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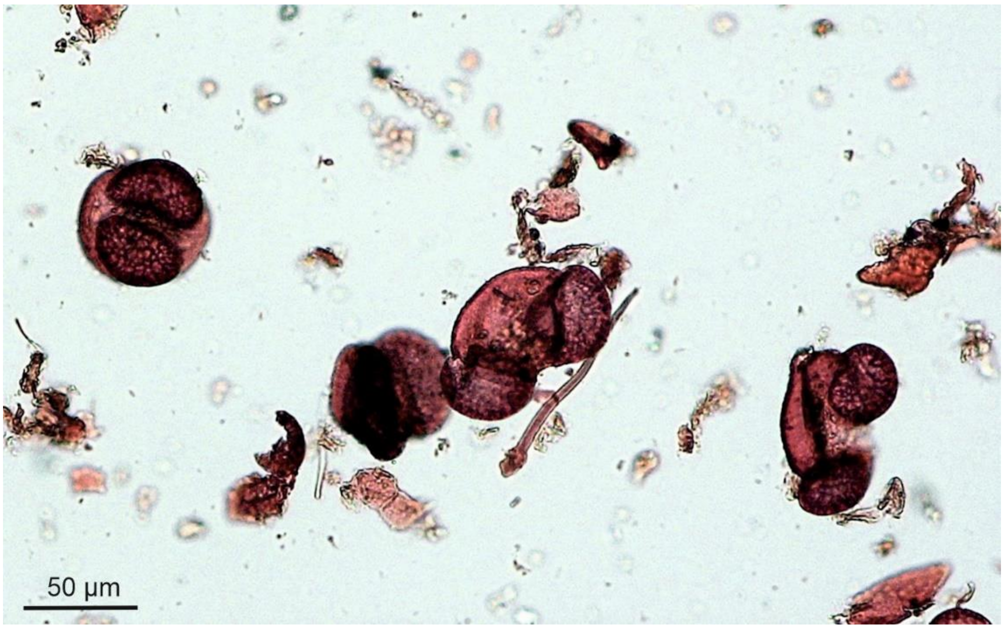
Tiina Eskola

The late Middle and Late Pleistocene environmental and glaciation history of Northern Ostrobothnia and Finnish Lapland



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Pollen grains of *Pinus sylvestris* (Scots pine) in a sample treated with modified LST Fastfloat method. Photographed with 400 x magnification under light microscope.

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Academic dissertation to be presented with the assent of the Doctoral Training Committee of Technology and Natural Sciences of the University of Oulu for public defence in auditorium L6, University of Oulu, on December 17th, 2021 at 12 o'clock noon.

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The late Middle and Late Pleistocene environmental and glaciation history of Northern Ostrobothnia and Finnish Lapland

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Abstract

The Scandinavian Ice Sheet (SIS) covered Fennoscandia numerous times during the Pleistocene, but the exact number, extent of ice and precise time and duration of glacial and non-glacial phases have not been fully established for the eastern flank of the SIS. At several sites, only incomplete sedimentary records have been preserved owing to different rates of erosion and glaciotectonic deformation during several glacial advances and the intervening non-glacial phases. The most complete sediment successions have been found in northern and west-central Finland, in an area that has escaped erosion due to the vicinity of the ice-divide zone and frozen bed conditions.

The main objective of this thesis was to examine the paleoenvironment and glaciation history of the Weichselian (MIS 5–2) and the late Saalian (MIS 6) stages in northern and west-central Finland. This thesis specifically concentrates on pollen stratigraphy and its use in correlation although other stratigraphical and geochronological tools have also been applied. Sediment sequences from three different sites located in northern and central Finnish Lapland and Northern Ostrobothnia, central western part of Finland, were studied using stratigraphical and dating methods. Furthermore, a safer heavy liquid pollen preparation method for minerogenic sediments was introduced and validated. Based on the results, it is suggested that the modified LST Fastfloat method gives comparable results compared to the conventional hydrofluoric acid (HF) method.

The thesis provides new geochronologically and biostratigraphically constrained data to establish the more complete stratigraphy for northern and central Finland and beyond. Results indicate that the ice sheet advanced further south than previously thought during the Early Weichselian Herning stadial (MIS 5d). Results also strengthen the view that ice-free conditions prevailed during the Middle Weichselian (MIS 3) stage. Moreover, results from the Kaarreoja site from northern Finnish Lapland indicate that the climate was warmer than previously suggested.

Keywords: Scandinavian Ice Sheet, Weichselian, Eemian, glaciation, OSL, paleoenvironment, pollen, heavy liquid, biostratigraphy, lithostratigraphy

Myöhäisen Keski- ja Myöhäis-Pleistoseenin ympäristö- ja jäätiköitymishistoria Pohjois-Pohjanmaalla ja Lapissa

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Tiivistelmä

Skandinavian mannerjäätikkö (SIS) peitti Fennoskandian useita kertoja Pleistoseenin aikana, mutta jäätiköityneiden ja jäästä vapaiden jaksojen tarkkaa lukumäärää, jääkentän laajuutta, täsmällistä aikaa ja kestoa ei ole voitu täysin todentaa Skandinavian mannerjäätikön itäisimmälle osalle. Monin paikoin on säilynyt vain epätäydellisiä sedimenttisarjoja johtuen useiden jäätiköitymisjaksojen aiheuttamasta eroosiosta ja glasiotektonisesta deformaatiosta. Kattavimmat sedimenttisarjat ovat löytyneet Pohjois-Suomesta ja Keski-Suomen läntisestä osasta, jossa eroosio oli hyvin vähäistä johtuen jäänjakajavyöhykkeen läheisyydestä ja kylmäpohjaisesta jäätiköstä.

Tämän väitöskirjatyön päätavoitteena oli tutkia Veikselin (MIS 5–2) ja myöhäis-Saalen (MIS 6) vaiheiden aikaista muinaista ympäristöä ja jäätiköitymishistoriaa Pohjois-Suomen ja läntisen Keski-Suomen alueilla. Tässä väitöskirjatyössä keskitytään erityisesti siitepölystratigrafiaan ja sen käyttöön korrelaation välineenä muiden stratigrafisten ja geokronologisten tutkimusmenetelmien lisäksi. Sedimenttisarjat kolmesta eri paikasta, jotka sijaitsevat Suomen Lapin pohjois- ja keskiosissa sekä Pohjois-Pohjanmaalla, tutkittiin stratigrafisilla menetelmillä ja erilaisilla ajoitusmenetelmillä. Lisäksi työssä esiteltiin mineraaliainespitoisille sedimenteille soveltuva, turvallisempi raskasneste-erotteluun perustuva siitepölynäytteiden valmistusmenetelmä. Tutkimustulosten perusteella voidaan todeta muunnellun LST Fastfloat -menetelmän antavan vertailukelpoisia tuloksia perinteiseen fluorivetyhappomenetelmään (HF) verrattuna.

Tämä väitöskirjatyö tarjoaa uutta geokronologisesti ja biostratigrafisesti tuotettua tietoa, joka auttaa muodostamaan kattavamman stratigrafisen kuvan Pohjois- ja Keski-Suomesta. Tutkimustulokset osoittavat jääpeitteen edenneen aiemmin uskottua etelämmäksi varhais-Veikselin Herning -stadiaalin (MIS 5d) aikana. Tulokset vahvistavat myös käsitystä jäättömästä keski-Veiksel -vaiheesta (MIS 3). Lisäksi tulokset Kaarreojalta, Pohjois-Lapista, osoittavat ilmaston olleen aiemmin oletettua lämpimämpi.

Keywords: Skandinavian mannerjäätikkö, Veiksel, Eem, jäätiköityminen, OSL, paleoympäristö, siitepölyt, raskasneste, biostratigrafia, litostratigrafia

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Oulu, November 2021

Tiina Eskola

ORIGINAL PUBLICATIONS

This dissertation is based on the following four peer-reviewed publications:

Paper I — Sarala, P. & Eskola, T. 2011. Middle Weichselian interstadial deposit at Petäjäselkä, Northern Finland. E&G Quaternary Science Journal 60 (4), 488-492. https://doi.org/10.3285/eg.60.4.07

Paper II — Sarala, P., Väliranta, M., Eskola, T. & Vaikutiené, G. 2016. First physical evidence for forested environment in the Arctic during MIS 3. Scientific Reports 6, 29054. https://doi.org/10.1038/srep29054

Paper III — Eskola, T., Kontio, R. & Lunkka, J. P. 2021 Comparison between modified LST Fastfloat and conventional HF methods for pollen preparation in highly minerogenic sediments. Bulletin of the Geological Society of Finland 93, 5–18. https://doi.org/10.17741/bgsf/93.1.001

Paper IV — Eskola, T. & Lunkka, J. P. (in press). Sediment sequence at Muhos, western Finland – a window to the Pleistocene history of the Scandinavian Ice Sheet. Boreas. https://doi.org/10.1111/bor.12560

CONTRIBUTION OF THE AUTHOR

P.S. planned the article, made the sedimentological study and wrote most of the article in Paper I. T.E. performed the pollen analysis and participated in the interpretation and writing of the manuscript.

In Paper II, P.S., T.E. and M.V. planned the study, did the field work and collected samples. P.S. conducted the sedimentological study and interpretation, T.E. made pollen analyses, M.V. macrofossil analyses and G.V. diatom analyses. The manuscript was written by P.S. and M.V. with assistance and comments from T.E. and G.V.

T.E. and R.K. designed the study in Paper III. R.K. performed the laboratory analyses, T.E. counted the samples and made the interpretation. T.E. wrote the manuscript with assistance and comments from R.K. and J.P.L.

J.P.L. designed the study with contribution from T.E. in Paper IV. T.E. and J.P.L. wrote the manuscript. T.E. performed pollen and diatom analyses, and J.P.L. performed sedimentological analysis. Both T.E. and J.P.L. contributed to the interpretation of the data and writing of the manuscript.

CONTENTS

1. INTRODUCTION

The Scandinavian Ice Sheet (SIS) covered Fennoscandia several times during the Pleistocene (e.g., Svendsen *et al.* 2004, Hughes *et al.* 2016 – Fig. 1). However, the exact number of the glacial phases, the ice extent, and the time and duration of the ice cover over Fennoscandia is not known since the existing sedimentary record is incomplete due to a different rate of erosion at various glacial and non-glacial phases. The most complete Pleistocene sedimentary sequences discovered in Finland occur in central Finnish Lapland and in Ostrobothnia, western Finland (e.g., Hirvas 1991; Nenonen 1995; Johansson *et al.* 2011) (Fig. 1).

Fig. 1. Locations of study sites (stars; Petäjäselkä, Kaarreoja and Muhos) and the sites referred in the text, in order of appearance. 1 = Sokli; 2 = Leveäniemi; 3 = Tepsankumpu; 4 = Paloseljänoja; 5 = Mertuanoja; 6 = Riipiharju; 7 = Oulainen; 8 = Marjamurto; 9 = Kauvonkangas; 10 = Ruunaa; 11 = Pilgrimstadt; 12 = Hitura; 13 = Ollala; 14 = Vesiperä; 15 = Viitala; 16 = Ukonkangas; 17 = Norinkylä; 18 = Põhja-Uhtju; 19 = Peski; 20 = Vimpeli; 21 = Horonkylä; 22 = Rautuvaara; 23 = Hannukainen; 24 = Rissejauratj; 25 = Veskoniemi.

It has been postulated that an ice divide zone (i.e., glacier centre with cold glacial base) located in central Finnish Lapland several times during the Pleistocene and this was the main reasons for weak erosion in that area. Similarly, frozen bed conditions also might explain weak glacial erosion in Ostrobothnia (Hirvas 1991; Kleman & Hättestrand 1999; Kleman *et al.* 1997, 2008; Stroeven *et al.* 2016).

Based on previous studies, the SIS covered western Finnish Lapland five times during the Weichselian stage (ca. 116–10 ka; e.g., Johansson *et al.* 2011); during the Early Weichselian Herning (Marine Isotope Stage, MIS 5d; 113–103 ka) and Rederstall stadials (MIS 5b; 92–83 ka), in the beginning of the Middle Weichselian substage (MIS 4; ca. 72–60 ka) and at the end of the Middle Weichselian substage (MIS 3; ca. 49–35 ka) and, also during the Late Weichselian substage (MIS 2; ca. 25–10 ka) (Johansson *et al.* 2011; Lunkka *et al.* 2015; Howett *et al.* 2015; Fig 2).

