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Raimo Kujansuu, Brita Eriksson & Tuulikki Grönlund

Lake Inarijärvi, northern Finland: Sedimentation and late Quaternary evolution

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Lithostratigraphy, varves, diatom and pollen stratigraphies were studied from the Lake Inarijärvi, the third largest lake (1386 km^2) in Finland. Main stages during its Holocene history can be divided into: 1) the "late-glacial" stage of varved mineral matter and rapid sedimentation that lasted about 500 years, beginning as an ice-dammed lake, being later connected with the Arctic Ocean via the Paatsjoki river valley. Proto-Inari stage continued for as long as the meltwaters continued to flow into the basin and affected the sedimentation there; 2) the "postglacial" stage of long and slow sedimentation, during which pine and birch forests similar to those occurring today were dominant. Diatoms represent gradual oligotrofication of water. Changes in climate and vegetation, e.g. paludification of the environment, caused minor changes in the properties of gyttja. The sediments in depressions underwent anaerobic decomposition under oligotrophic conditions, resulting in the formation of sulphide-bearing bands. Throughout the existence of the lake, 1 kg carbon per hectare, on average, has been bound to sediments annually.

Key words (GeoRef Thesaurus, AGI): paleolimnology, lakes, lake sediments, varves, lithostratigraphy, diatoms, pollen analysis, biostratigraphy, glaciolacustrine sedimentation, carbon, Holocene, Lake Inarijärvi, Finland

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Inarijärven, Suomen kolmanneksi suurimman järven (1386 km^2) pohjakerrostumista on tutkittu kerrosjärjestystä, raekoostumusta, humuspitoisuutta, lustoja, piileviä ja siitepölyjä. Järven holoseenikautinen kehitys voidaan jakaa kahteen vaiheeseen. Myöhäisglasiaalinen, nopean sedimentaation ja lustosedimentin luonnehtima vaihe kesti noin 500 vuotta. Kerrostuminen alkoi Inarin altaan itäosassa mannerjäätikön reunan patoamaan jääjärveen, jonka pinta vähitellen laski jäätikön reunan vetäytyessä lounaaseen ja joka yhtyi lopulta lyhytaikaisesti Paatsjoen laakson kautta Pohjoiseen Jäämereen. Tämä Alku-Inari vaihe kesti niin kauan kuin mannerjäätikön sulamisvesiä virtasi Inarin altaaseen. Toisen vaiheen, jääkaudenjälkeisen pitkän ja hitaan sedimentaation aikana nykyisen kaltaiset koivu- ja mäntymetsät olivat vallitsevia. Piilevät kuvastavat järven hidasta oligotrofoitumista. Ilmaston ja kasvillisuuden muutokset, mm. soistuminen aiheuttivat vain vähäisiä muutoksia kerrostuvan sedimentin ominaisuuksiin. Syvänteiden sedimenteissä tapahtui oligotrofisissa oloissa anaerobisia muutoksia, joiden tuloksena sedimenttiin syntyi sulfidipitoisia mustia juovia. Järven olemassaolon aikana sen sedimentteihin on sitoutunut hiiltä keskimääriin noin yksi kilogramma hehtaaria kohden.

Asiasanat (Fingeo-sanasto, GTK): paleolimnologia, järvet, järvisedimentit, lustot, litostratigrafia, piilevät, siitepölyanalyysi, biostratigrafia, glasilakustrinen sedimentaatio, hiili, holoseeni, Inarijärvi, Suomi

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CONTENTS

GENERAL

Lake Inarijärvi, or Inari, is located in Finnish Lapland, northeast of the fell arc of Saariselkä (Fig. 1). Finland's third largest lake, it has a surface area of 1386 km^2, of which about 300 km^2 is covered by islands. Its maximum length is 80 km, width 41 km and depth 95 m. Two large rivers empty their

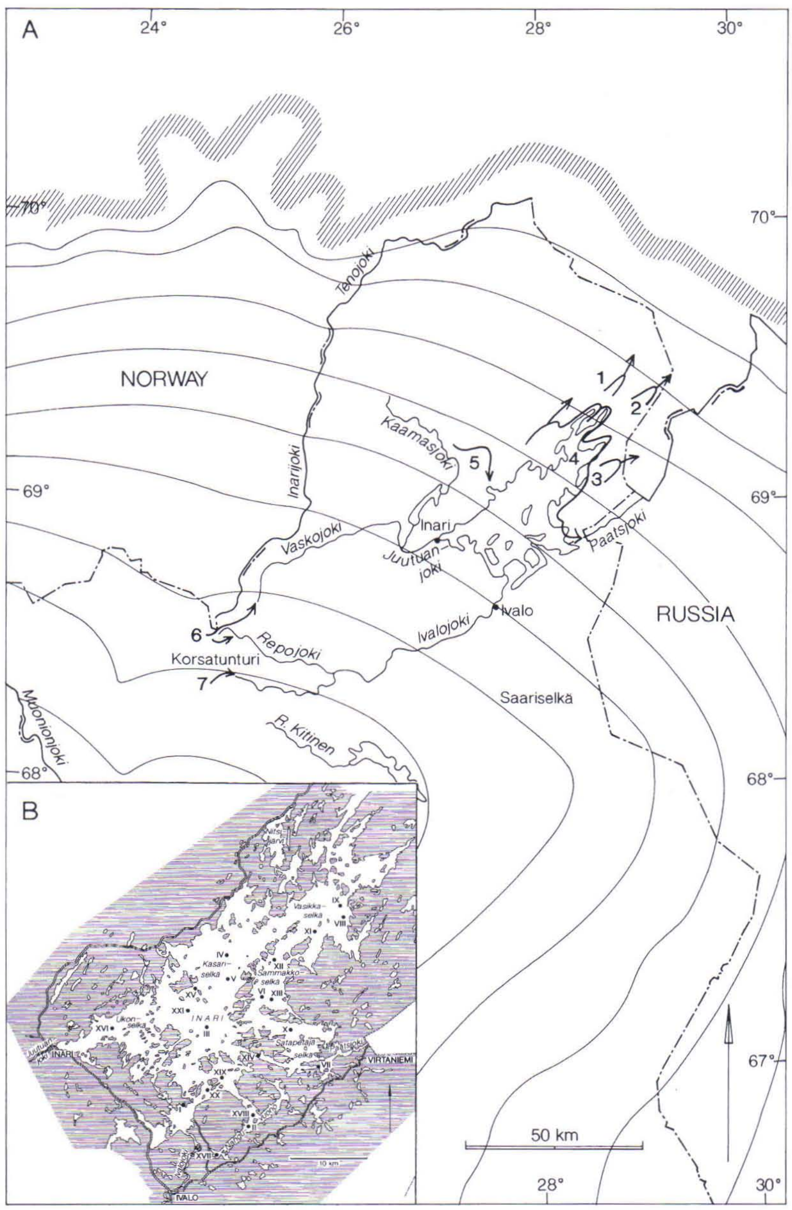

Fig. 1. **A.** Northern Fennoscandia, showing the location of Inarijärvi, the zone of Younger Dryas end moraines (hatched), the withdrawal of the ice front in the area of the Inarijärvi basin (narrow lines) and the glacial lakes with their discharge channels that contributed to the evolution of Inarijärvi (schematic): 1) Suolisjärvi, 2) Surnujärvi, 3) Nammijärvi, 4) Inari glacial lake proper, 5) Kaamasjoki, 6) Repojoki and 7) Korsatunturi. **B.** Location of coring sites.

waters into the lake, the Juutuanjoki from the west and the Ivalojoki from the southwest. The outlet channel of the lake is in the east, where the river Paatsjoki conducts the waters into the Arctic Ocean. Because of regulation, the water level in the lake fluctuates between 117 and 119.5 m asl (mean water level 118 m). At its closest, the main water divide is 25-30 km to the south and southwest of the lake.

The Inarijärvi basin (Inari lake lowland) is a kettle depression produced by Tertiary block faulting (Mikkola 1932, Tanner 1938). Boundaries between the blocks, faults and fracture zones are visible in the present morphology as rectilinear or gently winding valleys and bays ("*vuonos*", fjords), straits ("*nuoras*") and lake depressions (Figs 2 and 3). The dominant fractures strike southwest-northeast and northwest-southeast and are also clearly visible in the orientation of lake shores. The depressions oriented in the dominant flow direction of the continental ice sheet, southwest-northeast, are distinctly wider and flatter than those trending in other directions (Ristiluoma 1968). The lake is mostly less than 20 m deep; the few areas in which the depth exceeds 60 m are located in narrow and elongated depressions (fracture zones) in the waters of Kasariselkä, Sammakkoselkä and Vasikkaselkä.

There are two esker chains in the Inari lake lowland running roughly from southwest to northeast (depositional direction): one following the northwestern shore of the lake and the other in the southeast, a short distance from the lake (Fig. 3). These subglacial meltwater systems that deposited the eskers terminated in the ancient Inarijärvi, Proto-Inari, at the deglaciation stage and thus contributed to late-glacial sedimentation of the lake. East of the lake there are four small eskers (Fig. 3), of which some may start on the floor of the present Inarijärvi. The till cover in the area tends to be patchy and thin. There are numerous bedrock outcrops around the lake and the shores are particularly rocky. Depressions are usually occupied by mires with only a thin peat covering.

About 10 000 yr BP the front of the continental ice sheet withdrew from the end moraines (Fig. 2) that had formed in Norway no more than 50-60 km from the Inarijärvi basin during the Younger Dryas. The Inarijärvi basin was liberated from the ice a few centuries later, probably about 9500 yr BP. The ages

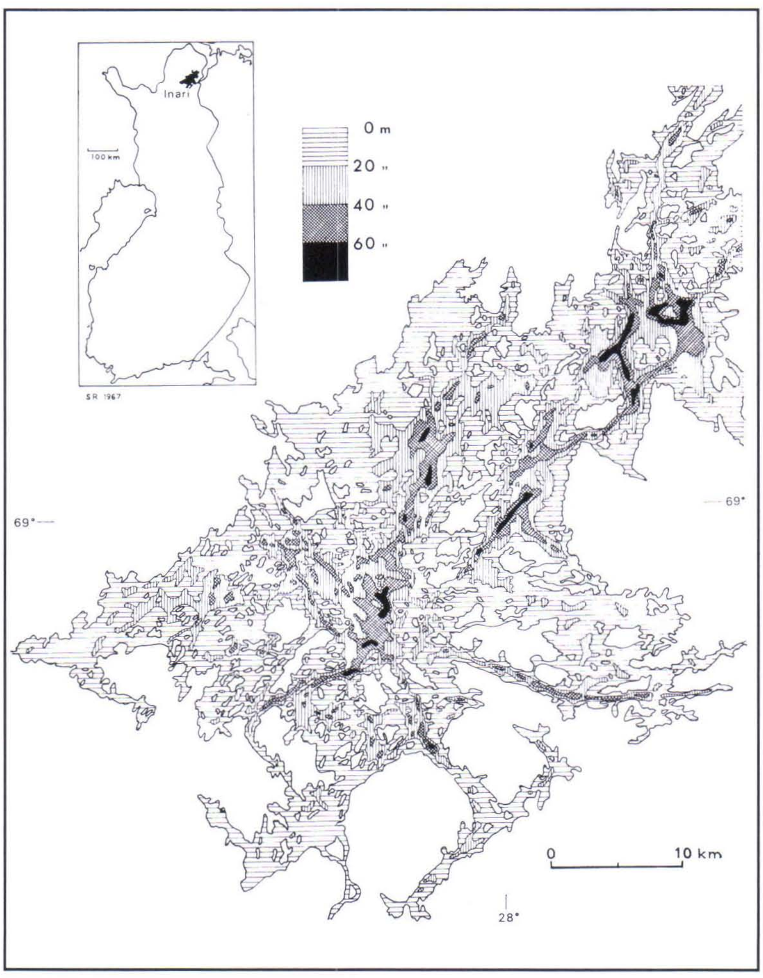

Fig. 2. Bathymetric map of Inarijärvi after Ristiluoma (1968).

referred to here are radiocarbon years and are mainly based on the investigations of Hyvärinen (1975).

