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Chronology of the Weichselian Glaciation in the southeastern sector of the Scandinavian Ice Sheet

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CONTENTS

LIST OF ORIGINAL PUBLICATIONS

This thesis is based on the following published papers, which are referred to in the text by their Roman numerals. The papers are reprinted by kind permission of the publishers.

I. **Lasberg, K**., Kalm, V., Kihno, K., 2014. Ice-free intervals corresponding to Marine Isotope Stages 4 and 3 at the Last Glacial Maximum position at Kileshino, Valdaj Upland, Russia. Estonian Journal of Earth Sciences (accepted for publication).

II. Kalm, V., Raukas, A., Rattas, M., **Lasberg, K**., 2011. Chapter 8 – Pleistocene Glaciations in Estonia. Ehlers, J., Gibbard, P.L., Hughes, P.D. (Eds.). Quaternary Glaciations – Extent and Chronology – A Closer Look (95–104). Amsterdam, the Netherlands: Elsevier.

III. **Lasberg, K**., Kalm, V., 2013. Chronology of Late Weichselian glaciation in the western part of the East European Plain. Boreas, 42(4), 995–1007.

Author's contribution

Paper I: The author contributed to fieldwork and sampling, was responsible for data analysis and interpretation and the writing of the manuscript.

Paper II: The author contributed to fieldwork and sampling for obtaining additional chronological data, was responsible for upgrading the chronological database and revision of chronostratigraphy and complemented the writing of the manuscript.

Paper III: The author was responsible for upgrading the chronological database, revision of chronological data and selection of dates for the development of chronology, data analysis and interpretation and the writing of the manuscript.

ABBREVIATIONS

SIS	Scandinavian Ice Sheet
LGM	Last Glacial Maximum
ISC	ice stream complex
MIS	Marine Isotope Stage
SU	sedimentary unit
AMS	refers to the radiocarbon dating by accelerator mass spectrometry
^{14}C	refers to radiocarbon
^{10}Be	refers to cosmogenic beryllium
OSL	refers to optically stimulated luminescence
TL	refers to thermoluminescence
ESR	refers to electron spin resonance
ka	thousand years
m a^{-1}	metres per year
cal. ^{14}C BP	calibrated radiocarbon age (calendar years), reported ‘Before Present’ (before year 1950)

1. INTRODUCTION

As acknowledged by the Intergovernmental Panel on Climate Change, vulnerability of Greenland and Antarctica to on-going global warming and related discharge feedbacks remains a major source of uncertainty in projected sea-level rise. To understand this uncertainty, determining the responses of past ice sheets to climate changes, their expansion and demise histories and effect on deglacial sea-level change are of utmost importance. The behaviour of global ice volume during the Last Termination is recorded in sea-level fluctuations in response to the collapse of ice sheets caused by warming (Fairbanks 1989; Yokoyama *et al.* 2000; Tarasov & Peltier 2005; Clark *et al.* 2009). However, the exact chronology, origin and consequences of these ice-sheet melting episodes remain unclear (Carlson & Clark 2012; Deschamps *et al.* 2012), partly because of temporally poorly constrained ice volume and coverage models and because of different behaviour of individual ice sheets. As improvements in the modelling of ice sheets is possible only through the improved constraints on the ice margin histories (Lambeck et al. 2010; Shepherd *et al.* 2012), further work is needed to understand available chronologies and to build new, direct (if possible) ones. The current thesis contributes to these activities by reviewing available and adding new chronometric data to the knowledge about the behaviour of ice sheets on the East European Plain during the Weichselian Cold Stage, with the aim of better understanding of the unified history and forcing mechanisms of Scandinavian Ice Sheet (SIS). The study area of the thesis encompasses the SE sector of the SIS between the Baltic Sea and the Last Glacial Maximum (LGM) position in the western part of the East European Plain.

The Weichselian Glaciation is most extensively studied. Still, the occurrence of Early to Middle Weichselian glaciation in this region remains controversial because the advancing ice sheet has a great destructive potential for soft unconsolidated sediments and most of the sediments of former glaciations have been removed. However, evidence of glacial sediments attributed to the Middle Weichselian has been found in several sites in northern, central and eastern Europe: southern Finland (Nenonen 1995), Estonia (Liivrand 1991), Latvia (Zelčs & Markots 2004), Lithuania (Molodkov *et al.* 2010), Poland (Marks 1998, 2004) and Denmark (Houmark-Nielson 2007). Nevertheless, opinions about the extent of the SIS during the Middle Weichselian glaciation are contradicting. Some studies claim that the SIS reached the western part of the East European Plain during MIS 4 (74–59 ka) (Arslanov 1993; Zarrina 1991), but others suggest that the SIS did not extend beyond the Baltic Sea depression and Russian Karelia during that time (Chebotareva & Macarycheva 1982; Demidov *et al.* 2004; Guobyte & Satkūnas 2011; Velichko *et al.* 2004, 2011). Since the chronological data concerning the glaciation during the Middle Weichselian in the study area are also scanty, especially from the region close to the Valdai Upland at the LGM position, further research is required to improve the chronology of the SIS advance.

More is known about the last glaciation as many studies have focused on the timing of the Late Weichselian ice advance and deglaciation. Most of these studies, however, are country-based contributions and chronological data are therefore unevenly distributed. For this reason the timing of the advance of the last SIS and its arrival at the position of the LGM are continuously debated. According to the most widely accepted view (Demidov *et al.* 2006; Rinterknecht *et al.* 2006; Wysota *et al.* 2009; Marks 2010), the SIS did not reach the LGM position isochronously and occurred at different times in the southeastern area of the Scandinavian glaciation.

More data have been published on the recession of the last SIS than on its advance. However, studies do not cover the entire SE sector of the Scandinavian glaciation. Many authors (Kalm 2006, 2012a; Rinterknecht *et al.* 2006, 2007, 2008; Raukas 2009; Satkūnas *et al.* 2009; Guobytė & Satkūnas 2011; Zelčs *et al.* 2011; Bitinas 2012) have provided ages for ice recession stadials in the western part of the East European Plain over the years, but opinions concerning the positions of ice-marginal zones, their ages and correlations are controversial. The problem could partly stem from the variety of dating methods and dated material/sediments as most of the methods are indirect and reflect rather the age limits.

A persistent problem in glacial geology and geomorphology has been the acquisition of suitable material for dating and the accuracy of obtained ages. The usage of the radiocarbon (^{14}C) method is limited because very often datable organic material is lacking in glacial terrain or specific landforms and only ages up to ~45 ka can be obtained with this method. Recent advent of optical luminescence and cosmogenic dating resolves the necessity to find organic material and instead the age of the deposition of sediments and erratic boulders is evaluated. Radiocarbon, optically stimulated luminescence (OSL), thermoluminescence (TL) and cosmogenic beryllium (^{10}Be) dates were available for the current review to evaluate the chronology of the Weichselian glaciation in the SE part of the SIS. However, the distribution of dates is uneven in both spatial and temporal sense in the study area; the interpretations of the ice sheet behaviour are conflicting.

These uncertainties have necessitated the revision of the chronological data. The main goal of the current thesis was to assess the behaviour of the SIS during the Weichselian Glaciation on East European Plain through the collection, review and synchronozation of all available chronological data.

The specific objectives of this research were:

- to determine the duration of the ice-free period before the last glaciation;
- to establish an overall chronology for the last SIS advance;
- to refine a deglaciation chronology in conjunction with the current understanding of the ice-flow pattern;
- to determine overall rates of ice-sheet advance and recession necessary for understanding the subglacial processes and further modelling of ice sheets.

2. BACKGROUND

2.1. Last glacial cycle and extension of the Scandinavian Ice Sheet in its southeastern sector

The last, best-studied glacial cycle is a key period for understanding the Earth's response to orbital (Milankovitch events) and other forcing of the climate (Mangerud 1991). This cycle started about 130 ka years ago with a warm stage, named the Eemian interglacial stage in central and northern Europe (Mikulino in eastern Europe) and is traditionally correlated with Marine Isotope Stage (MIS) 5e (Fig. 1). During this interglacial stage the Eemian Sea covered a larger area than the present Baltic, White and Barents seas. This has been explained by the greater extent and thickness of the Saalian ice sheets compared to the Weichselian ice sheets and the different deglaciation histories of these periods (Ehlers 2007).

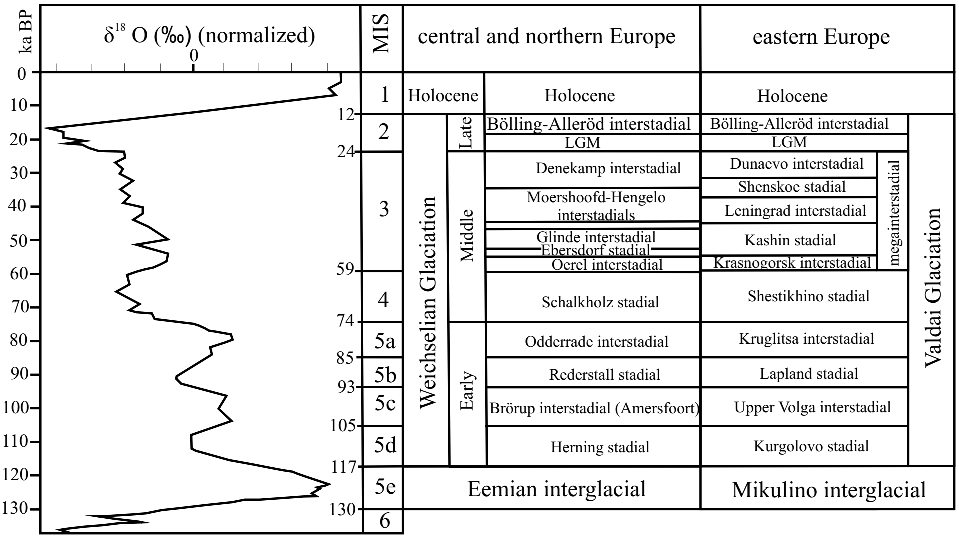


Fig. 1. Stacked marine oxygen isotope record of the last glacial cycle from Martinson *et al.* (1987) with marine isotope stages (MIS) and correlation with terrestrial chronostratigraphy of the last glacial cycle in central, northern and eastern Europe. Compiled according to Behre (1989), Mangerud (1991), Arslanov (1993) and Velichko *et al.* (2011).

The last cold stage, known as the Weichselian in northern Europe, Würm in central Europe (Alps) and Valdai in eastern Europe, started about 117 ka ago and is correlative with the Wisconsin Glaciation in North America. During the Weichselian Glaciation, which lasted about 105 ka, the SIS advanced several times further from the glaciation centre in the northern Bothnia Bay area in Scandinavia, covering the whole of Fennoscandia, northwestern Russia and northern continental Europe, and coalesced with the Barents and British Ice Sheets. The Weichselian Cold Stage (Weichselian Glaciation) is usually divided into the Early (Lower) Weichselian (MIS 5d-5a), Middle Weichselian (MIS 4 and 3) and Late (Upper) Weichselian (MIS 2) Substages. The climate fluctuated throughout the Weichselian Glaciation with several cold (stadial) and warm (interstadial) periods (Fig. 1).

The first advance of the SIS after the Eemian interglacial to the Russian mainland occurred as early as 80–100 ka in the Early Weichselian (MIS 5d and 5b), blocking all drainage and damming huge lakes in West Siberia and the northwestern part of Russia (Fig. 2).

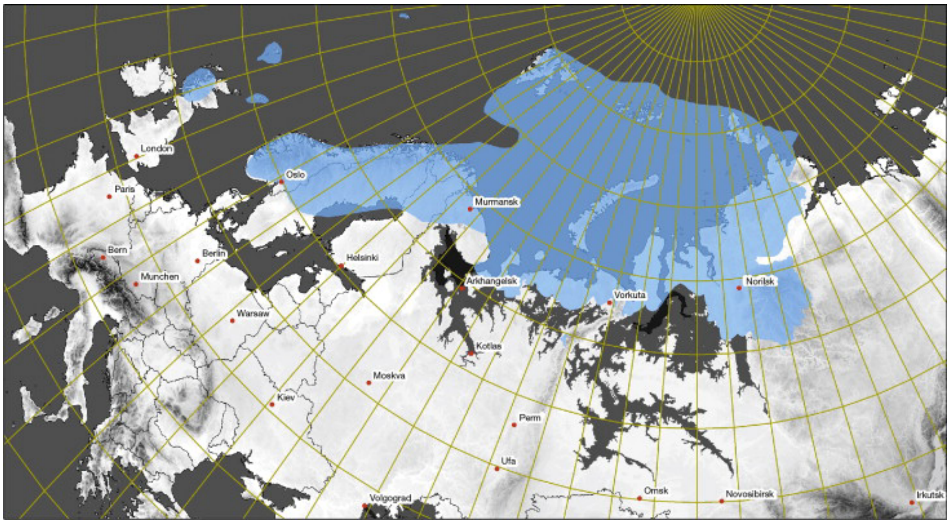


Fig. 2. Extent of the Early Weichselian (MIS 5d and 5b) glaciation in northern Eurasia (Ehlers *et al*. 2013).

Drainage was diverted southwards towards the Caspian Sea and the Black Sea. Although the Early Weichselian SIS was most extensive in the east, a few traces of this ice sheet are also found in the western regions (Ehlers *et al.* 2013). Nevertheless, the SIS did not reach the western and southern parts of Finland (Lunkka *et al.* 2004). The Early Weichselian Substage included two interstadials, Brörup (MIS 5c) and Odderade (MIS 5a), when climate became slightly milder.

About 60 ka BP (MIS 4), the second advance of the SIS occurred, as the Middle Weichselian Ice Sheet covered large parts of Fennoscandia and northern areas in NW Russia and Siberia (Ehlers *et al.* 2013; Fig. 3). The knowledge of Middle Weichselian climatic events (MIS 4 and 3) and the extent of the SIS in eastern Europe and European Russia is quite limited and the evidence of its timing is still rather sparse (Saks 2010). Opinions about the extent of the SIS during the Middle Weichselian glaciation are contradicting. Some studies claim that the SIS reached the western part of the East European Plain during MIS 4 (Zarrina 1991; Arslanov 1993), others, however, suggest that the SIS did not extend beyond the Baltic Sea depression and Russian Karelia during that time (Chebotareva & Macarycheva 1982; Demidov *et al.* 2004; Guobyte & Satkūnas 2011; Velichko *et al.* 2004, 2011).

