Vegetation and climate during Weichselian ice free intervals in northern Sweden – interpretations from fossil and modern pollen records

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This doctoral thesis consists of four papers and a synthesis. The four papers, listed below, are referred to as Paper I-IV in the text:

Paper I: Hättestrand, M., Robertsson, A.-M.: Weichselian ice free intervals at Riipiharju, northern Sweden - interpretations of vegetation and climate from fossil and modern pollen records. *Boreas*, submitted.

Paper II: Hättestrand, M., 2007: Weichselian interstadial pollen stratigraphy from a Veiki plateau at Rissejauratj in Norrbotten, northern Sweden. *GFF* 129, 287-294.

Paper III: Hättestrand, M.: Eight years of annual pollen monitoring in northern Sweden, from the boreal forest to above the forest-line of birch. Manuscript.

Paper IV: Hättestrand, M., Jensen, C., Hallsdóttir, M., Vorren, K.-D., 2008: Modern pollen accumulation rates at the north-western fringe of the European boreal forest. *Review of Palaeobotany and Palynology* 151, 90-109.

Introduction

Glacial cycles

The Earth's climate system shifted into a prominent cold climatic period about 2.5 million years ago (e.g. Kukla and Zhisheng, 1989; Shackleton, 1997). This cold period, the Quaternary, has lasted until present and is characterized by large fluctuations in climate, recurrent glaciations, and extreme variations in global environment. Glacial cycles are intervals during which the global climate has changed in a saw-toothed pattern starting with a warm interglacial (of c. 15 000-20 000 years, with a climate similar to the present or warmer) progressing into a mild early glacial and a cold late glacial, finally ending with a rapid warming being the start of the next glacial cycle (Broecker and van Donk, 1970) (Fig. 1). In the early part of the Quaternary period the glacial cycles lasted for about 40 000 years while in the later part of the period the cycles lasted for c. 100 000 years (e.g. Berger, 1978). Evidence of the glaciations have been found in deep ocean sediment records, ice cores, raised coral reefs, lake sediment records, loess deposits, glaciofluvial sediments, and the landform record. The timing of the glacial cycles has been linked to variations of the Earth´s orbit around the sun (e.g. Hays *et al.*, 1976; Kukla and Gavin, 2005). These orbital changes influence the geographical and seasonal distribution of solar insolation, while the total annual insolation at the top of the atmosphere has been more or less constant through time (e.g. Kukla and Gavin, 2005). The orbital cycles are 22 000 years for the precession (the timing of the closest approach of the earth to the sun), 41 000 years for the obliquity (the variation of tilt from 22.5-24° of the earth´s axis), and 100 000 and 400 000 years for the eccentricity (the roundness of the earth´s orbit) (e.g. Milankovitch, 1920; 1941). Changes in summer insolation at high latitudes (c. 65°) correlate well with the timing of past ice ages (Imbrie, 1982), but, the mechanisms linking the astronomic variables to the climatic and environmental changes on earth still remain largely unexplained (e.g. Kukla and Gavin, 2005).

Marine oxygen isotope records, retrieved from deep sea sediments can be used as a proxy of the total volume of water bound to ice sheets at different times and hence, provide long and continuous records on climate variability (Shackleton, 1987). Marine isotope stages have been determined (Shackleton and Opdyke, 1973) and terrestrial records are often correlated to these stages to enable precise communication of timing of stratigraphical sequences and events. Global ice volume changes are a rough record of climate variability and more detailed climatic records on continental and regional scales are needed to understand the response of the earth system to astronomical forcing. In addition to the astronomical forcing there is also a complex interplay between the atmosphere, ocean, glaciers, lithosphere and vegetation affecting the climate (Mangerud, 1991), and therefore information of these parameters are also needed to understand past climate. If we can reconstruct past variations in climate the predictions of future climate variability will become more solid.

Outside the glaciated areas in Europe, several long and detailed terrestrial sedimentary records representing the Weichselian glacial stage have been retrieved; for example at Grand Pile, Vosges, France (Woillard and Mook, 1982; de Beaulieu and Reille, 1992); Les Echets, near Lyon, France(de Beaulieu and Reille, 1984; Wohlfarth *et al.*, 2008); Velay Maar, Massif Central, France (Reille and de Beaulieu 1990); Valle di Castiglione, Roma, Italy (Follieri *et al.*, 1988) and Tenaghi Phillipon, northern Greece (Wijmstra, 1969; Tzedakis *et al.*, 2006). Evidence of climatic fluctuations outside the ice margin is valuable for interpretation of glacial records from Fennoscandia. However, the distance between the sites in south-central Europe and Fennoscandia is too large for biostratigraphical correlations based on pollen stratigraphy.

The last glacial cycle in northern Europe

The last glacial cycle, starting about 130 000 years ago, is a key period for understanding the Earth's response to orbital and other forcing, since it is the cycle known in most detail (Mangerud, 1991). It started with the Eemian interglacial stage generally correlated to marine isotope stage (MIS) 5e, but in some records also correlated with a substantial part of MIS 5d (e.g. Kukla *et al.*, 1997; Tzedakis *et al.*, 2003). At about 120 000 years ago the climate deteriorated (reflected later in some south European records), marking the beginning of the Weichselian glacial stage. This glacial stage lasted until c. 10 000 years ago when the climate had again attained close-to-present conditions at the beginning of the Holocene interglacial stage, in which we are still living today, started. The Weichselian glacial stage in northern Europe is broadly equivalent to the glacial stages Würm in central Europe and Wisconsinan in North America. The Weichselian glaciation is commonly divided into Early (Lower) Weichselian (MIS 5d-5a), Middle Weichselian (MIS 4 and 3) and Late (Upper) Weichselian (MIS 2). During the glacial stages the climate fluctuated, between relatively cold periods (stadials) and milder periods (interstadials) (Fig 1). The warmest Weichselian interstadials recorded in northwest-