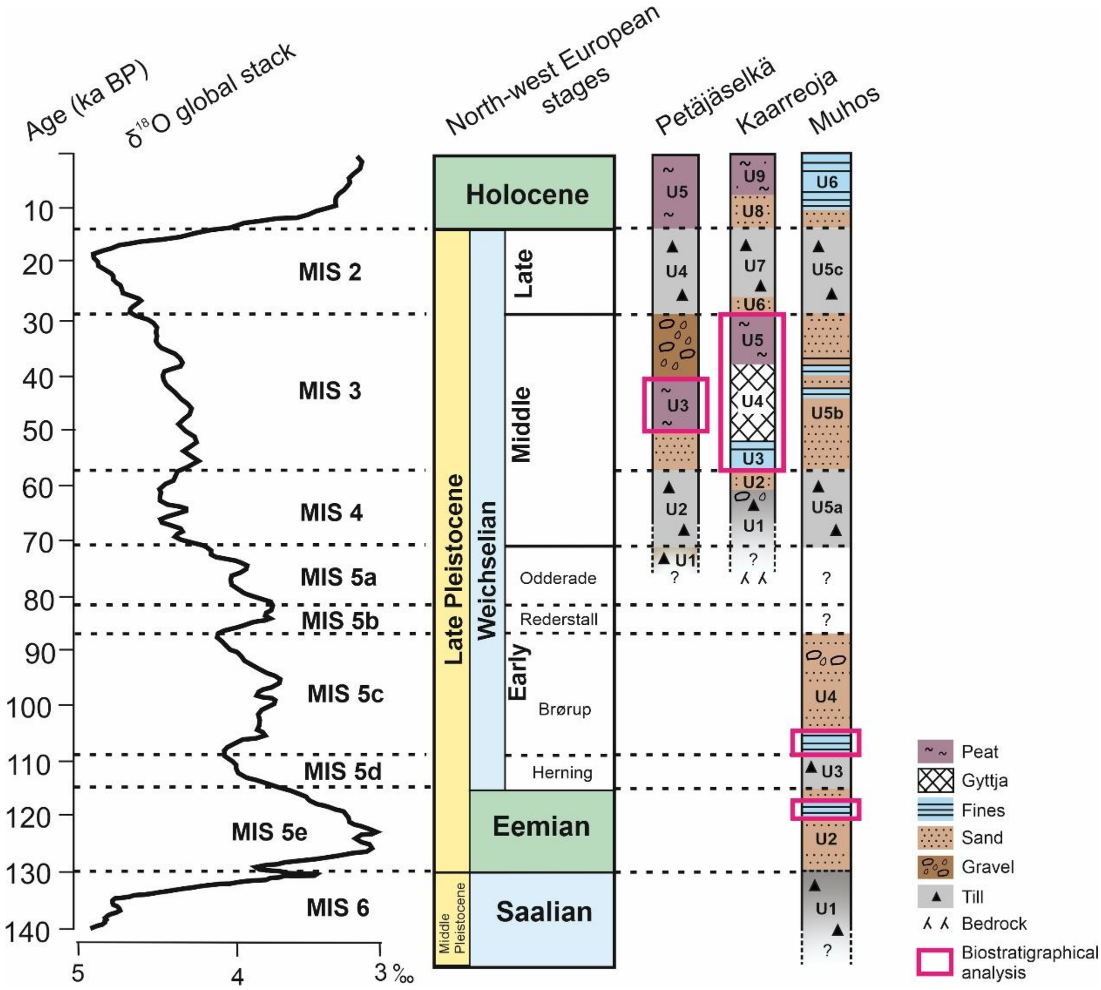

Fig. 2. A suggested stratigraphical correlation of the Petäjäselkä, Kaarreoja and Muhos sections with the northwestern European terrestrial stages and substages and the Marine Isotope Stages (MIS 6 – 2). Sedimentary units in the sections are indicated with a capital letter "U" and an appropriate unit number. The time scale, global benthic δ18 stack and MIS stages on the left according to Lisiecki & Raymo (2005).

So far, the most comprehensive sediment sequence studied by Helmens *et al.* (2000, 2007a) is located at Sokli (no. 1 in Fig. 1), eastern Finnish Lapland. Sediments in the Sokli boreholes represent the last interglacial – glacial cycle (MIS 5 – 2) suggesting that eastern Lapland was ice free from the Eemian interglacial (MIS 5e) until the Rederstall stadial (MIS 5b) and during several long, but still poorly understood and defined interstadial stages in the Middle Weichselian (MIS 3). The entire eastern Finnish Lapland region became ice covered sometime after c. 25 kyr (Putkinen *et al*. 2020). Lunkka *et al.* (2015) presented a tentative glaciation curve from a transect from west to east across central Lapland where glacial and non-glacial phases in time and space during the Weichselian were shown (see also Salonen *et al.* 2014). Their main conclusion was that the SIS covered western central Lapland already during the Herning stadial (MIS 5d) while the SIS entered to the Sokli area, eastern Lapland not until Rederstall stadial (MIS 5b) (Lunkka *et al.* 2015). In addition, the ice free Middle Weichselian (MIS 3) interstadial sediments were also discovered in central western Finnish Lapland (Salonen *et al.* 2014; Howett *et al.* 2015) but their stratigraphical correlation to those at Sokli could not be established. Lunkka *et al*. (2015) emphasised that there is a need to obtain more absolute ages from subtill sediments in order to get a more precise picture on glaciation history of northern Finland.

According to the present-day knowledge, southern Finland, from the Gulf of Bothnia to the Gulf of Finland in the south and to the Russian border to the east has been glaciated only three times during the Weichselian glaciation (e.g., Saarnisto & Salonen 1995; Saarnisto & Lunkka 2004; Lunkka *et al*. 2004; Johansson *et al.* 2011); twice during the Middle Weichselian (MIS 4; 72–60 ka and MIS 3; 49–35 ka) and once during the Late Weichselian (MIS 2; 25–11 ka).

However, the extent and precise ages and duration of glacial and non-glacial phases have not been fully established for the eastern flank of the SIS. Therefore, the data presented in this thesis which includes lithostratigraphical and biostratigraphical data together with Optically Stimulated Luminesence (OSL) and radiocarbon (^{14}C) dating results from sites in Finnish Lapland and western central Finland (Fig. 1) sheds light on the glaciation history of these areas and provides new geochronologically and biostratigraphically constrained data to establish a more complete stratigraphy for northern and central Finland and beyond.

Quaternary stratigraphy is ultimately a form of climatostratigraphy and based on the recognition of climatic variations within the Quaternary strata. Conventionally, the separation/classification between interglacial and interstadial phases in formerly glaciated terrains have been made by using pollen analysis. A vegetational succession of the cryocratic to the telocratic vegetation indicates interglacial phases while the vegetational successions of the cryocratic and protocratic vegetation normally indicates interstadials. As comprehensive sediment records from active ice-flow areas are fragmentary, and the distance between the stratigraphically important sites is usually large, and may lack robust dating, the spatial correlation between interglacial and interstadial sediments e.g., from northern to southern latitudes have turned out to be difficult. However, the present stratigraphical correlation scheme for the eastern flank of the SIS outlined below lists the main stratigraphically important interglacial and interstadial sites, their pollen characteristics and correlation to the north-western European (and MIS) chronostratigraphical stages.

1.1 Eemian interglacial (~MIS 5e)

The best-preserved sediments correlative to the Eemian interglacial (MIS 5e) from northern Fennoscandia have so far been found at Leveäniemi (no. 2 in Fig. 1), eastern Swedish Lapland (Lundqvist 1971; Robertsson 1997), Tepsankumpu (no. 3 in Fig. 1), western Finnish Lapland (Hirvas 1991; Saarnisto *et al.* 1999), Paloseljänoja (no. 4 in Fig. 1), central Finnish Lapland (Hirvas 1991) and Sokli (no. 1 in Fig. 1), eastern part of Finnish Lapland (Ilvonen 1973; Helmens *et al.* 2000; 2007a). Overall, pollen assemblages at these sites show variation in pollen composition presenting nearly the entire Eemian vegetational succession starting with the dominance of pioneering *Betula* (*Betula* assemblage zone) in the Early Eemian phase, shifting to the rise of *Pinus* and *Alnus* alongside *Betula* (*Betula* – *Pinus* assemblage zone in Tepsankumpu and *Pinus* – *Betula* assemblage zone in Leveäniemi and Sokli) during the early-temperate phase and followed by the increase of *Picea* percentage together with *Pinus*, *Betula* and *Alnus* during the late-temperate phase. Gradually the succession ends with the dominance of *Betula* due to the cooler climate. Temperate deciduous trees such as *Quercus*, *Ulmus*, *Corylus* and *Larix*, except the latter in the Leveäniemi site, are present in minor proportions. The Eemian succession is also well-preserved at Mertuanoja (no. 5 in Fig. 1), western central Finland (Eriksson *et al.* 1999), and partially preserved in many sediment sections from southern central Finland (Eriksson 1993). The Eemian pollen succession in central Finland is similar to the succession in the northern key sites mentioned above, but with a greater proportion of temperate deciduous trees.

1.2 Early Weichselian interstadials (~ MIS 5c and MIS 5a)

The Early Weichselian interstadial sediments, Brørup (MIS 5c) and Odderade (MIS 5a) interstadial sediments, have been found at several sites across the northern Fennoscandia. Most of the sites where the interstadial sediments are preserved show only one interstadial stage. Therefore, it is often difficult to infer if the sediments were deposited during the Brørup (MIS 5c), Odderade (MIS 5a) or during both interstadial stages (Lokrantz & Sohlenius 2006). Most of these interstadial sediments are also fragmentary as well and may not be in situ. As the pollen assemblages deposited during interstadial stages resemble each other, the importance of the robust dating analyses and the acquisition of the suitable material is important. ^{14}C method is commonly used to date organic sediments but the age range obtained within this method is limited to ca. 45 ka (e.g. Donner 1995). Developments of different luminescence dating methods during past decades have provided a relatively reliable dating tool which can be used to date sediments deposited during the last glacial cycle (Murray and Olley 2002; Murray *et al.* 2007; Wintle 2008). However, OSL technique may sometimes produce uncertain results (e.g., Houmark-Nielsen 2008; Alexanderson & Murray 2012).

As the knowledge on stratigraphical timing of the Weichselian substages has become more accurate, the re-evaluation of previous stratigraphical interpretations has emerged (e.g., Johansson *et al*. 2011). As the result, many of the previously suggested Early Weichselian interstadials deposits have been reinterpreted as being of Middle Weichselian age (e.g. Mäkinen 2005; Sarala 2005; Johansson *et al.* 2011). However, there are still many alternative correlation schemes where interstadial sediments at various sites are correlated within the Early and the Middle Weichselian for example, at the Riipiharju site in northern Sweden (no. 6 in Fig. 1) (Hättestrand & Robertsson 2010). So far, the most representative Early Weichselian Brørup interstadial sites are Sokli, (Helmens 2000, 2007a; Helmens *et al*. 2012), Oulainen (no. 7 in Fig. 1) (Forsström 1982, 1988; Jungner 1987; Nenonen 1995) and Marjamurto (no. 8 in Fig. 1) (Peltoniemi *et al*. 1989; Lunkka *et al*. 2016) in western central Finland. At these sites the beginning of the pollen assemblage is dominated by *Betula* tree and followed by *Pinus* -dominated assemblage. At Sokli site, *Pinus*-dominated phase is followed by a short phase with maximum peak of *Picea* and gradually the taxa change to *Betula* – dominated phase (Helmens *et al*. 2012).

1.3 Middle Weichselian interstadial (~ MIS 3)

Ice-free conditions during the Middle Weichselian interstadials (MIS 3) have been extensively studied during the past three decades. In the 1990's Ukkonen *et al.* (1999) dated fossil mammoth bones and teeth from several sites across central and southern Finland showing that the land area south and east of the Bothnian Bay was ice free during ca. 36 to 26 ka years ago. In addition, the OSL dates of sub-till sands at several sites in central western Finland (e.g., Nenonen 1995) and Finnish Karelia, eastern Finland (Lunkka *et al.* 2008) indicate perhaps several ice-free phases during the MIS 3.

The prevailing concept up until ca. 2010 was that northern Fennoscandia was continuously glaciated from Middle Weichselian (MIS 4) to Late Weichselian (MIS 2) substages (Kleman *et al.* 2021). Several comprehensive litho- and biostratigraphical studies accompanied with ^{14}C and OSL dates from northern Fennoscandia, e.g., Kaarreoja (Sarala *et al.* 2016; Fig. 2), Petäjäselkä (Sarala & Eskola 2011; Fig. 2), Sokli (Helmens *et al.* 2007a; Helmens & Engels 2010), and re-interpreted Kauvonkangas (no. 9 in Fig. 1) (Mäkinen 1979; 2005), Ruunaa (no. 10 in Fig. 1) (Lunkka et al. 2008), Riipiharju (no. 6 in Fig. 1) (Hättestrand & Robertsson 2010) and Pilgrimstad (no. 11 in Fig. 1) (Alexanderson et al. 2010; Wohlfarth 2010) (Fig. 1), have shown that ice free period(s) existed also in northern Fennoscandia during the MIS 3 i.e., the latter part of the Middle Weichselian. However, the sites with palynostratigraphic/ biostratigraphic information are scarce, but there are several sites dated by ^{14}C, OSL and Thermo Luminescence (TL) methods to support this (e.g., Robertsson & Ambrosiani 1988; Olsen *et al.* 1996; Olsen *et al.* 2001; Olsen & Hammar 2005; Mäkinen 2005; Sarala & Rossi 2006; Auri *et al*. 2008; Salonen *et al.* 2008; Sarala *et al.* 2010; Ukkonen *et al*. 2011; Möller *et al.* 2013; Salonen *et al.* 2014; Lunkka *et al*. 2015; Howett *et al.* 2015). Overall, the pollen assemblages obtained from e.g., Sokli, Kauvonkangas and Ruunaa are dominated by *Betula* tree. *Pinus* is well represented at Sokli and Ruunaa but the value is low at Kauvonkangas. At Hitura (no. 12 in Fig. 1), Ostrobothnia, the pollen assemblage obtained from fine-grained sediments resemble those at Sokli and Ruunaa although the authors proposed that the pollen assemblage suggests redeposited interstadial material (Salonen et al. 2008). Recent studies have shown that the climate during the Middle Weichselian interstadial (MIS 3) was warmer than previously suggested (Helmens 2014; Sarala *et al.* 2016; Alexanderson *et al.* 2021a).