Only a few studies have been published on Inarijärvi and its sediments. Järnefelt (1956) studied the limnology and plankton population of Inarijärvi. The most common plankton diatoms were *Asterionella formosa*, *Cyclotella stelligera*, *Melosira (= Aulacoseira) distans* and *Tabellaria fenestrata*. Alhonen (1969) investigated the *Bosmina*, pollen and diatom stratigraphies of Nanguvuono from a 125-cm-thick gyttja deposit resting on sand. He divided the Nanguvuono gyttja into three pollen assemblage zones (I, II-III and IV). According to

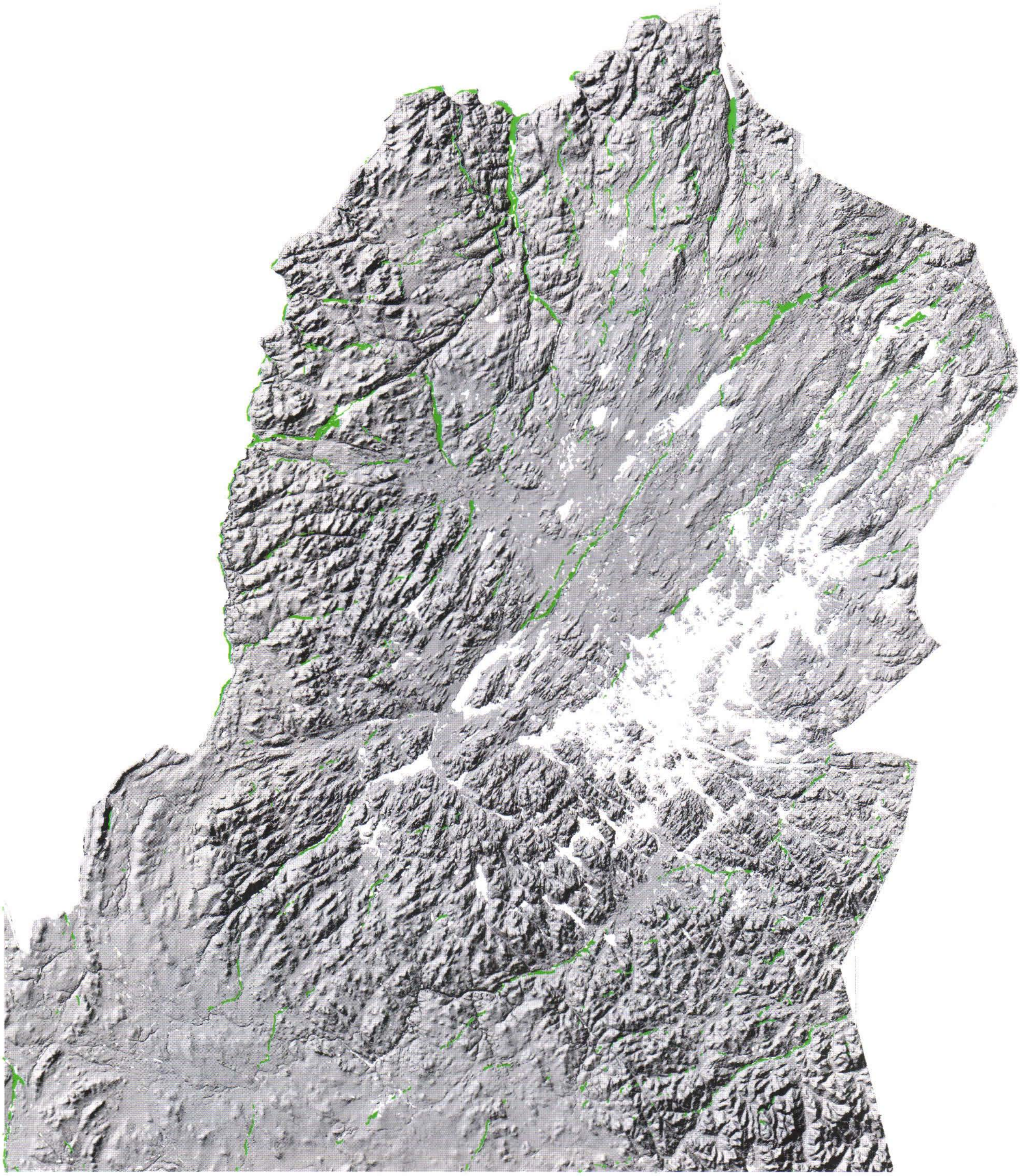

Fig. 3. Relief and eskers (green) in the northernmost Finland to the scale 1:1 000 000. The shaded image has been produced from the elevation model data of National Land Survey of Finland, licence no. 287/MAR/98.

Table 1. Studied cores from Inarijärvi: 1) lithostratigraphy, 2) varves), 3) pollen, 4) diatoms, and 5) grain size and humus content.

Core		1	2	3	4	5
I	Inari, Isolahti			x		
II	Inari, Nanguvuono	x	x	x	x	
III	Inari, Kasariselkä S			x	x	
IV	Inari, Kasariselkä N	x	x	x	x	x
V	Inari, Kasariselkä	x	x			
VI	Inari, Sammakkoselkä	x	x	x	x	x
VII	Inari, Lusmanuora	x			x	
VIII	Inari, Vasikkaselkä	x			x	
IX	Inari, Vasikkaselkä N	x	x			
X	Inari, Satapetäjäselkä	x	x	x	x	
XI	Inari, Vasikkaselkä W	x	x			
XII	Inari, Sammakkoselkä N	x	x			
XIII	Inari, Sammakkoselkä S	x	x	x		
XIV	Inari, Kaikunuora	x	x			
XV	Inari, Kahkusaarensalmi	x	x			
XVI	Inari, Ukonselkä	x				
XVII	Inari, Nanguvuono S	x	x			
XVIII	Inari, Nanguvuono E	x	x			x
XIX	Inari, Nanguvuononselkä	x	x			
XX	Inari, Moossinaselkä	x	x			x
XXI	Inari, Kasariselkä W		x			

the *Bosmina* and diatom analyses, the Nanguvuono gyttja deposited in oligotrophic water although a slightly alkaline stage prevailed at the onset of deposition (Alhonen 1969). The present stage and evolutionary trend of Inarijärvi was studied in 1992-1997 (Marttunen et al. 1997).

The material presented here was collected in the 1970s and '80s in conjunction with the general geological mapping of Quaternary deposits to the scale 1 : 400 000. The objective was to establish the amount of sediments deposited on the lake floor since glaciation and the extent to which they differ from those in the vicinity. The samples were studied in different years by various people. Consequently, when compiling the present paper we could no longer check or supplement the material or bring the results into line with the standards of present-day research. The results of the microfossil studies, for instance, are therefore usually based on 100 determined specimens. Even so, the outcome gives a good overall picture of the Inarijärvi deposits and their genesis.

Twenty-six cores were taken with a piston corer from the floor of Inarijärvi; data on 21 are given here (Table 1). Owing to the shortage of relevant information (cf. Alhonen 1969), the coring was planned on the basis of the bathymetric map compiled by Ristiluoma (1968), as we assumed that the abundance of sediments was highest in the lake depressions. We also attempted to study the mode of occurrence and distribution of sediments with an echo-sounder (Atlas Monograph), but due to the large size of the lake the attempts were not altogether successful.

INARIJÄRVI SEDIMENTS

The lithostratigraphy of the lake sediments turned out to be very similar in all depressions (Figs 4 and 5). Eight cores reached till. Lowermost or resting on the till in all cores was a layer of varved sediment; six cores are more or less deformed. The mean thickness of the varved sediment is 113 cm (range 44-235 cm). The layer is composed of three parts: lowermost there is a layer, 50 cm thick on average, of distinctly varved silt or lean clay, which shows that the sedimentation rate declined as the ice sheet front withdrew from the area. The proximal varves are up to several centimetres thick, usually, however, 2-5 mm. In the next layer the grain size becomes finer upwards. The clay content increases to 65-75% (Fig. 6), and the thickness of the varves is down to 0.5-1 mm. Finally the varves can no longer be distinguished as the sediment gradually becomes increasingly homogeneous. This layer of fat clay is no more than 10 cm thick at its maximum (Fig. 7) and is overlain by a distinctly varved lean clay with a sharp contact in between. The grain size of this clay becomes slightly coarser upwards, implying an increase in the sedimentation rate (varves up to 2-4 cm thick). After a thick

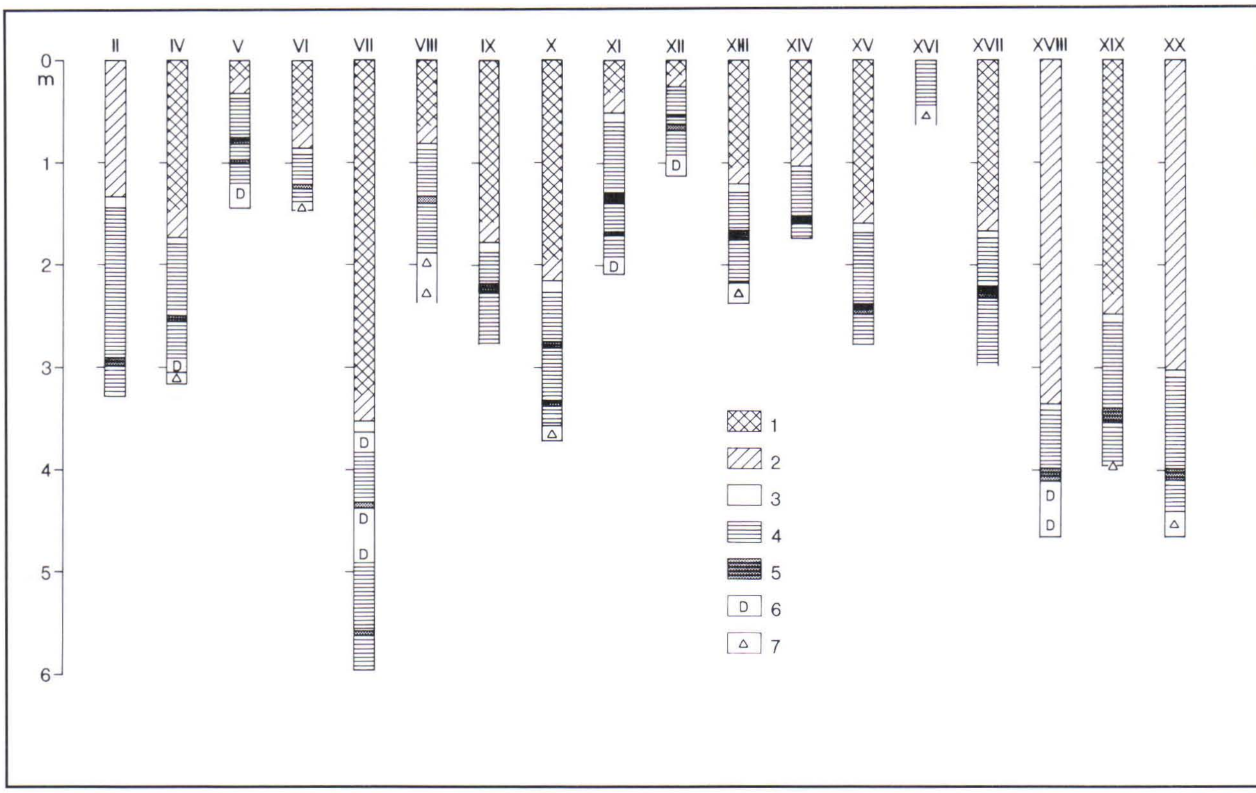

Fig. 4. Lithostratigraphy of cores investigated: 1) clayey gyttja, 2) gyttja clay, 3) homogeneous clay, 4) varved clay/silt, 5) fat clay, 6) deformations, 7) till.