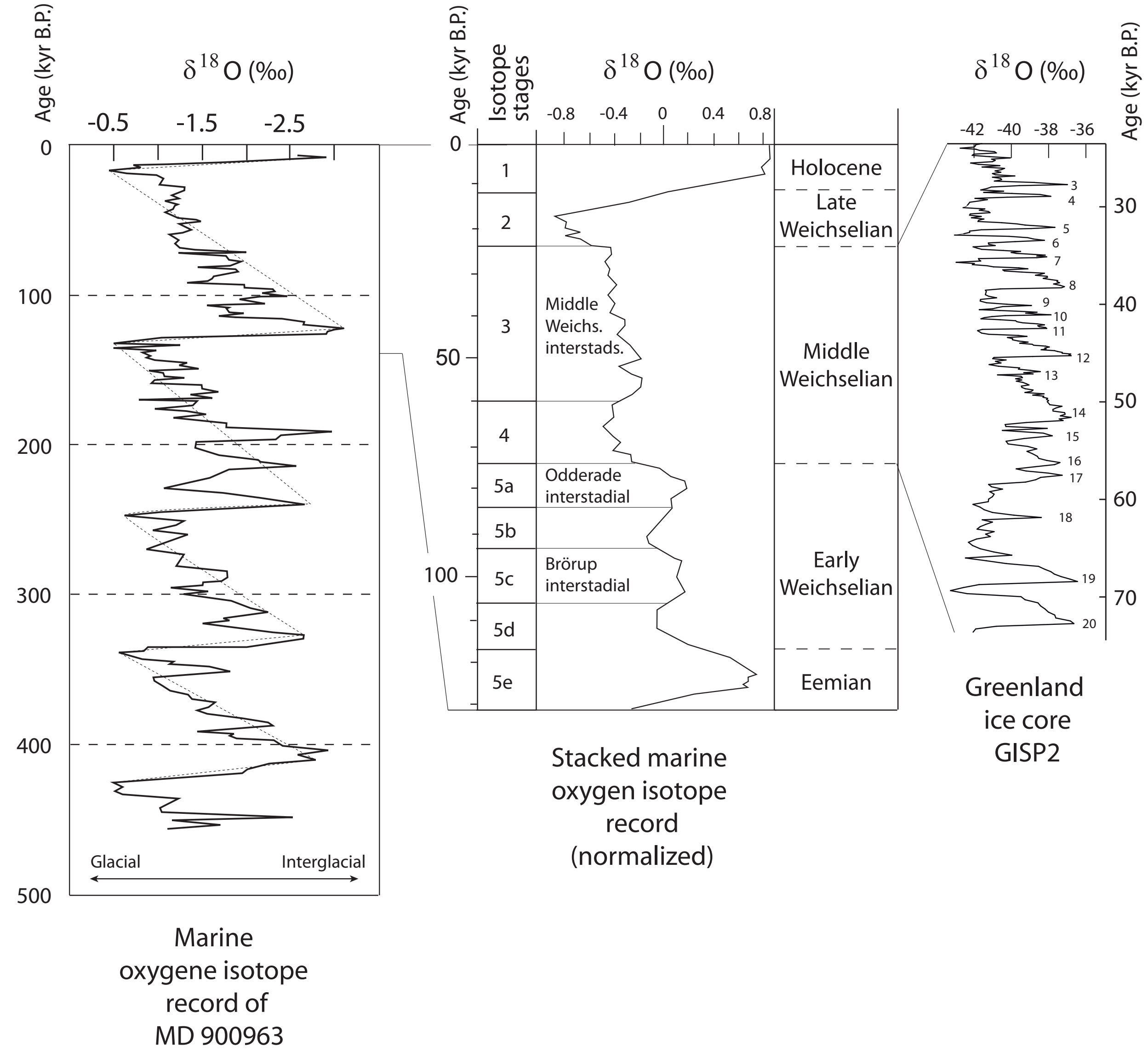

Figure 1. Oxygen isotope record of MD900963 from Bassinot et al. (1994) showing the saw toothed pattern of the last four glacial cycles. The stacked marine oxygen isotope record from Martinson et al. (1987) is showing the last interglacial-glacial cycle and its correlation to the discussed chronostratigraphy of northwestern Europe (Mangerud 1991). A climatic record for Greenland is indicated in the GISP2 core (Alley et al., 1995) in which the Greenland Interstadials are marked with numbers.

ern Europe are the Early Weichselian interstadials Brörup (MIS 5c) and Odderade (MIS 5a). During the Middle Weichselian (MIS 3) the interstadials of Oerel, Glinde, Moershoofd, Hengelo and Denekamp are recorded (e.g. Zagwijn, 1974; Kolstrup and Wijmstra, 1977; Kolstrup, 1980; Behre, 1989; Ran, 1990; Caspers and Freund, 2001; Behre and van der Plicht, 1992). However, the Middle Weichselian records in this part of Europe are usually discontinuous and represent short time intervals (e.g. Kolstrup, 1992; Whittington and Hall, 2002; Bohncke *et al.*, 2008). During MIS 3 and 2 rapid climatic shifts on centennial to millennial time scales, named Dansgaard-Oeschger cycles and Heinrich events, are recorded in marine-, ice core- and terrestrial records (e.g. Bond *et al.*, 1992; Dansgaard *et al.*, 1993; Veres, 2007; Wohlfarth *et al.*, 2008). The Scandinavian ice sheet reached its maximum extent during MIS 2, at c. 20 000 years before present (Ehlers and Gibbard, 2004). Shortly after this the ice sheet started to melt and at about 9 000 years ago Scandinavia was almost fully deglaciated (Lundqvist, 1994).

One large obstacle when studying the last glacial cycle is that sediments older than c. 25 000 years are difficult to date accurately with the radiocarbon method. Other absolute dating methods often used on Weichselian glacial terrestrial sediments are thermoluminescence (TL) and optically stimulated luminescence (OSL). For example OSL has been used in reconstructing the glacial history in northern Eurasia. However, the methods can be difficult to apply and require certain depositional and preservational conditions to be reliable (e.g. Murray *et al.*, 2007; Alexanderson and Murray, 2007). In a comparison between OSL dates and AMS-^{14}C dates on Danish Lateglacial sediments the OSL ages are generally slightly younger than the AMS-^{14}C ages (Kolstrup *et al.*, 2007). For Weichselian ice free intervals records in northern Sweden, no absolute chronology has been established. Because of absence of reliable dates the chronology of individual depositional sequences are often based on correlation between stratigraphies at different sites (number and characteristics of till beds etc.). In the formerly glaciated part of northern Europe the sedimentary sequences from the Weichselian glacial are scarce and commonly fragmented, increasing the problems of correlation between records.

