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LITHOSTRATIGRAPHY AND AGE OF PRE-LATE WEICHSELIAN SEDIMENTS IN THE SUUPOHJA AREA, WESTERN FINLAND

by

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ABSTRACT

Different types of laterally extensive sand- and gravel-dominated deposits, up to several tens of metres thick, were investigated in the Suupohja area of western Finland. The studied sediments were deposited in glacial, ice-marginal, glaciofluvial, sea or lake, littoral and terrestrial environments during several glacial-non-glacial cycles. Seventeen pre-Late Weichselian and three Late Weichselian/Holocene sedimentary units were identified. These were divided into ten formally and two informally defined formations that were together termed the Suupohja Group. Every unit are nevertheless not detectable throughout the study area. The informally defined “Karhukangas lower deposits” represent the lowest units in the Suupohja Group. The Karhukangas lower deposits with 5 till units, 3 glaciolacustrine/-marine units and 2 sand units, were interpreted as having been deposited during possibly four glacial-non-glacial cycles before the Late Pleistocene Subepoch (MIS 6 or earlier). The Kankalo Sand above the Karhukangas lower deposits comprises glaciofluvial and aeolian sands of Late Saalian, Eemian or Early Weichselian origin (MIS 6–MIS 5c). The Kariluoma Till above the Kankalo Sand was possibly deposited during the Late Saalian glacial advance, although an Early Weichselian origin is also possible. The Harrinkangas Formation, with glaciofluvial and quiet-water sediments, is interpreted as having been deposited during the Late Saalian and Eemian Stages (MIS 6–MIS 5e). The uppermost units in the deposits studied, the Kodesjärvi Formation (shore deposit), Isojoki Sand (aeolian), Rävåsen Formation (glaciofluvial), Vanhakylä Formation (shore line deposit), Dagsmark Till and Kauhajoki Till, were deposited during the Weichselian Stage (MIS 5d–MIS 2). In addition, Early Holocene (MIS 1) eskers without till cover were informally termed the “Holocene esker deposits”. The Lumikangas Formation represents gravelly shore deposits formed in the Holocene Epoch, when these areas last emerged from the sea. The first Weichselian ice expansion possibly reached the western part of Suupohja in the Early Weichselian Substage (MIS 5d?), but it did not expand further to the east. The second Weichselian glaciation of relatively short duration occupied the southern part of Finland in the later part of Middle Weichselian (MIS 3). Thus, the southern half of the country remained ice-free for the majority (~65–75%) of the Weichselian Stage. Instead, both humid temperate and periglacial conditions alternated. In the initial part of Middle Weichselian, this area was partly submerged, which indicates eastward expansion of the Scandinavian ice sheet(s), depressing the lithosphere. The exceptionally thick sediment cover, multiple lithofacies, relict landscape and preserved preglacially weathered bedrock are evidence of weak glacial erosion in the Suupohja area during the latest as well as earlier glaciations, making this area one of the key areas in Quaternary research.

This thesis consists of an itroductory chapter (synopsis) and four published articles dealing with lithostratigraphy and sedimentary history of Pleistocene deposits of the Suupohja area, western Finland. The topics of the four articles are listed below.

Paper 1: Pitkäranta, R., 2005. A proposal for formal lithostratigraphical names in the Suupohja area, western Finland. In: A.E.K. Ojala (ed.), Quaternary studies in the northern and Arctic areas of Finland. Geological Survey of Finland, Special Paper 40, 91–95.

Paper 2: Pitkäranta, R. 2009a. Lithostratigraphy and age estimations of the Pleistocene erosional remnants near the centre of the Scandinavian glaciations in western Finland. Quaternary Science Reviews 28, 166–180.

Paper 3: Pitkäranta, R. 2009b. Pre-late Weichselian podsol soil, permafrost features and lithostratigraphy at Penttilänkangas, western Finland. Bulletin of the Geological Society of Finland 81, 53–74.

Paper 4: Pitkäranta, R., Lunkka, J.-P. & Eskola, K.O. 2013. Lithostratigraphy and OSL age determinations of pre-Late Weichselian sand and gravel deposits in the Suupohja area, western Finland. Boreas, DOI: 10.1111/bor.12030, 1–15.

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“Paper 1…4” are used when referred in the text.

CONTENTS

1. INTRODUCTION

Since the beginning of the 1970s, an increasing number of deposits with multiple lithofacies, representing both glacial and interglacial/interstadial sedimentary events, have been found in the Suupohja area of the southern part of Ostrobothnia, western Finland (Fig. 1). These deposits are typically composed of glaciofluvial, littoral and aeolian sediments, overlain and/or intercalated by till beds. Locally, waterlain fine-grained sediments, peat and gyttja layers are also intercalated between coarse-grained clastic sediments. Palaeosols and permafrost-induced structures are relatively common (see also Niemelä & Tynni 1979, Donner 1988, Gibbard *et al.* 1989, Kujansuu *et al.* 1991, Kujansuu 1992, Nenonen 1995, Saarnisto & Salonen 1995, Lunkka *et al.* 2004, Papers 1–3). These sediments are typically very tightly packed (overconsolidated), indicating a later glacial advance over them. In glaciated areas, the scouring and remoulding of the last glaciation have normally destroyed and redeposited earlier unlithified sediments, leaving little, if any, evidence of earlier sedimentary events. This, however, seems not to be the case in the Suupohja area.

The Suupohja area, which comprises the majority of the study area, includes the towns of Kaskinen, Kauhajoki, Kristiinankaupunki and Närpiö and the communes of Isojoki, Karijoki and Teuva in western Finland (Figs 1 and 2). Some of the studied deposits continue to the south, to the communes of Merikarvia, Siikainen, Honkajoki and Karvia in North Satakunta, as well as to the north to the town of Kurikka. The study area covers approximately 5 800 km^2, which is almost 2% of the land area of Finland.

The first thorough Quaternary geological descriptions of the study area were presented in the explanations of 1:400 000 geological maps: sheet B2, Tampere (Sauramo 1924), and sheet B3, Vaasa (Mölder & Salmi 1954). However, no observations of the rich diversity in lithostratigraphy were presented in those explanations, most probably because of the absence of deep open exposures at the time of mapping of the deposits. On the above-mentioned geological maps, as well as on the 1:1 000 000 scale map of Quaternary deposits of Finland (Kujansuu & Niemelä 1984), many of the deposits were mapped as till deposits, although thick layers of sand and gravel occur below the covering till bed(s).

Iisalo *et al.* (1974), Niemelä (1978, 1979), Niemelä & Tynni (1975, 1979) and Kujansuu & Niemelä (1984) were the first to discover the so-called “till-covered eskers” and outline their boundaries in the Suupohja area. Later, these boundaries were re-evaluated. Niemelä *et al.* (1993) presented new, previously unmapped till-covered sand and gravel deposits (not necessarily eskers) in the 1:1 000 000 scale map of Quaternary deposits of Finland and the northwestern part of the Russian Federation. Subsequently, further new sites with multiple lithostratigraphic units have been discovered (Pitkäranta 1996, 1999a,b, Papers 1–3). From the beginning, these deposits were interpreted as older than the last glaciation.

In addition to the Suupohja area, pre-Late Weichselian deposits have been discovered in Finland north of Suupohja, in more northern part of southern and middle Ostrobothnia at Peräseinäjoki, Alajärvi, Vimpeli, Lappajärvi, Evijärvi, Haapavesi, Haapajärvi, Ylivieska, Oulainen and Vihanti as well as in western part of northern Ostrobothnia and Lapland (see the reviews of Donner 1995, Saarnisto & Salonen 1995, Lunkka *et al.* 2004, Johansson *et al.* 2011, with references). Common to these sites are their fairly close proximity not only to the latest but also to the previous ice-divide zones of the former Scandinavian ice sheets (SIS). The bulk of the observed pre-Late Weichselian deposits in Finland have been interpreted as having been deposited either in the Weichselian or Eemian Stages, but also Saalian origin has been assumed to be possible at a number of the sites studied. However, exposed sections extending to Saalian or even older Middle Pleistocene sediments are rare in Finland, as well as in Fennoscandia as a whole (e.g. Lundqvist 2004, Mangerud 2004, Mangerud *et al*. 2011, Johansson *et al.* 2011). The only known site, where pre-Saalian sediments are exposed, is the Naakenavaara site in Kittilä, central Lapland (Aalto *et al.* 1992). Pre-Saalian sediments have been discovered in a few deep drillings in Finland (e.g. Perttunen 1985, Salonen *et al.* 1992). Interpretation of the age of those deposits has been mainly based on lithostratigraphy without datings.

This thesis comprises a synopsis and four articles. The articles include lithostratigraphical and sedimentological observations and dating results from sand and gravel-dominated Pleistocene deposits in the Suupohja area. The field investigations utilized in the articles as well as in this synopsis are presented in Table 1. All the described units are formally termed the Suupohja Group (Paper 1). The main purpose of this study is to examine deposits that can increase knowledge of Pleistocene glacial and non-glacial events in the central area of the former SIS. The documentation of sediment sequences with multiple lithofacies is extensively performed. The results shed light on the complex lithostratigraphy of the Suupohja area and discusses the litho-, chrono- and climatostratigraphical significance of the presented observations. The presented lithostratigraphical units are more rare elsewhere in Fennoscandia, and the possible reasons for their occurrence in this area are also discussed.

All the studied sand and gravel-dominated deposits are overlain by one or two till beds. In addition, till occurs as interlayers between sorted sediments. The topmost till, the fine-grained dark grey Kauhajoki Till, is interpreted as having been deposited in the Late Weichselian Substage (see Gibbard *et al.* 1989, Bouchard *et al.* 1990, Pitkäranta 1996, Papers 1 and 2). Consequently, all the deposits below the Kauhajoki Till are considered older than the last glaciation, i.e. older than ~25 ka.

The common geological features of the study area are briefly described below. In addition to the lithofacies descriptions and interpretations in the attached papers, those and some previously unpublished observations are reported in this synopsis.

The observed lithofacies of the Suupohja Group are summarized in Table 2, which also includes formal names and interpretations of the sedimentary facies. Formal names are used in order to avoid vague, descriptive terms. According to the common usage in Quaternary studies, the term “Stage” (or Substage) is used instead of “Age” also in cases when discussing time of sedimentation (*cf.* Salvador 1994).

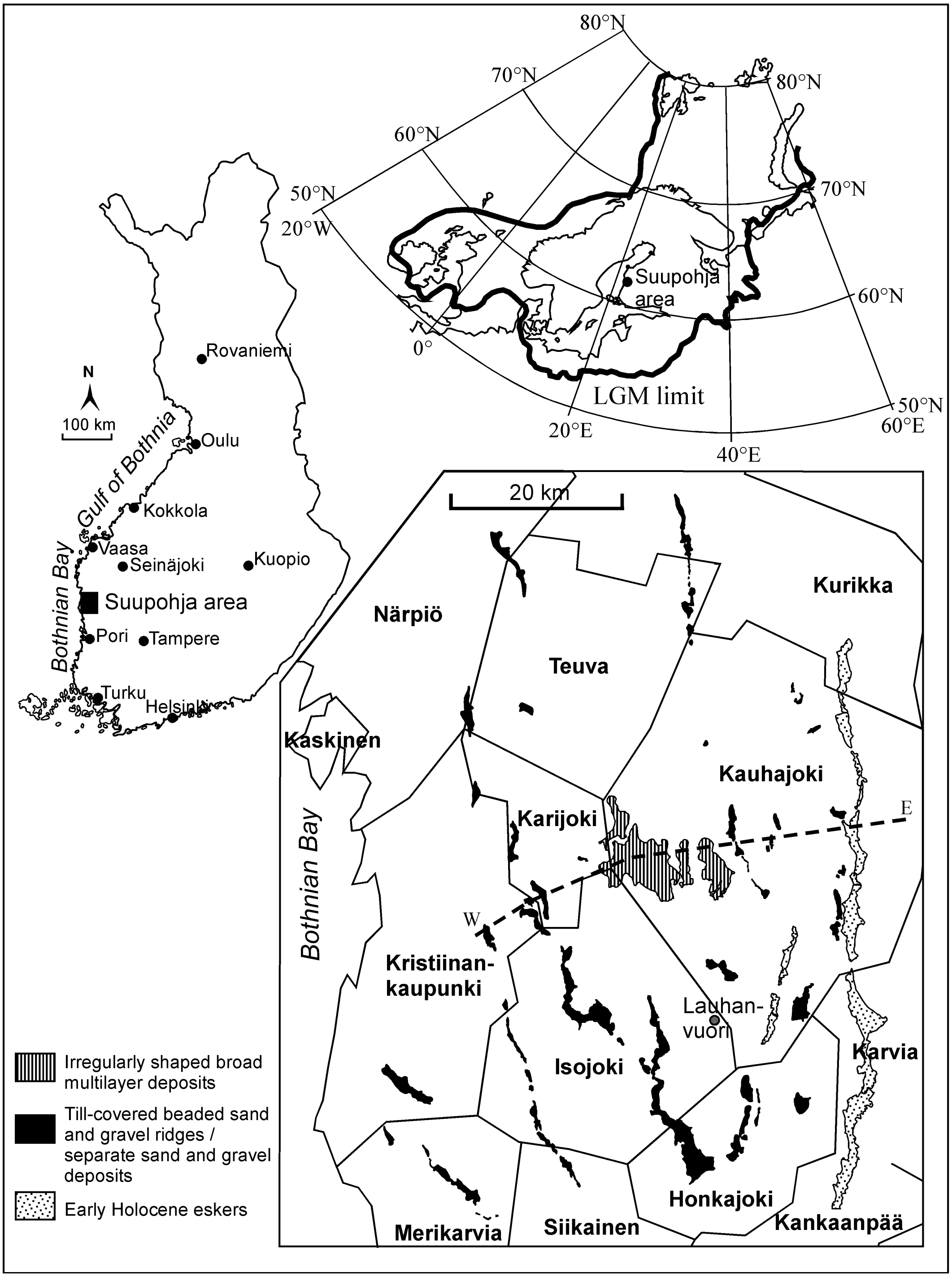


Fig. 1. The Suupohja area in western Finland lies in the central part of the former Scandinavian Ice Sheet (SIS) (the upper right figure, modified after Svendsen *et al.* 2004). Some of the deposits continue to the northern Satakunta region in the south. Different types of deposits and the cross-section line (dashed line W–E) of Fig. 9 are also indicated (see chapter 3.4). The Karhukangas accumulation in the central part of the figure is here interpreted to be larger than presented in Papers1–3.

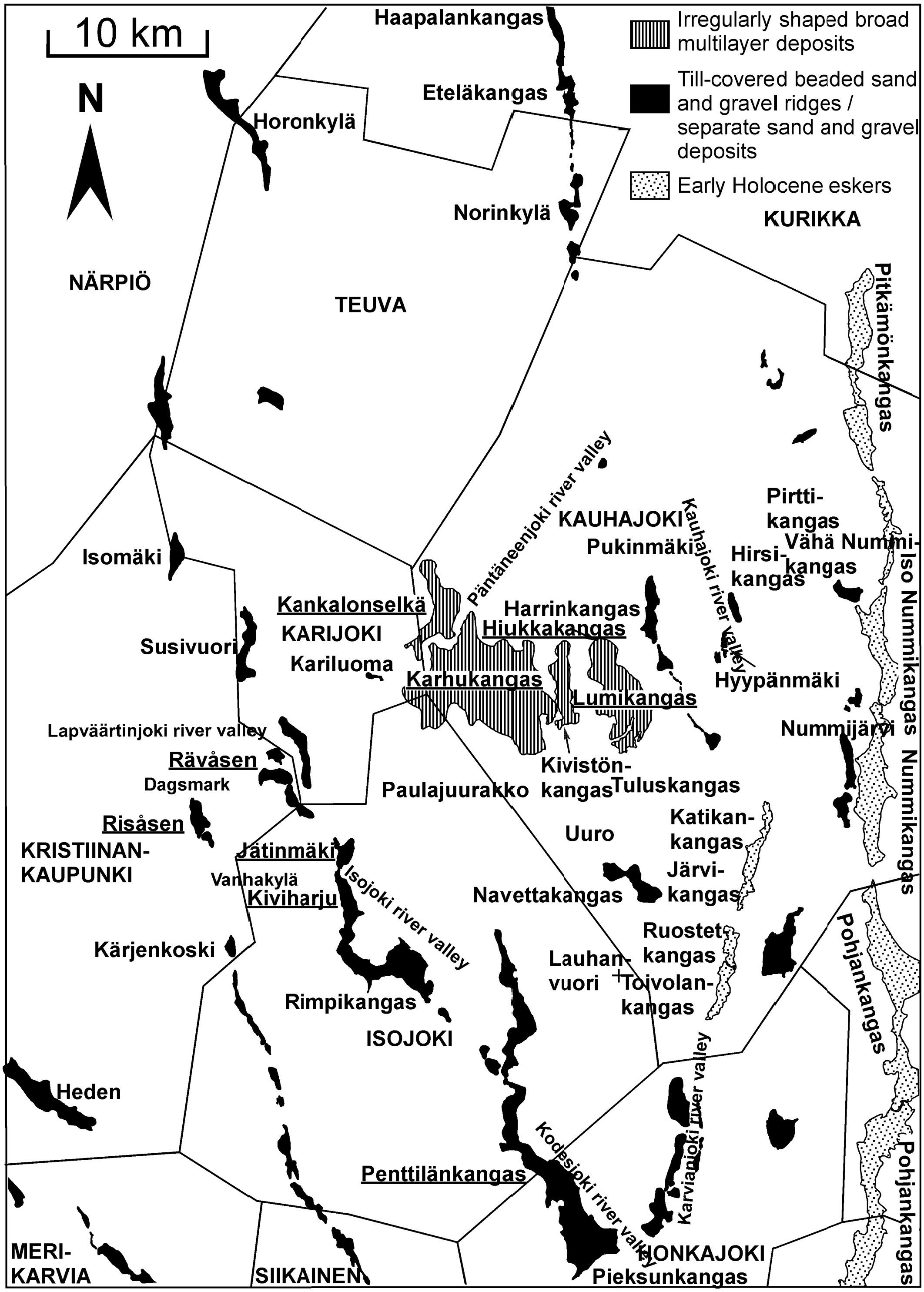


Fig 2. Locations of the studied sites and the other sites referred to in the text. The sites examined in papers 1–4 are underlined.

2. METHODS

The field methods included topographic map interpretations (all papers), conventional sedimentological observations from open exposures, test pits and drillings, refraction seismic and ground-penetrating radar measurements and magnetic susceptibility measurements. Methods used in the laboratory included grain-size and loss-on-ignition determinations, macrofossil identifications, pollen and diatom determinations and optically stimulated luminescence datings (OSL). Formal lithostratigraphy is used in all papers.

The type and quantity of different field measurements and laboratory analyses included in this study are mentioned in the appropriate papers. However, some of the results of field observations, measurements and laboratory analyses have not previously been published. The different field investigations carried out in the area are summarized in Table 1. Some of the investigations were conducted in conjunction with earlier inventory studies, while others were carried out as part of this study.

2.1 Sedimentological logging

Sedimentological logging is the most important method in studying past sedimentary processes. Sedimentological loggings include a detailed description and illustration of the lithostratigraphy, texture and sedimentary structures of the sediments, as well as fabric analyses, clast roundness, lithology determinations and palaeocurrent measurements. These sediment properties can mirror the provenance, age and sedimentary genesis of different lithofacies (e.g. Reineck & Singh 1986, Fritz & Moore 1988, Collinson & Thompson 1989, Gale & Hoare 1990, Tucker 2011).

Fabric analyses were carried out on diamictons and some gravelly units. Each analysis included 35–100 measurements (mostly 40–60). The measured clasts were 1.5–25 cm in diameter and the long/short axis ratio was >1.5 (see Krüger 1970, Lawson 1979). Dip directions of foresets of cross-bedded sands and gravels were also measured (3–20 measurements/lithofacies) to interpret palaeocurrent directions. The results from the fabric and palaeocurrent measurements are mostly presented as rose diagrams with scatter plots, the values projected in the Schmidt's lower hemisphere. Significance values (S_1) were also presented in Paper 4 to indicate the strength of the pebble orientation in diamictons (Mark 1973, Clark & Hansel 1989). Clast lithologies were determined from some diamicton and gravel beds, each analysis comprising 100–150 clasts (diameter 2–25 cm). The roundness of the clasts was only visually assessed in the field.

Sedimentological observations were recorded from 95 test pits: 66 of the test pit observations were carried out in conjunction with an inventory of sand and gravel resources in Kauhajoki (Kurkinen *et al.* 1994), 11 were performed by the Geological Survey of Finland (GSF) in conjunction with national till investigations (unpublished) and 18 specifically for this study (Table 1). The depths of the test pits were usually 3–4 m. Open exposures were studied at 29 locations, where altogether 61 exposures were available for observation. The exposures observed were relatively shallow, usually less than 8 m, but a few 15–20 m-high exposures were also observable.

Particle sizes were normally analysed visually in the field. In addition, *c.* 40 samples were dry and/or wet sieved. The particle-size distributions of fine-grained sediments were analysed with a Coulter LS200, which measures particle sizes with laser diffraction. The organic carbon content of palaeosols, fine-grained sediments and some diamictons was determined by loss on ignition (LOI).

2.2 Ground-penetrating radar

In addition to sedimentological observations, ground-penetrating radar (GPR) was abundantly used in studying the thickness, lithostratigraphy and sedimentary structures of the upper parts (<20 m) of the deposits. GPR is a geophysical method that utilizes radiofrequency waves transmitted into the ground (e.g. Davis & Annan 1989, Neal 2004). Measuring the reflected and refracted signals arriving at the receiver, a kind of mirror image from the subsurface ground can be obtained. The transmitted signals are reflected and refracted according to the dielectric properties of the ground, which are mostly dependent on the moisture content in the sediments. The moisture content, in turn, is largely dependent on the grain size and porosity of the sediment or rock. These properties often make it possible to even observe sedimentary structures in the sediment. The smallest detectable object, structure or layer depends on the studied material itself and on the antenna frequency (Davis & Annan 1989). The penetration of GPR signals in favourable conditions can even reach 47 m with a 50-MHz antenna and 28 m with a 100-MHz antenna (Smith & Jol 1995).

