DISSERTATIONES GEOLOGICAE UNIVERSITATIS TARTUENSIS

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UPPER-PLEISTOCENE STRATIGRAPHY AND DEGLACIATION HISTORY IN NORTHWESTERN ESTONIA

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CONTENTS

LIST OF ORIGINAL PUBLICATIONS

The present thesis comprises the following original papers, which are referred to by their Roman numerals:

I. Miettinen, A., Rinne, K., Haila, H., Hyvarinen, H., Eronen, M., Delusina, I., **Kadastik, E.,** Kalm, V., Gibbard, P. 2002. The marine Eemian of the Baltic: new pollen and diatom data from Peski, Russia, and Põhja-Uhtju, Estonia. *Journal of Quaternary Science,* 17, 445–458.

II. **Kadastik, E**., Kalm, V., Liivrand, E., Mäemets, H., Sakson, M. 2003. Stratigraphy of a site with Eemian interglacial deposits in north Estonia. *GFF*, 125, 229–236.

III. **Kadastik, E.** and Kalm, V. 1998. Lithostratigraphy of Late Weichselian tills on the West Estonian Islands. *Bulletin of the Geological Society of Finland* 70, 1–2, 5–17.

IV. Kalm, V. and **Kadastik, E.** 2001. Waterlain glacial diamicton along the Palivere ice-marginal zone on the west Estonian archipelago, Eastern Baltic Sea. *Proceedings of Estonian Academy of Sciences. Geology,* 50, 2, 114–127.

V. **Kadastik, E.** and Ploom, K. 2000. Pleistocene deposits and deglaciation of the Nõva-Padise area (NW Estonia). *Bulletin of the Geological Survey of Estonia,* 9/1, 4–10.

The author of this thesis is fully responsible for data collection, for the morphological and sedimentological analysis and for writing the manuscripts of papers II, III and V. The author was one of the field geologists who mapped north-western Estonia. While employed at the Geological Survey of Estonia, she authored numerous map sheets, cross sections and geomorphological schemes used in reports involving the Quaternary cover and geomorphological overview of the study area. The micropalaeontological analyses in paper II were done by E. Liivrand, H. Mäemets, and M. Sakson. The author was responsible for data collection and sedimentological interpretation of Põhja-Uhtju section, northern Estonia in paper I. Prof. Volli Kalm, Tartu University, Estonia, did 50% of the writing of paper IV. Kuldev Ploom took most of field observations and was responsible for the data collection and some sedimentological interpretations in paper V.

Kadastik, E. 2004. Upper-Pleistocene stratigraphy and deglaciation history in northwestern Estonia. Dissertationes Geologicae Universitatis Tartuensis, 14, Tartu University Press, 129 pp.

ABSTRACT

This study comprises data from five main scientific papers devoted to the Upper-Pleistocene stratigraphy in northwestern Estonia. Till stratigraphic studies launched in 1987 have yielded observations and data from over 5500 sections and 1335 sediment samples from northwestern Estonia. Representative reference sections were selected from the survey data. Lithofacies analysis and geological information relevant to the dating and correlation of the deposits is presented. An overall review is given of the detailed Upper-Pleistocene litho-stratigraphy and deglaciation history of the area based on synthesis of all available data.

The stratigraphical position where interglacial Eemian sediments underlie Upper-Pleistocene deposits was determined in detail in northwestern Estonia and in Gulf of Finland. Eemian interglacial sediments have been found and studied at two new sites — at Juminda-2 and Põhja-Uhtju, and correlated with other sites in the region. Till deposits of the Late-Pleistocene glaciation are common in Estonia. The majority of the Upper-Pleistocene sediments in north-western Estonia are of Late-Weichselian age.

Chiefly lodgement and melt-out tills were deposited during the Late-Weichselian deglaciation. In some sections these tills are segregate from each other by sorted glaciolacustrine sediments. One of the most important results of this study was distinguishing the different diamicton units which were correlated event-stratigraphically to the last (Pandivere and Palivere) ice advances of the most recent (Late-Weichselian) glaciation and included into the Võrtsjärve Subformation according to Estonian stratigraphic nomenclature. Between the Palivere and Pandivere Stadial tills, interstadial deposits were noted at Kõpu, Sõrve and Mõntu. The correlatives of the Palivere and Pandivere Tills in southwestern Finland, south of Salpausselkä I, are thought to be the Espoo and Siuntio Tills, respectively.

The detailed sedimentological investigations in northern Estonia and on the islands of the Gulf of Finland provide insight into paleoenvironmental conditions during the last Eemian interglacial and the following Late-Pleistocene glaciation. Several oscillations of ice margin also occurred during the Late-Weichselian glaciation and deglaciation. After the Pandivere Stadial the ice margin must have retreated northward at least 70 km, as the occurrence of buried interstadial deposits at Kõpu site proves that the Kõpu Peninsula must have been ice-free during the Pandivere/Palivere (later Pan/Pal) interstadial.

After the initial Palivere ice re-advance, the general recession of the ice sheet slowed, and the ice margin stopped at Tahkuna-Audevälja line, followed by a standstill or minor oscillation at Tahkuna. The Tahkuna-Audevälja ice-marginal zone is almost subparallel to the Palivere zone and located about 20–30 km northward. Well-sorted delta deposits in front of the glacier margin refer to an existence of a periglacial body of water in northwestern Estonia during the Tahkuna-Audevälja Phase.

Key words: lithostratigraphy, diamicton, till, deglaciation, interstadial, Quaternary, Upper-Pleistocene, Eemian interglacial, Late-Weichselian glaciation, northwestern Estonia, Pandivere Stadial, Palivere Stadial, Tahkuna-Audevälja Oscillation.

INTRODUCTION

Earlier research has shown that most of the Pleistocene sediments in northwestern Estonia *(Fig. 1)* were deposited during the youngest, Late-Weichselian deglaciation period (Raukas and Kajak 1997b). The oldest Upper-Pleistocene deposits are represented by Eemian interglacial deposits, which occur in a number of sections along the Gulf of Finland (*Fig. 2*).

Although Pleistocene deposits in Estonia have been studied for over a century, the Upper-Pleistocene deposits have not yet to be classified into morphostratigraphical beds on geological maps and sections. Attempts to distinguish the stadial glacial deposits were initiated only a few years ago (Eltermann 1993a, 1993b; Kadastik 1994, 1995, 1996; Kajak 1996; Kadastik and Kalm 1998 — PAPER 3; Kalm and Kadastik 2001 — PAPER 4; Kadastik and Ploom 2000 — PAPER 5).

The primary objective of this study was to determine the best expressed lower boundary — interglacial sediments — distinguishing the Upper-Pleistocene deposits and to detail the composition and extent of Eemian deposits in order to characterise the sedimentary basin of the Eemian Sea.

The second objective was to provide a sedimentologically based lithostratigraphy of till beds, to discuss their sedimentological properties and to detail the Upper-Pleistocene lithostratigraphical scheme in northwestern Estonia. This study is based on sedimentological, palynological and geomorphological analyses. A great number of sedimentological (grain size, chemical and mineral) analyses revealed till beds of different age and genesis. The large amount of new material obtained during geological mapping supported the lithostratigraphical and palaeogeographical conclusions drawn.

The third objective was to assign sedimentologically based characteristics to the Upper-Pleistocene stratigraphic units with which to correlate Estonian and Finnish litho- and morphostratigraphic beds.

The fourth objective was to detail the existing stratigraphical scheme of Upper-Weichselian deposits and to incorporate the different genetic beds into the scheme.

The fifth objective was to furnish a palaeoenvironmental interpretation of the Weichselian in northwestern Estonia during the Late-Pleistocene, especially the final deglaciation. The palaeogeographcal situation during Late-Pleistocene in northwestern Estonia was revised, particularly that of the final retreat of the glacier (Palivere and Pandivere Stadials) of the most recent (Late-Weichselian) glaciation. Interstadial deposits were studied and correlated between northwestern Estonia and southwestern Finland. The distance of ice recession northwest of Pandivere zone and average velocity of ice movement during deglaciation of northwestern Estonia are discussed.

The final objective of the research was to re-establish the deglaciation history in order to distinguish the glacier stagnation zones or oscillations in the northwestern most part of Estonia.

The study comprises data from five main scientific papers devoted to Upper-Pleistocene stratigraphy in northwestern Estonia, which are summarised in the following section.

PAPER I

Miettinen, A., Rinne, K., Haila, H., Hyvarinen, H., Eronen, M., Delusina, I., **Kadastik, E.,** Kalm, V., Gibbard, P. 2002. The marine Eemian of the Baltic: new pollen and diatom data from Peski, Russia, and Põhja-Uhtju, Estonia. *Journal of Quaternary Science,* 17, 445–458.

Two new clayey and silty deposits covered by till, one at Peski, Russia, and the other Põhja-Uhtju, Estonia, were studied for pollen and diatom content. At Peski, the deposits representing the Eemian interglacial are 3.8 m thick. The polyhalobous diatom flora in the *Corylu*s and *Carpinus* zones indicates the maximum of the marine transgression during the climatic optimum. Later, the increasing proportion of brackish water diatom flora indicates a lowering of the relative sea-level, and finally, during a very late phase of the Eemian, the sharply increasing proportion of freshwater species indicates the isolation of the sedimentary basin from the Eemian Sea. The pollen records at Põhja-Uhtju suggest the Eemian deposit is 3.5 m thick. Diatoms occur only in a layer 1.6 m thick, which represents the period of the climatic optimum. The brackish-marine diatom flora consists mainly of littoral, shallow water species. This publication proves that the spreading of interglacial Eemian level can be very distinctive lower boundary of Weichselian deposits.

PAPER II

Kadastik, E., Kalm, V., Liivrand, E., Mäemets, H., Sakson, M. 2003. Stratigraphy of a site with Eemian interglacial deposits in north Estonia. *GFF*, 125, 229–236.

Sediment lithology, lithofacies relationships, palynological and diatom analysis indicate that two drill cores extracted from ancient valleys of the Juminda Peninsula, north Estonia, represent a previously undetected interglacial sedimentary sequence between the Middle- and Upper-Pleistocene glacigenic deposits. Four different-coloured major lithofacies associations (units), representing two glacigenic cycles, and deposits with Late-Saalian pollen assemblages zone (LS1), the uppermost Eemian (E9), and Early-Weichselian pollen zone (EW) were distinguished at the section. The bottom-most depositional unit consists of brownish-coloured clay, diamicton and gravel beds. The second depositional unit, correlative to the Eemian Interglacial, consists of a black organic-rich palaeosoil and stratified sand. A thick grey-coloured bed of massive and partly stratified Weichselian diamicton, sand, clay and silt comprises the third unit, and the fourth, the topmost depositional unit, consists of yellowish-grey sands and silts of the Baltic Sea. The paper examined the sedimentological differences between deposits of two last glaciations and restored some palaeoenvironmental aspects during the formation of Late-Pleistocene deposits.

PAPER III

Kadastik, E. and Kalm, V. 1998. Lithostratigraphy of Late Weichselian tills on the West Estonian Islands. *Bulletin of the Geological Society of Finland* 70, 1–2, 5–17.

Glacial stratigraphy of the West-Estonian Islands comprises three different diamicton units that are correlated event-stratigraphically to the Pandivere and Palivere ice advances of the most recent (Late-Weichselian) glaciation and included into the Võrtsjärve Subformation according to the Estonian stratigraphic nomenclature (Raukas and Kajak 1995). A large number of till samples and drillcore sections were analysed in order to determine the genesis and composition of sediments from which the lithostratigraphical conclusions are derived. Two morphostratigraphical till beds (Palivere and Pandivere ones) and their genetic varieties were distinguished. Lacustrine Kõpu Sands separate the Palivere and Pandivere tills on the Kõpu and Sõrve Peninsulas. The correlatives of the Palivere and Pandivere tills in Southern Finland, south of Salpausselkä I are thought to be the Espoo and Siuntio tills, respectively.

PAPER IV

Kalm, V. and **Kadastik, E.** 2001. Waterlain glacial diamicton along the Palivere ice-marginal zone on the west Estonian archipelago, Eastern Baltic Sea. *Proceedings of Estonian Academy of Sciences. Geology,* 50, 2, 114–127.

A sporadic distribution of up to 25 m thick subaqueous waterlain glacial diamicton (WGD) was observed on both the distal and proximal sides of the Palivere end moraine zone on the West-Estonian Archipelago. The WGD lies at an altitude between –15 m and +10 m relative to contemporary sea level. During the Palivere Stadial the distribution area of WGD was at least 50–60 m below the water table of the Baltic Ice Lake. The WGD was deposited at the grounding zone of the glacier by continuous subaqueous basal meltout from floating ice with minor involvement of sediment flows, dumping and grounding. According to texture, the WGD resembles glaciolacustrine clay with increased amounts of gravel and clay fractions. Compared to the basal tills of the area, the WGD contains less gravel (21.5% and 6.8%, respectively) but is rich in silt and clay. Petrographic, mineralogical and chemical analyses suggest a similar source for the Palivere basal till and the WGD.

PAPER V

Kadastik, E. and Ploom, K. 2000. Pleistocene deposits and deglaciation of the Nõva-Padise area (NW Estonia). *Bulletin of the Geological Survey of Estonia,* 9/1, 4–10.

This paper provides data on the distribution, sedimentology and formation of the Upper-Pleistocene deposits of Nõva-Padise area, northwestern Estonia. Results of extensive field work, as well as the grain-size, petrographic and chemical composition of glacigenic deposits in a large number of samples and drillcore sections were analysed in order to determine sediment genesis and sedimentology. This area is characterised by extremely complicated geological structure. According to Estonian Pleistocene stratigraphy, these glacigenic units belong to the Võrtsjärve Subformation. These sediments were deposited after ice-retreat from ice-marginal zone of the Palivere Stadial (the Late-Weichselian glaciation). The studied till shares similar lithological properties with the Palivere till described on the West-Estonian Islands. A new stable ice-marginal zone represented with buried end-moraines and glaciofluvial marginal deposits was distinguished at Kõpu-Tahkuna-Harju-Risti-Audevälja line.

1. STUDY AREA

Relationships based on sedimentological data are relevant only in limited areas under similar glaciodynamic conditions, because the structure of the Pleistocene sequence and the composition of deposits are strictly regional (Raukas 1995). Therefore almost all areas chosen for detail study (*Fig. 1*) have similar, chiefly carbonaceous, bedrock. Compositional analysis of fine fractions of sediments in areas with similar underlying bedrock can provide valuable information with respect to the direction and character of glacial movement with which to determine palaeoenvironmental conclusions.

The most noteworthy geomorphological feature in northwestern Estonia is the Klint — a steep escarpment sculptured in Cambrian and Ordovician or in Silurian sedimentary bedrock (Miidel 1997). The area north of the Klint forms the Foreklint Lowland. The area south of the Klint forms a fairly even plain, named Viru-Harju Plateau and West-Estonian Lowland (Tavast and Raukas 1982), which are cut by deep bedrock depressions — ancient valleys (*Fig. 2* in Kadastik *et al.* 2003 — PAPER 2; Kadastik and Kalm 1998 — PAPER 3; Kadastik and Ploom 2000 — PAPER 5). In terms of glacial stratigraphy and lithogenesis, the bedrock valleys are the main objects of interest. The valleys bear considerable evidence of glacial erosion. The thickness of Quaternary cover varies from a few centimetres up to 151 m in the deepest northern Estonian bedrock valley — Aabla-Pudisoo (*Fig. 2* in Kadastik *et al.* 2003 — PAPER 2). The till cover of northwestern Estonia usually lies directly on carbonate bedrock and its colour varies from greenish-grey to dark brown.

The research area (*Fig. 1*) was chosen for several reasons. First of all, as the Quaternary cover is relatively thin in northwestern Estonia, bio- and chronostratigraphical data are rare or are scientifically unsuitable (Karukäpp and Raukas 1997). Therefore, sedimentological analysis and study of fabric petrography of differently coloured diamictons are the main methods for distinguishing or correlating till units in areas with few interglacial or interstadial sections.

Secondly, the study area contains three stratigraphically important sites — Prangli (Kajak 1961; Liivrand 1991), Põhja-Uhtju (Miettinen *et al.* 2002 — PAPER 1) and Juminda-2 (Kadastik *et al.* 2003 — PAPER 2). The data from these sites enable construction of the palaeoenvironmental conditions, especially those of the Baltic Sea — White Sea connection during the Eemian. The occurrence of the Eemian deposits in some core sections provides an easily recognisable stratigraphic "base" for Upper-Pleistocene glacigenic deposits in the region (*Fig. 2*).

Thirdly, the northwestern part of Estonia has proven to be a key area to ascertain the palaeogeographical regime with respect to the deglaciation of the Gulf of Finland during the Late-Pleistocene. The most remarkable morphologically expressed ice-marginal zones of the Palivere Stadial of Late-Weichselian glaciation were formed in this area before the ice recession into the Gulf of Finland and Salpausselkä marginal zones. The areas for detailed research were chosen near the proposed boundaries of the Palivere Stadial (*Fig. 1*).

