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Pukinmäki, a hill in Southern Ostrobothnia, Finland, composed mainly of interglacial silt – evidence for deglaciation of the area by distintegration of the ice and for only one Weichselian glaciation phase.

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Abstract

The hill of Pukinmäki in Southern Ostrobothnia rises more than 10 m above its surroundings and possesses a thin till cover but is otherwise composed of silt, gyttja-silt and sand. The relative abundance of pollen of trees and bushes requiring warm growing conditions such as *Quercus*, *Ulmus*, *Fraxinus* and *Corylus* and of a diatom flora indicative of saline water in the silt show that it was laid down in the Eemian sea during the last interglacial.

These interglacial deposits have largely been preserved because there was little glacial erosion in the Pukinmäki area after the last interglacial, the eventual deglaciation taking place in the form of melting of dead ice and disintegration of the ice, during which processes the hill was formed by extrusion of interglacial material into fault zones between the ice boulders.

The preservation of the silt and the presence of a thin cover till on the hill suggest that the area was covered by ice only once during the Weichselian, the ice advance probably having taken place during the first Weichselian stadial, OIS 5d. Known deposits in the glaciated area of Fennoscandia and its immediate surroundings enable a model to be constructed for the glaciation history of the Early Weichselian with which individual data sets fit well.

Key words: Pukinmäki, Ostrobothnia, interglacial, pollen, diatoms, Weichselian glaciation.

1. INTRODUCTION

There is an extensive area of Southern Ostrobothnia, in the west of Finland, where the esker chains are predominantly overlain by till (Niemelä, 1979). These eskers are relatively gently sloping, discontinuous and difficult to distinguish from their surroundings, so that inventories of sand and gravel reserves have been continued by means of coring until very recent times. One of the sites investigated in this process has been the hill of Pukinmäki, which rises more than 10 m above its surroundings and was thought to represent part of a till-covered esker chain. Coring to a depth of 27 m nevertheless demonstrated that it is composed predominantly of gyttja-silt, the salt-water diatom flora contained in which was typical of the Eemian sea during the last interglacial (Kurkinen et al., 1993).

Organic material interpreted as interglacial or interstadial in origin has been discovered at many sites in the till-covered eskers of Southern Ostrobothnia (Niemelä & Tynni, 1979; Donner, 1988; Punkari, 1988; Gibbard et al., 1989; Grönlund, 1991; Kujansuu, 1992; Eriksson, 1993; Punkari & Forsström, 1995), as also in Central Ostrobothnia (Forsström, 1982; Hirvas & Nenonen, 1987; Forsström et al., 1988; Peltoniemi et al., 1989; Nenonen et al., 1991; Eriksson & Kujansuu, 1994; Grönlund & Ikonen, 1996), and various opinions exist regarding the ages of the eskers and the nature of the organic material found in them. Niemelä and Tynni (1979) interpreted the known cases at the time of writing as *in situ* organic deposits, i.e. interglacial or interstadial material that had originally accumulated directly on top of these eskers. This would imply that the eskers themselves must at least be older than the last interstadial, so that only the cover till represents the final glacial advance. Most of the above authors have been in agreement with this, and dates obtained for such deposits by the thermoluminescence (TL) and optically stimulated luminescence (OSL) methods have been considered to support such an interpretation (Kujansuu, 1992; Hütt et al., 1993). In their summary of these views, Saarnisto and Salonen (1995) conclude that the glaciofluvial material in these eskers must have been deposited during the melting of the Saalian glaciation and the long ice-free period followed this until the return of the ice to the area during the OIS 4 phase, c. 70,000 BP. This would imply that the organic material had accumulated during the last interglacial or during the Early Weichselian interstadials. The picture of the glacial history of the area put forward by Nenonen (1995a, b) corresponds fairly well with that of Saarnisto and Salonen (1995), except that he assumes that glacial conditions returned to Southern Ostrobothnia somewhat later in the Weichselian, perhaps only around 50,000 BP.

Punkari (1979, 1980) drew attention to the location of the till-covered eskers of Southern Ostrobothnia in a zone of relatively immobile passive ice lying between two large, powerfully flowing lobes, so that they would have received a cover of ablation till at the deglaciation stage. This would mean that the till is not in this case an indicator of great age of the eskers, even though conditions in the area might have favoured preservation of its early glacial morphology on account of the weak glacial erosion (Punkari, 1979). Similarly, the present writer has conjectured that the differences in ice flow rates between areas of till-covered and ‘ordinary’ eskers (cf. Aartolahti, 1972) serve to explain the occurrence of the former in Southern Ostrobothnia and that the redeposited organic material discovered in them cannot be used for dating them (Forsström, 1982).

Among the sites in Southern Ostrobothnia described by Niemelä and Tynni (1979) was Risåsen, where an ancient humified soil horizon appeared to be contained within a till-covered esker (see also Kujansuu, 1992; Hütt et al., 1993). This was interpreted in Forsström (1982) as redeposited organic material transported by the glacier, so that the ‘humified soil horizon’ had developed beneath the till in postglacial times, as in the case of a previously described deposit (Aario & Forsström, 1979). Punkari (1988, 1991) interpreted a number of such organic horizons as redeposited, including that at Risåsen, and Punkari and Forsström (1995), discussing the well-known till-covered esker section at Harrinkangas (Punkari, 1988; Gibbard et al., 1989), concluded that the organic material discovered there must have been redeposited and probably represented the cool later stages of the last interglacial. The occurrence of well-preserved organic horizons in esker deposits was explained in that context as implying that the material had been taken up by the ice directly from the surface of the ground as it spread to the area after the interglacial and had eventually been deposited in the esker when the ice melted. This was regarded as indicating that the area had been covered by ice only once since the interglacial, and that it had already spread there during the first Weichselian stadial, OIS 5d. Forsström (1989, 1991) came to similar conclusions in the case of other corresponding deposits, as also did

Forsström and Punkari (1997) in their discussion of the commencement of the Weichselian glaciation.

The Pukinmäki deposits nevertheless represent a hitherto unknown type with respect to both the morphology of the formation and the thickness of the interglacial deposits, and an explanation for the origin of the formation can be expected to increase our knowledge of the glacial history of the area and help us to gain a better understanding of the behaviour of the Fennoscandian ice sheet as a whole.

2. THE HILL OF PUKINMÄKI

Location

The location of Pukinmäki is indicated schematically in Figure 1, which shows the esker chains and major marginal formations of southern Finland and Russian Karelia, which in turn serve to outline the flow patterns of the main ice lobes (grey areas) and the bodies of passive, stagnant ice left between them (blank areas). The ice lobes defined here by reference to the eskers and marginal formations are similar in form to those described by Punkari (1979, 1980) on the basis of more variable indications. Pukinmäki is located in the area of passive ice in western Finland that Punkari (1980) refers to as the 'South Bothnian triangle'. A corresponding area in which large numbers of deposits interpreted as being of interglacial or interstadial origin have been discovered (references above) is in the centre of the figure. Certain sites of organic deposits that will be referred to below are indicated on the map by the numerals 2, 3, 4 and 5.

Pukinmäki and its surroundings are depicted in Figure 2. The hill rises to a relative height of nearly 15 m and is almost entirely encircled by fields. It lies in effect at the head of a valley, so that it is overlooked on its west, south and east sides by rocky hills that exceed it in height by some 20 – 30 m. It can be deduced from the incidence of bedrock outcrops and boulder fields that the cover till on these hills is thin. The low-lying areas are composed of clay or silt deposits of unknown thickness. The coring site on the top of Pukinmäki is marked on Figure 2. Although the core extended to a depth of 27.5 m, no definite evidence for the position of the bedrock surface was obtained.