After the MIS 3 ice-free phase, the SIS covered eastern Fennoscandia after 25 ka ago and gained its maximum extent in its eastern flank between 18 – 17 ka (e.g., Saarnisto & Lunkka 2004).

The area between northern and southern Finland lies in the Northern Ostrobothnia and Kainuu regions, approximately between the latitude 64° and 65° north (Fig. 1). As indicated above, previous studies have shown that the glacial history of northern and southern Finland in the Weichselian stage is different (e.g., Lunkka *et al.* 2004; Johansson *et al*. 2011). Although there is no consensus on detailed Weichselian ice sheet behaviour or dynamics neither in the northern nor in southern parts of Finland, it seems most likely that while the SIS covered northern Finland already in the Early Weichselian, southern Finland remained ice free during the entire Early Weichselian. The overall aim of this thesis is to study glaciation history of the Weichselian and the late Saalian (MIS 6) stages in northern and central Finland and to make a stratigraphical correlation across the crucial boundary between northern (i.e., Finnish Lapland) and southern Finland. This thesis specifically concentrates on pollen stratigraphy and its use in correlation although other stratigraphical and geochronological tools have also been applied.

2. STUDY SITE LOCATIONS

Sediment sequences from three different sites located in Finnish Lapland and central western part of Finland were studied using stratigraphical and dating methods (Fig. 1). Petäjäselkä study site (Paper I) is located in central Finnish Lapland (67,83˚ N; 25,78˚ E, approximately 270 m above the present sea level (a.s.l)), around 140 km north of the Arctic Circle, close to Tepsankumpu Eemian interglacial site (Hirvas 1991; Saarnisto *et al.* 1999). The drill core site lies in a peat bog surrounded by relatively low-relief cover moraine composed of basal till.

The Kaarreoja study site (Paper II) is located in the Lemmenjoki area, northern Finnish Lapland (68,65˚ N; 25,63˚ E, approximately 350 m a.s.l) around 230 km north from the Arctic Circle. The section studied is exposed in the valley side between fells.

The Muhos study site (Paper IV) is located in Northern Ostrobothnia, western central Finland (64.81° N; 26.04° E, approximately 29 m a.s.l.), close to Montanlampi Holocene sections studied by Gibbard (1979). The drill core site lies in the Oulu River Valley, around 30 km southeast of the city of Oulu and the present shoreline of the Bothnian Bay, and around 200 km south from the Arctic Circle. The sample material analysed in Paper III utilizes the samples collected from the Muhos study site (Paper IV).

3. METHODS

This study comprises numerous methods used in the field of paleoenvironmental research. Pollen analysis is the main tool used in this thesis and it is used in all papers (I – IV). Other methods used in the articles in addition to pollen analysis are diatoms (Papers II and IV), plant macrofossils (Paper II) and lithofacies analysis (Papers I, II and IV). 95% confidence intervals were calculated for selected pollen and spores to assess the margin of error according to Mosimann (1965) (Paper III). Plant macrofossil analysis was used in Paper II to create reliable estimation of the paleoenvironment. Minerogenic samples were dated using Optically Stimulated Luminescence (OSL) method (Papers I, II and IV) according to the SAR protocol according to Murray & Wintle (2000, 2003) and organic material from bulk samples using conventional radiocarbon (^{14}C) dating (Paper I) and radiocarbon dating from organic pieces, e.g., wood, using Accelerator Mass Spectrometer (^{14}C AMS) (Papers II and IV).

3.1 Pollen analysis

This thesis is comprised of three different datasets of pollen. Pollen analysis carried out in Paper I consist of organic (peaty) layer between till beds. The laboratory procedure follows standard technique described in Berglund & Ralska-Jasiewiczowa (1986). Minerogenic material removal was done in cold hydrofluoric acid (HF) for overnight followed by 10 min boiling in 10% potassium hydroxide (KOH) and acetolysis. The samples were mounted and stored in glycerine.

Pollen analysis described in Papers II – IV follows the same laboratory treatment. Sample materials consist of organic gyttja to peat (Paper II) and organic-bearing silt and clayey silt (Papers III and IV). Minerogenic material removal was carried out by using modified LST Fastfloat heavy liquid method described in detail in Paper III. Samples were treated with 10 % KOH for 8 min followed by acetolysis. Comparative pollen samples discussed in Paper III follow the conventional HF method, also described in detail in Paper III.

3.2 Diatom analysis

Diatom analyses were carried out in Papers II and IV. Diatom samples were processed with a standard technique described in Battarbee (1986 and 2001). The organic material removal was processed with 40 % hydrogen peroxide (H_2O_2) and coarse mineral fraction was removed by repeated decanting. The residual samples were mounted in Naphrax® and counted using light microscopy with oil immersion object at x 1000 magnification. The identification and taxonomy of diatoms were mainly based on Krammer and Lange-Bertalot (1991a; 1991b; 1997a; 1997b) and taxonomic nomenclature was updated using AlgaeBase (Guiry & Guiry 2019).

4. REVIEW OF THE ORIGINAL PUBLICATIONS

Paper I – Sarala, P. & Eskola, T. 2011. Middle Weichselian interstadial deposit at Petäjäselkä, Northern Finland. E & G Quaternary Science Journal 60 (4), 488-492. https://doi.org/10.3285/eg.60.4.07

The first publication describes Middle Weichselian (MIS 3) sorted sediment layers with gravel, sand and sandy peat beneath the basal till in Petäjäselkä, Central Finnish Lapland. The study site is located in the center of the Scandinavian Ice Sheet (SIS) ice divide zone. The stratified organic-bearing layer was found in 2005 as part of a percussion drilling program for geochemical exploration in two sites and the re-sampling was performed in 2008. The focus of the study was to broaden the view of the extent and timing of the ice-free Weichselian interstadial stage.

The lithofacies description was performed from the sediment cores and the organic peat layer was analysed for its pollen content. Organic layer was dated with ^{14}C method and the sands below and above the organic layer were dated with OSL method. The ages showed consistent chronology where the till units 1 and 2 have deposited during the Early Weichselian phase, followed the Middle Weichselian sorted sediments and organic layer. The pollen content of the organic layer was interpreted to represent open birch-dominated forest. However, the pollen counted were somewhat worn and crumbled but still clearly identifiable, thus the transportation and re-deposition of organic layer cannot be ignored.

Paper II – Sarala, P., Väliranta, M., Eskola, T. & Vaikutiené, G. 2016. First physical evidence for forested environment in the Arctic during MIS 3. Scientific Reports 6, 29054. https://doi.org/10.1038/srep29054

The second publication introduces a multiproxy study of inter-till organic peat layer covering nearly entire Middle Weichselian interstadial (MIS 3) from Kaarreoja, Finnish Lapland. The Kaarreoja section covers a continuous stadial-interstadial-stadial cycle from the Middle Weichselian glaciation (MIS 4) to the Middle Weichselian interstadial (MIS 3) and to the latest/most recent Late Weichselian glaciation (MIS 2). The Kaarreoja section is one of the rare MIS 3 sediment sections preserved in glaciated areas in northern Fennoscandia and the biostratigraphical data depict/represent the full vegetation succession of the ice-free phase MIS 3. The study is based on plant macrofossils, pollen and diatoms together with the lithofacies description. The age of the sand beneath the peat layer was determined using the OSL method and ^{14}C method was used to date one bulk peat sample and one piece of wood (AMS ^{14}C) below the bulk peat sample.

Based on the macrofossil and aquatic pollen data the July temperature reconstructions estimate the July temperature at least 14.4 °C which is higher than the present-day July temperature at the study site. The revealed data support the presence of pine and birch forest rather than open environment and the fact that the glacial-interstadial-glacial cycle have been more dynamic than previously thought.

Paper III - Eskola, T., Kontio, R. & Lunkka, J. P. 2021. Comparison between modified LST Fastfloat and conventional HF methods for pollen preparation in highly minerogenic sediments. Bulletin of the Geological Society of Finland 93, 5–18. https://doi.org/10.17741/bgsf/93.1.001

The third paper is a methodological paper. The publication introduces an improved low-toxic heavy liquid separation method (LST Fastfloat). Pollen analysis is one of the principal methods to reconstruct the past vegetation and climate. Pollen analysis has been used over a century, but the pollen preparation method has remained quite similar. Removal of minerogenic matter from the sediments is one of the key components to improve pollen visibility and thus identification as well as speed up the counting procedure. Many of the chemicals used in mineral material removal are of very toxic or toxic to human health (and environment), and in many countries the use of substitutes for toxic chemicals, if available, is set by legislation. This publication introduces a modified step-by-step method in order to remove minerogenic matter from silt and clay –rich sediments with low-toxic heavy liquid LST Fastfloat. The aim of the study is to clarify whether the results obtained with modified LST Fastfloat are in line with the conventional hydrofluoric acid (HF) method.

This case study presents pollen results from five (5) paired samples. In each sample pair the subsamples were treated both LST Fastfloat and conventional HF method in order to remove the mineral material, otherwise the treatment was identical. At least 700 terrestrial vascular pollen and spores were calculated under light microscope to achieve statistical robustness. The 95 % confidence intervals were calculated for the taxa reaching 5 or more percent at least in one sample pair.

The study indicates that the LST Fastfloat and conventional HF results are comparable and there are no systematic nor significant differences between the taxa with the exception of *Betula* and *Pinus*. The percentages of *Betula* were systematically somewhat higher in LST Fastfloat –processed samples and on the contrary, the *Pinus* percentages were somewhat lower in LST Fastfloat –processed samples. The results were within the calculated 95 % confidence intervals except in one sample pair, where the 95 % confidence interval difference between LST Fastfloat and HF methods for *Pinus* was exceeded by only one hundredth of a percent.

Paper IV – Eskola, T. & Lunkka, J. P. (in press). Sediment sequence at Muhos, western Finland – a window to the Pleistocene history of the Scandinavian Ice Sheet. Boreas. http://doi.org/10.1111/bor.12560

The fourth publication introduces a 54 meters deep sediment core results from Muhos, northern Ostrobothnia, representing tills interbedded with sorted sediments. The sediment core covers sediments at least from the Saalian glaciation (MIS 6) to the Holocene sediments (MIS 1). The sediment core was subjected to sedimentological, mainly sediment structure and texture, and pollen and diatom analysis. The total recovery of the sediments retained was over 75 %. Four current bedded sand samples were dated with OSL method and one wood twig with ^{14}C AMS method. The sediment core represents a unique archive to shed light to the glacial history of the area.

Altogether six lithostratigraphical units can be described comprising four till units interbedded with sorted sediments. The grain size in the sorted sediments varies from gravelly sand to clayey silt and organic-bearing silt. Pollen and diatom analysis were conducted from the organic-bearing silt layer and clayey silt layer. The sediment record indicates that there was a freshwater basin in the Muhos area during the Late Eemian interglacial (MIS 5e). Sediments suggesting the Brørup interstadial (MIS 5c) are also present.

The results of this study show that there were at least four glacial growth phases across the Muhos area: One during the Saalian glaciation, one during the Early Weichselian Herning stadial, one during the Middle Weichselian and the last during the Late Weichselian substages. Based on these results, the estimation of the Early Weichselian Herning stadial (MIS 5d) extent is more southern than previously suggested.

5. DISCUSSION

The overall purpose of this study is to shed light on the extent and timing of the glacial and intervening non-glacial phases during the Late and Middle Pleistocene in the central part of the SIS. As the outlines of the different substages of the Weichselian stage are known, details are still missing from the pre-Late Weichselian (MIS 2) substage. In this thesis, a closer look on the pollen analysis and the use of the biostratigraphical approach together with the lithostratigraphical and absolute dating (^{14}C and OSL) is made to unravel the complex glaciation history of northern Fennoscandia.

Pollen analysis used as a stratigraphic tool is an important and widely used method when correlating Quaternary deposits. It has traditionally been the primary method to distinguish interglacial and interstadial deposits. Due to the limitations of the radiocarbon dating method, (organic) sediment deposits older than the late Middle Weichselian age (ca. 40 ka ^{14}C years) cannot be directly dated which highlights the importance of pollen analysis for biostratigraphical correlation. However, correlation of the interstadial or interglacial sediment sequences in formerly glaciated areas is further hampered by the fragmentary nature of the sediment deposits which does not show the complete succession from the pioneering shrubs and trees to the climatic optimum followed by a climatic deterioration (e.g., Donner 1995; Armstrong & Brasier 2005). Moreover, the robust correlation of the sediment sequences between southern and northern Finland is problematic because the climate and thus the vegetation in these areas far apart are different. It should also be acknowledged that the depositional environment influences the pollen source area and spatial resolution (Birks 2005). Thus, correlation of pollen assemblages from e.g. local–scale peat deposit is not straightforward compared to pollen assemblages obtained from e.g. regional-scale large water basins, and therefore it should be taken into consideration when correlating pollen assemblages (e.g., Helmens *et al.* 2000; Birks 2005).