Figure 2. Location map with sites discussed in the text.

The Weichselian glacial stage in central and northern Fennoscandia

The Scandinavian mountain range, situated high in latitude (from 58° to 71° N), has a step western margin, with deep fjords along the Norwegian coast. The terrain is gradually lowering towards the east in Sweden, shifting into a low relief landscape. The precipitation is high in the western part of the mountain range, close to the Atlantic Ocean, and decreases towards the east where the climate is more continental. During glaciations the mountain range constitutes the first and last glaciation centres. The ice divide of the Fennoscandian ice sheets is in the beginning of glaciations centred along the mountain range elevation axis (Ljungner, 1949; Lundqvist, 1961; Fredin, 2002). However, when ice sheets grow larger precipitation pattern changes and ice divides and ice dome centres migrate eastwards, causing shifts in ice flow directions over the central areas of glaciation (Kleman *et al.*, 1997). Studies of glacial landform and sediment records have revealed several different ice configurations during the Weichselian in Fennoscandia (e.g. Hirvas *et al.*, 1988; Hirvas, 1991; Kleman *et al.*, 1997). A summary of published studies of interstadial sites in central and northern Fennoscandia is given below. For location of sites, see Figure 2.

Sweden: At Riipiharju, Takanenmännikkö and Onttovaara in northern Sweden, close to the core areas of the Fennoscandian glaciations, Weichselian sediments indicate ice free conditions during at least two periods, separated by a glaciation (Lagerbäck and Robertsson, 1988). Lagerbäck and Robertsson (1988) interpreted the Weichselian ice free environments to have been characterised by subarctic shrub tundra during the first interstadial and open cold arctic steppe during the second ice free phase, and they tentatively correlated the intervals to Brörup and Odderade. It has been discussed if the two north Swedish ice free phases could be of younger age, i.e. belonging to Odderade and Middle Weichselian time, however, this alternative has been regarded as less likely (e.g. Lagerbäck and Robertsson, 1988; García Ambrosiani, 1990). Reworked pollen spectra in complex stratigraphies dominated by minerogenic sediments, most of them interpreted as till, have been used to reconstruct the Weichselian stratigraphy in the Tåsjö-Hoting area in central Sweden (Lundqvist and Miller, 1992). The oldest till contains redeposited sediments from the early Eemian (or older) and is overlain by two sequences of glacial sediments containing redeposited pollen corresponding to two younger interstadials. The interpretation is that two Early Weichselian interstadials, of which the first is named Pilgrimstad and the second Tåsjö, occurred in central Sweden and that a lithostratigraphic unit consisting of clayey basal dark till indicates a glacial stage that separates the interstadials. The sediments below the dark till are correlated with the Jämtland interstadial complex in central Sweden, defined and discussed by Lundqvist (1967a, b). Lundqvist and Miller (1992) suggested that the Pilgrimstad and Tåsjö interstadials correlate with Brörup and Odderade respectively. The exact timing and extent of the Middle Weichselian glaciation following the Odderade interstadial is, however, unknown and there are indications of ice-free condition in large parts of Fennoscandia during interstadial parts of MIS 3 (e.g. Olsen, 1988; Helmens *et al.*, 2000, 2007a, b; Ukkonen *et al.*, 2007, Salonen *et al.*, 2008). So far, however, the only evidence in northern and central Sweden are radiocarbon datings on mammoth remains, which yielded Middle Weichselian ages for the bones (Ukkonen *et al.*, 2007).

Norway: Fjøsanger, Bø and Skjonghelleren, on the western coast of Norway, are key sites for studies of Weichselian ice free intervals (Andersen and Mangerud, 1989; Mangerud, 1991, 2004). At Fjøsanger, Eemian deposits are overlain by glaciomarine silt. Above the silt there is a layer of gravel reflecting an Early Weichselian interstadial (Fana), correlated to Brörup, which is overlain by a till (Mangerud *et al.*, 1981a). At Bø, sediments from the last interglacial and two interstadials (Torvastad and Bø), correlated to Odderade and the early Middle Weichselian time are recorded (Andersen *et al.*, 1983; Sejrup, 1987). At the Skjonghelleren cave the Middle Weichselian Ålesund interstadial is identified (Larsen *et al.*, 1987; Mangerud *et al.*, 1981b; Valen *et al.*, 1996). Of the two recorded Middle Weichselian interstadials in western Norway, Bø is the older one (about 55-45 ka BP) and Ålesund/Sandnes is the younger (about 40-28 ka BP). The Ålesund interstadial corresponds to the Greenland Interstadials 7 and 8 and is dated to c. 35-28 ka BP (Mangerud *et al.*, 2003). According to studies of regional Quaternary stratigraphy, fossil content, palaeomagnetic data, and numerous datings (mainly AMS-^{14}C), there were rapid climatic shifts from glacial to interstadial conditions in Norway in the interval from c. 45-40 ka to 10 ka BP (Olsen *et al.*, 2001). The climatic fluctuations occur in semi-cycles of five to seven thousand years and the recorded interstadials are named the Hattefjelldal interstadial I (39-30 ka BP) and II (27-24 ka BP), and the Trofors interstadial (21-17 ka BP). From Finnmark in northern Norway, two major Weichselian interstadials are described, the Eiravarri interstadial recorded at Vuolgamasjohka (c. 105-85 ka BP) and the Sargejohka interstadial (c. 60-35 ka BP), dated mainly through TL and OSL dating (Olsen *et al.*, 1996).