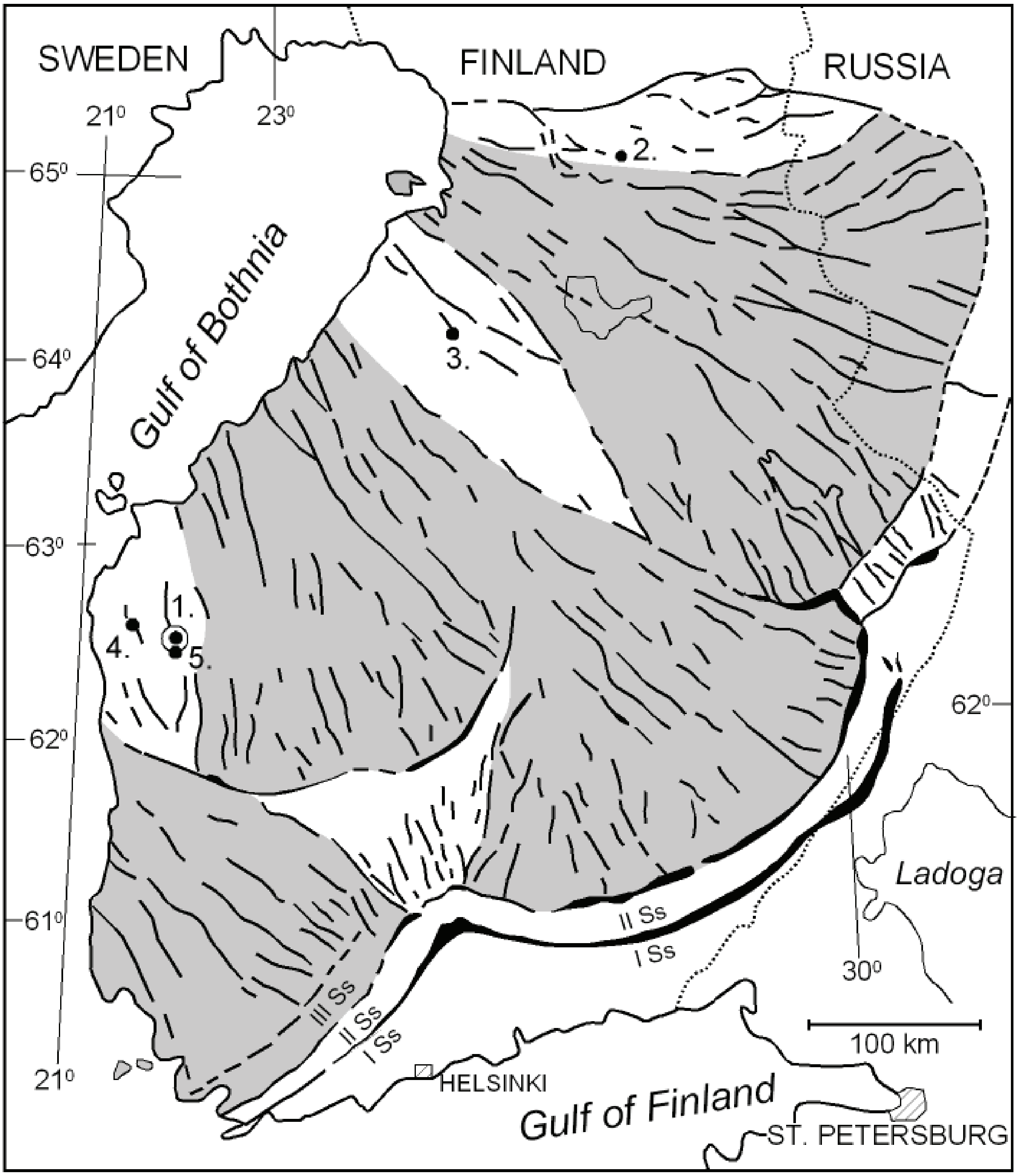

Fig.1. Ice lobes in southern Finland and Russian Karelia. 1 = Pukinmäki, 2 = Ruottisenharju, Pudasjärvi, 3 = Oulainen, 4 = Horonkylä, 5 = Harrinkangas, Ss I = Salpausselkä I, Ss II = Salpausselkä II, Ss III = Salpausselkä III.

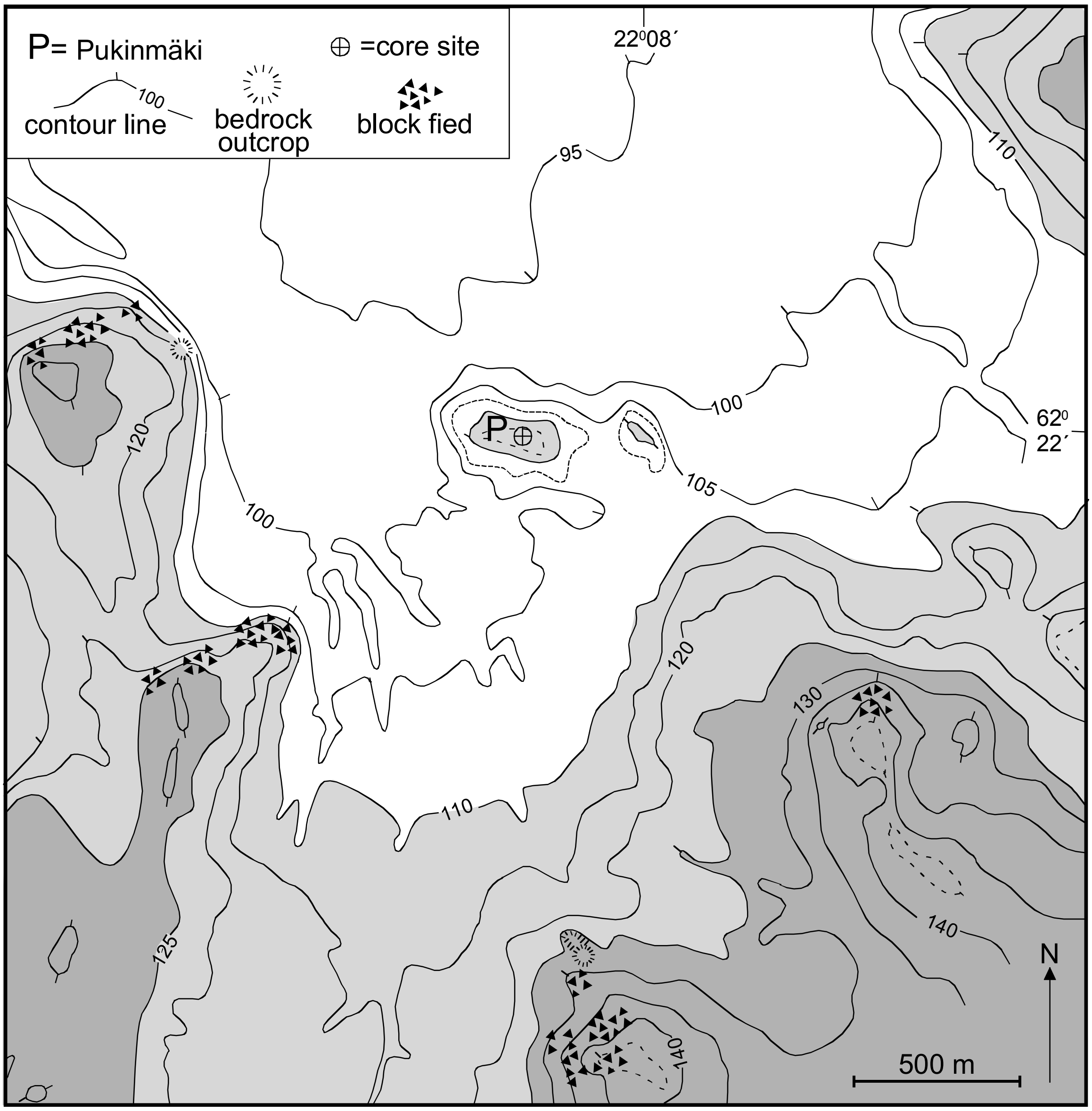

Fig. 2. Relief map of Pukinmäki and its surroundings.

Lithology

The lithology of Pukinmäki has been studied from core samples, and the material available to the present author consisted of the published data (Kurkinen et al., 1993) and the samples presented as lithology columns on the pollen (Fig. 3) and diatom diagrams (Fig. 4). The lithology was determined in terms of the grain-size distribution and organic content of the samples. Each sample represents a 0.5 m stretch of core, and the results are presented as means for these stretches.