5.1 Reliability of the modified LST Fastfloat method

One objective of this work was to establish a robust pollen preparation method for minerogenic sediments to substitute conventional HF preparation method, as the European legislation obligates the substitution of hazardous chemicals to less hazardous or non-toxic chemicals. Although different heavy liquids, both toxic and low-toxic, have been used several decades in palynological studies, relatively few comparative pollen methodology studies have yet been published. Björck *et al*. (1978) compared conventional HF method with zinc chloride ($ZnCl_2$) with 16 paired samples composed of clay gyttja, clay and silty clay, and resulted good correspondence although slight systematic but not significant difference within few taxa were obtained. Nakagawa *et al.* (1998) tested HF against solution of cadmium iodide (CdI_2) and potassium iodide (KI) in 11 paired gyttja clay, gyttja and peat samples. Their study showed that the pollen percentage values differed by more than 5% within 4 taxa in 5 samples. However, there was no systematic difference between methods showing that the two methods were comparable. Lentfer and Boyd (2000) also compared HF and solution of CdI_2 and KI in 6 sample pairs from sand, clay and clay loam. Their study suggested comparable results for most sediments tested, however, there was evidence for differential selection between pollen taxa. Zabenskie (2006) compared HF and sodium polytungstate (SPT) methods in two paired arctic lake sediment samples, and the X^2-test suggested methods statistically comparable. Campbell *et al.* (2016) also compared HF and SPT for 30 paired samples from organic-rich silt, silt and clay, and their study revealed no significant differences between the two methods. Leipe *et al*. (2019) tested HF, SPT and lithium heteropolytungstate (LST) from 5 paired peat, silty clay and organic-rich clay and silt samples showing partly significant differences in the most frequent pollen taxa. However, the differences obtained were not taxa-specific but rather sample-specific.

The comparative test between LST Fastfloat and conventional HF methods with paired samples showed that there is no systematic nor significant difference between pollen percentages or concentrations studied. However, slight systematic discrepancy was found within two common taxa. Given the fact that all sample pairs except one were within the 95 % confidence interval, it can be concluded that the results between LST Fastfloat and conventional HF methods are comparative. Therefore, the correlation of pollen assemblages obtained in this work can be reliably correlated with the pollen result of different sediment units presented in previous studies from Fennoscandia. It should be kept in mind that the density of pollen and spores increase during the time of deposition, thus the assumed age of the deposit should be acknowledged in such a density-based separation method.

5.2 (Bio)stratigraphical correlation in Fennoscandia

5.2.1 Eemian interglacial (MIS 5e)

There are only a few sites in northern Fennoscandia where till unit/units occur underneath the marine and/or terrestrial Eemian interglacial sediments. Till unit below the Eemian interglacial sediments at Tepsankumpu (Saarnisto *et al*. 1999), Sokli (Helmens *et al*. 2000) and Mertuanoja (Nenonen 1995), are the best examples where the late Saalian till is documented. In addition to these "stratotype sites", different stratigraphical and geochronological evidence show that the Saalian glacial sediments are well-preserved throughout northern Fennoscandia (e.g., Hirvas 1991; Nenonen 1995; Donner 1995; Olsen 1998; Olsen *et al.* 2013). In this research, the sediment sequence obtained from Muhos, the lowermost till complex (Unit 1, Fig. 2) is interpreted to represent tills deposited during the Saalian glaciation (MIS 6). The overall 13 m thick till unit varies in lithological and mineralogical composition (cf. Lunkka *et al.* 2013) suggesting that parts of the Unit 1 may have deposited during earlier glacial phases that predate the Late Saalian glaciation.

Although many of the interglacial and interstadial deposits found from northern Fennoscandia are fragmentary, attempts to correlate the Eemian interglacial sediments to western and central European Eemian interglacial pollen assemblages is not straightforward. As the Eemian interglacial pollen assemblages in central and western Europe are typically defined by the dominance of temperate deciduous trees (e.g. Zagwijn 1996), their occurrence declines towards higher latitudes. This, in turn, hampers the correlation.

The Eemian pollen assemblage obtained from 9 m diatom gyttja at Sokli (no. 1 in Fig. 1) shows nearly complete Eemian vegetation succession (Helmens *et al*. 2000; Helmens 2014; Helmens *et al*. 2015). The Early Eemian phase begins with the dominance of *Betula* tree and *Alnus* suggesting sub-arctic birch forest (pre-temperate phase), followed by *Pinus*-dominated forest (early-temperate phase) and mixed boreal forest with *Picea* (< 10%) and *Larix* (late-temperate phase). Eventually, towards the end of the Eemian interglacial, the boreal forest is replaced by *Betula*-dominated sub-arctic birch forest (post-temperate phase) (Helmens *et al.* 2000;

Helmens 2014; Helmens *et al*. 2015). Similar pollen assemblage and vegetation succession is obtained from Leveäniemi (no. 2 in Fig. 1), northern Sweden, except there are no findings of *Larix* (Robertsson 1997; 2000).

At Tepsankumpu (no. 3 in Fig. 1), till-covered gyttja shows the *Betula*-dominated early Eemian phase, followed by *Pinus* and *Alnus* and eventually *Picea* (Hirvas 1991; Saarnisto *et al.* 1999). However, *Betula* tree dominates the entire sediment sequence, whereas at Paloseljänoja (no. 4 in Fig. 1), suggested to represent the late Eemian phase, shows indisputably a *Pinus*-dominated phase followed by the Late Eemian *Betula* phase (Hirvas 1991; Saarnisto *et al.* 1999).
The Mertuanoja site (no. 5 in Fig. 1) represent the most complete Eemian sediment deposit obtained from west-central Finland (Eriksson *et al.* 1999). Within Ostrobothnia, several fragmented inter-till sites suggested as Eemian age with temperate deciduous trees have been preserved, e.g. at Haapavesi (Ollala site, no. 13 in Fig. 1; Forsström *et al*. 1988 and Vesiperä site, no. 14 in Fig.1; Nenonen *et al.* 1991), Peräseinäjoki (Viitala site, no. 15 in Fig. 1; Nenonen *et al.* 1991), Kärsämäki (Ukonkangas site, no. 16 in Fig. 1; Eriksson 1993) and Teuva (Norinkylä, no. 17 in Fig. 1; Eriksson 1993). Based on these results, Eriksson (1993) correlated and compiled the Eemian pollen assemblages for central Finland. The pollen assemblage from till-covered minerogenic sediments at Mertuanoja (Eriksson *et al*. 1999) also represent the pre-, early-, late- and post-temperate phases as obtained at Sokli, Tepsankumpu and Leveäniemi. However, temperate deciduous trees such as *Quercus*, *Ulmus*, *Fraxinus* and *Corylus* are explicitly present at Mertuanoja sequence after the *Betula*-dominated pre-temperate phase (Eriksson *et al.* 1999). At more southern location, a nearly continuous Eemian sediment sequence correlative to the Ostrobothnian pollen assemblages is obtained e.g. from Põhja-Uhtju (no. 18 in Fig. 1), Estonia, and Peski (no. 19 in Fig. 1), Karelian Isthmus, although the overall number of temperate deciduous trees at these sites are greater (Miettinen *et al*. 2002). However, the *Betula*-dominated early Eemian phase is missing at Peski site.

Results from the Muhos sediment sequence (Paper IV) indicate that the 8-cm-thick fine-grained sediment interval from Unit 2 (Fig. 2) is suggested to represent either the Early Eemian Betula-dominated pre-temperate phase or more likely, the Late Eemian post-temperate phase. This conclusion is based on the pollen analysis supported by the OSL ages. The overall pollen assemblage is dominated by *Betula*, but the pollen assemblage contradict correlation to the early Eemian phase, as the pollen composition includes conifers in abundance (both well-preserved *Pinus* and *Picea*) and grains of thermophilous trees and *Osmunda* rather than the dominance of *Betula* tree, as shown in the Haapavesi (Vesiperä), Peräseinäjoki (Viitala)

(Nenonen *et al.* 1991) and Ylivieska (Mertuanoja) sequences (Eriksson *et al.* 1999). At these sites the proportion of *Picea* is nearly nonexistent and *Pinus* is present with c. 10% although the sites have southern locations. Thermophilous taxa are occasionally present at these sites except for *Corylus*, which is constantly present with a few percentages. Correlation of the Muhos Unit 2 pollen assemblage to Late Eemian pollen assemblage at Mertuanoja seems, however, plausible.

At the time the Eemian interglacial sediments at Muhos were deposited, the area was covered by a relatively deep freshwater basin based on the laminated silt rhythmites and mostly planktonic freshwater diatom taxa. Based on the diatom assemblage, these sediments were deposited during either the early Eemian freshwater phase or the late Eemian freshwater phase, as suggested in Paper IV. Similar freshwater taxa have been described from several sites in Ostrobothnia (Grönlund 1991; Nenonen *et al.* 1991; Eriksson *et al*. 1999). These authors suggest that the freshwater deposits were deposited during the early Eemian interglacial stage, as the freshwater taxa is substituted by marine taxa, i.e., the Eemian Sea phase. Also, a freshwater phase following the Eemian sea phase has been registered in Ostrobothnia and northwestern Russia, at Haapavesi (Ollala site) (Forsström *et al.* 1988; Grönlund 1988), Teuva (Norinkylä B site) and Kärsämäki (Ukonkangas site) (Grönlund 1991), Ylivieska (Mertuanoja site) (Eriksson *et al*. 1999) and the Karelian Isthmus (Peski site, no. 19 in Fig. 1) (Miettinen *et al*. 2002). However, similar early Eemian freshwater diatom taxa have not been found from central Sweden (Robertsson 2000), but a short freshwater phase prior to the Eemian Sea has been observed in western Baltic Sea area based on dinoflagellates (Head 2007), ostracods (Kristensen *et al.* 2000) and diatoms (Haila *et al.* 2006). Lambeck *et al*. (2006) suggested that the possible early Eemian freshwater phase preceding the warmer marine phase was caused by meltwaters from the residual ice sheets on the Kara-Barents shelves.

Overall, the organic and inorganic deposits overlying tills with interglacial-type pollen assemblages have been correlated robustly with Eemian sediments. The pollen successions through the sites discussed here show the cooler, *Betula*-dominated pre-temperate Eemian phase and the freshwater phase preceding the Eemian Sea. During the Eemian Sea phase the warm early and late temperate with *Pinus* and followed by broadleaved deciduous trees, although reduced towards the north, and eventually *Picea* dominated the forests. Towards the post-temperate phase and cooler climate, the dominance of *Betula,* Poaceae and Cyperaceae increased.

The actual end of the Eemian interglacial is not preserved in any of the previously studied sites, as there is no complete sediment succession covering the entire Eemian interglacial in Finland although at the Sokli site, where most of the Eemian might have been preserved (Helmens *et al.* 2015; Salonen *et al*. 2018). Towards the Early Weichselian glaciation, the pollen assemblages at Sokli and Tepsankumpu turn again to *Betula*-dominated taxa with increased amount of Poaceae and Cyperaceae, indicating cooler climate (Saarnisto *et al*. 1999; Helmens *et al*. 2019).

5.2.2 Early Weichselian (MIS 5)

By the time the first Early Weichselian glacial phase (Herning stadial; MIS 5d) had reached Muhos area and beyond, as suggested in Paper IV, there is, however, no clear indication of such a glacial advance further south (Fig. 3). However, Pitkäranta *et al*. (2014) suggested that possibly the Early Weichselian Herning stadial might have reached the eastern coastal area of the Gulf of Bothnia. The reconstructions for glaciation during the Early Weichselian Herning stadial suggest that southern and northeastern Finnish Lapland, including Sokli, were ice-free, but western, central and northern Finnish Lapland were glaciated (Johnsen 2010; Olsen *et al.* 2013). Nearly entire Finland was ice-free during the Early Weichselian Brørup interstadial (MIS 5c) (e.g., Lunkka *et al*. 2004; Johansson *et al*. 2011; Johnsen 2010; Olsen *et al*. 2013; Bachelor *et al.* 2019). Overall, the comparison of Early Weichselian interstadials is rather tentative in many cases, as the absolute chronologies are still inadequate.