The weakest aspect of the GPR method is its poor penetration into moist clay and fines-rich sediments, e.g. clayey till. Penetration into moist clay can be as low as only some tens of centimetres.

The GPR measurements were carried out using the RAMAC/GPR (produced by MalåGeoScience Ltd) with 50- and 100-MHz antennas. In addition, results from the GPR measurements of Kurkinen *et al.* (1994) were utilized, which were conducted with a Geophysical Survey Systems, Inc., SIR-8 equipped with an 80-MHz antenna. Altogether, *c.* 200 km of GPR survey lines were measured on the studied deposits (Table 1). The equipment was both carried and pulled with a car.

2.3 Seismic soundings

In the refraction seismic method, artificially generated shock waves refract and reflect from underground layer boundaries, where the elastic properties of the material change. The time between the generation moment of the shock waves and their arrival at each geophone is measured. Utilizing both the measured arrival times and distances between the geophones and the impact points, the thicknesses of different lithofacies associations can be calculated. The composition of the materials can also be roughly determined according to the seismic velocities (e.g. Redpath 1973, Sjögren 1984, Palmer 1986).

As with the GPR method, the refraction seismic method also has some weak points. To obtain reasonable results, at least the following prerequisites should be fulfilled:

i) The elastic properties of different underground sediment layers should deviate from each other.

ii) The difference in the elastic properties between superimposing layers should be large enough to be detectable.

iii) Each sediment layer should be thick enough to be detectable.

iv) The seismic velocity should increase with depth.

Other geological properties, such as continuous layers and horizontal or gently sloping layer boundaries through the geophone spread, also improve the accuracy of the results. Some of the irregularities in the geological materials, however, can be adjusted for using different correction methods (e.g. Sjögren 1984, Palmer 1986).

The seismic measurements were performed using 12-channel Geometrics ES-1225 and ES-2401 seismographs (Geometrics Ltd). The equipment includes the seismograph, geophones, a shock wave generator (sledge hammer or explosion equipment) and the cables between these different parts. When using the hammer, stacking operation was used, which effectively amplified the hit force and improved the depth penetration.

Depending on whether a distance of 5 or 10 m between the geophones was used, the single line length was 55 or 110 m, respectively (12 geophones). A hammer was used in generating the shock waves in about 70% of the measurements, the rest of which were performed using dynamite. Depending on the length of the geophone spread and available space, distances of 25–150 m were used in offset shot points (see Redpath 1973, Sjögren 1984).

Altogether, 293 refraction seismic lines were surveyed in the study area. The total length of the lines was *c*. 45 km. These figures also include the seismic soundings carried out by Mäkelä *et al.* (1990), Kurkinen *et al.* (1994) and those by GSF in conjunction of other research activities (see Table I).

2.4 Optically stimulated luminescence datings

The optically stimulated luminescence method (OSL) was used in dating sandy sediments. With the OSL method, it is possible to estimate the point of time when sediment grains were last exposed to daylight before burial under younger sediments. Light releases charge from light-sensitive electron traps in mineral crystals, such as quartz and feldspar. A sufficient amount of light causes the trapped charge to drop to a zero level, which is usually referred to as bleaching. When the bleached grains become covered under sediments, the trapped-charge population starts to increase again due to natural radiation arising from the sediment grains themselves and partly from cosmic radiation. The rate of increase in the trapped charge (dose rate) can be measured or estimated, and hence the time since the burial can be calculated (see e.g. Murray & Olley 2002, Lian & Roberts 2006, Wintle 2008). Altogether, 14 samples from 10 sites were subjected to OSL dating. Two age results were rejected because of excessively large scatter in the results. Water diminishes the annual dose rate to the sediments. In all the datings in this study, it was assumed that the sediments had mostly been under the sea or the groundwater table, and hence a water content of 20 wt-% was used in the correction equation of Aitken (1985).

2.5 Microfossil analyses

Microfossil analyses were performed on fine-grained waterlain sediments and organic horizons of palaeosols. The preparation of the pollen slides has been described in Bennet & Willis (2001) and that of the diatom slides in Battarbee *et al.* (2001). In contrast to the instructions, some of the pollen samples were prepared without acetolysis treatment in order to preserve the plant cell tissue. As the pollen content was in most cases negligible, plant cell tissue offered useful information on the palaeoenvironment. Altogether, about twenty samples were subjected to microfossil determination.

Table 1. The field investigations and analyses utilized in this study.

Investigation method	**Number of measurements/analyses/ field investigations**	**Carried out by/in conjunction with**
Seismic soundings	105 lines, total length *c.* 7 km	This study
	120 lines, total length *c.* 8 km	Mäkelä *et al.* (1990), Kurkinen *et al.* (1994)
	68 lines, total length *c.* 30 km	GSF (unpublished)
GPR measurements	210 lines, total length 124 km	This study
	35 lines, total length 76 km	Kurkinen *et al.* (1994)
Test pits	18	This study
	66 (in the Kauhajoki area)	Kurkinen *et al.* (1994)
	11	GSF (unpublished)
Drillings	45	Kurkinen *et al.* (1994)
	1	Huhta (1997)
Observations/ loggings of open sections	29 sites, 61 sections	This study, observations of other researchers have also been utilized
Palaeodirection measurements	77 fabric analyses from till	This study
	18 fabric analyses from gravel	
	20 striation measurements	
	10 measurements from the fold axis of glacial deformation (push structures)	
	Palaeocurrent measurements from *c.* 250 lithofacies	
Clast lithology counts	52 lithofacies	This study
OSL	12 (+2 rejected)	This study
	c. 40	Niemelä & Jungner 1991, Hütt *et al.* 1993, Nenonen 1995, Auri *et al*. 2008
TL	*c*. 15	Donner 1988, Gibbard *et al.* 1989, Niemelä & Jungner 1991, Hütt *et al.* 1993
Pollen and/or diatoms	4 palaeosols 12 fine-grained units	This study
	5 sites with organic and fine-grained sediments	Niemelä & Tynni 1979, Donner 1988, Gibbard *et al*. 1989, Nenonen 1995

2.6 Stratigraphy

Stratigraphy is most commonly divided into litho-, bio- and chronostratigraphy, although other types of division also exist (Hedberg 1976, Salvador 1994, North American Commission on Stratigraphic Nomenclature 2005). Stratigraphy includes description, classification, naming and correlation. As Gibbard & West (2000) defined, "Stratigraphy is the organization of rock strata into successions of units and their interpretation as sequences of events in earth history". In this study, the main purpose was to examine Quaternary lithostratigraphy in the Suupohja area, although the chronostratigraphical perspective was also strongly considered.

Stratigraphy clarifies the correlation between units in different areas. Detectable units in a rock body, including igneous, metamorphic and sedimentary rocks (lithified or unlithified) or loose sediments, can be named, for instance, on the basis of their lithology, architecture, texture, chemical or mineralogical composition, fossil content, seismic properties, electrical properties, magnetic polarity and so on. Units that are assigned formal names should be properly defined, characterized, described and proposed. The formal name typically has two or three parts and the initial letters of the words are capitalized (Hedberg 1976, Salvador 1994). Usually, formal names include the local geographic designation, geological description and/or stratigraphic rank. Units can also be named informally, although the use of informal names in publications is discouraged. Informal names are written in the lower case letters (except the possible geographic name), and formal stratigraphical terms should be avoided in these names (Hedberg 1976, Salvador 1994). The lithostratigraphical units named in this study are ranked as formations (with the exceptions of two informally termed lithofacies associations).

3. OBSERVATIONS AND INTERPRETATIONS

3.1 Pre-Quaternary base

The study area belongs to the Svecofennian Domain of the Baltic Shield (Gaál & Gorbatschev 1987). The bedrock is predominantly composed of granites, pyroxene bearing granitoids, quartz- and granodiorites, tonalites and mica gneisses (Korsman *et al.* 1997, Lehtonen *et al.* 2004) (Fig. 3). Smaller occurrences of felsic and intermediate volcanites, metavolcanites, gabbros, diorites and peridotites are additionally present. These rocks are also well-represented in the clast lithologies analysed from gravels and diamictons. The crystalline bedrock in the base is *c.* 1800–1900 Ma old, i.e. it was formed in the Palaeoproterozoic Era (Lehtonen *et al.* 2004). In places, the upper part of the bedrock is weathered (disintegrated) to a depth of several metres.

Weathered crystalline bedrock is commonly found around and to the north of Lauhanvuori. Tor-like weathering forms are common, especially on the rims of Lauhanvuori. Elsewhere, weathering crust several metres thick also occurs locally (Fogelberg 1973, Kurkinen & Niemelä 1979, Hyyppä 1983, Söderman *et al.* 1983, Söderman 1985, Pitkäranta 1996, 1999a) (see below). The weathering is most common in coarse-grained red granite (microcline granite).

Because weathered bedrock was observed below the sandstone at Lauhanvuori (see below), the initial weathering has been interpreted to have preferably occurred before the Cambrian Period, although later weathering is also possible (Hyyppä 1983, Söderman *et al.* 1983). The weathering nevertheless predates the Pleistocene Epoch, because the weathering process clearly took place in warmer and moister conditions than prevailed in the Pleistocene.

The occurrence of unmetamorphosed sandstone and conglomerate immediately above the Precambrian crystalline bedrock around the Lauhanvuori area (Fig. 3) is a special feature in the study area, as this is the largest of the few Palaeozoic sandstone occurrences in Finland (e.g. Laitakari 1998). The sandstone and conglomerate are interpreted as having been deposited in the Cambrian Period, possibly in shallow marine environment over 500 Ma ago (see Sederholm 1913, Simonen & Kouvo 1955, Lehtovaara 1982, Tynni & Hokkanen 1982). The sandstone has been proposed the name "Lauhanvuori Sandstone Formation" after its type area in the vicinity of the Lauhanvuori hill (Paper 2). The observed thickness of the sandstone is some tens of metres in this area, and only a few small sandstone outcrops emerge from beneath the thick Quaternary cover.

Seismic soundings indicate that the sandstone possibly has a larger extent than previously estimated (see Figs 3 and 4) (see also Pitkäranta 1996, 1999a, Paper 2). Sandstone was also detected in the deep drilling at Karhukangas in Kauhajoki, 20 km to the NNW of Lauhanvuori (Fig. 2), which was a new discovery (Huhta 1997).

The occurrence of sandstone and weathered bedrock hampered the interpretation of seismic measurements, because their seismic velocities are close to those of unlithified Quaternary sediments. An approximately 20 m-thick layer of weathering crust with seismic velocities of 1120–1300 m/s was measured from outcropped weathered bedrock at Hirsikangas, Kauhajoki (Pitkäranta 1996, Paper 2). At another outcrop of weathered bedrock at Pirttikangas, Kauhajoki, similar velocities were obtained from the upper 5 m, but deeper in the bedrock the velocity gradually increased to 2000 m/s (Ristaniemi *et al.*

1991). At Tuluskangas, Kauhajoki, a 20 m-thick layer of weathering crust also gave velocities of 1750–2000 m/s (Paper 2). According to Hyyppä (1983), weathered bedrock occurrences in the Suupohja area are comparable in extent to those in central Lapland. In these two areas, weathering has considerably greater vertical and horizontal dimensions than elsewhere in Finland.

Field investigations indicate that the topography of the solid crystalline bedrock below the unlithified overburden is fairly rough. Relative differences of 100 m in bedrock altitude were detected within a distance of 1 km. The thick covering sediments, however, effectively flatten the ground surface topography.

Areas with seismic velocities of 1800–3800 m/s at the base are shown in Figure 4. These are potentially the areas where disintegrated bedrock or sandstone occurs below the Quaternary sediments. Figure 4 also illustrates that bedrock outcrops are rare in the central part of the study area, where most of the studied pre-Late Weichselian deposits occur.

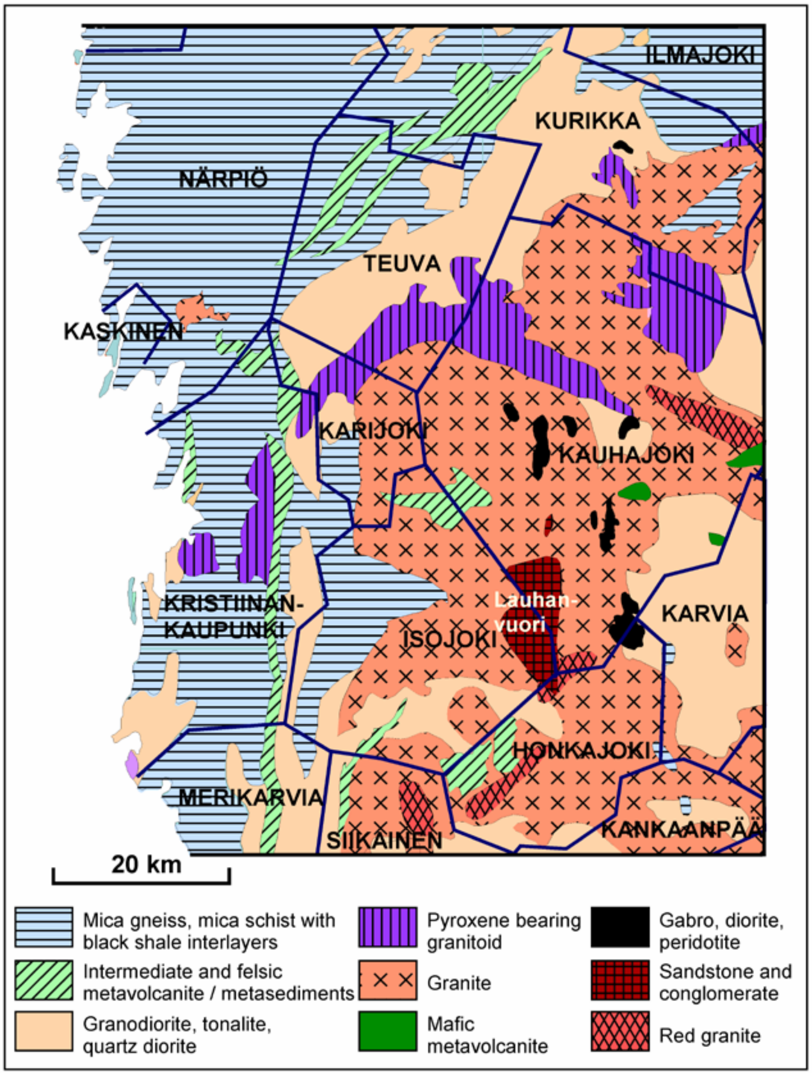


Fig. 3. Bedrock map of the study area (modified from Korsman *et al*. 1997). The bedrock is *c*. 1.8–1.9 billion years old, except for the Lauhanvuori Sandstone Formation, which is interpreted to be of the order of 500 Ma old.

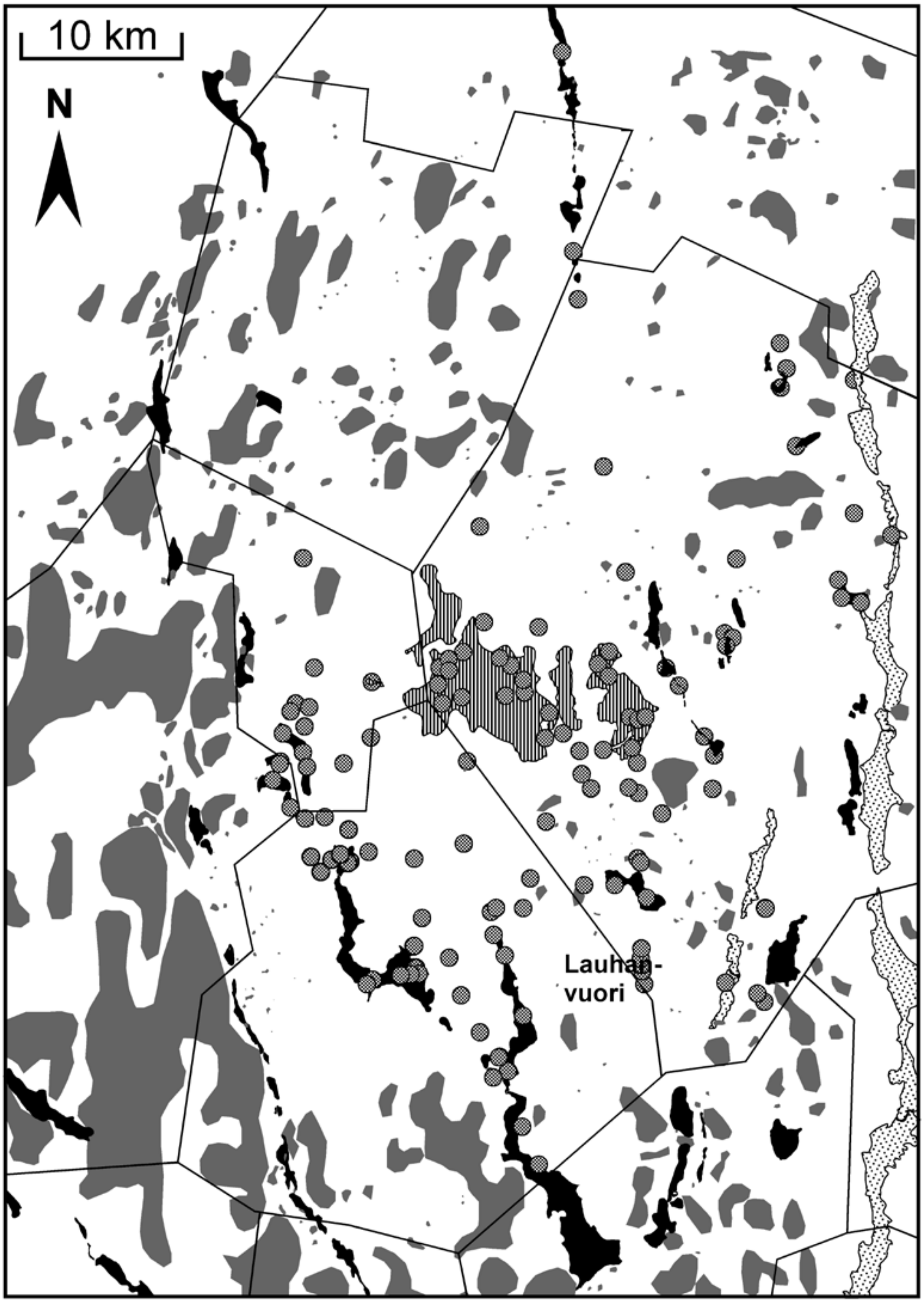


Fig. 4. Areas where seismic velocities of 1800–3800 m/s were measured from the bottommost layer (shaded dots). Disintegrated crystalline bedrock or weathered sandstone potentially occurs in these areas below the Quaternary sediments. Exposed bedrock areas are also indicated (grey areas). The central part of the study area has only a few small bedrock outcrops.

3.2 Thickness of the Quaternary sediments

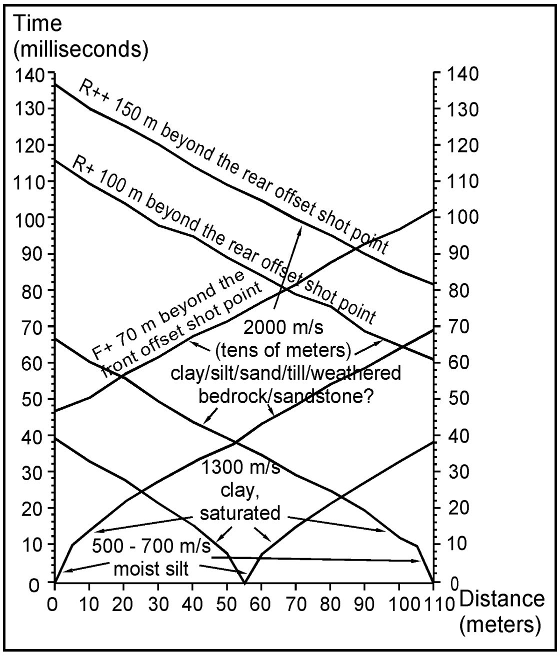
As few drillings were available that had reached the bedrock, the thickness of the Quaternary sediment cover was mostly studied using the refraction seismic method (the Quaternary sediment cover is usually too thick for the GPR method). However, the depth of solid bedrock could not be detected at 20 locations, because sufficiently strong shock waves to reach the bedrock could not be generated with a hammer, even when using the stacking operation. This means that solid bedrock at these locations is deeper than about 35 m according to the measurement configuration used (*cf.* Mäkelä & Illmer 1992). Solid bedrock could not be detected even at one explosion seismic line in the Päntäneenjoki river valley (Figs 2 and 6), although a 150-m offset shot point was used (Fig. 5). This indicates a sediment thickness of at least ~70 m at that site.

Based on 293 seismic lines, covering a total line length of 45 km, the average thickness of the Quaternary sediment cover at the studied sites is about 24 m. Sediment thicknesses of 30–50 metres are common both in valley areas and on hilly terrains. The deepest thickness, *c.* 150 m, was measured at Karhukangas (Fig. 2) (Kurkinen & Palmu 1992, Pitkäranta 1996), but the refracted waves partly came from fractured sandstone (see Huhta 1997).