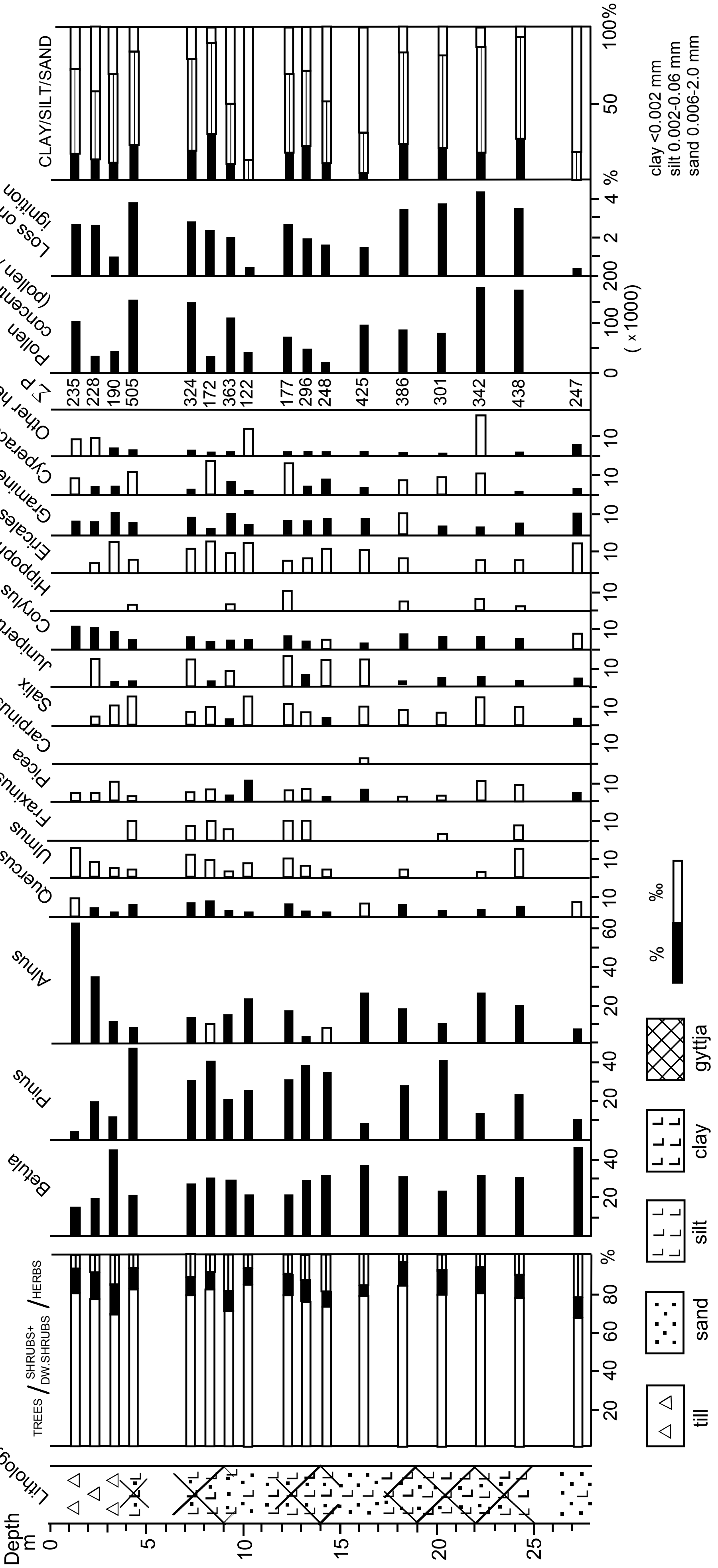

Fig. 3. Pukinmäki pollen diagram.

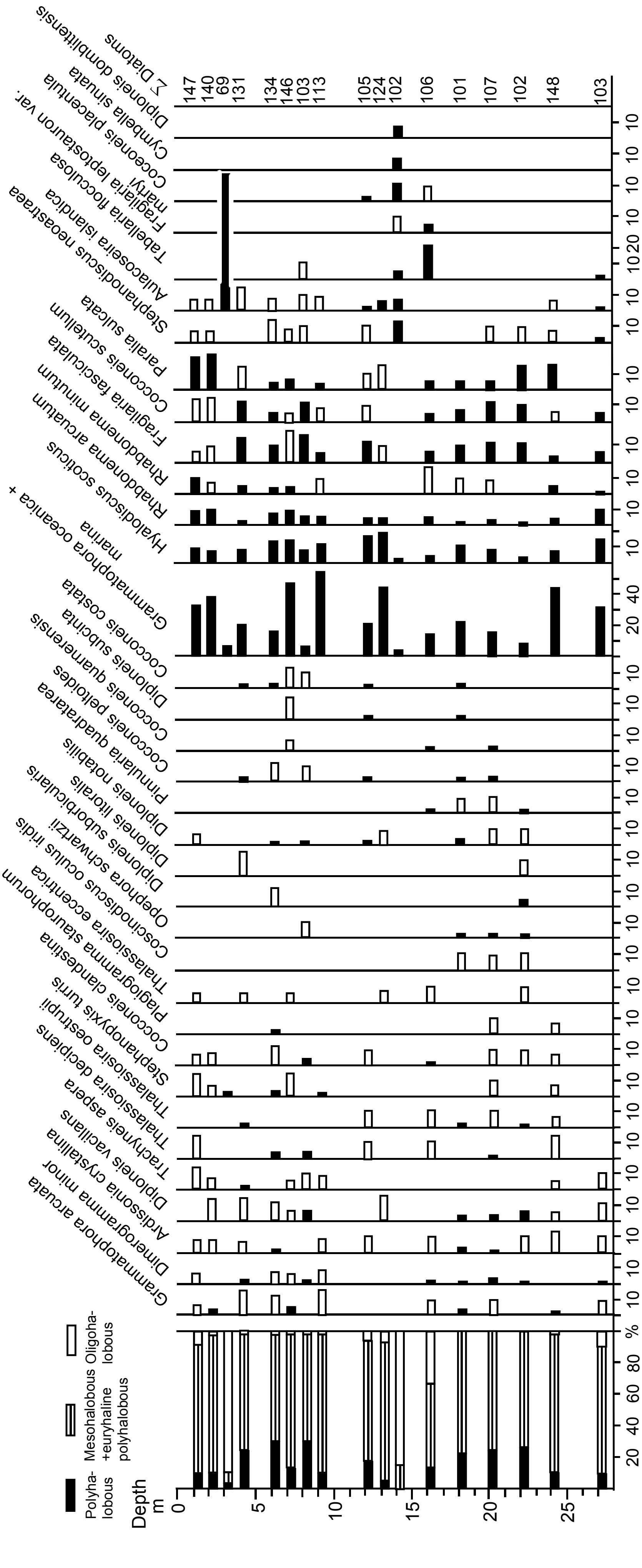

Fig. 4. Pukinmäki diatom diagram, showing selected species.

The surface part of the core, to a depth of almost 1 m, consists of grey, loose leached till, while the material occupying the interval 1–3 m is bluish-grey silty till with relatively few stones. Lower down, to a depth of 24–24.5 m, it is mostly gyttja-silt or silt, with a mean organic content of 2% (Fig. 3). It is only in the intervals 6–6.5 m and 10–10.5 m that something closer to sand is found, just as the grain-size also becomes slightly coarser in the deepest sample of all, at 27–27.5 m.

Pollen

All the samples of Pukinmäki represent 0.5 m lengths of the core. Pollen was studied in all the samples after HF treatment and acetolysis. Pollen concentrations in the samples, determined by the addition of Lycopodium tablets, were fairly regularly some tens of thousands of grains per cm^3, but the grains themselves were frequently in rather poor condition. The results of the pollen analyses are presented in Figure 3.

Betula is the dominant pollen taxon in the lowermost sample studied, accounting for 46% of the total, while *Pinus* and *Alnus* reach 10% and 7%, respectively, and *Picea* 3%. Of the shrubs, *Juniperus* and *Salix* are present at levels of a few percent, while Gramineae and Cyperaceae are the most common herbs. Arboreal pollen makes up a fairly low proportion of total pollen, only 68%.

No great fluctuations in pollen composition occur in the interval 24–18 m. *Betula*, *Pinus* and *Alnus* continue to be the most common arboreal pollen taxa, but all the samples also contain about 5% *Quercus* pollen, and the shrub pollen similarly includes more or less the same proportions of *Corylus* and *Juniperus* throughout, together with a little *Hippophae* in most samples.

Betula and *Alnus* are still to be found in abundance at 16 m, but *Pinus* is reduced to 8% and *Quercus* to less than 1%. *Picea,* which had previously been rare, increases to 7% at this point, however, and higher values are also recorded for Gramineae and Cyperaceae among the herbs.

The pollen percentages vary greatly in the samples from 14 m to 1 m, as exemplified by *Picea,* which is fairly common at 14 and 16 m but scarcely present at all at 12 and 13 m, becoming more plentiful again at 10 and 9 m but being very sporadic above this.

Diatoms

All the samples of Pukinmäki contained diatoms, but they were frequently so badly fragmented that it was impossible to assess the species composition with any accuracy. The most commonly occurring species and the proportions of salt-water and freshwater diatoms are presented in the diagram in Figure 4, the salinity classification employed for the latter purpose being that of Simonsen (1962), modified to apply to brackish conditions. This means that the polyhalobous species cover all those that require at least a salinity of 8‰, i.e. they include Simonsen's oligoeuryhaline (>30‰), meioeuryhaline (>17–20‰) and mesoeuryhaline (>8–10‰) polyhalobous species. Correspondingly, those classified as mesohalobous, i.e. that tolerate a lower level of salinity, are with very few exceptions ones that require a salinity of at least 0.2‰, i.e. they include Simonsen's pleioeuryhaline polyhalobous (>3–5‰), holoeuryhaline mesohalobous (35–0‰) and euryhaline mesohalobous (30–0.2‰) species. The true freshwater diatoms, some of which are nevertheless able to survive at fairly high salinities, are termed oligohalobous. The group of polyhalobous diatoms consists of species that have been alien to the Gulf of Bothnia or at least rare in it during the Holocene, the occurrence of which can be assumed to indicate pronounced salinity, while an abundance of mesohalobous or freshwater diatoms implies a lower salinity.