varve or varves the sedimentation rate declines to the 1-2-mm level and the grain size becomes slightly finer once again. According to colorimetric determinations, the abundance of organic matter in the whole varved sediment layer is 0.5-1% (Fig. 6).

Separated by a moderately distinct contact, the varved clay is overlain by 10 cm of homogeneous clay (Fig. 8), in which the humus content rapidly rises to over 2%. The clay layer grades upwards into gyttja clay (2-6% humus), in the upper part of which there are occasional black sulphide bands and the mineral matter becomes less sorted in grain size. The abundance of clay remains at 30% but that of coarse silt and even fine sand increases slightly at the expense of fine and medium silt. The gyttja clay layer, too, is often only 10 cm thick, and grades upwards into clayey gyttja (>6 % humus). In some cores the sediment remains gyttja clay up to the surface. In the light of the four cores investigated (Fig. 6; IV, VI, XVIII and XX), we may conclude that the organic matter transported to the open part of the lake or formed there from plankton deposited mainly in depressions (Fig. 6; cores IV and VI). Owing to this accumulation of sediment in depressions, the moderate production of organic matter in the lake resulted in high humus concentrations. The number of sulphide bands increases as the concentration of organic matter rises to over 6%, and vivianite precipitates visible to the naked eye appear in the sediment. The humus content of the glayey gyttja remains fairly constant, ranging only from 7.5% to 9%. The grain size, too, remains constant right up to the surface. In the southwestern part of the Inarijärvi basin, close to the present mouth of the river Ivalojoki (Fig. 6; XVIII and XX), the concentration of organic matter remains below 6%. The properties of the gyttja clay are fairly constant right up to the surface.

The mean thickness of the gyttja clay/clayey gyttja layer is almost 1.5 m, fluctuating between 20 and 338 cm. At one coring point (XVI, Ukonselkä), the gyttja clay/clayey gyttja layer is absent.

In the Nanguvuono core studied by Alhonen (1969) and taken from close to the shore, the clayey gyttja layer is underlain by sand, and the varved sediment is absent. According to loss-on-ignition determinations, the concentration of organic matter is about 9% to start with but declines rapidly to 2%. The core reflects local littoral conditions, and the results obtained from it cannot be correlated with those from depression cores.

The total thickness of the deposits is estimated not to exceed 6 m (Fig. 4). The maximum length of core (without deformations) taken with the piston corer was 4.5 m, and it is possible that a few tens of centimetres of sediment are missing from the upper part. The sediment layers are thicker in the southern part of the lake.

Varves were counted in 15 cores (Fig. 9). From the lower part of core XXI we only had a photo at our disposal, and from this we could estimate the number of varves in the lowermost varved clay. Although most of the varves were distinct we could not count those in the fat clay unambiguously. For the most difficult parts we estimated the number of varves from the thickness of the layer and the mean thickness of the nearest varves. Not all cores reached the till, however, and we had to estimate the number of missing varves. Some cores had been heavily deformed and for them, too, we had to assess the sedimentation rate from the mean varve thickness in the nearest parts of the sediment that could be recognised reliably. Many of the cores, however, contained varves or groups of varves that could be identified with certainty and on the basis of these we were able to correlate the cores with each other.

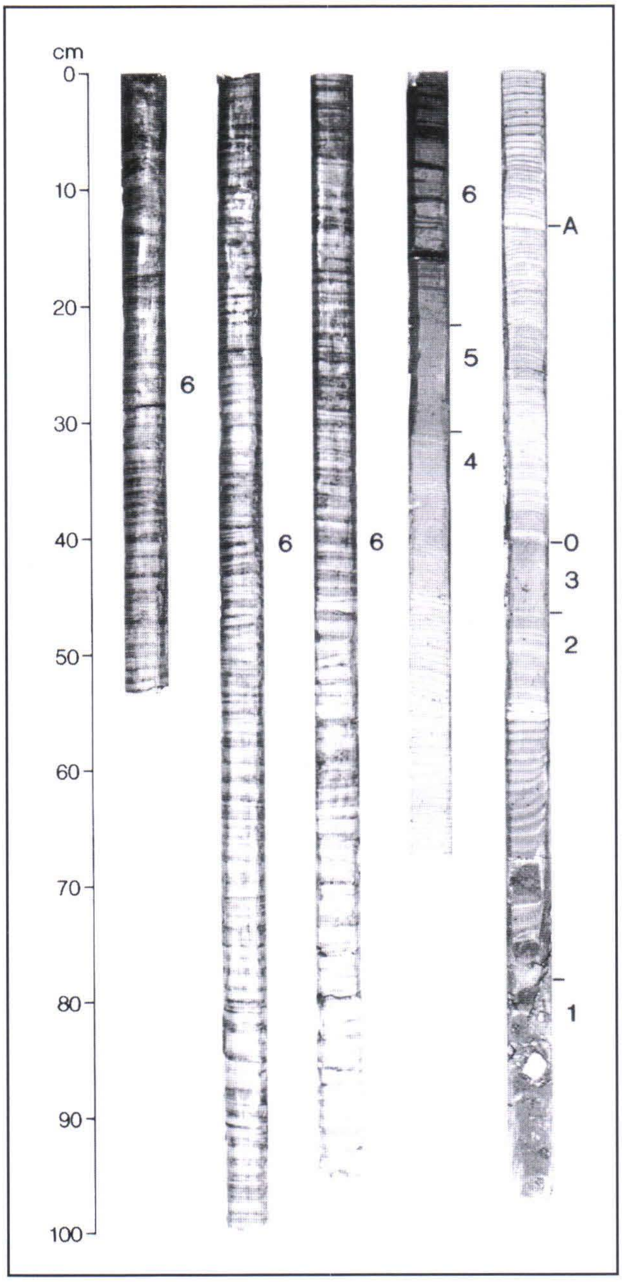

Fig. 5. Photograph of core XX containing the following stratigraphic units: 1) till, 2) lower varved clay, 3) fat clay, 4) upper varved clay, 5) homogeneous clay, 6) gyttja clay/clayey gyttja) and varves O and A.

The first varve succeeding the deposition of fat clay, which, in all cores except those from Nanguvuono (Figs IB and 9; II, XVII and XVIII), probably represents the same depositional stage, is named varve O (Figs 5, 7 and 9). Depending on the core, the fat clay layer might contain from 50 to 90 varves, consequently representing sedimentation from 50 to 90 years.

A thick varve, named varve A (Figs 5, 9 and 10), is recognisable in the upper varved clay, most distinctly in cores from the southwest of the lake (except in the Nanguvuono area) (Figs. 1B and 9; cores IV, XII, XIII, XIV, XIX and XX). This varve deposited about 122 varves later than varve O, and was followed by another 113 varves; in other words, the last varve formed about 235 years after varve O. On a large scale, the upper varved clay shows regular variations in sedimentation rate that are visible in the Nanguvuono area but no longer in the Kasariselkä or Sammakkoselkä areas (Figs 1B and 9; cores II, XIV, XVII, XVIII, XIX and XX). Despite the shortcomings in the varve count, large variations in sedimentation rate are visible in Nanguvuono core II, too.

An exceptionally thick varve, varve B, that is particularly prominent in the lower varved clay in the centre of the lake (Figs 1B and 9; cores V, VI, IX and XIII) records a rapid sedimentation event. When the front of the ice sheet was roughly in the line Kahkusaari (coring point XV) - Satapetäjäselkä (coring point X), a fairly large glacial lake impounded in the headwaters of the Kaamasjoki discharged its waters from the northwest. Since the discharge is represented by only one varve, which is clearly thicker than the others, the maximum intensity of discharge did not last more than a year. Thereafter the flow and sedimentation in the Inarijärvi basin levelled off, corresponding to the prevailing normal meltwater activity.

The closer the cores were to each other, the more reliably they could be correlated, also for the lower varved clay. The correlation is fairly reliable between cores IV, V, XII, XIV, XV, XIX, XX and XXI. A relative ordinal number can be given to the bottom varve of these cores, remembering, however, that only cores III, XV, XIX and XX reached till. We did not attempt to estimate the number of missing varves in the lowermost part, but it was probably not very high. We delineated the posi-