As a comparison, the average thickness of the Finnish Quaternary sediment cover has been estimated to be about 8.6 m, the most common thickness being 3–4 m (Okko 1964). This estimation was based on over 4700 drillings and excavations around Finland. Furthermore, data from deep seismic investigations in Lapland have demonstrated that the average thickness of the Quaternary cover measured along roads over a distance of 627 km is 5.7 m and the median 4.7 m (Maijanen *et al.* 2008). The deepest measured thickness along the seismic lines in Lapland was a little over 30 m. The distance between measuring points was 50 m and a total of 12 548 depth calculations were performed. These average thickness calculations are based on investigations in areas where bedrock is not exposed.

The bedrock is too deep to be detected with GPR in the central part of the study area. Only two of 46 drillings made in the Kauhajoki area reached crystalline bedrock (Kurkinen *et al.* 1994). The drillings usually terminated in very compact sediments at a depth of 5–30 metres, even when using a heavy drilling machine. The deepest drilled sediment thickness is almost 100 m (Huhta 1997). Bedrock was reached in only five test pits, and in four of them it was strongly weathered. Bedrock is visible in only one gravel pit at Harrinkangas. Along with the thick clay deposits in SW Finland and thick late-glacial sediment sequences in the Salpausselkä zones, probably the thickest Pleistocene sediment cover in Finland occurs in the Suupohja area.

Fig. 5. Seismic time-distance diagram from refraction seismic sounding carried out in the river valley of Päntäneenjoki (see Figs 2 and 6). The seismic velocity of 2000 m/s continues to a depth of at least ~70 m. In the 15 m-deep drilling carried out at this site (Kurkinen *et al.* 1994), post-glacial clay continues to the depth of 4 m and fines-rich till to the depth of about 8 m, the rest being medium-grained compact sand in which the drilling terminated. Compact sediments, homogeneously weathered bedrock or sandstone are possible materials deeper in the substratum.



3.3 Geomorphological features

The present geomorphology in the study area is a result of deposition and erosion in glacial, glaciofluvial, fluvial, littoral and aeolian processes. Waterlain fine-grained (clay, silt and fine sand) and organic (peat) sediments level topographic depressions of the land surface. The topography of the central part of the study area is smoothly undulating (Fig. 6). Broad and flat river valleys are surrounded by gently sloping highland areas. The highest point, 231 metres above sea level, is at the summit of the Lauhanvuori hill in the southern part of the study area (Figs 1, 2 and 6). The study sites are situated *c.* 50–170 m above sea level (Topographic Database, National Land Survey of Finland, 2008). The relative differences in altitudes between high- and lowland areas are usually 20–60 m. The ground surface gradually lowers from east to west, where it finally reaches the sea level at the coast of the Bothnian Bay. In places, rivers have eroded 10–20 m deep, steep-sided canyons.

Bedrock outcrops are scattered and small in the central part of the study area, where a distance of up to 15–20 km separates neighbouring bedrock outcrops (Fig. 4). The bedrock relief is usually not mirrored in the ground surface topography. Polished bedrock with identifiable glacial striations does not occur in the central part of the study area.

The study area lacks clearly distinguishable geomorphological features that could be associated with typical glacigenic depositional forms, such as drumlins, flutings, ablation moraines or ice-marginal deposits. Eskers are also usually flat and discontinuous and geomorphologically indistinct. Most of the Quaternary deposits resemble “smoothened” erosional remnants rather than primary depositional forms. The absence of forcible glacial drift as a whole is also reflected in the complex surface boulder transport distribution, with abundant far-travelled boulders and with a high standard deviation in the boulder transport distribution (Salonen 1986). At many localities, till fabric is inconsistent even within a single till bed (Fig. 7).

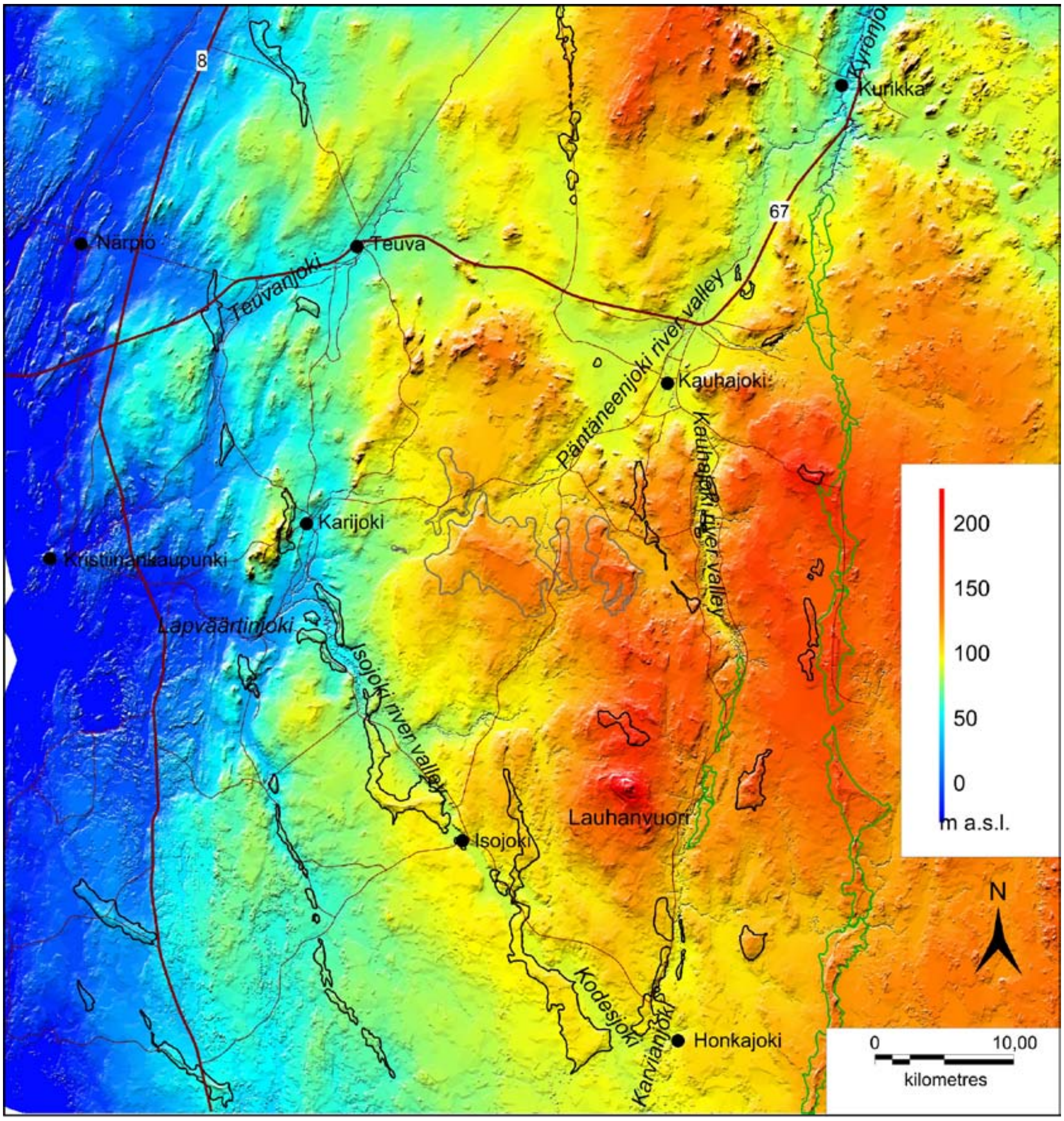


Fig. 6. Shaded relief image of the land surface of the study area (grey boundaries: irregularly shaped broad multilayer deposits; black boundaries: till-covered beaded gravelly ridges and separate till-covered sand and gravel deposits; green boundaries: eskers without till cover (see also chapter 3.4 and Figs 1–2). Major roads are marked as brown lines.The topography of the area is smoothly undulating and lacks prominent depositional forms. Modified using Topographic Database © National Land Survey of Finland (2008).

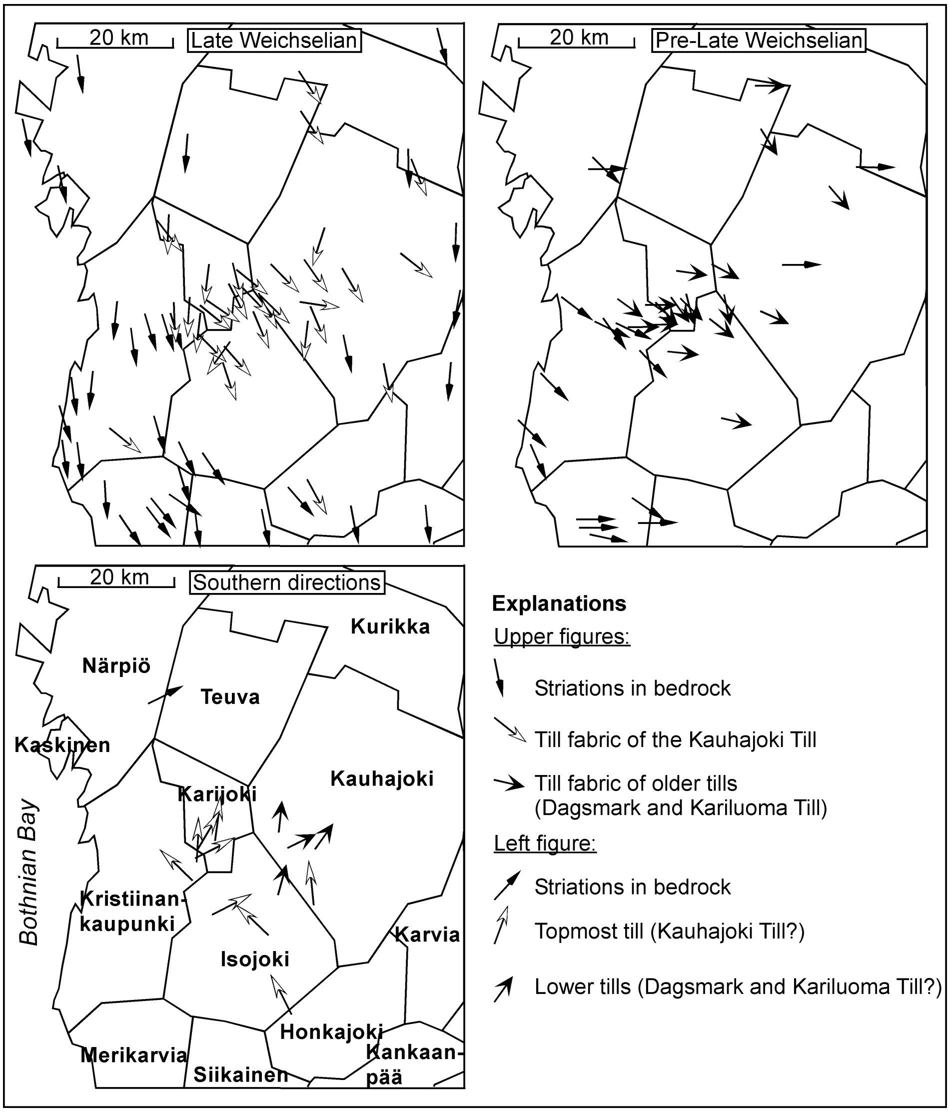


Fig. 7. Glacial flow directions, mostly inferred from clast fabric measurements of diamictons, bedrock striations and recumbent folds in the sorted sediments below the diamictons. The observations show divergent ice-flow directions even during a single glaciation. Post-depositional re-orientation of clasts should nevertheless be considered possible in places. **Upper left**: till fabric of the topmost Kauhajoki Till and recumbent folds in the sorted deposits beneath indicate predominantly northwestern (i.e. glacier flowed from the NW to SE) Late Weichselian ice flow directions in the central part of the study area. More northern glacial flow directions were measured from striations in bedrock and till fabric in the west and east of the study area. This indicates the passive nature of the local ice sheet in the area during the Late Weichselian. **Upper right**: western and northwestern directions predominate in the pre-Late Weichselian glaciations (more than one glaciation is probably represented in these directions). **Lower left**: southwestern directions were also measured from till fabric, although these observations were not recorded uniformly from a single till unit. These observations should be considered anomalous, caused possibly by post-depositional deformation. More observations would be needed to prove that there really existed ice advances from the southwest.

Many erosional forms seem to be associated with deglacial or terrestrial erosive processes rather than with glacial erosion. Good examples of these erosional remnants are the irregularly shaped broad multilayer deposits in Kauhajoki. Some of them seem to have channel-like forms on top and around the deposits, although no modern rivers occur at these locations (Paper 2).

The present shapes of the accumulations seem to primarily originate from sedimentation and erosion processes before the Late Weichselian glaciation, i.e. they represent a relict landscape (*cf.* Kleman 1994). It appears that the Late Weichselian glaciation and its deglaciation had only a secondary influence on the geomorphology of the study area; stagnant ice possibly just melted and sublimated *in situ* without readvances and thus without disturbing earlier landforms. Post-glacial (Holocene) erosion and redeposition had only a minor influence on the geomorphology in this area. One of the main reasons for these features is obviously the location of the Suupohja area in a passive interlobate ice sheet during the Late Weichselian glaciation. Weak glacial movements and divergent ice-flow directions are typical in interlobate ice sheets (Punkari 1997a,b). These features are also discussed in chapters 4.1 and 4.2.

3.4 The Suupohja Group sediments

According to the geomorphology, dimensions, lithostratigraphy and position in relation to neighbouring deposits, the deposits studied are divided into three types: irregularly shaped broad multilayer deposits, till-covered beaded gravelly ridges (“till-covered eskers”) and separate till-covered sand and gravel deposits. A common feature for these deposits is that they are covered by at least one till bed representing the Late Weichselian glacial advance.

The lithostratigraphy of the irregularly shaped broad multilayer deposits clearly deviates from the other till-covered sand and gravel deposits, and they are therefore presented separately. The geomorphology and lithostratigraphy of the till-covered beaded gravelly ridges and separate till-covered sand and gravel deposits have common features, and they are thus presented together. In addition, eskers without till cover, interpreted as having been deposited in the Early Holocene (“young eskers”, Niemelä 1979), are also briefly described, although investigations on them were not carried out in this study.

The geomorphology and lithostratigraphy of the different types of deposits are briefly described below. The examination also includes interpretation of the genesis and inferred age of the sediments. The presented units are included in the Suupohja Group, which is specified in Table 2 and illustrated in Figure 8. In addition to the lithostratigraphical division presented in Paper 1, five formally (Dagsmark Till Formation, Isojoki Sand Formation, Kodesjärvi Formation, Rävåsen Formation, Vanhakylä Formation) and one informally defined unit (“Holocene esker deposits”) are here included in the Suupohja Group (see Papers 3 and 4). A schematic cross-section through the deposits in the central part of the study area is presented in Figure 9.

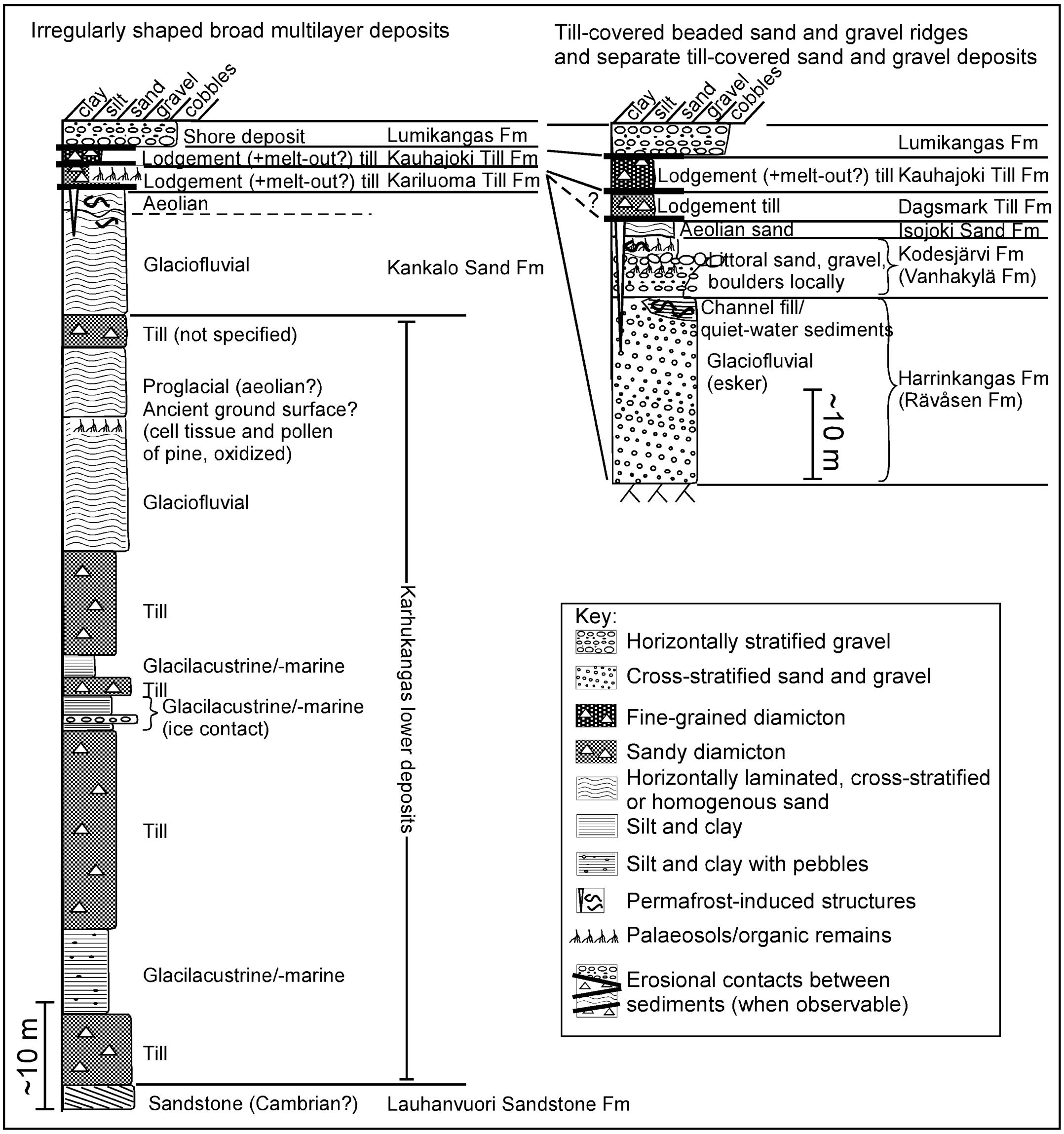


Fig. 8. Schematic logs of the observed units and their lithostratigraphical positions in the sediment sequences. Rävåsen Formation and Vanhakylä Formation (Formation abbreviated as Fm) occur in the same lithostratigraphic position as Harrinkangas Fm and Kodesjärvi Fm. However, it is assumed that the Rävåsen and Vanhakylä Formations are probably younger than the Harrinkangas and Kodesjärvi Formations.

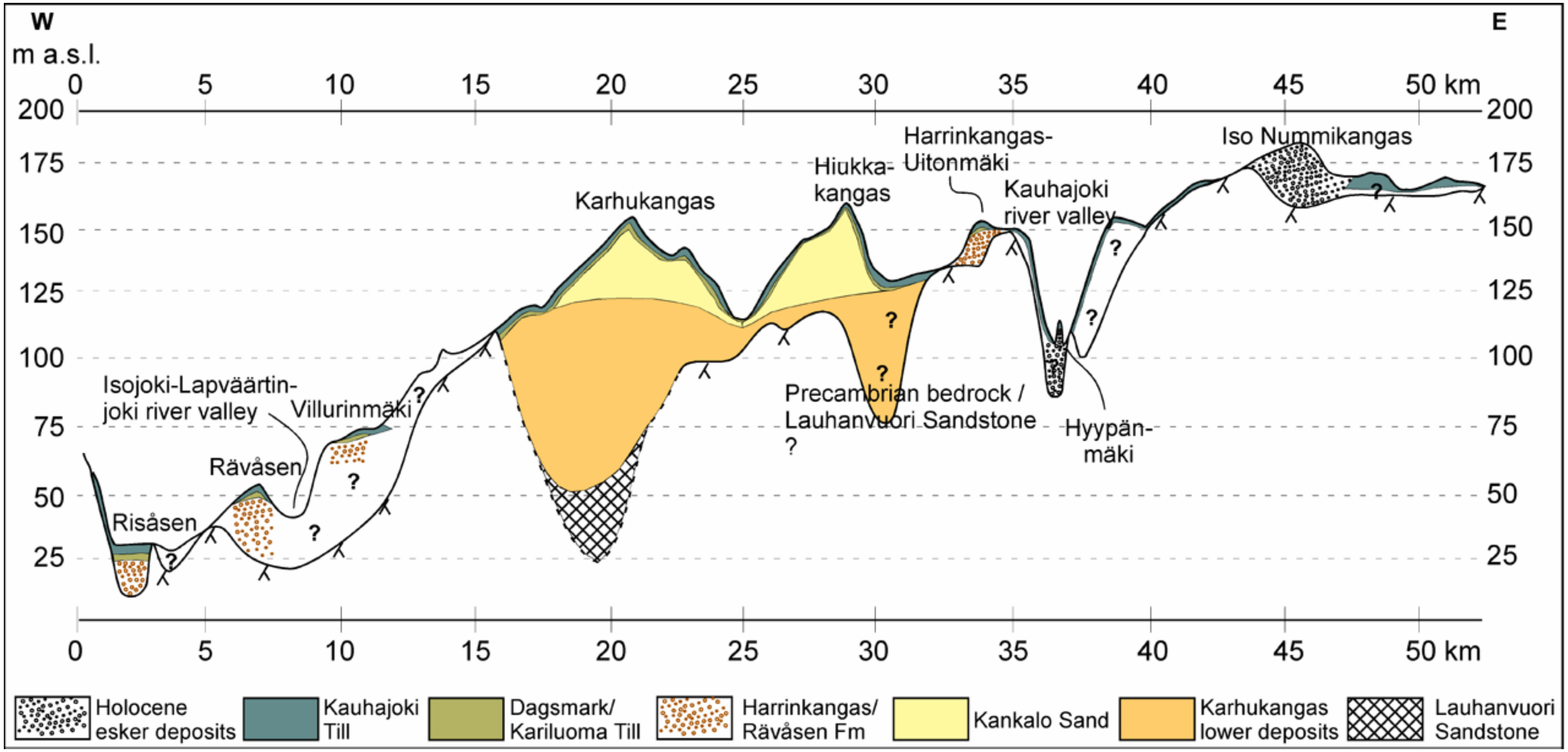


Fig. 9. A schematic cross-section across the study area with the main identified sedimentary units.