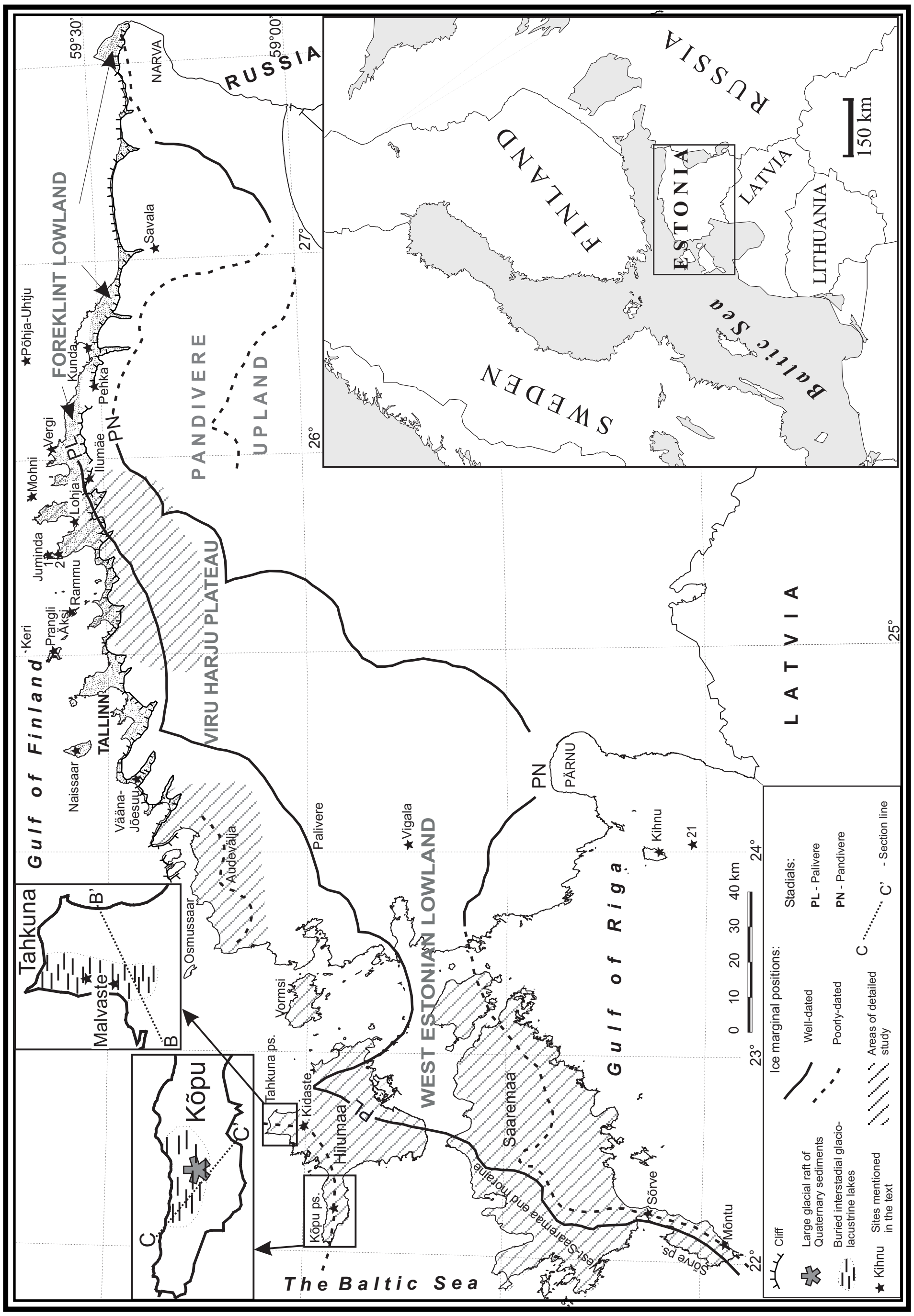

Figure 1. Study area, with major stadials and sites mentioned in the text.

2. METHODS AND DATA

The factual material for this study was obtained through extensive fieldwork, sampling and laboratory analyses during geological mapping of Quaternary deposits at a scale of 1: 50 000, 1: 25 000 and 1:10 000. The author participated in the geological mapping in the area as a geologist in 1987–2000. Previous detailed stratigraphic and sedimentological data were incorporated and combined with new observations in order to integrate all available information from the study area. Conventional geological maps and well-log data were evaluated for regional background information.

2.1. Sedimentological methods

The sedimentological study presented is based on 1335 grain-size, petrographic, mineral and chemical analyses, as well as grain size analyses from various geological engineering investigations. Because the tills are usually overlain by younger deposits, most samples were collected from drillcores. Descriptions and data were collected from about 5500 drillholes.

Conventional grain size, mineral, petrographic, chemical and X-ray diffraction analyses were performed as outlined in Lewis and McConchie (1994), Kalm *et al*. (1992) and in the author's earlier publications (Kadastik 1994, 1995). Grain-size samples were analysed by screen and pipette methods. The description of grain-size was based on the grain-size classification of terrigenous rocks by A. Vilo (1971): >2 mm, coarse grained material (gravel, pebble and cobble); 2–0.05 mm, sand; 0.05–0.002 mm, silt and <0.002 mm, clay. Based on grain size data, typical statistical coefficients (Wentworth 1936) were calculated: arithmetic mean — M_d (mean grain-size), standard deviation — σ (sorting), coefficient of asymmetry — S_k, and excess — E. The mineral composition of tills was determined on the light (e<2.89 g/cm^3) and heavy (e>2.89 g/cm^3) fractions of the 0.1–0.25 mm (fine sand) fraction. Approximately 300 light and 500 heavy mineral grains were counted in each sample. The petrographic composition was determined for the >2 mm fraction. Chemical composition was determined by wet-silicate analysis on the <1 mm fraction. Clay mineral composition was studied by X-ray diffraction analysis (Kalm *et al*. 1992; Jürjens 1988).

2.2. Bio- and chronostratigraphical methods

Samples for pollen analysis were taken from interstadial and interglacial levels. The pollen analyses were done by H. Mäemets, E. Liivrand and K. Rinne. Volumetric samples of 0.5–1 cm^3 were processed by standard chemical laboratory and counting methods (Liivrand 1991). The technique for identification and separation of re-deposited pollen was based on the methods described by E. Liivrand (1976, 1990, 1991) and K. Rinne (2002).

M. Sakson and H. Haila carried out diatom studies from Juminda-2 and Põhja Uhtju site at the Department of Quaternary Research, Stockholm University and at the Department of Geology and Palaeontology, Helsinki University, respectively. The samples were prepared according to the standard methods described in Battarbee (1986). The diatoms were identified under a light microscope with ×1000 magnification using oil immersion.

Sample for OSL analysis was taken from an interstadial level from Pehka site (*Fig. 1*). The sampling technique and dating method are described by G. Hütt (Hütt *et al*. 2001).

2.3. Stratigraphic nomenclature

Estonian stratigraphic nomenclature (*Tables 1* and *2*) is used for stratigraphic terms (formations and subformations) in this thesis local. Equivalent northern European chronostratigraphic units are given with the local nomenclature in Table 1.

2.4. Palaeogeographical methods

The palaeogeographical reconstructions and correlations of the Late-Glacial events presented in this thesis are based on morphological data supported by sedimentological investigation in the field. Geomorphological maps schemes on scales of 1: 50 000 and 1: 100 000 were compiled for detailed study. The main geomorphological criteria were morphogenetical diagnostics (Chemekov 1987) and the construction of more than a hundred geological cross-sections incorporating data from drillholes and wells. The horizontal scales of these cross-sections were 1: 10 000; 1: 25 000 and 1: 50 000 and the vertical scale was 1:1000. Both geomorphological maps and cross-sections were used to make palaeogeographical interpretations and to draw conclusions.

Table 1. Stratigraphical scheme of north Estonian Quaternary deposits and correlative events and deposits in northern Europe and southwestern Finland (after Raukas and Kajak 1995; Ehlers 1996 and Nenonen 1995).

<table>
<tr><th rowspan="2">System</th><th rowspan="2">Stage</th><th rowspan="2">Substage</th><th colspan="2">Estonian local units</th><th colspan="2" rowspan="2">Northern European chronostratigraphic units</th><th rowspan="2">Events and deposits in southern and western Finland</th></tr>
<tr><th>Formation</th><th>Sub-formation</th></tr>
<tr><td rowspan="9">QUATERNARY</td><td colspan="7">Holocene</td></tr>
<tr><td rowspan="8">PLEISTOCENE</td><td rowspan="5">Upper-Pleistocene</td><td rowspan="4">Järva</td><td>Võrtsjärve</td><td rowspan="4">Weich-selian (Vistulian)</td><td>Late-Weich-selian</td><td>Weichselian maximum</td></tr>
<tr><td>Savala</td><td>Middle-Weich-selian</td><td>Horonpää sponge bed?</td></tr>
<tr><td>Valgjärve</td><td rowspan="2">Early-Weich-selian</td><td rowspan="2">Glacier fluctuations extend to Ostrobothnia</td></tr>
<tr><td>Kelnase</td></tr>
<tr><td colspan="2">Prangli/Rõngu</td><td colspan="2">Eemian</td><td>Vesiperä geosol Mertuanoja clay</td></tr>
<tr><td rowspan="3">Middle-Pleistocene</td><td rowspan="3">Ugandi</td><td>Upper-Ugandi</td><td rowspan="3">Saalian</td><td>Late-Saalian</td><td>Glaciation</td></tr>
<tr><td>Middle-Ugandi</td><td>Middle-Saalian</td><td>Virtasalmi interstadial</td></tr>
<tr><td>Lower-Ugandi</td><td>Early-Saalian</td><td>Glaciation</td></tr>
</table>

Table 2. Stratigraphical chart of Estonian Late-Glacial deposits and correlative Late-Glacial ice-marginal formations (after Pirrus and Raukas 1996 and Raukas *et al.* 2004).

Chronological scale, yr BP	Stage	Substage	Chronozone		Index		Definition of boundaries, yr BP	Palynozone	Index	Baltic Sea stage	Ice-marginal zones in Estonia (age in the scale of ^{14}C years)
	Holocene	Lower Holocene	Pre-boreal		PB	PB_2	9500	*Betula*	B	Anc.L	
10 000						PB_1	10000	*Betula-Pinus*	B-P	Yoldia "Sea"	
11 000	Pleistocene	Upper-Järva (Võrtsjärve)	Subarctic	Younger-Dryas	DR_3		10800	*Artemisia-Betula-nana*	Ar-Bn	Baltic Ice Lake	
				Allerød	AL	AL_b	11300	*Pinus*	P		
11500						AL_a	11800	*Pinus-Betula*	P-B		Palivere zone (11800–11630yr BP)
12000			Arctic	Older-Dryas	DR_2		12200	*Artemisia*-Chenopodiaceae	Ar-Ch		Pandivere zone (12480–12230yr BP)
13000				Bølling	BØ		13200	*Betula*-Cyperaceae	B-Cy		Otepää zone (12800–12600yr BP)
13500				Oldest-Dryas	DR_1						Haanja zone (13500yr BP)

3. UPPER-PLEISTOCENE STRATIGRAPHY OF THE AREA

3.1. Stratigraphy of Pre-Late-Weichselian deposits

Pre-Weichselian deposits extend over a limited territory and are recognised only from drillcores. Sediments older than the last (Weichselian) glaciation are those deposited during the Saalian glaciation and the subsequent Eemian warming, which distinguishes the beginning of the Late-Pleistocene. The distinction between Saalian and Weichselian deposits is based on recognition of interlying Eemian sediments and on sedimentological characteristics (*Fig. 2*; Kadastik et al. 2003 — PAPER 2). However, in northwestern Estonia the Eemian interglacial deposits occur only in Foreklint Lowland — in ancient valleys and on islands in the Gulf of Finland (Raukas 1978; Liivrand 1991; Miettinen *et al.* 2002 — PAPER 1; Kadastik *et al.* 2003 — PAPER 2). As the shoreline of the Eemian Sea was close to the current shoreline (Raukas 1991; Miettinen *et al.* 2002 — PAPER 1; Kadastik *et al.* 2003 — PAPER 2), the Eemian interglacial sediments are usually represented by marine deposits, e.g. Prangli Formation (Prangli, Põhja-Uhtju), although the palaeosoil at Juminda-2 site represents the freshwater Eemian — Rõngu Formation (analogue to Prangli). In the Gulf of Riga the Prangli Formation (Eemian sediments) was encountered in drillhole No 21 near Kihnu Island (Kalnina and Jushkevics 1998; Kalnina *et al.* 2000).

The most thoroughly studied Eemian sites in northern Estonia are Prangli, Põhja-Uhtju and Juminda-2. Liivrand (1991) distinguished seven local pollen assemblage zones at a depth of 65.9–78.2 m at a stratotype site of Prangli Formation in Prangli section (*Fig. 2*). Sand, silt and clay assemblages up to 12.3 m thick at Prangli site represent marine Eemian sediments (Liivrand 1991). In addition, diatom and pollen records indicate that the Põhja-Uhtju site includes almost the entire Prangli (Eemian) interglacial pollen and sediment sequence at a depth of 47.5–51.4 m (PLATE I A; Miettinen *et al.* 2002 — PAPER 1). Shell fragments have been described in the Prangli Formation and its underlying layer at Prangli, Lohja and Põhja-Uhtju sites (Kajak 1961; Miettinen *et al.* 2002 — PAPER 1; Kadastik *et al*. 2003 — PAPER 2). Rõngu (freshwater Eemian — analogue to Prangli) deposits represented by a very thin layer (0.13 m) of a palaeosoil occur at Juminda-2 site at a depth of 52.0 m (*Fig. 2;* Kadastik *et al*. 2003 — PAPER 2). Data from Juminda-2 site suggest that a relatively cold freshwater environment characterises the end of Eemian (Kadastik et al 2003 — PAPER 2).

The grey silt in Juminda-1 section (*Fig. 2*) at the same depth (54.0–56.2 m) had been interpreted as Prangli (Eemian) (Raukas 1978), but later studies have reinterpreted this deposit as possible Kelnase (Early-Weichselian) beds with re-deposited Eemian pollen (Liivrand, personal communication; Kadastik *et al.* 2003 — PAPER 2).

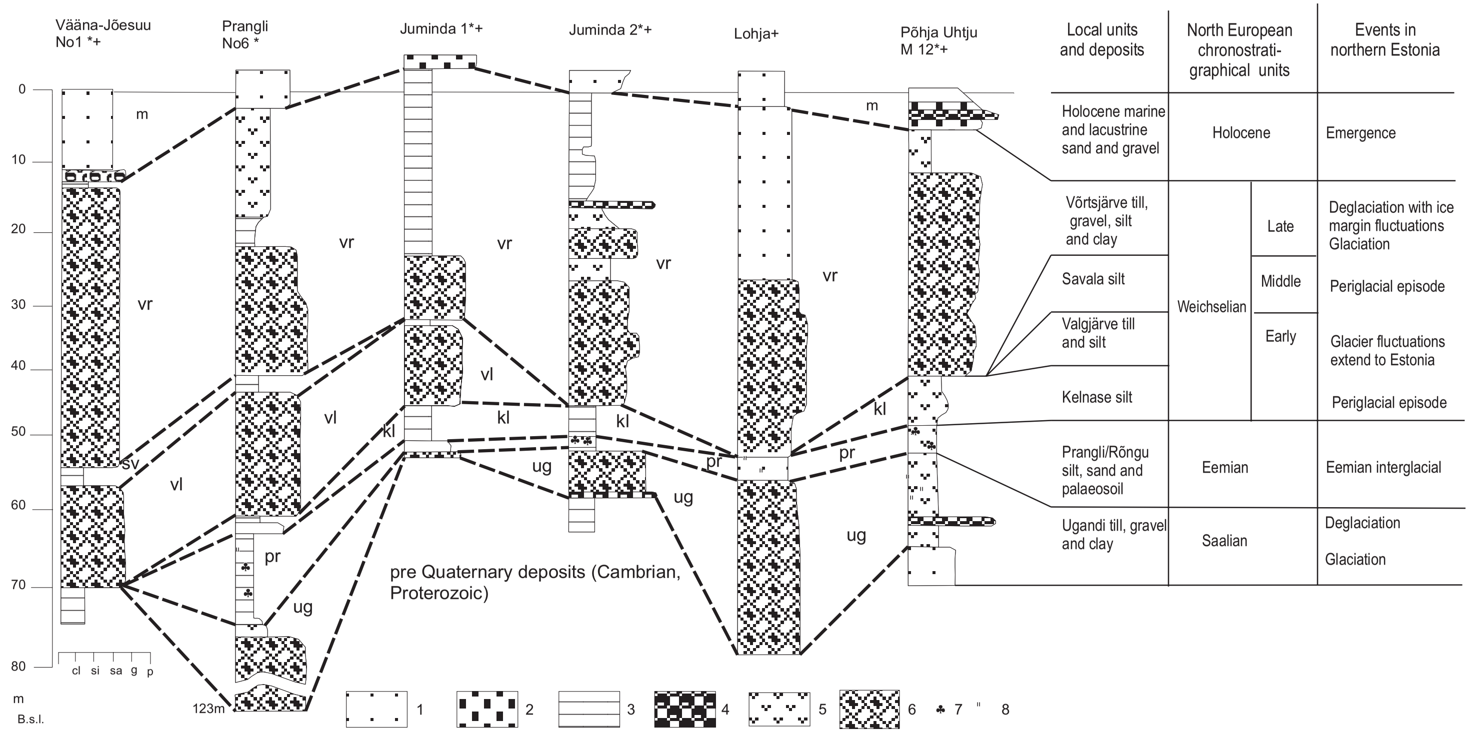

Figure 2. Pleistocene sections in Foreklint Lowland, northern Estonia and formal stratigraphy of Upper-Pleistocene deposits (after Raukas 1978, Raukas and Kajak 1997b — Vääna-Jõesuu section; Raukas and Kajak 1997a — Prangli section; Raukas 1978 — Juminda-1 section).
* — micropalaeontologically studied site; + — sedimentologically studied site; m — Holocene deposits; vr — Võrtsjärve Subformation; sv — Savala Subformation; vl — Valgjärve Subformation; kl — Kelnase Subformation; pr — Prangli and Rõngu Formation; ug — Ugandi Formation. 1 — sand; 2 — gravel; 3 — clay; 4 — pebble and cobble; 5 — silt; 6 — till; 7 — plant remains; 8 — fragments of molluscs.