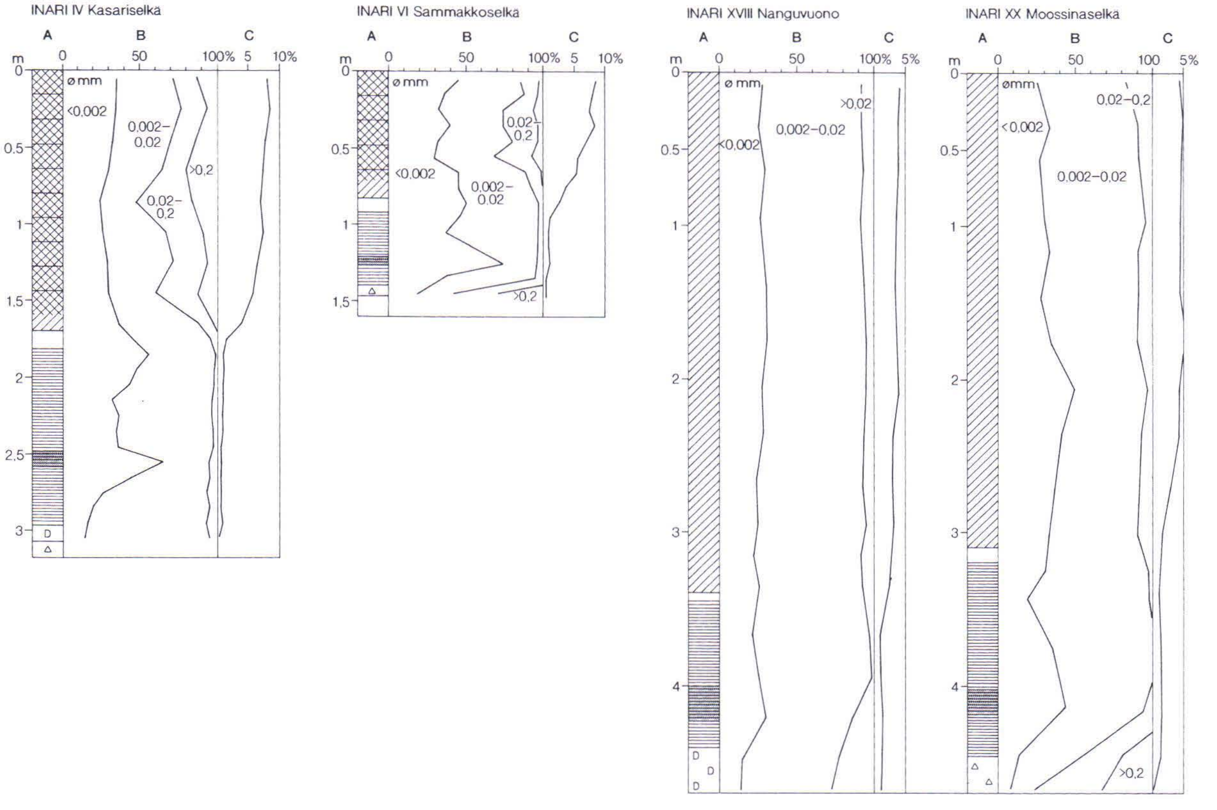

Fig. 6. Properties of cores IV, VI, XVIII and XX: 1) lithostratigraphy, for symbols, see Fig. 4, 2) grain-size distribution and 3) humus content by colorimetry.

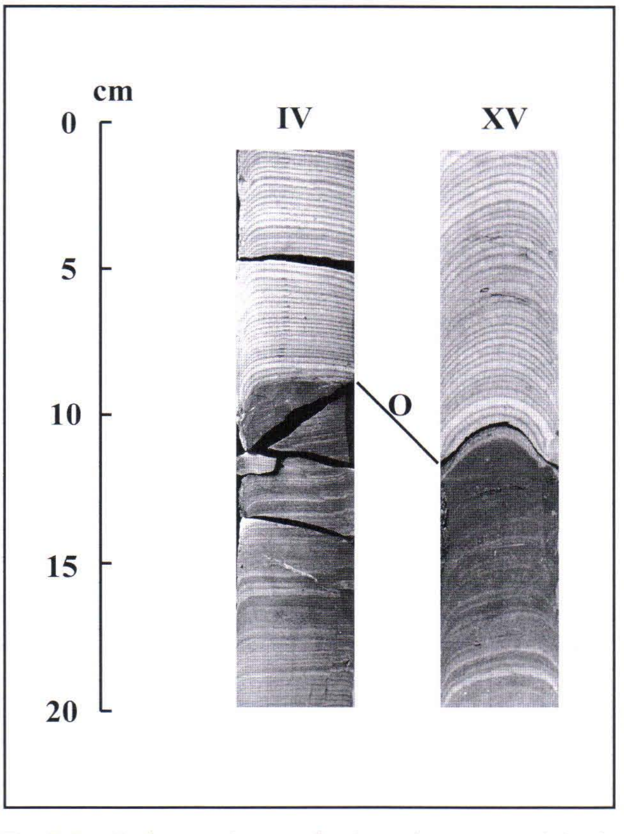

Fig. 7. Detail of contact between fat clay and upper varved clay in cores IV and XV.

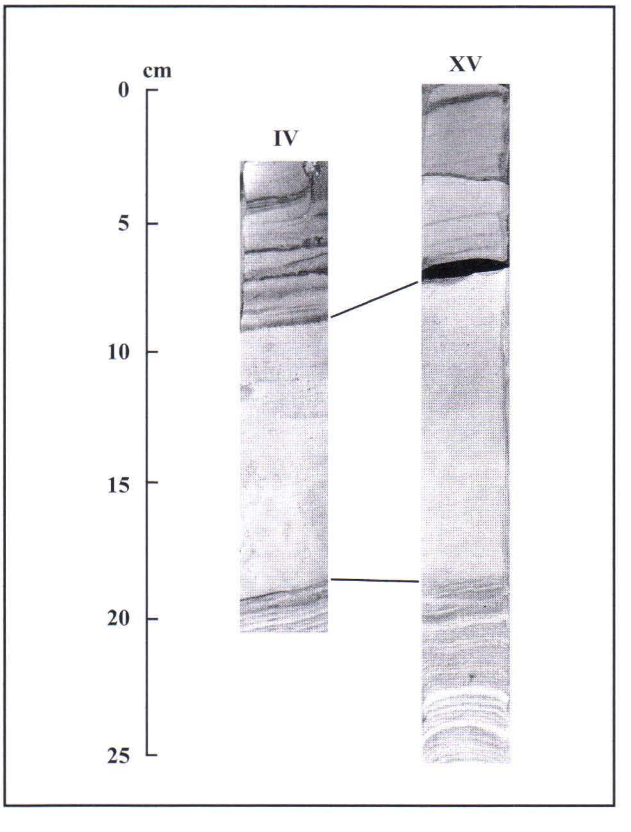

Fig. 8. Detail of a layer of homogeneous clay between upper varved clay (below) and gyttja clay (above) in cores IV and XV.

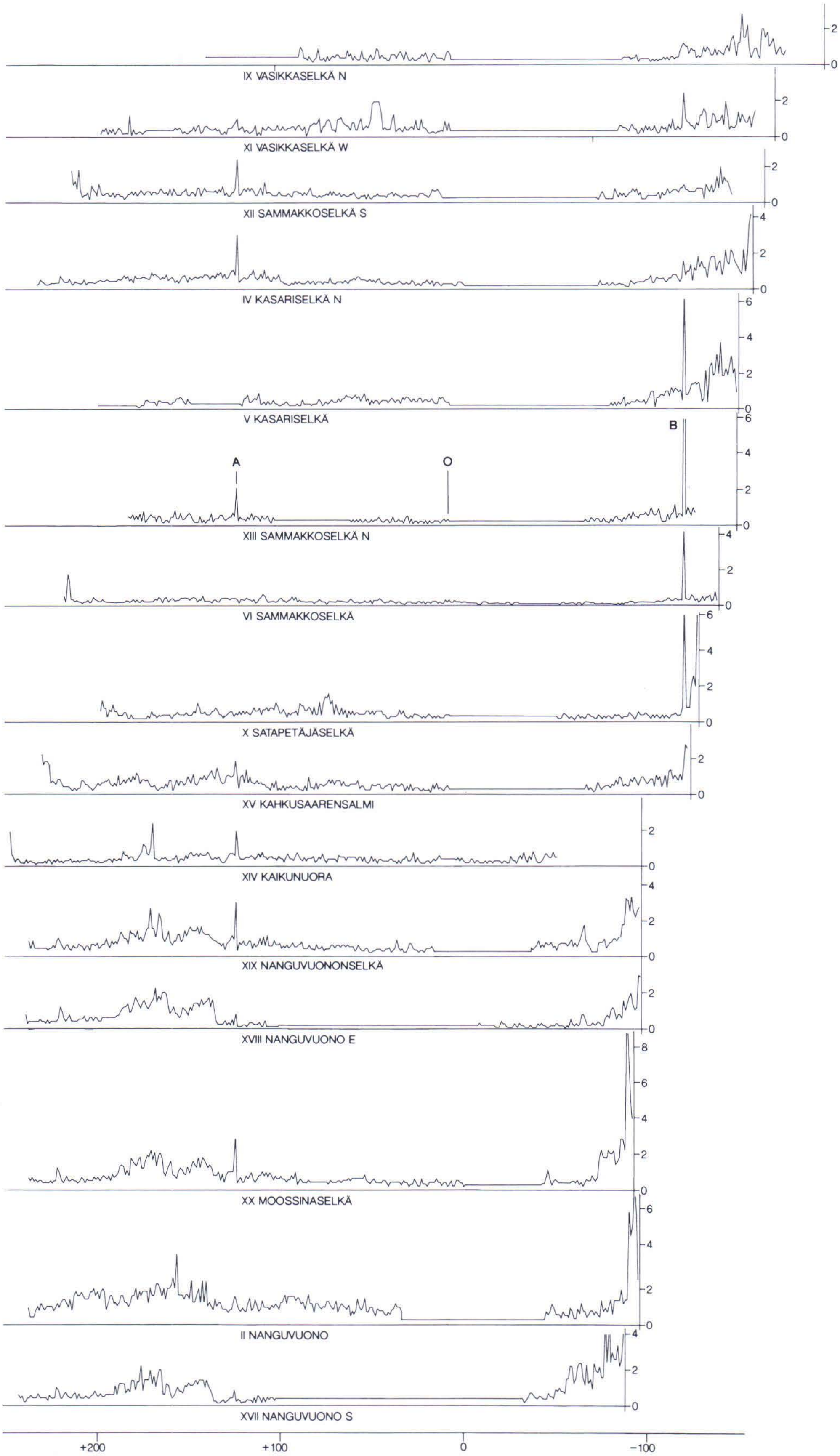

Fig. 9. Correlation of varve diagrams based on the change in sediment type at the contact between fat clay and the upper varved clay, varve O and discharge varves A and B. The varve numbers downwards from varve O are provided with minus and those upwards with plus signs.

tions of the ice front in the central parts of Inarijärvi from the ordinal numbers of the bottom varves (Fig. 11). The coring sites are, however, too far apart for reliable connections to be made.

The varve diagrams were correlated on the basis of common features (Fig. 9). Had the varve counts been faultless, all varves O would be on the same vertical line and the distance to varve A of equal length in all cores. That this is not the case implies that either we did not identify and count all the varves or that some of them had eroded away. The average number of varves counted in cores was 369 (range 329-412). However, from the number of varves we can deduce fairly reliably that deposition of the varved sediment in the Inarijärvi basin lasted about 400 years, in the northeastern part slightly more and in the southwestern part slightly less.

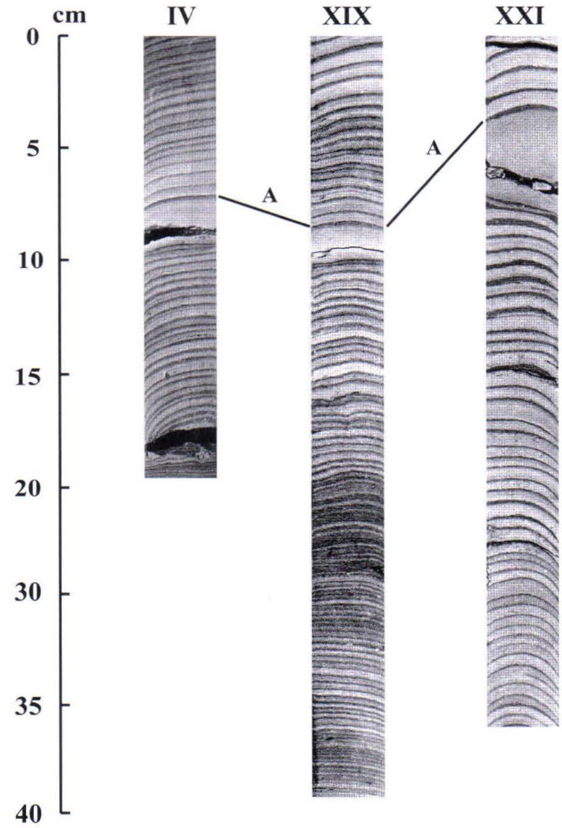

Fig. 10. Detail of varve A, cores IV, XIX and XXI.