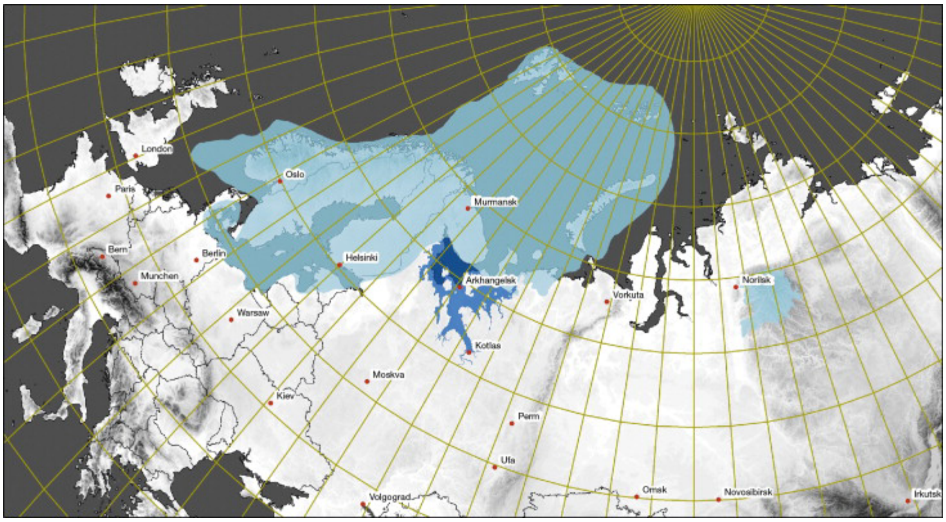


Fig. 3. Extent of the Middle Weichselian glaciation (MIS 4) (Ehlers *et al.* 2013).

Nevertheless, evidence of the Middle Weichselian (MIS 4) glaciation has been reported from several sites in northern, central and eastern Europe: southern Finland (Nenonen 1995), Estonia (Liivrand 1991), Latvia (Zelčs & Markots 2004), Lithuania (Molodkov *et al.* 2010), Poland (Marks 1998, 2004) and Denmark (Houmark-Nielson 2007). The subsequent warm period, namely MIS 3 'megainterstadial' in European Russia (Oerel to Denekamp interstadials in central Europe), is characterized by alternating warm and cold phases, while the glaciation was mostly restricted to the Scandinavian mountains mostly (Ehlers 2007; Velichko *et al.* 2011).

The Late Weichselian glaciation in northern Eurasia started about 28 ka ago. In the eastern part of the SIS it was restricted to the shelf areas of the Barents and Kara seas (Fig. 4). In the western part of the SIS, this was the most extensive Weichselian glaciation. Rapid ice-advances of the SIS across southern and central Finland into the western part of the East European Plain took place after 25 ka (Johanson *et al.* 2011), covering central and northern Europe and European Russia (Ehlers 2007; Ehlers *et al.* 2013).

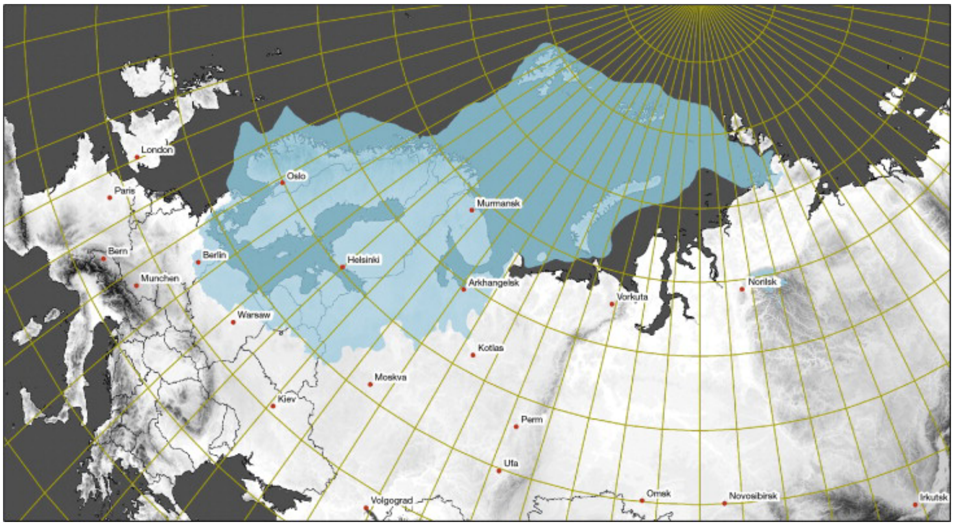


Fig. 4. Extent of the Late Weichselian (MIS 2) glaciation in northern Eurasia (Ehlers *et al.* 2013).

The SE sector of the Late Weichselian SIS reached its maximum extent between 21 and 19 ka (MIS 2) synchronously with the global record of ice volume changes, but in the SW sector of the SIS the maximum extent was reached earlier during MIS 4 and 3 (Houmark-Nielsen 2011). Thus, it is clear that the various sectors of vast continental ice sheets like the SIS exhibit complex responses to the global climate signal, with the global LGM being only one of a series of major advances of varying size (Hughes *et al.* 2013). Furthermore, also the SE sector of the SIS did not reach the LGM position isochronously. The LGM has been estimated to have occurred at different times: 18 OSL ka BP in the Vologda area, NW Russia (Lunkka *et al.* 2001); not earlier than 22.3 cal. ^{14}C ka in NW Belarus and 19.2 cal. ^{14}C ka BP in NE Belarus (Rinterknecht *et al.* 2007); 18.3 ^{10}Be ka in Lithuania (Rinterknecht *et al.* 2008) and not earlier than 26–20 TL ka in SE Lithuania (Guobyte & Satkunas 2011); 22–20 ka BP (OSL and cal. ^{14}C dates) in Denmark (Houmark-Nielsen 2004, 2008); 18–20 TL ka and 19.7 ^{36}Cl ka in NE Poland close to the SW Lithuanian and NW Belarus border (Krywicki 2002; Dzierżek & Zreda 2007) and 24–19 ka BP (cal. ^{14}C and ^{10}Be ages) in Poland (Marks 2010). This is explained by the different ice streams and their complexes operating in the SE sector of the SIS during the Late Weichselian (Kalm 2012a; Fig. 5).

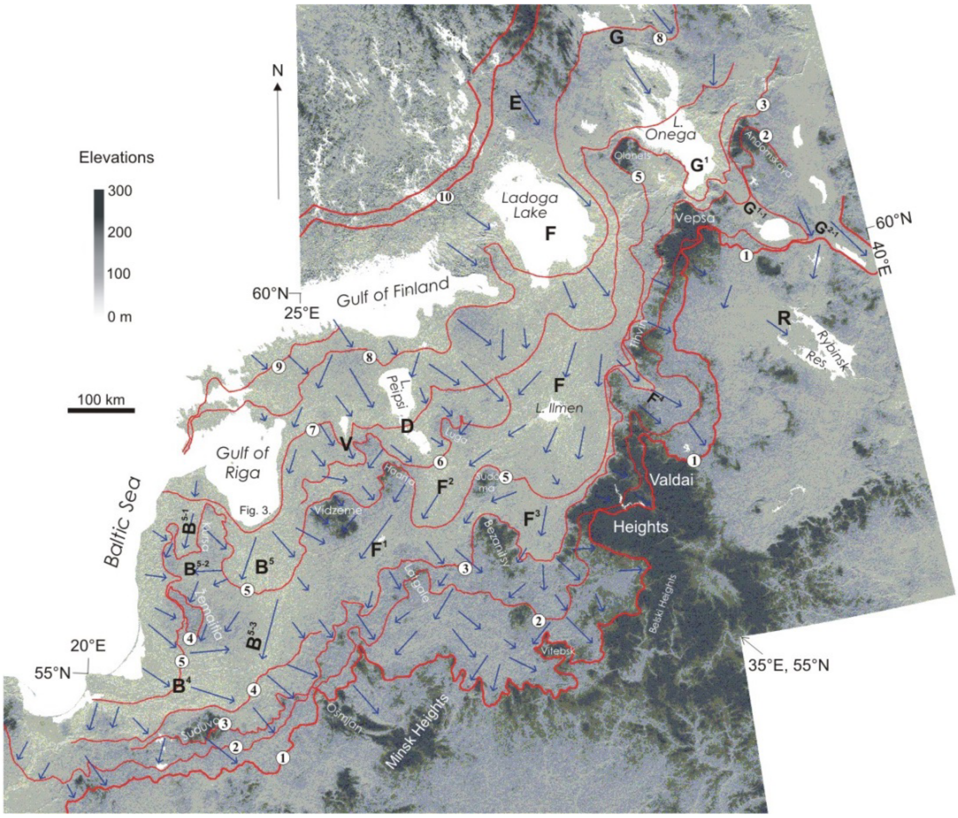


Fig. 5. Ice lobes and marginal positions of the last SIS southeast of the Baltic Sea (Kalm 2012a). Ice streams and their complexes are: Baltic ice stream complex (B) with Neman (B4) and Riga (B5) ice streams and Usma (B5-1), Vadakste (B5-2) and Zemgale (B5-3) sub-ice-streams; Peipsi–Pskov ice stream (D); Võrtsjärv ice stream (V); Karelian ice stream complex (E) with Ladoga–Ilmen–Lovat' ice stream (F) and Lubana (F1), Velikaja (F2), Kunja (F3) and Msta (F4) sub-ice-streams; White Sea ice stream complex (G) with Onega (G1) ice stream and Beloye Ozero (G1-1) and Kubenskoye (G2-1) sub-ice-streams. Rybinsk (R) ice stream is located outside of the estimated LGM limit. Ice-marginal zones are: 1 – LGM (Gruda in Lithuania), 2 – Baltija (= Pomeranian or Vepsian in Karelia and western Russia), 3 – South Lithuanian (Sebezha and Krestets in Russia and Karelia), 4 – Middle Lithuanian, 5 – North Lithuanian (Haanja and Luuga in Latvia, Estonia and Russia), 6 – Otepää, 7 – Sakala (Valdemarpils in Latvia), 8 – Pandivere (Neva in Russia and Karelia), 9 – Palivere, 10 – Salpausselkä I (Rugozero in Karelia). Names of major highlands are shown in white colour.

The SIS began to retreat soon after the LGM and by the end of the Bölling–Alleröd interstadial (12 cal. ^{14}C ka BP) the area between the Salpausselkä I ice-marginal zone in southern Finland and the LGM position in the western part of the East European Plain was deglaciated. During the last demise major ice sheet stagnations appeared, which can also be seen in the present topography where different authors have distinguished up to eight ice-marginal zones in the SE sector of the SIS (Fig. 5) (Guobytė & Satkūnas 2011; Karabanov & Matveyev 2011; Zelčs *et al.* 2011, Kalm 2012a). Most reconstructions of the last deglaciation of the SIS show the ice limits as unbroken lines extending up to several hundreds of kilometres (Lundqvist & Saarnisto 1995; Raukas 1992; Rattas & Kalm 2005; Kalm 2012a). However, correlation of deposits and landforms associated with particular limits is difficult and conflicts exist between many interpretations.

3. MATERIAL AND METHODS

3.1. Study area

The study area encompasses the southeastern sector of the last Scandinavian Ice Sheet between the Baltic Sea and the LGM position in the western part of the East European Plain (Fig. 6).

The topography of the study area is rather flat, with average elevations between 100 and 200 m above sea level (a.s.l) and with maximum heights of about 353 m a.s.l in the Valdai region. Current glacial accumulative topography has mostly been designed by the last, Late Weichselian glaciation. Meridionally oriented glacial depressions mark the footprints of major ice lobes (Kalm 2012a), while ice divides in between are marked by the radial series of insular-like uplands. In the northern part plinth-type uplands with an outstanding bedrock core and thin (<10 m) Quaternary cover are lower (100–175 m) than the maximum of around 300 m, characteristic of the glacial-accumulative heights with a thick Quaternary cover located in the central and southern parts of the SIS extension area. A series of outstanding uplands mark also the LGM zone of the SIS.

The palaeogeographic situation before the LGM is not well documented in northern Europe, because the last glaciation has removed most of the sediments of former glaciations. The SIS did not reach the East European Plain during the Early Weichselian (MIS 5d–a) and interstadial deposits have been found and dated in few sections from of the study area (Ehlers *et al.* 2011). According to modelling, in the Middle Weichselian the SIS reached only the NW part of the study area along the Baltic Sea coast (Fig. 6), but the evidence of its timing and extent is still rather sparse. More is known about the Late Weichselian glaciation. The ice sheet model of the LGM shows that the thickness of the SIS was about 2200 m at the southern shores of the Baltic Sea and 100–500 m at the LGM position (Svendsen *et al.* 2004; Zuzevičius 2010). Two major ice stream complexes (ISC) were operating during the Late Weichselian in the study area: the Baltic ISC about 1200 km long in western Estonia, western Latvia, Lithuania and northwestern Belarus and the Karelian ISC about 800 km long in eastern Estonia, eastern Latvia, northeastern Belarus and Russia (Punkari 1997; Boulton *et al.* 2001; Karukäpp 2004; Kalm 2012a). The ice sheet advanced to the LGM position generally from the northwest and deglaciated in the opposite direction. The Baltic ice stream first followed the Baltic Sea depression to the southwest and later advanced to the southeast, to the western part of the East European Plain (Boulton *et al.* 2001; Kalm 2012a). The bedrock in the study area was not frozen throughout the last glacial advance and the base of the SIS probably thawed during the Late Weichselian (Jõeleht 1998; Jirakova *et al.* 2011). This supposition is also supported by distribution of Weichselian subglacial landforms in Estonia and Latvia, which could have been formed only in unfrozen conditions under the ice sheet (Rattas 2004; Saks 2010). Such conditions probably accelerated both the advance and decay of the last SIS (Jirakova *et al.* 2011).

