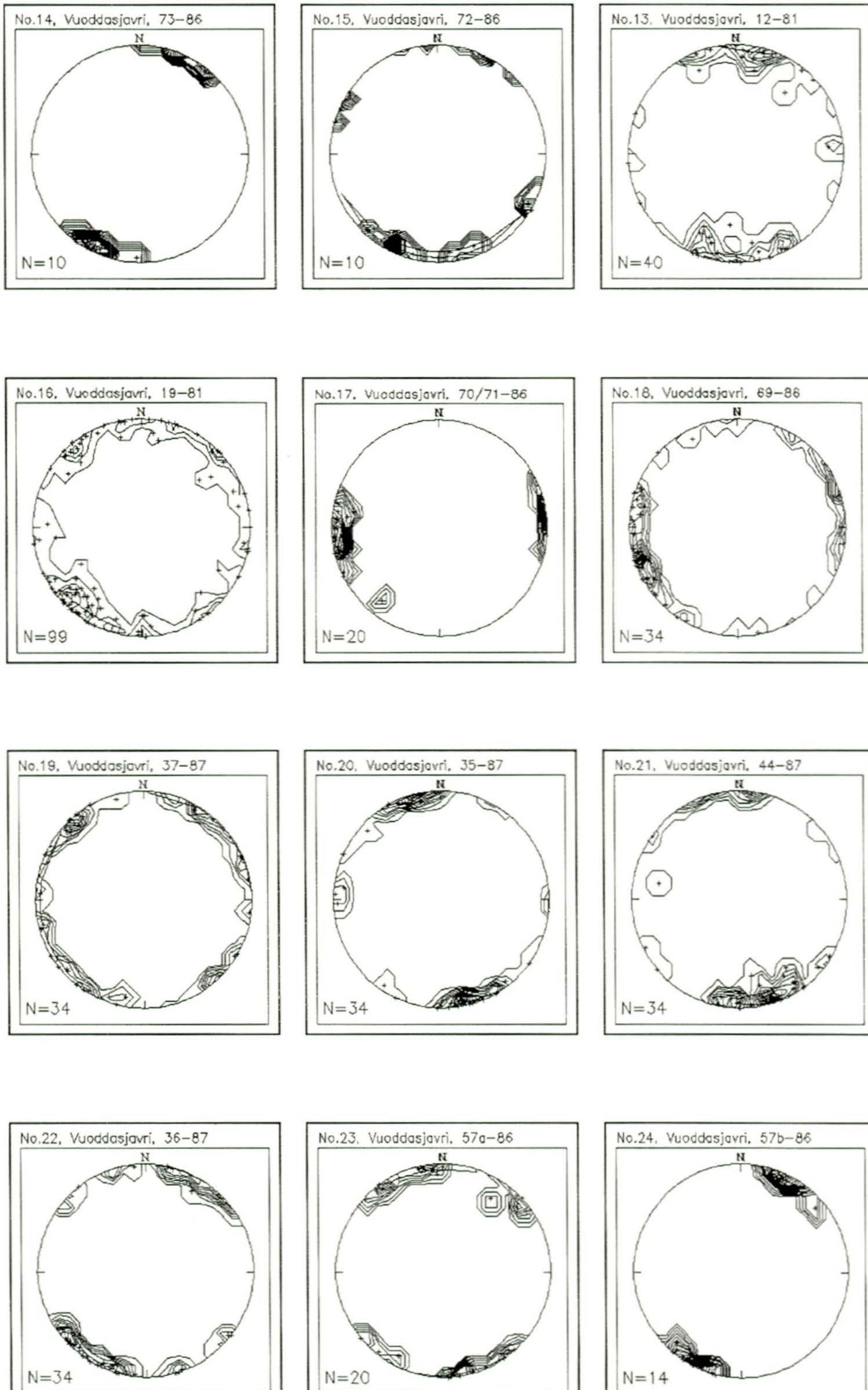
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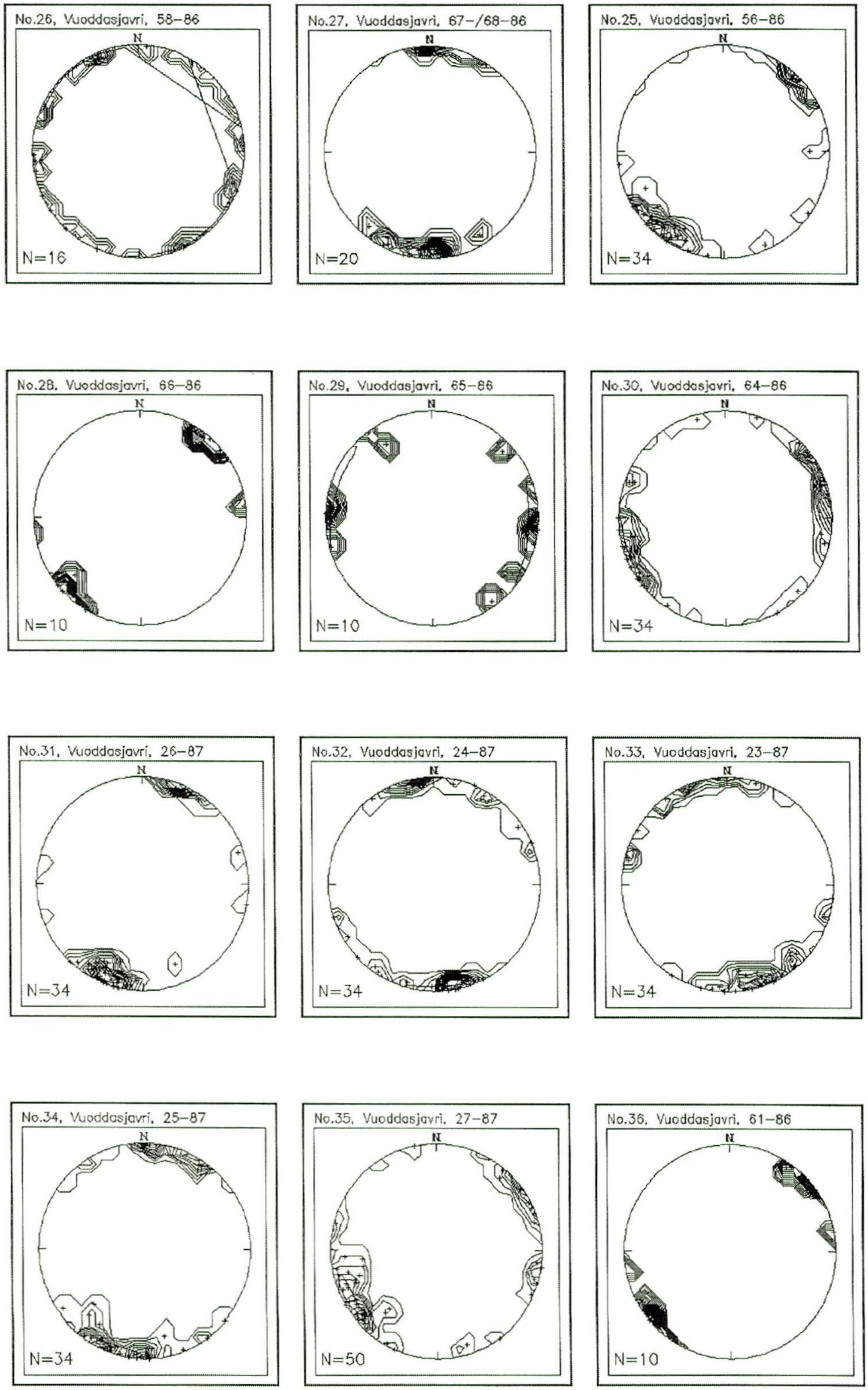
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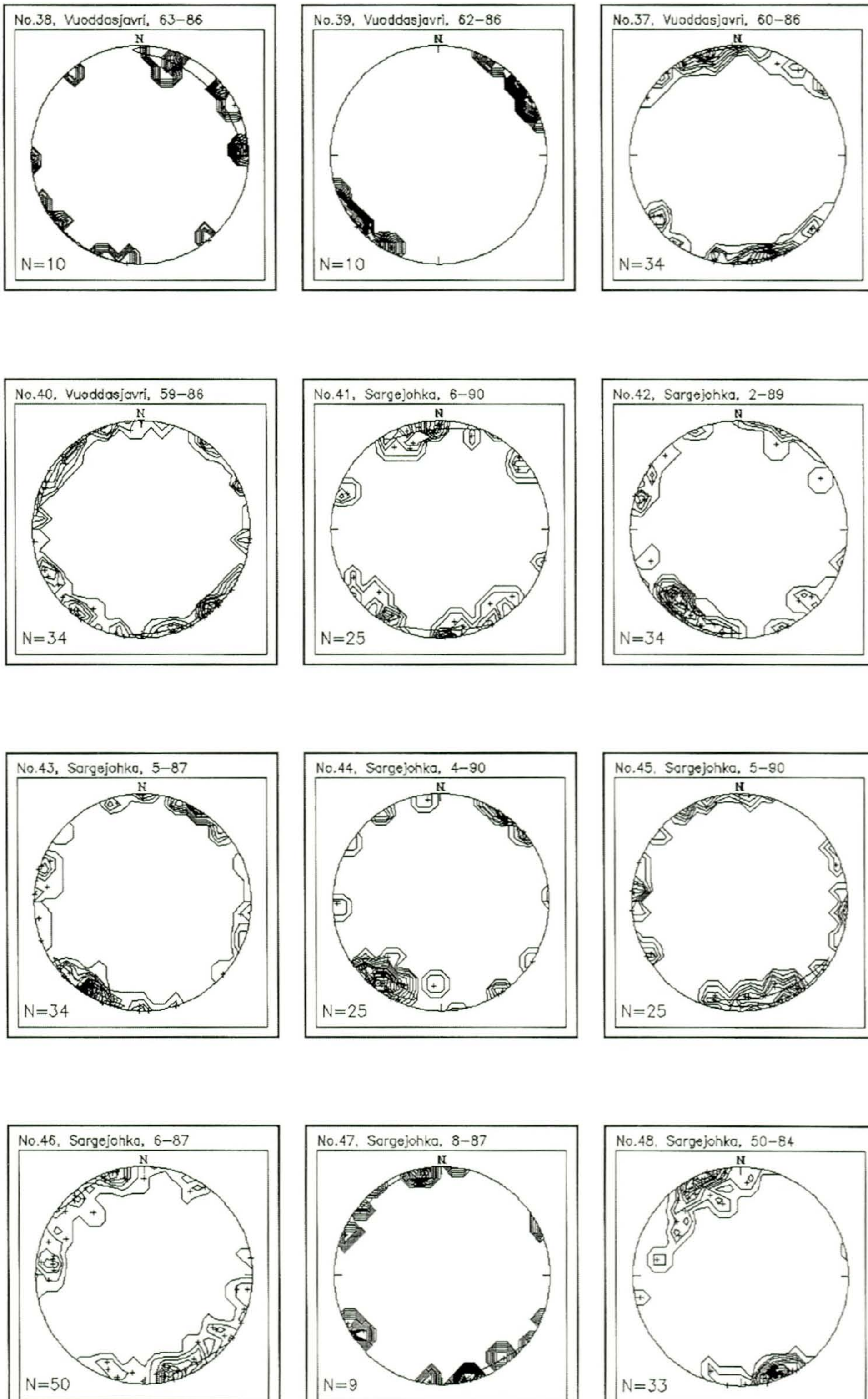