In the Juminda buried valley and on some islands (e.g. Prangli, Naissaar) in the Gulf of Finland the Prangli Formation is underlain by sediments of the Ugandi Formation deposited during the Saalian deglaciation (Raukas 1978). The oldest identified sediments, the Ugandi deposits, were also encountered beneath Eemian deposits in the Prangli and the Põhja-Uhtju sections (Kajak 1961; Liivrand 1991; Miettinen *et al*. 2002 — PAPER 1; Kadastik *et al.* 2003 — PAPER 2). Compacted brownish glaciolacustrine Upper-Ugandi clay up to 3 m thick occurs in the sections above the Ugandi gravel and pebble deposits or till. These Upper-Ugandi (Late-Saalian) clays have been micropalaeonthologically studied at Prangli, Juminda-2 and Põhja-Uhtju sites (Liivrand 1991; Miettinen *et al.* 2002 — PAPER 1; Kadastik *et al.* 2003 — PAPER 2). Ugandi till consists of a brownish diamicton with numerous clasts of igneous and metamorphic rocks (Kadastik *et al.* 2003 — PAPER 2).

Like the older Quaternary deposits, the lower part on Järva Formation (Early- and Middle-Weichselian) sediments — consisting of the Kelnase, Valgjärve and Savala Subformations — overlying the Prangli/Rõngu (Eemian) Formation (*Tab. 1*) occur within limited areas (in buried bedrock valleys and islands in the Gulf of Finland). The micropalaeontology of the sediments formed during Early- and Middle-Weichselian has been studied in the Prangli, Juminda-2, Põhja-Uhtju and Vääna-Jõesuu sections (Raukas and Liivrand 1971; Liivrand 1991; Kadastik *et al.* 2003 — PAPER 2; Miettinen *et al.* 2002 — PAPER 1).

The Järva Formation begins with Kelnase Subformation (deposited at the beginning of the Weichselian glaciation) periglacial deposits represented by fine silt and clay. The Early-Weichselian pollen assemblages were determined at Prangli (Liivrand 1991; Cheremisinova 1961), Põhja-Uhtju (Miettinen *et al.* 2002 — PAPER 1; Rinne 2002); Juminda-2 (Kadastik *et al.* 2003 — PAPER 2), Kihnu (E. Liivrand, personal communication) sites and in drillhole No 21 in the Gulf of Riga (Kalnina and Jushkevics 1998). The pollen data of these deposits indicate cold and moist climate during deposition (kryohydratilous stage). The Kelnase Subformation is represented by silt and clay with high Al_2O_3 and K_2O contents. The Fe and Mg content in the <1 mm fraction is higher than in the overlying and underlying glacigenic deposits (Kadastik *et al.* 2003 — PAPER 2).

In earlier publications the thick grey Valgjärve (Early-Weichselian) till was distinguished in several sections in the Foreklint Lowland, e.g., Vääna-Jõesuu, Tallinn, Juminda-1 sites and on Naissaar and Prangli Islands in the Gulf of Finland (Raukas 1978; Raukas and Kajak 1997a; Raukas and Gaigalas 1993). Liivrand (1991) suggests that the deposition of this till bed is related possibly to an earlier Weichselian stadial following the Early-Weichselian.

Terrestrial Middle-Weichselian interstadial deposits containing pollen assemblages indicative of cold and dry periglacial conditions have been encountered at few sites (Vääna-Jõesuu, Prangli and Savala; Raukas *et al*. 2004; Liivrand 1991; Raukas and Kajak 1997a, 1997b). Dating of fine-grained sand underlain by glaciofluvial gravel (PLATE II C) from the Pehka site in northern Estonia resulted in an age of 26 800 ±3500 OSL years. This date places this deposit in the Savala Subformation of Middle-Weichselian age *(Tab. 1*). Correlation of this deposit to the northern European scheme suggests deposition during the Denekamp interstadial warming (van der Hammen *et al*. 1967). This is supported by the dating of mammoth remains from Estonia and Finland, most of which date about 31 000–22 000 radiocarbon years (Lepiksaar 1992; Lõugas *et al.* 2002). This evidence supports the conclusion that northern Estonia was not ice-covered during the Middle-Weichselian.

3.2. Stratigraphy of Late-Weichselian deposits

Based on the morphological evidence of the Late-Weichselian glaciation stadials, Kajak (1996) differentiated Palivere, Pandivere, Otepää, Haanja and Misso morphostratigraphical units within the Võrtsjärve Subformation. Tills and related deposits of the Haanja, Otepää, Pandivere and Palivere Stadials feature specific colour and composition (Raukas 1963, 1978) and can be regarded as lithostratigraphical units of the lowest taxonomic rank (beds) (Raukas and Kajak 1997b). Differentiation of these units, representing distinct ice advance phases (*Tab. 2),* thus far was not supported by sedimentological data, or by bio- or chronostratigraphic evidence from northwestern Estonia, where two stadials — the Pandivere and Palivere — were morphologically distinguished (Raukas 1986).

The deglaciation history of Estonia has been dated by conventional varve chronology, non-calibrated radiocarbon chronology and TL/OSL methods. However, varve chronology and ^{14}C methods are inapplicable in northwestern Estonia because suitable deposits are absent in the region. Previous data on the deglaciation of the study area were prone to errors and uncertainties and therefore correlations west- and eastward were unreliable. The greatest difficulties concern the dating and correlation of Palivere ice-marginal deposits with deposits located outside Estonia. Attempts to determine the age of the Palivere zone have been made in the Kunda section at a site located between the Palivere and Pandivere ice-marginal zones (Pirrus and Raukas 1969; Raukas 1992b). In this section the Pandivere till is overlain by glaciofluvial sand, varved clay, lacustrine sand and lake marl. Thomson (1935) proposed that the varved clay was deposited during the Bølling and lake marl in Allerød time. Wooden particles taken from the lower part of lake marl were dated by ^{14}C method at 11 690±150 years BP (Ilves *et al*. 1974). Some researchers consider this date to be overestimated because of the “hard water effect” (Raukas 1995). This "hard water effect" has proven to be a serious complication in northern Estonia because of the presence of carbonaceous bedrock, and therefore dating in this region is considered unreliable (Donner and Jungner 1974). Pollen data of organic sediments from Lake Kunda (Pirrus and Raukas 1969) suggest that the organic matter was formed at the end of Younger-Dryas. Varved clay and glaciofluvial sediments underlying these organic lake sediments may have accumulated during the Allerød or even during the Older-Dryas (Raukas 1992b).

In the absence of reliable bio- or chronostratigraphical data, information on the superposition of differently coloured diamictons has been the only method to distinguish or correlate till units in the area.

As a result of extensive geological mapping and drilling in northwestern Estonia, it became known that the Upper-Weichselian glacial deposits comprise three different laterally spread diamictons (Kadastik 1996; Kadastik and Kalm 1998 — PAPER 3) attributed to Pandivere and Palivere Stadials of the Late-Weichselian glaciation. All three till beds belong to the Võrtsjärve Subformation (*Tab. 1, 2*). Grain size distribution, petrographic, mineral and chemical compositions provide a reliable basis for lithostratigraphic differentiation of these till beds (*Tab. 3*).

The lowermost laterally spread diamicton in northwestern Estonia is a basal till from the Pandivere Stadial, which is dated at 12 480–12 230 BP (Raukas *et al.* 2004). This till has been mapped on most of Saaremaa, Hiiumaa and smaller West-Estonian islands (Kadastik and Kalm 1998 — PAPER 3). In the north-western part of the Estonian mainland the Pandivere till occurs only on the floor of buried valleys. The Pandivere till, whose thickness attains 40 m in end-moraine zones, lies unconformably on the carbonaceous bedrock. Consequently, the Late-Weichselian glaciers have eroded all the earlier deposited sediments from the region (with the exception of deep bedrock valleys). In some deep buried valleys the Pandivere till is underlain by interstadial, or interglacial silt and sands and an older till (Sõrve, Mõntu — Kadastik, 1996; Kadastik and Kalm 1998 — PAPER 1998). The Pandivere till is a massive light grey diamicton, rich in coarse limestone clasts, represented mostly by subglacial lodgement till (Kadastik and Kalm 1998 — PAPER 3). On the Sõrve Peninsula in the southern part of Saaremaa Island, the Pandivere till in the Mõntu section contains abundant silicious sand and acritarchs from the Middle-Devonian Narva Regional Stage (Liivrand, personal communication). Interestingly, the current outcrop of Devonian sandstone (after Suuroja 1997) is located far south from the Mõntu site and no Devonian outcrops occur to the north. This indicates that the advancing ice sheet eroded off a layer of Devonian sandy bedrock and incorporated the material into till. According to the Bedrock Geological Map of Estonia (1997), the Quaternary deposits at Mõntu site are underlain by rocks of Kaugatuma Regional Stage (Middle-Silurian). In the case of normal bedding the Middle-Silurian rocks should occur at least 40–45 m below the Devonian Narva Stage rocks (Suuroja 1997). This means that the advancing ice eroded at least 40–50 m of bedrock cover consisting of Upper-Silurian limestones, marls and all Devonian sandstone between the Kaugatuma (Middle-Silurian) and the Narva Stage (Middle-Devonian).

The Pandivere and Palivere tills were differentiated on the basis of their colour and composition. The two topmost laterally spread diamictons in the area represent genetic varieties of till from the Palivere Stadial (11 800–11 630 BP, Raukas *et al.* 2004) namely waterline melt-out till underlain by basal till (Kadastik and Kalm 1998 — PAPER 3).

Table 3. Main compositional data of the tills discussed in the paper.

Till unit	Gravel + pebbles > 2mm %	Sand + silt 2-0.002mm %	Clay <0.002 mm %	Mean grain-size mm	Sorting	(Cal+Dol)/(Q+Fp), 0.25-0.1 mm fraction	Ilm+Magn, 0.25-0.1 mm fraction, %	Lim+Hem 0.25-0.1 mm fraction, %	Kaolinite <0.002 mm	Chlorite <0.002mm	Crystalline clastics 5-10mm	SiO_2 < 1 mm fraction, %
Pandivere basal till												
n	284	284	284	284	284	63	63	63	13	13	7	70
M	**36.3**	**55.5**	**8.2**	**0.78**	**1.39**	**3.5**	**3.5**	**4.0**	**3.0**	**18.0**	**3.3**	**34.72**
SD	20.3	12.5	5.0	1.28	0.21	4.2	1.9	5.2	4.7	13.3	5.13	15.1
Palivere basal till												
n	260	260	260	260	260	35	35	35	23	23	35	51
M	**22.7**	**67.0**	**9.6**	**0.18**	**1.20**	**0.4**	**6.2**	**4.4**	**9.0**	**9.0**	**22.8**	**58.9**
SD	7.0	4.2	7.5	0.20	0.20	0.2	4.2	5.8	9.1	2.6	19.9	11.7
Palivere waterlain melt-out till												
n	265	265	265	265	265	27	27	27	7	7	19	9
M	**6.8**	**60.9**	**32.3**	**0.02**	**1.12**	**0.1**	**6.8**	**5.4**	**10**	**7**	**29.0**	**53.3**
SD	6.1	14.6	16.2	0.03	0.20	0.1	4.8	4.7	5.5	1.3	20.7	7.4
Till on Viru-Harju Plateau, north Estonia												
n	44	44	44	44	44	12	12	12	–	–	15	–
M	**17.7**	**77.0**	**5.2**	**0.30**	**1.18**	**0,38**	**2,9**	**4,6**	**–**	**–**	**24.3**	**–**
SD	10.4	10.1	3.30	0.23	0.16	0.54	2.2	4.8	–	–	18.6	
Till on Foreklint Lowland, north Estonia												
n	17	17	17	17	17	7	7	7	–	–	13	–
M	**7.3**	**76.1**	**16.9**	**0.17**	**1.11**	**0.02**	**7.1**	**4.2**	**–**	**–**	**99.8**	**–**
SD	4.4	12.5	14.4	0.22	0.14	0.04	3.4	4.9	–	–	0.8	

n = number of analysed samples; m = mean; SD = standard deviation; Minerals: Cal = calcite; Dol = dolomite; Q = Quartz; Fp = feldspars; Ilm = ilmenite; Magn = magnetite; Lim = limonite; Hem = hematite; – = data not avaiable.

The Palivere basal till is a massive greyish-beige or brown diamicton, rich in coarse clasts, and resting on older till or directly on bedrock. A comparative sedimentological study of the diamictons (Kadastik 1994, 1995, 1996; Kadastik and Kalm 1998 — PAPER 3; Kalm and Kadastik 2001 — PAPER 4; Kadastik and Ploom 2000 — PAPER 5) shows that the Palivere till directly overlies the Pandivere till in some regions of the area, particularly on the West-Estonian Islands. The thickness of the Palivere basal till approaches 28 m in endmoraine formations. At some locations (Kõpu, Sõrve, Mõntu, *Fig. 1*) interstadial lacustrine deposits bearing organic matter occur between Pandivere and Palivere basal tills. The basal erosional unconformity and deformation of the underlying till indicate the overriding of active ice (Kadastik and Kalm 1998 — PAPER 3). In the northwestern part of Estonian mainland this till lies generally on carbonaceous bedrock and is underlain by older Pleistocene deposits only in buried valleys (Kadastik and Kalm 2001; Kadastik and Ploom 2000 — PAPER 5).

The Palivere waterline melt-out till is the uppermost laterally spread diamicton in the West-Estonian Archipelago and in some sequences in the Gulf of Finland (Kadastik and Kalm 1998 — PAPER 3; Kalm and Kadastik 2001 — PAPER 4). This till is a massive fine-grained clay-rich cacao-brown or grey deposit with laminated clayey deposits or brecciated varved clay inclusions and coarse-clastic diamicton lenses, and gravel- or pebble-size clasts and dropstones (PLATE 1 C; Kadastik and Kalm 1998 — PAPER 3; Kalm and Kadastik 2001 — PAPER 4). The Palivere melt-out till is up to 25 m thick. Several authors (Raukas 1963; Eltermann 1993a; Kadastik 1994, 1995; Kadastik and Kalm 1998 — PAPER 3) consider this till a melt-out till or waterlain till or glaciolacustrine deposit. The formation of this till unit is discussed in detail in Kalm and Kadastik 2001 — PAPER 4. On Saaremaa Island and on islands in the Gulf of Finland the Palivere waterline melt-out till has a gradational boundary with overlying varved clay or silt.

All three laterally spread till beds are distinctive with respect to their sedimentological parameters (*Tab. 3*). The particle size data demonstrate that the less contact the glacier and the deposited till had with the bedrock below, the more uniform the till is in grain-size distribution (Kadastik and Kalm 1998 — PAPER 3). The basal tills are more poorly sorted, of which the oldest, the Pandivere till, is the coarsest and most heterogeneous according to the variability of mean grain size and sorting (*Fig. 3*). Better sorting relative to the two basal tills is characteristic of the waterlain melt-out till, whose smallest mean grain size is the result of specific conditions of sedimentation in ice-melting water environment. The two Palivere tills (basal and melt-out) contain fewer clasts of local carbonaceous bedrock and significantly higher amount of minerals derived from igneous and metamorphic rocks than the Pandivere till (*Fig. 4*). Examination of coarse clasts and the mineral and chemical compositions of the fine fractions indicate a similar source material for the Palivere basal and waterlain tills (Kadastik 1994, 1995, 1996; Kadastik and Kalm 1998 — PAPER 3; Kalm and

Kadastik 2001 — PAPER 4). Of the three tills the waterlain melt-out till is richest in Fe-minerals (*Tab. 3*). In addition, the clay-fraction of Palivere waterlain melt-out till and Palivere basal till contains 5–10% more kaolinite than the Pandivere till (Kalm *et al.* 1992; Kadastik 1996; *Tab. 3*).