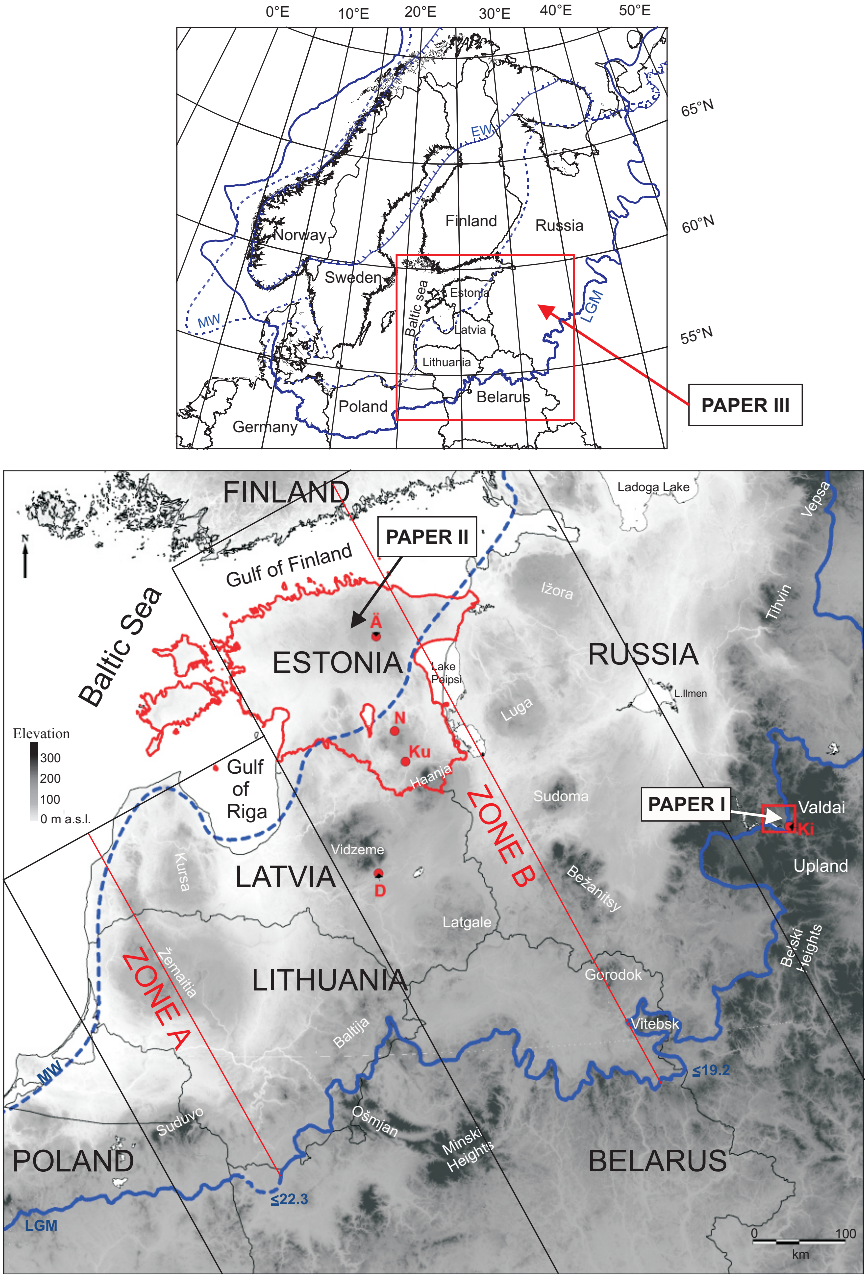


Fig. 6. Map showing the maximum extent of Weichselian glaciations in Fennoscandia and on the East European Plain (Ehlers & Gibbard 2004; Ehlers *et al.* 2012; Kalm 2012a) together with indication of the study area. Zones A and B, are used to simplify the data handling in the study area. Ages of the LGM are based on Rinterknecht *et al.* (2007). The red line denotes the azimuth line as the general direction of ice flow. Red dots show new investigated sites: Ä = Äntu; N = Nõuni; Ku = Kurenurme; D = Dreimanis and Ki = Kileshino.

The present relief of the study area clearly reflects the topography of the bedrock surface as all larger ice streams followed the bedrock depressions (Kalm 2012b). Major ice sheet stagnations can be seen in the present topography as the zones of ice-marginal landforms. Different authors have distinguished up to eight ice-marginal zones (Guobytė & Satkūnas 2011; Karabanov & Matveyev 2011; Zelčs *et al.* 2011; Kalm 2012a) in the study area.

3.2. Fieldwork and sampling

Fieldwork and sampling were performed in 2009–2011. The Kileshino outcrop close to the LGM in the Valdai Upland was described, sampled and photographed, lithofacies were distinguished and sediment colour was identified according to Munsell's colour system chart (1998). Four cores (Äntu, Kurenurme, Dreimanis, Nõuni) from Estonia and Latvia were studied in order to obtain additional chronological data (Fig. 6). From all studied sites 23 samples were taken for radiocarbon and 4 samples for OSL age determination. Sixteen AMS samples were analysed in Poznań Radiocarbon Laboratory, Poland and 7 AMS samples in the Beta Analytic Radiocarbon Dating Laboratory, Florida, USA. The OSL samples were measured by the Risø TL-DA-12 reader and equivalent doses were estimated using a single-aliquot regenerative-dose (SAR) protocol (Murray & Wintle 2000) in the Laboratory of Chronology, University of Helsinki.

3.3. Chronological data

This thesis is based on the collected chronological data, which are organized into a database. Some portions of the earlier data have been submitted also to the DATED database (Gyllencreutz *et al.* 2007). Since the year 2007 the author of this thesis has been responsible since the year 2007 for collecting the chronological data and upgrading the database regularly on the basis of previously and newly published articles. The database includes different types of dates (^{14}C, OSL, TL, ESR, ^{10}Be) from published and unpublished (Äntu, Nõuni, Kurenurme, Dreimanis, Kileshino) sources. For the moment about 670 dates with inclusive information about the dating method, geographical coordinates, dated material and its depth from the surface, superposition, etc. are available for the time range of 74–11.7 cal. ^{14}C ka BP (Middle and Late Weichselian). Nevertheless, not all collected dates could be used for establishing chronology, primarily the dates concerning the development of the last glaciation. Therefore the data needed a critical revision and selection was made based on different characteristics as discussed below.

Interstadial MIS 3.1., with the time range of 35–28 cal. ^{14}C ka BP, was followed by a glaciation (MIS 2, 28–11.7 cal. ^{14}C ka BP), when the last SIS expanded from the glaciation centre into the Baltic Sea depression and further to our study area (Lambeck *et al.* 2010). Dates between 35.0 and 11.7 cal. ^{14}C ka BP, marking, respectively, the MIS 3.1. and the Holocene boundary, were preliminarily chosen for the development of the last SIS chronology. Although several dates in the database might reflect the Middle Weichselian or Late Weichselian ages, some mismatch is observed when these ages are considered together with the stratigraphical position of sediments in the geological section (for example, sediments dated to the Late Weichselian age lying below the Late Weichselian till). To obtain more reliable results, dates from sediments, which presumably were contaminated with old carbon (MacDonald *et al.* 1991) (lake marl, carbonate-rich sediments), were not used because of their possible age overestimation. While handling the data, the accuracy of some dates in comparison with others from the same area, became questionable. For this reason not all available dates were used. The causes of under- and overestimation of ages and their rejection from further analysis are discussed in more detail in PAPER III. It should be noticed that radiocarbon dates reflect the timing of organic sedimentation synchronous with vegetation development and therefore give an indirect age for both the advance and decay of the glacier. The OSL and ^{10}Be dates directly reflect the deposition of sediments and erratic boulders if assuming that the requirements for accurate dating are adequate. In conjunction, these dating methods cover the whole time range of interest, while the radiocarbon dating method is limited to ~45 ka.

Dates from key sites, which are directly relevant for the developed chronology are reported below, in Chapter 4.2. and are presented with the indication of the dating method in the discussion. All currently used radiocarbon dates were calibrated with the IntCal09 calibration curve (Reimer *et al.* 2009) and the OxCal v.4.1 program (Bronk Ramsey 2009), reported here with 1σ uncertainty and rounded to the nearest 100 years.

3.4. Ice-flow pattern and data handling

As two different ice streams were operating during the Late Weichselian in the western part of the East European Plain and the last SIS did not reach the LGM synchronously, the study area was tentatively divided into two parts, where ages and ice sheet dynamics were analysed separately. The western part, the Baltic ISC area, is considered as zone A and the eastern part, the Karelian ISC area, as zone B (Fig. 6). For the chronological reconstructions of the ice margin dynamics, the geographical location of all used dates was marked on the map. Based on their distance and location between ice-marginal zones, the dates were converted proportionally to an overall deglaciation and probable glaciation onset azimuth line (Boulton *et al.* 2001; Kalm 2012a) in tentative zones A and B, separately (Fig. 7). The results are displayed as time-distance diagrams (Chapter 4.2. and PAPER III), where medians of the ages are shown and used further in the discussion.

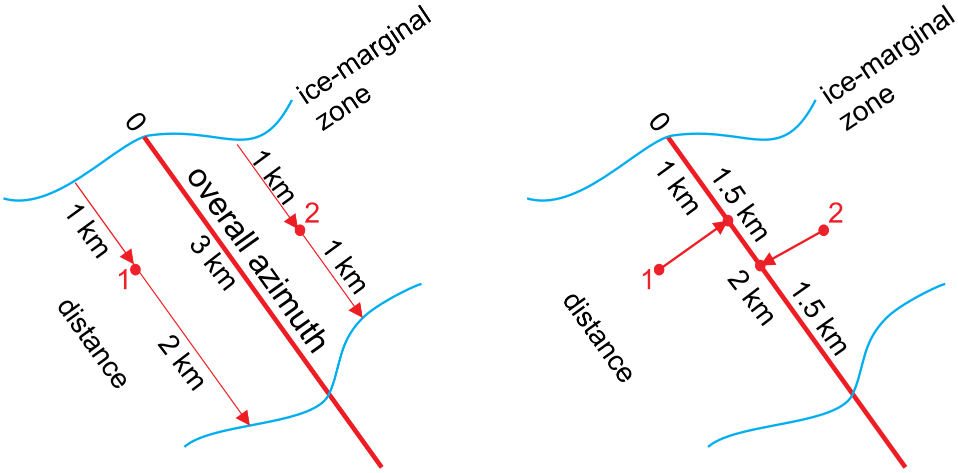


Fig. 7. Sketch illustrating how the dates were converted proportionally to an overall deglaciation azimuth (red) line on the basis of their distance and location between ice-marginal zones. Red dots mark the location of dated sites, red arrows show the distance and blue lines indicate tentative ice-marginal zones.

4. RESULTS AND DISCUSSION

The duration of the ice-free period in the study area before the last Scandinavian glaciation was determined based on detailed sedimentological and chronological study at the Kileshino outcrop in the Valdai Upland (PAPER I) and on available Middle Weichselian dates (PAPERS II and III). The chronology of the last glaciation for the study area is based on the published dataset together with several new dated sites (PAPERS II and III).

4.1. Ice-free interval before the last Weichselian glaciation in the western part of the East European Plain

The presence of non-glacial palaeoenvironments during the Early Weichselian has been determined everywhere in the study area (Ehlers *et al*. 2011). Data about the Middle Weichselian are not so straightforward because the last glaciation probably removed most of the sediments of former glaciations and the incomplete record of this time period has complicated the study of the SIS extent, especially in the Valdai Upland.

The Valdai Upland in the NW part of Russia (Fig. 8) was chosen for the study because the chronological data from the area are still insufficient and there have been contradictory opinions about the SIS advance during the Middle Weichselian in this region.

Detailed sedimentological studies at the Kileshino outcrop revealed nineteen lithofacies and in conjunction with dated samples, five main sedimentary units (SU1–SU5) were distinguished each expressing different climatic and sedimentological conditions (Fig. 9) (PAPER I). The lower portion of the section (SU1) comprises glaciolacustrine varved clay indicating cold periglacial conditions. However, as only one infinite ^{14}C AMS date was available, the age of these sediments was interpreted as older than 43.5 cal. ^{14}C ka BP. Dates (57.5 OSL to 33.8 cal. ^{14}C ka BP) from non-glacial sediments (SU2) resting on top of varved clay indicate that during MIS 3 the Kileshino site was ice-free and SU1 could not have been deposited at that time. The OSL ages (72.2–40.8 OSL ka) obtained from the sedimentary unit SU3, which is believed to have been transported by the last SIS advance from the NW of Kileshino, express the ice-free time also for the Kileshino site during MIS 4 and 3, as the general direction of the last SIS advance was from NW to SE. Thus the SIS could not have reached further to the Kileshino site while ice-free conditions still persisted in the NW. The lowest age available below the till layer (SU4) shows the Late Weichselian (Valdai) age and indicates that the last SIS overrode the studied area after 33.8 cal. ^{14}C ka. The above leads to the conclusion that periglacial sediments, which have been recognized in the Kileshino outcrop in the lowest sedimentary unit (SU1), are older than 72.2 OSL ka. Thus the SIS did not reach the Kileshino site during MIS 4 (74 and 59 ka), while there ice-free conditions existed there between 72.2 OSL and 33.8 cal. ^{14}C ka BP.

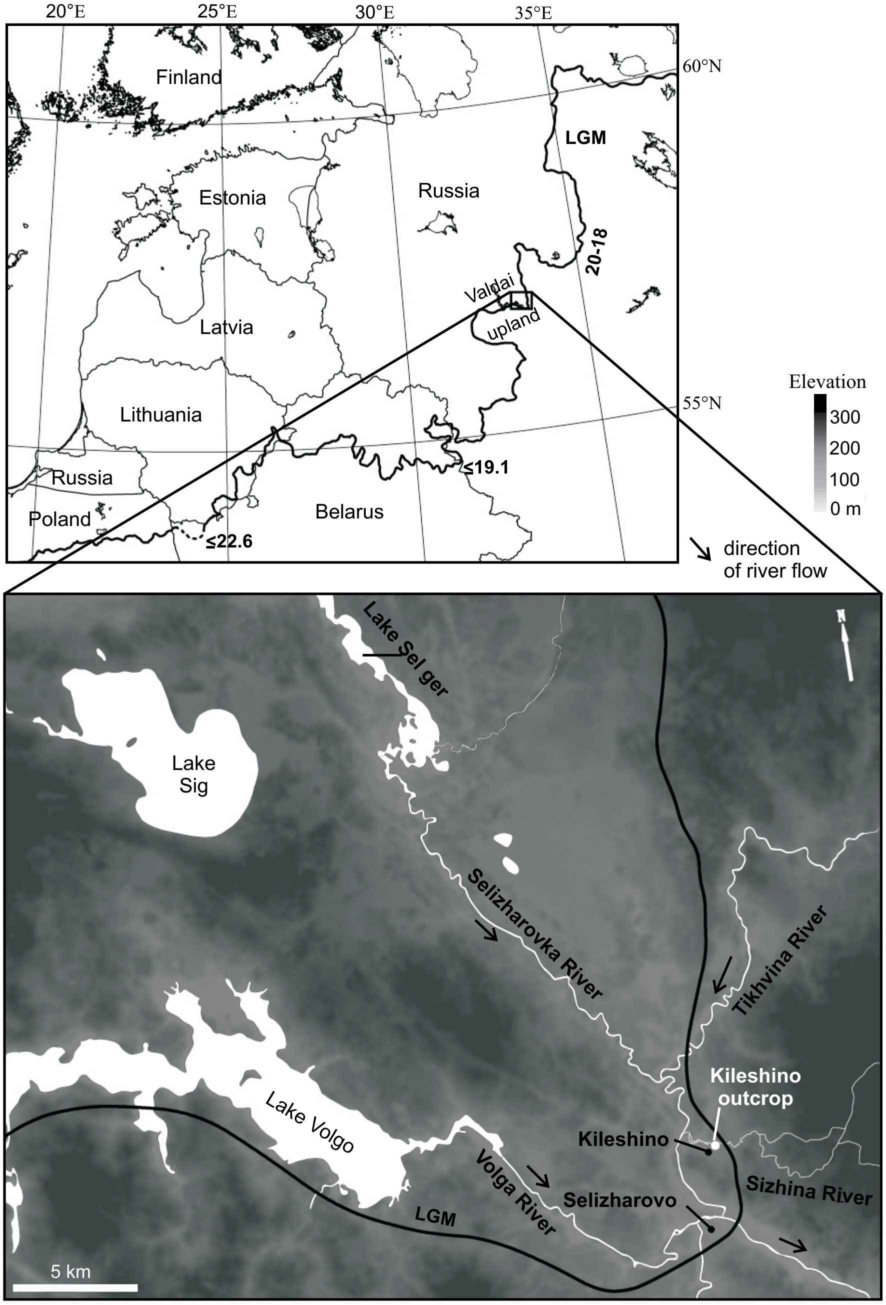


Fig. 8. Valdai Upland and location of the Kileshino outcrop near the Kileshino village on the left bank of the Sizhina River.