Table 2. Description and interpretation of the observed lithostratigraphical units in the Suupohja area. Five formations were added to the Suupohja Group compared to those presented in Paper 1: Kodesjärvi Formation, Isojoki Sand Formation, Rävåsen Formation, Vanhakylä Formation and Dagsmark Till Formation.

Unit	**Description**	**Additional notes**	**Interpretation**	**Inferred age**	**Type section/area**
Lumikangas Formation	Cross-bedded or stratified sand and gravel	This unit covers all the other studied sediments on hilly terrains.	Littoral	Holocene (MIS 1)	Lumikangas 62° 17.500' 22° 9.000' 170 m a.s.l
Holocene esker deposits	Cross-bedded (in various scales) and stratified sand and gravel, loosely packed	These sediments are not overlain by till bed(s)	Glaciofluvial	Late Weichselian/ Early Holocene (MIS 1)	Nummikangas 62° 10.000' 22° 27.000' 170 m a.s.l.
Kauhajoki Till Formation	Dark grey massive fine-grained diamicton	35–60% fines (<0.06 mm), 7–20% clay (< 0.002 mm), clasts dipping mostly towards 340–360º, LOI 0.5–3%. Described originally by Gibbard *et al.* (1989) and Bouchard *et al.* (1990).	Lodgement till (melt-out till locally in the upper part)	Late Weichselian (MIS 2)	Harrinkangas 62° 20.400' 22° 9.800' 140 m a.s.l.
Dagsmark Till Formation	Light brownish grey massive or sheared sandy diamicton, compact	Clasts dipping to W–NW, content of fines 10–15% and clay <3%.	Lodgement till (?)	Middle Weichselian (MIS 3?)	Risåsen 62° 12.300' 21° 38.400' 45 m a.s.l.
Isojoki Sand Formation	Cross-bedded, stratified or homogenous fine- or medium-grained sand, locally cryoturbated, compact	Organic streaks locally occur in this unit (*cf.* also Kujansuu *et al.* 1991, Kujansuu 1992, Hütt *et al.* 1993 and Nenonen 1995).	Aeolian	Middle Weichselian (MIS 4/3)	Penttilänkangas 62° 1.750' 22° 4.350' 110 m a.s.l.
Vanhakylä Formation	Cross-bedded or stratified sand and gravel, permafrost-induced structures, compact	Lithostratigraphical correlation with the Kodesjärvi Formation questionable.	Littoral	Middle Weichselian (MIS 4)	Jätinmäki 62° 11.634' 21° 49.068' 93 m a.s.l.
Rävåsen Formation	Stratified sand and gravel, cobbles and boulders	Detected only in the western part of the Suupohja area.	Glaciofluvial	Early Weichselian (MIS 5d?)	Rävåsen 62° 14.786' 21° 43.229' 64 m a.s.l.
Kodesjärvi Formation	Cross-bedded, stratified or homogenous sand and gravel, sometimes boulder lags, compact	Well-developed palaeosols (fossil podsol soil profiles), correlative with the Ostrobothnia Geosol (Kujansuu *et al.* 1991), were found on top of this unit. Cryoturbation structures and ice-wedge casts.	Littoral	Early/Middle Weichselian (MIS 5e?)	Penttilänkangas 62° 1.750' 22° 4.350' 110 m a.s.l.
Harrinkangas Formation	Stratified gravel, sand, silt and gyttja, strong plastic deformation especially at the westernmost sites, compact	Described originally by Gibbard *et al.* 1989 and Bouchard *et al.* 1990. Microfossils of the organic-bearing and fine-grained sediments on top refer to interglacial origin.	Glaciofluvial, covered locally by quiet-water sediments	Late Saalian/ Eemian (MIS 6–5e)	Harrinkangas 62° 20.400' 22° 9.800' 140 m a.s.l.
Kariluoma Till Formation	Yellowish or light olive brown, massive sandy diamicton with abundant boulders, compact	10–30% fines, <5% clay, LOI < 1%, extremely compact, ~ 20–30% of clasts weathered in places, deformed palaeosols on top. Poorly oriented clasts with high dip angles, a lot of disintegrated clasts	Weathered and deformed till	Late Saalian (MIS 6)	Kankalonselkä 62° 19.900' 21° 54.900' 125 m a.s.l.
	Grey or olive grey, massive or sheared clast-poor sandy diamicton, a lot of boulders locally, compact	Clasts dipping with low dip angles mostly to 320–340º	Lodgement (?) till		Karhukangas 62° 17.850' 21° 54.500' 128 m a.s.l.
Kankalo Sand Formation	Cross-stratified and horizontally stratified medium-grained sand	Well-rounded and abraded grains, moderately to well-sorted Very compact, post-depositional deformation in the upper part of the unit: folds and faults (ice-push), ice- and sand-wedge casts, cryoturbation structures	Aeolian	Saalian (MIS 7–)	Kankalonselkä 62° 19.900' 21° 54.900' 125 m a.s.l.
	Large-scale, planar and through cross-bedded or ripple cross-laminated sand	Occasional pebbles, gravelly layers in places	Glaciofluvial		Karhukangas 62° 18.050' 21° 56.100' 145 m a.s.l.
Karhukangas lower deposits	Sandy diamicton	14% fines, 1% clay, high clast content	Till	Pre-Saalian - Saalian (MIS 8–)	Type area: central part of Karhukangas 62° 18.050' 21° 56.100' 145 m a.s.l.
	Silty sand/fine sand, slight stratification observable in some samples	20–50% fines, 1–2% clay, a few pollen grains and cell tissue of pine at the level of 123.5 m a.s.l., no diatoms	Glaciofluvial/ aeolian (transition to subaerial conditions ?)		
	Sandy/silty diamicton	23–37% fines, 3–5% clay, coarsening upwards	Till		
	Laminated silty sand, silt and clay	42–95% fines, 6–68% clay, LOI 0.5–1.8%, no microfossils found	Glacimarine/ -lacustrine		
	Sandy diamicton	20% fines, 2% clay	Till		
	Silt and fine sand with cobbles and clay clasts, slight stratification, partly deformed	86% fines, 13% clay, stony interlayer, LOI 1%, no diatoms nor pollen	Glacimarine/ -lacustrine		
	Fines-rich diamicton with abundant cobbles	~47% fines, 9% clay, long gaps in the sampling, consists of possibly more than one lithofacies	Till		
	Laminated clayey silt with coarse sand particles	65–90% fines, 6–29% clay, LOI 1–1.3%, no pollen nor diatoms found	Glacimarine/ -lacustrine		
	Sandy diamicton	~30% fines, 5% clay, LOI 0.3%	Till		
Lauhanvuori Sandstone Formation	Lithified quartz sandstone		Shallow marine sand	Cambrian (?)	Lauhanvuori 62° 9.150' 22° 10.450'

3.4.1 Irregularly shaped broad multilayer accumulations

Geomorphology

The largest and thickest deposits studied are broad, sand-dominated multilayer deposits that occur in the central part of the study area in Kauhajoki. Their dimensions are usually difficult to discern from the surroundings because of post-depositional erosion and partial burial under younger sediments, especially till and littoral deposits. The highest parts of these deposits rise 60 metres from their surroundings, their steepest slope gradients being about 5%. The top parts of these deposits have a gentle, smoothly undulating topography (Fig. 6).

The broad multilayer deposits are of the order of 20–100 m thick and they cover a total area of about 70 km^2. Karhukangas (Fig. 2), covering an area of 40 km^2, is the largest of these deposits.

Observations of the sediments

Altogether, up to 13 lithofacies associations were identified in the broad multilayer deposits (Table 2 and Fig. 8). They are interpreted as having been deposited in glacial, glaciofluvial, glaciomarine/-lacustrine, littoral and aeolian environments. Possibly up to six glacial and deglacial sedimentary events were required for the formation of these deposits. It should be stressed, however, that in complex sedimentary processes, several different lithofacies may have formed during a relatively short time interval.

Karhukangas lower deposits

The units of the Karhukangas lower deposits are not visible in any open exposures in the study area, nor have they been reached in test pits. The observed lithostratigraphy is based on 3 drillings as well as on the GPR and seismic soundings. The most complete observations were made from the almost 100 m-deep drilling carried out by the Geological Survey of Finland (GSF) in 1996 (Huhta 1997). The nine units detected are described and interpreted in Table 2 and illustrated in Fig. 8 (see also Paper 2). They include the following layers, from bottom to top (with the observed thicknesses in parentheses):

1) massive sandy diamicton (8 m)

2) horizontally laminated clayey silt with pebbles, slightly deformed, no microfossils (9 m)

3) fine-grained diamicton (24 m)

4) horizontally laminated fine sand and silt with clasts, deformed, no microfossils (2 m)

5) sandy diamicton (2 m)

6) varved silt and clay, no microfossils (2 m)

7) sandy diamicton (12 m)

8) fine sand or silty sand with slight horizontal lamination, a few pine pollen grains and small pieces of charred pine cell tissue in an oxidized horizon in the middle of the unit, a possible palaeosol (21 m)

9) sandy diamicton (4 m).

No diatoms were found in any of the fine-grained sediments.

According to the drilling and seismic measurements, the maximum observed thickness of the Karhukangas lower deposits is 85 m at Karhukangas. The seismic velocity is typically 1600–2000 m/s. The thickness is markedly lower (20–50 m) at Lumikangas, Hiukkakangas, Kivistönkangas and Kankalonselkä (locations in Fig. 2), and hence some of the units listed above are probably missing there.

The Karhukangas lower deposits are interpreted as having been deposited in glacial, glaciofluvial, (glacio)marine/lacustrine, aeolian and possibly littoral environments during up to four glacial-interglacial/interstadial cycles (Paper 2). Naming these lithofacies does not fulfil the recommendations of the stratigraphic guides (Hedberg 1976, Salvador 1994, North American Commission on Stratigraphic Nomenclature 2005), as inadequate observations of the units and their boundaries are available. Here they are therefore only informally defined. Thus, the formal term proposed by Pitkäranta (Papers 1 and 2) should be abandoned until more accurate observations are available.

No datings were undertaken from the Karhukangas lower deposits. Based on the lithostratigraphical position, buried under at least two till beds and a thick sand unit (Fig. 8), Pitkäranta (Paper 2) suggested that the Karhukangas lower deposits were probably deposited in the Saalian Stage or earlier. The deposition of the nine different units may have required up to four glacial-non-glacial cycles.

Kankalo Sand Formation

The Karhukangas lower deposits are covered by an approximately 20 m-thick cross-bedded medium-grained sand, the Kankalo Sand Formation (Papers1 and 2). As a thick and extensive layer, this unit is predominantly responsible for the shapes of the broad multilayer deposits.

Two subunits were observed in the Kankalo Sand. However, the upper subunit is in many places absent. Large-scale, planar and through cross-bedded or ripple cross-laminated structures occur in the lower subunit (Fig. 10 a, b). Occasional pebbles and gravelly layers some centimetres thick occur in this unit. The thickness of the lower subunit is of the order of 10–20 m according to a few drillings and GPR measurements, although the lower contact is not visible in the exposures. Measurements of the dip directions of the foresets indicate that water currents that deposited the sand came from between W and NE. The lower subunit is interpreted as glaciofluvial sand (Paper 2). The lack of coarse particles indicates deposition at some distance away from a retreating glacier.

The upper subunit is cross-stratified and horizontally stratified medium-grained sand, in which no pebbles or larger clasts are present (Fig. 10 c). Its thickness is typically 2–6 m. It has well-rounded and abraded grains and a moderately to well-sorted grain-size distribution. The foresets predominantly dip to W–S–E directions. The sand of the upper subunit possibly represents aeolian facies (Paper 2, see also Kujansuu & Uutela 1997).

The Kankalo Sand seems to represent emergence from subaquatic proglacial to subaerial conditions. Indisputably littoral facies were not detected, although during the emergence these sands underwent a littoral phase.

The texture and microfossils of the Kankalo Sand have also been studied by Kujansuu and Uutela (1997). They did not distinguish different subunits in the sand, but because of the shallow sampling depths and the observations made, their samples were probably taken from the upper subunit. The sand grains are commonly matte-surfaced, moderately or well-rounded, and 70–90% of the grains are quartz, the rest being mainly micas and feldspars. A small amount of limestone is also present, as the sand reacted with 10% hydrochloric acid.

Kujansuu and Uutela (1997) found a few grains of pine, spruce, birch and heather pollen in the sand. However, it is possible that the few pollen grains have been redeposited, for instance by water infiltrating through the sediments. In addition, they found acritarchs in the sand. The distinguished acritarchs were *Veryhachium trisulcum*, *Baltisphaeridium microspinosum*, *Baltisphaeridium multipilosum*, *Micrhystridium stellatum*, *Polygonium pellicidum* and *Revinotesta parva*. These species lived in Late Cambrian–Devonian waters and are now extinct. Kujansuu and Uutela suggested that these acritarcs were derived from the sedimentary rocks on the floor of the Gulf of Bothnia. However, it is also possible that they were derived from more local sedimentary rocks that are now underlain by a thick Quaternary sediment cover.

The Kankalo Sand is typically very tightly packed, enabling exposure walls many metres high to remain vertical without collapsing. The tight packing also caused difficulties in the drillings, as the sampler became repeatedly stuck in the sand. The seismic velocity of dry Kankalo Sand is 30–150% greater (600–1500 m/s) than the typical values for sand above the groundwater table (see Pitkäranta 1999a). The Kankalo Sand is visible in several exposures at Kankalonkangas, Karhukangas, Kivistönkangas, Hiukkakangas and Lumikangas (localities in Fig. 2). The top part of the Kankalo Sand is usually deformed by frost action and/or glaciotectonism (Fig. 10 d). Cryoturbation and involutions are the most common permafrost-induced structures. Ice wedges and one sand wedge were also observed (Paper 2). The glacial deformation structures include faults, recumbent folds, chaotic irregular structures and overturned cross-bedding.

Three OSL datings from the Kankalo Sand (two from Karhukangas and one from Hiukkakangas) gave ages of 102±20 to 123±9 ka, but there were some uncertainties in the datings (Paper 2). Two thermoluminescence (TL) datings from the Kankalo Sand at Karhukangas and Hiukkakangas, reported by Kujansuu and Uutela (1997), exceeded the range of the method. These dating results infer that the Kankalo Sand was deposited in the Eemian interglacial or in the Early Weichselian (MIS 5e–5c). However, based on the lithostratigraphy and because of uncertainties in the OSL datings, Pitkäranta (Paper 2) considered the obtained ages too young and the Saalian age more probable for the sand (*cf.* also Kujansuu & Uutela 1997). The dating uncertainties largely arise from these ages being fairly close to the saturation point of quartz grains, i.e. the maximum determinable age with the OSL method. Possible incorrect estimation of the palaeowater content may also cause up to 10–20% errors in the calculated age.

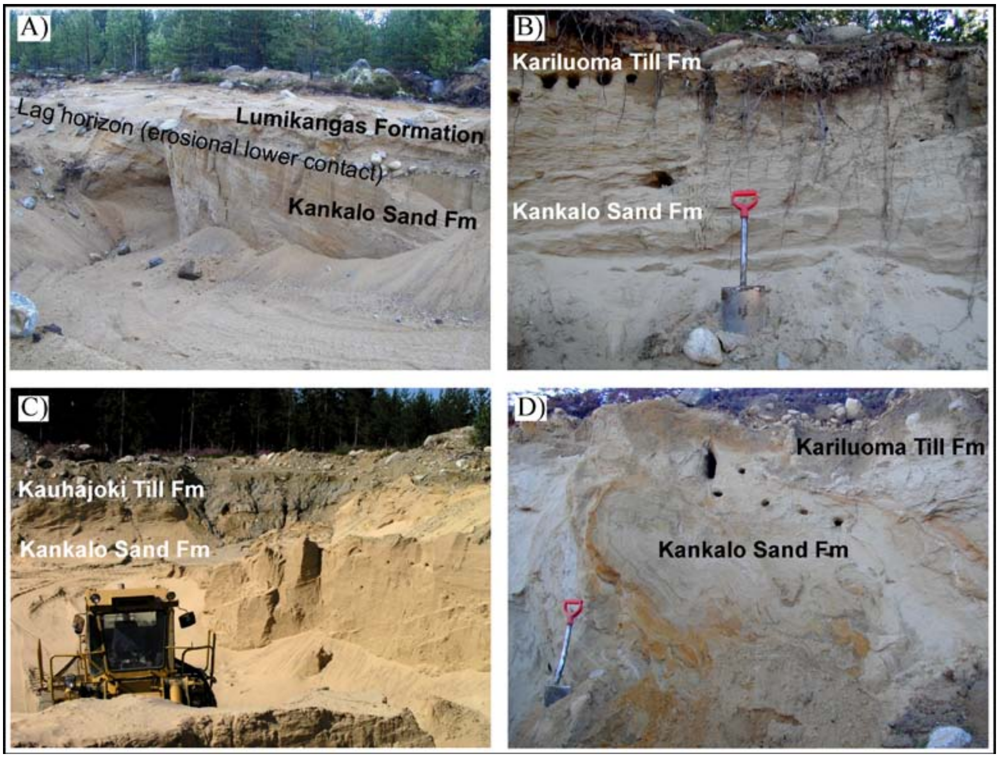


Fig. 10. Examples of exposures excavated in the Kankalo Sand. A) Inclined bedding in the glaciofluvial Kankalo Sand at Hiukkakangas. Only the thin littoral Lumikangas Formation (see below) covers the Kankalo Sand at this site. The height of the exposure is about 6 m. B) Ripple cross-lamination in the Kankalo Sand at Hiukkakangas. C) Aeolian Kankalo Sand at Kankalonselkä, Kauhajoki. The Kauhajoki Till erosively cuts the sand. D) Ice-push structures in the Kankalo Sand at Hiukkakangas. See also Fig. 11.

Kariluoma Till Formation

Light greyish brown or brownish grey massive sandy diamicton commonly overlies the Kankalo Sand (Fig. 11). Like the Kankalo Sand, this diamicton is also compact (over-consolidated). The content of fine-grained particles (≤0.06 mm) is typically 10–30% and that of clay (≤0.002 mm) <5% (see Table 2). LOI is under 1%. The observed thickness of this till is usually 0.5–3 m.

Two different lithofacies types were distinguished in the diamicton. One is yellowish or light olive brown with weakly developed clast fabric and with high dip angles of the clasts. The other is light grey or olive grey, massive or sheared clast-poor with fairly well-developed fabric (S_1 ~0.6) dipping mostly to the west or northwest (280–330°). Both types usually have large rounded or sub-rounded boulders. Many of the clasts and even boulders have been strongly weathered and can be crushed with a spade. The diamicton is interpreted as lodgement till that locally has been reworked by later glacial events and/or frost action, which partly disturbed the original texture. The two lithofacies types were included in one till formation, the Kariluoma Till Formation, because they are sometimes difficult to distinguish from each other and they occur in the same lithostratigraphic position.

Deformed and partly eroded fossil podsol soil profiles were observed at the top of the Kariluoma Till at Uuro and Paulajuurakko (locations in Fig. 2). The number of preserved pollen grains in the organic horizons of the podsols was negligible. Most of the pollen grains were badly worn and thus unidentifiable. Only a few grains of *Pinus* could be detected at Paulajuurakko. In addition, cell tissue belonging to coniferous trees, possibly pine, was abundantly observed on the slides. The fossil podsol soils are correlated to the Ostrobothnia Geosol, defined by Kujansuu *et al.* (1991).

Pitkäranta (Paper 2) interpreted the Kariluoma Till as having been deposited in the Late Saalian glaciation (MIS 6). The main reason for this age interpretation was the lithostratigraphical position below the Kauhajoki Till (see below), and because the Kauhajoki Till was then considered to be the only till representing Weichselian glaciation, the natural chronostratigraphical position of the Kariluoma Till was the Late Saalian Substage. However, more recent interpretations (Paper2) indicate that another till, the Dagsmark Till Formation (see below), was also deposited during the Weichselian, probably in the Middle Weichselian. This newer interpretation does not nevertheless change the age interpretation of the Kariluoma Till. Also Nenonen (1995) interpreted the lower till at Horonkylä (Fig. 2), the Horonkylä Till, as having been deposited in the Middle Weichselian.

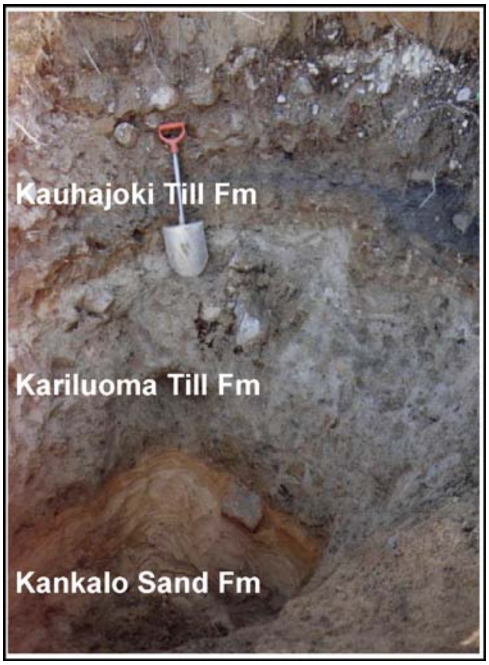


Fig. 11. The Kariluoma Till Formation between the Kauhajoki Till Formation and Kankalo Sand Formation in the southwestern part of Karhukangas. The till as well as the sand beneath are very compact and difficult to dig with a spade. See also Fig. 10.