Finland: The most complete Weichselian sequence in northern Finland comes from Sokli where three interstadials; the Sokli, Maaselkä and Tulppio interstadials, are recorded (Helmens *et al.*, 2000, 2007a, b). During the first Weichselian stadial (MIS 5d), the Sokli site was most probably not overrun by an ice sheet, but show pollen spectra indicating harsh climatic conditions (Helmens *et al.*, 2007). The subsequent interstadials recorded at Sokli are separated by sediments indicating glaciation at the site. The interstadials are correlated to Brörup (Sokli: MIS 5c), Odderade (Maaselkä: MIS 5a) and Middle Weichselian time (Tulppio: MIS 3). Helmens *et al.* (2007a, b) suggest, based on the biostratigraphy that forests including pine grew in the area during the Sokli interstadial, while the site was close to the birch forest limit during the Maaselkä interstadial. Furthermore, they suggest that the Middle Weichselian sediments at Sokli could have been deposited during the Greenland Interstadial 14, recorded in the Greenland ice core record, since this is the first Middle Weichselian warm period long and warm enough for the Sokli area to become deglaciated. A radiocarbon date of 54±7/4 ka BP (uncalibrated) was obtained from the suggested Middle Weichselian sediments from the Tulppio interstadial, while the underlying sediments were dated with OSL to 48±16 ka BP. According to Helmens *et al.*´s (2007a, b) reconstructions of the Tulppio interstadial environment at Sokli shrub tundra vegetation grew in the area, but temperatures are indicated to have been at present day levels (mean July temperatures of c. 13°C).

At the Hitura open pit in Ostrobothnia, central Finland, an up to 50 m thick sediment sequence covers the Late Saalian to the Holocene (Salonen *et al.*, 2008). From OSL-datings it was interpreted that the Hitura site was ice covered at 79 ka for the first time during the entire Weichselian and that the ice sheet retreated again from the site at about 62-55 ka ago (Salonen *et al.*, 2008). At the Oulainen site in Ostrobothnia, interstadial sediments of the Oulainen interstadial are recorded (Donner *et al.*, 1986; Donner, 1988). Pollen spectra from the interstadial sediments show a vegetation development from birch forest to pine forest and back to birch forest again. The Oulainen interstadial has been correlated to Brörup (MIS 5c), and the vegetation development is similar to that recorded in the Brörup sediments at Sokli. At Maaselkä in central Finnish Lapland the Maaselkä interstadial sequence, dominated by birch pollen, is recorded (Hirvas, 1991). Helmens *et al.* (2000) correlated the Maaselkä interstadial to the second interstadial recorded at Sokli (Odderade). The Peräpohjola interstadial was described from the Peräpohjola region in southern Finnish Lapland where interstadial sediments were found between till beds at several sites (Korpela, 1969). Later Permantokoski was used as type site for the Peräpohjola interstadial (Donner *et al.*, 1996).

The till beds underlying the sediments of the Maaselkä and Peräpohjola interstadials have till fabrics indicating ice-flow from the northwest. Originally the Oulainen, Maaselkä and Peräpohjola interstadials

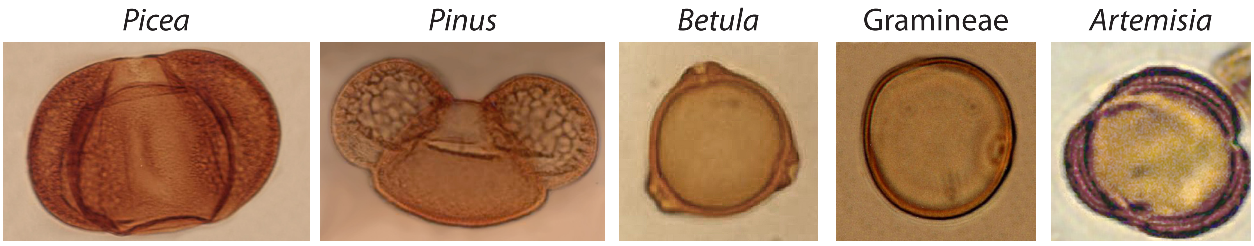

Figure 3. Examples of pollen grains as seen under microscope magnification. Photo: Sven Karlsson.

were all correlated with Brörup. However, Forsström (1988) discussed that the interstadial pollen records from the Oulainen and Peräpohjola interstadials were too different in composition to represent the same interstadial, and suggested that the warmer Oulainen interstadial rather corresponded to Brörup while the colder Peräpohjola interstadial corresponded to Odderade. This interpretation is in accordance with the records from the Sokli site. Oulainen is, however, an example of problems/uncertainties on how to correlate fragmentary pre-late Weichselian sequences, since it was first suggested to be of interglacial (Eemian) age (Forsström, 1982).

Fossil podzols in southern and central Ostrobothnia have been dated by the TL and OSL methods (Nenonen, 2006). The dates fall into three age groups: 1/ 163-120 ka, 2/ 106-76 ka and 3/ 32-44 ka, of which the latter suggests a Middle Weichselian age. Middle Weichselian ages are also recorded from AMS-^{14}C datings on subfossil mammoth remains in Finland (Ukkonen *et al.*, 1999). The ages fall between c. 32 ka and 22.5 ka BP and the data is interpreted to indicate that large ice-free areas existed in Finland during the Middle Weichselian.

South of Finland, in Estonia, a compilation study of data from 29 sites reveal ice free conditions between 105-68 ka BP and 43-27 ka BP (Kalm, 2006). The chronostratigraphy is based on OSL/TL and ^{14}C-datings on sediments and AMS-^{14}C-datings on mammoth bones. The data suggest a possible glaciation during the Middle Weichselian in Estonia between 68-43 ka BP.

More detailed reviews on Fennoscandian interstadial stratigraphies are found in e.g. Lundqvist (1981, 1992, 2004); Andersen and Mangerud (1989); Hirvas (1991); Mangerud (1991, 2004); Robertsson and Ambrosiani (1992); Olsen *et al.* (1996) and Lunkka *et al.* (2004).

Pollen analysis

Pollen analysis is a method to study past changes in vegetation and the results can be used as a proxy for climate. All flowering plants are producing pollen grains, and the morphology of the grains varies between plants (Fig. 3) so that most grains can be identified to genus level and some grains even to species level. Pollen grains are usually well preserved, produced in large amounts and well spread, and therefore they occur in many types of sediments e.g. marine and freshwater deposits, peat and reworked in till. Pollen analysis as a method to study past changes in vegetation was first introduced by the Swedish scientist Lennart von Post in a meeting of Scandinavian naturalists in Oslo in 1916 (von Post, 1918). Since 1916 methodological developments in sampling, laboratory treatment and interpretation of pollen data have been made and the last c. 50 years of pollen analysis in Fennoscandia (1954-2004), with focus on methodological and conceptual developments, is reviewed in Birks (2005). Pollen analysis has been widely used around the world and many important investigations on changes in vegetation, environment and climate are based on this method.