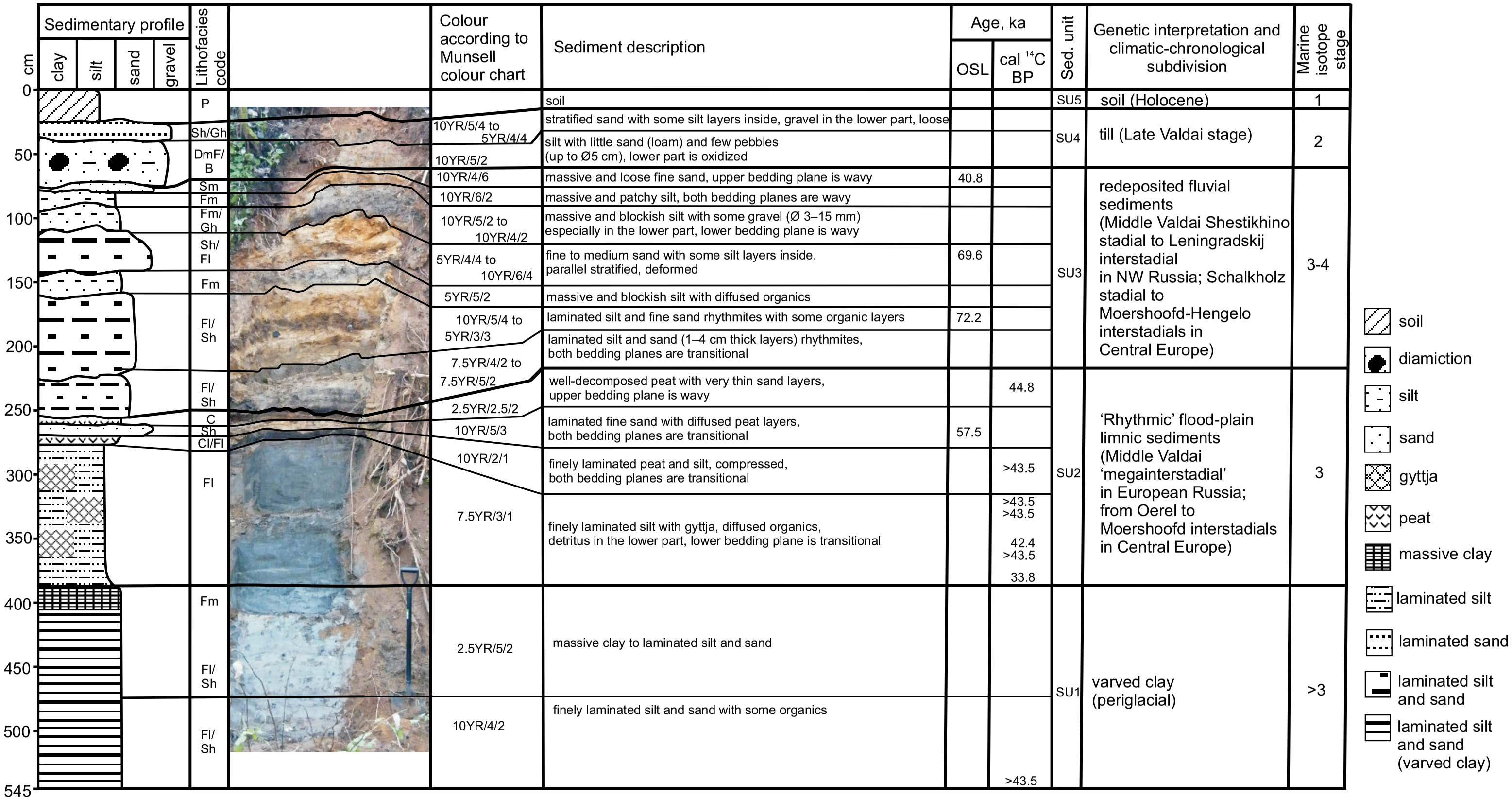


Fig. 9. Description of theKileshino outcrop with main sedimentary units and genetic interpretation. Climatic-chronological subdivisions are according to Velichko *et al.* (2011).

Findings from the Kileshino site and lithological data from the nearby areas (Arkhanglsk region, Karelia and Vologda area), where only one till has been found above Eemian interglacial sediments (Demidov *et al.* 2004) show that the SIS did not reach the western part of the East European Plain. This concerns also the areas to the south of our study site as only one Weichselian till has been found in northern Belarus and it is interpreted to be of Late Weichselian age (Karabanov & Matveyev 2011).

Glacial sediments attributed to the Middle Weichselian have been found in Denmark (Houmark-Nielsen 2011), Poland (Marks 2004, 2011), Latvia (Zelčs *et al.* 2011), Estonia (Liivrand 1991) and Finland (Nenonen 1995). Propositions for the timing of possible Middle Weichselian glaciation in Lithuania and Latvia have been made by several authors on the basis of chronological data. Molodkov (2010) suggested that the SIS reached the coastal area of Lithuania during MIS 4 (74–59 ka) or could have even covered all of western Lithuania. Recent data from Lithuania shorten the possible time range for the Middle Weichselian glaciation as northern Lithuania was ice-free at least between 55 and 33 ka (Satkunas *et al.* 2012). Zelčs *et al.* (2011) suggested a possible early Middle Weichselian glaciation in Latvia between 74 and 59 ka when the SIS probably reached only coastal plains and, possibly, the adjoining Northern Kursa Upland in central Latvia. Additional dates from western Latvia confirm ice-free conditions at least between 52 and 26 OSL ka (Saks 2010). Chronological data from Estonia (PAPER II) indicate ice-free conditions at least between 44 and 27 and together with Early Weichselian ice-free time, it leaves some 24 ka (68–44 ka) for possible early Middle Weichselian glaciation. However, this conclusion is tentative, as Molodkov *et al.* (2007) found no evidence in the Voka outcrop, northern Estonia, suggesting the presence of glacigenic sediments deposited during the period between 115 and 31 OSL ka. If that holds true, the question arises how the second till from the surface, which is widely distributed in central and southern Estonia, and overlying Eemian interglacial deposits (Raukas 1978; Kajak 1995), should be interpreted. It is notable, that the Middle Weichselian glaciation has been recorded in western Finland between 62 and 55 ka (Salonen *et al.* 2008) and has been interpreted to have reached at least SE Finland (Lunkka *et al.* 2008).

4.2. Last Weichselian glaciation

Currently developed chronology of the last Weichselian glaciation in the study area is based on 311 radiocarbon (^{14}C, ^{14}C AMS), 87 OSL and 72 ^{10}Be ages from 204 different sites/sections (PAPERS II and III). Only calibrated ages are used in further discussion, while all dates (both uncalibrated and calibrated ages) from key sites (Fig. 10), which were directly used for establishing the chronology and mentioned therefore in the discussion, are reported in Table 1. Based on time-distance diagrams (Figs. 11, 12), rest of the dates concerning the advance and decay of the SIS in the study area were considered relatively young or old, nevertheless all dates are shown in the figures. Note that hereafter the results are given separately for the eastern (Karelian ISC area) and western (Baltic ISC area) parts of the study area and it is advisable to follow the discussion in conjunction with the time-distance diagrams.

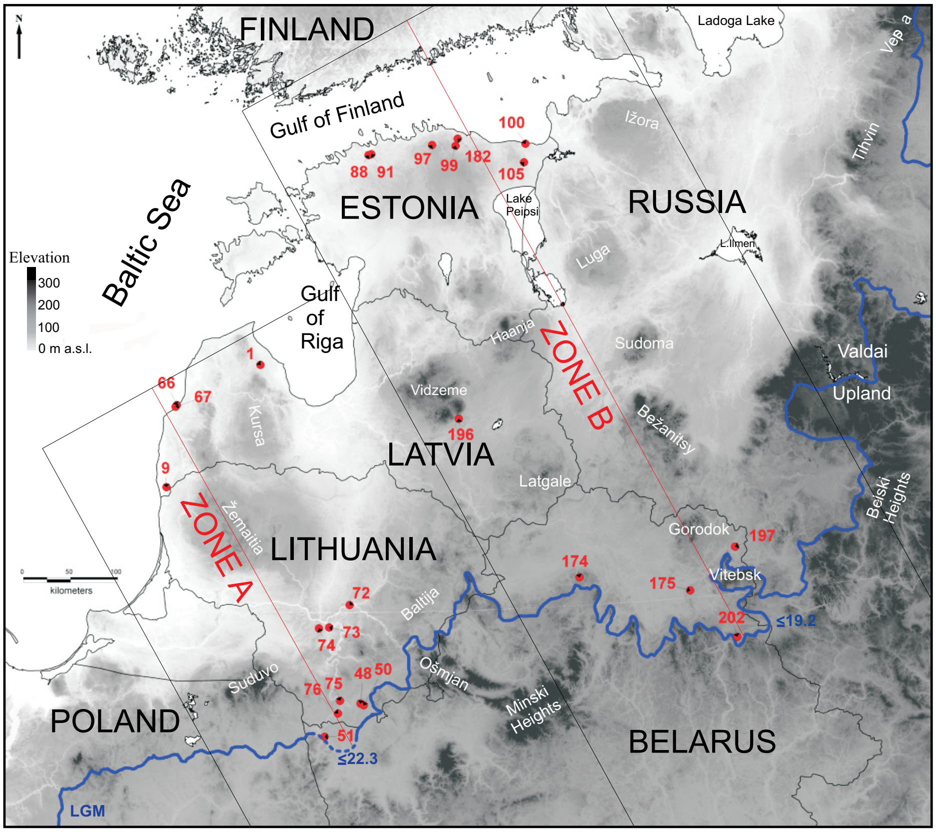


Fig. 10. Study area. Zones A and B, used to simplify the handling of the data and to evaluate ice sheet dynamics in different parts of the study area. The glacial maximum extent of the last SIS (Ehlers & Gibbard 2004; Kalm 2012a) is marked with a blue line and the ages are based on Rinterknecht *et al.* (2007). The red line denotes the azimuth line as the general direction of the ice-flow. Red dots show the dated sites mentioned in text: 1 = LAT-1; 9 = Rucava; 48 = Mančhiagine; 50 = Zervynos; 51 = Gozha; 66 = Ulmale; 67 = Baltmuiža; 72 = Turženu; 73 = Jiesia; 74 = Rokai; 75 = Jonionys; 76 = Netiesos; 88 = Pääsküla; 91 = Männiku; 97 = Pikassaare; 182 = Pehka; 99 = Haljala; 100 = Voka; 105 = Räätsma; 174 = Lozoviki; 175 = Latyshi; 196 = Smeceres sils; 197 = Drcihaluki; 202 = Chizhovka.

Table 1. List of key dates. Gd*– analysed in Gliwice Radiocarbon Laboratory, na –laboratory number unavailable; ^{14}C conv. – conventional radiocarbon method

Site no.	Lab. no.	Section	Lat. (°N)	Long. (°W)	Dated material	Superposition	Dating method	Original ages (ka)	Cal. ^{14}C ages BP, with 1σ uncertainty and rounded off to hundred (ka)	Median ages (cal. ^{14}C, TL, OSL, ^{10}Be) (ka)	References
1	LAT-1		57.352	22.725	quartz	na	^{10}Be	14.23 ± 1.29		14.2	Rinterknecht *et al.* (2006)
9	LuS 7538	Rucava	56.162	21.162	mammoth molar	na	^{14}C AMS	12.875 ± 0.07	15.1 - 15.6	15.4	Arppe & Karhu (2010)
48	Vs-5	Manĉhiagire	54.133	24.450	peat	river cut-off meander lentil	^{14}C conv.	17.34 ± 0.84	19.6 - 21.6	20.8	Serebryannyj (1978)
50	Vs-4	Zervynos	54.117	24.500	moss	below cut-off meander lentil	^{14}C conv.	18.35 ± 0.95	20.6 - 23.3	22	Zimenkov *et al.* (1985)
51	LU-76A	Gozha	53.817	23.867	plant detritus	from alluvial sand	^{14}C conv.	18.73 ± 1.23	20.6 - 24.1	22.6	Vigdorchik *et al.* (1974)
66	Ulmale 01	Ulmale	56.952	21.291	fine sand	below uppermost till	OSL	26.00 ± 4.10		26	Saks (2010)
67		Baltmuiža	56.930	21.262	fine sand	below uppermost till	OSL	26.00 ± 2.60		26	Saks (2010)
72	LuS 7528	Turženu	55.072	24.279	mammoth molar	na	^{14}C AMS	21.40 ± 0.12	25.4 - 25.9	25.6	Arppe & Karhu (2010)
73	LuS 7529	Jiesia	54.859	23.939	mammoth molar	na	^{14}C AMS	13.80 ± 0.08	16.8 - 17	16.9	Arppe & Karhu (2010)
74	Gd*	Rokai	54.849	23.772	peaty soil	below uppermost till	^{14}C	21.73 ± 0.36	25.5 - 26.7	26.1	Gaigalas *et al.* (2005)
74	UG-5564	Rokai	54.849	23.772	silt	below uppermost till	TL	30.60 ± 0.50		30.6	Gaigalas *et al.* (2005)
75	LU-129A	Jonionys	54.159	24.119	peat	between two uppermost tills	^{14}C conv.	20.67 ± 0.27	24.4 - 25	24.7	Serebryannyj (1978)
76	UG-5787	Netiesos	54.039	24.084	sand	below glaciofluvial deposits	TL	31.90 ± 4.40		31.9	Gaigalas & Fedorowicz (2009)
88	Ua-15319	Pääsküla mire	59.354	24.667	seeds	from homogenous clay	^{14}C AMS	11.42 ± 0.095	13.2 - 13.4	13.3	Heinsalu & Veski (2007)
91	TlnOSL-R-32	Männiku	59.362	24.719	medium and fine sand	from glaciofluvial delta	OSL	21.00 ± 2.50		21	Raukas (2004)
97	TlnOSL-R-38	Pikasaare	59.438	25.856	fine sand	from kame field	OSL	23.00 ± 6		23	Raukas (2004)
99	Ua-33187	Haljala	59.424	26.295	seeds	from clayey silt	^{14}C AMS	23.65 ± 0.07	28.2 - 28.6	28.4	Saarse *et al.* (2009)
100	GliOSL-1169	Voka	59.414	27.599	sand	from silt	OSL	25		25	Raukas & Stankowski (2005)
105	Ta-687	Räätsma lake	59.239	27.554	Bryales moss	from lacustrine tufa	^{14}C conv.	12.05 ± 0.12	13.8 - 14	13.9	Ilves (1980)
105	Ta-688	Räätsma lake	59.239	27.554	Bryales moss	from sand below tufa	^{14}C conv.	12.04 ± 0.10	13.8 - 15	13.9	Ilves (1980)
174	IGSB-464	Lozoviki lake	55.267	28.117	peat	below gyttja	^{14}C conv.	13.74 ± 0.85	15.3 - 17.8	16.6	Zernitskaya *et al.* (2007)
175	Lu-617	Latyshi	55.067	29.933	plant detritus	from sand	^{14}C conv.	13.63 ± 0.10	16.7 - 16.9	16.8	Zimenkov *et al.* (1985)
182	TlnOSL-1337	Pehka	59.492	26.338	sand	below glaciofluvial deposits	OSL	26.80 ± 3.50		26.8	Kadastik (2004)
196	LAT05/42	Smeceres Sils	56.827	26.188	sand	from kame terrace	OSL	19.60 ± 1		19.6	Raukas *et al.* (2010)
197	Tln-469	Drichaluki	55.442	30.744	plant detritus	from lower detritus interlayer between two uppermost tills	^{14}C conv.	15.96 ± 0.18	18.9 - 19.4	19.1	Zimenkov (1989)
202	LU-1148B	Chizhovka	54.589	30.640	humic acids	fraction soluble in hot alkaline solution	^{14}C conv.	16.19 ± 0.12	19 - 19.5	19.3	Zimenkov (1989)