Kauhajoki Till Formation

All the above-mentioned units are usually overlain by a laterally extensive, massive fine-grained dark grey till, named the Kauhajoki Till Formation by Gibbard *et al.* (1989) and Bouchard *et al.* (1990), after its type area in the district of Kauhajoki. The Kauhajoki Till is also informally commonly known as “mäkisavi” (hill clay). In addition, Rainio & Lahermo (1976, 1984) named this till as the “Dark Till”. Its content of fines is normally 30–60% and clay 7–20%. LOI values vary between 0.5 and 3% (see also Niemelä & Tynni

1979, Rainio & Lahermo 1984, Bouchard *et al.* 1990, Lintinen 1995, Pitkäranta 1996, Paper 2).

The thickness of the Kauhajoki Till varies from a few tens of centimetres to about 5 m, but it is locally also absent (Figs 12 a and b). It is easily detectable in exposures as a dark band in the upper parts of the exposures. Due to the low permeability of this till, bogs and small lakes have formed on top of it at a perched water table. In places, clay and silt occur as small patches or lenses in the till (see also Niemelä & Tynni 1979, Gibbard *et al.* 1989, Bouchard *et al.* 1990).

Niemelä & Tynni (1979) studied pollen and diatoms in the clay patches of the till and the till matrix itself at Maalahti, 70 km to the northwest of Kauhajoki and at Risåsen, Susivuori and Norinkylä. On the basis of the fairly common findings of pollen from rare deciduous trees of the genus *Corylus, Ulmus, Quercus, Tilia* and *Carpinus*, and spores of *Osmunda*, as well as diatoms of, *i.a. Actinoptychus senarius*, *A. kützingii*, *Biddulphia rhombus*, *Campylodiscus thuretii*, *Cerataulus turgidus*, *Chaetoceros sp.*, *Cocconeis clandestine*, *C. costata*, *C. quarnarensis*, *C. granulosus*, *Dimerogramma minor*, *Diploneis coffaeiformis*, *Grammatophora arcuata*, *G. oceanica*, *Navicula monilifera*, *Opephora marina*, *Raphoneis nitida*, *Stephanopyxis turris* and *Thalassiosira gravida*, they concluded that the fine-grained material in the till was at least partly derived from the Eemian Interglacial sediments. However, the sediments also contained taxa that could have lived in cooler interstadial environments. The above-listed diatom flora represents saline and either warm or arctic taxa, indicating more saline water than at present in the Baltic Sea and hence a probable connection to the Arctic Ocean through the White Sea.

Longitudinal clasts of the Kauhajoki Till are moderately or well oriented (S_1 values 0.6–0.85) and dip predominantly to the northwest or north (320–020°), indicating glacier advances from these directions. However, southwestern dip directions were also observed (Fig. 7), which could indicate post-depositional deformation (re-orientation of the clasts) or divergent glacier movements (see chapter 4.2). The majority of the clasts are moderately or well rounded, although angular clasts also occur in places. The clast content is usually fairly low, although in places boulders occur abundantly. The Kauhajoki Till typically has a sharp and/or erosional contact with the underlying sediments (examples in Figs 12 c and d). It usually abruptly cuts, for example, the foresets of the underlying sands and gravels. In places, stratified layers of the underlying sediments have been tilted in the direction of ice movement. Striated clasts also occur locally at the contact of this till and underlying sediments.

The Kauhajoki Till is interpreted as lodgement till, although melt-out facies is also distinguishable in places (Bouchard *et al.* 1990, Paper 2). In addition to Kauhajoki, this till bed is met throughout the Suupohja area and in the northernmost part of North Satakunta. It is litho- and probably also chronostratigraphically correlative with the Horonpää Till, described by Nenonen (1995) at Horonkylä, Teuva.

Because the Kauhajoki Till is the topmost continuous till bed in the study area, it was probably deposited during the Late Weichselian (MIS 2). Only sporadic occurrences of loose sandy till were observed overlying the Kauhajoki Till (Kurkinen *et al.* 1994), but these occurrences possibly represent the same glacial stage that deposited the Kauhajoki Till, and it is here included in the same till formation.

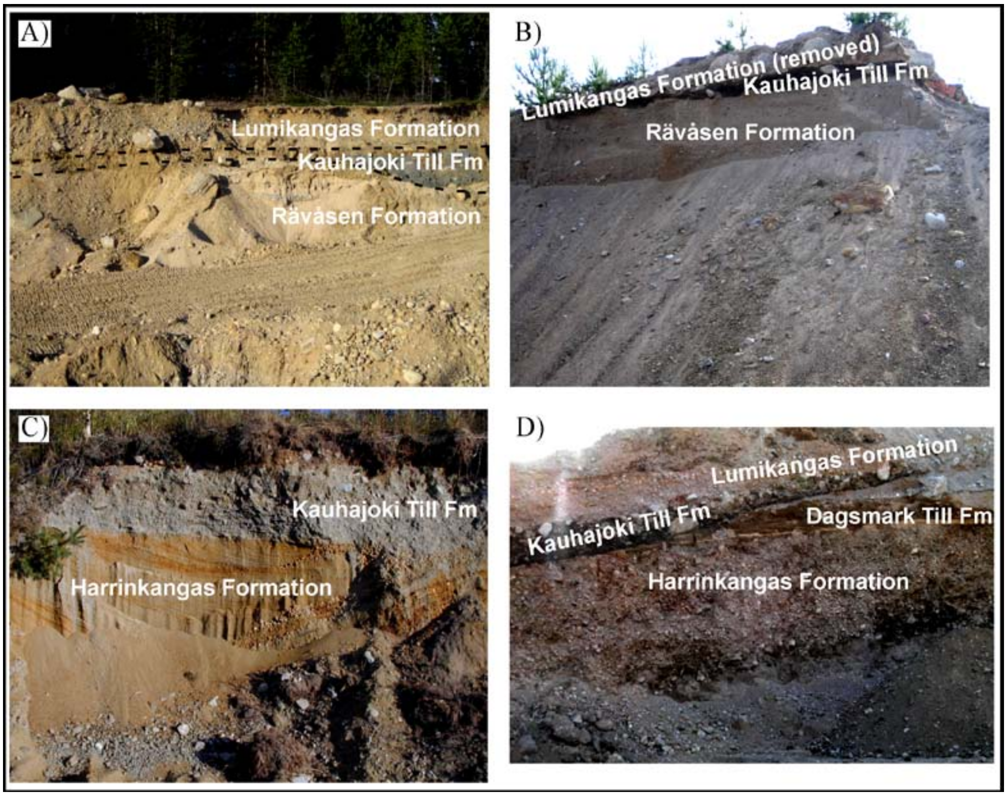


Fig. 12. Exposures of the Kauhajoki Till Formation. A) The thickness and colour of the Kauhajoki Till varies. Unoxidized till is dark grey or bluish grey (right half of the photo), whereas oxidized till is usually brown (left half). A brown colour predominates close to contacts as well as when the till layer is thin. Photo from Rimpikangas, Isojoki. B) In places the Kauhajoki Till is only a few centimetres thick or completely absent. Photo from Rävåsen, Kristiinankaupunki. The Kauhajoki Till erosively cuts the glaciofluvial Harrinkangas Formation at Isomäki, Karijoki (C) and both Harrinkangas Formation and Dagsmark Till at Risåsen, Kristiinankaupunki (D).

Lumikangas Formation

Stratified sand and gravel from a few tens of centimetres to about 5 metres thick, sometimes boulder-rich, covers most hills in the study area (see e.g. Figs 10–12 and Fig. 14). This topmost unit was named the Lumikangas Formation after its type area at Lumikangas, Kauhajoki (Fig. 2, Paper 1). It represents a shore line deposit, formed during the latest regression of the Baltic Sea. Lumikangas is an extensive elevated area (150–170 m. a.s.l.), draped by an almost continuous layer of sandy and/or gravelly shore deposits.

The Lumikangas Formation was formed after the final melting of the last glacier. The deposition of the Lumikangas Formation took place at the beginning of the Holocene Epoch.

3.4.2 Till-covered beaded sand and gravel ridges and separate till-covered sand and gravel deposits

Geomorphology

Longitudinal till-covered beaded sand and gravel ridges and separate till-covered sand and gravel deposits are more easily detectable on topographic maps than the irregularly shaped multilayer deposits. However, many of these deposits also are fairly flat and discontinuous. Single ridges are typically from a few hundreds of metres to several kilometres long and up to 1 km wide. They rise 5–25 m above their surroundings. The steepest slope gradient is 8%, while the gradients are mostly below 3%. Three clearly discernible ridges and one uncertainly interpretable ridge of this type are detectable in the study area (Figs 1, 2 and 6). These deposits cover a total area of *c.* 80 km^2.

The covering fines-rich Kauhajoki Till levels the topography of the ridges and keeps the ground surface moist. The moist topsoil is mirrored in the vegetation, such that these ridges often resemble till deposits, although 10–50 m of dry sand and gravel occur below the till. Bogs and small lakes also occur on a perched water table above the till.

The till-covered beaded sand and gravel ridges are the most studied deposits in the study area. Reported sites (see locations in Fig. 2) are Harrinkangas (Punkari 1988, Gibbard *et al.* 1989, Bouchard *et al.* 1990, Punkari & Forsström 1995), Norinkylä (Niemelä & Tynni 1979, Donner 1988), Haapalankangas (Niemelä & Jungner 1991, Nenonen 1995), Horonkylä (Nenonen 1995), Kärjenkoski (Kujansuu *et al.* 1991, Kujansuu 1992), Penttilänkangas, Jätinmäki and Kiviharju (Papers 3and 4). These ridges have commonly been called “till-covered eskers” (e.g. Niemelä & Tynni 1979, Niemelä & Jungner 1991), although this term is not recommended, because it mixes genesis and morphology (Gibbard 1992). These ridges continue ~5–20 km to the north and south beyond the Suupohja area.

The geomorphology of the separate till-covered sand and gravel deposits resembles that of the till-covered beaded sand and gravel ridges, although the deposits do not form beaded ridges. On topographic maps, separate till-covered sand and gravel deposits are discernible mostly as irregularly shaped or slightly elongated hummocks. They occur separately, away from known esker ridges. Most of these hummocks were earlier mapped as till deposits (Mölder & Salmi 1954, Kujansuu & Niemelä 1984). The deposits typically rise 10–20 m above their surroundings. They are 1–2 km long and 500–800 m wide. The dimensions of these deposits are often difficult to measure, because they are buried under till and littoral deposits, and locally also aeolian sands. The 20 detected deposits of this type cover a total area of close to 45 km^2.

The longitudinal shape of many of the separate till-covered sand and gravel deposits indicates that they possibly originally belonged to continuous eskers or ice-marginal ridges, but parts of them have later been eroded or buried. Some of these deposits seem to have continuations further away. The cap between adjoining distinguishable deposits is from 5 to over 10 km. Risåsen, Susivuori, Rävåsen and Isomäki (Fig. 2) are the most studied deposits of this type.

Observations of the sediments

Harrinkangas Formation

Sediments at the base of the till-covered beaded sand and gravel ridges and the separate till-covered sand and gravel deposits consist of thick layers of stratified and cross-bedded sand and gravel, named as the Harrinkangas Formation by Gibbard *et al.* (1989) (see also Bouchard *et al*. 1990) after the type section at Harrinkangas, Kauhajoki. The sorted sediments are predominantly coarser than in the sorted parts of the broad multilayer deposits. Well-rounded stones and boulders, up to a metre in diameter, also occur commonly in this unit (Fig. 13). Palaeocurrent measurements indicate that the melt waters that deposited the sands and gravels came predominantly from western directions (SW–W–NW).

The Harrinkangas Formation is typically 10–50 m thick. The sediments are very compact and in places strongly deformed (examples in Fig. 13). Because of the high compactness, up to 20 m-high exposures remain vertical without collapsing (Fig. 13 b). Cryoturbation and ice-wedge casts occur in places in the upper parts of the unit. Where the Dagsmark Till (see below) or the Kauhajoki Till directly covers the Harrinkangas Formation, the contact between these units is usually erosional. The primary sedimentary or deformation structures do not continue to the upper till beds (Figs 12 and 13 c). In places, the inclined beds have been tilted to almost a vertical position (Fig. 13 d).

Thin layers of silt, clay, gyttja and/or peat, usually deformed, occur above the sands and gravels in places at Harrinkangas, Norinkylä and Horonkylä (Niemelä & Tynni 1979, Donner 1983, 1988, Gibbard *et al.* 1989, Kujansuu *et al.* 1991, Kujansuu 1992, Nenonen 1995, Hütt *et al*. 1993, Paper 3). These were also included to the Harrinkangas Formation at Harrinkangas (Gibbard *et al*. 1989, Bouchard *et al*. 1990). The most common pollen findings in these sediments were *Alnus*, *Asteraceae*, *Betula*, *Calluna*, *Carpinus*, *Corylus*, *Ericacea*, *Pinus*, *Poaceae*, *Rosaceae*, *Salix* and *Typha*, while *Querqus* and *Ulmus* pollen grains as well as *Osmunda* spores were occasionally also present (see also Niemelä & Tynni 1979, Donner 1983, 1988, Gibbard *et al*. 1989, Nenonen 1995).

The deformed fossil podsol soil profile found on top of the Harrinkangas Formation at Risåsen (Paper 4) is probably the chronostratigraphical equivalent to the Ostrobothnia Geosol, defined by Kujansuu *et al.* (1991) (see chapter 4.3). The pollen grains found in the organic horizon of the paleosol at Risåsen included the following taxa (number in parentheses): *Alnus* (3), *Asteraceae* (18), *Betula* (18), *Calluna* (10), *Corylus* (12), *Cyperaceae* (1), *Ericaceae* (8), *Fraxinus* (2), *Pinus* (9), *Poaceae* (42), *Rhamnus* (1) and *Salix* (3). Cell tissue and even small pieces of charcoal from coniferous trees were also found. The taxa indicate either interstadial or interglacial flora, except for the findings of *Corylus* and *Fraxinus*, which demand a more temperate climate than presently prevails in the study area.

In an earlier unpublished pollen study (see Paper 4), heavy liquids were used to concentrate pollen in two organic-rich sandy peat samples in the soil horizon lying in the Harrinkangas Formation at Risåsen. In the first sample (467 pollen grains), the proportion of arboreal pollen (AP) was 30% of the total pollen sum. AP pollen consisted of *Pinus* (20.6% of the total pollen sum), *Betula* (8.1%), *Corylus* (1.9%), *Alnus* (0.4%), *Tilia* (0.4%) and *Picea* (0.4%). Non-AP pollen spectra mainly consisted of *Phragmites* (17.6%), *Ericales* (16.1%), *Typha latifolian* and *T. angustifolia* (10.9%) and *Calluna vulgaris*

(6.9%). In the second sample (424 pollen grains), the amount of AP pollen was 17% of the total pollen sum. The AP taxa consisted of *Pinus* (11%), *Betula* (3.5%), *Corylus* (1.2%), *Alnus* (0.5%) and *Salix* (0.7%). The non-AP taxa were mainly composed of *Phragmites* (51.4% of the total pollen sum), *Poaceae* (8.7%), *Typha latifolia* (5.9%), *Asteraceae* (5.2%), *Ericaceae* (3.8%) and *Calluna vulgaris* (3.5%). The pollen taxa clearly show that the area was forested and locally or temporarily also wet.

The sands and gravels in the Harrinkangas Formation are obviously of glaciofluvial origin, deposited in close contact with an ice sheet deduced from large clasts, for instance as subaquatic ice-marginal fan or ice-marginal tunnel-mouth deposits (*cf*. Hebrand & Åmark 1989, Brodzikowski & Van Loon 1991, Lønne 1995, Lunkka & Alhonen 1996). The organic-bearing fine-grained sediments above the glaciofluvial sediments were deposited after deglaciation in more temperate non-glacial conditions. Part of the deformation in these sediments possibly originates from the sedimentation process, but probably the main deformation was caused by a later glacial advance across these deposits. The permafrost-induced structures, on the other hand, indicate that cold periglacial conditions prevailed in the area before the following ice advance.

According to most interpretations, the glaciofluvial deposits of the Harrinkangas Formation were deposited preferably during the final melting of the Saalian ice (MIS 6). The non-glacial, mainly waterlain fine-grained sediments in the upper part of the Harrinkangas Formation were deposited in the Eemian Interglacial (MIS 5e) and possibly partly also in the Early Weichselian (MIS 5a and 5c) (Niemelä & Tynni 1979, Donner 1988, Gibbard *et al.* 1989, Bouchard *et al.* 1990, Hütt *et al.* 1993, Nenonen 1995, Papers 1–4). The age interpretation is based mainly on litho- and biostratigraphy, as well as on luminescence datings. One of the most important arguments favouring an interglacial origin is that the organic-bearing sediments contain pollen from plants that have preferably required interglacial conditions, at least as warm and moist as has prevailed in the Holocene.

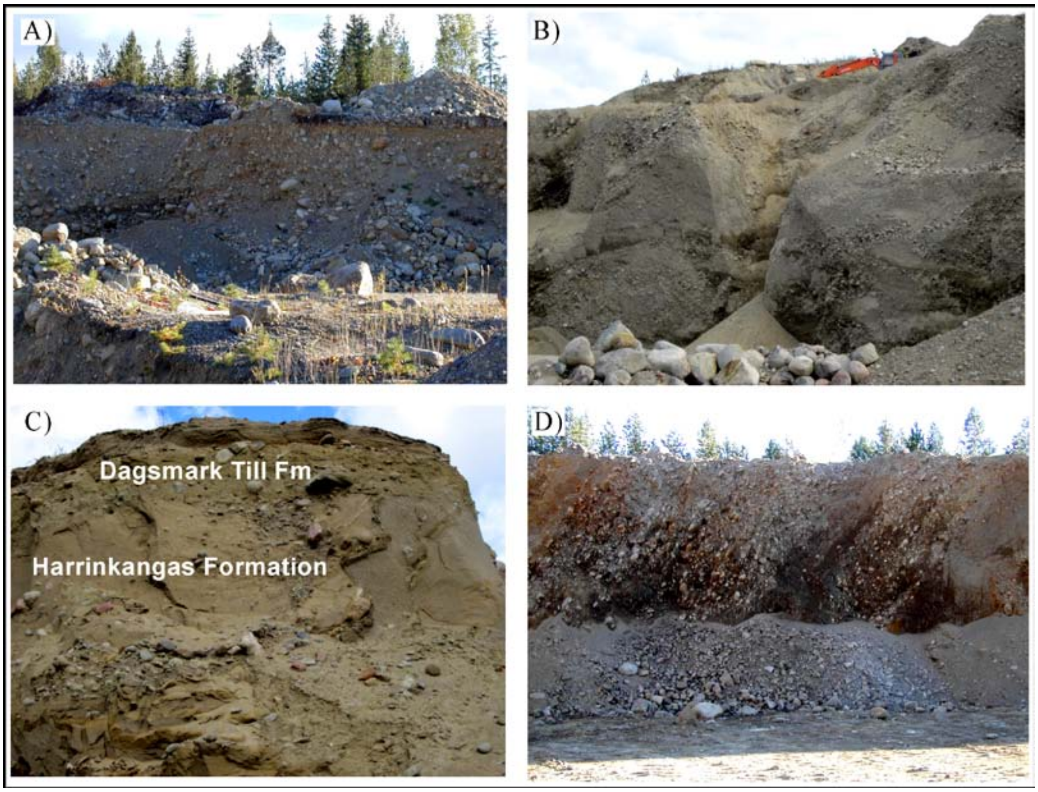


Fig. 13. Excavated sections in the Harrinkangas Formation. A) Boulder-rich glaciofluvial sediments were observed at Isomäki, Harrinkangas, Pieksunkangas, Risåsen, Rävåsen and Susivuori (see locations in Fig. 2). In this figure, the largest rounded boulders in the ca. 15 m-high exposure at Isomäki are about 1 m in diameter. B) The high compactness of the glaciofluvial sediments is indicated by vertical section walls. For example, at Risåsen, section walls of about 20 m high remain vertical without collapsing. C) The erosive contact between the deformed glaciofluvial sediments and the covering till at Risåsen indicates that the deformation took place before the subsequent glacial advance. D) Tilted inclined bedding at Isomäki was possibly caused by ice-push. The dip angle of 60º of the inclined gravel layers cannot be depositional. Dip directions of 70º were also measured.

Kodesjärvi Formation

The Harrinkangas Formation is locally overlain by stratified gravel, a boulder-rich lag horizon and/or horizontally layered, cross-bedded or homogeneous sand (Fig. 14). They are named the Kodesjärvi Formation, after the type section at Penttilänkangas (see Paper 3) near Lake Kodesjärvi, which is also the name of the local village. The thickness of this unit is of the order of 2–12 m, and the sediments are very compact. The Kodesjärvi Formation lies below the Isojoki Sand, Dagsmark Till (see below) and Kauhajoki Till. Its chronostratigraphical correlation with the Vanhakylä Formation (see below) is somewhat uncertain. Inclined beds and foresets dip predominantly towards the NE and E, although considerable dispersion occurs in these directions. Both brittle and ductile deformation structures (cryoturbation, ice-wedge casts and thermal contraction cracks), caused by permafrost and possibly also glaciotectonism, are common in this unit.