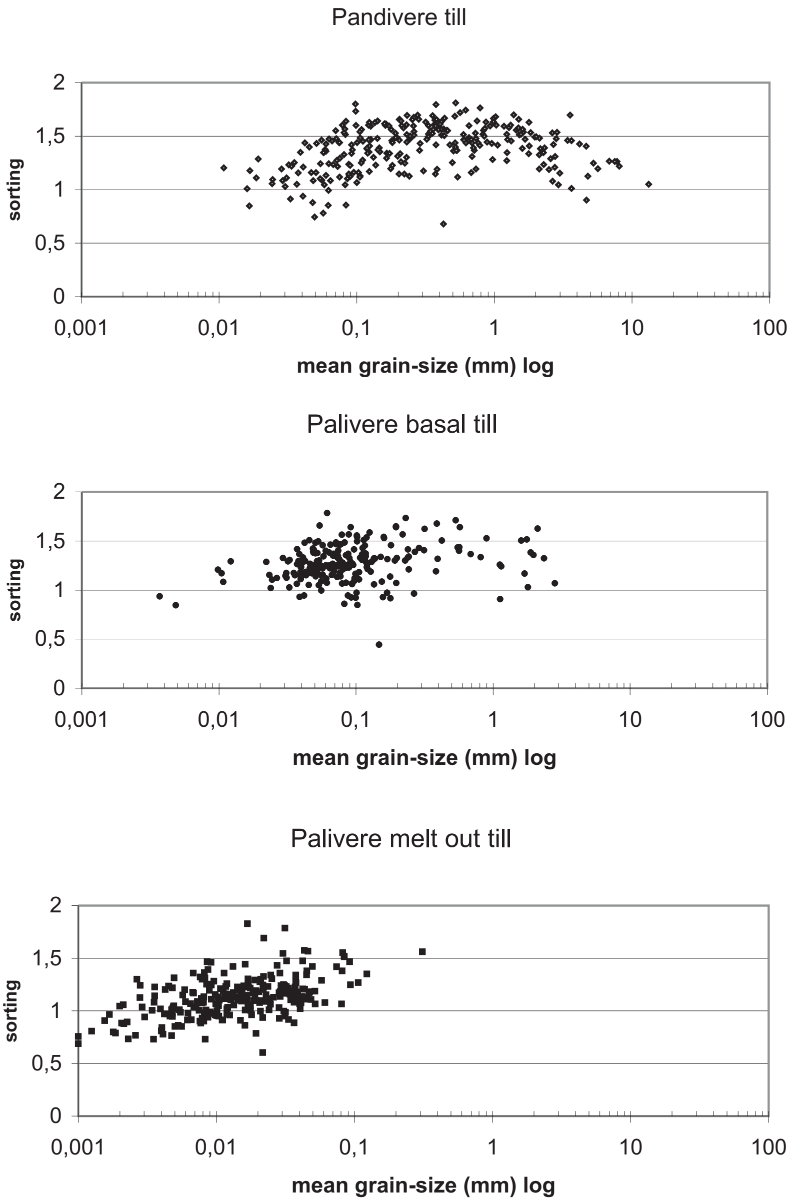

Figure 3. Relationship between the mean grain-size and sorting of tills in study area.

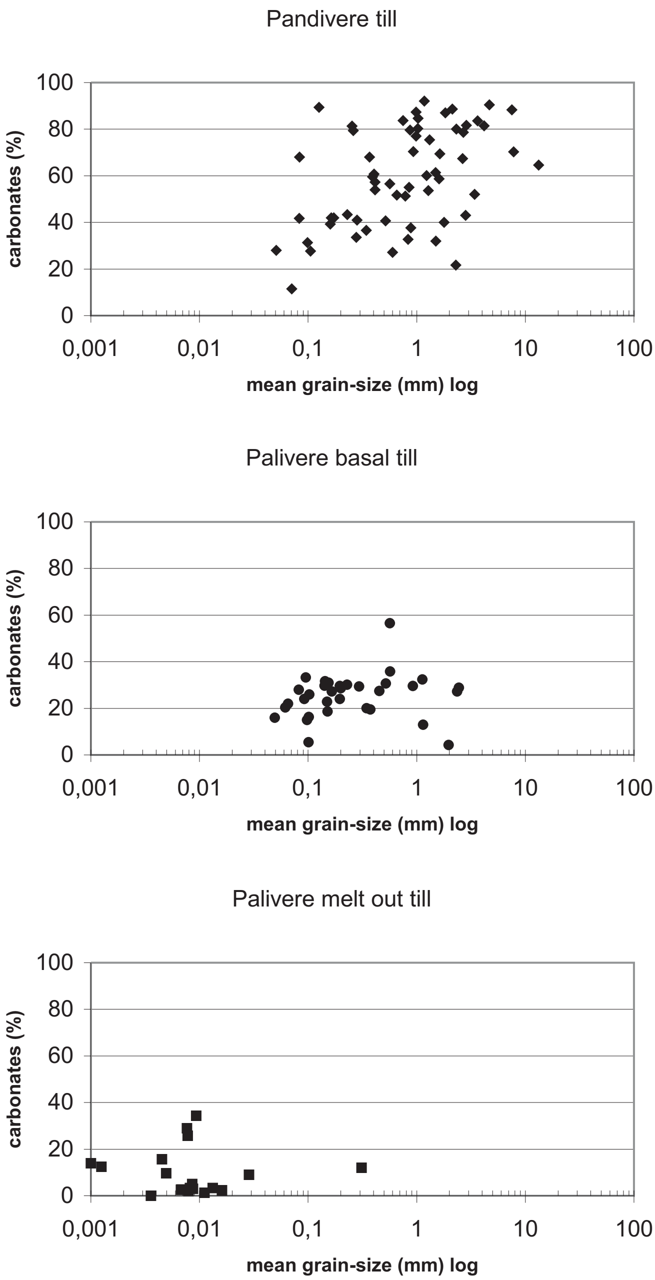

Figure 4. Relationship between the mean grain-size and content of carbonates in different types of tills in study area.

Previous research had investigated the interstadial or interphasial layers between the different till beds at some sites in northern Estonia e.g. on the island of Prangli (Raukas and Rähni 1966; Raukas 1978). Unfortunately these deposits are rich in re-deposited pollen, which hampered the correlation of sections and the determination of palaeogeographical conditions during the interstadial events (Raukas and Karukäpp 1997).

Among the sites examined for the first time in this thesis (*Fig. 5, 6*), the Pandivere and Palivere tills are separated by a 36.5-m thick succession of interstadial sand and silt deposits at Kõpu (*Fig. 5, 6, 7*), whereas at Sõrve and Mõntu sites the interstadial deposits are thinner. These organic-containing interstadial deposits of the Pan/Pal warming event had been studied previously within the area of Palivere glacial advance and at Ilumäe site located between the Pandivere and Palivere ice-marginal formations (*Fig. 6*). In the latter case the Palivere till does not cover the interstadial deposits. A comparison of the sites on the mainland (Ilumäe) and those on islands (Mõntu, Sõrve, Kõpu) shows that the climatic conditions for plant growth and pollen dispersal were less favourable on the islands, although the trends of vegetation development seem to have remained the same in western and northern Estonia. This is reflected by the high content of herb pollen, especially *Artemisia* in cold periods and by an increase in *Betula* during warmer intervals (Liivrand *et al*. 1999). The pollen spectra of the Pan/Pal beds, which were deposited in a large waterbody, are presumably rich in distantly transported pollen. Only single pollen zones were discovered at the Sõrve site and at Mõntu site, both consisting mainly of herbs, *Betula nana* and *Pinus* pollen. The pollen concentration at Kõpu was very low, but similar in composition as at Mõntu (Liivrand *et al.* 1999). At the Ilumäe site several warming and cooling episodes were distinguished; the interstadial Pan/Pal zone and Allerød warming is characterised by higher contents of *Betula nana, Betula humilis*, *Picea* and *Pinus* pollen and the Palivere cooling event by an increase in herbs (Liivrand *et al.* 1999).

In addition to the laterally spread tills, some local diamictons were identified. In some deep core sequences located in buried valleys of Foreklint Lowland, e. g. Juminda and Lohja, a diamicton rich in igneous and metamorphic rocks was found below Late-Glacial glaciolacustrine deposits (Kadastik *et al.* 2003 — PAPER 2). According to the proposed location-line of the Palivere ice-marginal zone in this area (Karukäpp *et al*. 1992) this clast-rich layer at the Lohja and Juminda-2 site is most probably the Palivere till (Kadastik *et al.* 2003 — PAPER 2). In this case the grey interstadial silt below this diamicton may have been deposited during the Pal/Pan interstadial.

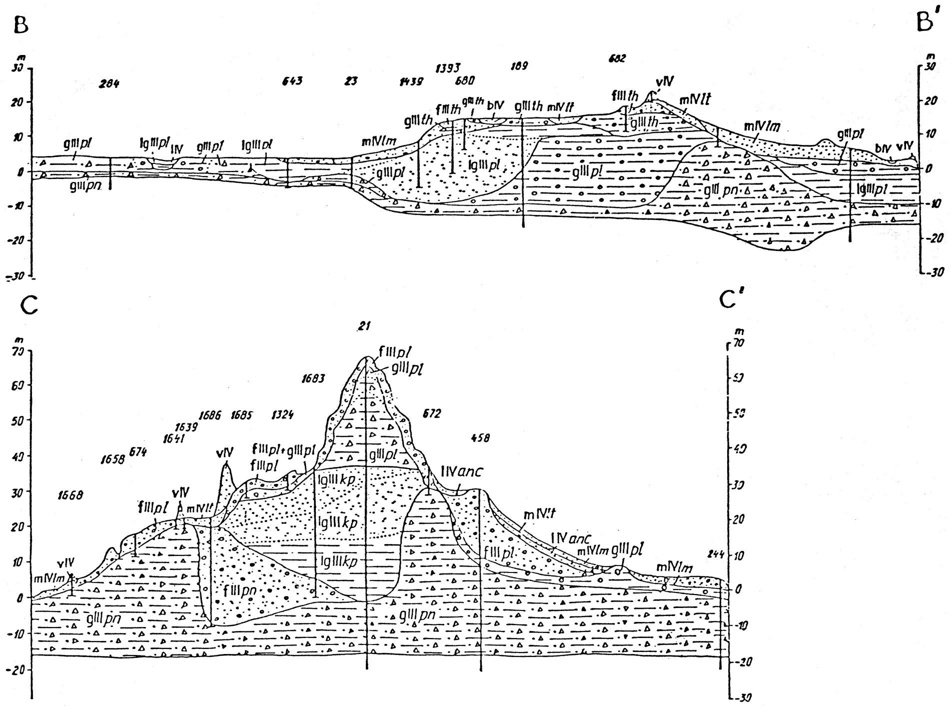

Figure 5. Geological cross-sections of Tahkuna and Kõpu Peninsulas (Kadastik and Eltermann, 1994). For locations of cross-sections see Fig. 1.

gIII *pn* — Pandivere till; fIII *pn* — glaciofluvial gravel and sand of Pandivere Stadial; lgIII*kp* — glaciolacustrine sand, silt and clay of Pal/ Pan interstadial; gIII*pl* — Palivere till; fIII*pl* — glaciofluvial gravel and sand of Palivere Stadial; lgIII*pl* — glaciolacustrine sand, silt and clay of Palivere Stadial; gIII*th* — Tahkuna till; fIII*th* — glaciofluvial gravel and sand of Palivere Stadial; mIV*lm*, mIV*lt*, lIV*anc* and vIV — Holocene sand and gravel.

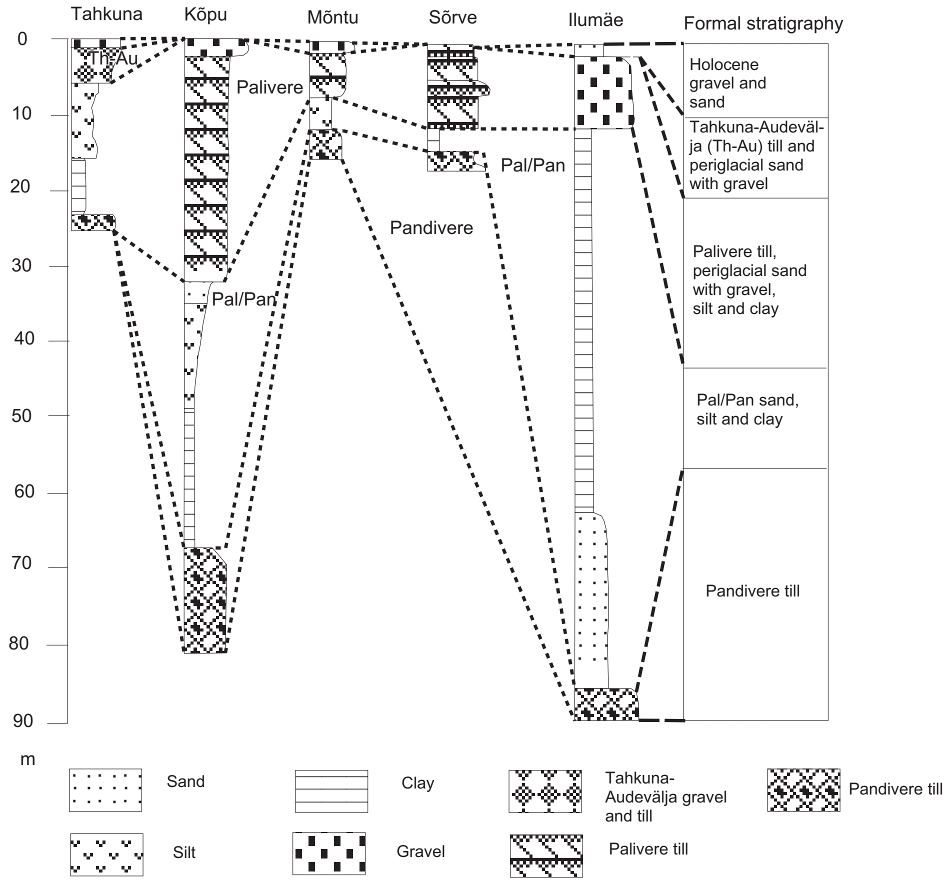

Figure 6. Sections with Pan/Pal Interstadial deposits in area studied. For location of sites see Fig. 1.

The grey Võrtsjärve (Late-Weichselian) till unit in the Foreklint Lowland rests on the fine-grained Kelnase (Early-Weichselian) sediments (Miettinen *et al.* 2002 — PAPER 1; Kadastik *et al.* 2003 — PAPER 2). The relatively high content of silt and sand fraction in this basal or melt-out till indicates the significant influence of local sandy and silty bedrock consisting of Cambrian and Vendian sandstone (*Fig. 2* in Kadastik and Kalm 1998 — PAPER 3). Presumably this till layer (*Fig. 6* in Miettinen *et al.* 2002 — PAPER 1; *Fig. 3* in Kadastik *et al*. 2003 — PAPER 2) was deposited during the decay of the Late-Weichselian glacier.

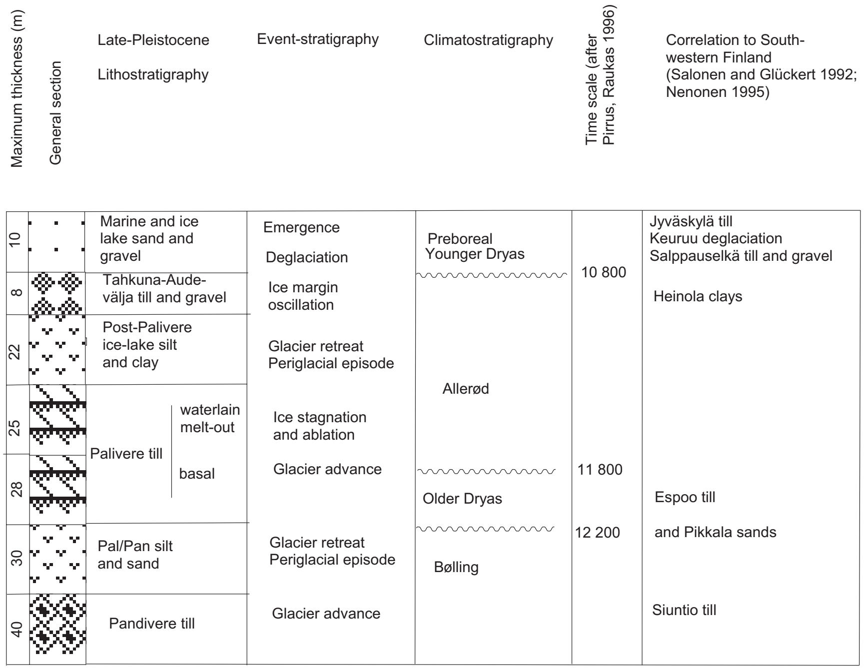

Figure 7. Present state of the Late-Weichselian stratigraphical investigations of northwestern Estonia and correlation with southwestern Finland.