The lowest sample examined, 27–27.5 m, contained few diatoms, and those that were present were severely damaged. The species identified nevertheless represented a saline environment in 90% of cases and were polyhalobous in about 10% of cases. Since even those classified as mesohalobous fell into the polyhalobous category of Simonsen (1962), the water in which they lived could well have been more saline than at any time during the Holocene. On the other hand, 10% of the diatoms were oligohalobous, i.e. freshwater species which could not have lived in such saline water. The most common of these, *Stephanodiscus neoastreae*, *Aulacoseira islandica* and *Tabellaria flocculosa*, could admittedly have inhabited brackish water as well (Mölder & Tynni, 1967, 1968), but

Eunotia sp., *Cyclotella radiosa* and *Pinnularia borealis*, which are not shown on the diagram, represent a distinctly freshwater flora.

The saline diatom flora at depth 24 m is the same as in the lowest sample, with just a few differences in the proportions of the species, e.g. a higher incidence of *Paralia sulcata*. One clear difference, however, is the almost total disappearance of the freshwater diatoms, with only a few specimens of *Stephanodiscus neoastraea* and *Aulacoseira islandica* present. The flora at 22, 20 and 18 m then represents for practical purposes an entirely saline composition with a large proportion of high salinity polyhalobous species, over 20%.

At 16 m the salt-water flora is still dominant, but freshwater species now account for more than 30% of the total and more than 30 species of these were identified, most commonly of the genera *Fragilaria*, *Tabellaria* and *Cymbella*. This freshwater assemblage then becomes the dominant flora at 14 m, so that the salt-water species account for no more than about 15% and the number of freshwater species is high, with over 40 identified. Only a metre further up the core, however, the salt-water diatoms are again in the majority, with only 20% freshwater species, while further up still, at 12 m, the latter amount to no more than about 7% and a considerable proportion of the salt-water diatoms, 16%, represent polyhalobous species.

A saline flora continues to predominate in the upper part of the core, with the exception of the 3 m sample, where 90% of the rather sparse diatom population is of the freshwater kind, almost entirely *Aulacoseira islandica*, with just one specimen of *Cyclotella* sp. Thus the composition departs markedly from the freshwater flora found at 14 m, for instance.

Such sharp alternations between saline and freshwater species are to be found in the diatom flora that they can scarcely represent a natural succession, but rather each layer represents material that has been mixed to some extent. This affects the interpretation of the results to the point where support is required from the pollen findings.

Deposition of the Pukinmäki sediments in the Eemian interglacial sea

Marine deposits representing the Eemian interglacial have been identified at many sites on the coast of the Gulf of Bothnia (see references above), and although they are regularly of a redeposited kind and mixed to varying degrees, a schematic picture has emerged of the stages in the history of the Eemian sea and the development of the vegetation during the interglacial (Forsström et al., 1988; Grönlund, 1991; Eriksson, 1993; Forsström & Punkari, 1997). The virtually complete, undisturbed Prangli interglacial deposit discovered on the coast of Estonia (Liivrand, 1991) has been of considerable assistance in the construction of this scheme.

The microfossils in the Pukinmäki sediments represent a typical flora for the Eemian interglacial, and the material can undoubtedly be correlated with the Eemian. The changes in the pollen and diatom composition nevertheless do not follow trends typical of the Eemian, so that it may be presumed that the sediments have been mixed in the course of redeposition. Again *Picea* pollen may be taken as an example. Although this taxon generally appears only in small quantities of less than 1%, a figure of 7% was recorded at 16 m and 12% at 10 m, with less than 1% in the intermediate samples, taken at 12 and 13 m. *Picea* should show one distinct peak towards the later part of the Eemian interglacial, however, and no evidence has been reported elsewhere for random variations in its values of the kind found here (Liivrand, 1991; Eriksson, 1993; Forsström & Punkari, 1997).

The variation in diatom composition points even more clearly to mixing of the sediment than do the pollen data. The majority (85%) of the diatoms recovered at a depth of 14 m represent a freshwater flora, whereas the horizons below and above this are dominated by saline species. This again does not conform in any way to existing data for the Eemian sea, which suggest a consistent saline marine phase throughout (Grönlund, 1991; Liivrand, 1991).

It may thus be concluded that the Pukinmäki interglacial sediments are composed of mixed redeposited material and that they do not allow any conclusions to be reached regarding vegetational trends during the interglacial or the stages of the Eemian sea. The fact that the sediments have been preserved and that Pukinmäki is such an unusual formation nevertheless call for an explanation that must be consistent with the glacial history of Fennoscandia.

3. KORKIAMÄKI

About 9 km north of Pukinmäki is the hill of Korkiamäki, which rises a few metres above the surrounding clay and silt plain. Here a core taken to a depth of 12.6 m has revealed a 2 m layer of surface till overlying a material analogous to that at Pukinmäki (Kauhajoen sora- ja hiekkavarat, 1994). The author has studied pollen and diatoms in a few samples from this core.

Pollen composition (trees + *Corylus*) at depth 12–12.5 m: *Betula* 23%, *Pinus* 40%, *Quercus* 11%, *Ulmus* 1.5%, *Alnus* 11%, *Corylus* 7%.

At depth 5–5.5 m: *Betula* 29%, *Pinus* 14%, *Quercus* 5.5%, *Ulmus* 0.5%, *Alnus* 18%, *Picea* 7%, *Corylus* 4%.

At depth 2–2.5 m: *Betula* 35%, *Pinus* 13%, *Quercus* 3.5%, *Ulmus* 1%, *Alnus* 25%, *Fraxinus* 0.5%, *Picea* 1.5%, *Carpinus* 0.5%, *Corylus* 14%.

The large quantities of diatoms found in the samples represented the same flora as at Pukinmäki, the assemblages at 12–12.5 m and 5–5.5 m consisting almost entirely of salt-water species while those in the uppermost sample, 2–2.5 m, included fairly large numbers of freshwater specimens, mainly *Aulacoseira*, although the diatoms in this sample were so fragmented that it was impossible to form a reliable picture of the proportions of the species.

Examination of the microfossil content of the Korkiamäki sediments suggests that they represent the same kind of material originally deposited in the Eemian sea as virtually all the whole of the Pukinmäki formation. The same interglacial material can in fact be assumed to exist fairly generally in the bedrock depressions of this area, but usually beneath thick layers of younger sediments.

4. DISCUSSION

The occurrence of thick interglacial sediments in both Pukinmäki and Koskiamäki is evidence of the weak erosional effect of the Weichselian glaciation in this area. The explanation for this is probably to be found in the general glacial history of Finland, the various interpretations of which are briefly summarized below, together with comments by the author based on evidence from certain critical deposits.

1. Korpela (1969) interpreted organic deposits indicative of a cold climate that were found between till layers in northern Finland as interstadial in origin and presumed that they divided the Weischselian glaciation into two parts, as Lundqvist (1967) had concluded from Swedish material.

2. Extensive studies of the till stratigraphy of Finnish Lapland (Hirvas, 1991) have also suggested that the Weichselian glaciation in northern Finland consisted of two phases separated by an interstadial.

3. Nenonen (1995a, b) deduced on the basis of deposits in southern Finland that the glaciation had spread to that area during the Middle Weichselian and that the area had been free of ice in the Early Weichselian. The presumed interstadial deposits mentioned above would in this model be regarded as representing Early Weichselian interstadials, either the Brørup (Andersen, 1961) or the Odderade (Averdieck, 1967).

4. Radiocarbon dates obtained for mammoth remains in Finland and one deer antler have led to the assumption that large parts of Finland were free of ice at least 10,000 years during the last stages of the Weichselian (Ukkonen et al., 1999).

5. Descriptions of the last glaciation in Eurasia (Svendsen et al., 1999, 2004) take both the interstadial interpretation of Korpela (1969) and the assumptions based on the mammoth dates as being correct.