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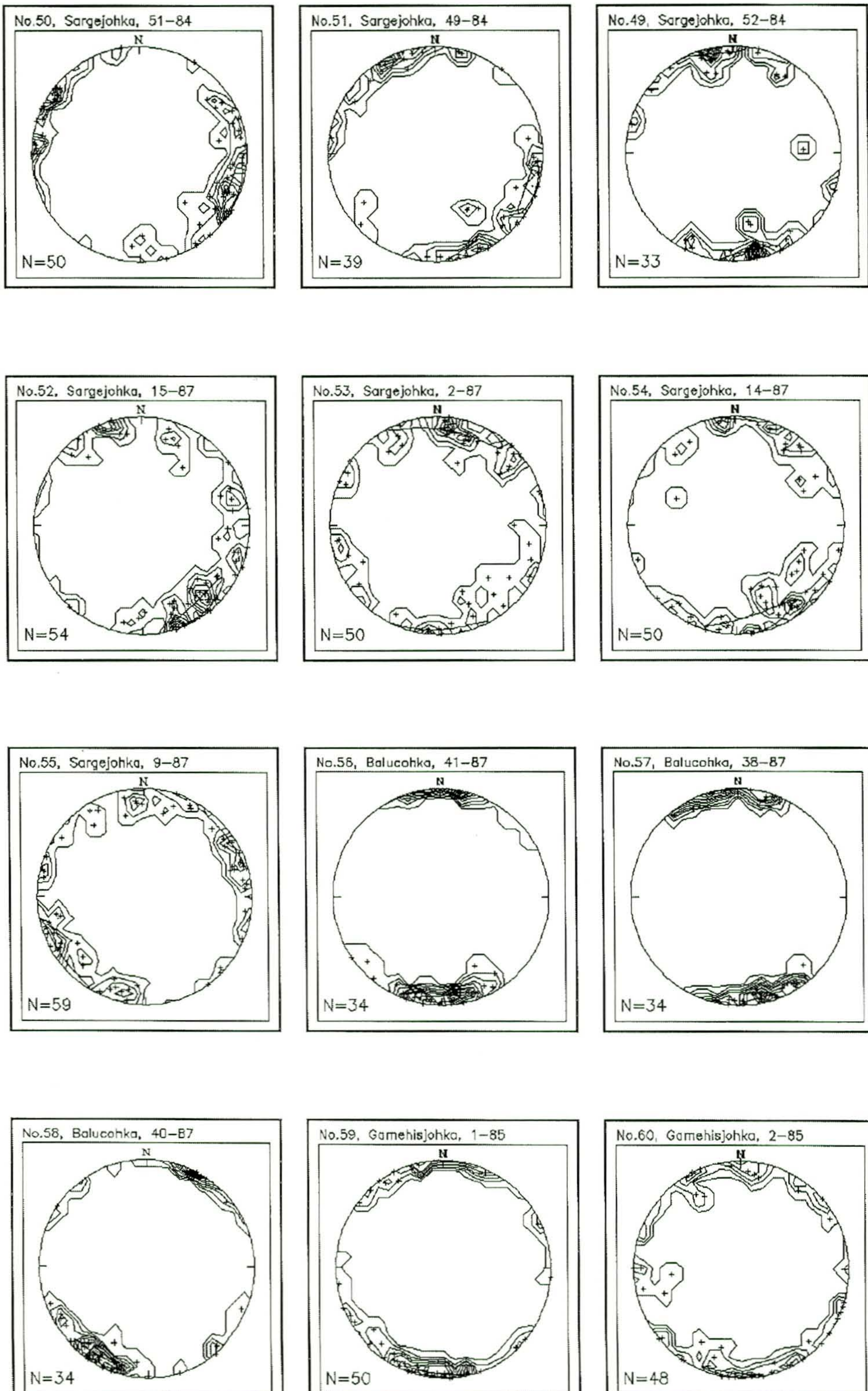
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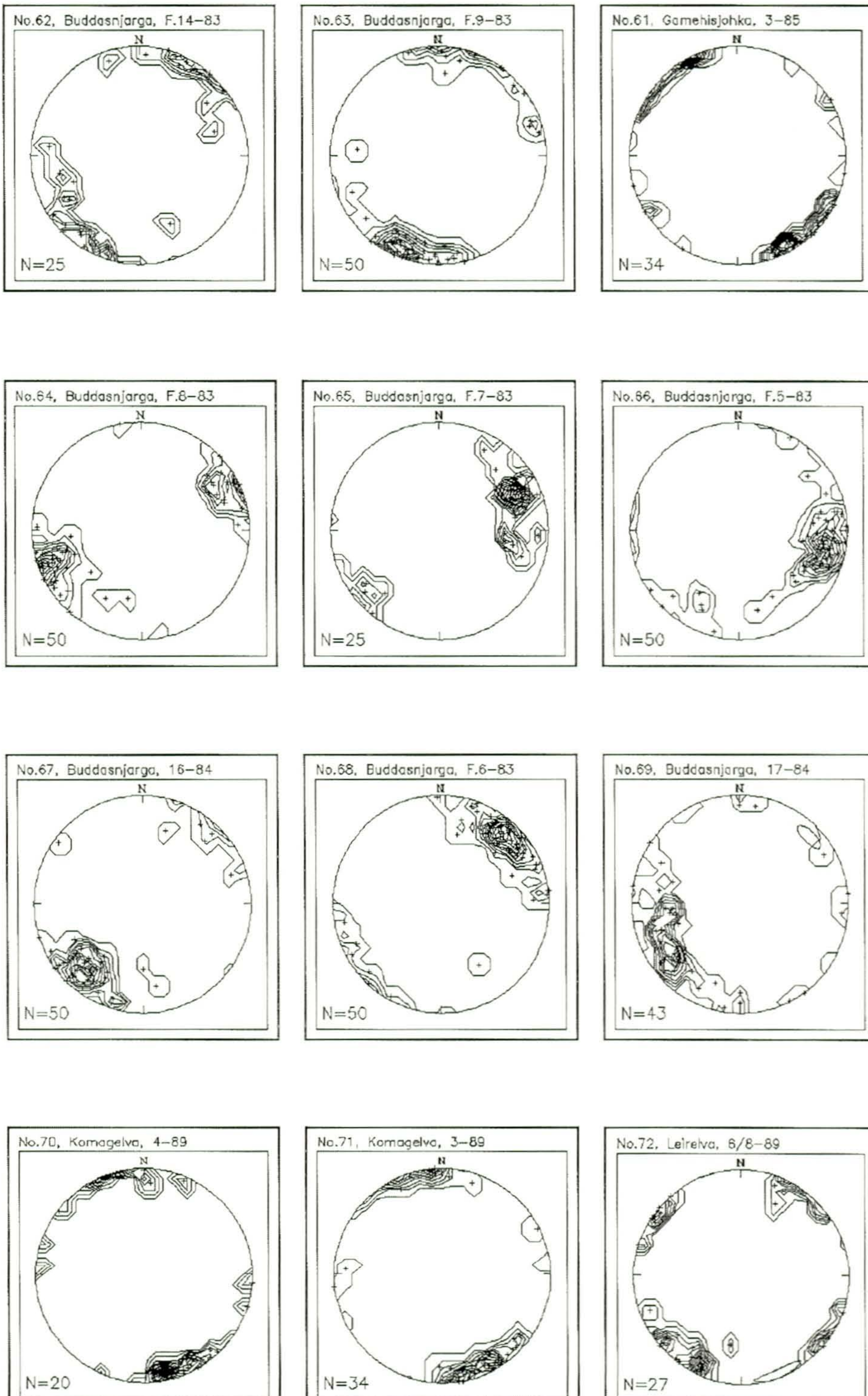
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C TABLE 2.1, continution (see also Table 2.1, p. 9)

Dates from northern Finland by K. Mäkinen (Mejdahl 1990,1991)				
Risø no.	Material	TL-age(ka)	Corr.age(ka)	Comments
R-893201	Glaciofluvial sand	115 ±10	156 ± 14	Correction according to our suggestion
R-893202	Glaciofluvial sand	151 ± 15	205 ± 20	"
R-893203	Proglacial sand	38 ± 5	52 ± 7	Ice advance (?)
R-893204	Glaciofl. sand-silt	49 ± 5	67 ± 7	Ice retreat (?)
R-893205	Glaciofl. sand-silt	46 ± 5	63 ± 7	Ice retreat (?)
R-893206	Glaciofl. sand-silt	52 ± 5	71 ± 7	Ice retreat (?)