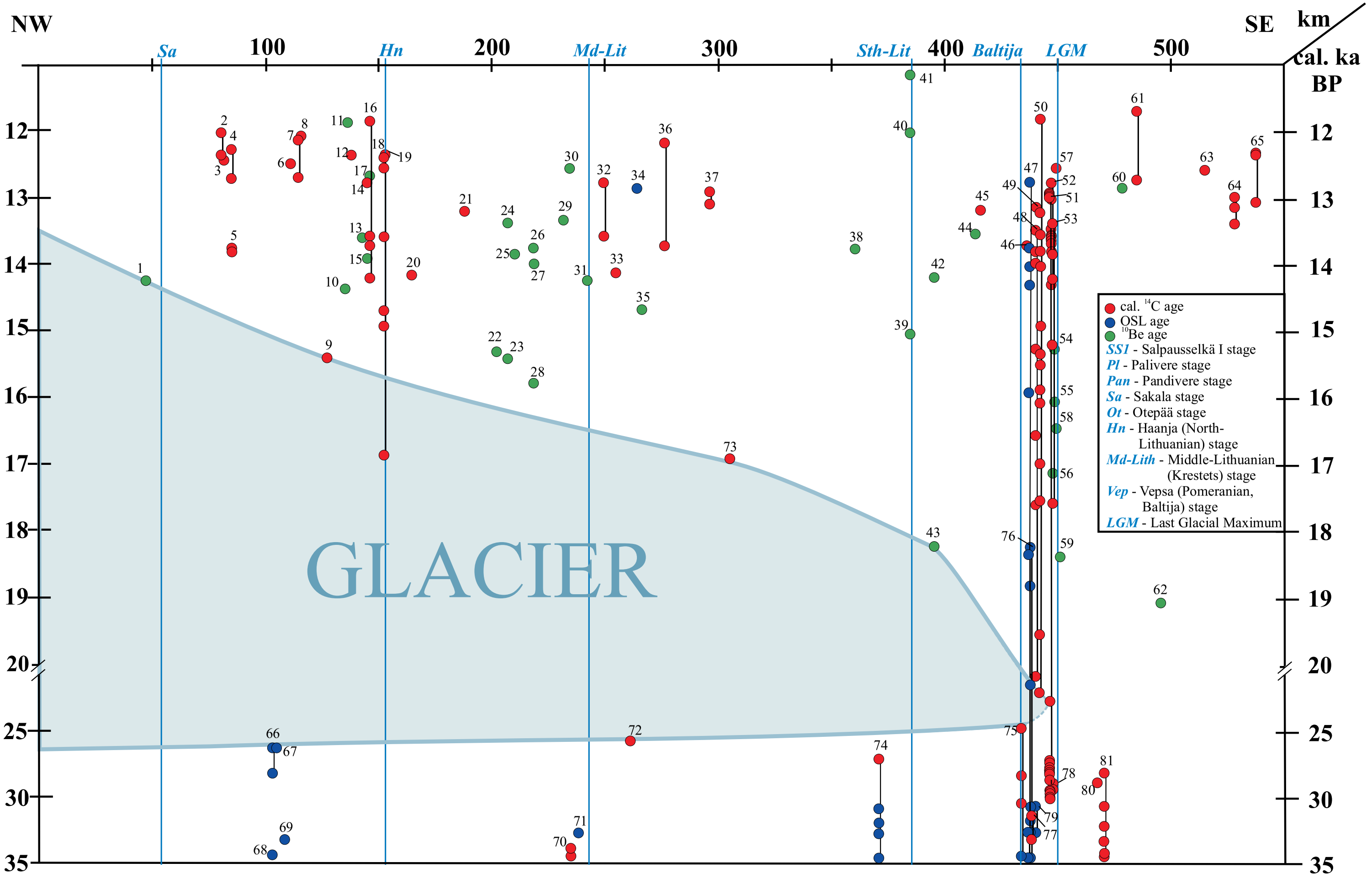
4.2.1. The advance of the last Scandinavian Ice Sheet to the western part of East European Plain

Baltic ISC area in the west (PAPER III)

In the western Baltic ISC area, dates below the uppermost till from the western shores of Latvia (Ulmale = 66, Baltmuiža = 67 in Figs. 10, 11 and Table 1) yielded an age of 26 OSL ka (Saks 2010). Preglacial organic sediments from the adjoining area in Poland gave a similar age, 27.8–25.0 cal. ^{14}C ka BP (Marks 2002). Dates of mammoth findings from central Sweden (39–31 cal. ^{14}C ka BP, Ukkonen *et al.* 2007)) show that the SIS should have reached areas further from the glaciation centre after 31 cal. ^{14}C ka BP. These results and dates from western Latvia indicate that the last SIS advanced to western Latvia from the Baltic Sea depression not before 26 OSL ka. Therefore the ice-free period, which started already in the Middle Weichselian, can be extended to the beginning of the last glaciation (26 OSL ka) in the western part of the current study area.

The estimation about the last SIS advance (not before 26 OSL ka) suggests a longer ice-free period for previously dated sites, where the youngest preglacial-time sediments yielded an age of 31.9 OSL ka close to the southern border of Lithuania (Netiesos = 76) and an age of 30.6 OSL ka in central Lithuania (Rokai = 74) (Figs. 10, 11; Table 1) (Gaigalas *et al.* 2005). Furthermore, a single ^{14}C date below the uppermost till from central Lithuania (Rokai) is 26.1 cal. ^{14}C ka BP (Gaigalas & Pazdur 2004). As the mentioned sites are further from the glaciation centre than sites of western Latvia, they should have been ice-free for a longer time and the last SIS should have reached central and southern Lithuania later than 26 OSL ka. This is supported by recent TL dates (26–20 TL ka) from lacustrine sand below the uppermost till from SE Lithuania, suggesting even longer ice-free conditions (Guobytė & Satkūnas 2011).

The currently presented ice advance model (time-distance diagram) for the last SIS in the western part of the study area includes two key sites in central and southern Lithuania (Turženu = 72, Jonionys = 76) and one in NW Belarus (Gozha = 51) (Figs. 10, 11; Table 1). A mammoth molar from central Lithuania (Turženu) yielded an age of 25.6 cal. ^{14}C ka BP (Arppe & Karhu 2010) and the youngest peat samples from southern Lithuania (Jonionys) from between the two uppermost tills, gave an age of 24.7 cal. ^{14}C ka BP (Serebryanny 1978). Plant detritus from laminated lacustrine clays in NW Belarus (Gozha site) gave an age of 22.6 cal. ^{14}C ka BP (Vigdorchik *et al.* 1974; Pavlovskaya *et al.* 2002). Although these clays were not covered by till, the palaeobotanic studies from the same sequence suggested that the site was close to the LGM position, under periglacial conditions (Pavlovskaya *et al.* 2002). This has been questioned by Karabanov & Matveyev (2011) whose geomorphological studies suggested that the last SIS overrode the Gozha site, yet there is no geological evidence to confirm this view.


NW
SE
km
cal. ka BP
Sa
Hn
Md-Lit
Sth-Lit
Baltija
LGM
100
200
300
400
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12
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18
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25
30
35
GLACIER
● cal. ¹⁴C age
● OSL age
● ¹⁰Be age
SS1 - Salpausselkä I stage
Pl - Palivere stage
Pan - Pandivere stage
Sa - Sakala stage
Ot - Otepää stage
Hn - Haanja (North-Lithuanian) stage
Md-Lith - Middle-Lithuanian (Krestets) stage
Vep - Vepsa (Pomeranian, Baltija) stage
LGM - Last Glacial Maximum
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80 81

Fig. 11. Time-distance diagram in the western part of the study area (Baltic ISC area as zone A) along the azimuth line shown in Fig. 10. Dated sites: *1 = LAT-1*; 2 = Lici; 3 = Ozolnieki; 4 = Sarkanais mals; 5 = Progress; 6 = Sarnate; 7 = Kaltiki; 8 = Kaulezers; *9 = Rucava*; 10 = NLIT-3; 11 = NLIT-2; 12 = Rakani; 13 = NLIT-1; 14 = Vartaja; 15 = Lat-3; 16 = Lake Kašučiai; 17 = LAT-8; 18 = Ventes Ragas; 19 = Abavas Rumba; 20 = Krikmani; 21 = Lielause; 22 = MLIT-1; 23 = MLIT-3; 24 = MLIT-4; 25 = Balti-18; 26 = MLIT-5; 27 = MLIT-8′′; 28 = MLIT-6; 29 = LIT-8; 30 = Balti-7; 31 = Balti-6; 32 = Rekyva; 33 = Juodonys; 34 = Bebrjai; 35 = Balti-9; 36 = Daktarishke; 37 = Petrašiunai; 38 = Balti-2; 39 = Balti-3; 40 = Balti-4; 41 = Balti-5; 42 = LIT-2; 43 = LIT-3; 44 = LIT-9; 45 = Vievis; 46 = Bebrukas; 47 = Vilkiškes; *48 = Mančhiagire*; 49 = Varenis; *50 = Zervynos; 51 = Gozha;* 52 = Pamerkis; 53 = Rudnia; 54 = Gruda-1; 55 = Bel-19; 56 = Lit-1; 57 = Krokšlys; 58 = BEL-3; 59 = Lit-7; 60 = Bel-2; 61 = Naroch; 62 = Lit-5; 63 = Morino; 64 = Komaryshki; 65 = Kobuzi; *66 = Ulmate; 67 = Baltmuiža*; 68 = Strante; 69 = Ecenieki; 70 = Purviai; 71 = Kvesai; *72 = Turženu*; *73 = Jiesia*; *74 = Rokai*; *75 = Jonionys*; *76 = Netiesos*; 77 = Ratnycia; 78 = Plaskovsky; 79 = Ula; 80 = Kukli; 81 = Medininkai. Key sites are in Italic.

Relying on the presented time-distance diagram (Fig. 11), the ice-free period before last glaciation in central and southern Lithuania could be extended up to the time range between 25.6 and 24.7 cal. ^{14}C ka BP (Turženu, Jonionys), which indicates that the ice-free period ended 5 ka later than suggested previously on the basis of OSL dates from central Lithuania (Rokai) (Gaigalas *et al.* 2005). Similarly, the ice-free period in S Lithuania (Netiesos) and NW Belarus lasted presumably 6 ka longer than indicated by earlier OSL ages (Gaigalas *et al.* 2005) and should be prolonged to the time range of 24.7–22.6 cal. ^{14}C ka BP (Jonionys, Gozha).

The youngest preglacial dates close to the LGM position (Jonionys) yielded an age of 24.7 cal. ^{14}C ka BP (25–24.4cal. ^{14}C ka BP; Table 1) in southern Lithuania (Jonionys) (Serebryanny 1978) and 22.6 cal. ^{14}C ka BP (24.1–20.6 cal. ^{14}C ka BP; Table 1) in NW Belarus (Gozha site) (Vigdorchik *et al.* 1974). As both of these sites were under periglacial conditions near the proposed LGM position during the last glaciation, the dates indicate that the last SIS should have reached the LGM position in the Baltic ISC area between 24.4 and 20.6 cal. ^{14}C ka BP, when considering the whole time range instead of median calibrated ages. Furthermore, if two post-glacial dates also near the LGM position with the ages of 20.8 cal. ^{14}C ka BP (Mančhiagine = 48) (Zimenkov *et al.* 1985) and 22 cal. ^{14}C ka BP (Zervynos = 50) (Serebryanny 1978) are taken into account, it can be suggested that the last SIS reached and/or remained at the LGM position between 24.4 and 19.6 cal. ^{14}C ka BP in the Baltic ISC area (Figs. 10, 11; Table 1). The TL dates from lacustrine sand below till in SE Lithuania also suggest that the SIS reached its maximum extent not earlier than 26–20 TL ka (Guobytė & Satkūnas 2011). In the adjoining area of NE Poland, the SIS reached the LGM position before 19.7 ^{36}Cl ka (Dzierżek & Zreda 2007) and between 20 and 18 TL ka (Krzywicki 2002). These dates correspond quite well with our estimated age range, considering that ^{36}Cl or TL dates have larger errors than radiocarbon dates.

Karelian ISC area in the east (PAPERS II and III)

The last SIS advance started about 4 OSL ka later in the eastern, Karelian ISC area than in the Baltic ISC in the west of the study area. A date from northern Estonia (Männiku = 91; Figs. 10, 12; Table 1) yielded an age of 21 (± 2.5) OSL ka (Raukas & Stankowski 2005), which expresses the time of ice-free conditions before the site was glaciated. Many other dated sites in northern Estonia (Pikasaare = 97, Haljala = 99, Voka = 100, Pehka = 182; Figs. 10, 12; Table 1) also confirm the ice-free period at least between 43.9 and 23 OSL ka (Kadastik 2004; Raukas & Stankowski 2005; Molodkov *et al.* 2007; Saarse *et al.* 2009). Therefore, it can be assumed that the last SIS reached the southern shores of the Gulf of Finland not before 21 OSL ka. Thus, the ice-free period which started in the Middle Weichselian can be prolonged to ca 21 OSL ka when the last SIS reached the eastern part of the study area. Based on a date from the Vidzeme Upland (Smeceres sils = 196; Figs. 10, 12; Table 1) (Raukas *et al.* 2010), the last SIS reached central Latvia not before 19.6 (± 1) OSL ka, which leaves about 1.4 ka for the SIS to have advanced from northern Estonia to central Latvia.

Ice streams of the Karelian ISC reached the LGM position in NE Belarus (Chizhovka site = 202 in Figs. 10, 12 and Table 1) not before 19.3 cal. ^{14}C ka BP (Zimenkov 1989). As at some sites (Drichaluki = 197, Brigitpole = 198, Shapurovo = 200, Kasplyane = 201 in Figs, 10, 12 and Table 1) in NE Belarus, including the one from LGM position (Chizhovka = 202), the dated material originates from the same stratigraphic layer (Zubakov 1974), the youngest date among them can be used to evaluate the arrival of the last SIS to LGM position. Therefore, the dated plant detritus from Drichaluki between the two uppermost tills suggests that the last SIS should have reached the LGM position not earlier than 19.1 cal. ^{14}C ka BP (19.4–18.9 cal. ^{14}C ka BP; Table 1).