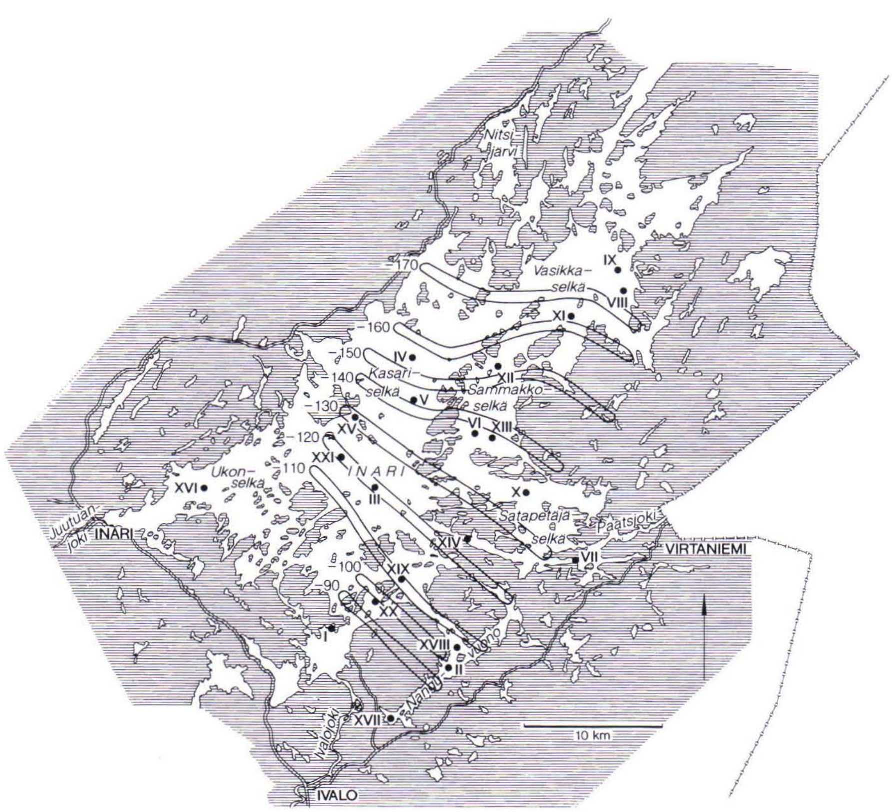

Fig. 11. Positions of continental ice sheet front in the Inarijärvi basin at 10-year periods according to varve count. Numbers show the positions before the deposition of the varve O.

DISTRIBUTION AND AMOUNT OF LAKE SEDIMENTS AND THE AMOUNT OF CONTAINED CARBON

The echo-sounder and sediment data imply that glacial sediments (varved silt/clay) are fairly common throughout the Inarijärvi floor. Rocky and till-dominant floor types occur on elevations and steep slopes (Fig. 12). The depth of the basin, however, does not seem to have had a marked effect on the occurrence of sediments. We estimate that the average amount of varved sediments in the basin is a good half of the mean thickness of these sediments in the cores studied, 113 cm, i.e. about 60 cm. Taking into account the surface area of 1000-odd km^2, we deduce that the Inari basin contains about 600-700 million m^3 of silt and clay, probably washed from glaciofluvial deposits and till while these were forming.

The thickest deposits of postglacial sediments (gyttja clay/clayey gyttja) are probably in basins where depositional conditions were tranquil, e.g. in Nanguvuono and the depressions in large open waters. As the allochthonous production, which is mainly humus, is more intense near the inlets of rivers, that of the Ivalojoki in particular (Kerminen and Nenonen 1967), the postglacial deposits are thickest in the western parts of the lake. Sampling demonstrated that postglacial deposits are absent from only one coring point. West of Ukonselkä, off Inari village, there was less than half a metre of clay on the floor. The average thickness of postglacial sediments in the whole basin can be assumed to be 60 cm, since they seem to favour the basins more than do the glacial sediments. Hence, their total amount, too, is probably about 600-700 million m^3.

Assuming that the glacial sediments contain, on average, 0.5% humus and 30% water and that the density of the dry matter is 1.6 g/cm^3 and further that the postglacial sediments contain 5% humus and 60% water and that the density of dry matter is 1.1 g/cm^3 and humus contains 50% carbon we can calculate that the sediments in Inarijärvi contain somewhat less than 10 million tonnes of carbon. This implies that, on average, 1 kg carbon per hectare has deposited in Inarijärvi annually during the 10 000 years that have elapsed since the last glaciation.

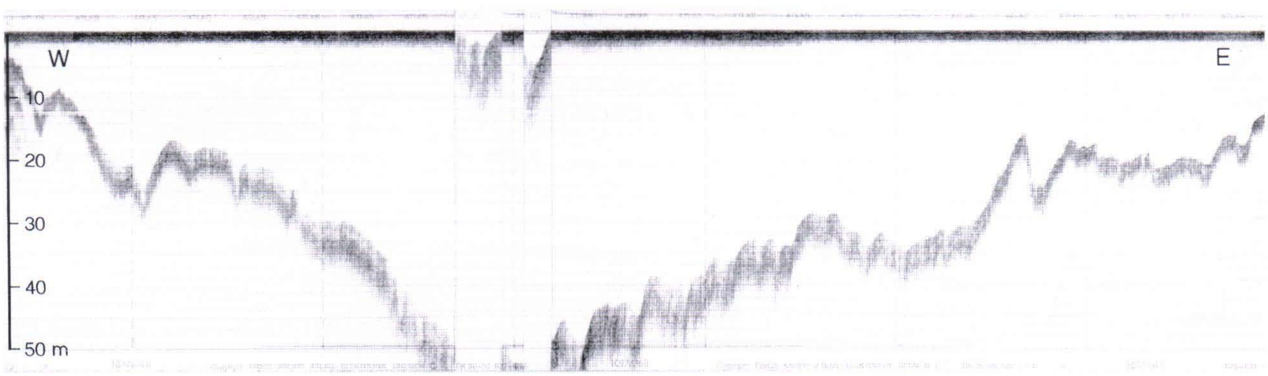

Fig. 12. Echo-sounding profile (about 5 km long) across Kasariselkä from west to east between the coring sites IV and V showing the distribution of the sediments on the lake floor. The lake sediments are missing only from the shallowest parts of the lake bottom.

BIOSTRATIGRAPHY

Pollen

Seven cores were submitted to pollen analysis to delineate the vegetation history and establish potential palynostratigraphic markers in the sediments. All the pollen sequences reflect the same historical development of forests; the proportion of the local pollen flora is very small, as the cores were taken far from the shore. We present here pollen diagrams for two cores (Figs 13 and 14) : Nanguvuono and Sammakkoselkä (Fig. 1B; cores II and VI).

The postglacial vegetation succession in Peräpohjola and Forest Lapland started with a brief period of open-land vegetation, after which birch forests spread to the area, reaching their largest extent 9000 yr BP (Auer 1927, Sorsa 1965, Hyvärinen 1975, 1978, 1996). The rapid increase in pine prevalence that occurred about 8500-7500 yr BP is the most distinctive marker horizon in the pollen diagrams of Lapland and Peräpohjola. As shown by pollen analyses and the dates of subfossil pine trunks found in bogs and ponds (cf. Eronen & Huttunen 1993, Hyvärinen 1993), the pine forests, when at their largest - ca 7000-6000 yr BP - extended to the present birch zone on the fells and to the coast of the Arctic Ocean in the north. When the climate deteriorated around 5000 yr BP or shortly after, the tree lines started to withdraw, a process that lasted for a couple of thousand years, until they reached their present positions. Spruce advanced to the northernmost parts of its distribution about 3000 yr BP.

Inarijärvi and its surroundings belong to the Forest-Lapland phytogeographical region of the north boreal vegetation zone (Alalammi 1988) where only pine and birch form forests. Dry, nutrient-poor lichen-predominant pine forests are common; spruce is encountered only occasionally. North of and above the pine limit there are mountain birch forests and dwarf shrub heathlands. The climate is mildly continental (Ahti et al. 1968), the mean temperature in February ranging from -11 to -13 °C and in July from +12 to +14 °C (Alalammi 1987).

Three local pollen assemblage zones (P.A.Z.) can be distinguished in the pollen stratigraphy of the Inarijärvi cores, exemplified here by the diagrams of Nanguvuono and Sammakkoselkä (Figs 13 and 14).

Betula zone. The major part of the varved sediment contains abundant redeposited, mainly arboreal, pollen. Some of the pollen grains are probably contemporaneous, having been transported by wind from distant sources. In this part of the sediment, which represents a period of only a few centuries, the relative pollen frequency is very low. The contemporaneous vegetation was a mosaic of park-