R-893207	Proglacial sand	45 ± 5	61 ± 7	Ice advance (?)
R-893208	Glaciofl. sand-silt	50 ± 5	68 ± 7	Ice retreat (?)
R-893209	Proglacial sand	44 ± 5	60 ± 7	Ice advance (?)
R-893210	Glaciofl. silt	55 ± 5	75 ± 7	Ice retreat (?)

Dates from Oulainen in central Finland (Jungner 1987)				
Sample no.	Material	TL-age(ka)	Corr.age(ka)	Comments
7	Sand	91 ± 9	124 ± 13	Correction according to our suggestion
8	"	91 ± 9	124 ± 13	"
-	"	97 ± 18	132 ± 25	"
5	"	102 ± 10	138 ± 13	"
6	"	88 ± 9	120 ± 13	"
4	"	96 ± 10	130 ± 13	"
3	"	94 ± 10	128 ± 13	"
2	"	97 ± 10	132 ± 13	"
1	"	94 ± 9	128 ± 13	"
9	Sand	117 ± 12	159 ± 17	"
-	"	150 ± 30	203 ± 40	"
10	"	119 ± 12	161 ± 16	"
11	"	128 ± 13	174 ± 18	"

Dates from Vimpeli in central Finland (Jungner 1987)				
Sample no.	Material	TL- age (ka)	Corr. age (ka)	Comments
101	sand	225	304 ± 30	Correction according to our suggestion
103	"	107	145 ± 15	"
107	"	99	134± 15	"
110	"	115	156 ± 15	"
112	"	214	290 ± 30	"
114	"	116	225 ± 20	"
118	"	184	249 ± 25	"

Dates from northern Sweden (Garcia Ambrosiani 1990; and R. Lagerbäck, pers. comm. 1991)				
Sample no.	Material	TL-age(ka)	Corr.age(ka)	Comments
R-861601	Sand	125 ± 10	169 ± 13	Corr. done by us
R-861603	"	105 ± 10	142 ± 13	"
R-861603	"	133 ± 10	180 ± 13	"
"RL-1"	Sand	34 ± 4	47 ± 5	"Tärendø interst" sand
"RL-2"	"	36 ± 4	49 ± 5	"

Dates of samples from central South Norway (Bergersen et al. 1991, and unpubl. data)				
Sample no.	Material	TL-age(ka)	Corr.age(ka)	Locality/Comments
R-873303	*Gl.fl. sand*	*99 ± 10*	*134 ± 13*	*Fåvang*
Fåvang 1	Gl.fl. gravel	69 ± 7	94 ± 10	Fåvang
Fåvang 2	Gl.fl. gravel	68 ± 7	93 ± 10	Fåvang
Fåvang 3	Gl.fl. gravel	71 ± 7	97 ± 10	Fåvang
Fåvang 4	Gl.fl. gravel	54 ± 5	74 ± 7	Fåvang
Fåvang 5	Gl.fl. gravel	32 ± 3	44 ± 4	Fåvang
Fåvang 6	Gl.fl. gravel	107 ± 11	145 ± 15	Fåvang
Fåvang 7	Gl.fl. gravel	89 ± 9	121 ± 12	Fåvang
Fåvang 8	Gl.fl. gravel	115 ± 12	156 ± 16	Fåvang
Fåvang 9	Gl.fl. gravel	81 ± 8	110 ± 11	Fåvang
R-863301	Gl.fl. gravel	57 ± 15	78 ± 20	Haugalia
R-873301	Eolian sand	40 ± 7	55 ± 10	Sorperoa
Sorperoa 1	Eolian sand	39 ± 4	54 ± 6	Sorperoa
Sorperoa 2	Eolian sand	37 ± 4	51 ± 6	Sorperoa
Sorperoa 3	Eolian sand	40 ± 5	55 ± 7	Sorperoa
Fiskvik 1	Gl.fl.sand	50 ± 5	68 ± 7	Fiskvik (M.Thoresen, pers. comm. 1992)
Fiskvik 2	Gl.fl. sand	61 ± 6	83 ± 8	"