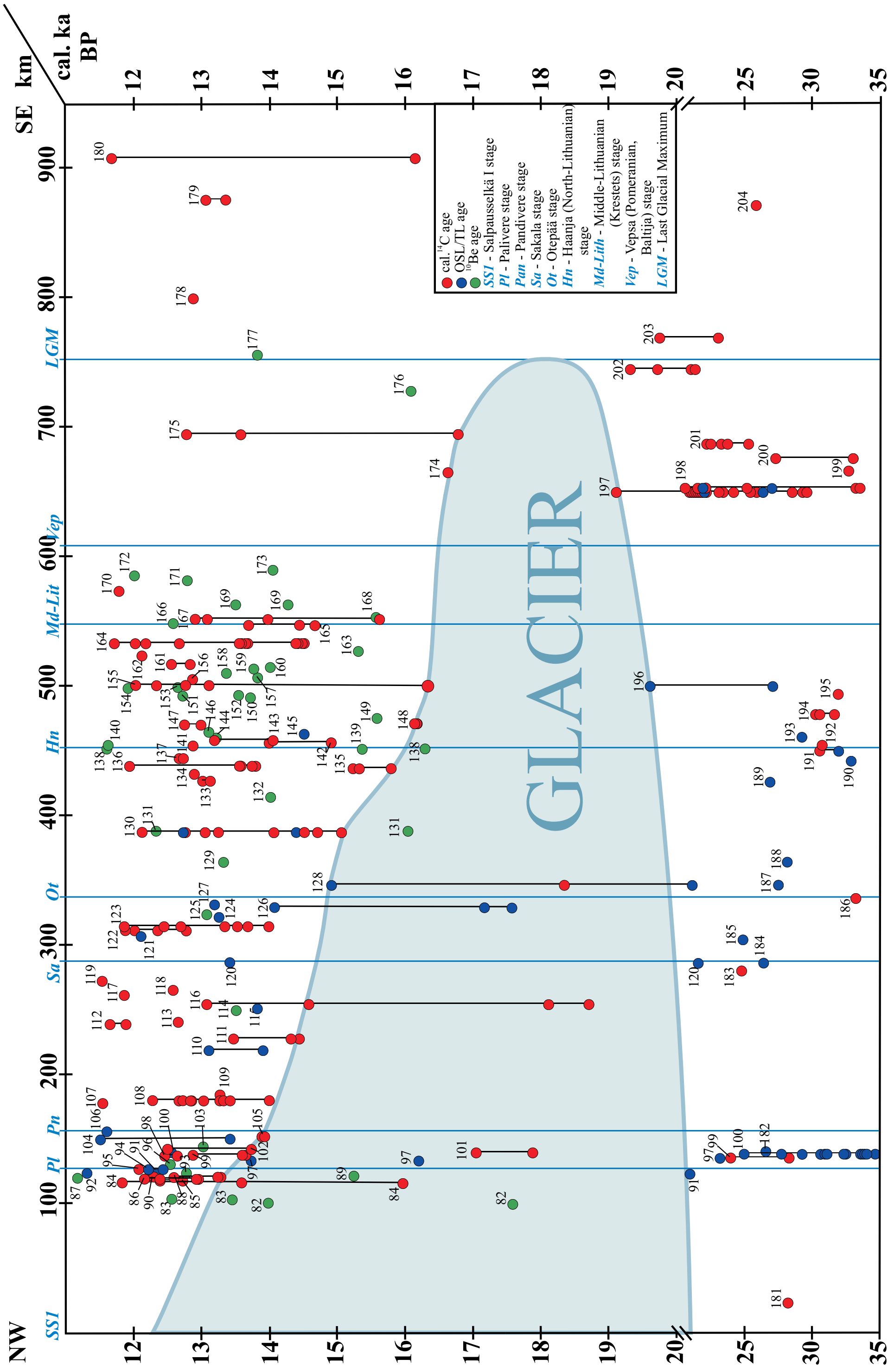
Considering the whole time-range of dates relevant to determining the age of the LGM, and also taking into account the ages of 16.6 cal. ^{14}C ka BP (17.8–15.3 cal. ^{14}C ka BP) from the Lozoviki site (Novik *et al.* 2010) and 16.8 cal. ^{14}C ka BP (16.9–16.7 cal. ^{14}C ka BP) from the Latyshi site (Zimenkov *et al.* 1985) of NE Belarus where the start of vegetation development after deglaciation has been dated, the last SIS should have rested at the LGM zone between 19.4 and 17.8 cal. ^{14}C ka BP (Lozoviki = 176, Drichaluki = 197 in Figs. 10, 12 and Table 1) in the east of our study area.

Comparison of the SIS advance in two parts of the study area (PAPER III)

Based on chronological data and constructed time-distance diagrams, it can be concluded that the last SIS acquired a maximum extent earlier in the west, in the Baltic ISC area, than in the east, in the Karelian ISC area, even if the whole time range of the relevant dates is considered. Comparison of the SIS advance diagrams (Figs. 11, 12) shows that in the western part of the study area, the last SIS reached the LGM position in NW Belarus not earlier than 22.6 cal. ^{14}C ka BP, while in the eastern part of the study area it had not yet reached the southern shores of the Gulf of Finland at that time. This conclusion is supported by the ^{14}C AMS and OSL dates from western, southern and eastern Finland (Nenonen 1995; Ukkonen *et al.* 1999; Lunkka *et al.* 2001; Lunkka *et al.* 2008) confirming the ice-free period between 35 and 25 ka in Finland, which is closer to the glaciation centre than our study area at the southern shores of the Gulf of Finland. Boulton *et al.* (2001) also concluded that in the southeastern sector of the Scandinavian glaciation, the maximum glacial extent reached the west earlier and the east later, and that the ice sheet was still advancing in the east whilst already retreating in the west.

Based on advance timing and LGM ages, the mean linear rate of the advance of the last SIS from the Baltic Sea coast to the LGM position was calculated. The mean rate was three times faster in the Karelian ISC area, from the southern shores of the Gulf of Finland to the LGM in NE Belarus (330 m a^{-1}), than in the Baltic ISC area, from the western shores of Latvia to the LGM in NW Belarus (110 m a^{-1}). However, it has to be kept in mind that the calculated mean linear rates of the advance are not absolute, and values are mostly based on scanty Middle Weichselian ages from limited areas. For comparison, Lunkka *et al.* (2001) suggest that the last SIS expanded across Finland to its maximum position in the northern Russian Plain within 7 ka. This yields a mean advance rate of about 140 m a^{-1}, which is smaller than the currently calculated rate for the eastern part of the study area, yet the two areas are located next to each other. This phenomenon can be explained by the fact that when calculating the last SIS linear advance rate, spatial fluctuations and temporal oscillations of different ice streams and the ice margin are not taken into account.

The calculated mean advance rates of the last SIS (330 and 110 m a^{-1}) are in accordance with the ice sheet model of Paterson (1981), which is similar to the SIS during the LGM. The ice cap was assumed to be in a steady state and the velocity of the ice sheet about 135 m a^{-1} at a distance of 950 km from the glaciation centre. However, the LGM position was farther from the glaciation centre than this (Donner 1989) and, as the ice sheet is not in a steady state in reality, the velocity might have been even higher than suggested by Paterson.
Surface velocities of several hundred to thousand metres per year are achieved through basal motion, which requires basal temperatures at the pressure-melting point (Paterson 1981; Clarke 1987; Lundqvist 2007). Accordingly, based on calculated advance rates, it can also be assumed that the bedrock beneath the last SIS in the study area was not frozen throughout the advance. Furthermore, the water-filled cavities must have existed at places where the sliding velocity was higher than 100 m a^{-1}, which had a triggering effect to increase glacier velocities (Paterson 1981). Several studies also support this suggestion as the base of the SIS was obviously in a liquid state during the Late Weichselian in the study area (Jõeleht 1998; Rattas 2004; Saks 2010; Jirakova *et al.* 2011).


NW
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500
600
700
800
900
12
13
14
15
16
17
18
19
20
25
30
35
GLACIER
cal. ^{14}C age
OSL/TL age
^{10}Be age
SS1 - Salpausselkä I stage
Pl - Palivere stage
Pan - Pandivere stage
Sa - Sakala stage
Ot - Otepää stage
Hn - Haanja (North-Lithuanian) stage
Md-Lith - Middle-Lithuanian (Krestets) stage
Vep - Vepsa (Pomeranian, Baltija) stage
LGM - Last Glacial Maximum

Fig. 12. Time-distance diagram in the eastern part of the study area (Karelian ISC area as zone B) along the azimuth line shown in Fig. 10. Dated sites: 82 = Nõva; 83 = Tabasalu; 84 = Kunda; 85 = Saha mire; 86 = Rae mire; 87 = Kuusalu; *88 = Pääsküla* mire; 89 = Käsmu; 90 = Ruila lake; *91 = Männiku*; 92 = Sillaotsa; 93 = Kemba; 94 = Valgejõe; 95 = Vaharu lake; 96 = Palmse; *97 = Pikasaare*; 98 = Viitna; *99 = Haljala*; *100 = Voka*; 101 = Loobu; 102 = Udriku; 103 = Kallukse; 104 = Pannjärve; *105 = Räätsma*; 106 = Iisaku; 107 = Mannjärve; 108 = Äntu; 109 = Varangu; 110 = Laiuse; 111 = Prossa; 112 = Puurmani; 113 = Elistvere; 114 = Vedu; 115 = Laeva; 116 = Peipsi; 117 = Saviku; 118 = Vasula; 119 = Naritsa; 120 = Vana-Kuuste; 121 = Kuliska; 122 = Nõuni; 123 = Lake Nakri; 124 = Nohipalu; 125 = Äidu; 126 = Kammeri; 127 = Taimeaia; 128 = Kaagvere; 129 = Lat-4; 130 = Kurenurme; 131 = Lat-3, Lat-3B; 132 = Lat-2; 133 = Viesuleni; 134 = Tamula; 135 = Līdumnieki; 136 = Solova; 137 = Remmeski; 138 = Jaanimäe; 139 = MLIT-13; 140 = EST-23; 141 = Viitka; 142 = Petruse; 143 = Veclaicene; 144 = MLIT-11; 145 = Lodesmuiža; 146 = MLIT-15; 147 = Lake Kūži; 148 = Raunis; 149 = Balti-12; 150 = MLIT-17; 151 = MLIT-19; 152 = MLIT-22; 153 = MLIT-21; 154 = MLIT-16; 155 = Dreimans; 156 = Sece; 157 = Balti-18; 158 = Lat-7; 159 = NLIT-4; 160 = Balti-15; 161 = Kurjanovas; 162 = Rudzāti; 163 = Balti-16; 164 = Lake Lielais Svētiņu; 165 = Leonovo; 166 = Balti-17; 167 = Burzava; 168 = Balti-13; 169 = Bel-15, Bel-15a; 170 = Zhizhitskoe; 171 = Bel-16; 172 = Bel-14; 173 = Bel-13; *174 = Lozoviki; 175 = Latyshi*; 176 = Bel-19; 177 = Bel-9; 178 = Studenets; 179 = Sudoble; 180 = Svjatoe; 181 = Töölö; *182 = Pehka*; 183 = Peedu; 184 = Tõrva; 185 = Laguja; 186 = Valga; 187 = Dores; 188 = Aabissaare; 189 = Lorupe; 190 = Mēri; 191 = Rõngu; 192 = Veselava; 193 = Misso; 194 = Dunayevo; 195 = Plavinas; *196 = Smeceres Sils*; *197 = Drichaluki*; 198 = Brigitpole; 199 = Borisovo; 200 = Shapurovo; 201 = Kasplyane; *202 = Chizhovka*; 203 = Rubezhnitsa; 204 = Sloboda Dvina. Key sites are in Italic.

4.2.2. Deglaciation and chronology of the last termination in the SE part of the Scandinavian glaciation

Deglaciation in the study area is mostly assessed on the basis of radiocarbon dates because these are more numerous than dates obtained by other methods. However, there was no preference among different dating methods. Radiocarbon dating has an advantage over other dating methods as it contains smaller errors and therefore also gives a smaller time range than, for example, OSL or ^{10}Be ages. However, even on the background of radiocarbon dates, deglaciation occurred so rapidly that the dating errors often cover the time difference between neighbouring ice-marginal formations. It should also be borne in mind that radiocarbon dating reflects the start of organic deposition and vegetation development after the retreat of the ice sheet, which might have taken hundreds of years after the area became ice-free (Hodkinson *et al.* 2003; Amon 2011).

More dates relevant to establishing the deglaciation chronology for our study area are available from the eastern part which is better covered by chronological data than the western part. Differences and similarities between the decay of the last SIS in the western Baltic ISC area and the eastern Karelian ISC area can be observed in time-distance diagrams (Figs. 11, 12) and are discussed below.

Baltic ISC area in the west (PAPER III)

In the Baltic ISC area, the last deglaciation started not earlier than 22.6 cal. ^{14}C ka BP in NW Belarus close to the LGM position (Gozha = 51). Within ca 8 ka the ice margin retreated to the NW of Latvia (site 1; Figs. 10, 11; Table 1), but not before 14.2 (± 1.3) ^{10}Be ka (Rinterknecht *et al.* 2006). The following six major SIS stagnations occurred in the western part of the study area during this deglaciation (starting with the oldest one): LGM, Baltija, South-Lithuanian (Sth-Lit), Middle-Lithuanian (Md-Lit), Haanja (Hn) and Sakala (Sa) (Fig. 13).

Different authors have suggested various correlations of the ice-marginal zones across the glaciated area (Kalm 2006, 2012a; Zelčs *et al.* 2011; Bitinas 2012). The Baltija ice-marginal zone in the western and the Vepsian ice-marginal formation in the eastern part of the study area are often correlated morphologically (Kalm 2012a), yet the synchronous timing of their formation based on the time-distance diagrams is questionable. According to our study, the Baltija ice-marginal zone appears to be about 4.5 ka older than the Vepsian ice-marginal zone. The time-distance diagram (Fig. 11) suggests that the decay of the last SIS was most rapid between the LGM and the South-Lithuanian ice-marginal zone. Karabanov & Matveyev (2011) are of the same opinion and explain this fact by wide distribution of ice-dammed lakes in front of the ice margin in NW Belarus, which provoked a relatively high rate of ice melting and calving. The calculated last SIS recession rate between the South-Lithuanian and Sakala ice-marginal zones is rather similar. Still, more dates from this area are absolutely necessary, to confirm this conclusion, as presently only two dates from mammoth remains from central Lithuania (Jiesia = 73) and SW of Latvia (Rucava = 9 in Figs. 10, 11 and Table 1) are significant for constructing the chronology of the decay of the last SIS in the Baltic ISC area (Arppe & Karhu 2010). Based on the time-distance diagram, most of the dates involving deglaciation in the western part of the study area are relatively young for assessing the decay of the last SIS. For example, some radiocarbon ages (sites 4, 5 and 7 in Fig. 11) between the Haanja and Sakala ice-marginal zones express the time of deposition of the Baltic Ice Lake sediments, as the samples for dating were taken from glaciolacustrine sands above varved clay (Danilans 1973). Furthermore, ^{14}C dates express the onset of vegetation in a particular area and thus do not directly reflect the timing of deglaciation. Cosmogenic beryllium dates are also mostly too young for the assessment of the deglaciation chronology in this part of the study area, possibly because the dated erratic boulders were not exposed to cosmic rays immediately after deglaciation (Heyman *et al.* 2011) but were covered by waters of glacial lakes.