Comments

The Lapland till studies (Hirvas, 1991) were criticised at an early stage for failing to take account of the shifting of the ice divide in the course of deglaciation. If this shift is accepted, the two Weichselian tills can both be correlated with a single cycle of growth and melting of the glacier and no interstadial needs to be proposed as occurring between them (Aario & Forsström, 1979; see also Punkari, 1984). It can similarly be concluded that both till beds were laid down during the last deglaciation. Evidence in favour of this interpretation include the coincidence of the assumed directions of ice flow in the Early Weichselian with the orientations of the major esker chains that quite definitely belonged to the last deglaciation phase, and also the lack of eskers during the last Weichselian deglaciation in Hirvas' interpretation (figs. 2 and 3 in Forsström, 1995).

Ruottisenharju in Pudasjärvi

Ruottisenharju in Pudasjärvi (no. 2 in Fig. 1, Fig. 5) is a till-covered esker in which a deposit reminiscent of an ancient soil horizon has been discovered beneath the till. The organic material contained in this horizon was interpreted as having been transported in the glacier and redeposited, as confirmed by the existence of similar material deeper in the same esker. The majority of the material was charred pine wood, but some birch bark was also recovered, a pine seed and a large number of *Empetrum* seeds. The pollen composition of the deposit, featuring high proportions of *Pinus* and *Betula*, corresponds well to the macroscopic remains (Aario & Forsström, 1979; Forsström, 1988), both representing a pine-birch vegetation typical of an open dry heath forest. The deposits can be assumed to represent an organic horizon carried away by the glacier as a frozen slab directly from the ground surface, a situation that would explain both the nature of the material (the birch bark, pine seed and *Empetrum* seeds) and its good state of preservation. Furthermore, the material can be assumed to represent the last ice-free stage in the area prior to the Holocene, as it would scarcely seem possible for older material to have existed on the ground surface before the last ice advance.

The author originally interpreted the organic material at Ruottisenharju as representing an interstadial (Aario & Forsström, 1979; Forsström 1988), but later correlated it with the end of the last interglacial, that would be the last ice-free stage in the area before the

Holocene (Forsström, 1989, 1991; Forsström & Punkari, 1997). This interpretation no longer suffers from the need to explain how it was that pine forest could grow in Pudasjärvi, not far from the Arctic Circle, during an interstadial when it is known for certain that open coniferous forest existed in Central Europe, some 1000 km further south (Behre, 1989; Satkūnas et al., 2003).

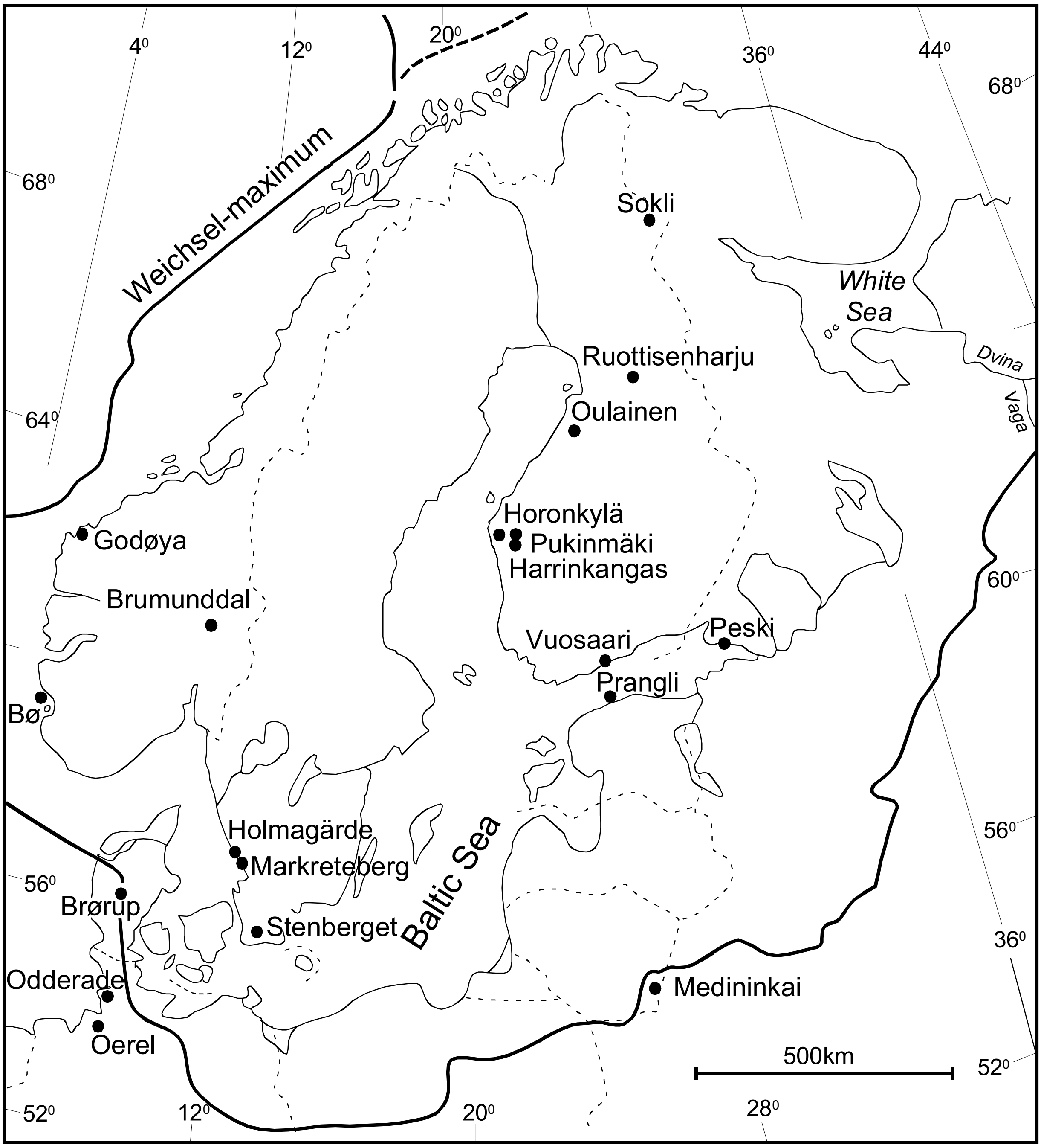

Fig. 5. Sites in or around the area of the Weichselian ice sheet discussed in this paper.

Oulainen

Although the author interpreted an organic horizon buried beneath till at Oulainen (no. 3 in Fig. 1, Fig. 5) as an *in situ* deposit representing the beginning of the last interglacial (Forsström, 1982), further investigations in the same area showed that this could not be so (Forsström et al., 1988), and that the probable explanation was that it was an interstadial deposit (Donner, 1983; Forsström, 1988). Following a more extensive examination of the interglacial/ interstadial problem, however, the author settled for the explanation that the Fennoscandian ice sheet was fairly extensive throughout the Weichselian and that all the assumed interstadial deposits in Finland were in fact redeposited material from the last interglacial (Forsström, 1989, 1991, 1995). The Oulainen sediments would then represent the latter half of the interglacial and would have been transported to their present site as frozen slabs in the base of the glacier. This is consistent with the pine phase denoted by their pollen assemblage, which if related to pollen quantities recorded during the Holocene, must have continued for at least 4000 years (Forsström, 1982).

In their description of the Marjamurto deposit in the same esker chain as Oulainen, Peltoniemi et al. (1989) also noted that *Pinus* was the dominant pollen taxon and that *Betula* pollen also occurred in large amounts. Since the gyttja-silt layer representing this pine-dominated forest vegetation at Marjamurto was more than 2 metres in depth, it can be assumed that the phase was of fairly long duration. On the same grounds as at Oulainen, these sediments can be assumed to represent the later stages of the last interglacial.

Horonkylä

Both Nenonen (1995) and Grönlund and Ikonen (1996) described the stratigraphy of a till-covered esker at Horonkylä (no. 4 in Fig. 1, Fig. 5) which included a gyttja-diatomite horizon that was more than a metre thick in places and contained a largely *Pinus*-dominated pollen flora, rendering it comparable to the material found at Oulainen and Marjamurto. This horizon is clearly in a secondary position, as it is located at a depth of about 6 m inside the esker, with several esker gravel and till layers on top of it (see fig. 18 in Nenonen, 1995a). A stratigraphy of this kind points to the melting of dead ice *in situ*, so that the frozen organic material and till layers in ice were able to be deposited over a relatively broad area and preserve their form with relatively little intermixing, as was also the case at Oulainen and Marjamurto.

Harrinkangas

Thin peat horizons and charred pine remains discovered in the till-covered esker of Harrinkangas (no. 5 in Fig. 1, Fig. 5; Gibbard et al., 1989; Punkari and Forsström, 1995) were interpreted as redeposited organic material representing the later stages of the Eemian in terms of the macrofossils and microfossils contained in it (Punkari & Forsström, 1995), as with the other organic deposits mentioned above.