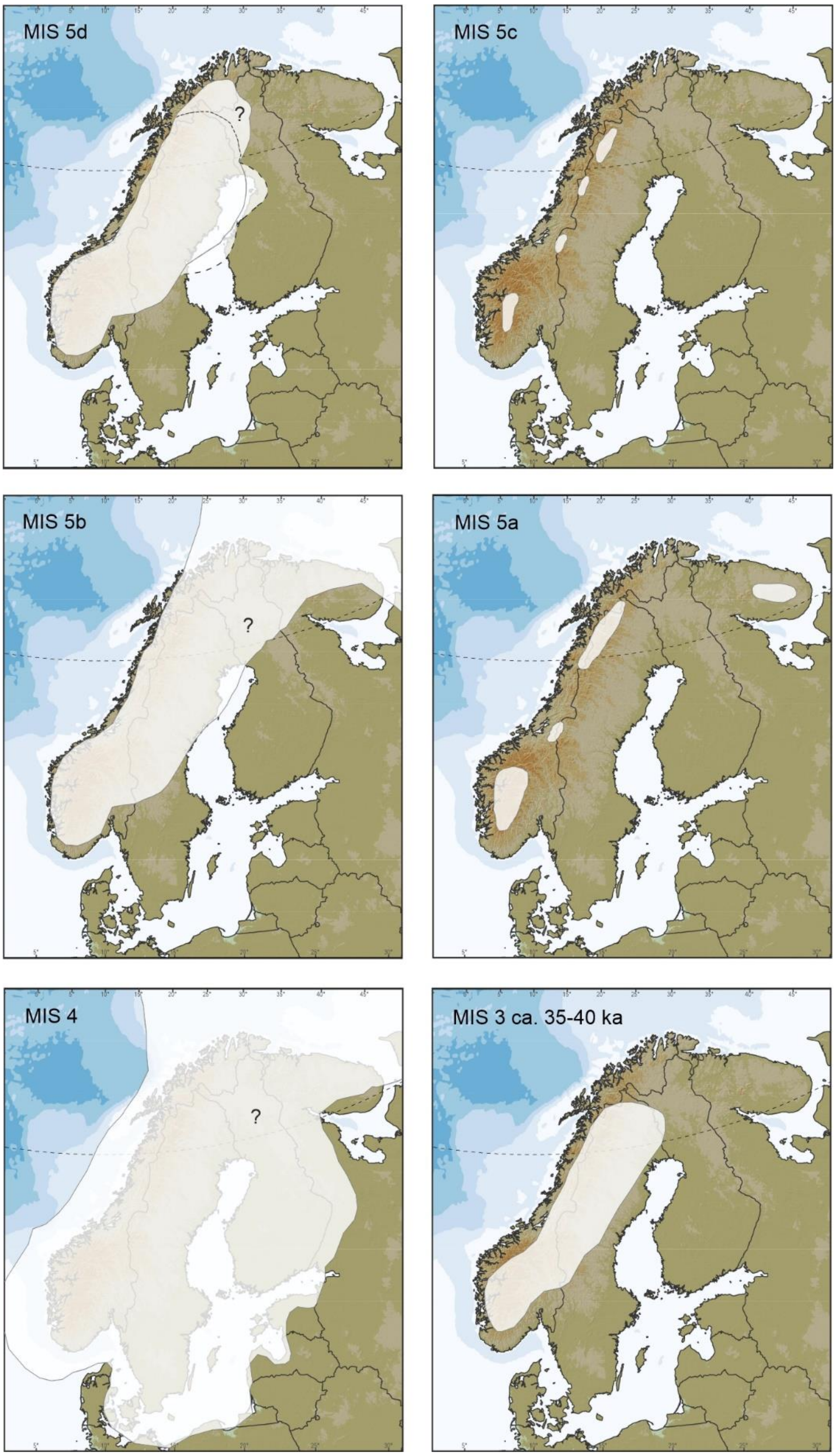

Fig. 3. Hypothetical extensions of the Scandinavian Ice Sheet (SIS) during the different substages of the Weichselian glaciation. Reconstruction is compiled from Bachelor *et al*. (2019), Olsen *et al*. (2013), Johnsen (2010) and the results presented in this thesis. In the top left reconstruction (MIS 5d), the dashed lines indicate the modification based on results presented in this thesis (Paper IV) and the area adjacent to Gulf of Bothnia according to Pitkäranta *et al.* (2014).

The fine-grained and laminated sediment at the base of Muhos Unit 4 (Fig. 2) suggests that the sediments were deposited in a relatively deep-water basin. The pollen assemblage of the fine-grained sediment layer is dominated by *Betula* tree with *Alnus*, *Pinus* and a minor presence of *Picea*, suggesting birch-dominating forested environment with alder and perhaps pines. High AP (arboreal pollen; trees)/NAP (non-arboreal pollen; shrubs, dwarf shrubs and herbs) -ratio reflects closed forest rather than an open environment. Due to the monotonous nature of the pollen assemblage throughout the sediment interval, it is difficult to correlate solely the pollen spectra alone to the other sub-till sediment pollen assemblages in the region. As there are no remarkable changes in the pollen composition, the vegetation (and thus climate) has probably remained rather stable. However, the pollen assemblage is suggested to represent the beginning of an Early Weichselian interstadial, corresponding to the Brørup interstadial. This interpretation is supported by the OSL ages obtained from the horizontally and ripple-bedded sands above the fine-grained sediments. Occasional grains of thermophilous trees such as *Carpinus*, *Quercus*, *Tilia* and *Ulmus* are most likely redeposited or transported from a distance rather than indicate their local presence. Overall, conifers (both pine and spruce) were intact which suggest that redeposition is not likely.

Sediments correlative to one of the Early Weichselian interstadials have been preserved at several sites within Ostrobothnia, e.g. at Marjamurto (Peltoniemi *et al.* 1989), Oulainen (Forsström 1982; Donner 1988), Vimpeli I (Aalto *et al.* 1983; 1989) and Horonkylä (Nenonen 1995; Grönlund & Ikonen 1996). At Oulainen (no. 7 in Fig. 1), the sediment succession constituting sand and sand with gyttja begins with a *Betula*-dominated phase with subordinate *Pinus* (Forsström 1982). *Picea* is absent and *Alnus* occurs only occasionally. Thermoluminescence ages of 96±10, 94±10, 97±10 and 94±9 ka were obtained from the sand deposit above the gyttja deposit, and TL ages of 117±12, 119±12 and 128±13 ka for sand deposit below the gyttja (Jungner 1987). At Horonkylä (no. 21 in Fig. 1), Teuva, the diatomite unit between sand and gravel layers below and a sand bed and two till layers above shows a *Betula*-dominated beginning with < 20 % *Pinus* (Nenonen 1995; Grönlund & Ikonen 1996). *Alnus* is present only in small quantities and *Picea* is absent. However, the pollen from the diatomite were partly worn and thin-walled (Grönlund & Ikonen 1996). The OSL age obtained from the deformed sand overlying the diatomite yielded an age of 54±8 ka (Nenonen 2006) suggesting that the diatomite might have deposited during the Early Weichselian if the till unit above was deposited during the MIS 4 as assumed by Nenonen (1995).

At Vimpeli I site (no. 20 in Fig. 1), a disturbed silt and peat layer beneath a till layer was observed (Aalto *et al.* 1983), where the base is dominated by *Betula* and ca. 20–30% *Pinus*. *Alnus* and *Picea* are present with low quantities. Several TL samples were taken from the Vimpeli II site, 180 m apart from the Vimpeli I site, from sand above the disturbed peat layer. The age range varied between 99 to 225 ka and as there is such a tremendous difference in age scatter, the ages must be considered highly suspicious (Jungner 1987). However, at Marjamurto (no. 8 in Fig. 1), where the sediment sequence consisting of fine sand covered by gyttja, the *Betula* phase is missing (Peltoniemi *et al*. 1989). The thermoluminescence (TL) age of the horizontal-bedded sand covering the gyttja deposit have yielded age of 107±15 ka which is in good agreement with the correlation to Brørup interstadial (Peltoniemi *et al.* 1989).

Overall, the sediment at Muhos Unit 4 cannot be directly correlated to the Oulainen, Vimpeli and Horonkylä sites. Nevertheless, as the Muhos Unit 4 fine-grained sediments were deposited in rather large water basin, thus representing regional pollen rain over a large area. At Oulainen, the *Betula*-dominated sediment is suggested as glaciofluvial sand, and the pollen accumulated are suggested to been leached from above and resulted to selective pollen deposition (Forsström 1982). Although not presented in the pollen diagram, Forsström (1982) made an attempt to separate *Betula nana* from *Betula* trees, and concluded that even though uncertain identification, ca. 50–30 % of the total *Betula* grains were identified as *B. nana*. This even hampers the correlation to Muhos Unit 4.

The most comprehensive Early Weichselian sediment sequence is obtained at Sokli (Helmens *et al*. 2012; Helmens 2014). Laminated gyttja shows a similar pollen assemblage compared to Muhos with high *Betula* tree (40 – 65%), low *Pinus* percentages (< 14%) and the constant presence of *Alnus* (< 20%) in the beginning of the MIS 5c (Helmens *et al.* 2012). *Picea* is present with low values except peak with 6% occurrence. The pollen assemblage in the early MIS 5c is suggested to represent a sub-arctic birch forest with alder and possible conifers present, followed by a boreal forest and finally the return to more open vegetation towards the glacial advance (MIS 5b) (Helmens *et al.* 2012; Helmens 2014). Overall, the macrofossil indicator plant species suggest that the minimum mean July temperatures during the warm phase were several degrees higher than at present (Helmens *et al*. 2012; Helmens 2014). Two OSL ages from sands covering the gyttja have yielded ages of 94±16 and 94±19 ka, which support the interpretation of the Early Weichselian Brørup interstadial (Helmens *et al.* 2012).

5.2.3 Middle Weichselian (MIS 4 – 3)

Preliminary results from the pollen samples obtained from the Muhos Unit 5b fine sand and fine-grained sediments show sparse pollen content, if any. Some of the pollen found were worn and thin-walled, which may suggest redeposition. The fine sand and fine-grained sediments in Unit 5b has been suggested to represent Middle Weichselian interstadial (MIS 3), and the till deposit below (Unit 5a) and above (Unit 5c) the sorted sediments are suggested to present Middle Weichselian (MIS 4) and Late Weichselian glaciation, respectively (Fig. 2).
The sediments from Kaarreoja shows nearly continuous interstadial sequence (Paper II). Organic sediments from Kaarreoja (Paper II) and Petäjäselkä (Paper I) are interpreted as Middle Weichselian (MIS 3) age (Fig. 2). ^{14}C dating was performed at both sites (bulk samples from both sites and wood piece from Kaarreoja) and OSL samples from sand below the peat at Kaarreoja and Petäjäselkä as well as above the peat at Petäjäselkä. The dating results clearly suggest the ice-free conditions during Middle Weichselian (MIS 3); however, the duration of the ice-free phase cannot be estimated.

Apart from the Late Weichselian, the Middle Weichselian sediments have the most comprehensive age control, as the latter part of the Middle Weichselian (MIS 3) nearly covers the ^{14}C dating age range/limit. Only few sites with dated biostratigraphical data from central and northern Finland and Sweden have been obtained representing Middle Weichselian interstadial substage (MIS 3). Although numerous organic inter-till layers have been found over the central areas of the glaciated terrain, many of these inter-till organic layers/ sites lack reliable dating results. So far, the most comprehensive biostratigraphical analyses with dating results besides the Kaarreoja (and Petäjäselkä) have been described in Sokli (Helmens *et al*. 2000; 2007a), Ruunaa (Lunkka *et al*. 2008), Riipiharju (Lagerbäck & Robertsson 1988; Hättestrand 2008; Hättestrand & Robertsson 2010; Wohlfarth 2010) and Pilgrimstad (Robertsson 1991; Alexanderson *et al.* 2010). At several sites there are either dated sedimentology, e.g., at Hitura (Salonen *et al*. 2008) (no. 12 in Fig. 1), Rautuvaara (Lunkka *et al*. 2015; Howett *et al*. 2015) (no. 22 in Fig. 1) and Hannukainen (Salonen *et al*. 2014) (no. 23 in Fig. 1) or pollen stratigraphy, e.g. at Rissejauratj (Hättestrand 2007) (no. 24 in Fig. 1). Mäkinen (2005) has dated several sediment sequences from southwestern Finnish Lapland using OSL, TL and ^{14}C -methods. Korpela (1969) studied pollen and macrofossil contents from several sites from southern Finnish Lapland and dated them by using conventional ^{14}C -method. Majority of these pollen assemblages were dominated by birch and named as Peräpohjola interstadial and suggested to represent ice-free Middle Weichselian substage. The

Peräpohjola interstadial was later correlated to Early Weichselian interstadial substage, either Odderade or Brørup (e.g. Hirvas & Nenonen 1985 and references therein; Nenonen 1995; Sutinen & Middleton 2021), but the recent interpretations suggest that at least some of the Peräpohjola interstadial sediments are Middle Weichselian age (e.g. Mäkinen 2005; Sarala 2005; Johansson et al. 2011; Helmens 2014; Kleman *et al*. 2021).