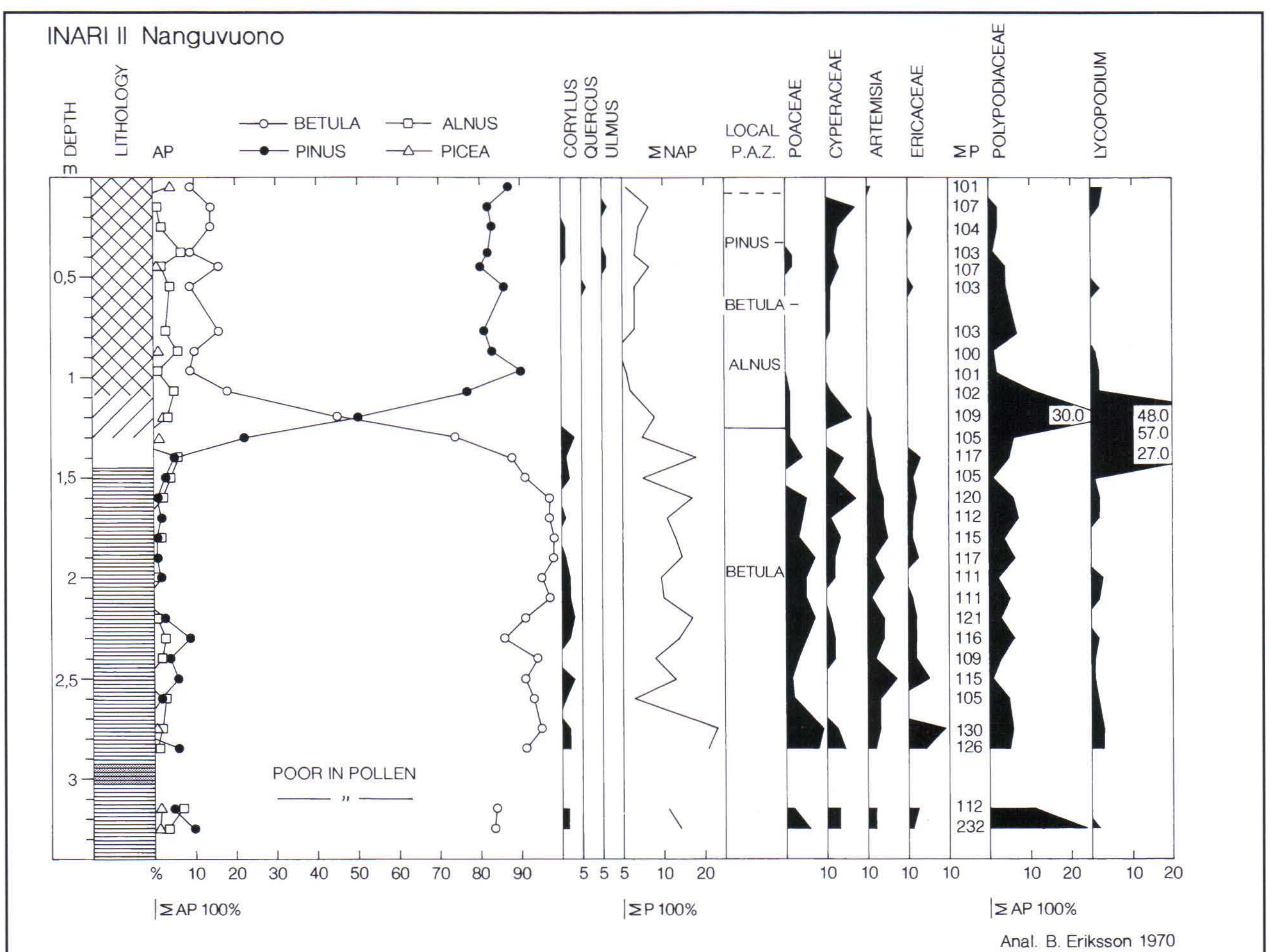

Fig. 13. Abridged pollen diagram. Inari II, Nanguvuono. For sediment symbols, see Fig. 4.

like birch forests and open-land vegetation colonies in areas that had emerged from the ice and water. *Salix*, Ericaceae, Poaceae, Cyperaceae and *Artemisia* predominated in the shrub and field layer. The assemblage also included Asteraceae, *Saxifraga*, *Polygonum viviparum* and *Selaginella*. The Ericaceae pollen show a small maximum followed by a low and fairly continuous curve in the varved Nanguvuono and Sammakkoselkä sediment. In other Inarijärvi cores, the abundances of Ericaceae pollen are lower and the occurrence of pollen grains is less regular. Hyvärinen (1996) defined a separate Ericales subzone (1a) in the *Betula* zone (1), dating its termination to about 9000 yr BP.

The relative pollen frequency starts to increase in the upper part of the varved sediments, being fairly high in the homogeneous clay and gyttja clay, where the abundance of redeposited pollen is very low. The pollen composition of the upper part of the *Betula* zone reflects vegetation dominated by continuous birch forests. Distinct maxima of Polypodiaceae and *Lycopodium* spores at the border between the *Betula* and *Pinus-Betula-Alnus* zones are visible in all cores studied. The pollen series of the surroundings of Inarijärvi (Sorsa 1965, Seppälä 1971, Hyvärinen 1975) demonstrate that lycopods and ferns were abundant in the area during the birch forest stage. Hyvärinen (1996) dates the *Lycopodium* subzone (1b) he separated from the *Betula* zone to 9000-7500 yr BP. This pollen assemblage has no counterpart in the area of present birch forests (Hyvärinen 1975). The coincidence of the *Lycopodium* maximum with the rise of the pine curve in the pollen stratigraphy of Inarijärvi is probably due to long-distance transport by wind of pine pollen into the large water basin and/or the water transport of pollen from the catchment before pine became prevalent in the area.

Pinus-Betula-Alnus zone. The pollen assemblage of the clayey gyttja layer in the Nanguvuono and

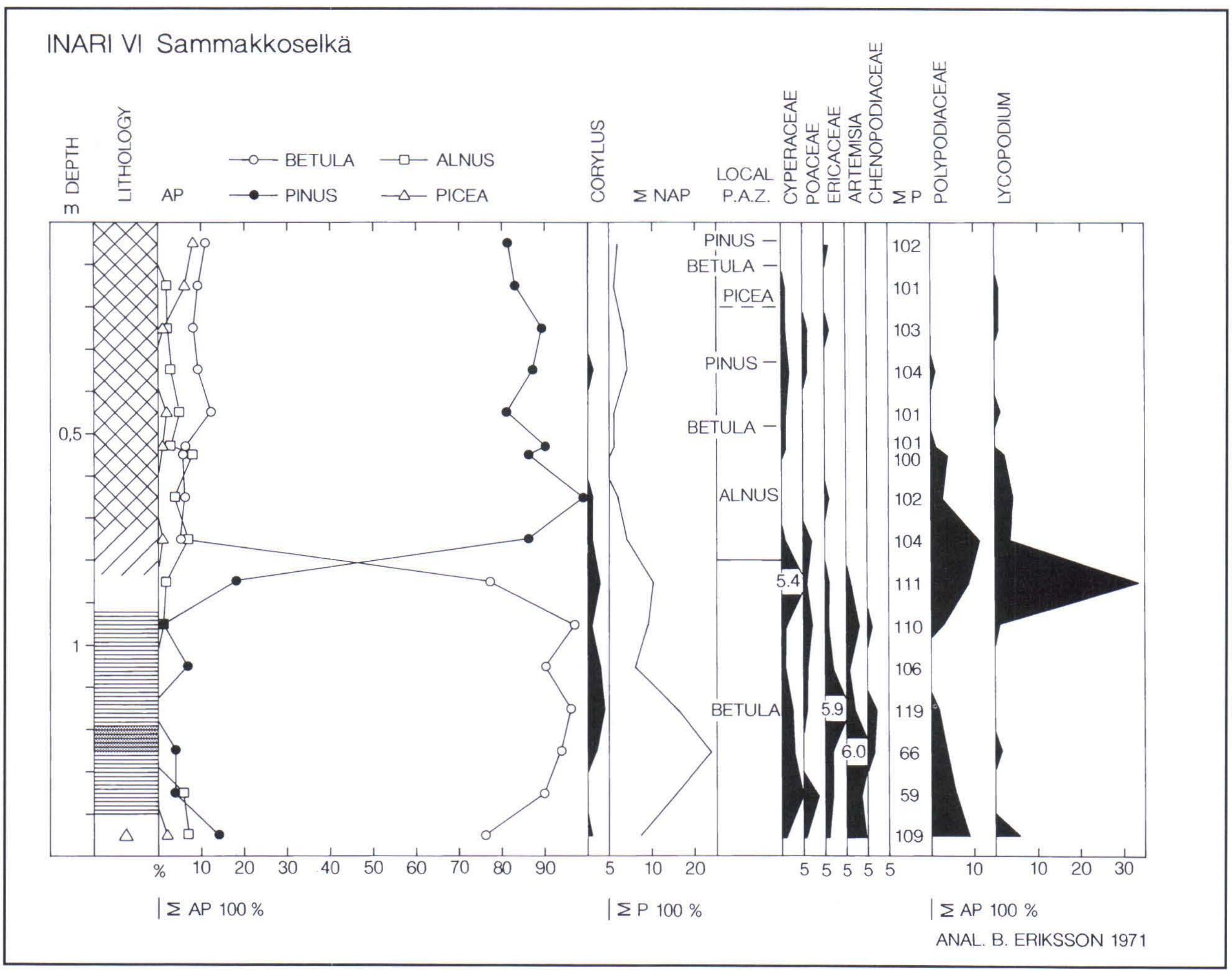

Fig. 14. Abridged pollen diagram. Inari VI, Sammakkoselkä. For sediment symbols, see Fig. 4.

Sammakkoselkä cores reflects the occurrence of pine and birch forests similar to those of today. The pollen values of *Alnus* are at their highest in this zone, implying that alder colonies grew on wetlands and lake shores during the climatic optimum. The vegetation indicated by the pollen zone prevailed in the area 7500-3200 yr BP (Hyvärinen 1996).

Betula-Pinus-Picea zone. The arrival of spruce 3200 yr BP (Hyvärinen 1996) is not recorded in the Nanguvuono core. However, the continuous spruce pollen curve of the Sammakkoselkä core shows that the species had spread to the Peräpohjola phytogeographical region, to the south of Forest Lapland. The pollen values are fairly high (maximum 3.5-4.5%) compared with most of the other Inarijärvi cores and with other cores studied from the area (e.g. Sorsa 1965, Hyvärinen 1975). Since the northern spruce forest limit was then, as it is now, south of the study area, the spruce pollen grains in the Inarijärvi cores are mainly due to distant transport by wind and possibly also by waters of the river Ivalojoki. The nearest spruce forests currently grow along the Ivalojoki and at the same latitude close to the eastern national border; however, the spruce limit runs north of the area (Alalammi 1988; Fig. 5a). Since the immigration of spruce the forests in the area have been similar to those occurring today.

The cores only occasionally contained *Potamogeton* pollen, *Isoëtes* spores and *Pediastrum* colonies; one pollen grain of *Myriophyllum alterniflorum* was also found. Exceptionally, the clayey gyttja in the Kasariselkä core (Fig. 1B; III) contained abundant *Isoëtes* spores, most of all in the upper part of the layer where their dominance was over 20%. *Isoëtes lacustris* and *I. echinospora* as well as *Myriophyllum alterniflorum* are submerged plants that grow in oligotrophic lakes.