Sokli

The first author to describe the ancient organic horizons discovered at Sokli in northern Finland (Fig. 5) was Ilvonen (1973), who concluded from the cores that they occupied a till-covered basin some 2 km^2 in area and probably represented the Eemian interglacial. The present author made a pollen analysis of one core and similarly correlated the material with the Eemian (Forsström, 1990). Later, Helmens et al. (2000) concluded on the strength of new cores that the sediments represented not only the Eemian interglacial but also various younger stadials and interstadials. The author nevertheless considers it likely that the material was entirely interglacial in origin but was mixed somewhat as a consequence of glacial transport so that the "interstadial" strata indicative of a cold climate in fact consist of material from the later stages of the interglacial. The data presented by Helmens et al. (2000) do in fact contain evidence of such mixing, as the horizon with pine-dominated pollen assemblages in the upper part of the deposit is interpreted as redeposited while the horizons below and above are said to be in an *in situ* position.

Prangli

Although the deposits of Prangli on the coast of Estonia (Fig. 5) were interpreted by Liivrand (1991) as representing a complete sediment stratigraphy extending from the end of the Saalian glaciation to the Early Weichselian interstadials, Forsström and Punkari (1997) assumed that the ice had already spread to the Prangli area during the first Weichselian stadial. This was based on changes in the sediments and their pollen composition that suggested that the ice must at least have come so close to Prangli at that time that varved clay was deposited there (see fig. 29 in Liivrand, 1991). The preservation of the varved clay and the occurrence of till immediately on top of it can be understood more readily if we assume that they were deposited during the same stadial, i.e. that the glacier extended as far as Prangli during the first Weichselian stadial.

Vuosaari

Hirvas et al. (1995) described a 12 m thick deposit at Vuosaari in Helsinki (Fig. 5) in which three till beds could be distinguished, separated by two sorted material horizons, concluding on the basis of other material from southern Finland that the lowermost till bed "may represent pre-Weichselian glacigenic sediments possibly deposited during the Saalian" and that the upper ones belonged to the Weichselian. The laminated silt, clay and sand units between the till beds were assumed to be remnants of glaciolacustrine sediments.

The pollen content of the lowermost till bed at Vuosaari corresponds well to the Eemian interglacial flora (Hirvas et al., 1995), so that the till was in all probability laid down after the Eemian and presumably represents the first Weichselian stadial, the time when, in the light of the Prangli data, the ice extended as far as the coast of Estonia. The subsequent layer of sorted material can then be correlated with the first Weichselian interstadial, the Brørup, during which the south coast of Finland would have been free of ice. The second Weichselian stadial and the associated ice advance must then be represented by the middle till bed at Vuosaari, while the next sorted horizon would correspond to the Odderade, the second Weichselian interstadial, when the south coast was again ice-free. The uppermost till bed can then be assigned to the Middle and Late Weichselian, a period during which the ice did not melt from south coast of Finland. This interpretation conforms well to the present author's earlier proposals regarding the stages of the Weichselian (Forsström, 1989, 1991) and to the later scheme presented by Forsström and Punkari (1997).

Brumunddal

Helle et al. (1981) correlated a peat horizon found buried beneath till at Brumunddal in southern Norway (Fig. 5) with the Early Weichselian Brørup interstadial, on the grounds that a pollen analysis showed that the local vegetation at the time of its deposition had included *Larix*, which is known to have grown at the type site of Brørup in Denmark (Fig. 5) during the interstadial. The author has indicated that he regards it as improbable that coniferous forest grew in the interior of Norway during the Brørup interstadial and has preferred to look on this peat as redeposited material representing the last interglacial, on the grounds that *Larix* could have spread to the area from the north during the interglacial, since it is known to have grown in Finnish Lapland at that time (Forsström, 1990).

Peski

In their studies of a sediment sequence observed at Peski on the Karelian Isthmus (Fig. 5), Miettinen et al. (2002) concluded from the pollen and diatom evidence that the material represented a fairly complete set of Eemian marine deposits that subsequently grade to Early Weichselian freshwater sediments. The diatom flora points to a drop in water level in the basin towards the freshwater phase, with a new rise at the very end of the sequence, possibly as a consequence of isostatic depression of the earth's crust in response to the approach of the advancing ice margin (Miettinen et al., 2002).

Medininkai

A sediment sequence covering the whole of the Eemian and Weichselian is described by Satkūnas et al. (2003) at Medininkai in Lithuania (Fig. 5). Both of the main Early Weichselian interstadials in the sequence, Jonionys 1 (Brørup) and Jonionys 2 (Odderade), are represented by an open forest vegetation, but they differ in the proportions of their arboreal pollen taxa, in that where the *Betula* peak at the beginning of Jonionys 1 is replaced by a *Pinus* peak towards the end, with low figures for *Picea* and *Larix*, Jonionys 2 is conifer-dominated throughout with a pollen flora characterized by *Pinus*, *Picea* and *Larix*. The presence of macrofossils of a number of thermophilous plants in the Jonionys 2 horizon also points to a slightly warmer climate than during the Jonionys 1 phase (Satkūnas et al., 2003). Both horizons are nevertheless entirely devoid of broad-leaved thermophilous trees, and their NAP percentages are fairly high. A vegetation of this kind, which is indicative of a cool climate, would suggest that either treeless tundra or persistent ice prevailed in the north of Finland at the same time, as the author had previously suggested (Forsström, 1991). The cold-climate Middle Weichselian deposits at Medininkai similarly fit in well with the author's early opinion that the whole of Finland was under ice during that period (Forsström, 1982).

Radiocarbon dates for Finnish mammoth remains

Donner et al. (1979) reported finite ages of c. 25,000 years and 15,500 years for two samples representing a number of mammoth bones found in Finland, and argued on the strength of these and a date of 34,000 BP obtained for a reindeer antler found in northern Finland (Siivonen, 1975) that the majority of the country must have been free of ice at these times. Subsequent re-dating confirmed these results, and more ages were obtained for Finnish mammoth finds (Ukkonen et al., 1999), leading the latter authors to assume that large parts of present-day Finland were free of ice for at least 10,000 years during Oxygen Isotope Stage 3, and that the ice did not spread to eastern Finland until after 22,500 years BP.

The present author has speculated that the youngest of the mammoth dates, 15,500 BP, may apply to an individual that had wandered across the ice sheet and succumbed in the process, as the site of the find must surely have been covered by ice at that time (Forsström, 1982), but in effect the other finite dates also point to times when the total volume of the earth's ice caps was high and it can be assumed that Finland was entirely covered by ice. Similarly, the total lack of sediments representing those times in Finland would require some sort of explanation if the dates were to prove correct and the area had indeed been free of ice at the time.

Southern Sweden

No firm evidence is available as to the time at which the ice spread to southern Sweden after the Eemian, but the question can be examined in the light of the sites of Markreteberg (Påsse et al., 1988) and Holmagärde (Påsse, 1992) in south-western Sweden (Fig. 5). Eemian sediments and associated periglacial structures have been described at both sites (the latter comprising ice wedge casts at Holmagärde and solifluction sediments in the surficial parts of interglacial deposits at Markreteberg), implying that the ice sheet did not extend to those areas during the first Early Weichselian stadial at least. According to Berglund and Lagerlund (1981), the ice may have reached the Stenberget site a little further south (Fig. 5) only in Late Weichselian times.

North-western Russia

A great deal of research has been carried out into the Weichselian glacial history of north-western Russia in recent times, and a model has been constructed for the stages recognised (Svendsen et al., 1999, 2004). The results suggest that the ice sheet in the Kara Sea and Barents Sea areas spread to its maximum extent at a relatively early stage, during the Early or Middle Weichselian (Mangerud et al., 1999; Houmark-Nielsen et al., 2001), whereas this point was reached in Fennoscandia only in the Late Weichselian (Larsen et al., 1999; Svendsen et al., 1999; Lyså et al., 2001).

It is assumed that the ice on the Kara Sea and the Barents Sea extended as far as the coast in the Early Weichselian, even though no detailed information is available on this point (Svendsen et al., 2004). Some indication is nevertheless provided by the discovery of proglacial lacustrine sediments with OSL ages around 90–110 ka in the River Pyoza in the Arkhangelsk region, in a position where there are overlain by a presumed interstadial organic horizon suggestive of an arboreal vegetation involving *Picea*, *Pinus* and *Betula* in the area (Houmark-Nielsen et al., 2001). The present author is nevertheless inclined to regard this organic horizon as redeposited material representing the end of the interglacial.