Previous studies from Finnish Lapland and southern and eastern Finland have shown that one or two ice-free phases occurred during the Middle Weichselian (MIS 3). At western Finnish Lapland, Rautuvaara and Hannukainen, there is evidence of two glacial advances during the Middle Weichselian, during MIS 4 and 3 (Salonen *et al*. 2014; Lunkka *et al*. 2015; Howett *et al*. 2015). However, none of these sites have organic sediments or pollen preserved. At Petäjäselkä, Kaarreoja and Sokli, peat and gyttja and laminated clay-silt sediment show forested pollen assemblage. At these sites, the interstadial sediment layer is situated between till beds suggesting that the areas were glaciated during the early Middle Weichselian (MIS 4) and during the Late Weichselian (MIS 2). At Sokli, a 2 m thick lacustrine, laminated clay-silt sediment sequence dated as early MIS 3 sediments, have been analysed by its micro- and macrofossil content (Bos *et al*. 2009; Helmens *et al*. 2007b). Based on pollen results, tree percentage varies between 30 and 50 % where *Betula* (30–50%) and *Pinus* (15–20%) are the dominant trees. *Picea* and *Alnus* are present with low values (Bos *et al.* 2009). The reconstruction for the early MIS 3 (Tulppio interstadial) at Sokli was suggested as low-arctic shrub tundra with possibly *Betula* trees present, although the mean July temperature reconstructions suggest present-day temperatures, i.e. ca. 13 ˚C (Bos *et al.* 2009; Helmens *et al*. 2007b; Helmens 2014).

Thus far, the Riipiharju II core composed of mostly minerogenic sediment sequence obtained from a kettle hole represents the most complete Weichselian sediment sequence from northern Sweden (Lagerbäck & Robertsson 1988; Hättestrand & Robertsson 2010) (no. 6 in Fig. 1). The pollen assemblage in LPAZ 2 is dominated by *Betula* tree (up to 50%). *Pinus* is constantly present with maximum of 5 % and single spores of *Picea*, suggested to present long-distance transport, occur throughout sediment record (Hättestrand & Robertsson 2010). The vegetation was interpreted as subarctic birch forest or subarctic shrub tundra, with mean July temperatures around 10 ˚C (Hättestrand & Robertsson 2010) and it is suggested to represent the early part of the Middle Weichselian interstadial (MIS 3) (Hättestrand 2008; Hättestrand & Robertsson 2010; Wohlfarth 2010; Alexanderson *et al.* 2011). Recent results from Veiki moraine plateau support the MIS 3 age (Alexanderson *et al*. 2021a). Alternative correlation options are also discussed in Hättestrand & Robertsson (2010).

At Pilgrimstad (no. 11 in Fig. 1), central Sweden, minerogenic gyttja beneath a till layer with multi-proxy investigations suggests ice-free conditions between c. 80 – 36 ka ago, i.e. from the late Early Weichselian to the Middle Weichselian substages (Wohlfarth *et al.* 2011). The pollen assemblage is dominated by *Betula* tree up to nearly 60% (Robertsson 1991). *Pinus* (maximum over 10%) and *Picea* are constantly present (Robertsson 1991). The pollen taxa suggest open sub-arctic vegetation shifting to sparce birch forest, interrupted by a cooler phase, and continued with an open treeless environment with possibly *Betula* trees and *Picea* (Wohlfarth *et al*. 2011 and references therein).

The inter-till sorted sediments was studied by Lunkka *et al*. (2008) at Ruunaa in eastern Finland (no. 10 in Fig. 1). The pollen assemblage from the laminated fine-grained sediments is dominated by *Betula* tree (ca. 40–63%) with *Pinus* (2–12%) and *Alnus*. *Picea* is present with low values. The authors interpreted the climate conditions were relatively cold, possibly periglacial, as many of the pollen counted were clearly worn and probably reworked (Lunkka *et al*. 2008). The three OSL ages obtained indicate that the laminated and sorted sediments were deposited during the Middle Weichselian (MIS 3) and the till beneath was deposited prior ca. 50 kyr, thus indicating glacial advance during the early Middle Weichselian (MIS 4), and the topmost till represent the Late Weichselian ice advance (MIS 2).

Overall, pollen and macrofossils dated to Middle Weichselian sediment archives are dominated by *Betula* except sediment sequence (peat sample) at Petäjäselkä. The original interpretation at Petäjäselkä was changed to more boreal, pine and birch –dominated environment based on plant macrofossils analysis (Väliranta *et al*. 2012). Data from Kaarreoja and Sokli suggest that the climate was warmer than it is at present at those sites. Moreover, recent macrofossil results from Veiki moraine zone, northern Sweden, suggest that the ice-free phase during 55–35 ka (MIS 3) was as warm as it is at present (Alexanderson *et al*. 2021b). The difference in pollen assemblages between the above-mentioned sites suggested as Middle Weichselian (MIS 3) age may be due the natural processes, but it may also be result of the different time window as proposed in Paper II. Different ice sheet reconstructions from Fennoscandia also suggest that there might have been more than one ice-free phase during the Middle Weichselian (MIS 3) substage (e.g. Olsen *et al*. 2013; Batchelor *et al*. 2019 and references therein), and the ice sheet dynamics may have been more diverse than earlier thought. Moreover, there are indications that ice-free conditions could have lasted in the northernmost Fennoscandia much longer (up to 21–24 ka ago in the Veskoniemi area; Sarala *et al*. 2010 (no. 25 in Fig. 1) than the models and reconstructions show.

Korsakova (2021) published the compilation of litho- and biostratigraphical data from the Kola Peninsula and Northern Karelia which have been previously published in Russian. However, the study does not provide detailed pollen assemblages but the overall vegetation interpretation. Based on the compilation, it is suggested that parts of the Kola Peninsula were glaciated during the early Middle Weichselian (MIS 4) and the vegetation during the late Middle Weichselian (MIS 3) represent forest-tundra with *Betula* tree and/or *B. nana* (Korsakova 2021 and references therein). Duration of the Middle Weichselian ice free substages was reviewed and assessed by Kleman *et al*. (2021). They compiled OSL, TL, ^{14}C, and cosmogenic nuclide dating results from previously published sites from southern central Norway, west central and central Sweden, central and northernmost Finland, and concluded that the central Scandinavia was ice free between 55 and ca. 35 ka.

It can be concluded that after the extensive glaciation during Middle Weichselian MIS 4, the SIS advanced second time to northwestern Finnish Lapland, as evidenced from Rautuvaara and Hannukainen (Lunkka *et al*. 2015; Salonen *et al*. 2014, respectively), but the second advance did not extend to Petäjäselkä area (Fig. 3). Results from Veiki moraine zone, northern Sweden, suggest that it represent the SIS margin during at least one re-advance or still-stand during MIS 3 deglaciation, dated with OSL to 55–35 ka (Alexanderson *et al*. 2021b).

6. CONCLUSIONS

Following conclusions can be drawn based on this thesis:

- Modified LST Fastfloat method is a safe and reliable pollen preparation method and the results are comparable to the conventional HF method (Paper I).
- Sediment succession obtained from Muhos shows long and nearly continuous sediment succession spanning from the Saalian glaciation (MIS 6) to the Holocene time (MIS 1) (Paper IV).
- Pollen evidence combined with litho- and chronostratigraphic evidence from Muhos core suggest sedimentation during the late Eemian interglacial (MIS 5e) and the Early Weichselian Brørup interstadial (MIS 5c) phases (Paper IV).

- Results from the Muhos core suggest that the SIS advanced more south during the Early Weichselian Herning stadial (MIS 5d) than previously estimated (Paper IV).
- Results from Petäjäselkä and Kaarreoja support and strengthen the previous suggestion of ice-free phase during the MIS 3 (Papers II and III). However, the exact duration cannot be determined.
- The nearly continuous stadial-interstadial-stadial cycle from Kaarreoja suggest that the northermost part of Finnish Lapland experienced only one ice-free phase during the MIS 3 (Paper III).
- The pollen and macrofossil evidence from Kaarreoja suggest warmer than present temperatures, thus warmer climate than previously inferred (Paper III).

7. REFERENCES

Aalto, M., Donner, J., Niemelä, J. & Tynni, R. 1983. An eroded interglacial deposit at Vimpeli, South Bothnia, Finland. Geological Survey of Finland Bulletin 324, 43 pp.

Aalto, M., Donner, J., Hirvas, H. & Niemelä, J. 1989. An interglacial beaver dam deposit at Vimpeli, Ostrobothnia, Finland. Geological Survey of Finland Bulletin 348, 34 pp.

Alexanderson, H., Johnsen, T. & Murray, A. S. 2010. Re-dating the Pilgrimstad Interstadial with OLS: a warmer climate and a smaller ice sheet during the Swedish Middle Weichselian (MIS 3)? Boreas 39, 367–376. https://doi.org/10.1111/j.1502-3885.2009.00130.x

Alexanderson, H., Hättestrand, M. & Buylaert, J. P. 2011. New dates from the Riipiharju interstadial site, northernmost Sweden. Conference abstract. In Johansson, P., Lunkka, J. P. & Sarala, P. (eds.): Late Pleistocene Glacigenic Deposits from the Central Part of the Scandinavian Ice Sheet to Younger Dryas End Moraine Zone. INQUA Periblatic Workin Group Meeting and Excursion. June 12–7, 2011.

Alexanderson, H. & Murray, A. S. 2012. Problems and potential of OSL dating Weichselian and Holocene sediments in Sweden. Quaternary Science Reviews 44, 37–50. https://doi.org/10.1016/j.quascirev.2009.09.020

Alexanderson, H., Hättestrand, M., Karlsen, A. K., Lindqvist, M. A. & Sigfúsdóttir, T. 2021a. Lakes and trees on the deglaciating margin of the Scandinavian ice sheet during MIS 3 in northern Sweden. Poster. 2nd International PALEOARC Conference, 24.-28.5.2021.

Alexanderson, H., Hättestrand, M., Karlsen, A. K., Lindqvist, M. A. & Sigfúsdóttir, T. 2021b. Lakes and trees on the deglaciating margin of the Scandinavian ice sheet during MIS 3 in northern Sweden. Abstract. 2nd International PALEOARC Conference, 24.-28.5.2021. Doi.org//10.3301/ABSGI.2021.02

Armstrong, H. A. & Brasier, M. D. 2005. Microfossils. 296 pp. Blackwell Publishing, Oxford.

Auri, J., Breilin, O., Hirvas, H., Huhta, P., Johansson, P., Mäkinen, K., Nenonen, K. Sarala, P. 2008. Tiedonanto eräiden myöhäispleistoseenikerrostumien avainkohteiden ajoittamisesta Suomessa. Geologi 60, 68–74.

Batchelor, C. L., Margold, M., Krapp, M., Murton, D. K., Dalton, A. S., Gibbard, P. L., Stokes, C. R., Murton, J. B. & Manica, A. 2019. The configuration of Northern Hemisphere ice sheets through the Quaternary. Nature Communications 10, 3713. https://doi.org/10.1038/s41467-019-11601-2

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

Battarbee, R.W, Jones, V.J., Flower, R.J., Cameron, N.G., Bennion, H., Carvalho, L. & Juggins, S. 2001. Diatoms. In: Smol, J.P., Birks, H.J.B & Last, W.M. (eds.), Tracking Environmental Change Using Lake Sediments. Volume 3: Terrestrial, Algal, and Siliceous Indicators. Kluwer Academic Publisher, Dordrecht, 155–202.

Berglund, B.E. & Ralska-Jasiewiczowa, M. 1986. Pollen analysis and pollen diagrams. In: Berglund, B.E. (ed.), Handbook of Holocene Palaeoecology and Palaeohydrology. Wiley, Chichester, 455–484.

Birks, H. J. B. 2005. Fifty years of Quaternary pollen analysis in Fennoscandia 1954–2004. Grana 44, 1–22. https://doi.org/10.1080/00173130510010477

Björck, S., Persson, T. & Kristersson, I. 1978. Comparison of two concentration methods for pollen in minerogenic sediments. Geologiska Föreningens I Stockholm Förhandlingar 100, 107–111.

Bos, J. A. A., Helmens, K. F., Bohncke, S. J. P., Seppä, H. & Birks, H. J. B. 2009. Flora, vegetation, and climate at Sokli, north-eastern Fennoscandia, during the Weichselian Middle Pleniglacial. Boreas 38, 335–348. https://doi.org/10.1111/j.1502-3885.2008.00070.x

Campbell, J. F. E., Fletcher, W. J., Hughes, P. D. & Shuttleworth, E. L. 2016. A comparison of pollen extraction methods confirms dense-media separation as a reliable method of pollen preparation. Journal of Quaternary Science 31, 631–640. https://doi.org/10.1002/jqs.2886

Donner, J. 1988. The Eemian site of Norinkylä compared with other interglacial and interstadial sites in Ostrobothnia, western Finland. Annales Academiae Scentiarum Fennicae Series A III 149, 31 pp.

Donner, J. 1995. The Quaternary History of Scandinavia. 200 pp. Cambridge University Press, Cambridge.

Eriksson, B. 1993. The Eemian pollen stratigraphy and vegetational history of Ostrobothnia, Finland. Geological Survey of Finland Bulletin 372, 36 pp.