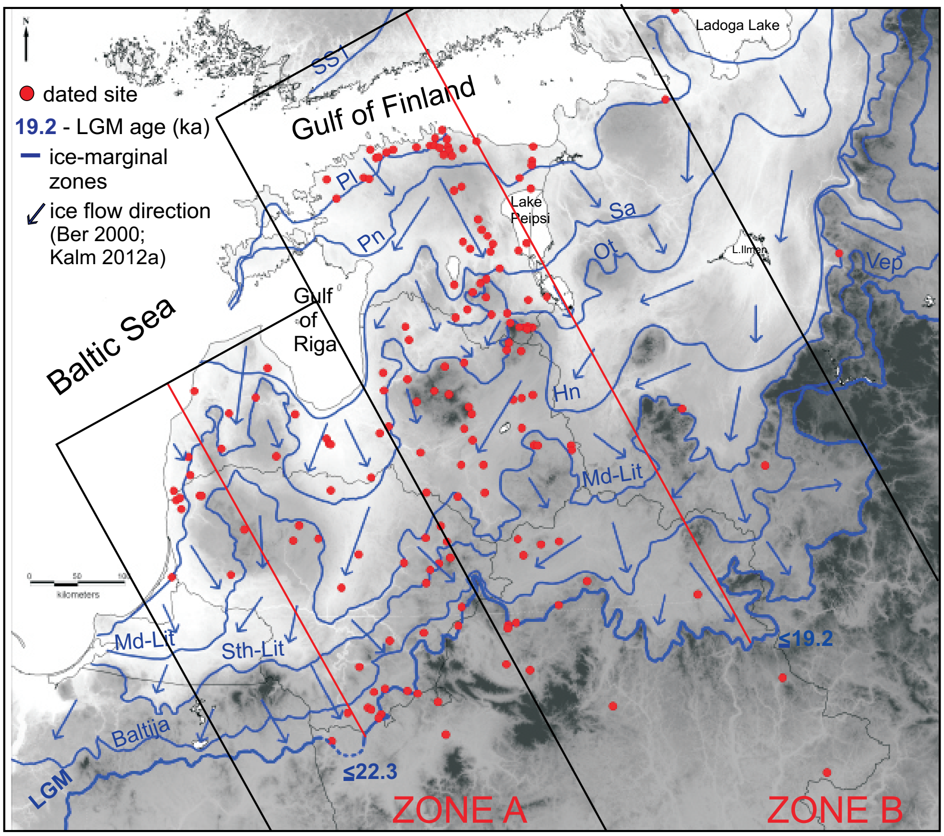

Fig. 13. Location of sites with dated sediments of Late Weichselian (post-LGM) age on the background of the ice-flow pattern.

Karelian ISC area in the east (PAPERS II and III)

The decay of the last SIS in the Karelian ISC area started after the SIS reached the LGM position at 19.1 cal. ^{14}C ka BP (Drichaluki = 198). The time-distance diagram (Fig. 12) indicates an approximately 2.6 ka standstill or dead ice field at the position of the maximum SIS extent, as suggested by Karabanov & Matveyev (2011), because ages from the modelled LGM position, which would fall into the time range of 19.1–16.8 cal. ^{14}C ka BP (median age at the Drichaluki and Latyshi sites) are lacking. The first date that can confirm deglaciation in the Karelian ISC area from the LGM position towards the southern shores of the Gulf of Finland is the one from NE Belarus, about 40 km west of the Vitebsk Upland (Latyshi = 176 in Figs. 10, 12 and Table 1), showing an age of 16.8 cal. ^{14}C ka BP (Zimenkov *et al.* 1985). Within 3.5 ka the whole area from the LGM to the southern Gulf of Finland was deglaciated, as indicated by the radiocarbon age (13.3 cal. ^{14}C ka BP) of lake deposits from northern Estonia (Pääsküla = 88; Figs. 10, 12; Table 1) (Heinsalu & Veski 2007). Thus the deglaciation in the Karelian ISC area was about twice as fast as in the Baltic ISC area. The faster retreat of the last SIS in the eastern part of the study area could be explained by large meltwater bodies in front of the SIS, which favoured more rapid decay of the ice margin due to calving. Eight major SIS stagnations occurred during deglaciation of the Karelian ISC area, resulting in the formation of ice-marginal zones – LGM, Vepsian (Vep), Middle-Lithuanian (Md-Lit), Haanja (Hn), Otepää (Ot), Sakala (Sa), Pandivere (Pn) and Palivere (Pl) (Fig. 13). The distance between different ice-marginal zones is mainly in the range of 20–100 km, which is much smaller than in the western part of the study area and implies a faster decay of the SIS. Although the deglaciation rate was different in the west and in the east, some ice-marginal zones such as the Middle-Lithuanian, Haanja and Sakala zones, have a similar formation-time in both parts of the study area as shown in the time-distance diagrams (Figs. 11, 12). A possible explanation is that calculation of the deglaciation rate does not take into account other features such as the possible surges or fan-shape flow of ice streams and fluctuations of the ice sheet margin.

Although it is difficult to achieve an exact timing of the formation of ice-marginal zones across the study area, an attempt has been made to determine the age for the five youngest ice-marginal zones in its eastern part, Estonia (PAPERS II and III). The modelled decay of the last SIS in Estonia is shown in Fig. 14.

Haanja ice-marginal zone

The age of the oldest Estonian ice-marginal zone, Haanja, is traditionally (Pirrus & Raukas 1996; Raukas 2009) determined from dating the Raunis interstadial sediments below the Haanja till (between 15.7 and 15.9 cal ^{14}C ka BP; Dreimanis & Zelčs 1995; Zelčs & Markots 2004) in northern Latvia (Fig. 14). After the ice front retreated from the northern slopes of the Haanja Heights, varved clay deposition started in Lake Tamula ca. 14 675 varve years ago (Sandgren *et al.* 1997; Kalm 2006; Raukas 2009). Consequently, dates from below and above the Haanja stadial till place the formation of the ice-marginal zone between ca 15.7 and 14.7 cal. ka BP. Raukas (2009) reported two new (10.5 and 10.4 cal ^{14}C ka BP) dates from the Raunis section and questioned the interstadial age of the sediments there. However, even if the organic sediments in the Raunis section are not interstadial, the Haanja ice-marginal zone formed before the start of varved clay deposition in Lake Tamula, which took place before 14.7 ka BP. During the Haanja phase of deglaciation a small northeast–southwest oriented ice tongue operated between the Haanja and Otepää uplands (Karukäpp 2004; Kalm 2010). It is probably responsible for burial of pieces of wood, gyttja and sand layers under the surficial till in few locations (Kurenurme, Kaagvere in SE Estonia).

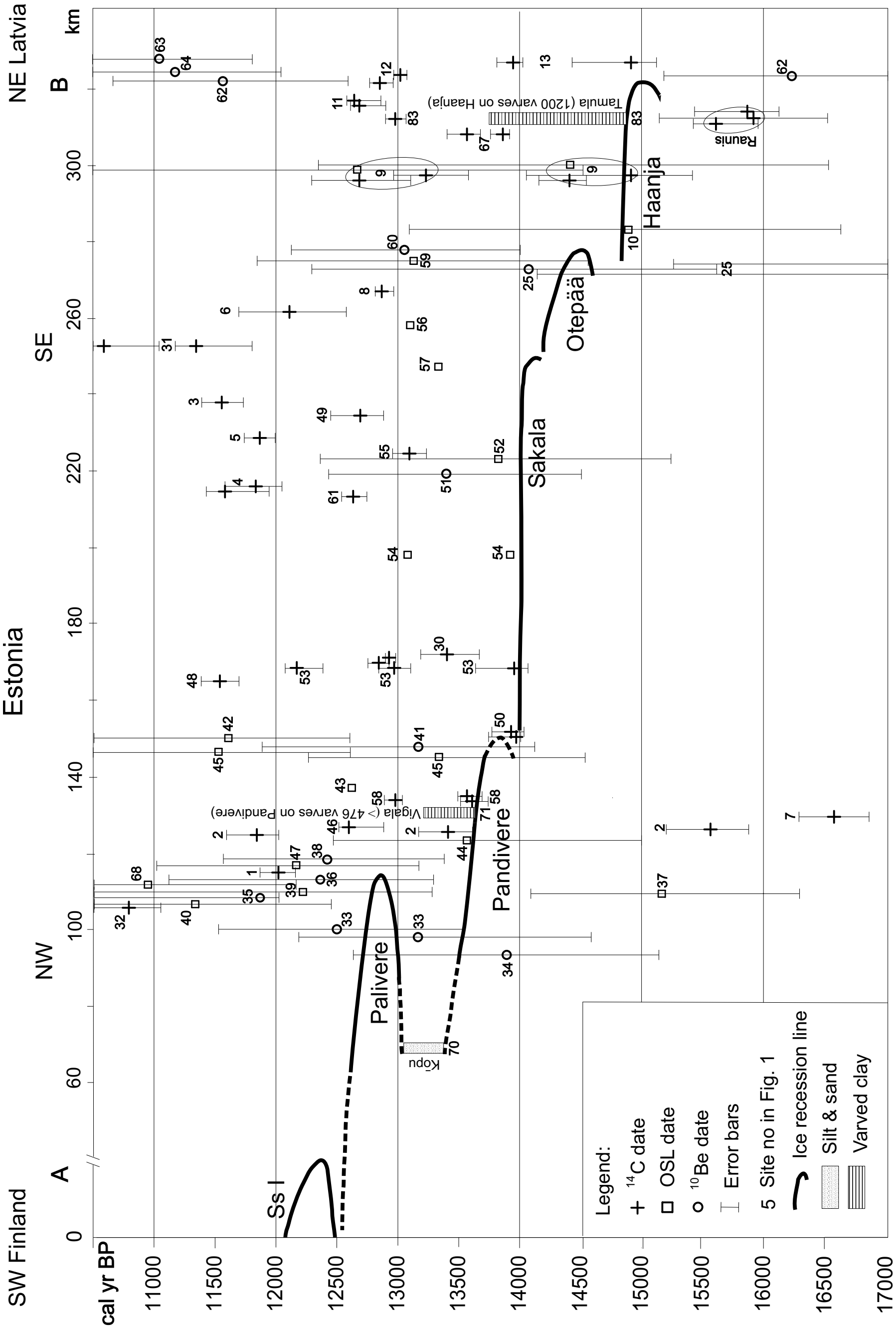

Fig. 14. Modelled decay of the Late Weichselian ice in Estonia along the general azimuth line. The sites mentioned in the discussion concerning the chronology in Estonia: 8 = Nõuni, 9 = Kurenurme , 10 = Kaagvere, 11 = Remmeski, 12 = Viitka, 13 = Petruse, 55 = Lake Peipsi , 56 = Nohipalu, 59 = Taimeaia, 70 = Kõpu, 71 = Vigala, 83 = Tamula.

The oldest ^{14}C ages from buried organics under the Haanja till in Kurenurme (14.5 and 14.9 cal. ^{14}C ka BP) and OSL ages of buried sand in Kurenurme and Kaagvere (12.7, 14.5 and 14.9 cal. ^{14}C ka BP) confirm that the Haanja zone was formed before 14.9 cal. ^{14}C ka BP. All five measured ^{14}C ages from the Haanja Upland beyond the Haanja ice-marginal belt (between 12.8 and 14.9 cal ^{14}C ka BP; Kalm 2006) are restricted to superficial organic deposits (Remmeski) or plant detritus and peat buried under the slope wash and debris of hummocky moraine topography (Viitka, Petruse). The first organic sediments (gyttja, peat and plant detritus) on the Haanja Upland started to accumulate at the time (≤14.9 cal. ^{14}C ka BP) when the upland was surrounded by ice from the west, north and east.

Otepää ice-marginal zone

The formation time of the Otepää ice-marginal zone is older than its direct dating from the region of the Otepää Upland. The 12.9 cal ^{14}C ka BP age of the first lateglacial organics in the Nõuni section of lacustrine deposits (Saarse 1979), which is situated just on the proximal side of the Otepää ice-marginal zone, indicates the start of vegetation after deglaciation rather than direct deglaciation time. In addition, two 13.2 OSL ka ages from sand of the glaciofluvial delta (Taimeaia) and kame (Nohipalu) (Raukas & Stankowski 2005), located also in the proximal position relative to the Otepää ice-marginal zone, indicate an earlier retreat of the ice from that zone. Radiocarbon dates (12.9 to 13.9 cal. ^{14}C ka; Saarse & Liiva 1995; Sohar & Kalm 2008; Kalm & Sohar 2010) and OSL ages (13.1–14.0 ka) from glaciofluvial deposits (Raukas & Stankowski 2005) between the Otepää and Pandivere ice-marginal zones, suggest ice recession from the Otepää ice-marginal zone well before 14 OSL ka.

Sakala ice-marginal zone

The Sakala ice-marginal zone has been suggested to occur between the Otepää and Pandivere ice-marginal zones (Pirrus & Raukas 1996; Raukas *et al.* 2004; Kalm 2010). However, it is morphologically difficult to identify and accurate dating is problematic.

Pandivere ice-marginal zone

Based on varve studies in eastern Estonia, Hang (2003) concluded that deglaciation of the northern part of the glacial Lake Peipsi started around 13 500 varve ka ago and ended ca 370 years later. Hang (2003) also suggested that the first 184 varves in glacial Lake Peipsi were deposited before the ice margin withdrew from the Pandivere ice-marginal zone. According to him, the start of deposition of distal varves some 13300–13320 varve years ago corresponds to the withdrawal of the ice from the Pandivere zone. Based on Saarse *et al.* (2009) and PAPER III, it can be concluded that ice cover of the Pandivere Upland started to perish already before 13.9 cal. ^{14}C ka BP, that is some 0.5 ka earlier than in the depression of Lake Peipsi.

Palivere ice-marginal zone

Hang & Sandgren (1996) counted 476 annual varves at Vigala in western Estonia between the Pandivere and Palivere ice-marginal zones and dated the Palivere marginal formations to about 11 800 years BP. With the correction of missing 875 varves according to Swedish varve chronology (Andren *et al.* 1999), they assigned the Palivere ice-marginal zone an age of 12.675 years BP, from which an age for the Palivere re-advance around 12.7 cal ^{14}C ka BP was derived. However, eight ^{10}Be ages from the Palivere ice-marginal zone have a weighted mean age of 13.6 ka (Rinterknecht *et al.* 2006), which predates even the ^{10}Be age (13.1 ka) of the Haanja ice-marginal zone in SE Estonia. However, according to overall deglaciation chronology in the eastern part of the study area (the Karelian ISC area; PAPER III and Saarse *et al.* 2012), the Palivere ice-marginal zone formed before 13.3 cal. ^{14}C ka BP. This result corresponds well with the suggestion by Lunkka *et al.* (2004) that the ice margin of the SIS reached the coastal areas of southern Finland 13.1 ka ago. Similar studies from the Vologda area, NW Russia, confirm that the Lake Onega basin between the Pandivere and Salpausselkä ice-marginal zones was deglaciated between 14.25 and 12.74 cal. ^{14}C ka BP (Lunkka *et al.* 2001; Saarnisto & Saarinen 2001).