The history of the Fennoscandian ice sheet in the Arkhangelsk region is known largely from observations made in the valleys of the rivers Dvina and Vaga (Fig. 5; Devyatova, 1982; Larsen et al., 1999; Lyså et al., 2001). Marine deposits from the last interglacial are common in the area, and these can be used to correlate critical horizons. It is assumed, largely on the basis of luminescence dates, that a hiatus occurs in the stratigraphy of deposits located within the boundaries of the Fennoscandian ice sheet, so that sediments representing the Early Valdai period are absent, which means in turn that several megaclasts of detrital peat up to 1.5. m long are regarded as belonging to the Middle Valdai, during which time the area was occupied by a sparse tree vegetation (Lyså et al., 2001). The present author regards it as improbable that conifers were growing there at that period, and again assumes that the peat megaclasts represent redeposited material from the end of the interglacial, material of a kind that it is claimed may have been eroded away entirely.

5. MODEL OF GLACIATION

The first Weichselian stadial, OIS 5d

Only indirect information exists from scattered sites regarding the extent of the Fennoscandian ice sheet during the first stadial of the Weichselian, OIS 5d, and the interpretations of the sites concerned are conflicting, especially regarding Finland (Forsström, 1989; Lundqvist, 1992; Forsström & Punkari, 1997; Svendsen et al., 2004). It has nevertheless been possible on the basis of the author's deductions presented above and other published material to construct a map of the boundaries of the ice sheet (Fig. 6). The apparently complete succession to be found at Bø on the west coast of southern Norway, in which sediments from the end of the Eemian interglacial grade to glacially deposited material (Forsström & Punkari, 1997), suggests that the ice sheet bordered on the sea in that area, and a similar extent is pointed to by the sandur to be found at Godøya, the formation of which has been dated by the thermoluminescence method (Mangerud, 1991).

The grading of the interglacial sediments at Prangli in the Gulf of Finland to varved clay (Liivrand, 1991) in the course of one cycle of climatic deterioration suggests that the ice sheet extended at least quite close to Prangli during the first Weichselian stadial. This varved clay is overlain directly by till, and its preservation can be understood if it is assumed that the till was deposited during the same ice advance, i.e. that the ice sheet just reached as far as Prangli (Fig. 6). In the same way it is possible that the ice just extended as far as Peski on the Karelian Isthmus, although the existing data allow us only to conclude that it came relatively close to the site (Miettinen et al., 2002). It is conceivable that the ice flowed somewhat further south in the deep eastern part of the Baltic Sea (Fig. 6).

There are many sites on the coast of the Kola Peninsula where glacilacustrine clay, silt and fine sand has been found deposited on top of interglacial marine sediments (Mangerud et al., 2004), which again points to the proximity of the ice sheet. The timing of the ice advance is not clear, however, as there is evidently a hiatus in the sequence between the interglacial and glacilacustrine sediments. Sand layers deposited on top of the latter offer mainly the Early Weichselian thermoluminescence dates (Mangerud et al., 2004). No firm data are available on whether the ice reached the White Sea, but the situation on the Kola Peninsula leads us to presume that at least the main part of this sea area was free of ice (Fig. 6).

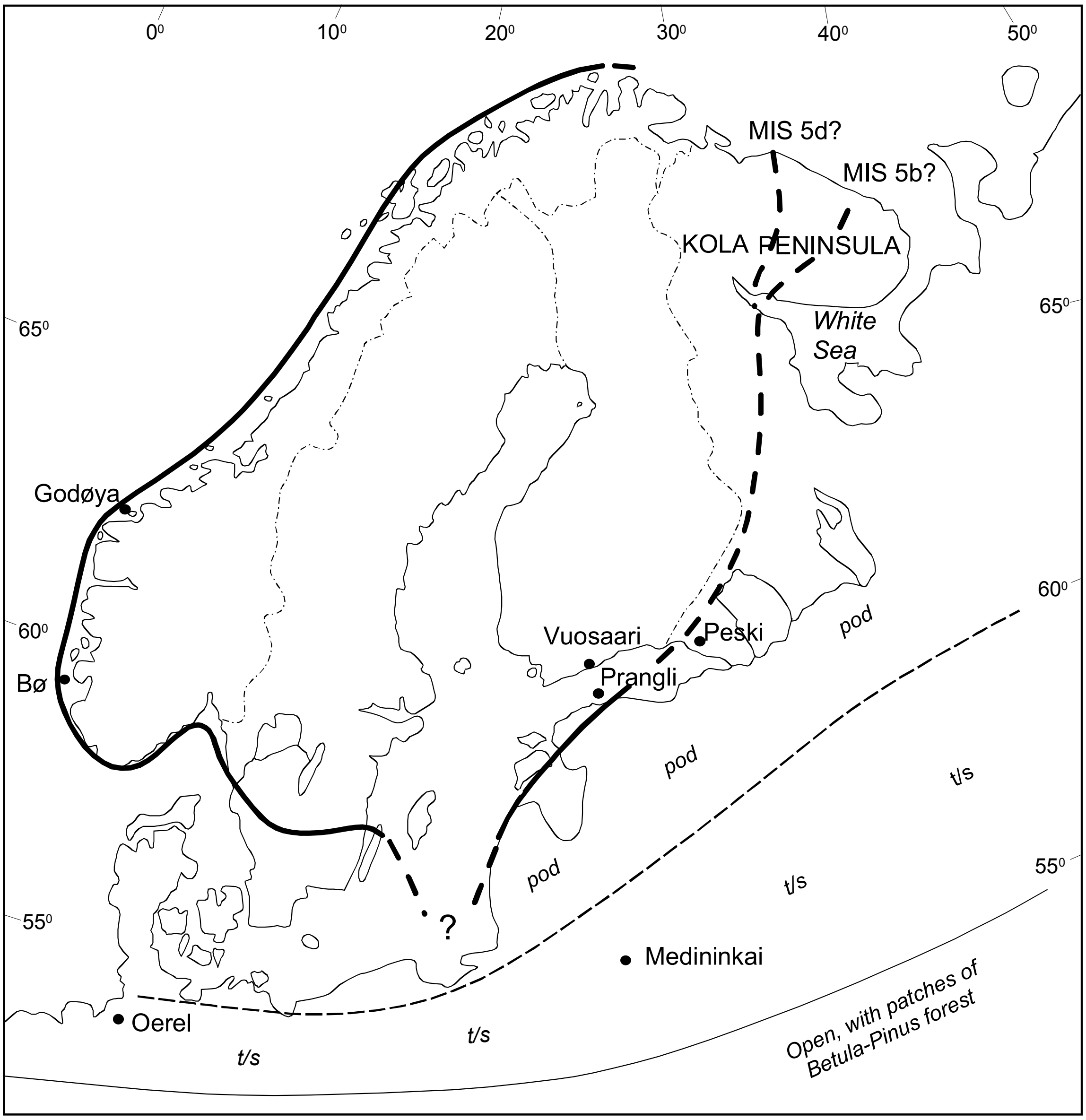

Fig. 6. Extent of the Fennoscandian ice sheet in the Early Weichselian stadials OIS 5d and OIS 5b, with adjacent vegetation zones. pod = polar desert, t/s = tundra/cold steppe.

The vegetation zones that prevailed in the southern part of the Baltic region during the stadial OIS 5d are presented in Figure 6 on the basis of existing data for these regions. The vegetation in the southernmost zone is thought to have been open, with patches of *Betula-Pinus* forest (Zagwijn, 1989). Oerel in Germany (Figs. 5 and 6) is known to have been devoid of vegetation at the beginning of the stadial and to have had only tundra even at its best (Behre, 1989), so that it is placed here in the tundra/cold steppe zone, along with Medininkai in Lithuania (Satkūnas et al., 2003). A zone of polar desert evidently existed on the very edge of the ice sheet, but no precise information exists on its breadth.

The first Weichselian interstadial, OIS 5c

During the first Weichselian interstadial, OIS 5c, the Brørup interstadial, the glaciers melted to the extent that the sea level rose at least 30–40 m (Shackleton, 1987). Forsström and Punkari (1997) maintain that the Bø Sand section on the coast of Norway, with pollen indicating an open, cold-climate vegetation and a cool mollusc fauna (Andersen et al., 1983), represents this interstadial. Thus the ice sheet is drawn in Figure 7 as having retreated inland from the Norwegian coast, but not very far (Forsström, 1991), although Helle et al., (1981) are inclined to correlate the inland site of Brumunddal with Brørup itself.

Vuosaari on the south coast of Finland was probably free of ice during the Brørup interstadial, whereas Harrinkangas on the west coast would have remained under the ice (Fig. 7). The eastern boundary of the ice sheet as marked on the map is arbitrary, as no definite Brørup deposits are known in that area. It is assumed, however, that the high fjeld area in the western part of the Kola Peninsula will have retained its ice cover.