Initially, pollen data were presented as percentage values, based on the relation of each pollen taxon to the total pollen sum. This is still the most common way to present results from pollen analysis, although recently, also pollen accumulation rates (PARs) have been used. PAR data provide a measure of the amount of pollen deposited for each taxon per surface unit and year (grains cm^{-2} $year^{-1}$) and offers a possibility to evaluate the pollen deposition of each taxon separately. PAR values are particularly valuable for interpretation of pollen records from forest-line ecotones and of pollen spectra for which there is no modern analogue vegetation (Birks and Birks, 1980; Birks, 1984; Hicks and Hyvärinen, 1999; Birks *et al.*, 2000; Rull *et al.*, 2005; Hicks, 2006; Seppä and Hicks, 2006). However, detailed and reliable data on sedimentation rates are required to calculate PARs from pollen counts on fossil records (e.g. Jensen *et al.*, 2002; Telford *et al.*, 2004; Seppä and Hicks, 2006). Modern reference data for interpretation of fossil PARs have been recorded from lake surface sediments and pollen traps (e.g. Hyvärinen 1975, 1976; Fredskild, 1983;

Hicks, 1992, 1994, 2001; Hicks and Hyvärinen, 1999; Hicks *et al.*, 1994; Bennett and Hicks, 2005; Jensen *et al.*, 2007; Karlsson, 2008). Pollen traps are usually monitored so that accumulation rates are received with annual resolution. Parameters affecting pollen deposition in lakes, such as inflowing streams, soil erosion and catchment size (e.g. Bonny, 1976, 1978; Bergman, 2005), are avoided when using traps. Therefore, PARs received from pollen traps are suitable both as reference material for fossil PARs (e.g. Barnekow, 1999a, b; Barnekow and Sandgren, 2001; Bjune *et al.*, 2004; Giesecke, 2004, 2005; Bjune, 2005; Bergman, 2005; Karlsson *et al.*, 2007; Karlsson, 2008) and for detailed studies of the mechanisms of pollen production and deposition (e.g. Paper IV; Hicks and Hyvärinen, 1999; Hicks, 2001; Autio and Hicks, 2004).

An important development in pollen analysis is the recognition that different sites receive their pollen from different sized source areas (Birks, 2005). The relevant source area of pollen, RSAP, is defined as the area beyond which the correlation between vegetation and pollen percentage data does not improve, while the background pollen component is the pollen coming from beyond this area (Sugita, 1994). The radius of the RSAP is depending on vegetation composition around the studied site and on vegetation structure. The RSAP can range between 50 m, as shown for samples from forest hollows in USA by Sugita (1994) and Calcote (1995), and 1800 m, as for samples from small lakes in Denmark (Nielsen, 2003). For moss polster samples in the forest-tundra ecotone in west-central Sweden, the RSAP is 500 m (von Stedingk *et al.*, 2008) and for moss polster and lake sediment surface samples from open and semi-open landscapes in southern Sweden the RSAP is 200-1000 m (Broström, 2002). According to model simulations, the vegetation structure influences the radius of the RSAP so that landscapes with large patches of different vegetation types have larger RSAP than landscapes with smaller patch size (Broström, 2002). The amount of pollen coming from beyond the RSAP can be over 50-60% of the total pollen in a sample (Sugita, 1994; Calcote, 1995).

When performing studies of Holocene vegetation and climate, the number of possible sampling sites is often rather large. Therefore, sampling sites suitable for specific research questions can usually be selected. For example, cores from the forest-line ecotone can be used to interpret past forest-line changes, cores from small lakes and hollows can be used to clarify local vegetation changes, and cores from large lakes can be used to interpret regional vegetation changes. Selection of interstadial key sites is commonly based on the time interval and temporal resolution represented in cores or sections, since interstadial sequences are relatively few, especially within formerly glaciated areas. Therefore, in order to increase the accuracy in the interpretation of received pollen records, the environmental conditions during sedimentation has to be estimated (e.g. Kolstrup and Wijmstra, 1977; Behre, 1989; Lagerbäck and Robertsson, 1988; Helmens *et al.*, 2000, 2007a).

The thesis – background and objectives

The present thesis is based on studies of Weichselian and Early Holocene sediments, and on monitoring of modern pollen deposition. When this project first started the main objective was to increase the present knowledge of the Weichselian ice free intervals in northern Sweden. The purpose was to carry out detailed analysis of Weichselian stratigraphies in previously retrieved cores. However, it was also suggested that data on early Holocene and modern pollen deposition at the core sites could be useful as reference material for interpretation of the fossil sequences (Robertsson pers. comm.).

The topography has been approximately the same at the north Swedish Weichselian sites, since deposition of the sediments. This is due to the cold based nature of the ice sheets covering the sites after the Weichselian sediments were deposited. Initially, the depressions were probably occupied by lakes (as recorded by diatoms in the Riipiharju I core; Lagerbäck and Robertsson, 1988). Later the basins were infilled by sediments, totally or partly, and mire vegetation started to grow.

Pollen monitoring can show if present day pollen deposition at selected sites within the same vegetation zone is largely influenced by local factors such as vegetation patchiness around the sites. If so, it could be expected that Weichselian pollen spectra from the same sites also would differ significantly, since the morphology of the landscapes then was largely the same as today, with lakes or mires in the lower lying surfaces and possibilities for tree growth on the elevated drier surfaces. The local landscape would probably influence the pollen deposition at the sites mostly during periods of tree growth since the RSAP would then be smaller and the local patchiness of vegetation would have a larger impact on the deposited pollen assemblages. During treeless phases of the Weichselian, when the vegetation probably was steppe-like, the RSAP would increase around the sites and local differences in vegetation pattern would likely be of less importance for the recorded pollen spectra. Instead, long-distance transported pollen would have