In the easternmost part of the research area (*Fig. 1*) there is only one till with sedimentological properties similar to the Palivere till (*Tab. 3*), regardless of its position south or north of the Palivere Stadial ice margin. This similarity can be explained in two ways:

1. The eastern part of study area (*Fig. 1)* is located near numerous deep buried valleys where Cambrian and Vendian bedrock crops out and therefore the entire till cover is more silicious and almost uniform both laterally and vertically.
2. As in this area the Palivere ice-marginal zone is not geomorphologically well expressed; the genuine maximum advance of the Palivere Stadial can differ from the proposed one and may have occurred south of Palivere Stadial limit proposed previously (Karukäpp *et al*. 1992; Raukas *et al.* 2004).

In addition to the Pandivere and Palivere Stadial moraines, the Tahkuna-Audevälja ice-marginal zone was identified at Tahkuna on Hiiumaa Island and at Audevälja in northwestern Estonia (Eltermann 1993a, 1993b; Kadastik 1994; Kadastik and Ploom 2000 — PAPER 5). A mosaic layer, consisting of silty till, rich in igneous and metamorphic clasts, glaciofluvial gravel, cobbles and erratic boulders represents sediments of Tahkuna-Audevälja standstill and oscillation, which overlie the interstadial glaciolacustrine deposits formed after the Palivere Stadial (PLATE I D; *Figs. 5, 6, 7*).

4. DEGLACIATION HISTORY IN NORTHWESTERN ESTONIA

During the maximum of the Late-Weichselian glaciation (22 000–18 000 BP years ago) the thickness of the ice cover over Estonia may have extended to 2100–2300 m (Ehlers 1990, 1996; Boulton *et al.* 2001). During the general decay of the glacier the combined influence of the active glacial ice and the subglacial surface led to the formation of varied glacial landforms, such as drumlin-like forms on the southern slope of the Gulf of Finland. Stress in the glacial ice formed a number of cracks and crevasses, which later filled with till and coarse glaciofluvial material (Karukäpp *et al.*, 1996).

4.1. Pandivere Stadial

The Pandivere ice-marginal zone (*Fig. 1*) is dated at 12 480–12 230 BP (Raukas *et al.* 2004) and formed during Older-Dryas (Karukäpp *et al.* 1992). According to glacial striae measurements (Männil 1962) and the fabric of till clasts (Raukas *et al.* 1971), the accumulation of tills during the Pandivere Stadial resulted from southerly or southwesterly ice flow (PLATE II B; *Fig. 8*).

The most prominent ice-marginal formations in western Estonia were originally formed during the Pandivere Stadial. One example is the West-Saaremaa endmoraine, which is 45 km long, 5–6 km wide, up to 35 m tall, and extends northwards on southern part of Hiiumaa island as the buried moraine ridges and moraines forming the islets in the Väinameri Sea (*Fig. 8*). The glacial retreat was interrupted by temporarily as indicated by features such as marginal deltas in the central part of northern Estonia. Several zones of buried Pandivere end moraines (Eltermann 1993a; Kadastik 1994, 1996) indicate the recession of the Pandivere ice after the formation of Pandivere ice-marginal zone (*Fig. 8*).

4.2. Pandivere/Palivere Interstadial

After the Pandivere ice-retreat, the glacier margin came to a halt north and northwest of Hiiumaa (Eltermann 1993b; Kadastik 1996) at least beyond the Kõpu and Tahkuna Peninsula (*Fig. 8*). The Pandivere ice retreated at least so far as indicated by the discovery of interstadial deposits in the vicinity (Eltermann 1993b). According to the varve chronology at Vigala site, the ice-free period between Pandivere and Palivere Stadials (Pan/Pal) must have extended at least 476 varve years (Hang and Sandgren 1996; Hang 1997). Pollen spectra, consisting mainly of herbs, *Betula nana* and *Pinus* pollen representing periglacial environment have been noted in sand and silt deposits in interstadial lakes formed in a small depression between the Pandivere endmoraine ridges at Kõpu

(*Figs. 1, 5*) (Liivrand *et al*. 1999). Compared to sites on the mainland (Ilumäe, *Fig. 1*), the climate conditions on islands (Kõpu, Sõrve, Mõntu, *Fig. 1*) were less favourable for plant growth and pollen dispersal, although vegetation development seems to have remained generally the same in western and northern Estonia. This is expressed by the high content of herb pollen, especially *Artemisia* in cold periods and by increases in *Betula* during warmer intervals (Liivrand *et al*. 1999). Glacial retreat during this warming was significant, apparently reaching the coastal area of Finland where Pikkala sands between were found two till beds (Bouchard *et al.* 1990; Nenonen 1995). These two till beds can be correlated to the Palivere and Pandivere Stadial tills distinguished in West-Estonian Islands (Kadastik and Kalm, 1998 — PAPER 3).

If northern and northwestern Estonia were virtually ice-free during the Pan/Pal interstadial, the location of the glacier margin must have been northward. The subsequent cooling caused a new Palivere ice advance and the formation of Palivere marginal relief forms.

4.3. Palivere Stadial

The Palivere ice-marginal zone has been dated at 11 630–11 800 BP (Raukas *et al.* 2004). In contrast to other oscillatory phases in Estonia, the Palivere clearly reflects a re-advance, as suggested by glaciotectonic features and by the fact that older glaciolacustrine sediments are overlain by glaciofluvial and glacial material (Raukas and Rähni 1966; Kadastik 1996; Kadastik and Kalm 1998 — PAPER 3). On Hiiumaa Island, a rapid re-advance of the glacier of the Palivere Stadial left a 24 m thick till raft on top of glaciolacustrine deposits on the Kõpu Peninsula (*Figs. 5, 8;* Eltermann 1993a; Kadastik 1996). Although Eltermann (1993a) interpreted the genesis of this till like glacier raft, there is also a possibility that the high steep-sloped moraine ridge is a push-moraine originating from older buried moraine ridges in the north. If the accumulation of tills in the Pandivere Stadial was affected by southerly or southwesterly directed ice flows, the ice flow during the Palivere Stadial was towards to the southeast (Raukas *et al.* 1971; Raukas and Karukäpp 1978; Raukas 1986, 1992b, 1995). The advancing Palivere glacier reached the Palivere line on the mainland (PLATE II A), approximately the Väinamere Sea Islets line in Hiiumaa (PLATE II D), and the West-Saaremaa end moraine in Saaremaa.

The eastern limit of the Palivere ice-advance is not so clearly traceable, but the clast-rich upper till layer in the buried valleys of northern Estonia could have formed during the Palivere ice advance (Kadastik *et al*. 2003 — PAPER 2). The lithostratigraphical study of these deposits shows that the eastern limit of Palivere melt-out tills is located approximately 20 km south of the limit of Palivere ice-marginal formations (*Fig. 1* in Kadastik and Kalm 1998 — PAPER 3). Therefore the Palivere shelf-type glacier margin has to extend even further south than the morphologically distinguished Palivere marginal zone (Kalm and

Kadastik 2001 — PAPER 4). At the end of the Palivere Stadial, deposition took place within a decaying ice field, and as a result the marginal moraine ridges formed on West-Estonian islands (*Fig. 8*). After the retreat of the ice margin from the Palivere line, a field of stagnant ice remained in the Gulf of Finland. Large glaciolacustrine basins then formed along the Palivere zone in north-western and northern Estonia (PLATE I B), where the thickness of glaciol-acustrine sand approaches 25 m at Lohja. The composition of pollen in the supramorainic deposits at Kunda, northern Estonia, suggests that the Palivere endmoraine zone became free of ice at the beginning of the Allerød at the latest (Pirrus and Raukas 1969; Raukas 1992b).

4.4. Tahkuna-Audevälja Phase

After the ice retreat from the Palivere endmoraine zone, another stable phase or weak re-advance of the ice margin from north to south occurred, which is traceable along the Tahkuna-Audevälja line (Fig. 8; Kadastik and Ploom 2000 — PAPER 5) and can be correlated with the Tahkuna Stadial distinguished by Eltermann (1993b). A minor oscillation with glacier advance is morphologically better expressed in the west at Tahkuna (Eltermann 1993a), where glaciofluvial delta deposits cover glaciolacustrine sand and silt (PLATE I D; *Figs. 5, 6*), whereas on the mainland at Audevälja, only the buried end-moraine ridges and glaciofluvial sediments mark the ice margin standstill at Audevälja-Harju-Risti-Pedase line (*Fig. 6* in Kadastik and Ploom 2000 — PAPER 5).

The deposits of varved clay beneath till on the proximal side of Salppauselkä ridges in Finland were formed during the Heinola deglaciation (Hirvas and Nenonen 1985). The Heinola deglaciation may have occurred during the Allerød Interstadial (Glückert 1990) when the final melting of Palivere ice was most intensive.

5. DISCUSSION

Although the occurrence of Eemian interglacial deposits is most valuable to distinguish the Upper-Pleistocene and older deposits, the number of studied Eemian sites in northwestern Estonia is limited. In addition to the sedimentologically and micropalaeontologically studied sites (*Fig. 2*), it is assumed that organic-containing Eemian deposits occur on the islands of Mohni, Keri, Äksi and Vergi in the Gulf of Finland, where occurrences of natural gas have been recorded (Raudsep 1997).

As determined in several studies (Björck *et al*. 2000; Kukla *et al*. 2002; Müller 1974; Woillard 1979), the termination of the Eemian was sudden and therefore the sediments deposited during the very last Eemian stage E9, distinguished at Juminda-2 site (Kadastik *et al.* 2003 — PAPER 2) are sparse and thin. The remnants of mostly minerogenic marine sediments as well as freshwater organic sediments are usually deformed and eroded by the Weichselian ice or proglacial waters. These waters eroded sediments deposited earlier and therefore the Eemian pollen has been re-deposited into Weichselian strata (Kihnu, Juminda-1, Vääna-Jõesuu, Juminda-2, Põhja-Uhtju) (Raukas 1978; Liivrand 1991; Raukas and Liivrand 1971; Kadastik *et al.* 2003 — PAPER 2; Miettinen *et al*. 2002 — PAPER 1).

According to some later studies in Scandinavia (Andersen and Mangerud 1989; Donner 1995), the Early-Weichselian glacier did not reach Estonia, which is supported by investigation of northern Estonian sections where only one Weichselian till bed was found (Kadastik *et al.* 2003 — PAPER 2; Miettinen *et al.* 2002 — PAPER 1). Our investigations in northern Estonia (Juminda-2 and Põhja-Uhtju) indicate that only fine-grained periglacial deposits represent the Early-Weichselian stadial in the area (Kadastik *et al*. 2003; Miettinen *et al*. 2002). This supports the conclusion regarding periglacial conditions in northern Estonia during the Early-Weichselian by which the ice margin was located north of northwestern Estonia. Therefore the stratigraphic position of till beds distinguished as Valgjärve in Vääna-Jõesuu, Prangli and Juminda-1 sites (*Fig. 2*; Raukas 1978) is questionable.

Until recently, the identification of Middle-Weichselian deposits of the Savala Subformation in northern Estonian sections had been difficult. According to earlier research (Raukas and Liivrand 1971; Liivrand 1991), Middle-Weichselian deposits are represented by grey clay, silt and till in northern Estonia as represented at Prangli, Vääna-Jõesuu and Savala sites, where their thickness approaches 17 m (Savala). At Prangli site a glaciolacustrine interlayer alleged to be of the Middle-Weichselian age is found at a depth of 43.0–45.5 m, dividing the Lower- and Upper-Weichselian (Raukas and Kajak 1997a). According to Liivrand (1991) the tills and silts distinguished as Valgjärve and Savala Subformations at Prangli site by Raukas and Kajak (1997b; *Fig. 2*) were both formed during Middle-Weichselian.

Investigations of the texture and mineral composition of till at Vääna-Jõesuu (Raukas and Liivrand 1971) show that the lithological properties of both grey till layers (interpreted as Middle- and Upper-Weichselian tills in Liivrand (1991) and as Lower- and Upper-Weichselian tills in Raukas (1978)) are similar. Some minor differences have been noted in the mineral composition of micas and chlorites in the fine sand fraction. Consequently, the till layers cannot be divided into Middle- and Upper-Weichselian beds without micropalaeontological investigation. Similarly, the stratigraphic position of possible Lower-Weichselian till layers (Naissaar, Tallinn, Prangli, Juminda-1) described in earlier publications (Raukas 1978) is unclear and not well grounded in light of Scandinavian investigations (Anderson and Mangerud 1989; Donner 1995). Therefore these lower till beds attributed to Lower- or Middle-Weichselian by previous researchers (Liivrand 1991; Raukas 1978; Raukas and Kajak 1997a and 1997b) may have formed during a single Late-Weichselian glaciation and belong to the Võrtsjärve Subformation.

A direct lithostratigraphic correlation of Upper-Weichselian till units across the Gulf of Finland is impossible because bedrock composition in Finland and Estonia is completely different. A formal glacial lithostratigraphy by Bouchard et al. (1990) with two till units south of Salppauselkä I was later complemented with an informal time scale (Salonen and Glückert 1992). This enables correlation of the Finnish and Estonian lithostratigraphical units in the area between Salppauselkä and the Pandivere Stadial based on preliminary chronological approximations (*Fig. 7*; Kadastik and Kalm 1998 — PAPER 3). However, because the approximate timing of stadial/interstadial episodes in both southwestern Finland and northwestern Estonia are neither chronostratigraphically verified (Hirvas and Nenonen 1987; Salonen and Glückert 1992; Hirvas *et al*. 1995; Raukas 1992a; Hang 1997), nor directly determined, lithostratigraphic correlation is the most optimal method at present. South of the Salppauselkä I end moraine in southern Finland (between SSI and the Palivere endmoraine) two (Hirvas and Nenonen 1987; Bouchard *et al.* 1990; Salonen and Glückert 1992; Saarnisto and Salonen 1995) or three (Hirvas *et al.* 1995) till units in Kela Formation are distinguished. According to Bouchard (1990) and Salonen and Glückert (1992), the silt-rich Siuntio till was deposited by ice flowing from north to south. The direction of ice-flow was similar during deposition of the Pandivere till in Estonia (Raukas *et al.* 1971). Presumably the Siuntio till is the lowermost till in southwestern Finland and formed as a lodgement till during the Pandivere Stadial of the Late-Weichselian glaciation whose advance terminated in Estonia (Kadastik and Kalm 1998 — PAPER 3). The Espoo till member as an upper sandy basal melt-out till was deposited by ice flowing from the northwest and is supposed to be correlative to the Palivere Stadial (*Fig. 7*; Kadastik and Kalm 1998 — PAPER 3).

After the Pandivere Stadial the ice margin must have receded at least 70–90 km northward (in front of the Kõpu Peninsula; *Fig. 8*), because the occurrence of buried interstadial deposits at Kõpu site (Kadastik and Kalm 1998 —

PAPER 3; Liivrand *et al.* 1999) proves that the Kõpu Peninsula must have been ice free during the Pan/Pal interstadial. The location of the buried end moraine ridges of the Pandivere Stadial at Kõpu and Tahkuna (*Fig. 8*) supports this conclusion. However, the glaciofluvial outwash deposits in front of the Klint are correlated provisionally with sandy deposits on the Kõpu (Noormets and Floden, 2002). Therefore, the ice could have receded even further northward during the Pan/Pal interstadial than suggested in *Fig. 8*. The estimated distance of the Pan/Pal ice recession (70–90 km) is valid only if it is accepted that the margin of the Pandivere Stadial during its maximum extent was located on Saaremaa Island (*Fig. 8*). The complication is that the Pandivere marginal zone is poorly expressed morphologically and lithologically in West-Estonia. Only two low marginal ridges mark the location of the Pandivere marginal zone on Saaremaa Island (*Fig. 8*). The sedimentological properties of tills surrounding the suggested Pandivere ice-marginal zone are similar (Kadastik 1995, 1996). Therefore our data support the standpoint that the margin of the Pandivere ice may have not been located on Saaremaa Island as previously suggested (Rattas and Kalm 2004; Salonen and Glückert 1992), rather may have been located southward as suggested by Eltermann (1993b; *Fig. 8*). This means that ice may have covered the Gulf of Riga during the Pandivere Stadial and the distance of the recession of the ice margin could have been greater (about 150 km).

Correlating the Pikkala sands (Salonen and Glückert 1992) with the Pan/Pal interstadial (Kadastik and Kalm 1998 — PAPER 3; Liivrand *et al*. 1999) implies that the glacier margin must have been located in southern Finland during the Pan/Pal interstadial, in which case the ice recession was about 150 km (*Fig. 8*).

The calculation shows that the ice advance (distance from Kõpu Peninsula where the interstadial deposits were found) to the limit of maximum extent of the glacier during the Palivere Stadial (Raukas 1986) was at least 30 km (*Fig. 8*). This distance may have been up to 120 km, had the Gulf of Finland been entirely ice-free during the Pan/Pal interstadial.