A well-preserved mature fossil podsol soil profile, probably age equivalent to the Ostrobothnia Geosol (Kujansuu *et al.* 1991), was observed in the topmost sandy part of the Kodesjärvi Formation at Penttilänkangas (Paper 3), Isojoki. The fossil podsol soil profiles at Kärjenkoski, Risåsen, Susivuori and Norinkylä (locations in Fig. 2) are found in similar types of sands and lithostratigraphical position as that at Penttilänkangas (see Kujansuu 1992, Hütt *et al.* 1993). The sands in these locations are probably lithostratigraphical equivalents to the Kodesjärvi Formation. Pollen grains identified in the organic horizon of the Ostrobothnia Geosol at Penttilänkangas contained the following taxa: *Alnus*, *Betula*, *Calluna*, *Carpinus*, *Corylus*, *Ericaceae*, *Pinus*, *Poaceae*, *Salix* and *Typha* (Paper 3). The pollen grains were nevertheless badly worn and a considerable proportion of them were unidentifiable. In addition, cell tissue and pieces of coniferous tree charcoal were found in the organic horizon.

The sediments in the Kodesjärvi Formation are interpreted as having been deposited at a shore line of a large water body, primarily as washover (*cf.* Schwarz 1982, Massari & Parea 1988) or prograding spit-platform deposit (Nielsen *et al.* 1988, Novak & Pedersen 2000, Mäkinen & Räsänen 2003). The palaeocurrent measurements indicate that the strongest waves that reworked the earlier deposited sediments came from the west and southwest, where the largest open water body of the Baltic Basin occurred. The strongest winds at present also usually come from these directions.

Most of the TL and OSL datings in Suupohja have been made from sands that correspond lithostratigraphically to the Kodesjärvi Formation, Vanhakylä Formation or Isojoki Sand (see below). The obtained ages cover a fairly long time span, from the Late Saalian (MIS 6) to the Middle Weichselian (MIS 3) (see Fig. 17 in chapter 4.5). Niemelä & Jungner (1991) and Hütt *et al.* (1993) obtained two age groups: 160–120 ka and 106–76 ka (altogether 17 OSL and 12 TL measurements). Pitkäranta (Paper 3) reported an OSL age 72±5 from sand belonging to the Kodesjärvi Formation at Penttilänkangas. The Kodesjärvi Formation is chronostratigraphically older than the littoral Vanhakylä Formation (Paper 4, see below), although they both seemingly occur in the same lithotratigraphical position.

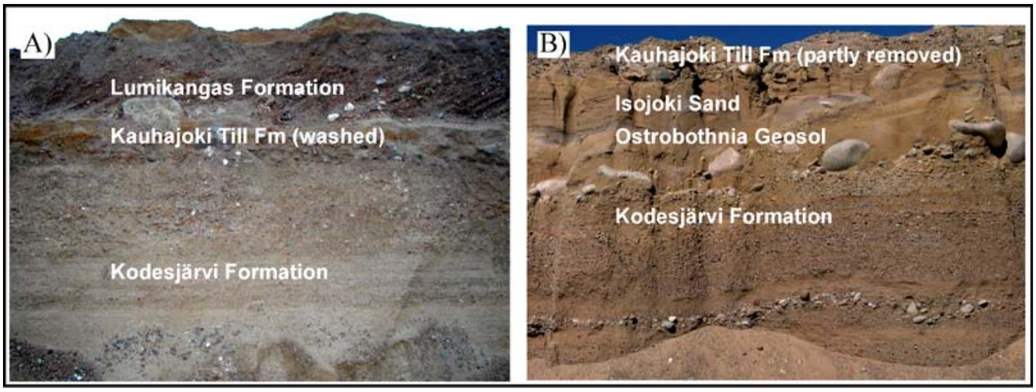


Fig. 14. A) Compact sediments of the Kodesjärvi Formation, covered by a thin, washed Kauhajoki Till and Holocene littoral Lumikangas Formation at Penttilänkangas, Isojoki. The Kodesjärvi Formation is here interpreted as washover or prograding spit-platform deposits (Paper 3). B) A bouldery lag horizon, overlain by beach sand, occurs in the upper part of the Kodesjärvi Formation at Penttilänkangas. The lag horizon and the sand above have been deformed by glaciotectonism or frost action. A well-preserved fossil podsol soil, the Ostrobothnia Geosol, occurs at the upper surface of the Kodesjärvi Formation.

Rävåsen Formation

Stratified and cross-bedded sand and gravel occur beneath two till units at Rävåsen. The grain size of this unit varies from sand to large cobbles. The lower contact is not visible in the exposures, but according to seismic measurements the thickness of this unit is of the order of 20–40 m. It probably lies directly on the bedrock. The lithostratigraphical position is similar to that of the Harrinkangas Formation. Locally, a fine-grained sediment layer a few tens of centimetres thick also covers the sand and gravel. Like the Harrinkangas Formation, this unit is also interpreted as a glaciofluvial deposit. The fine-grained sediments that locally cover the glaciofluvial sediments were deposited in standing water.

An OSL sample from glaciofluvial sand yielded an age 94±15 ka. Based on this age result, it is hypothesised that the 20 km-long chain of glaciofluvial deposits, starting from Rimpikangas in the south and terminating at Rävåsen in the north (Fig. 2) was deposited during an Early Weichselian ice advance, which did not expand further to the east. This unit is considered younger than the Harrinkangas Formation and is thus assigned a different lithostratigraphical name, the Rävåsen Formation (Paper 4).

Vanhakylä Formation

The Rävåsen Formation identified at Rävåsen, Jätinmäki and Kiviharju (Fig. 2) is overlain by stratified or homogeneous sand and gravel, 1–10 m thick. The lower contact with the Rävåsen Formation at Rävåsen and Kiviharju is abrubt and conformable. This unit is interpreted as littoral deposit.

Pitkäranta *et al.* (Paper 4) obtained OSL ages 79±10, 73±9, 72±5, 71±18, 66±8, 64±5 and 54±8 ka from the littoral sands and gravels above the Rävåsen Formation at Rävåsen, Jätinmäki and Kiviharju (Fig. 2). This unit is considered younger than the Kodesjärvi Formation, and is named the Vanhakylä Formation (Paper 4).

Isojoki Sand Formation

The Harrinkangas and Kodesjärvi Formations are locally overlain by fine or medium-grained sand, the Isojoki Sand Formation, e.g. at Risåsen, Kärjenkoski, Susivuori, Haapalankangas and Penttilänkangas (locations in Fig. 2). The sand is stratified, cross-bedded or homogeneous and compact. Its thickness varies from a few tens of centimetres to about 1.5 m. The brittle deformation observed in the sand comes from glaciotectonism and ductile deformation (cryoturbation) from permafrost. Organic-bearing streaks occur in places where the sand overlays a palaeosol (Fig. 15). The streaks were probably detached from the organic horizons of the palaeosols. This sand is identified as aeolian sand.

As presented above, several earlier luminescence age determinations with a large age distribution have been made from sands that could be interpreted either as the Kodesjärvi Formation or Isojoki Sand. Earlier studies of sands lithostratigraphically correlative with the Isojoki Sand yielded ages of 95±11, 94±15, 89±4, 87±9 ka and 86±9 ka at Risåsen and Norinkylä (Niemelä & Jungner 1991, Hütt *et al.* 1993). In contrast, the OSL datings of Pitkäranta (Paper 3) and Pitkäranta *et al.* (Paper 4) yielded ages of 63±4 and 65±10 ka for the Isojoki Sand at Risåsen and Penttilänkangas, respectively. The age results indicate aeolian sedimentation in the Early and/or Middle Weichselian Substages (MIS 5c/b and MIS 4), as well as possible cool terrestrial conditions during those times.

Fig. 15. Aeolian Isojoki Sand Formation in the type section at Penttilänkangas, Isojoki. Dark organic-bearing streaks in the sand were probably detached from the fossil podsol soil beneath.

Dagsmark Till Formation

A grey or greyish brown, compact, massive or sheared, 0.5–2 m-thick sandy diamicton unit was observed below the Kauhajoki Till at Risåsen and Rävåsen. Locally, the Kauhajoki Till is absent. The fabric of this sandy diamicton dips to the west or northwest (270–330º, S_1 values at Risåsen 0.70 and 0.87), and the clast lithologies differ from those in the Kauhajoki Till (differences of 10–20% in abundance of the same rock types occur). The lower contact with the glaciofluvial sediments at Risåsen is sharp and erosional. The above-mentioned properties of this diamicton imply that it is lodgement till. Because of the differences in the texture, fabric and clast lithologies compared to the Kauhajoki Till, this till was evidently deposited during a different glacier advance, and it is called the Dagsmark Till Formation after the local village near the Risåsen and Rävåsen sites.

The Dagsmark Till is intercalated between the Isojoki Sand and Kauhajoki Till. This implies that it was deposited in the Middle Weichselian glacial advance, which is supported also by the OSL ages from the Isojoki Sand. It is in the same lithostratigraphical position as the Horonkylä Till in Horonkylä, Teuva (Nenonen 1995, location in Fig. 2).

Kauhajoki Till Formation

As in the irregularly shaped broad multilayer deposits, the Kauhajoki Till is also the topmost laterally extensive glacigenic unit in the beaded till-covered sand and gravel ridges and in the till-covered separate sand and gravel deposits. The thickness of the Kauhajoki Till is the same as in the broad multilayer deposits, ~ 0.5–5 m. Referring to chapter 3.4.1 above, this till is lodgement till, but in places a melt-out origin is also possible.

Loose, boulder-rich sandy diamicton has occasionally been met above the Kauhajoki Till (see also Iisalo *et al.* 1974, Niemelä & Tynni 1975, 1979, Niemelä 1978, Kurkinen *et al.* 1994). Its observed thickness varies between 0.5 and 1.5 m. This diamicton was laid down during the final melting of the Late Weichselian ice, possibly as ablation or sublimation till, and it can be included in the Kauhajoki Till Formation.

Lumikangas Formation

The sand- and gravel-dominated Holocene Lumikangas Formation, representing a shore deposit, covers most of these deposits in the study area (*cf.* chapter 3.4.1). Its thickness varies from a few tens of centimetres to about 5 m.

3.4.3 Eskers without till cover

Geomorphology

Altogether three eskers without till cover occur in the Suupohja area. The largest of these extends through the eastern part of the study area (Fig. 1). The visible part of the esker in Figure 1 is 66 km long and has an area of 70 km^2. The total length of the esker is over 100 km. It branches in the village of Koskenkorva, Ilmajoki, in the north (22 km to north beyond the figure). In the south it terminates at the extensive Hämeenkangas accumulation (18 km to south beyond the figure). The esker extends through the communes of Ilmajoki, Kurikka, Kauhajoki, Karvia and Kankaanpää. Extensive deposits belong to this esker chain: Pitkämönkangas (7.4 km^2), Iso Nummikangas (7.2 km^2), Nummikangas (11 km^2) and Pohjankangas (over 50 km^2) (Figs 1 and 2). The thickness of these deposits is usually 10–30 m, and the width varies from a few hundred metres to 3 km. These deposits usually rise 10–20 m above their surroundings, and the steepest slope gradients are of the order of 7%.

Another smaller esker chain without till cover is also situated in the eastern part of the study area in Kauhajoki. It is 14 km long and covers an area of about 7 km^2. The maximum width of the esker is *c.* 800 m. The highest parts of the esker rise only 7 m above their surroundings. The glaciofluvial deposits in the esker are usually 5–10 m thick, but depths of 20 m have also been measured seismically in bedrock depressions (Kurkinen *et al.* 1994). Katikankangas, Järvikangas, Ruostetkangas and Toivolankangas belong to this esker chain (Fig. 2).

Lithostratigraphy and age

Cross-bedded (at different scales) and stratified sand and gravel are almost the only sediments met in the eskers without till cover. Their observed thickness varies from a few metres to *c.* 30 m. Fine sand, silt and clay layers sometimes occur in the strata, especially at the rims of the deposits. In contrast to the till-covered sorted deposits, sediments in these deposits are not compressed. Deformation structures are rare, and permafrost-induced structures are absent in the sediments.

The sediments are interpreted as glaciofluvial deposits. The fine-grained sediments above the glaciofluvial deposits were deposited in a large water body in the former stages of the Baltic Sea. The upper few metres of these eskers have usually been reworked by waves. The waves considerably levelled the original ridges and redeposited sediments from the crests downhill. These shore deposits are litho- and chronostratigraphical equivalents to the Lumikangas Formation.

No datings were carried out on these deposits, but the lithostratigraphy, loosely packed sediments and lack of deformation structures imply that they have not been buried under glacial ice. Thus, they were obviously deposited during the recession of the latest Weichselian glaciation, i.e. during the Early Holocene (MIS 1). These are considered as “young eskers” (*cf.* Niemelä 1978, 1979).

“Holocene esker deposits” is tentatively proposed as an informal name for these late glacial glaciofluvial deposits. The type area for these deposits could be Nummikangas, which is a large glaciofluvial deposit in the southeastern part of the study area (Fig. 2).

4. DISCUSSION

4.1 Reasons for the occurrence of old sediments in the study area

The abundant occurrence of pre-Late Weichselian sediments in Suupohja indicates weak glacial erosion during the Late Weichselian glaciation. However, thick multiple layers, deposited in different sedimentary environments and presumably during a longer time period than merely the Weichselian infer that erosion during glacial and non-glacial events has been incomplete not only during the latest, but also during earlier glacial-interglacial cycles. In this respect, this area resembles the areas of relict landscape and pre-Late Weichselian deposits in central and northern Sweden, described by Lundqvist (1967), Lagerbäck (1988a,b), Lagerbäck & Robertsson (1988), Kleman (1994), Kleman *et al.* (1997, 1999, 2008) and Hättestrand & Stroeven (2002), as well as in Finnish Lapland (Kujansuu 1967, Korpela 1969, Mäkinen 1985, 2005, Hirvas 1991, Johansson 1995, Johansson *et al.* 2005, Sarala 2005). The reasons for the preservation of old sediments in all these areas are possibly at least partly the same.

Both lithostratigraphy and dating results indicate that the preserved sediments in the basal parts of the oldest deposits, e.g. the Karhukangas lower deposits in the irregularly shaped broad multilayer deposits, originate before the Late Pleistocene Epoch. The sediments in the longitudinal till-covered beaded sand and gravel ridges and separate till-covered sand and gravel deposits are younger, although they also predate the Late Weichselian glacial advance. Seven possible reasons, partly interactive and partly alternative, are suggested to be responsible for the common occurrence of sediments preserved from glacial erosion. These reasons are presented below.

i) One of the major reasons for the preservation of pre-Late Weichselian sediments is the location of the study area close to the ice-divide zone in the central area of the SIS during the latest and probably also during earlier glaciations (Paper 2). Stagnant, cold-based ice is more common in central parts than in more distal areas of ice sheets (Sudgen & John 1976, Boulton & Clark 1990, Kleman 1994, Kleman *et al.* 1997, 1999, 2008, Hättestrand & Stroeven 2002, Stroeven *et al.* 2002). Glacier movements were weak and divergent, and subglacial melting was poor in these areas, which diminished the erosion.

ii) During the most recent Late Weichselian glaciation, the study area belonged to a passive interlobate ice sheet, where glacial movement and thus erosion was restricted (*cf.* Punkari 1997a,b). This evidently contributed to the preservation of sediments from erosion by the latest glaciation.

iii) Subglacial hydrology obviously had an essential role in the ice dynamics. As noted in chapter 3.1, deeply weathered bedrock and/or fractured sandstone commonly occur below the Quaternary sediments in the study area. The permeable substratum beneath glaciers improved drainage at the base of ice sheets (*cf.* Boulton & Hindmarsh 1987). The ability of water to infiltrate in large areas at the bottom of an ice sheet keeps the interface of the ice and the substratum more or less dry, diminishing or prohibiting glacier movement, and thus preventing abrasion (*cf.* Weertman 1972, Clayton *et al.* 1985, Boulton & Dobbie 1993, Boulton *et al.* 1995, 2009). Subglacial hydrology is one of the main factors regulating the erosive and deformable behaviour of an ice sheet (e.g. Shoemaker 1986, Boulton & Hindmarsh 1987, Benn & Evans 1996, Hart & Rose 2001, Rattas & Piotrowski 2003), although its effect has also been debated (Boulton *et al.* 2001, Piotrowski *et al.* 2001, 2002).

The water at the bottom of an ice sheet usually originates from melting of the ice due to geothermal heat, friction between the thick ice and solid substratum (pressure melting) and from gravitational water flowing along fractures from the upper parts of the ice, preferably at decaying ice margins (e.g. Shreve 1985, Paterson 1993, Boulton *et al.* 2007). When the water is able to escape deeper from the interface of the ice and the substratum, its lubricant and liquefying (deformable) effect disappears. This, in turn, easily stops the ice movement, at least at the base, and hence abrasion cannot take place.

iv) Deformations caused by permafrost, such as cryoturbation, involutions and ice-wedge casts, occurring below the Kauhajoki Till indicate that the sediments were deeply frozen prior to the Late Weichselian glacial expansion to the study area. The frozen ground effectively resisted erosion and deformation during the initial phase of the latest glaciation. It probably also contributed to the cold-based ice, which does not usually slide along its base (e.g. Eyles *et al.* 1983, Drewry 1986).

Ductile deformation structures nevertheless occur in places in the sediments below the Kauhajoki Till. This indicates that the sediments were locally unfrozen to a depth of at least a few metres. Areas of cold-based ice (dry bed) with patchy occurrences of wet-based ice were also reported, for instance, by Kleman (1994) from northern Sweden. It is also possible that wet-based ice turns to cold-based ice by basal freeze-on (Christoffersen & Tulaczyk 2003). Ductile deformation preferably forms in areas of wet-based ice (*cf.* Benn & Evans 1996, Hart & Rose 2001, van der Meer *et al.* 2003). However, the permeability of frozen ground is several orders of magnitude lower than that of unfrozen ground (Burt & Williams 1976, Piotrowski1997 a,b), which is not in full agreement with third item (iii) above.

v) The study area belongs to the southern part of the elevated Suomenselkä main water-divide zone in western Finland. This area is typically snowy in winters, because moisture coming from the Bothnian Sea often falls as snow in the late autumn and early spring, while in the neighbouring lowland areas water concurrently precipitates as rain. Especially on Lauhanvuori hill, which is the highest point in southern Finland (231 m a.s.l.), the winter snow cover lasts on average two months longer than in the nearby areas below 100 m a.s.l. Measurements of snow water equivalent values from twelve years (1990–2002) demonstrate that the annual snow cover on Lauhanvuori contains c. 50–100% more water than measured at lower lying sites (<50 m a.s.l.) at the observation stations in Ylistaro (100 km to the NNE) and Ikaalinen (60 km to the SE) (statistics from the Finnish National Board of Waters and the Environment, Hydrological Office 2003). During the initial phases of glaciations, the thick snow cover did not completely melt in summers. Gradually, the bottom parts of the permanent snow may have turned to firn ice. The permanent snow/ice protected this area from glacial erosion. This could also be one explanation for the preservation of the tors and boulder fields around Lauhanvuori (see Söderman *et al.* 1983).

vi) Some of the pre-Late Weichselian sediments in the central part of the study area are found in bedrock depressions. The higher bedrock areas around the depressions possibly protected the sediments from glacial erosion. The depressions acted as sediment traps.

vii) The dark grey fines-rich Kauhajoki Till, deposited at the contact of the ice and the substratum, could have acted as a lubricant against the Late Weichselian glacial erosion. This, however, only prevented erosion during the latest glacial stage. The high content of fines in the till has been attributed to the poor dewatering of the till in the passive interstream zone, where eskers are rare (Lintinen 1995, Punkari 1997a). The poor dewatering, in turn, led to inadequate washing of till fines.

Three of the above-listed items (i, iv and vii) were also mentioned by Lunqvist (1967) as being possible reasons for the occurrence of sub-till pre-Late Weichselian deposits in the county of Jämtland, central Sweden. The mechanism of erosion and deformation beneath ice sheets has been studied in numerous papers in the past four decades, indicating that these processes are complicated (e.g. Shoemaker 1986, Boulton & Hindmarsh 1987, Walder & Fowler 1994, Benn & Evans 1996, Boulton *et al.* 2001, Hart & Rose 2001, Piotrowski *et al.* 2001, Kjær *et al.* 2003, van der Meer *et al.* 2003). The role of each listed factor is not clear. The study area, with no or few scattered bedrock outcrops, seems to be analogous to the ‘thick drift cover zone’, which once established appears to have also resisted glacial erosion in subsequent glaciations, such that only partial ‘edge-trimming’ has taken place (Kleman *et al.* 2008).

4.2 Ice dynamics and landforms

As noted in chapter 3.3, glacigenic streamlined forms, such as drumlins, flutings or polished bedrock with striations, are almost absent in the study area. This indicates that no substantial ice movement took place during the end of the last glaciation. Oriented longitudinal clasts in the Kauhajoki Till, striated clasts at the contact of the till and the underlying sediments as well as recumbent folds and over-turned cross-bedding in the till-covered sediments, however, are evidence of glacier movement in the initial part of the Late Weichselian glaciation before this part of the ice sheet stagnated as a passive interstream ice lobe.

Older ice-flow directions are also locally represented in the Kariluoma and Dagsmark Tills, as well as in bedrock striations (Fig. 7). Local dispersion was nevertheless recorded in till fabric both in single analyses (no clear orientation detectable) and also in measurements from the same till beds at neighbouring sites, i.e. the clast fabric directions seem not to be fully consistent in the same till beds.

Possible reasons for deviating till fabric and striation directions are as follows:

i) Different directions are caused by glacial advances of different glacial stages; some of the stages are represented as till beds of only limited lateral extent, and some of the till beds may have eroded away.

ii) Post-depositional deformation or later glacial advance have disturbed or re-oriented the original clast orientation.

iii) Depending on the sedimentation process, till fabric does not always mirror any ice-flow directions (e.g. Dreimanis 1989).

iv) Divergent glacial movements, common in the interlobate zones (Punkari 1997 a,b), are possible during a single glaciation.