Diatoms

Diatoms were studied in seven cores taken from the central, eastern and southeastern parts of the lake (II, III, IV, VI, VII, VIII, X). Owing to the similarity of the diatom stratigraphies the results of only two cores (Figs 1B; II and X) are given in diagrams (Figs 15 and 16). The highest number of

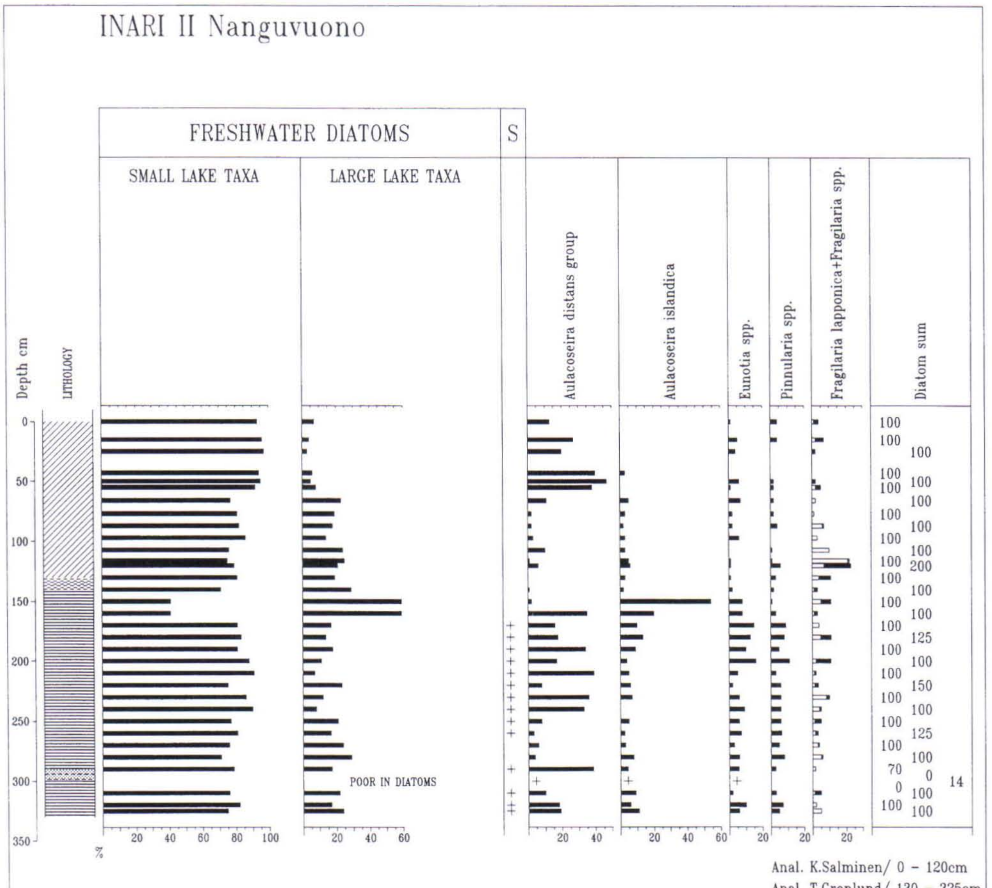

Fig. 15. Distribution of diatoms on the basis of their habitat. Inari II, Nanguvuono. S = diatoms living under marine conditions and stratigraphy of selected taxa. For sediment symbols, see Fig. 16.

diatoms named from Inarijärvi was 255 taxa/core. A total of 436 diatom species from the seven cores studied were named (see Grönlund 1998). The nomenclature was updated from the level of the 1970s (Williams et al.1988, Round et al.1990, Round and Bukhtiyarova 1996 and Bukhtiyarova and Round 1996).

Apart from a few saline water diatoms found in lower parts of the cores and interpreted as redeposited, the cores contain only freshwater diatoms. The diatoms have been grouped into large-lake and small-lake species on the basis of their typical habitat. Large-lake diatoms are characteristic of cool, alkaline fresh water, poor in humic matter and with moderate content of electrolytes , such as water of the Ancylus Lake and the Baltic Ice Lake of the Baltic Sea. The other freshwater diatoms represent small-lake species. The presence of saline species is marked with a cross in diagrams.

The diatom stratigraphies of the cores are very similar, small-lake species being dominant in all of them. The lower parts of certain cores are poor in diatoms, and some of them may be secondary, at least those requiring a saline habitat. The abundance of diatoms starts to increase in the horizon in which the concentration of humus starts to rise. The

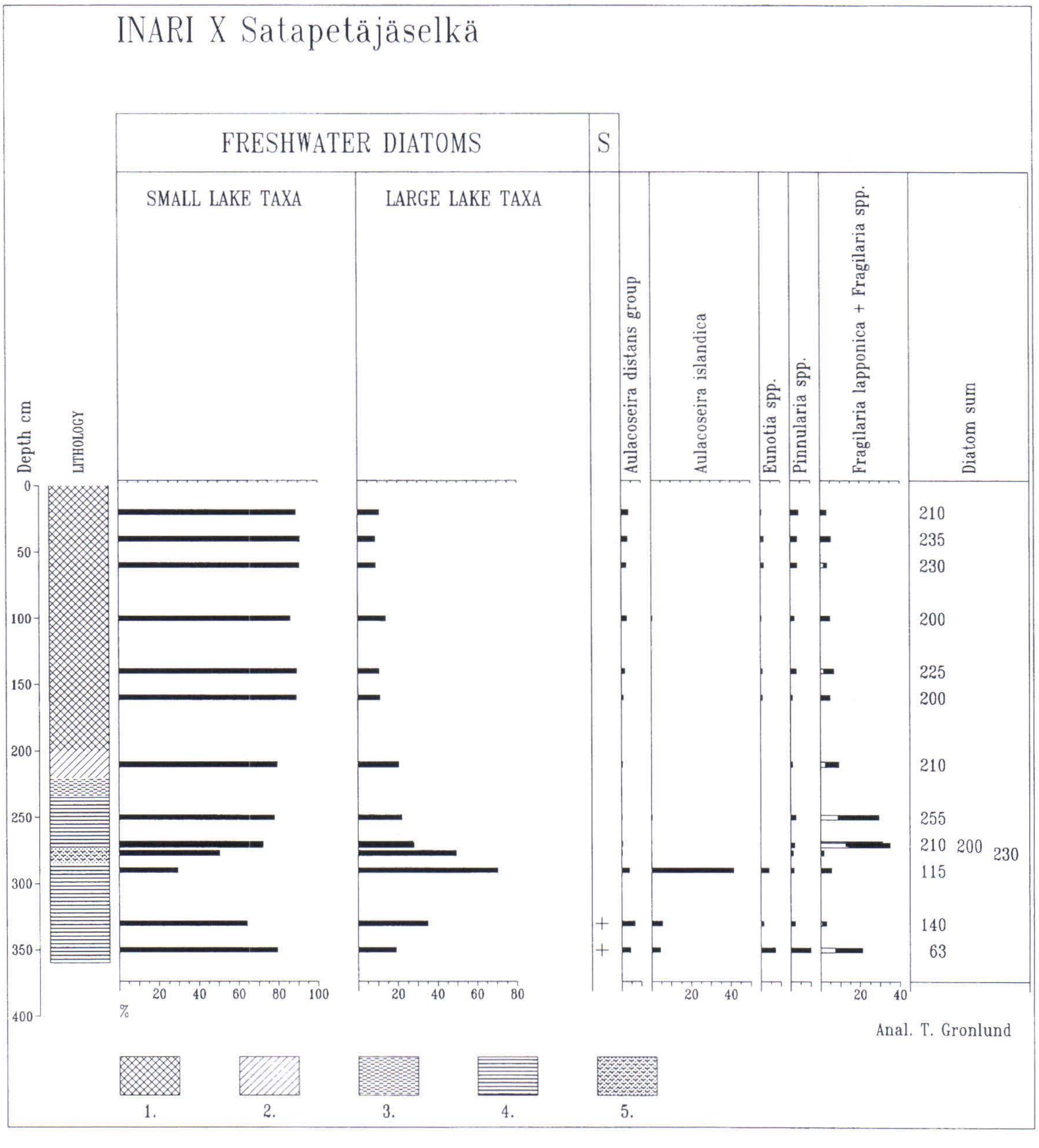

Fig. 16. Distribution of diatoms on the basis of their habitat. Inari X, Satapetäjäselkä. S = diatoms living under marine conditions and stratigraphy of selected taxa. Sediment symbols: 1) clayey gyttja, 2) gyttja clay, 3) homogeneous clay, 4) varved clay, 5) fat clay.

abundance of large-lake diatoms is at its highest in the upper part of the varved clay layer and in the lower part of the gyttja clay/clayey gyttja layer. *Aulacoseira islandica* (Müller) Simonsen (including the morphotype *A. islandica* ssp. *helvetica* (Müller) Simonsen), *Cyclotella bodanica* Grunow and *Stephanodiscus neoastrea* Håkansson & Hickel, all of which live in plankton, are the most common large-lake species. Of them, the first two are cool-water species, as is *Cyclotella antiqua* W. Smith (Mölder & Tynni 1970), a species typical of oligotrophic lakes in Lapland. *Ellerbeckia arenaria* (Ralfs & Moore) Crawford, *Campylodiscus noricus* Ehrenberg, *Cymbella aspera* (Ehrenberg) Peragalli, *C. lanceolata* (Ehrenberg) Cleve and *Gyrosigma attenuatum* (Kützing) Rabenhorst are littoral large-lake species.

The diatom flora in the uppermost clay gyttja / clayey gyttja does not show marked change in species. Small-lake species *Cyclotella iris* Brun, *Tabellaria fenestrata* (Lyngbye) Kützing, *T. flocculosa* (Roth) Kützing and *Aulacoseira*, *Eunotia* and *Pinnularia* species are common.

Alkaliphilous species of the *Fragilaria* genus are also abundant; the northern species, *Fragilaria lapponica* Grunow, is particularly common. The increase in the abundance of *Fragilaria* species coincides with or immediately follows the maximum of the large-lake diatoms, being clearest in cores VII and X. The mass occurrence of the *Fragilaria* genus is typical of the initial stage of the evolution of lakes.

EVOLUTION OF INARIJÄRVI

Tanner (1906, 1907, 1915, 1930), who studied Quaternary geology in the northern parts of Fennoscandia, argued that during the deglaciation stage the sea extended to the Inarijärvi basin. Synge (1969) provided more detailed information on the highest shore and its characteristics in the Inarijärvi basin, and came to the same conclusion as Tanner: the highest shore marks represent a marine transgression. It is nonetheless generally held that isostatic uplift exceeded the eustatic rise in sea level throughout the postglacial stage, except at the margins of the uplift area (e.g. Pirazzoli 1991), thus precluding the possibility of a transgressive stage. Morphological observations show that the highest shore, which at Virtaniemi - at the present outlet of the river Paatsjoki - is at 131 m asl, rises from the eastern part of the lake southwestwards; thus at Nanguvuono it is at 145 m and 3 km east of Ivalo at 151.6 m asl. These shore marks are located on the same tilted plane, with a gradient of 0.47 m/km (Synge 1969).

The marine stage is not, however, recorded in the diatom stratigraphy of the lake, only a few saline water diatoms having been found in the sediment. At least some of these are redeposited from older sediments, such as *Hemiaulus* sp. and *Triceratium trifoliatum* Cleve, both of them probably Tertiary in origin (Grönlund 1977, Tynni 1982). *Auliscus sculptus* (W. Smith) Ralfs, *Biddulphia* spp., *Coscinodiscus* sp., *Paralia sulcata* (Ehrenberg) Cleve and *P. sulcata* var. *sibirica* (Grunow) Cleve are probably from the Eemian interglacial.

During deglaciation, small local lakes were impounded by the front of the ice sheet in the northeastern part of the Inarijärvi basin, in basins now occupied by the lakes Surnujärvi, Suolisjärvi and Nammijärvi. Initially, these glacial lakes drained over the water divide into the Arctic Ocean. As deglaciation proceeded the basins at the highest elevations gradually joined those at lower elevations, eventually joining the Inari glacial lake proper. To start with, its discharge channel was at the northern end of the present lake Nitsijärvi, at a level slightly less than 130 m asl. From west of the lake, there are observations of a water level a few metres above the highest shore line (Synge 1969); these are obviously from this glacial lake stage. In the course of deglaciation the ice front withdrew southwestwards and several small glacial lakes around the eastern end of Inarijärvi drained into it. The Inari glacial lake stage terminated when the ice front reached the starting point of the river Paatsjoki and the water level in the lake coincided with that in the Ocean. This was the start of the Proto-Inari stage, which is characterised by the proximity of the continental ice sheet, an abundance of meltwaters and the great amount of sediments transported by these waters.