Marginal moraine ridges represent the Late-Weichselian stadial marginal zones in the West-Estonian Archipelago. On the Estonian mainland, the stadial ice-marginal zones consist of meltwater accumulation deposits, especially in northern Estonia, where the marginal zones are represented by glacifluvial deltas formed in front of the ice margin. These deltas with well-laminated glaciofluvial deposits indicate open bodies of water in front of the retreating ice margin of a passive glacier. The moraine ridges representing the marginal zone in West-Estonian islands indicates an active and advancing ice during the Palivere Stadial. Presumably the melting of ice was much less intensive in western part of the study area and shelf type glacier margin with icebergs broken off from the Palivere ice margin covered the body of water in front of the advancing glacier. This assumption explains the formation of waterlain melt-out till in front of the Palivere ice-marginal zone and, therefore, also the lithologically expressed limit of the distribution of Palivere till, which is located east of the morphological limit of Palivere marginal zone (Kadastik 1996; Kadastik and Kalm 1998 — PAPER 3; Kalm and Kadastik 2001 — PAPER 4). However, some researchers (Noormets and Floden 2002) acknowledge that 50–60 m deep water on Saaremaa during the formation of the Palivere waterline melt-out till (Kalm and Kadastik 2001 — PAPER 4) seems insufficient to indicate an ice-shelf type of glacier margin. In addition, Noormets and Floden (2002) mentioned that the twofold structure of the ice-marginal deposit offshore west of Sõrve Peninsula could have formed without an ice-margin re-advance. These conclusions were drawn based primarily on continuous seismic reflection data, without detailed sedimentological analysis of glacial deposits.

After the initial Palivere re-advance, the general recession of the ice sheet slowed, and the minor oscillation of Tahkuna-Audevälja took place (*Figs. 5, 8*). The Tahkuna-Audevälja ice-marginal zone is subparallel to and located about 20–30 km northwest of the Palivere zone (Kadastik and Ploom 2000 — PAPER 5). However, according to Eltermann (1993b), the ice margin receded far north before the Tahkuna re-advance after the Palivere Stadial. The lack of glacio-tectonic disturbances in this area and the limited extent of glacigenic deposits of the Tahkuna-Audevälja oscillation suggest that this recession and following oscillation were relatively weak. Moreover, the mosaic layer of till, erratics, silt lenses and delta deposits lying on glaciolacustrine silts and clays at Tahkuna formed during a weak ice advance (at least 5 km, *Figs. 5, 8*). The well-sorted delta deposits in front of the glacier margin relate to the presence of the open body of water during the Tahkuna-Audevälja Oscillation Phase.

Then, in the Allerød interstadial, preceding the Younger-Dryas cooling substage, the ice margin receded northward (Lundquist 1989). It is not known how far this recession proceeded, but Rainio (1985) suggests a position about 80 km north of Salpausselkäs in Finland (*Fig. 8*). The Younger-Dryas cooling implies a re-advance of the ice margin, which is evident in Finland by the Salpausselkäs, far south of the preceding recession line (*Fig. 8*).

The question remains as to how long these advances and re-advances lasted, and whether it portrays a realistic scenario. For example, the recession of the ice margin in east-central Sweden occurred at an average rate of 200–300 m/y, with maximums of about 1000 m/y (Risberg *et al*. 1991). The distance of glacial retreat from the Palivere ice-marginal zone (dated at 11 800–11 630 BP; Raukas 1992a; Raukas 1992b; Raukas et al. 1994) to the recession line 80 km north of the Salppausselkäs — Heinola deglaciation (Rainio 1985) and including the distance to Salpausselkä I (dated by the revised Swedish varved clay chronology 11 100–11 300 BP years; Cato 1987; Strömberg 1990; Nenonen 1995) totals 300–330 km. The glacier needed to cover this distance within about 500 years, i.e. at a rate of 600–700 m/y. Using this average velocity to characterise the Palivere ice margin retreat and a minor oscillation 20–30 km northwestward, the Tahkuna-Audevälja Oscillation Phase was formed 40–50 years after the Palivere ice advance.

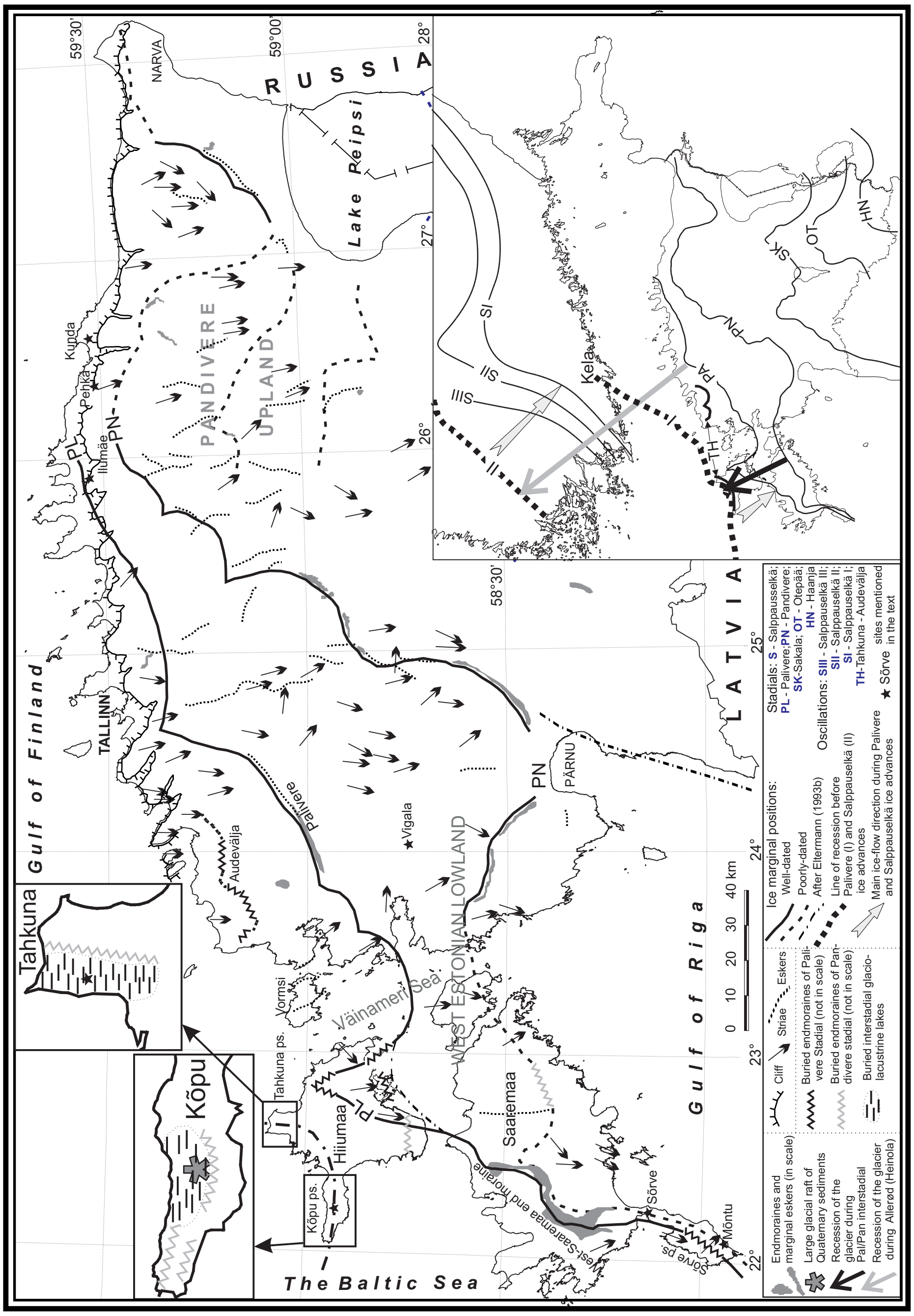

Figure 8. Palaeogeographical scheme of northwestern Estonia, modified from Rattas and Kalm 2004.

The distance of ice recession from Pandivere ice-marginal zone (Rattas and Kalm 2004), formed 12 480–12 230 BP years ago (Raukas 1992a), north of Kõpu Peninsula is 70–90 km. Adding the distance of glacier advance of Palivere Stadial (11 800 varve years ago or 11 630 BP years ago; Hang and Sandgren 1996; Raukas 1992a) yields 100–120 km. However, as suggested before, the Pan/Pal ice-free interstadial lasted at least 476 years (Hang and Sandgren 1996; Hang 1997). Therefore, the movement of the glacier margin between Palivere and Pandivere Stadials was at least 200–300 m/y, which is much slower than the ice margin movement from the Palivere line to Salppausselkä.

If the Pandivere Stadial ice margin was located southward in the Bay of Riga, as Eltermann (1993b) suggested, the velocity of ice-margin movement is 400 m/y, which is still slower than after the Palivere Stadial and Salpausselkä ice advance. Therefore we can not exclude that Pandivere ice margin could have been located south in Gulf of Riga.

Obviously the age of the Palivere Stadial maximum advance and following rapid melting of ice cover in northwestern Estonia suggested by T. Hang (1996) and T. Hang and P. Sandgren (1996) corresponds to the beginning of the warmer Allerød period (Pirrus and Raukas 1996). According to this study the Pan/Pal interstadial could exist as an earlier minor warming within the Older-Dryas (Liivrand *et al.* 1999).

CONCLUSIONS

Most of the Pleistocene sediments in northwestern Estonia were deposited during the Late-Weichselian deglaciation. In sites representing buried valleys in northern Estonian and on islands in the Gulf of Finland the general Pleistocene stratigraphy comprises sediments formed during two glaciations (Saalian and Weichselian). The oldest Late-Pleistocene sediments are represented by Eemian interglacial sediments, which were analysed sedimentologically and correlated within a wider territory (Estonia, Russia and Finland). The occurrence of interglacial Eemian deposits representing the Prangli/Rõngu Formation is the most optimal recognisable lower boundary of the Upper-Pleistocene. Eemian interglacial deposits studied in two new sites, Juminda Peninsula and Põhja-Uhtju Island, northern Estonia, distinguish deposits of different glaciations and divide sequences into Saalian and Weichselian deposits.

Upper-Pleistocene glacial stratigraphy of the West-Estonian Islands comprises three laterally spread till units, which are correlated event-stratigraphically to the Palivere and Pandivere ice-advances of the most recent (Late-Weichselian) glaciation. The two topmost diamictons are interpreted as genetic varieties of the Palivere till — waterlain melt-out and basal till. The Pandivere basal till is the lowermost widespread till on the islands, which lies unconformably between the Palivere till and carbonaceous bedrock. Additionally, the sporadically spread lenses of grey silty Tahkuna-Audevälja till were noted on a limited area on the Tahkuna Peninsula, Hiiumaa Island and a greenish-grey compact till of older, unknown age was found in the ancient valley on Sõrve Peninsula.

On the mainland of northwestern Estonia, northwest of the Palivere ice-marginal formations, only one laterally spread till unit was deposited during or after the Palivere Stadial. Similarly, only one laterally spread till unit is found on the Viru-Harju Plateau. The main differences in till sedimentology were distinguished between the area with the carbonaceous bedrock and the Foreklint Lowland area.

In the stratigraphy of Upper-Weichselian deposits in northwestern Estonia, the Pandivere/Palivere interstadial beds were appointed between Pandivere and Palivere till layers. The Upper-Weichselian lithostratigraphical scheme of Estonia was specified — two different lithostratigraphic units representing the Palivere beds and Tahkuna-Audevälja beds were added to the scheme.

Most of the Upper-Pleistocene stratigraphical units in the Estonian Quaternary stratigraphical scheme can be sedimentologically differentiated and correlated in the region. Correlation of lithostratigraphical units with those of southwestern Finland is proposed.

The distance of ice recession northwest of the Pandivere zone after 12 480–12 230 BP years must have been at least 70–90 km. The local Pandivere/Palivere (Pan/Pal) Late-Glacial interstadial was identified in northwestern

Estonia. Lacustrine interstadial Pan/Pal sediments separate the Palivere and Pandivere tills in Kõpu and on the Sõrve Peninsula, western Estonia and lie on the Pandivere till in front of the Palivere ice margin line at Ilumäe, northern Estonia. The ice advance (distance from Kõpu Peninsula where interstadial deposits were found) to the limit of maximum extent of the glacier during the Palivere Stadial dated 11 800–11 630 BP years ago must have been at least 30 km.

Following the Palivere Stadial, another ice–margin standstill and oscillation at Tahkuna-Audevälja line was distinguished in northwestern Estonia, represented by till and glaciofluvial deposits. Tahkuna-Audevälja Oscillation Phase represents a minor glacier advance (at least 5 km at western side of Tahkuna Peninsula, Hiiumaa Island) occurring about 50 years after the Palivere Stadial. The correlation of the Palivere and the Pandivere tills with southwestern Finland, south of Salpausselkä I formations, is proposed.

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REFERENCES

Andersen, B. and Mangerud, J. 1989. The last interglacial cycle in Fennoscandia. *Quaternary International,* **3/ 4**, 21–29.

Bedrock Geological Map of Estonia. 1997. Scale 1: 400 000. Compiled by Suuroja, K. Geological Survey of Estonia.

Battarbee, R. W. 1986. Diatom analysis. *In* Berglund, B.E. (ed.): *Handbook of Holocene Palaeoecology and Palaeohydrology,* 527–570, John Wiley & Sons.

Björck, S., Noe-Nygaard, N., Wolin, J., Houmark-Nielsen, M., Hansen, H. J. and Snowball, I. 2000. Eemian Lake development, hydrology and climate: a multi-stratigraphic study of the Hollerup site in Denmark. *Quaternary Science Reviews,* **19**, 509–536.

Bouchard, M.A., Gibbard, P. and Salonen, V.-P. 1990. Lithostratotypes for Weichselian and pre-Weichselian sediments in southern and western Finland. *Bulletin of the Geological Society of Finland,* **62**, 79–95.

Boulton, G. S., Dongelmans, P., Punkari, M. and Broadgate, M. 2001. Palaeoglaciology of an ice sheet through a glacial cycle: the European ice sheet through the Weichselian. *Quaternary Science Reviews,* **20**, 591–625.

Cato, I. 1987. On the definitive connection of the Swedish time scale with the present. *Sveriges geologiska Undersökning,* Ca **68***,* 55 pp.

Chemekov, Y. 1987. Geomorphological methods. *In* Ganeshin, G. S. (ed.): *Manual on methods to be used in the studies and geological survey of the Quaternary deposits, 137*–143. Nedra. (in Russian).

Cheremisinova, E. A. 1961. Diatoms of the marine interglacial deposits in the Estonian SSR. *Doklady Akademii Nauk SSSR,* **141** (3), 698–700 (in Russian).

Donner, J. 1995. *The Quaternary History of Scandinavia.* World and Regional Geology 7. Cambridge: Cambridge University Press. 200 pp.

Donner, J. and Jungner, H. 1974. Errors in the radiocarbon dating of deposits in Finland from the time of deglaciation. *Bulletin of the Geological Society of Finland*, **46**, 139–144.

Ehlers, J. 1990. Reconstructing the dynamics of the North-West European Pleistocene Ice Sheets. *Quaternary Science Reviews*, **9**, 71–83.

Ehlers, J. 1996. *Quaternary and glacial geology.* John Wiley & Sons. 578 pp.

Eltermann, G. 1993a. Hiiumaa geoloogi pilguga [New data on the geology of the Quaternary cover of Hiiumaa island]. *Eesti Loodus*, **3**, 103–105.

Eltermann, G. 1993b. Mandriliustiku hääbumine Lääne-Eesti saartel [Retreat of the Continental Ice Sheet on the West Estonian islands]. *Eesti Loodus*, **5/6**, 218–218.

Glückert, G. 1990. Yngre Dryaslinjen in Finland [The Younger Dryas line in Finland]. *Publicationes of the department of Quaternary geology.* University of Turku, **65**, 19 pp.

Hammen, T. van der, Maarleweld, G. C., Vogel, J. C. and Zagwijn, W. H. 1967. Stratigraphy, climatic succession and radiocarbon dating of the last glacial in the Netherlands. *Geologie en Mijnbouw,* **46** (3), 79–95.

Hang, T. 1996. Clay-varve chronology and the possible correlation with the St. Petersburg area and the Swedish time scale. *The Third Baltic Stratigraphical Conference. Abstracts and Field Guide.* Tartu. 136–139.

Hang, T. 1997. Clay varve chronology in the Eastern Baltic area. *GFF,* **119**, 295–300.

Hang, T. and Sandgren, P. 1996. Magnetostratigraphy of varved clays. *In* Meidla, T., Puura, I., Nemliher, J., Raukas, A. and Saarse, L. (eds.): *The Third Baltic Stratigraphical Conference. Abstracts. Field Guide,* Tartu, 152–154 (Abstract).