Despite some inconsistencies in the till fabric and striations in different parts of the study area, outlines of the main ice-flow directions can nevertheless be reconstructed (Fig. 7). Western and northern directions are the most common. The western directions (~270–330°), typical for Kariluoma and Dagsmark Tills, predominantly represent older glacial movement than the more northern directions (~320–20°), mainly measured from the Kauhajoki Till. These more northern directions represent the Late Weichselian glaciation.

There are, however, also northern directions originating from some earlier glacial advance. In addition, a few till fabric measurements indicated WSW–S–SSE (~160–240°) clast dip directions, but because these observations were only occasional and they were measured in different types of tills (Kariluoma Till Formation, Dagsmark Till Formation, Kauhajoki Till Formation or till possibly not correlative with the fore-mentioned tills), their palaeoglaciological significance is highly uncertain.

The area with deviating ice flow directions coincides well with the area where most of the pre-Late Weichselian deposits occur (see Fig. 7). The directions are more consistent surrounding the central part of the study area. This indicates weak and inconsistent ice movements in the central area. It seems that glaciers repeatedly stagnated in this area during the Middle/Late Pleistocene glaciations.

Ice-induced ductile deformation structures occur as patches, which imply that subglacial melting took place at least locally during glaciation(s). The melted parts were possibly so thin and small in extent and the ice movement restricted that total destruction of the sediments could not take place. This type of patchy deformation of earlier deposited sediments has also been observed, for instance, in northern Sweden (Kleman 1994, Hättestrand & Stroeven 2002). Ductile deformation does not take place, if sediment is deeply frozen.

All the sediments below the Kauhajoki Till are tightly packed. The compactness obviously resulted from the heavy load of the over-thrusted Late Weichselian (or earlier) ice sheet, which over-consolidated the underlying sediments (*cf.* Aario 1971, Boulton & Dobbie 1993, Larsen *et al.* 1995, Christoffersen & Tulaczyk 2003). High compactness of sediments was not observed in the eskers without till cover.

Recycling of sediment grains, stones and boulders through several glacial-deglacial-nonglacial cycles is probable. This is demonstrated by the high proportion of relatively fine-grained sediments in the irregularly shaped broad multilayer deposits and in the eskers without till cover. When glaciers overrode older sediments and incorporated them into the ice, the proportion of large clasts and boulders diminished during transportation, as normal glacial crushing took place. No bedrock outcrops were available over long distances in the direction of glacial transport, so no fresh bedrock blocks could have been incorporated into the ice. This possibly led to the enrichment of sand and finer material and correspondingly impoverished the proportion of pebbles and cobbles in these sediments.

Recycling of sediments is also demonstrated by the relatively well-rounded clasts that are common in all the observed till beds. The roundness of the clasts is probably due to the abrasion caused by multi-transportation in more than one glacial cycle. Furthermore, the diversity in clast lithologies in the different coarse-grained sediment units (including tills as well as glaciofluvial and littoral gravels) refers to multi-transportation, because the sediments of different provenance have been mixed in several sedimentation processes. The pre-Quaternary acritarchs found in the Kankalo Sand (Kujansuu & Uutela 1997) are also evidence of sediment recycling.

The thickness of the Late Weichselian and Early Holocene glacigenic sediments is in many places only 0.5–1.5 m and in some places totally absent (see e.g. the figures in chapters 3.4.1 and 3.4.2). At a number of sites observed, a thin layer of the Kauhajoki Till is the only lithofacies representing Late Weichselian and Holocene sediments. This is in agreement with Kjær *et al.* (2003), who observed that till is thin in areas where the substratum consists of permeable deposits.

Esker density in Finland is usually 7/100 km, being denser, 12–13/100 km, near the large ice-marginal Salpausselkä zones (Punkari 1994). This means an average distance of about 10–20 km between adjoining eskers. This density was enough to keep the subglacial ice, water and sediment pressures in balance during the last deglaciation. In contrast, the study area seems to have a distance of over 50 km separating eskers deposited during the Early Holocene deglaciation. The following are possible reasons for the sparse occurrence of Early Holocene eskers in the study area:

i) A permeable substratum allowed drainage over a large area at the base of the ice (see chapter 4.1); as the water could escape into the sediments from the ice bottom, subglacial melt-water tunnels did not form and the conditions were not therefore favourable for esker formation (*cf.* Boulton & Dobbie 1993, Piotrowski 1997a).

ii) The content of debris in the passive ice was so low that not enough material was available for esker formation.

iii) The ice possibly receded by surficial melting and sublimation, which diminished the amount of melt-water at the base of the ice, preventing the formation of subglacial conduits.

iv) Esker density is typically lower in interstream areas than in areas of active ice (Punkari 1997a).

v) In addition, Clark & Walder (1994) and Walder & Fowler (1994) have concluded that eskers are rare or absent in areas of low permeability fine-grained tills; the high clay content in the till is partly due to the absence of running water at the glacier sole and hence poor washing of the till (see also Lintinen 1995).

vi) Tunnel valleys or tunnel channels potentially drained the base of the ice (see e.g. Boulton & Hindmarsh 1987, Piotrowski 1994, 1997a,b, Piotrowski *et al.* 1999, Sjogren *et al.* 2002, Stewart *et al.* 2012, Janszen *et al.* 2013), however their existence is unconfirmed (see below).

Tunnel valleys are typical of areas with a permeable substratum, such as on Palaeozoic sediments outside the Baltic Shield in northwestern Russia, Poland, Germany, Denmark, Holland and the North Sea (e.g. Ehlers *et al.* 1984, Boulton & Hindmarsh 1987, Piotrowski 1997a). Tunnel valleys can effectively drain the base of a glacier, and hence ridge-shaped beaded eskers are not found in the same areas as tunnel valleys. In tunnel valleys, meltwater erodes soft sediments beneath a glacier without marked deposition. On impermeable solid crystalline bedrock, in contrast, erosion takes place in the softer party, the ice, depositing sand and gravel in the tunnels and thus building beaded ridges (eskers) that usually clearly rise above their surroundings.

The extensive river valley in Hyyppä (Kauhajoki river valley, location in Fig. 2), which is 16 km long, 2 km wide and up to 50 m deep, possibly represents a tunnel valley, although to prove this would require lithostratigraphical and sedimentological investigations in the area. The thick Hyypänmäki gravel deposit (Fig. 2) was possibly deposited in connection with the formation of the tunnel valley. Deposition of sand and gravel was possible in the shelter of the bedrock outcrop north of the Hyypänmäki hill (*cf.* Boulton & Hindmarsh 1987, Piotrowski 1997a). If Kauhajokilaakso is a tunnel valley that originated from the Early Holocene deglaciation, it would partly explain the sparse occurrence of Holocene esker deposits ("young eskers") in this area. However, it is also possible that Kauhajokilaakso represents a tunnel valley formed during a pre-Late Weichselian deglaciation. Similar potential tunnel valleys occur in the Päntäneenjoki and Karvianjoki river valleys, but to prove this would also necessitate further investigation.

4.3 Permafrost-induced structures and palaeosols

Traces of biological activity are usually missing and the preservation potential of microfossils is low in glacigenic terrestrial sediments. In contrast, permafrost-induced structures and palaeosols are valuable palaeoclimate indicators in areas where other signs of past environmental conditions are weakly represented. Permafrost-induced structures and palaeosols indicate prolonged subaerial conditions, cold and temperate, respectively. These features are relatively easily, although not implicitly (*cf.* e.g. Vandenberghe & Pissart 1993) detectable, and they are thus essential in lithostratigraphy, especially in glacigenic sediments.

Fossil permafrost structures and palaeosols are relatively common in the study area. The permafrost is usually represented as involutions, cryoturbation structures and ice-wedge casts. The palaeosols are fossil podsol soils formed under coniferous forests in a humid-temperate climate.

Permafrost-induced structures and palaeosols are valuable marker horizons in sediment sequences. Besides indicating a terrestrial environment and prolonged subaerial non-depositional events as such, they also indicate climatic conditions with at least some accuracy during these events. In addition, they contain time information: the development of permafrost and permafrost-induced structures as well as the development of palaeosols may require several thousands of years (see Paper 3), during which the area can not have been buried beneath continental ice.

Permafrost-induced structures

Cryoturbation and ice-wedges develop in a periglacial environment. Permafrost and a mean annual air temperature lower than -5 ºC are required for ice-wedge cracking (Péwé 1966, Black 1976, Harry & Gozdzik 1988, Van Vliet-Lanoë 1988, Huijzer & Vandenberghe 1998). Other factors, such as the vegetation, snow cover, parent material, soil water content and topography also play a role in wedge development (e.g. Svensson 1988). Cryoturbation alone, however, does not definitively indicate permafrost, as it can form in rather humid and cold climates without permafrost (Van Vliet-Lanoë 1988).

Cracked ice wedges in sediment sequences are usually filled with sediments detached from the walls of the parent material or with allochthonous sediments, commonly aeolian sand or loess, sometimes till (Vandenberghe & Pissart 1993). Ice wedges filled with sediment are called ice-wedge casts, and they have a good preservation potential in sediment sequences.

At present in Fennoscandia, the climate is cold enough for discontinuous or sporadic permafrost to form only in the mountainous areas of Norway and in the northernmost

Swedish and Finnish Lapland (Rapp 1982, Svensson 1988, Gavrilova 1993, Kejonen 1997, Seppälä 1982, 1997, Hirvas *et al.* 2000). Elsewhere in Fennoscandia, the climate is too mild for the development of permafrost. Ice wedges do not currently form in Finland.

Most fossil permafrost-induced structures in southern Finland have been detected south of the Salpausselkä II end moraines, in elevated areas that were exposed from ice and water during the cold Younger Dryas time (see a review in Kejonen 1997). Post-glacial permafrost-induced structures are relatively rare, because most of the Finnish territory was either under ice or water at the time when periglacial conditions existed in the Younger Dryas (see e.g. Andersen *et al.* 1995, Rainio *et al.* 1995). When the land finally emerged from the sea, the climate was too warm for the development of permafrost. Preglacial permafrost-induced structures, on the other hand, were usually eroded during the Late Weichselian glaciation. However, these structures, buried under till, are relatively common in the Suupohja area, as well as in several localities in Swedish and Finnish Lapland (Ristiluoma 1974, Mäkinen 1985, Lagerbäck 1988, Gibbard *et al.* 1989, Kejonen 1997, Papers 2 and 3). Polygonal networks (e.g. Black 1976, Mackay 1986, Svensson 1984, 1988, Murton *et al.* 2000) are nevertheless not detectable on the land surface, because the overlying till units and shore deposits obscure these features.

The development of permafrost requires a considerable amount of time. For example, Delisle (1998) calculated that permafrost needed up to 10 000 years to penetrate to a depth of 90–140 m in northern Germany and the Netherlands during the latest glacial event. However, during glaciations, permafrost can penetrate to a depth of even 800 metres in a periglacial environment in more northern areas (Vaikmäe *et al.* 1995, Lundqvist & Saarnisto 1995).

Reported ice-wedge cracking rates vary considerably, usually being between 1–35 mm/a. Not all wedges crack each year (Black 1976, MacKay 1974, 1975, 1986). Based on reported observations, Pitkäranta (Paper 3) estimated that the 1.2 m-wide ice-wedge cast at Kiviharju took at least 1 000 years to develop. According to Murton & Kolstrup (2003), ice-wedge development can take from a few years to thousands of years, and snow cover during winter may not exceed 1 m (see also Mackay 1986).

Palaeosols

Palaeosols represent ancient ground surfaces, and thus they indicate a prolonged stillstand in deposition. Palaeosols can occur buried, exhumed or relict (e.g. Mack *et al.* 1993, Nettleton *et al.* 1998, 2000). Subaerial conditions lasting at least hundreds of years are required for the development of a detectable soil profile, and up to several thousands of years are needed for the development of a mature soil profile (see discussion in Paper 3).

All the reported palaeosols in Finland are buried podsol profiles, some of which are incomplete and/or deformed (Niemelä & Tynni 1979, Kujansuu *et al.* 1991, Kujansuu 1992, Hütt *et al.* 1993, Nenonen 1995, Papers 2 and 3). Palaeosols that are covered beneath till bed(s) are considered older than the Late Weichselian Substage, and they are found in the same areas as fossil permafrost-induced structures. Buried podsol soil profiles observed by earlier authors at Risåsen, Kärjenkoski, Penttilänkangas, Harrinkangas, Norinkylä and Haapalankangas (locations in Fig. 2) occur either in the glaciofluvial deposits, lithostratigraphically correlative with the Harrinkangas Formation, or in the littoral sands covering the Harrinkangas Formation, lithostratigraphically correlative with the Kodesjärvi Formation (Niemelä & Tynni 1979, Donner 1988, Kujansuu *et al.* 1991, Kujansuu 1992, Hütt *et al.* 1993, Nenonen 1995, Papers 2 and 3). All these palaeosols are overlain by sand that is interpreted as aeolian and can lithostratigraphically be correlated with the Isojoki Sand (Paper 3). In addition, remains of podsol soils were discovered between the Kariluoma and Kauhajoki Tills at Paulajuurakko and Uuro (Paper 2).

Kujansuu *et al.* (1991) named the fossil podsol soils observed at Kärjenkoski, Risåsen, Harrinkangas and Norinkylä as Ostrobothnia Geosol. Based on lithostratigraphy, luminescence datings and the maturity of the soils, they deduced that the soils started to form preferably in the Eemian Interglacial, and soil formation probably continued well into the Early Weichselian (see also Kujansuu 1992, Hütt *et al.* 1993). This is in accordance with the interpretation of Pitkäranta (Paper 3). It is considered possible, however, that not all the palaeosols observed in Suupohja are chronostratigraphically correlative with each other, i.e. some of the soil profiles may represent different lengthy terrestrial subaerial events.

The pollen found in the organic horizons of the fossil podsol soils is presented in the unit descriptions in chapter 3.4.2 and in chapter 4.4 below.

Podsol is presently the predominant soil type on well-drained deposits across the whole of Finland. Podsol soil forms under coniferous forest in a humid temperate climate. Podsols can also form in a fairly cold climate, as long as coniferous forest can still grow (Tedrow 1977).

On the basis of the above, if both buried ice-wedge casts and a well-developed fossil podsol profile occur in the same lithostratigraphical position at the same site, a gap in deposition of the order of 5 000–10 000 years and subaerial terrestrial conditions should have been required, as the development of permafrost and podsol soil each take a considerable amount of time and these processes do not take place fully simultaneously. This time information should be taken into account when estimating the ages of deposits and palaeoenvironmental events in places where these features are present.

4.4 Microfossils and organic remains

Most of the microfossil analyses in the study area were conducted on organic horizons in the palaeosols. These included pollen and cell tissue determinations. In addition, an attempt was made to analyse diatoms and pollen from waterlain fine-grained sediments below the Kauhajoki Till.

The fine-grained waterlain sediments, lithostratigraphically correlative with the upper part of the Harrinkangas Formation, were practically devoid of microfossils. The LOI values in these sediments were usually only 0.5–1.5% (max 2.5%). These sediments were probably deposited in a glacial environment, in a subglacial lake or ice-marginal lake or sea, where biological activity was low and the sedimentation of microfossils was thus insignificant. In addition, if the sediments contained microfossils, they would probably have been destroyed in glacial and post-glacial environments.

In contrast to the waterlain fine-grained sediments, some of the organic horizons of the fossil podsol soil profiles contained small amounts of pollen, cell tissue and even pieces of charcoal. However, a considerable part of the pollen was strongly worn and thus unidentifiable. Cell tissue, derived from coniferous trees (pine or spruce), was nevertheless abundantly represented on the slides.

Pollen grains that were detected from the organic horizons in the fossil podsol soils at Penttilänkangas, Risåsen, Uuro and Paulajuurakko (locations in Fig. 2) were Alnus, Asteraceae, Betula, Calluna, Carpinus, Corylus, Ericacea, Pinus, Poaceae, Rosaceae, Salix and Typha. The fossil podsol soils are correlated with the Ostrobothnia Geosol, which at Penttilänkangas was formed in the Kodesjärvi Formation, at Risåsen in the Harrinkangas Formation and at Uuro and Paulajuurakko in the Kariluoma Till. At Risåsen, a considerable amount of Phragmites pollen was also found. Excluding the findings of Carpinus and Corylus, the pollen spectrum indicates a climate similar to or cooler than that prevailing at present in the study area. The proportion of Corylus was fairly high in the fossil podsol soils at Penttilänkangas and Risåsen. If the identification was correct (pollen were partly worn), it would mean that the soil was formed in a warmer climate than at present. Such a warm climate is thought to have prevailed latest during the Eemian interglacial. Without Corylus, neither the pollen nor the cell tissue explicitly reveal whether the soils formed in interstadial or interglacial conditions. In every case, the fossil podsol soils indicate that the area was forested during soil formation. The number of Carpinus grains was so low that no conclusions can be drawn from this. In addition, charcoal pieces up to about a centimetre in diameter, typically from coniferous trees, were found in the organic horizons.

In contrast to this study, Eemian and/or Lower Weichselian organic-bearing fine-grained sediments and organic horizons of the Ostrobothnia Geosol with preserved microfossils have earlier been reported in several studies from the study area. The sites reported are Harrinkangas (Gibbard *et al.* 1989), Nummijärvi (Niemelä & Tynni 1979), Risåsen (Niemelä & Tynni 1979, Donner 1988), Susivuori (Niemelä & Tynni 1979, Schulz *et al.* 2002), Norinkylä (Niemelä & Tynni 1979, Donner 1983, 1988), Haapalankangas (Nenonen 1995) and Horonkylä (Nenonen 1995) (see locations in Figs 1 and 2). In addition, numerous studies of pre-Late Weichselian deposits with microfossil identifications have been carried out in more northern parts of Ostrobothnia (e.g. Nenonen 1995, Eriksson *et al.* 1999 and Salonen *et al.* 2008, and references therein). Pollen taxa in the above-mentioned studies were largely the same as found in this study.

The pollen spectra in this as well as in the earlier studies do not indisputably reveal whether the studied sediments were deposited during interstadial or fully interglacial stages. Both warm and cold climate indicators have been found. However, in many analyses, pollen of Corylus, Carpinus, Fraxinus, Querqus and Ulmus, and occasionally also Osmunda spores have been present (e.g. at Risåsen, Susivuori, Harrinkangas, Norinkylä, Haapalankangas and Horonkylä). These species do not grow in the study area today. Consequently the analysed sediments have usually been interpreted as having been deposited during the Eemian interglacial, which was thought to have been the latest sufficiently warm phase before the Holocene (e.g. Behre 1989, Zagvijn 1989). Sediments with only cool climate indicators were interpreted as having been deposited during the cool part of the Eemian, either in its early or late phase, or alternatively in the Early Weichselian interstadials. Redeposition of the sediments and long-distance pollen transportation were also considered possible, and hence the interpretations should be regarded as somewhat uncertain. In contrast, recent multi-proxy studies with numerous datings contradict many of the earlier interpretations (see chapter 4.5). They indicate that many of the sediments are younger than previously expected and that a fairly warm climate also prevailed during the Weichselian interstadials, including the latest Middle Weichselian interstadial.

4.5 Chronology and correlation

Twelve new OSL age results are presented in Papers 2–4. The datings yielded ages from 123±9 ka to 54±8 ka. The oldest ages were measured from the Kankalo Sand at Karhukangas (123±9 ka) and Hiukkakangas (121±10 ka). The youngest ages were obtained from the Kodesjärvi Formation and Isojoki Sand at Risåsen (73±9 and 63±4 ka), Rävåsen (66±8 ka), Jätinmäki (54±8 ka), Kiviharju (79±10 and 71±18 ka) and Penttilänkangas (72±5, 65±10 and 64±5 ka). Thus, the oldest ages refer to the Eemian interglacial (MIS 5e) and the youngest ages to the latter part of the Early (MIS 5a) and the initial part of the Middle Weichselian (MIS 4 and partly MIS 3) (Figs 16 and 17). In addition, one age result from Karhukangas (102±20 ka) and one from Rävåsen (94±15 ka) fall in the middle part of the Early Weichselian (MIS 5c).

As is usual, the OSL datings in this study also contain uncertainties (Paper 4 and references therein; *cf.* also Alexanderson *et al.* 2010). The number of datings was likewise small. Hence, definitive conclusions from the dating results cannot be made. Some discrepancies also exist in the age determinations. The discrepancies are partly explained by uncertainties in the datings, such as incomplete bleaching, an erroneously estimated palaeowater content of the sediments, mixing of younger and older sediments due to deformation or errors in dose rates (see Papers 3 and 4). Consequently, some of the OSL age results are considered questionable.

The Harrinkangas Formation has previously been interpreted as having been deposited during the latest Saalian deglaciation (MIS 6, e.g. Niemelä & Tynni 1979, Gibbard *et al.* 1989, Bouchard *et al.* 1990, Niemelä & Jungner 1991, Kujansuu *et al.* 1991, Hütt *et al.* 1993, Nenonen 1995). The organic-bearing sediments in the upper part of the Harrinkangas Formation beneath the Kauhajoki Till, in turn, have usually been interpreted as having been deposited during the Eemian interglacial (MIS 5e) or possibly partly also during the Early Weichselian interstadials. The reasons for these interpretations are as follows:

i) The lithostratigraphy is compatible with these conclusions.

ii) The microfossils in the organic-bearing sediments beneath the covering till bed(s) include taxa that favour a climate as warm as or warmer than that prevailing at present, i.e. they preferably represent the warm Eemian interglacial.

iii) A number of the TL and OSL dating results from sandy sediments below covering till bed(s) refer to ages from Late Saalian to Early Weichselian; radiocarbon ages, on the other hand, usually represent ages that are close to or beyond the limit of the method and hence they have mostly been considered unreliable.

iv) This interpretation is chiefly in agreement with traditional interpretations of palaeoclimate and palaeo-ice sheet reconstructions (including marine isotope stratigraphy).