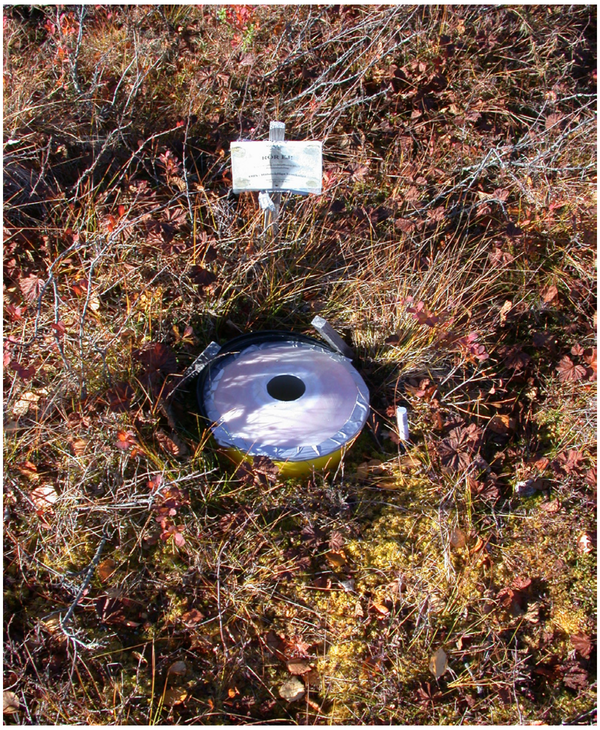

Figure 4. Pollen trap of modified Tauber type, used in the pollen monitoring study.

a larger impact on the pollen percentages, since the local pollen production is lower when trees are absent in the surrounding vegetation.

Pollen monitoring started at five sites from which the most complete Weichselian stratigraphies in northern Sweden had earlier been retrieved (Lagerbäck and Robertsson, 1988; Lagerbäck and Robertsson, pers. comm.). The monitoring was performed by using pollen traps (Fig. 4). Robert Lagerbäck joined in field work in 1996, placing the first traps at sites where he had earlier performed corings. To retrieve reference data also from sites with colder present day climate, possibly resembling the climate during Weichselian ice free phases, two more sites were added to the monitoring project the following years. Since topography probably plays a large role in pollen dispersal in mountain regions, one aim was to find additional reference sites in an area with as low relief as possible, to more resemble the topography at the sites from which the Weichselian sediments were earlier retrieved. The selected new reference sites were located northwest of Övre Soppero in northernmost Sweden, just above and below the present forest-line of birch. In this way the pollen deposition close to the birch forest-line could be investigated and compared to the interstadial pollen spectra with high percentages of birch pollen (described by Lagerbäck and Robertsson, 1988). The monitoring project ran between 1996 and 2004 and became a large part of the thesis work. Within the project a comparison between samples from pollen traps, lake surface sediments and moss polsters was also performed.

The present thesis is based on four papers and the order of the papers is selected to present the results in a logical order. In Paper I the longest record of Weichselian ice-free intervals in northern Sweden is presented. The record is retrieved from a kettle hole in the Riipiharju esker, which formed during the first major Weichselian ice sheet expansion in northern Sweden. In Paper II, a Weichselian interstadial sequence, retrieved from a Veiki moraine at Rissejauratj, is described. Possible correlations between the sedimentary sequence at Rissejauratj and the long Weichselian stratigraphy at Riipiharju are discussed. The two Weichselian ice free phases recorded in northern Sweden are in these papers given the local names Tärendö I (for the first Weichselian interstadial) and Tärendö II (for the second Weichselian ice free interval). The results from the pollen monitoring in northern Sweden are used as reference data in Papers I and II. The monitoring of the north Swedish pollen traps is described in detail in Paper III. In Paper IV the north Swedish pollen monitoring dataset is compared to monitoring data from Iceland, Svalbard, Norway and Finland and aspects of pollen deposition at the north-western fringe of the European boreal forest are discussed. The main aims of the pollen monitoring papers are 1/ to provide a useful reference data set for studies of fossil sequences from sites within the boreal/alpine-arctic ecotone, and 2/ to investigate mechanisms of pollen production, dispersal and deposition, both at the north-western fringe of the European boreal forest and in northern Sweden. Increased understanding of parameters influencing pollen deposition is important for the development of pollen analysis as a tool for reconstruction of past vegetation and climate.

Methods

Fossil pollen samples

The fossil pollen samples presented in Paper I and II were retrieved by Robert Lagerbäck at the Geological Survey of Sweden, using a Cobra vibration corer during winter time. The coring was performed in 1989 at Rissejauratj, in 1991 at Riipiharju II and in 1992 at Riipiharju III. Robert Lagerbäck was responsible for description of the lithostratigraphy and subsampling and Ann-Marie Robertsson for the laboratory treatment of the fossil samples. The core diameter is 33 mm. The samples were prepared for pollen analysis by concentrating the amount of pollen grains through chemical treatment. For the Holocene gyttja samples at Riipiharju the standard acetolysis method of Berglund and Ralska-Jasiewizcowa (1986) was used. Since the other samples generally had high minerogenic content and often showed low pollen frequencies they were prepared for pollen analysis according to the sedimentation-separation method described by Påsse (1976). The pollen samples were mounted on slides using glycerine as mounting medium. Pollen grains were analysed under a light microscope with a magnification of 400-1000x. In each sample, 200-600 pollen grains were counted. The Riipiharju II and III cores were analysed by Ann-Marie Robertsson and the Rissejauratj core was analysed by Martina Hättestrand. For identification of pollen grains the keys of Fægri and Iversen (1989) and Moore *et al.* (1991) were used together with the modern pollen reference collection at Stockholm University.