Hirvas, H. and Nenonen, K. 1985. The till stratigraphy of Finland. *In* Saarnisto, M. (ed): *INQUA till symposium, Finland 1985, Excursion guide*, *Geological Survey of Finland,* 19–38.

Hirvas, H. and Nenonen, K. 1987. The till stratigraphy of Finland. *Geological Survey of Finland, Special Paper* **3**, 49–63.

Hirvas, H., Lintinen, P., Lunkka J.P., Erikson, B. and Grönlund, T. 1995. Sedimentation and lithostratigraphy of the Vuosaari multiple till sequence in Helsinki, southern Finland. *Bulletin of the Geological Society of Finland*, **67**, 51–64.

Hütt, G., Jaek, I. and Vasilchenko, V. 2001. Photoionization of radiation- induced traps in quartz and alkali feldspars. *Applied Radiation and Isotopes* **54** (1), 175–182.

Ilves, E., Liiva, A. and Punning, J.-M. 1974. *Radiocarbon dating in the Quaternary Geology and Archaeology of Estonia.* Tallinn, Academy of Sciences of the Estonian SSR, 231 pp (in Russian).

Jürjens, E. 1988. *Ida-Saaremaa loodeosa kvaternaarigeoloogia [Quaternary geology of NW part of western Saaremaa].* Diploma Thesis, Tartu University, 80 p (unpublished).

Kadastik, E. 1994. About distribution, formation and lithological composition of tills on Hiiumaa Island, NW Estonia. *Bulletin of the Geological Survey of Estonia*, **4** (1), 4–11.

Kadastik, E. 1995. Texture and mineralogical characteristics of Weichselian till on Saaremaa Island. *Bulletin of the Geological Survey of Estonia*, **5** (1), 4–11.

Kadastik, E. 1996. *Comparative lithological analysis of till types and Late Glacial palaeogeography in West Estonian islands. MSc* thesis. University of Tartu, Estonia, 62 pp. (unpublished, in Estonian)

Kadastik, E. 1998. Buried end-moraine ridges of Pandivere stage (Late-Weichselian) on Hiiumaa Island, Western Estonia. *In*: Field Symposium on Glacial Processes and Quaternary Environment in Latvia. Abstracts of papers and posters. University of Latvia, Riga, 27–28 (Abstract).

Kadastik, E. and Eltermann, G. 1994. Cross-sections of the Quaternary deposits. Scale 1: 50 000. Appendix 3. Sheet 10. *In* Report of geological mapping of Hiiumaa in scale 1: 50 000 (unpublished report of Geological Survey of Estonia).

Kadastik, E. and Kalm, V. 1998. Lithostratigraphy of Late Weichselian tills on the West Estonian Islands. *Bulletin of the Geological Society of Finland,* **70** (1–2), 5–17.

Kadastik, E. and Kalm, V. 2001. Vormsi saare pinnakatte geoloogiast [Quaternary deposits on Vormsi Island]. *Maritima,* **5**, 29–34.

Kadastik, E. and Ploom, K. 2000. Pleistocene deposits and deglaciation of the Nõva-Padise area (NW Estonia). *Bulletin of the Geological Survey of Estonia,* **9**(1), 4–10.

Kadastik, E., Kalm, V., Liivrand, E., Mäemets, H. and Sakson, M. 2003. Stratigraphy of a site with Eemian interglacial deposits in north Estonia. *GFF*, **125**, 229–236.

Kajak, K. 1961. Prangli saare Kvaternaasete setete tüüpprofiil [Type section of Quaternary deposits on Prangli Island]. *In* VI Eesti loodusuurijate päev. Ettekannete teesid, Tartu, 21–24 (Abstract).

Kajak, K. 1996. *Quaternary type sections in Estonia (Pleistocene).* Geological Survey of Estonia, Report of the Information department. 20 pp. (unpublished).

Kalm, V. and Kadastik, E. 2001. Waterlain glacial diamicton along the Palivere ice-marginal zone on the West Estonian Archipelago, Eastern Baltic Sea. *Proceedings of Estonian Academy of Sciences. Geology,* **50**, 2, 114–127.

Kalm, V., Aruväli, J. and Einmann, A. 1992. Clay mineralogy of surficial fine-grained Quaternary deposits on Saaremaa Island, Western Estonia. *Acta et Commentationes Universitatis Tartuensis*, **956**, 95–113.

Kalnina, L. and Jushkevics, V. 1998. Late-Pleistocene lithostratigraphy and palaeo-environment in Latvia. *Geologija,* **25**, 39–48.

Kalnina L, Dreimanis A and Murniece S. 2000. Palynology and lithostratigraphy of Late Elsterian to Early Saalian aquatic sediments in the Ziemupe-Jurkalne area, western Latvia. *Quaternary International*, **68**, 87–109.

Karukäpp, R. and Raukas, A. 1997. Deglaciation history. *In* Raukas, A. Teedumäe, A. (eds): *Geology and Mineral Resources of Estonia.* Tallinn, Estonian Academy Publishers, 263–267.

Karukäpp, R., Raukas, A. and Hyvärinen, H. 1992. Deglaciation of the area. *In* Raukas, A. and Hyvärinen, H. (eds): *Geology of the Gulf of Finland,* 112–136 (in Russian).

Karukäpp, R., Moora, T. and Pirrus, R. 1996. Geological events determining the Stone age environment of Kunda. *PACT*, **51**, 219–229.

Kukla, G. J., Bender, M.J., Beaulieu, J.-L., Bond, G., Broecker, W.S., Cleveringa, P., Gavin, J. E., Herbert, T. D., Imbrie, J., Jouzel, J., Keigwin, L. D., Knudsen, K. -L., McManus, J. F., Merkt J., Muhls, D.R, Müller, H., Poore, R. Z., Porter, S. C., Seret, G., Shackleton, N. J., Turner, C., Tzedakis, P.C. and Winograd, I.J, 2002. Last interglacial climates. *Quaternary Research* **58**, 2–13.

Lepiksaar, J. 1992. Remarks on the Weichselian megafauna (Mammuthus, Coelodonta and Bison) of the "interglacial" area around the Baltic basin. *Annales Zoologici Fennici,* **28**, 229–240.

Lewis, D.W. and McConchie, D. 1994. *Analytical Sedimentology.* Chapman & Hall, 197 pp.

Liivrand, E. 1991. *Biostratigraphy of the Pleistocene deposits in Estonia and correlations in the Baltic area.* Ph.D. thesis, Report 19, Stockholm University, Department of Quaternary Research, Stockholm, Sweden. 114 pp.

Liivrand, E. 1990. *Methodical problems of the Pleistocene palynostratigraphy.* Tallinn. Valgus, 176 pp (in Russian with English summary).

Liivrand, E. 1976. Rebedded pollen and spores in Pleistocene deposits and their role in stratigraphy. *Palynology in continental and marine geologic investigations.* Riga. Zinatne, 166–178 (in Russian with English summary).

Liivrand, E., Kalm, V. and Kadastik, E. 1999. New data of the Late Glacial stratigraphy in Estonia. *In* Luksevics, E., Stinkulis, G. and Kalnina, L. (eds.) *The Fourth Baltic Stratigraphical Conference. Problems and Methods of Modern Regional Stratigraphy. Abstracts.* Riga, 52–53 (Abstract).

Lundquist, J. 1989. Late glacial ice lobes and glacial landforms in Scandinavia. In: Goldthwait and Matsch (eds). *Genetic claccification of glacigenic deposits,* 217–225. A. A. Balkema: Rotterdam.

Lougas L, Ukkonen P. and Jungner H. 2002. Dating the extinction of European mammoths: new evidence from Estonia. *Quaternary Science Reviews,* **21** (12–13), 1347–1354.

Miettinen, A., Rinne, K., Haila, H., Hyvarinen, H., Eronen, M., Delusina, I., Kadastik, E., Kalm, V. and Gibbard, P. 2002. The marine Eemian of the Baltic: new pollen and diatom data from Peski, Russia, and Põhja-Uhtju, Estonia. *Journal of Quaternary Science,* **17**, 445–458.

Miidel, A. 1997. Escarpments and waterfalls. *In* Raukas, A. and Teedumäe, A. (eds.): *Geology and Mineral Resources of Estonia*. 392–395. Estonian Academy Publishers.

Männil, R. 1962. Jääkriimude suunast Eestis [Directions of ice-striae in Estonia]. *In*: *Eesti Geograafia Seltsi aastaraamat 1960/61*, Estonian Geographical Society, Tallinn, 13–28 (in Estonian).

Müller, H. 1974. Pollenanalytische Untersuchungen und Jahresschichtenzahlung an der eem-zeitlichen Kieselgur von Bispingen/Luhe. *Geologisches Jahrbuch, A **21***, 149–169.

Nenonen, K. 1995. *Pleistocene stratigraphy and reference sections in Souhern and Western Finland.* Academic Dissertation. Kevama Graf: Kuopio, 94 p.

Noormets, R. and Floden, T. 2002. Glacial deposits and Late Weichselian ice-sheet dynamics in the northeastern Baltic Sea. *Boreas,* **31**, 36–56.

Pirrus, R. and Raukas, A. 1969. On the character and time of the last deglaciation of the territory of Estonia. *Voprosõ tshetvertitshnoi geologij,* **4**, 47–57 (in Russian).

Pirrus, R. and Raukas, A. 1996. Late-glacial stratigraphy in Estonia. *Proceedings of the Estonian Academy of Sciences, Geology,* **45** (1), 34–35.

Rainio, H. 1985. Förstra Salpausselkä utgör randzonen för en landis som avancerat pa nytt. *Geologi,* **37**, 70–77.

Raudsep, R. 1997. Mineral occurrences. *In* A. Raukas and A. Teedumäe (eds.) *Geology and Mineral Resources of Estonia*, 369–371. Estonian Academy Publishers.

Raukas, A. 1963. The lithology of Soviet Estonian moraines of a different age. *Trudõ Instituta Geologii Akademii Nauk, **12**, 3–21* (in Russian with Estonian and English summaries).

Raukas, A. 1978. *Pleistocene deposits of the Estonian SSR.* Tallinn, Valgus, 310 pp (in Russian with English summary).

Raukas, A. 1986. Deglaciation of the Gulf of Finland and adjoining areas. *Bulletin of The Geological Society of Finland*, **58**, 2, 21–33.

Raukas, A. 1991. Eemian interglacial record in the northwestern European part of the Soviet Union. *Quaternary International*, **10**–**12**, 183–189.

Raukas, A. 1992a. Late- and Postglacial Geological Development and Human Impact in Estonia. *In* Hackens, T., Lang, V. & Miller, U., (eds): *Estonia: Nature, Man and Cultural Heritage,* PACT **37**, 23–34. Rixensaart, Belgium.

Raukas, A. 1992b. Ice marginal formations of the Palivere zone in the eastern Baltic. *Sveriges Geologiska Undersökning*, Ser. Ca **81**, 277–284.

Raukas, A. 1995. Properties, origin and stratigraphy of Estonian tills. *In* Ehlers, J., Kozarski, S. and Gibbard, P. (eds.): *Glacial Deposits in North-East Europe*, 93–101. A.A. Balkema, Rotterdam, The Netherlands.

Raukas, A. and Gaigalas, A. 1993. Pleistocene glacial deposits along the eastern periphery of the Scandinavian ice sheets — an overview. *Boreas,* **22**, 214–222.

Raukas, A. and Kajak, K. 1995. Quaternary stratigraphy in Estonia*.* *Proceedings of the Academy of Sciences of Estonia, Geology*, **44**, 3, 149–162.

Raukas, A. and Kajak, K. 1997a. Ice ages. *In* Raukas, A. and Teedumäe, A. (eds.): *Geology and Mineral Resources of Estonia*. 256–262. Estonian Academy Publishers.

Raukas, A. and Kajak, K. 1997b. Quaternary cover. *In* Raukas, A. and Teedumäe, A. (eds.): *Geology and Mineral Resources of Estonia*. 125–136. Estonian Academy Publishers.

Raukas, A. and Karukäpp, R. 1978. Eesti liustikutekkeliste akumulatiivsete saarkõrgustike ehitus ja kujunemine. *In* Raukas, A. (ed.): *Eesti NSV saarkõrgustike ja järvenõgude kujunemine,* 9–28. Valgus, Tallinn.

Raukas, A. and Liivrand, E. 1971. Pleistocene deposits in the sequence of Vääna-Jõesuu borehole (North Estonia). *Eesti NSV Teaduste Akadeemia Toimetised, Keemia, Geoloogia* ***1****,* 60–72 (in Russian).

Raukas, A. and Rähni, E. 1966. Deglaciation during last Glacial in Estonian SSR. *In* Ezhegodnik Estonskogo Geografitsheskogo obshestva 1964/1965, 5–17. Valgus, Tallinn (in Russian).

Raukas, A., Rähni, E. and Miidel, A. 1971. *Marginal Glacial Formations in North Estonia*, Valgus, Tallinn, 226 pp. (in Russian).

Raukas, A., Kalm, V., Karukäpp, R. and Rattas, M. 2004. Pleistocene glaciations in Estonia. *In* Ehlers, J. and Gibbard, P. (eds): *Quaternary Glaciations — Extent and Chronology, Part 1: Europe,* 83–91. Elsevier, Amsterdam.

Rattas, M. and Kalm, V. 2004. Glaciotectonic deformation patterns in Estonia. *Geological Quarterly*, **48** (1), 15–22.

Rinne, K. T. 2002. Mariinisen Eem-kerrostuman siitepolyanalyysi: Põhja-Uhtju, Viro. *MSc* Thesis, Helsinki University, 77 pp. (unpublished).

Risberg, J., Miller, U. and Brunnberg, L. 1991. Deglaciation, Holocene shore displacement and coastal settlements in eastern Svealand, Sweden. *Quaternary International,* **9**, 33–37.

Saarnisto, M. and Salonen, V.-P. 1995. Glacial history of Finland. *In* Ehlers, J., Kozarski, S. Gibbard, P. (eds): *Glacial deposits in North-East Europe*, 3–10. A.A. Balkema, Rotterdam.

Salonen, V.-P. and Glückert, G. 1992. Late Weichselian glacial activity and sediments in southwestern Finland. *Sveriges Geologiska Undersöknung*, Ser. Ca **81**, 313–318.

Strömberg, B. 1990. A connection between the clay varve chronologies in Sweden and Finland. *Annales Academiae Scientarium Fennicae,* **A154**, 1–32.

Suuroja, K. 1997. Eesti aluspõhja geoloogiline kaart. Mõõtkavas 1: 400 000. Seletuskiri [*The bedrock geological map of Estonia. Scale 1: 400000*. Explanatory note]. Tallinn, 60 pp.

Tavast, E. and Raukas, A. 1982. *The bedrock relief of Estonia.* Valgus, Tallinn, 194 pp. (in Russian).

Thomson, P.W. 1935. Vorläufige Mitteilung über die spätglaziale Waldgeschichte Estlands. *Geologisk Föreningen Stockholm Förhandlinger*, **57**, 84–92.

Vilo, A. 1971. *Ehitusgeoloogia [Engineering Geology*]. Tallinn, 110 pp. Wentworth, C.K. 1936. The method of moments. *Journal of Sedimentary Petrology*, **6**, 158–159.

Woillard, G. M. 1979. Abrupt end of last interglacial s.s. in north-east France. *Nature,* ***281***, 558–562.

SUMMARY IN ESTONIAN

Ülem-Pleistotseeni stratigraafia ja liustiku taandumine Loode-Eestis

Käesolev väitekiri põhineb viiel publikatsioonil, mis kõik käsitlevad Hilis-Pleistotseenis, eriti Hilis-Weichseli ajal kujunenud setete stratigraafiat, litostratigraafiat ning Loode-Eesti paleogeograafiat (*joon. 1*). Moreenide litostratigraafia uurimisel on kasutatud materjali, mis on saadud Põhja- ja Lääne-Eesti territooriumi kompleksse geoloogilise kaardistamise käigus aastatel 1987–2000. Koondatud on ligikaudu 5500 pinnakatte puuraugu ja 1335 erinevate meetoditega analüüsitud setteproovi andmestik. Stratigraafia uurimiseks kasutati erinevaid sedimentoloogilisi (lasumistingimused, terasuurus, kivimiline, mineraalne, keemiline, savifraktsiooni mineraalne koostis) ja vähesemal määral ka bio- ja kronostratigraafilisi meetodeid (õietolmu-, diatomee- ning OSL-analüüs). Paleogeograafiliste järelduste tegemiseks kasutati hulgaliselt geomorfoloogilisi meetodeid, rohke puuraukudest saadud geoloogiline materjal võimaldas esmakordselt ka kaardistada ning uurida mattunud pinnavorme ning analüüsida nende tekkimise põhjuseid.