Eriksson, B., Grönlund, T. & Uutela A. 1999. Biostratigraphy of Eemian sediments at Mertuanoja, Pohjanmaa (Ostrobothnia), western Finland. Boreas 28, 274–291. https://doi.org/10.1111/j.1502-3885.1999.tb00220.x

Forsström, L. 1982. The Oulainen interglacial in Ostrobothnia, western Finland. Acta Universitatis Ouluensis. Series A, Scientiae Rerum Naturalium 136. Geologica, 4, 116 pp.

Forsström, L. 1988. The northern limit of pine forest in Finland during the Weichselian interstadials. Annales Academiae Scentiarum Fennicae Series A III 147, 24 pp.

Forsström, L., Aalto, M., Eronen, M., & Grönlund, T. 1988. Stratigraphic evidence of the Eemian crustal movement and relative sea-level changes in Eastern Fennoscandia. Palaeogeography, Palaeoclimatology, Palaeoecology 68, 317–335.

Gibbard, P. L. 1979. Late Pleistocene stratigraphy of the area around Muhos, North Finland. Annales Academiae Scentiarum Fennicae Series A III 129, 38 pp.

Guiry, M.D. & Guiry, G.M. 2019. AlgaeBase. World-wide Electronic Publication. National University of Ireland, Galway. Http//algaebase.org

Grönlund, T. 1988. The diatom flora of the Eemian deposit at Haapavesi, western Finland. Geological Survey of Finland, Report of Investigation 79, 14 pp.

Grönlund, T. 1991. New cores from Eemian interglacial deposits in Ostrobothnia, Finland. Geological Survey of Finland Bulletin 352, 31 pp.

Grönlund, T. & Ikonen, L. 1996. Early Weichselian biostratigraphy and vegetational development at Horonkylä, Pohjanmaa, Western Finland. Bulletin of the Geological Society of Finland 68, 68–84.

Haila, H. Miettinen, A. & Eronen, M. 2006. Diatom succession of a dislocated Eemian sediment sequence at Mommark, South Denmark. Boreas 35, 378–384. https://doi.org/10.1080/03009480600612385

Head, M. 2007. Last Interglacial (Eemian) hydrographic conditions in the southwestern Baltic Sea based on dinoflagellate cysts from Ristinge Klint, Denmark. Geological Magazine 144 (6), 987–1013. https://doi.org/10.1017/S0016756807003780

Helmens, K. F., Räsänen, M., Johansson, P. W., Jungner, H. & Korjonen, K. 2000. The Last Interglacial – Glacial cycle in NE Fennoscandia: a nearly continuous record from Sokli (Finnish Lapland). Quaternary Science Reviews 19, 1605–1623. https://doi.org/10.1016/j.quascirev.2013.12.012

Helmens, K. F., Johansson, P. W., Räsänen, M. E., Alexanderson, H. & Eskola, K. O. 2007a. Ice-free intervals continuing into Marine Isotope Stage 3 at Sokli in the central area of the Fennoscandian glaciations. Bulletin of the Geological Society of Finland 79, 17–39. http://doi.org/10.17741/bgsf/79.1.002

Helmens, K. F., Bos, J. A. A., Engels, S., Van Meerbeeck, C.J., Bohncke, S. J. P., Renssen, O., Heiri, O., Brooks, S. J., Seppä, H., Birks, H. J. B. & Wohlfarth, B. 2007b. Present-day temperatures in northern Scandinavia during the last glaciation. Geology 35, 987–990. https://doi.org/10.1130/G23995A.1

Helmens, K. F. & Engels, S. 2010. Ice-free conditions in eastern Fennoscandia during early Marine Isotope Stage 3: lacustrine records. Boreas 39, 399–409. https://doi.org/10.1111/j.1502-3885.2010.00142.x

Helmens, K. F., Väliranta, M., Engels, S. & Shala, S. 2012. Large shifts in vegetation and climate during the Early Weichselian (MIS 5d-c) inferred from multi-proxy evidence at Sokli (northern Finland). Quaternary Science Reviews 41, 22–38. https://doi.org/10.1016/j.quascirev.2012.02.008

Helmens, K. F. 2014. The Last Interglacial–Glacial cycle (MIS 5–2) re-examined based on long proxy records from central and northern Europe. Quaternary Science Reviews 86, 115–143. https://doi.org/10.1016/j.quascirev.2013.12.012

Helmens, K.F., Salonen, J.S., Plikk, A., Engels, S., Väliranta, M., Kylander, M., Brendryen, J., Renssen, H. 2015. Major cooling intersecting peak Eemian Interglacial warmth in northern Europe. Quaternary Science Reviews 122, 293–299. https://doi.org/10.1016/j.quascirev.2015.05.018

Helmens, K. F. 2019. The last 130 000 years in Fennoscandia reconstructed based on a long and fossil-rich sediment sequence preserved at Sokli in northern Finland: New evidence for highly dynamic environmental and climate conditions. SKB TR-18-04, Swedish Nuclear Fuel and Waste Management Co, 115 p.

Howett, P. J., Salonen, V-P., Hyttinen, O., Korkka-Niemi, K. & Moreau, J. 2015. A hydrostratigraphical approach to support environmentally safe siting of a mining waste facility at Rautuvaara, Finland. Bulletin of the Geological Society of Finland 87, 51–66. https://doi.org/10.17741/bgsf/87.2.001

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

Hirvas, H. 1991. Pleistocene stratigraphy of Finnish Lapland. Geological Survey of Finland Bulletin 354, 123 pp.

Houmark-Nielsen, M. 2008. Testing OSL failures against a regional Weichselian glaciation chronology from southern Scandinavia. Boreas 37, 660–677. https://doi.org/10.1111/j.1502-3885.2008.00053.x

Hughes, A. L. C., Gyllencreutz, R., Lohne, Ø. S., Mangerud, J. & Svendsen, J. 2016. The Last Eurasian Ice Sheets – a chronological database and time-slice reconstruction, DATED-1. Boreas 45, 1–45. https://doi.org/10.1111/bor.12142

Hättestrand, M. 2007. Weichselian interstadial pollen stratigraphy from a Veiki plateau at Rissejauratj in Norrbotten, northern Sweden. GFF 129, 287–294. https://doi.org/10.1080/11035890701294287

Hättestrand, M. 2008. Vegetation and Climate during Weichselian Ice Free Intervals in Northern Sweden: Interpretations from Fossil and Modern Pollen Records. Doctoral thesis, Stockholm University, 120 pp.

Hättestrand, M. & Robertsson, A.-M. 2010. Weichselian interstadials at Riipiharju, northern Sweden – Interpretation of vegetation and climate from fossil and modern pollen records. Boreas 39, 296–311. https://doi.org/10.1111/j.1502-3885.2009.00129.x

Ilvonen, E. 1973. Eem-kerrostuma Savukosken Soklilla. Geologi 25 (8), 81–84.

Johansson, P., Lunkka, J.-P. & Sarala, P. 2011. The Glaciation of Finland. In: Ehlers, J., Gibbard, P.L. & Hughes, P.D. (eds.): Quaternary Glaciations – Extent and Chronology, A closer look, 105–116. Developments in Quaternary Science 15, Elsevier, Amsterdam. https://doi.org/10.1016/B978-0-444-53447-7.00009-X

Johnsen, T. F. 2010. Late Quaternary ice sheet history and dynamics in central and southern Scandinavia. Ph.D. thesis, Stockholm University, 32 pp.

Jungner, H. 1987. Thermoluminescence dating of sediments from Oulainen and Vimpeli, Ostrobothnia, Finland. Boreas 16, 231–235.

Kleman, J., Hättestrand, C., Borgström, I. & Stroeven, A. 1997. Fennoscandian palaeoglaciology reconstructed using a glacial inversion model. Journal of Glaciology 43, 283–299. https://doi.org/10.3189/S0022143000003233

Kleman, J. & Hättestrand, C. 1999. Frozen-bed Fennoscandian and Laurentide ice sheet during the Last Glacial Maximum. Nature 402, 63–66. https://doi.org/10.1038/47005

Kleman, J., Stroeven, A. P. & Lundqvist, J. 2008. Patterns of Quaternary ice sheet erosion and deposition in Fennoscandia and a theoretical framework for explanation. Geomorphology 97, 73–90. https://doi.org/10.1016/j.geomorph.2007.02.049

Kleman, J., Hättestrand, M., Borgström, I., Fabel, D. & Preusser, F. 2021. Age and duration of a MIS 3 interstadial in the Fennoscandian Ice Sheet core area – Implications for ice sheet dynamics. Quaternary Science Reviews 246, 107011. https://doi.org/10.1016/j.quascirev.2021.107011

Korpela, K.1969. Die Weichsel-Eiszeit und ihr Interstadial in Peräpohjola (nördliches Nordfi nnland) im Licht von sub-moränen Sedimenten. Annales Academiae Scientiarum Fennicae A III: 99, 1–108.

Korsakova, O. 2021. Upper Pleistocene and Holocene stratigraphy in the Kola Peninsula and Northern Karelia (N–W Russia): Marine and glacial units. Quaternary International 605–606, 108–125. https://doi.org/10.1016/j.quaint.2020.11.040

Kristensen, P., Gibbard, P., Knudsen, K.L. & Ehlers, J. 2000. Last Interglacial stratigraphy at Ristinge Klint, South Denmark. Boreas 29, 103–116. https://doi.org/10.1111/j.1502-3885.2000.tb01204.x

Krammer, K. & Lange-Bertalot, H. 1991a. Bacillariophyceae 2/3. Centrales, Fragilariaceae, Eunotiaceae. In: Ettl, H.J., Gerloff, J., Heynig, H. & Mollenhauer, D. (eds.): Süßwasserflora von Mitteleuropa, 576 pp. Gustav Fisher Verlag, Stuttgart.

Krammer, K. & Lange-Bertalot, H. 1991b. Bacillariophyceae 2/4. Achnanthaceae, Kritische Ergänzungen zu Navicula (Lineolatae) und Gomphonema. In: Ettl, H.J., Gerloff, J., Heynig, H. & Mollenhauer, D. (eds.): Süßwasserflora von Mitteleuropa, 437 pp. Gustav Fisher Verlag, Stuttgart.

Krammer, K. & Lange-Bertalot, H. 1997a. Bacillariophyceae. 1/2. Naviculaceae. In: Ettl, H.J., Gerloff, J., Heynig, H. & Mollenhauer, D. (eds.): Süßwasserflora von Mitteleuropa, 876 pp. Gustav Fisher Verlag, Jena.

Krammer, K. & Lange-Bertalot, H. 1997b. Bacillariophyceae. 2/2. Bacillariaceae, Epithemiaceae, Surirellaceae. In: Ettl, H.J., Gerloff, J., Heynig, H. & Mollenhauer, D. (eds.): Süßwasserflora von Mitteleuropa, 610 pp. Gustav Fisher Verlag, Jena.

Lagerbäck, R. & Robertsson, A.-M. 1988. Kettle holes – stratigraphical archives for Weichselian geology and palaeoenvironment in northernmost Sweden. Boreas 17, 439–468.

Lambeck, K., Purcell, A., Funder, S., Kjær, K. H., Larsen, E. & Möller, P. 2006. Constraints on the Late Saalian to early Middle Weichselian ice sheet of Eurasia from field data and rebound modelling. Boreas 35, 539–575. https://doi.org/10.1080/03009480600781875

Leipe, C., Kobe, F. & Müller, S. 2019. Testing the performance of sodium polytungstate and lithium heteropolytungstate as non-toxic dende media for pollen extraction from lake and peat sediment samples. Quaternary International 516, 207–214. https://doi.org/10.1016/j.quaint.2018.01.029

Lentfer, C. J. & Boyd, W. E. 2000. Simultaneous Extraction for Phytoliths, Pollen and Spores from Sediments. Journal of Archaeological Science 27, 363–372. https://doi.org/10.1006/jasc/1998.0374

Lokrantz, H. & Sohlenius, G. 2006. Ice marginal fluctuations during the Weichselian glaciation in Fennoscandia, a literature review. SKB TR-06-36, Swedish Nuclear Fuel and Waste Management Co, 55 p.

Lundqvist, J. 1971. The interglacial deposit at Leveäniemi mine, Svappavaara, Swedish Lapland. Sveriges Geologiska Undersökning C 658, 163 pp.

Lunkka, J. P., Johansson, P., Saarnisto, M. & Sallasmaa, O. 2004. Glaciation of Finland. In: Ehlers, J. & Gibbard, P. L. (eds). Quaternary Glaciations: Extent and Chronology. Part 1: Europe, 93–100. Developments in Quaternary Science 2. Elsevier, Amsterdam.

Lunkka, J. P., Murray, A. & Korpela, K. 2008. Weichselian sediment succession at Ruunaa, Finland, indicating a Mid-Weichselian ice-free interval in eastern Fennoscandia. Boreas 37, 234–244.

Lunkka, J. P., Peuraniemi, V. & Nikarmaa, T. 2013. Application of till geochemical and indicator mineral data to the interpretation of the thick till sequence at Muhos, northern Finland. Geochemistry, Exploration, Environment, Analysis 13, 183–193.