Modern pollen spectra

Modern pollen samples were retrieved mainly by using pollen traps (Fig. 4), but also by collecting moss polsters at Riipiharju and Rissejauratj and lake surface sediments at Rissejauratj. Tauber pollen traps (Tauber, 1967, 1974; Hicks and Hyvärinen, 1986; Hicks *et al.*, 1996, 1999) were placed at seven sites in northern Sweden, from the boreal forest to above the forest-line of birch. At each site two traps were monitored. The pollen traps consist of 10 litre buckets with a lid that is slightly higher in the middle, where there is a circular hole, and sloping towards the sides. The first traps were placed in 1996 and they were collected and replaced each year until 2004. The traps were collected in September-October after the main pollen deposition season, but before too much snow accumulated in the area. The trap samples are named after the year of collection. Chemicals of glycerine (3 dl), formaline (10-20 ml) and thymol (c. 2g) were put in the traps at each replacement, to prevent drying out, moulding of animals fallen into the traps and growth of fungus in the trap content. A known amount of *Lycopodium clavatum* spores (Stockmarr, 1971, 1973), 3-6 tablets depending on site, was added to the collected traps so that the amount of deposited pollen in the trap volume could be calculated. In the laboratory, the trap content was first sieved through a kitchen sieve to remove all large macro objects, such as frogs and small rodents. The macro objects were rinsed with distilled water so that pollen from their surface would return into the traps. The trap content was thereafter sieved through a 0.25 mm mesh and filtered through a filter paper using a suction funnel, so that excess water was removed. The filter papers were dissolved by acetolysis and samples with high minerogenic content were treated with hydrofluoric acid (HF). The sampling and laboratory procedures of the pollen monitoring follow the guidelines of the Pollen Monitoring Programme (Hicks *et al.*, 1996, 1999), except that a larger opening size of the monitored traps were used (32 cm^2 instead of 19 cm^2). The lake surface sediment samples were treated by standard methods (Fægri and Iversen, 1989). The moss polster samples were boiled in NaOH and sieved through a 0.25 mm mesh before standard preparation was continued (Fægri and Iversen, 1989). The pollen samples were mounted on slides and the pollen analysis was performed in the same way as for the fossil samples.

Numerical analysis

Pollen percentage data: Pollen percentages were calculated on both the fossil and the modern pollen samples. Percentages for the analysed taxa were in each sample calculated on the sum of counted pollen from trees, shrubs, dwarf shrubs and herbs, called the basic sum (Σ P). For example, *Betula* % = Σ counted *Betula*/ (Σ P). Percentages of aquatic plants, spore plants and varia (unidentified) were calculated on the basic sum of pollen (Σ P) and the sum of each individual group (e.g. Σ Spore plants). For example, *Equisetum* % = Σ *Equisetum* / (Σ P) + Σ Spore plants.

For the fossil pollen samples only percentages were calculated since no precise dates were available to allow calculations of PARs. Pollen percentages were also calculated on the modern pollen samples (retrieved from pollen traps, lake surface sediments and moss polsters) to allow comparison between modern and fossil spectra. For the pollen traps the percentages were calculated on the pollen counts in each individual trap, and percentages were also calculated for traps with broken lids (usually broken through cracking). Pollen percentage diagrams were plotted using Tilia, Tilia graph and TGView (Grimm, 1991, 2004) and Adobe Illustrator CS2.

PAR data: PARs (grains cm^{-2} $year^{-1}$) were calculated from the pollen monitoring data. Traps with broken lids were excluded. The pollen deposition in the traps was obtained with yearly resolution and the PARs could be calculated through the relation of counted pollen to counted spores of *Lycopodium clavatum* in the analysed slides since the total amount of added spores to the total trap volume is known as well as the size of the trap opening. For example PARs of *Betula* are calculated through:

$$\frac{(\textit{counted}\ \text{Betula}/\textit{counted}\ \text{Lyc. clavatum})\ \textit{x}\ (\textit{added}\ \text{Lyc. clavatum})}{(\textit{size opening of the traps in cm}^2)} \qquad (1)$$

The PAR diagrams were constructed by using Microsoft Excel and Adobe Illustrator.

Ordination analysis: Ordination analysis was used to compare and illustrate differences between pollen samples and to identify major trends in pollen data. Principle component analysis (PCA) was applied in all papers. Principle component analysis is a linear ordination type that was chosen when the gradient length was shorter than 2.5 SD. According to ter Braak (1987) gradient lengths shorter than 2.5 SD indicate that most response surfaces in the data are linear. The gradient length of the datasets was checked by running detrended correspondence analysis (DCA). In Paper IV also a redundancy analysis (RDA) with Monte Carlo permutation test was performed. RDA is a constrained form of PCA in which pollen and environmental data are analysed together. The ordinations were performed in Canoco for Windows 4.5 (ter Braak and Smilauer, 2002) and they were drawn by using Canoco and Adobe Illustrator. The significance of the ordination axis in the PCAs were checked by using Psimpoll 4.25 (Bennett, 2005), which performs exeeding values generated by a broken-stick model of the distribution of variance amongst the included components (Legendre & Legendre, 1983; Jackson, 1993).

Regression analysis: Linear regression was performed on the pollen monitoring data set to compare the relation between PARs of *Betula*, *Pinus* and *Picea* and mean July temperatures the year prior to pollen release. An r^2 value is a measure of the strength of the correlation, describing how well the regression line fits to the individual values of the analysis. The r^2 value varies between 1 and 0 where 1 describes the perfect fit when all values are on the regression line and 0 corresponds to the case with no correlation between the variables. The regression analysis was performed by using Microsoft Excel and the diagrams were drawn by using Microsoft Excel and Adobe Illustrator.

Site description

The study area is located in northernmost Sweden from c. 30 km south of Jokkmokk in the south to about 50 km northwest of Övre Soppero in the north (Fig. 5). The recorded mean temperatures in the area during the period 1961-1990 were for July between +10 and +15°C and for January between -12° and -16° C (Raab & Vedin, 1995). The vegetational zones span from middle boreal forest in the south-southeast through northern boreal forest and birch woodland to areas above the forest-line in the north-northwest. The location of all studied sites is shown in Table 1 and Figure 5 and photos of the sites (aerial and field photos) together with short site descriptions are presented in Figure 6.

All sites except Keukiskero and Pulsujärvi are situated in a region of northeastern Sweden where major landscape features from a glaciation, interpreted to be of Early Weichselian age, has been preserved (Hirvas *et al.*, 1988). These pre-Late Weichselian landforms include large drumlins, eskers and lateral meltwater channels (Hättestrand, 1998). The orientation of the ice-flow parallel landforms is generally northwest-southeast and the crag-and-tail drumlins show that the ice flow was from the northwest (Fig. 7). The landscape features has been preserved during later glaciations because the ice sheets were largely cold-based in this area during subsequent Weichselian glacial ice cover (Lagerbäck and Robertsson, 1988; Hättestrand, 1998).