Extensive areas of Central Europe possessed a coniferous forest vegetation during the Brørup interstadial, with a pollen flora that includes pine, spruce and larch, while AP/NAP ratios suggest open forests at Brørup itself in Denmark (Andersen, 1965), at Odderade (Averdieck, 1967) and Oerel (Behre, 1989) in northern Germany and at Medininkai in Lithuania (Satkūnas et al., 2003), so that the vegetation somewhat closer to the ice margin can be assumed to have been shrub tundra.

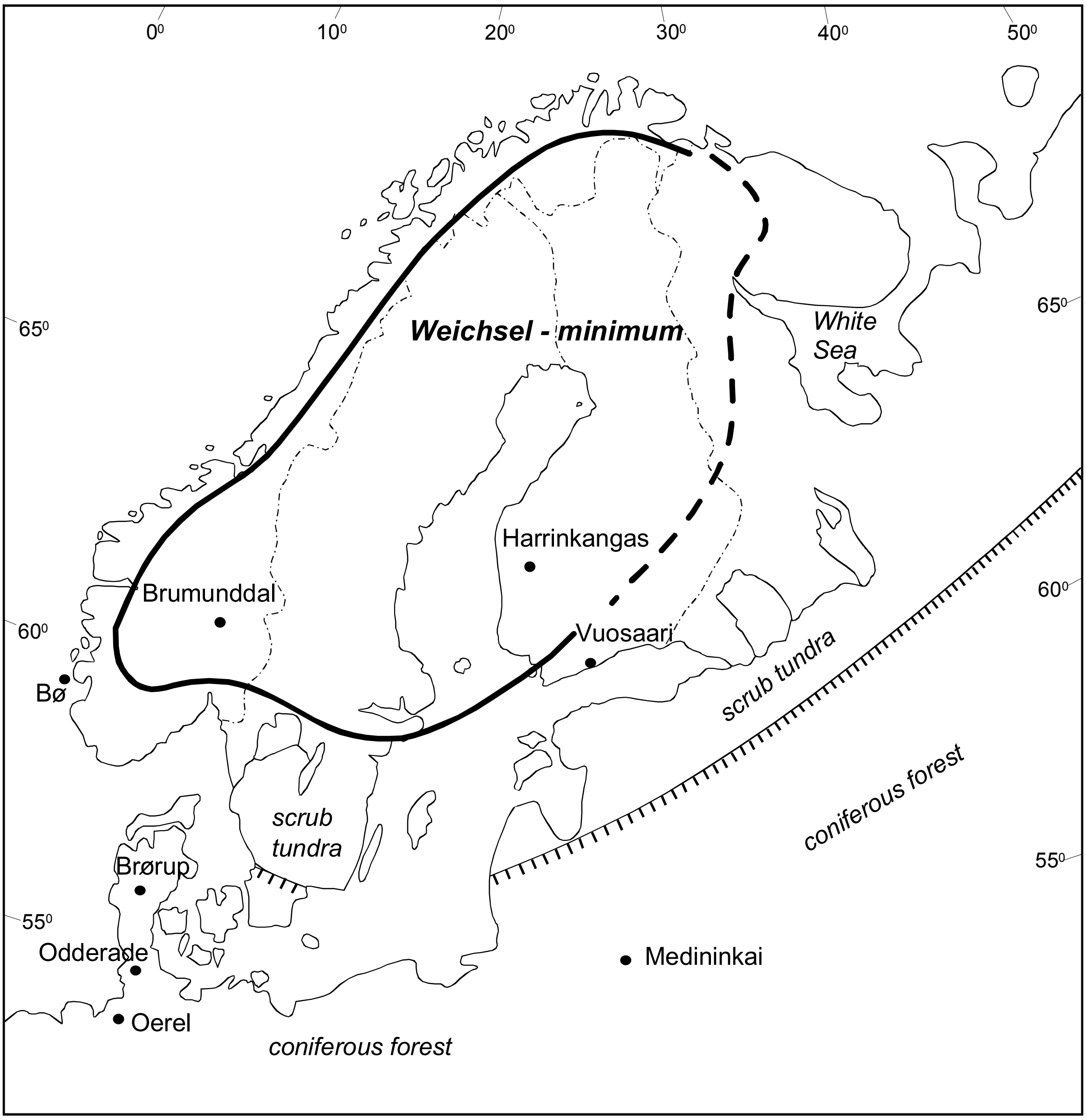

Fig. 7. Extent of the Fennoscandian ice sheet in the Early Weichselian interstadials OIS 5c and OIS 5a, with adjacent vegetation zones.

The second Weichselian stadial, OIS 5b

The climate deteriorated during the second Weichselian stadial to the extent that the vegetation disappeared from the Oerel site in Germany, for instance, and a thick layer of sand accumulated, which Behre (1989) takes as implying a climate that was at least as cold as during the first stadial, so that the vegetation of the Oerel area may represent a tundra/steppe type (Fig. 6).

No firm information is forthcoming on the extent of the ice sheet, but it probably advanced into the sea on the coast of Norway, as indicated by the IRD data for the Norwegian Sea (Baumann et al., 1995). At Vuosaari in Helsinki the almost 3 m thick till unit 4 (Hirvas et al., 1995) presumably represents this same glacial advance, a movement that may well have extended as far as northern Estonia, as was the case with the first Weichselian ice advance.

The Kola Peninsula is a problematic area (Mangerud et al., 2004), as the sand layer deposited on top of the Early Weichselian glacilacustrine silt and clay could be a consequence of partial melting of the ice sheet, which would have caused an isostatic rise in the earth's crust and drop in sea level. It would seem in the light of these deposits that only one ice advance took place on the Kola Peninsula during the Early Weichselian and not two as in the south, and current information also suggests that there was just one deglaciation, which probably occurred in the interval 100–80 ka BP.

The second Weichselian interstadial, OIS 5a

The second Weichselian interstadial, OIS 5a, the Odderade interstadial (Averdieck, 1967; Behre, 1989), closely resembles the first, the Brørup, in its vegetation history, so that the ice sheet may well have reached similar proportions (Fig. 7). It can be assumed that its western margin retreated inland from the Norwegian coast, and that Vuosaari in Helsinki was free of ice, as suggested by its uppermost clay, silt and sand horizon (Hirvas et al., 1995). The ice on the Kola Peninsula may well have retracted to its minimum for the Early Weichselian (cf. Svendsen et al., 2004), although no exact data are available for this area.

The Middle and Late Weichselian

At the beginning of the Middle Weichselian, OIS 4, the Fennoscandian ice sheet spread to such a degree that it extended into Denmark, Germany and Poland (Svendsen et al., 2004). It is the author's view that Finland then remained beneath the ice from that time onwards until the eventual Weichselian deglaciation (Forsström, 1989, 1991; Forsström & Punkari, 1997), a situation that would correspond to the glaciation model for Denmark put forward by Houmark-Nielsen (1989) and the climatic reconstruction of the Weichselian Pleniglacial in north-western and central Europe of Huijzer and Vandenberghe (1998).

6. CONCLUSIONS

The preservation of the more than 20 m thick Eemian interglacial deposit in the hill of Pukinmäki in south-western Finland indicates that glacial erosion must have been weak in the area, a fact attributable in part to the location of the site in an area of slow ice flow between the major ice lobes during the last deglaciation stage in the history of the Fennoscandian ice sheet. The fact that the hill rises to a considerable height above its surroundings is also attributable to the same circumstances, in that it was formed of silt from the Eemian sea that had been pushed up between dead ice boulders. The notion of weak glacial erosion fits in well with the interpretation that this area was invaded by ice only once during the Weichselian.

Detailed information has been gathered on the climatic and vegetational history of the Weichselian in Central Europe (Behre, 1989; Grüger,, 1989; Zagwijn, 1989; Satkūnas et al., 2003), and when the organic deposits discovered in Finland that are indicative of the presence of pine forests are correlated with that material they are seen to represent the last interglacial and not the Early Weichselian interstadials, which were still relatively cool climatic phases in Central Europe. The Finnish deposits correspond well with the notion of material representing the ground surface during the cool late stage of the interglacial being transported away by the glacier and ending up in a secondary position, frequently as part of an esker. The occurrence of such material in fairly extensive horizons also suggests that the areas concerned were subsequently covered by ice only once. The glaciation model that explains all these deposits best is one in which Finland was covered by ice from the first Early Weichselian stadial right up to the time of the eventual deglaciation, with the exception of parts in the south of the country which were free of ice during the Early Weichselian interstadials.

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