Comparison of the deglaciation in two parts of the study area

The calculated linear rate of deglaciation was slower in the Baltic ISC area than in the Karelian ISC area, whereas the formation of one ice-marginal zone in each of these areas took about 1.6 ka and about 0.5 ka, respectively. The calculated linear mean rate of the last SIS recession in the western part of the study area was ca 50 m a^{-1}, which is about two times slower than in SW Sweden, where the varve chronology suggests a retreat rate of 75–100 m a^{-1} (Ringberg & Erlström 1999). In the eastern part of the study area, the respective value was about 170 m a^{-1}, i.e. about ten times faster than in the west. Compared to mean recession rates of 150 m a^{-1}, previously suggested for the Karelian ISC area from varved clays in the Lake Peipsi depression (Hang 2001), and 110 m a^{-1} from the Haanja to Palivere ice-marginal zones in Estonia (Kalm 2006), the recession rate in this thesis is somewhat higher. In Russia, bordering on the eastern part of the study area, the ice-retreat rate from Kubenskoye to northern Lake Ladoga and Lake Onega was estimated to be 60–80 m a^{-1} (Lunkka *et al.* 2001). Based on varved clays, the maximum rate in the Onega area was about 200 m a^{-1} (Saarnisto & Saarinen 2001). This value is slightly higher, but still more or less in agreement with the calculated recession rate given in this thesis, because it is a maximum and not a mean rate.

5. CONCLUSIONS

The most important conclusions of this thesis are as follows:

- According to chronological data available from the Valdai Upland (Kileshino site), ice-free conditions existed between 72.2 OSL and 33.8 cal. ^{14}C ka BP in the western part of the East European Plain.
- The Scandinavian Ice Sheet reached the Valdai Upland (Kileshino site) only once during the last 72.2 ka – during the Late Weichselian after 33.8 cal, ^{14}C ka BP, and presumably between 19.1 cal. ^{14}C BP and 18 OSL ka.
- The last SIS in the Baltic ISC area reached the western shores of Latvia not before 26 OSL ka, advanced further to central Lithuania not before 25.6 cal. ^{14}C ka BP and reached southern Lithuania not before 24.7 cal. ^{14}C ka BP.
- In the Karelian ISC area, the last SIS reached the southern shores of the Gulf of Finland not before 21 OSL ka and central Latvia not before 19.6 OSL ka.
- The last SIS reached its maximum extent in NW Belarus not earlier than 22.6 cal. ^{14}C ka BP and in NE Belarus not earlier than 19.1 cal. ^{14}C ka BP.
- When considering the whole time range of individual dates and the youngest dates which express the beginning of vegetation development, the last SIS could have been at its maximum extent in the Baltic ISC area between 24.4 and 19.6 cal. ^{14}C ka BP, and in the Karelian ISC area between 19.4 and 17.8 cal. ^{14}C ka BP.
- The mean calculated linear advance rate of the last SIS in the western part of the study area was 110 m a^{-1} and about three times faster in the eastern part, 330 m a^{-1}. These values, however, are tentative because of the scanty data from the Middle Weichselian. Nevertheless, the calculated relatively high speed of ice advance suggests warm-based conditions and that the bed beneath the last SIS in the study area was not frozen throughout the SIS advance.
- Deglaciation in the Baltic ISC area started not earlier than 22.6 cal. ^{14}C ka BP. By 14.2 ^{10}Be ka, the entire area between the LGM position in NW Belarus and the western shores of Latvia was deglaciated. In the Karelian ISC area, the last SIS recession started not earlier than 19.1 cal. ^{14}C ka BP. By 13.3 cal. ^{14}C ka BP, the whole area between the LGM position in NE Belarus and the southern shores of the Gulf of Finland was ice-free.
- The last SIS recession rate in the study area was about three times faster in the east than in the west, 50 and 170 m a^{-1}, respectively.

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SUMMARY IN ESTONIAN

Weichseli jäätumise kronoloogia Skandinaavia jäätumise kagusektoris

Käesolev doktoritöö uurib Weichseli jäätumise ajalist kulgu, liustiku maksimaalse leviku ulatust ja liustiku pealetungi ja taandumise dünaamikat jäätumisele allunud Ida-Euroopa tasandiku lääneosas. Uuringuala hõlmab Skandinaavia jäätumise kagusektorit Läänemerest kuni viimase jäätumise maksimaalse leviku piirini. See ala on Weichseli jäätumise jooksul mitmeid kordi allunud liustike tegevusele. Jäätumiste ja eelkõige jää taandumisega kaasnevad kliima- ja keskkonnamuutused on olnud määravaks jäätumisalade geoloogia, pinnamoe, hüdrograafia, mullastiku ja seotud taimkatte aga ka inimasustuse kujunemisel. Veelgi enam, soojeneva kliima tingimustes toimunud liustike sulamisega kaasnenud sulaveehulgad mõjutasid märkimisväärselt ookeani veetaset ja soojusrežiimi. Paraku on andmed selle mõju ulatuse kohta puudulikud, mis omakorda takistab võimalike kliima ja veetaseme muutuste prognoose tänapäeval, mil eeldatav soojenemine võib kaasa tuua kaasaegsete jääkilpide sulamise ja ookeanitaseme tõusu. Seega on väga oluline varasemate liustike ajalis-ruumilise dünaamika selgitamine, mis võimaldaks paremini mõista ka eesootavat tulevikku. Varasemate liustike dünaamika selgub aga eelkõige läbi pinnavormide ja setete kronoloogiliste uuringute, millega tegeleb ka käesolev doktoritöö.

Vaatamata pikaajalistele ja mitmekülgsetele uuringutele, on teadmised Weichseli jäätumise ajalis-ruumilise kulgemise kohta Ida-Euroopa tasandikul väga lünklikud ja olemasolevad andmed jäätumisala lõikes väga ebaühtlased.

Eriti puudulik info on varasemate Vara- ja Kesk-Weichseli jäätumise kohta, kuna sellele järgnenud Hilis-Weichseli liustik on varasemaid setteid ja pinnavorme oluliselt ümber kujundanud või hoopis erodeerinud. Seetõttu on varasemate jäätumiste setteid leitud vaid üksikutest kohtadest Põhja-, Kesk- ja Ida-Euroopast. Viimase, Hilis-Weichseli jäätumise kohta on andmeid rohkem, kuid siiani on ebaselge liustiku saabumise aeg uuringualale ja laienemine maksimaalse leviku piirile. Aga ka viimase liustiku taandumise käik on põnevate diskussioonide teemaks. Mitmed autorid (Kalm 2006, 2012a; Rinterknecht jt. 2006, 2007, 2008; Raukas 2009; Satkūnas jt. 2009; Guobytė & Satkūnas 2011; Zelčs jt. 2011; Bitinas 2012) on pakkunud erinevaid mudeleid liustiku serva taandumise ajalist ebaühtlust väljendavate servamoodustiste vööndite paiknemise, korrelatsiooni ja vanuse osas. Seetõttu on käesoleva töö peamisi eesmärke koondada ja kriitiliselt analüüsida Weichseli jäätumise liustike ajalis- ruumilist dünaamikat iseloomustavat kronoloogilist andmestikku Ida-Euroopa tasandiku lääneosas. Spetsiifilised eesmärgid olid: *esiteks,* hinnata viimasele jäätumisele eelnenud jäävaba perioodi kestvust uuringualal; *teiseks,* hinnata viimase Weichseli liustiku pealetungi ajalist kestvust; *kolmandaks,* luua viimase jäätumise taandumise kronoloogia arvestades sealhulgas olemasoleva kronoloogilise andmestiku geograafilise paiknemise ja liustikukeelte dünaamikaga; *neljandaks,* hinnata liustiku pealetungi ja taandumise kiirust, mis on aluseks liustiku aluste protsesside mõistmisel ja suurte jääkilpide mudelite loomisel.

Eesmärkide saavutamiseks koondati kättesaadav kronoloogiline andmestik ning korrastati see andmekoguna kuhu lisandusid käesoleva uurimuse jooksul saadud uued radisosüsiniku (^{14}C), optiliselt stimuleeritud luminestsentsi (OSL), termoluminestsentsi (TL) ja kosmogeense berülliumi (^{10}Be) dateeringud. Andmekogu täiendati regulaarselt uueneva kronoloogilise andmestikuga.

Kronoloogilisest andmestikust tehti valik deteeringutest, mis on sobilikud ja asjassepuutuvad liustiku pealetungi ning taandumise hindamisel. Valik piirneb dateeringutega ajavahemikus 35 ja 11,7 tuhat aastat tagasi (a.t.). 35 tuhat a.t. tähistab siinkohal viimast soojenemisperioodi, merelise isotoopstaadiumi 3.1. (Lambeck jt. 2010) algust, millele järgnes viimase Skandinaavia liustiku laienemine uuringualale u 26 tuhat a.t. ja selle lõplik taandumine 11,7 tuhat a.t. Valikust jäeti välja näiteks radiosüsiniku dateeringud, mille vanus võib olla ülehinnatud stabiilse süsinikuga rikastumise tõttu (järvelubi, karbonaatsed setted). Kokku kasutati 311 radiosüsiniku, 87 optiliselt stimuleeritud luminestsents ja 72 kosmogeense berülliumi dateeringut. Valikusse alles jäänud dateeringud kanti koordinaatide järgi kaardile ja vastavalt liustikukeelte dünaamikale jaotati uuringuala kaheks; läänepoolne Balti jääkeelte ala ja idapoolne Karjala jääkeelte ala. Seejärel kanti kõik dateeringud proportsionaalselt üleüldisele jäätumistsentrisse orienteeritud liustiku laienemise ja taandumise asimuudile, arvestades nende asendit servamoodustiste suhtes ning koostati selle põhjal aeg-distants mudelid, mis olid aluseks järgnevale liustike dünaamika analüüsile.

Kronoloogiliste ja sedimentoloogiliste tulemuste põhjal selgus, et Skandinaavia liustik jõudis Valdai kõrgustikule (Kilešino uuringula) viimase Weichseli jäätumise maksimaalse levikupiiri lähedale ainult ühel korral viimase 72,2 tuhande aasta jooksul. See toimus Hilis-Weichselis, hiljem kui 33,8 tuhat a.t. aga suurema tõenäosusega ajavahemikul 19,1 kalendriaastat ja 18 tuhat a.t. Ajavahemikus 72,2 tuhat ja 33,8 tuhat a.t. oli Valdai kõrgustik jäävaba.

Viimane Skandinaavia liustik liikus uuringuala lääneosasse, seal oma maksimumlevikupiirini ja ka taandus varem kui idaosas. Lääneosas jõudis Skandinaavia liustik Läti läänerannikule mitte varem kui 26 tuhat (a.t.), laienes Kesk-Leedu aladele umbes 25,6 tuhat a.t. ja Leedu lõunaosasse mitte varem kui 24,7 tuhat a.t. Uuringuala idaosas jõudis Skandinaavia liustik Soome lahe lõunarannikule mitte varem kui 21 tuhat a.t. ja Läti keskaladele mitte varem kui 19,6 tuhat a.t. Oma maksimumleviku saavutas Skandinaavia liustik uuringuala läänesoas, Loode-Valgevenes, hiljem kui 22,6 tuhat a.t. ja Kirde-Valgevenes, mitte varem kui 19,1 tuhat a.t. Liustikuserva maksimaalsel levikupiiril püsimise kestvuse hindamiseks kasutati üksikdateeringute mediaanväärtuste asemel ajavahemikke ning liustiku taandumisejärgse orgaanilise taimestiku kujunemise kõige varasemaid dateeringuid. Sellele toetuvalt võib arvata, et Skandinaavia liustik oli maksimumlevikupiiril ajavahemikus 24,4 ja 19,6 tuhat a.t. uuringuala lääneosas ja ajavahemikus 19,4 ja 17,8 tuhat a.t. uuringuala idaosas. Kronoloogilise andmestiku geograafilise paiknemise analüüsile toetuva liustiku pealetungi kiiruse arvutused näitavad, et uuringuala lääneosas oli see u 110 m/a ja idaosas 330 m/a. Toetudes varasematele uuringutele võib arvata, et selline väga kiire liustiku liikumine on võimalik saavutada vaid siis, kui liustiku basaalne kiht on sulas olekus, ja seetõttu järeldame, et jää aluspind uuringualal ei olnud külmunud kogu Weichseli jäätumise kestel.

Viimase Skandinaavia liustiku taandumine algas uuringuala lääneosas mitte varem kui 22,6 tuhat a.t. ning liustiku maksimumlevikupiiri ja Läti läänerranniku vaheline ala sai lõplikult jäävabaks 14,2 tuhat a.t. Uuringuala idaosas algas Skandinaavia liustiku taandumine hiljem ja mitte varem kui 19,1 tuhat a.t. tagasi ning kogu ala liustiku maksimumlevikupiiri ja Soome lahe vahel sai jäävabaks 13.3 tuhat a.t. Liustiku taganemiskiirus lääneosas (50 m/a) on sarnaselt pealetungi kiirusele ligikaudu 3 korda aeglasem kui idaosas (170 m/a).

PUBLICATIONS

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Professional employment:

2014–…	University of Tartu, Department of Geology, specialist
2012–2013	University of Tartu, Department of Geology, main specialist
2008–2012	University of Tartu, Department of Geology, laboratory assistant
2006–2007	Kobras AS, assistant

Research activity:

Field of research:

- Quaternary sediments and glaciations, dating methods, chronology

Grants and scholarships:

2013	COST 'Pay-as-you-go System'
2011	SA Archimedes (Kristjan Jaagu programme)
2010	Doctoral school of Earth Sciences and Ecology

Professional development:

2013	training course – Benzene line and procedures of benzene synthesis, held by Institute of Environmental Geochemistry of the National Academy of Sciences of Ukraine and Conventional Radiocarbon Dating Laboratory, in Kyiv. Ukraine
2013	educational programme "LIDAR-based palaeogeographic reconstructions of the Baltic Sea", held by the Institute of Ecology and Earth Sciences of the University of Tartu and the Doctoral school of Earth Sciences and Ecology, Estonia

2012 participation in Summer Training School on Dating Methods and their applications, held by GFZ and GADAM Centre, in Potsdam and Gliwice, Germany and Poland

2011 training course 'LSC Basic', held by PerkinElmer, in Bad Orb, Germany

2011 participation in 'Youth in Action' Programme – Geoparc: Geoscience – Geoturism – Conservation, held by „Nationaler Geopark Eiszeitland am Oderrand", in Germany

2011 educational programme „Modelling of Palaeoshorelines of Baltic Sea", held by the Institute of Ecology and Earth Sciences of the University of Tartu, in Estonia

2010 participation in Geochronology Summer School – Dating Anthropogenic and Natural Changes in a Fragile Alpine Environment, held by University of Zurich, in Switzerland

Publications:

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Teadustegevus:

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2011	koolitus „LSC Basics", organiseeritud PerkinElmeri poolt Bad Orbis, Saksamaal

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