Papers 1–3 are in line with this earlier interpretation, although in Paper 3 a younger age was also mentioned as possible. In Paper 4, in turn, OSL ages refer to both glaciofluvial sedimentation and a high water level in the Baltic Basin in the Early and Middle Weichselian in westernmost Finland, which is not in full agreement with the earlier interpretation, although not in full contradiction with it, either.

Recent studies from different parts of the SIS area are changing the above-mentioned traditional interpretation. These studies provide further evidence of the complexity of the Weichselian stadials and interstadials with fairly rapid shifts from glacial to ice-free conditions and vice versa (see Ukkonen *et al.* 1999, 2007, Arnold *et al.* 2002, Mäkinen 2005, Sarala 2005, Kalm 2006, Auri *et al.* 2008, Lunkka *et al.* 2008, Näslund & Wohlfarth 2008, Salonen *et al.* 2008, Aleksanderson *et al.* 2010, Engels *et al.* 2010, Helmens & Engels 2010, Houmark-Nielsen 2010, Hättestrand & Robertsson 2010, Lambeck *et al.* 2010, Mangerud *et al.* 2010, Wohlfarth 2010, Wohlfarth *et al.* 2011, Anjar *et al.* 2012). In addition, the complexity of the Weichselian was already reported in numerous papers in the 1970s, 1980s and early 1990s (e.g. Lundqvist 1978, 1991, 1992, Donner *et al.* 1979, 1986, Hirvas & Nenonen 1987, Andersen & Mangerud 1990, Jungner *et al.* 1989, Bergersen *et al.* 1991, Forsström & Eronen 1991, Nenonen 1995). The temperature and vegetation gradients seem in some cases to have been steep between glaciated and ice-free areas, but moderate or low in the north–south direction (Willis & Andel 2004, Ukkonen *et al.* 2007, Väliranta *et al.* 2009, Engels *et al.* 2010). New and revised OSL and ^{14}C age results from Sweden, in the central part of the SIS, have clarified the picture of the later part of the Weichselian (Ukkonen *et al.* 2007, Alexanderson et al 2010, Wohlfarth 2010, Wohlfarth *et al.* 2011). Numerous luminescence datings (see Fig. 17) and glaciation models indicate that ice sheets were highly restricted during the Weichselian (e.g. Siegert *et al.* 2001, Arnold *et al.* 2002, Siegert & Dowdwswell 2004, Svendsen *et al.* 2004, Forsström 2005, Kjellström *et al.* 2010, Lambeck 2010). The recent studies have mostly focused on the Middle Weichselian Substage (MIS 4–3), but they also include information on Early Weichselian events. These new revisions together with the dating results of this study give reasons to re-evaluate at least some of the age interpretations of Papers 1–3. It appears that at least some of the deposits previously interpreted as Upper Saalian could actually be Lower or Middle Weichselian. Further datings should be performed on the various sand units overlain by the Kauhajoki Till.

It is somewhat difficult to designate the sediments presented in Paper 4 appropriately in the chronostratigraphy, as the obtained OSL ages as such poorly fit the existing interpretations of the climatic, eustatic and sedimentary events of the Weichselian Stage. The exact number, timing and extent of glaciated stadials and non-glacial warmer interstadials in different parts of Fennoscandia during the Weichselian are still debated. It is still not fully known whether the Early Weichselian ice covered part of southern Finland or not. Also somewhat unclear is the extent of the first Middle Weichselian ice, as well as the duration and climatic conditions during the Early and Middle Weichselian interstadials in the central part of the SIS. Studies from northern Finland indicate that the climate was warm in the interstadials of MIS 5c and MIS 3 (Väliranta *et al.* 2009, 2012).

Some of the OSL ages obtained in this study are erroneous, because in some places the lower lithofacies yielded younger ages than the upper ones in the same exposures. The younger ages should be considered more reliable, because incomplete bleaching, which probably is the largest uncertainty in the luminescence method, easily gives ages that are clearly too old. Six of the ages presented in Papers 3 and 4 represent sedimentary events that are associated with milder climates during the Weichselian, i.e. the study area was ice-free and partly also submerged. However, many of the OSL datings referred to the early Middle Weichselian (MIS 4, 74–59 ka BP), which in many studies has been considered as one of the coldest lengthy intervals of the Weichselian Stage, when ice sheets expanded over large areas (e.g. Donner 1995, 1996, Hirvas *et al.* 1995, Saarnisto & Salonen 1995, Lunkka *et al.* 2001, 2004, 2008, Saarnisto & Lunkka 2004, Salonen *et al.* 2008, Johansson *et al.* 2011). These conflicting age results mean either that western Finland, and thus probably also the whole southern half of the country, remained ice-free during MIS 4, or the obtained ages should be corrected as several thousands of years older or younger. If we take into consideration the error limits of the datings and allow an additional few thousand years of error, for instance because of erroneous dose rate or palaeowater content estimation, the sedimentary events would better fit to the known interstadials. In this study, it is suggested that during the Middle Weichselian (MIS 4–3), western Finland remained mostly ice-free. The ice-free phase was interrupted by a glacial advance of relatively short duration that deposited the Dagsmark Till. This took place most probably during a time interval between 55 and 35 ka ago. According to over 300 published TL and OSL datings illustrated in Figure 17, it appears that there are gaps of only some thousands of years, when ice could have covered large areas in Fennoscandia during the Weichselian. However, Figure 17 should be responded cautiously, as the ages have been obtained from different types of sediments, which means that the accuracy of the age results is very heterogenous.

It should be stated that the earlier luminescence datings, as well as those performed in this study, were mostly undertaken from sandy sediments that are lithostratigraphically correlative with the Kodesjärvi and Vanhakylä Formations and Isojoki Sand, and only few were carried out from glaciofluvial deposits in the base, lithostratigraphically correlative with the Harrinkangas or Rävåsen Formations (Paper 4). Thus, timing of these glaciofluvial deposits is still insufficient.

The lithostratigraphy and datings imply that the different sand- and gravel-dominated deposits in the study area are of a different age of origin. The oldest sediments occur in the irregularly shaped broad multilayer deposits in the central part of the study area. The Karhukangas lower deposits and probably also the Kankalo Sand are interpreted as older than the Upper Pleistocene (MIS 6–). The till-covered beaded sand and gravel ridges and separate till-covered sand and gravel deposits appear to have been deposited either during the Late Saalian Substage (MIS 6) or during the Early and Middle Weichselian (MIS 5d–3) stadials and interstadials. The eskers without till cover were deposited during the latest deglaciation of the Early Holocene (MIS 1) ice. Thus, the sand and gravel-dominated deposits in Suupohja can be divided into at least four different age categories: pre-Late Saalian, Late Saalian, Early Weichselian and Early Holocene.

Coastal processes reshaped the upper parts of the deposits during the transition from the Early to Middle Weichselian (MIS 5a–MIS 4) at altitudes of 50–90 m above the present sea level. As the global sea level in the Early and Middle Weichselian is commonly interpreted to have been lower than at present (see e.g. Shackleton 1987), the relatively high water table in the Baltic Basin at that time must refer to a glacioisostatic depression and/or the existence of a large lake (ice lake?). Both alternatives indicate that the ice margin of the SIS was relatively close to and possibly partly covered western Finland during the Early and Middle Weichselian Substages (*cf.* the maps in Lundqvist 1992 and Mangerud 2004, Mangerud *et al.* 2011), depressing the lithosphere. In this sense, the ice–water configuration possibly resembled the different sea phases of the Baltic Basin in the Holocene Epoch (*cf.* Nenonen 1995). Fluctuating ice possibly hindered major glacioisostatic land uplift in the SIS area during the Early and Middle Weichselian, which enabled relatively high water level in the Baltic Basin.

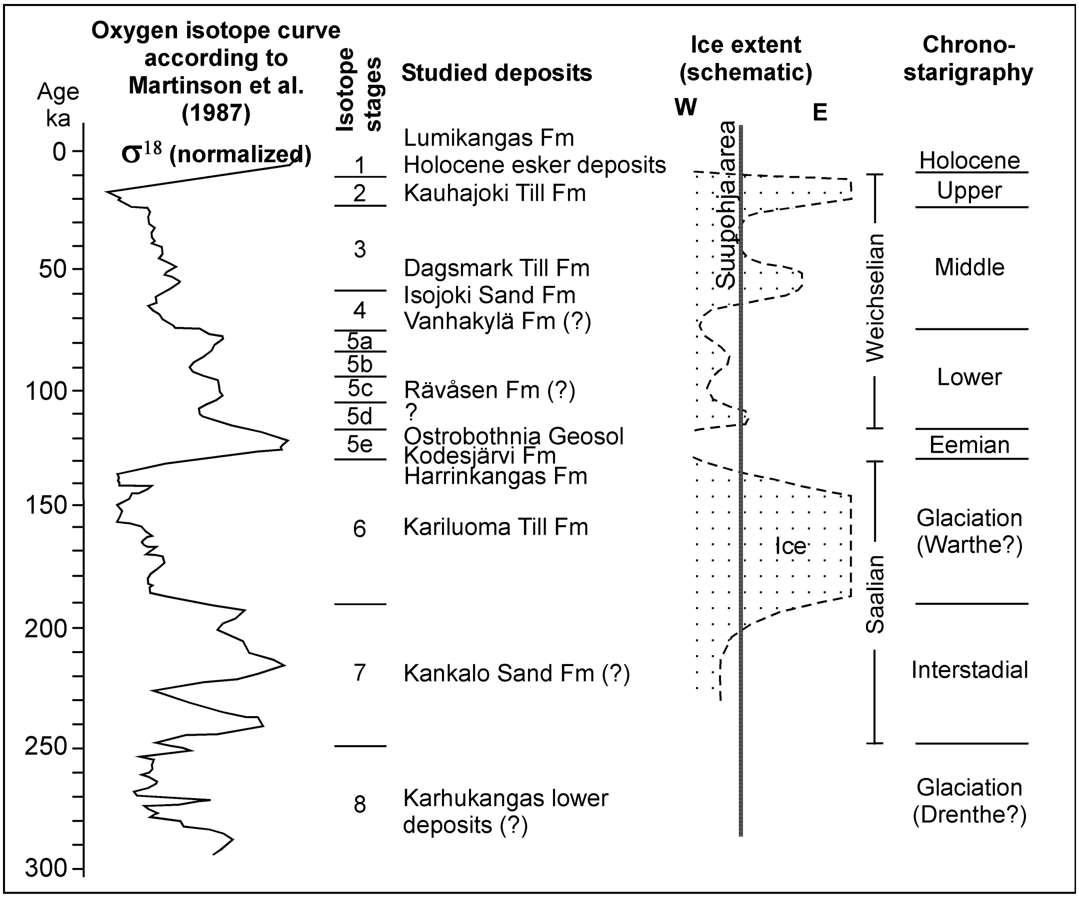


Fig. 16. Correlation of the examined formations with the marine isotope stages (modified after Martinson *et al.* 1987, Mangerud 1991, Nenonen 1995). Schematic ice extent in the middle part of Finland during different marine isotope stages is also presented.

Problems in litho- and chronostratigraphical correlation in glaciated areas

Because of the fragmentary geological evidence, the interpretation of glacial and deglacial sedimentary events and their timing is difficult in Fennoscandia. The number of observations and datings is most sparse in pre-Late Pleistocene sediments (see also Donner 1995, Lunkka *et al.* 2004, Lundqvist 2004, Mangerud 2004, Mangerud *et al.* 2011, Johansson *et al.* 2011). Therefore, it is not possible with the present data to reconstruct the chronology and extent of glacial and deglacial events during the Middle Pleistocene or earlier events in Fennoscandia. Moreover, details of the Late Pleistocene (MIS 5e–MIS 2) have still many open questions. In the central part of the former Scandinavian ice sheet, no sites have yet been found where undeformed continuous succession of Late Pleistocene sediments could be observed. As noted above, deposits preserved from earlier glaciations occur at several locations in Fennoscandia, but they usually deviate lithostratigraphically from each other and possibly represent a variety of mixtures of different glacial and/or deglacial events.

Uneven deposition in complex sedimentary processes and partial erosion of the deposits in glacial and deglacial environments make correlation between different units difficult (*cf.* Johnson & Hansel 1990, Brodzikowski & Van Loon 1991, Hambrey *et al.* 2001). This uneven sedimentation and erosion creates challenges when using formal lithostratigraphy in glaciated areas (*cf.* Gibbard 1992). As Lagerbäck (1988b) also noted, it is not certain that the last ice sheet left tracks in all places and it is thus sometimes difficult to determine whether a glacial or glaciofluvial accumulation was derived from the previous or some earlier glaciation.

The following features, in particular, make the lithostratigraphical correlation and interpretation of different glacial, glaciofluvial and non-glacial events difficult in the study area:

i) The Kauhajoki Till, which is usually a distinct lithostratigraphical unit and a good "marker horizon", is not always clearly detectable (its appearance and fabric varies in places) or it may be entirely missing in sediment sequences.

ii) Till beds that are observed only locally complicate the lithostratigraphical correlation.

iii) Glacial and non-glacial sediments occur in different combinations even at neighboring sites.

iv) Ice-flow directions during a single glaciation were not uniform;

v) Ice-flow directions in different glacial stages did not necessarily deviate noticeably from each other.

vi) Locally, post-depositional deformation has disturbed original clast orientation.

vii) There is a lack of reliably dated lithostratigraphical units that could be traced over large areas (except the Kauhajoki Till).

viii) There is dispersion in luminescence ages from the same lithostratigraphical units.

Being closer to the central part of the SIS, western Finland was probably covered by ice more often than the rest of southern Finland, contributing to the complex lithostratigraphy in this area. Expanding and waning ice-sheets also caused sea level fluctuations in the Baltic Basin, which has further complicated the lithostratigraphical and chronostratigraphical correlation.

Because of the above-mentioned features, the chronostratigraphy is still by and large floating not only in the study area but also in the whole central part of the SIS area (*cf.* Robertsson *et al.* 2005).

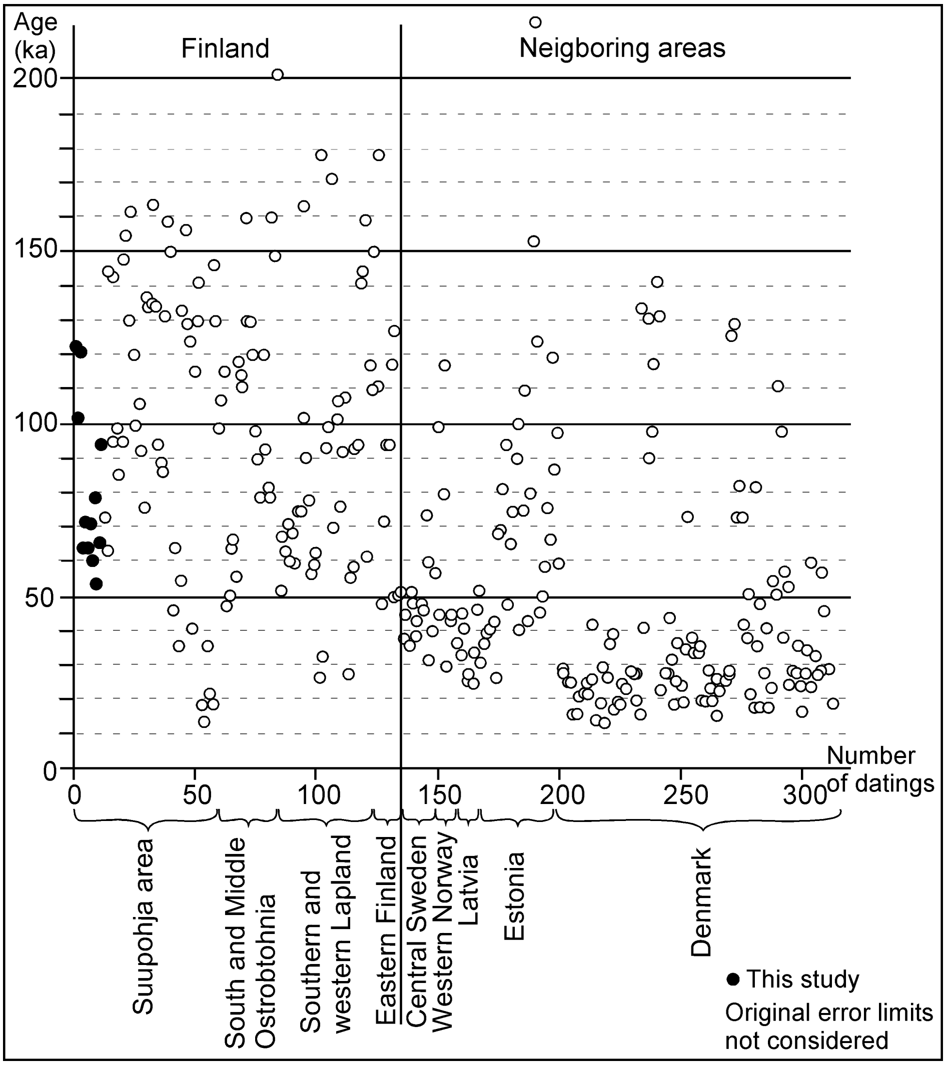


Fig. 17. Altogether 65 TL and 245 OSL luminescence dating results (without error limits) from glacigenic, littoral, waterlain and aeolian sediments from different parts of Fennoscandia and around the Baltic Basin give an impression that no extensive ice sheets could cover Fennoscandia during the Weichselian. Because of heterogeneity in the sediments dated and thus possible inaccuracy in the obtained ages, this illustration should be responded with caution. It nevertheless supports the interpretation that relatively short time of the Weichselian Stage was fully glaciated in Fennoscandia. Age results gathered from: Jungner (1987), Donner (1988), Aalto *et al*. (1989), Gibbard *et al*. (1989), Jungner *et al*. (1989), Hütt *et al*. (1993), Bergersen *et al*. (1991), Lundqvist (1991), Niemelä & Jungner (1991), Forström & Eronen (1991), Nenonen (1995), Helmens *et al*. (2000), Houmark-Nielsen & Kjær (2003), Mäkinen (2005), Kalm (2006), Auri *et al*. (2008), Lunkka *et al*. (2008), Salonen *et al*. (2008), Pitkäranta (Papers 2–4), Väliranta (2009), Alexanderson *et al*. (2010), Helmens & Engels (2010), Houmark-Nielsen (2010), Schulz (2010), Saks *et al*. (2012). It should be noted that a large number of ^{14}C dates are also available, but they were not used, because many of the radiocarbon dating results are close to the limit of the method. However, an increasing number of ^{14}C dates from mammoth bones and other organic matter indicate that ice-free phase(s) also occurred in the Middle Weichselian in Fennoscandia.

5 CONCLUSIONS

The current study is focused on sand- and gravel-dominated extensive pre-Late Weichselian deposits in the Suupohja area, western Finland. These deposits cover an area of over 190 km^2. In addition, sand and gravel deposits interpreted as having been deposited during the deglaciation of the Late Weichselian ice cover an area of *c*. 80 km^2. These deposits together comprise 5% of the land area of Suupohja. The sediment thickness of the studied sites is commonly of the order of 20–50 m, with a maximum of *c*. 100 m. Consequently, in addition to the geological information of the past glacial, deglacial and non-glacial events, this area provides considerable ground water as well as sand and gravel resources. The abundant occurrence of pre-Late Weichselian deposits is evidence of weak glacial erosion in this area during the latest as well as during earlier glaciations.

Altogether, up to nineteen sedimentary units, representing glacial, glaciofluvial and non-glacial sedimentary environments, were discovered in the study area. These units were divided into ten formally and two informally defined formations that were together named the Suupohja Group. The Suupohja Group sediments possibly represent up to six glaciated stadials with intervening interglacials or interstadials.

The glacial historical implications deduced from this study can be concluded as follows:

1. The oldest sediments occur in the irregularly shaped broad multilayer deposits in the central part of the study area. The lowermost sediments in these extensive deposits, informally termed the Karhukangas lower deposits, are probably older than Late Pleistocene (≥MIS 6), and they were possibly deposited during four glacial–interglacial/interstadial cycles.

2. A Middle or early Late Pleistocene retreating ice margin rested for a prolonged time in this area, depositing an extensive glaciofluvial complex (Kankalo Sand) above the Karhukangas lower deposits in the irregularly shaped broad multilayer deposits. These erosional remnants were left from later glacial and deglacial erosion.

3. Most of the glaciofluvial sediments in the till-covered beaded sand and gravel ridges and separate till-covered sand and gravel deposits were deposited during the Late Saalian Substage (MIS 6). However, it is suggested that the fragmentary ridge of glaciofluvial deposits between Rävåsen and Rimpikangas in the western part of the study area was deposited in the the Early Weichselian Substage, representing the easternmost limit of the Scandinavian Ice Sheet in the southern part of Finland before more extensive ice sheet growth in the Middle Weichselian.

4. Because the study area lies relatively close to the centre of the SIS, it was more sensitive to minor ice oscillations and glacioisostacy than the rest of southern Finland. This also may have caused complexity in the lithostratigraphy in this area.

5. Western Finland remained ice-free for most of the Weichselian Stage. Two glacial ice advances, represented by the Dagsmark Till and Kauhajoki Till, occurred in the Middle and Late Weichselian Substages, respectively. Definitive evidence of ice sheet growths over the whole study area in the Early Weichselian is lacking, although this possibility cannot be ruled out. It appears that western Finland, and actually the whole southern part of Finland, was glaciated for approximately 25–35% of the duration of the Weichselian Stage.

6. The Late Weichselian ice flowed from the north or northwest, whereas earlier ice sheets had predominantly more western flow directions.

The Suupohja area has possibly the largest uniform pre-Late Weichselian deposits in Fennoscandia, and it is thus a key area in studying Pleistocene glacial and non-glacial events in the northern hemisphere. Future drillings and excavations in this area could reveal even more complete sediment successions than presented in this work.

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