Hilis-Pleistotseeni jäätumise moreenid on Eestis laialt levinud. Stratigraafiliselt on Hilis-Pleistotseeni algus on hästi piiritletud Eemi mere e. Prangli/Rõngu kihistu interglatsiaalsete setetega, mille levikuala ja stratigraafilised tunnused on täpsemalt määratletud. Käesoleva töö tulemusena on senisele ainsale tõestatud Eemi setete leiukohale Loode-Eestis (Prangli) lisandunud veel kaks — Põhja-Uhtju ja Juminda-2, mis on ka korrelleeritavad teiste samas piirkonnas uuritud läbilõigetega ja millest saadud andmestik on võimaldanud täpsustada kunagise Eemi mere levikut ja iseloomu (*joon. 2*). Prangli kihistu setete lamami ja lasumi litostratigraafilised tunnused on ülekantavad ka laiemale territooriumile ja seetõttu võime kindlalt väita, et kõik lateraalselt levinud Loode-Eesti glatsiaalsed setted on moodustunud Hilis-Pleistotseenis ja kuuluvad kohaliku stratigraafilise skeemi järgi Ülem-Pleistotseeni Järva kihistu Võrtsjärve alamkihistusse. Võrtsjärve alamkihistu moreenid jagunevad Loode-Eestis Palivere ja Pandivere morfostratigraafilisteks kihtideks. Pandivere moreen on peamiselt esindatud põhimoreeniga, Palivere moreen põhi- ja basseinimoreeniga. Kõik väljaeraldatud moreenitüübid erinevad selgelt üksteisest ja on saanud litostratigraafilise põhjenduse. Pandivere staadiumi moreeni koostise kujunemisele on avaldanud teistest moreenitüüpidest enam mõju kohalik karbonaatne aluspõhi. Sellele moreenile on iseloomulik suurim keskmine terasuurus, jämepurdse materjali osakaal ja kõrgeim karbonaatsete kivimite ja mineraalide sisaldus. Palivere staadiumi moreenides on väiksem keskmine terasuurus ning kõrgem tard- ja moondekivimite ning silikaatse materjali osakaal (*joon. 3, 4*). Nii distaalsel kui proksimaalsel pool Palivere staadiumi servamoodustiste vööndit on kaardistatud savika basseinimoreeni sporaadiline levik. Basseinimoreen ladestus liustiku servavööndis, kus jää ei olnud enam aluspinnaga kontaktis ja liustiku pideva basaalse sulamise tulemusel vabanenud purdmaterjal settis läbi veekihi. Kivimiline, mineraalne ja keemiline koostis viitavad basseinimoreeni ja Palivere põhimoreeni sarnasele lähtematerjalile (Kalm ja Kadastik 1998 — PAPER IV). Palivere ja Pandivere moreenid on teineteisest eraldatud interstadiaalsete setetega Kõpu poolsaarel (*joon. 5*), Mõntus ning Sõrves. Mandrialale on nimetatud setted korrelleeritavad interstadiaalsete setetega Ilumäel (*joon. 6*). Töö tulemusena on esitatud senisest täiuslikum Ülem-Pleistotseeni litostratigraafiline skeem. Loode-Eestis välja eraldatud moreenitüübid on korrelleeritavad vastavate litostratigraafiliste üksustega Edela-Soomes (*joon. 7*).

Eesti territoorium vabanes viimasest mandrijääst ligikaudu 14 000 kuni 11 500 aastat tagasi. Tänu massilistele sedimentoloogilistele uuringutele on õnnestunud esmakordselt lisaks tavapärastele uuringutele avastada Holotseeni ja hilisglatsiaalsete setete alla mattunud liustikulised pinnavormid ja kasutada saadud informatsiooni paleogeograafiliste järelduste tegemisel. Hilis-Weichseli liustikujää taandumisele Loode-Eesti piirkonnas olid omased pidevad liustikuserva asendi fluktuatsioonid. Interstadiaalsete setete väljaeraldamine Kõpu poolsaarel Palivere ja Pandivere moreenide vahel võimaldab väita, et Pandivere jää taganes enne Palivere staadiumi vähemalt 70–90 km kaugusele praegusest Pandivere servaasendist ja Palivere jää tungis peale vähemalt 30 km kaugusele sellest piirist (*joon. 8*). Peale Palivere liustikujää pealetungi seiskus jääserv veel Tahkuna–Audevälja joonel ning toimus väiksemamahuline ostsillatsioon, kus liustikujää servamoodustiste vöönd on jälgitav Palivere servamoodustiste vööndist 20–30 km põhja pool. Tahkuna–Audevälja vöönd on selgemini eristatav Tahkuna poolsaare lääneosas, kus liustikujää ostsillatsiooniga seotud glatsigeensete setete sporaadiline levik on kindlaks tehtud 5 km laiuses vööndis.

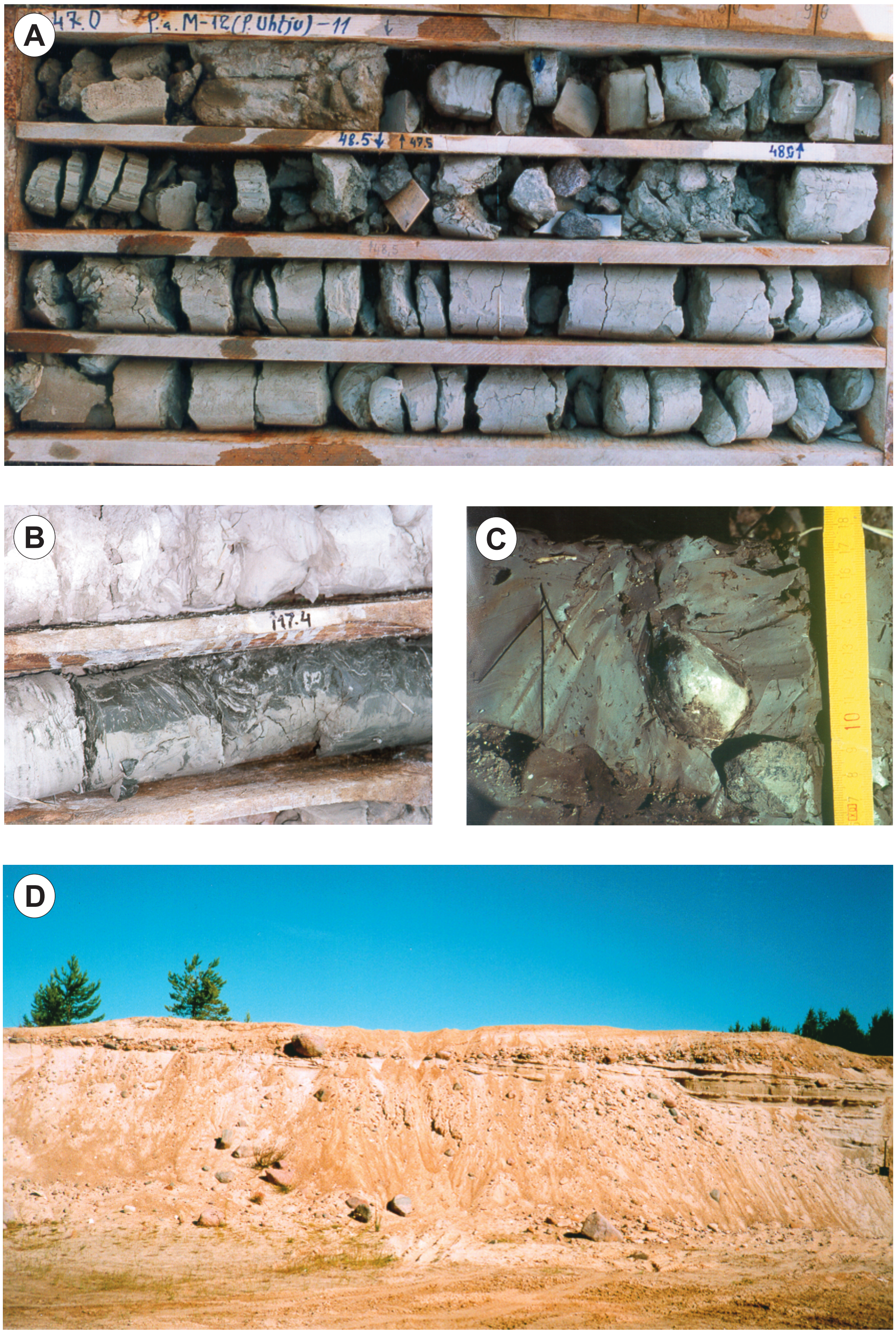

PLATE I. A — Eemian silt in Põhja-Uhtju drillcore at a depth of 48.8–51.4 m. Photo by Tõnis Saadre; B — Deformed Upper-Weichselian glaciolacustrine clay in Prangli drillcore (depth 18 m); C — Waterlain melt-out till, Kidaste, Hiiumaa Island. Arrow indicates north on horizontal level. Photo by Volli Kalm; D — Glaciofluvial sand with gravel of Tahkuna-Audevälja oscillation, Malvaste pit, Tahkuna, Hiiumaa Island. Photo by Tõnis Saadre.

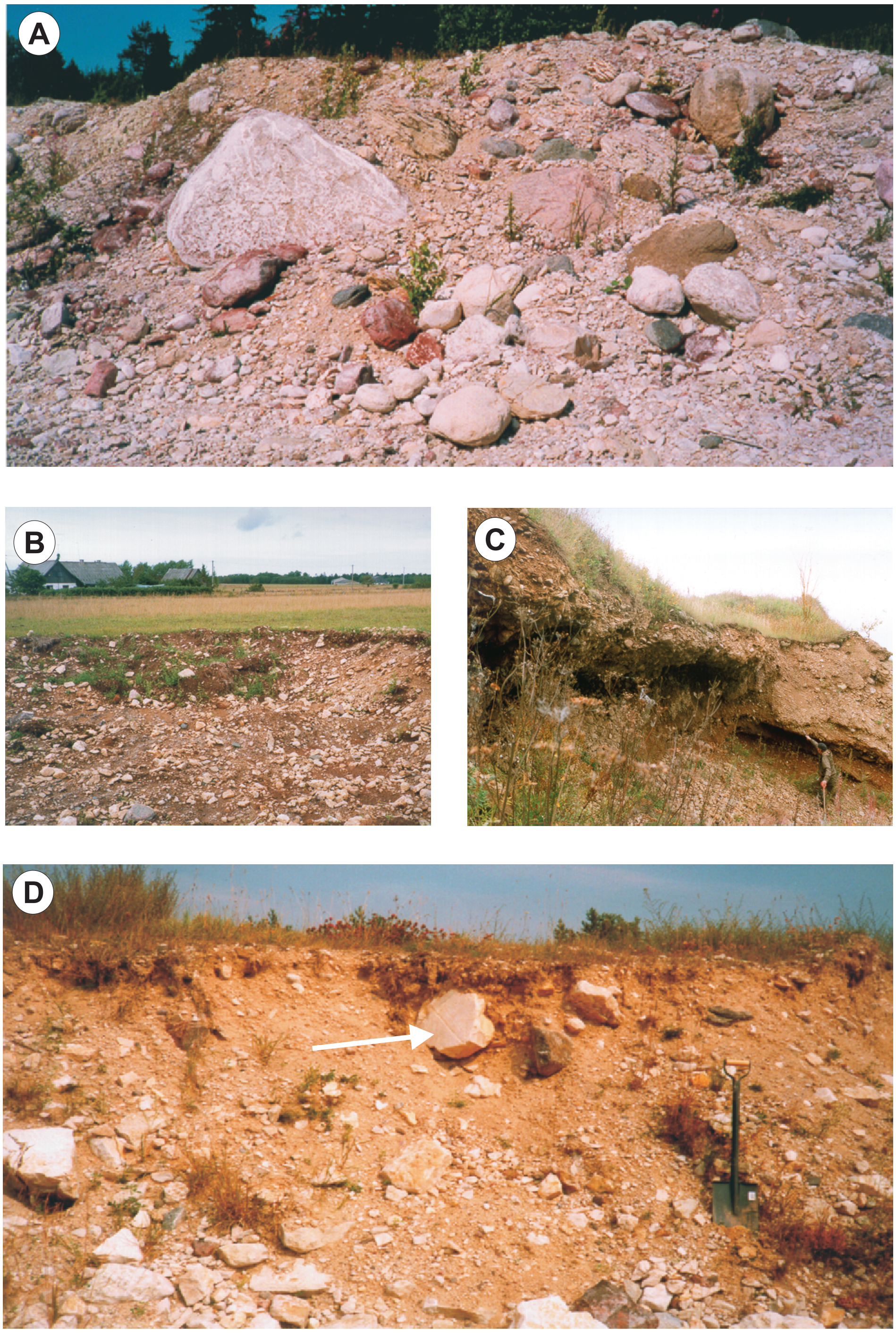

PLATE II. A — Ice-marginal deposits at Palivere zone; B — Pandivere Till rich in carbonate clasts on Pandivere Upland, northern Estonia; C — Upper-Weichselian glaciofluvial conglomerate at Pehka site, northern Estonia. Below this gravel the Middle-Weichselian sand was determined. Photo by Tõnis Saadre; D — Till rich in carbonate clasts in endmoraine of Palivere Stadial, southern part of Hiiumaa Island. Striated limestone raft has been carried here by ice from a place located 15 km northward.

PUBLICATIONS

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LIST OF OTHER PUBLICATIONS

1. **Kadastik, E**., 1994. About distribution, formation and lithological composition of tills on Hiiumaa Island, NW Estonia. *Bulletin of the Geological Survey of Estonia*, 4/1, 4–11.
2. **Kadastik, E**., 1995. Texture and mineralogical characteristics of Weichselian till on Saaremaa Island. *Bulletin of the Geological Survey of Estonia*, 5/1, 4–11.
3. **Kadastik, E**. 1996. Moreenitüüpide võrdlev litoloogiline analüüs ja hilisglatsiaali paleogeograafia Lääne Eesti saartel. *MSc* thesis. University of Tartu, Estonia, 62 pp (unpublished)
4. **Kadastik, E**. and Kalm, V., 1997. Lithology and stratigraphy of Weichselian tills in the Lahemaa National Park area, Northern Estonia. *The Late Pleistocene in Eastern Europe: Stratigraphy, Palaeoenvironment and Climate*. Abstract Volume and Excursion Guide of the INQUA-SEQS Symposium. Vilnius, 28.
5. Kalm, V. and **Kadastik, E**., 1997. Glaciomarine deposits along the Palivere ice-marginal zone, West-Estonian Islands. In: *Quaternary Deposits and Neotectonics in the Area of Pleistocene Glaciations.* Abstract volume of the field symposium, May, 12–16, 1997, Belarus, Minsk, 21.
6. **Kadastik, E**., 1998. Buried end-moraine ridges of Pandivere stage (Late-Weichselian) on Hiiumaa island, Western Estonia. *Field Symposium on Glacial Processes and Quaternary Environment in Latvia.* Abstracts of papers and posters. University of Latvia, Riga, 27–28.
7. **Kadastik, E.** 1999. Stratigraphy of Pleistocene deposits in ancient valleys in the central part of North-Estonia. In: Kirsimäe, K. & Ainsaar, L. (eds.). *Field symposium on Pleistocene Stratigraphy and Glacial Chronology: Southern Estonia.* Abstract Volume. Tartu, May 18–23, 13–14.
8. Liivrand, E., **Kadastik, E.,** Kalm, V. 1999. New data on the Late Glacial stratigraphy in Estonia. In: Luksevics, E., Stinkulis, G. & Kalnina, L. (Eds.). *The 4^{th} Stratigraphical Conference. Problems and methods of modern regional stratigraphy.* Abstracts. Jurmala, Latvia, September 27-October 2, 52–53.
9. **Kadastik, E.,** Suuroja, K. 1999. Maakondlikest maavarade säästliku kasutamise kontseptsioonidest Hiiumaa näitel. In: Puura, I. (ed.). *Kolmas Eesti Geoloogide Ülemaailmne Kokkutulek. Eesti maavarad.* Sümpoosiumi materjalid ja ekskursioonijuht. Eesti Geoloogia Seltsi Toimetised, 4, 10–11.
10. **Kadastik, E.,** Kalm, V. 2000. Stratigraphy of glacial deposits on Sõrve Peninsula, Saaremaa Island, western Estonia. In: *International Field Symposium on Quaternary Geology of Denmark,* August 29 – September 3, 2000, University of Aarhus, Denmark, Abstracts.
11. **Kadastik, E.** 2001. Lithology of Late-Pleistocene glacial deposits and ice-marginal formations of NorthWestern Estonia. In: *Field Symposium on Quaternary Geology in Lithuania.* Abstract volume, 19–25 May 2001, 23–24.

12. **Kadastik, E**., Kalm V. 2001. Vormsi saare pinnakate geoloogiast. *Estonia Maritima* 5, 29–34.
13. **Kadastik, E.** 2002. Pleistocene stratigraphy in Juminda Peninsula, North Estonia. In: *Field Symposium on Quaternary geology and geodynamics in Belarus*, 20–25 May 2002, Grodno. Abstract Volume, Minsk, 21–22.
14. **Kadastik, E.** 2003. Influence of the crater structure on the development of Quaternary cover on Hiiumaa Island, Estonia. In: *International Symposium on Human Impact and Geological Heritage*, 12–17 May 2003, Tallinn: Excursion Guide and Abstracts, 73–74.