A few large glacial lakes developed in the vicinity of Proto-Inari, often draining suddenly into the Inarijärvi basin. This is visible in sediments as increased deposition (thick varves) and explains the great fluctuations in thickness of the proximal varves. The correlation of an exceptionally thick varve with a given glacial lake stage in the lower varved clay is possible only for cores V, VI, XIII and X. At that time the ice front was slightly southwest of the sites from which these cores were taken and the waters of the glacial lake impounded in the headwaters of the river Kaamasjoki drained from the northwest into the Inarijärvi basin, depositing varve B.

The sedimentation rate declined, however, when the ice front withdrew southwestwards. Owing to ice calving the withdrawal was fairly rapid. After the ice front had reached the southwestern end of the basin, the basin acted for some time in a flow-through capacity. Consequently, abundant silty and fine sand sediments were transported into the basin and sedimentation remained fairly rapid. On reaching the supra-aquatic area west of the lake the ice front became stagnant for a while and the amount of glacial mineral matter declined, as shown by the thinning of varves and reduction in the grain size of the sediment. The suddenly increased sedimentation rate and the coarsening of sediment (upper varved clay) were due to an increase in meltwater activity, as shown by the sudden thickening of the varves.

Provided that the observations of the transgressive nature of the highest shore are valid (Tanner 1907, 1930, Synge 1969), the variation in sedimentation rate could also be explained by assuming that the basin was at first a flow-through basin and that abundant silt and fine sand were transported into it. Once transgression had reached its highest position, at Virtaniemi, a large strait controlled the water flow in the basin and flow-through became less intense. The sedimentation rate diminished as coarse sediments deposited in the deltas at river mouths and only clay was transported into the Inarijärvi basin. This concept could also explain the shortage of redeposited pollen in the fat clay layer (cf. Donner and Gardemeister 1971). The stage lasted 50-90 years. As the water level fell, the flow changed and fractions coarser than clay started to enter the basin once again. Meanwhile the ice front had withdrawn to the Saariselkä fells, and meltwaters accumulated in the Inarijärvi basin from an increasingly large area, carving channels and other erosional forms in their bed. Coarse fractions, gravel and sand deposited in river valleys as large glaciofluvial plains (deltas,v sandurs, valley fills) and the finer fractions were transported by water into the Inarijärvi basin, further promoting sedimentation. The rise in the sedimentation rate of the upper varved clay bears testimony to this evolution.

When the ice front had reached the water divide between the rivers flowing southwards to the Gulf of Bothnia and the Ivalojoki, the glacial lakes impounded beyond it discharged for some time along the river Vaskojoki and later along the Ivalojoki to Inarijärvi. It is possible that the thick varve that formed 123 years after the upper varved clay had started to deposit (A+122) is associated with the drainage of a large glacial lake. For instance, a glacial lake discharged through the headwaters of the river Repojoki, and its waters deposited a large sandur east of Reposelkä. The intense flow through the headwaters of the Repojoki probably lasted a few years. Waters from glacial lakes that had developed south of the main water divide flowed into the Inarijärvi basin for a good hundred years and the last glacial lake waters that came over the main water divide flowed to the headwaters of the Ivalojoki along the northern side of Korsatunturi fell. Deposition of the glacial (varved) sediments of Proto-Inari came to an end when the ice front had withdrawn so far to the south of the water divide that the meltwaters started to flow into rivers heading southwards. The average sedimentation rate during the glacial stage has been estimated at somewhat less than 3 mm/yr.

As deduced from varves, the withdrawal rate of the ice sheet in the basin was 240-330 m/yr (Fig. 11). It took the ice front from 400 to 500 years to withdraw from Vasikkaselkä in the eastern part of Inari to the main water divide, a distance of 120 km, implying a rate of about 250-300 m/yr. The rate is slightly higher than that estimated from the lateral drainage channels in the Saariselkä fell area (Tanner 1915, Penttilä 1963, Piirola 1982, Kujansuu and Hyyppä 1995, Johansson 1997).

The time following deglaciation is clearly recorded in the diatom stratigraphy, because the proximity of the ice sheet, its dynamics and the amount of meltwater affected the water, sedimentation and diatom flora of the basin. When sedimentation was rapid, few microfossils deposited, as demonstrated by the gaps in the pollen and diatom stratigraphies. As well as small-lake diatoms, the diatom flora contained abundant large-lake diatoms in the Proto-Inari stage.

The deposition of varved sediments with a *Betula*-dominant pollen assemblage terminated about 9000 yr BP, and the independent Inarijärvi stage started. Homogeneous clay began to deposit on the varved clay. The abundance of organic matter in the clay increased rapidly as the vegetation in the environment became more dense, and production started in the lake after the glacial influence had ceased. At the same time the total sedimentation declined markedly, being less than 0.2 mm/yr throughout postglacial time (150 cm in 9000 years). The deposition of gyttja clay/clayey gyttja has been very similar ever since.

Small-lake diatoms are dominant in the diatom flora. After a brief, more alkaline stage the lake became oligotrophic and has continued its evolution without great changes ever since; it is still oligotrophic today, although the quality of its water varies, being clearest and most oligotrophic in the north and slightly brownish due to river waters in the south and west (Marttunen et al. 1997). Acidification caused by atmospheric sulphate fall-out came to an end in the mid-1980s. Diatom analyses on the surficial parts of the sediment imply slight eutrophication since the late 1980s (Puro et al. 1997).

SUMMARY

The continental ice sheet withdrew from the northeastern end of the Inarijärvi basin southwestwards to the main water divide in 9700-9200 BP. On the basis of sediments, the evolutionary history of Inarijärvi (Fig. 17) can be divided into two main stages: 1) the "late-glacial" stage of varved mineral matter and rapid sedimentation that lasted about 500 years, during which Proto-Inari, at first an ice-dammed lake, which discharged at Sevetti over the water divide into the river Näätämöjoki, being later connected with the Arctic Ocean via the Paatsjoki river valley. There is, however, no record in the diatoms of the brief connection with the Ocean and saline water even though the ancient shores imply that it really did take place. Most likely, the vast amount of meltwater prevented the saline water from entering the Inarijärvi basin. The Proto-Inari stage continued for as long as the meltwaters continued to flow into the basin and affected the sedimentation there; 2) the "postglacial" stage of long and slow sedimentation, during which pine and birch forests similar to those occurring today were dominant, the lake became oligotrophic and gyttja clay/clayey gyttja deposited on the lake floor as a result of its own production but also partly transported by rivers discharging their waters into the lake. Changes in climate and vegetation, e.g. paludification of the environment, caused minor changes in the properties of sediment. The sediments in depressions underwent anaerobic decomposition under oligotrophic conditions, resultingFig. 17. Environmental interpretations and stratigraphic correlations of Inarijärvi sediments. 1) lithostratigraphy, 2) humus content, 3) sedimentation rate, 4) local pollen assemblage zones and relative pollen frequence, 5) diatoms, 6) developmental stages of Inarijärvi, 7) age in ^{14}C yr BP. in the formation of sulphide-bearing bands. Throughout the existence of the lake, 1 kg carbon per hectare, on average, has been bound to sediments annually.

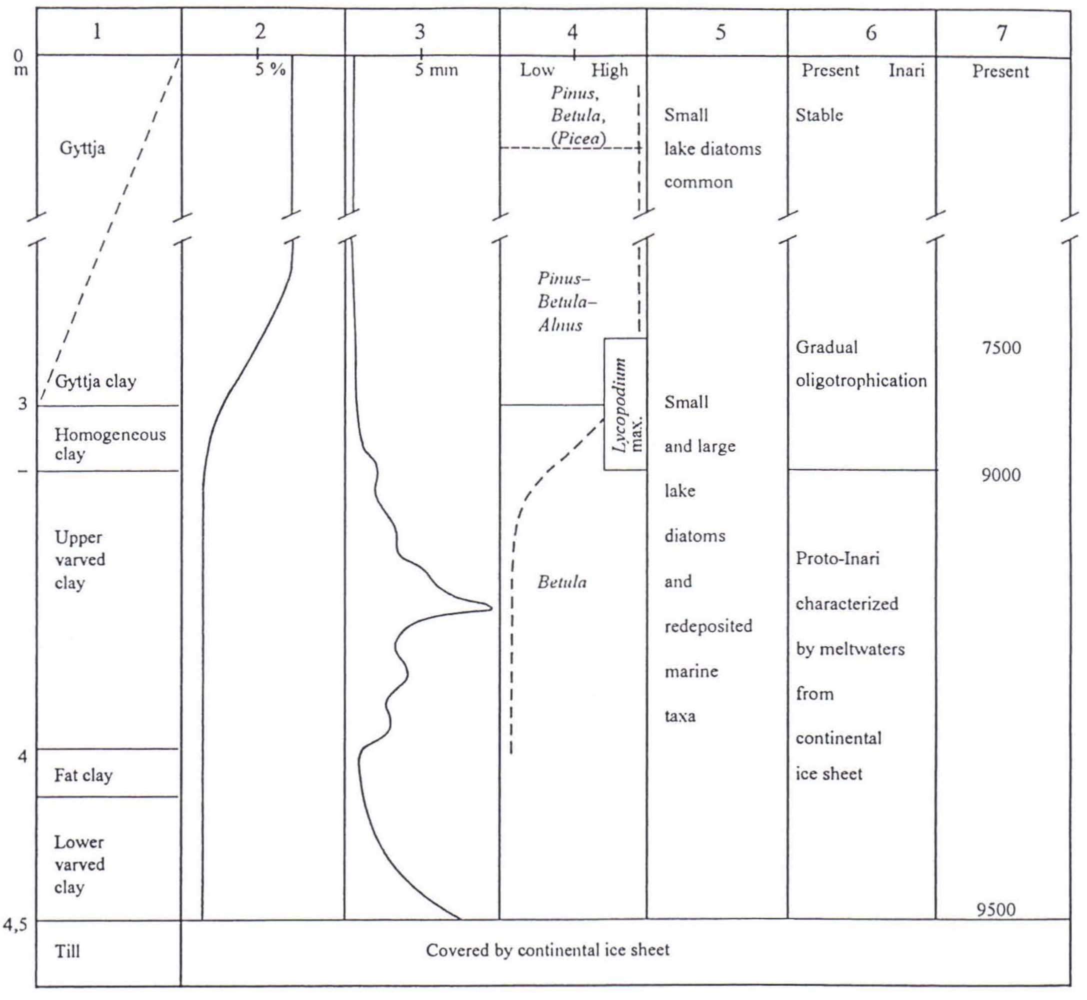

Fig. 17. Environmental interpretations and stratigraphic correlations of Inarijärvi sediments. 1) lithostratigraphy, 2) humus content, 3) sedimentation rate, 4) local pollen assemblage zones and relative pollen frequence, 5) diatoms, 6) developmental stages of Inarijärvi, 7) age in ^{14}C yr BP.

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