Lunkka, J. P., Sarala, P. & Gibbard, P. 2015. The Rautuvaara section, western Finnish Lapland, revisited – new age constraints indicate a complex Scandinavian Ice Sheet history in northern Fennosandia during the Weichselian Stage. Boreas 44, 68–80. https://doi.org/10.1111/bor.12088

Lunkka, J. P., Lintinen, P., Nenonen, K. & Huhta, P. 2016. Stratigraphy of the Koivusaarenneva exposure and its correlation across central Ostrobothnia, Finland. Bulletin of the Geological Society of Finland 88, 53–67.

Miettinen, A., Rinne, K., Haila, H., Hyvärinen, 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. https://doi.org/10.1002/jqs.706

Mosimann, J. E. 1965. Statistical Methods for the Pollen Analyst: Multinomial and Negative Multinomial Techniques. In: Kummel, B & Raup, D. (eds.). Handbook of Paleontological Techniques. Freeman, San Fransisco, 636–673.

Murray, A. S. & Wintle, A. G. 2000. Luminescence dating of quartz using an improved single-aliquot regenerative-dose protocol. Radiation Measurements 32, 57–73. https://doi.org/10.1016/S1350-4487(99)00253-X

Murray, A. S. & Olley, J. M. 2002. Precision and accuracy in the optically stimulated luminescence dating of sedimentary quartz: a status review. Geochronometria 21, 1–16.

Murray, A. S. & Wintle, A. G. 2003. The single aliquot regenerative dose protocol: potential for improvements in reliability. Radiation Measurements 37, 377–381. https://doi.org/10.1016/S1350-4487(03)00053-2

Murray, A. S., Svendsen, J. I., Mangerud, J. & Astakhov, V. I. 2007. Testing the accuracy of quartz OSL dating using a known-age Eemian site on the river Sula, northern Russia. Quaternary Geochronology 2, 102–109. https://doi.org/10.1016/j.quageo.2006.04.004

Mäkinen, K. 1979. Interstadiaalinen turvekerrostuma Tervolan Kauvonkankaalla. Summary: An interstadial peat layer at Kauvonkangas, Finnish Lapland. Geologi 31, 82–87.

Mäkinen, K. 2005. Dating the Weichselian deposits of southwestern Finnish Lapland. In: Ojala, A. E. K. (ed): Quaternary studies in the northern and Arctic regions of Finland. Proceedings of the workshop organized within the Finnish National Committee for Quaternary Research (INQUA), Kilpisjärvi Biological Station, Finland, 13 – 14 January 2005. Geological Survey of Finland, Special Paper 40, 67–78.

Möller, P., Anjar, J. & Murray, A. 2013. An OSL-dated sedimenti sequence at Idre, weste-central Sweden, indicates ice-free conditions in MIS 3. Boreas 42, 25–42. https://doi.org/10.1111/j.1502-3885.2012.00284.x

Nakagawa, T., Brugiapaglia, E., Digerfeldt, G., Reille, M., de Beaulie, J.-L. & Yasuda, Y. 1998. Dense-media separation as a more efficient pollen extraction method for use with organic sediment/deposit samples: comparison with the conventional method. Boreas 27, 15–24.

Nenonen, K. 2006. Jääkausikäsityksen muutos – Kutistuvatko jäälliset jaksot luultua lyhyemmiksi? Geologi 58 (1), 9–14. (in Finnish).

Nenonen, K., Eriksson, B. & Grönlund, T. 1991. The Till Stratigraphy of Ostrobothnia, Western Finland, with Reference to New Eemian Interglacial Sites. Striae 34, 65–76.

Nenonen, K. 1995. Pleistocene Stratigraphy and Reference Sections in Southern and Western Finland. Geological Survey of Finland, Regional Office for Mid-Finland. 94 pp.

Olsen, L. 1998. Pleistocene paleosols in Norway: implications for past climate and glacial erosion. Catena 34, 75–103. https://doi.org/10.1016/S0341-8162(98)00083-6

Olsen, L., Mejdahl, V. & Selvik, S. F. 1996. Middle and Late Pleistocene stratigraphy, chronology and glacial history in Finnmark, North Norway. Norges geologiske undersøkelse Bulletin 429, 1–111.

Olsen, L. O., Van der Borg, K., Bergström, B., Sveian, H., Lauritzen, S. E. & Hansen, G. 2001. AMS radiocarbon dating of glacigenic sediments with low organic carbon content - an important tool for reconstructing the history of glacial variations in Norway. Norwegian Journal of Geology 81, 59–92.

Olsen, H. & Hammar, Ø. 2005. A 6-ka climatic cycle during at least the last 50,000 years. Norges Geologiske Undersøkelse 445, 89–100.

Olsen, L., Sveian, H., Bergstrøm, B., Ottesen, D. & Rise, L. 2013. Quaternary glaciations and their variations in Norway and on the Norwegian continental shelf. Geological Survey of Norway Special Publication 13, 27–78.

Peltoniemi, H., Eriksson, B., Grönlund, T. & Saarnisto, M. 1989. Marjamurto, an interstadial site in a till covered esker area of central Ostrobothnia, western Finland. Bulletin of the Geological Society of Finland 61, 209–237.

Pitkäranta, R., Lunkka, J.-P. & Eskola, K. O. 2014. Lithostratigraphy and Optically Stimulated Luminescence age determinations of pre-Late Weichselian deposits in the Suupohja area, western Finland. Boreas 43, 193–207. https://doi.org/10.1111/bor.12030

Putkinen, N., Sarala, P., Eyles, N., Daxberger, H., Pihlaja, J. & Murray, A. 2020. Reworked Middle Pleistocene deposits preserved in the core region of the Fennoscandian Ice Sheet. Quaternary Science Advances 2, 100005, https://doi.org/10.1016/j.qsa.2020.100005

Robertsson, A.-M. & Ambrosiani, K. G. 1988. Late Pleistocene stratigraphy at Boliden, Northern Sweden. Boreas 17, 1–14.

Robertsson, A.-M., 1991. The biostratigraphy of the Late Pleistocene in Sweden 150,000 – 15,000 B.P. – a Survey. In Andersen, B.G. & Königsson, L.-K. (eds): Late Quaternary Stratigraphy in the Nordic Countries 150,000 – 15,000 B.P. Striae 34, 39–46.

Robertsson, A.-M. 1997. Reinvestigation of the interglacial pollen flora at Leveäniemi, Swedish Lapland. Boreas 26, 81–89.

Robertsson, A.-M. 2000. The Eemian interglacial in Sweden, and comparison with Finland. Netherlands Journal of Geosciences 79, 325–333. https://doi.org/10.1017/S0016774600021806

Saarnisto, M. & 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.

Saarnisto, M., Eriksson, B. & Hirvas, H. 1999: Tepsankumpu revisited – pollen evidence of stable Eemian climates in Finnish Lapland. Boreas 28, 12–22.

Saarnisto, M. & Lunkka, J. P. 2004. Climate variability during the last interglacial-glacial cycle in NW Europe. In: Battarbee, R. W., Gasse, F. & Stickley, C. E. (eds.): Past Climate Variability through Europe and Africa, 443–464. Developments in Palaeoenvironmental Research 6.

Salonen, J.S., Helmens, K.F., Brendryen, J., Kuosmanen, N., Väliranta, M., Goring, S., Korpela, M., Kylander, M., Philip, A., Plikk, A., Renssen, H. & Luoto, M. 2018. Abrupt high-latitude climate events and decoupled seasonal trends during the Eemian. Nature Communications 9, 2851. https://doi.org/10.1038/s41467-018-05314-1

Salonen, V.-P., Kaakinen, A., Kultti, S., Miettinen, A., Eskola, K. O. & Lunkka, J. P. 2008. Middle Weichselian glacial event in the central part of the Scandinavian Ice Sheet recorded in the Hitura pit, Ostrobothnia, Finland. Boreas 37, 38–54. https://doi.org/10.1111/j.1502-3885.2007.00009.x

Salonen, V.-P., Moreau, J., Hyttinen, O. & Eskola, K. O. 2014. Mid-Weichselian interstadial in Kolari, western Finnish Lapland. Boreas 43, 627–638. https://doi.org/10.1111/bor.12060

Sarala, P. 2005. Weichselian stratigraphy, geomorphology and glacial dynamics in southern Finnish Lapland. Bulletin of the Geological Society of Finland 77, 71–104. https://doi.org/10.17741/bgsf/77.2.001

Sarala, P., Johansson, P, Lunkka, J.-P. (eds.) 2006. Late Pleistocene Glaciogenic Deposits in the Central Part of the Scandinavian Ice Sheet: Excursion guide, The INQUA Peribaltic Group Field Symposium in Finland, September 11.-15.2006. Geological Survey of Finland, Rovaniemi, 62 pp.

Sarala, P. & Rossi, S. 2006. Rovaniemen–Tervolan alueen glasiaalimorfologiset ja -stratigrafiset tutkimukset ja niiden soveltaminen geokemialliseen malminetsintään. Summary: Glacial geological and stratigraphical studies with applied geochemical exploration in the area of Rovaniemi and Tervola, southern Finnish Lapland. Geological Survey of Finland, Report of Investigation 161, 115 p.

Sarala, P., Pihlaja, J., Putkinen, N. & Murray, A. 2010. Composition and origin of the Middle Weichselian interstadial deposit in Veskoniemi, northern Finland. Estonian Journal of Earth Sciences 59 (2), 117-124. https://doi.org/10.3176/earth.2010.2.02

Stroeven, A. P.., Hättestrand, C., Kleman, J., Heyman, J., Fabel, D., Fredin, O., Goodfellow, B. W., Harbor, J. M., Jansen, J. D., Olsen, L., Caffee, M. W., Fink, D., Lundqvist, J., Rosqvist, G., Strömberg, B. & Jansson, K. N. 2016. Deglaciation of Fennoscandia. Quaternary Science Reviews 147, 91–121. https://doi.org/10.1016/j.quascirev.2015.09.016

Sutinen, R. & Middleton, M. 2021. Porttipahta end moraine in Finnish Lapland is constrained to Early Weichselian (MIS 5d, Herning stadial). Geomorphology 393, 107942. https://doi.org/10.1016/j.geomorph.2021.107942

Svendsen, J., Alexanderson, H., Astakhov, V., Demidov, I., Dowdeswell, J., Funder, S., Gataullin, V., Henriksen, M., Hjort, C., Houmark-Nielsen, M., Hubberten, H., Ingolfsson, O., Jakobsson, M., Kjær, K., Larsen, E., Lokrantz, H., Lunkka, J., Lysǻ, A., Mangerud, J., Matiouchkov, A., Murray, A., Möller, P., Niessen, F., Nikolskaya, O., Polyak, L., Saarnisto, M., Siegert, C., Siegert, M., Spielhagen, R. & Stein, R. 2004. Late Quaternary ice sheet history of northern Eurasia. Quaternary Science Reviews 23, 1129–1271.

Ukkonen, P., Lunkka, J. P., Jungner, J. & Donner, J. 1999. New radiocarbon dates from Finnish mammoths indicating large ice-free areas in Fennoscandia during the Middle Weichselian. Journal of Quaternary Science 14, 711–714.

Ukkonen, P., Aaris-Sørensen, K., Arppe, L., Clark, P. U., Daugnora, L., Lister, A. M., Lõugas, L., Seppä, H., Sommer, R. S. Stuart, A. J., Wojtal, P. & Zupiņš, I. 2011. Woolly mammoth (Mammuthus primigenius Blum.) and its environment in northern Europe during the last glaciation. Quaternary Science Reviews 30, 693–712. https://doi.org/10.1016/j.quascirev.2010.12.017

Väliranta, M., Sarala, P. & Eskola, T. 2012. Uusia todisteita boreaalisista olosuhteista Veiksel-interstadiaalin aikana. Summary: New evidence of boreal conditions during Weichselian interstadial. Geologi 64, 9–14.

Wintle, A. G. 2008. Luminescence dating: where it has been and where it is going. Boreas 37, 471–482. https://doi.org/10.1111/j.1502-3885.2008.00059.x

Wohlfarth, B. Ice-free conditions in Sweden during Marine Oxygen Isotope Stage 3? Boreas 39, 377–398. https://doi.org/10.1111/j.1502-3885.2009.00137.x

Wohlfarth, B., Alexanderson, H., Ampel, L., Bennike, O., Engels, S., Johnsen, T., Lundqvist, J. & Reimer, P. 2011. Pilgrimstad revisited – a multi-proxy reconstruction of Early/Middle Weichselian climate and environment at a key site in central Sweden. Boreas 40, 211–230. https://doi.org/10.1111/j.1502-3885.2010.00192.x

Zabenskie, S. 2006. Post-Glacial climatic change on Boothia Peninsula, Nunavut, Canada. M.Sc. thesis, University of Ottawa, Canada, 98 pp.

Zagwijn, W. H. 1996. An analysis of Eemian climate in western and central Europe. Quaternary Science Reviews 15, 451–469. https://doi.org/10.1016/0277-3791(96)00011-XAalto, M., Donner, J., Niemelä, J. & Tynni, R. 1983. An eroded interglacial deposit at Vimpeli, South Bothnia, Finland. Geological Survey of Finland Bulletin 324, 43 pp.

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