Rissejauratj, the southernmost site, is situated in a landscape dominated by large northwest-southeast

Table 1. Investigated sites

Trap site	Lat.; Long	m.a.s.l.	Interstadial stratigraphy	Pollen monitoring	Modern vegetation zone
1. Rissejauratj	66.333 ˚N; 19.600 ˚E	495	X	X	Boreal forest
2. Rotheden	66.483 ˚N; 22.267 ˚E	100		X	Boreal forest
3. Lehtojärvi	67.517 ˚N; 22.617 ˚E	245		X	Boreal forest
4. Särkivuoma	67.517 ˚N; 22.583 ˚E	240		X	Boreal forest
5. Riipiharju	67.583 ˚N; 22.817 ˚E	275	X	X	Boreal forest
6. Keukiskero	68.267 ˚N; 21.533 ˚E	430		X	Birch woodland
7. Pulsujärvi	68.467 ˚N; 21.083 ˚E	590		X	Above the forest limit

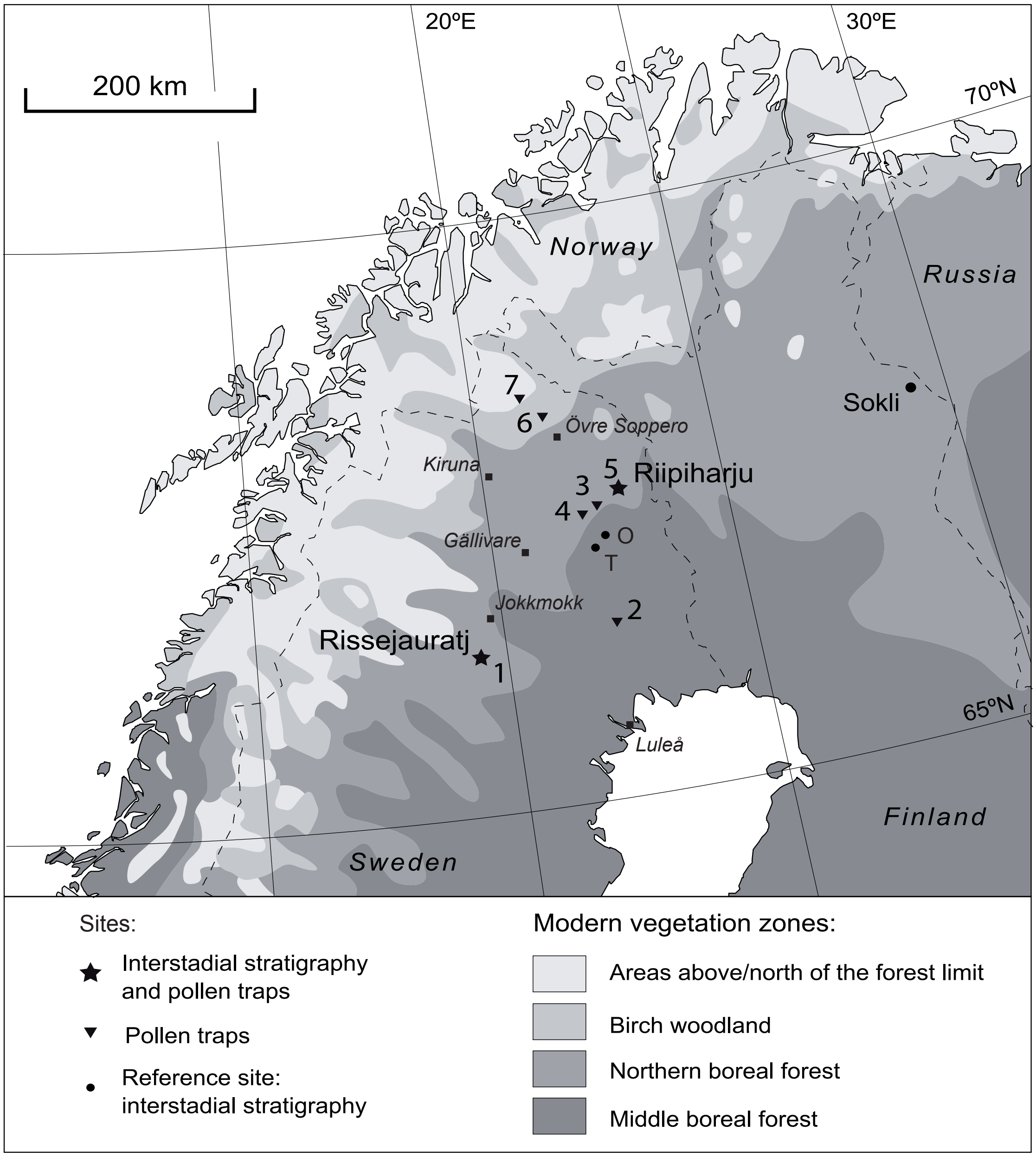

Figure 5. Location map, including the investigated sites 1- Rissejauratj, 2- Rotheden, 3- Lehtojärvi, 4- Särkivuoma, 5- Riipiharju, 6- Keukiskero and 7- Pulsujärvi. Interstadial reference sites discussed in the text are O- Onttovaara, T- Takanenmännikkö and Sokli.

oriented drumlins and Veiki moraine which is a hummocky moraine characterised by moraine plateaus and dead-ice basins. The general elevation in the area ranges between 350 and 700 m a.s.l. The Rissejauratj core is retrieved from a Veiki moraine area, today characterized by mires and small lakes, at about 495 m a.s.l.. The core was taken from one of the lakes and the pollen traps were placed on the mire surface.

Riipiharju, at c. 275 m a.s.l. is situated in a landscape characterised by a low undulating relief with scattered hills. The general elevation is 150-450 m a.s.l. and the glacial landscape is dominated by large rock-cored drumlins (1-5 km long), eskers and melt-water features indicating ice flow from the north-west (Lagerbäck and Robertsson, 1988; Hättestrand 1998). The presented Riipiharju cores (Riipiharju II and III) are retrieved from two kettle holes in the pre-Late Weichselian Riipiharju esker. At the Riipiharju II site the pollen traps were placed at the edge of a mire to avoid spring time ground-water inflow into the traps.

All monitoring sites within the boreal forest zone (Rissejauratj, Rotheden, Lehtojärvi, Särkivuoma and Riipiharju) are surrounded by forests dominated by trees of *Pinus sylvestris*, *Picea abies* and *Betula pubescens* ssp. *tortuosa*/ *Betula pendula*. Shrubs of *Salix* ssp.,

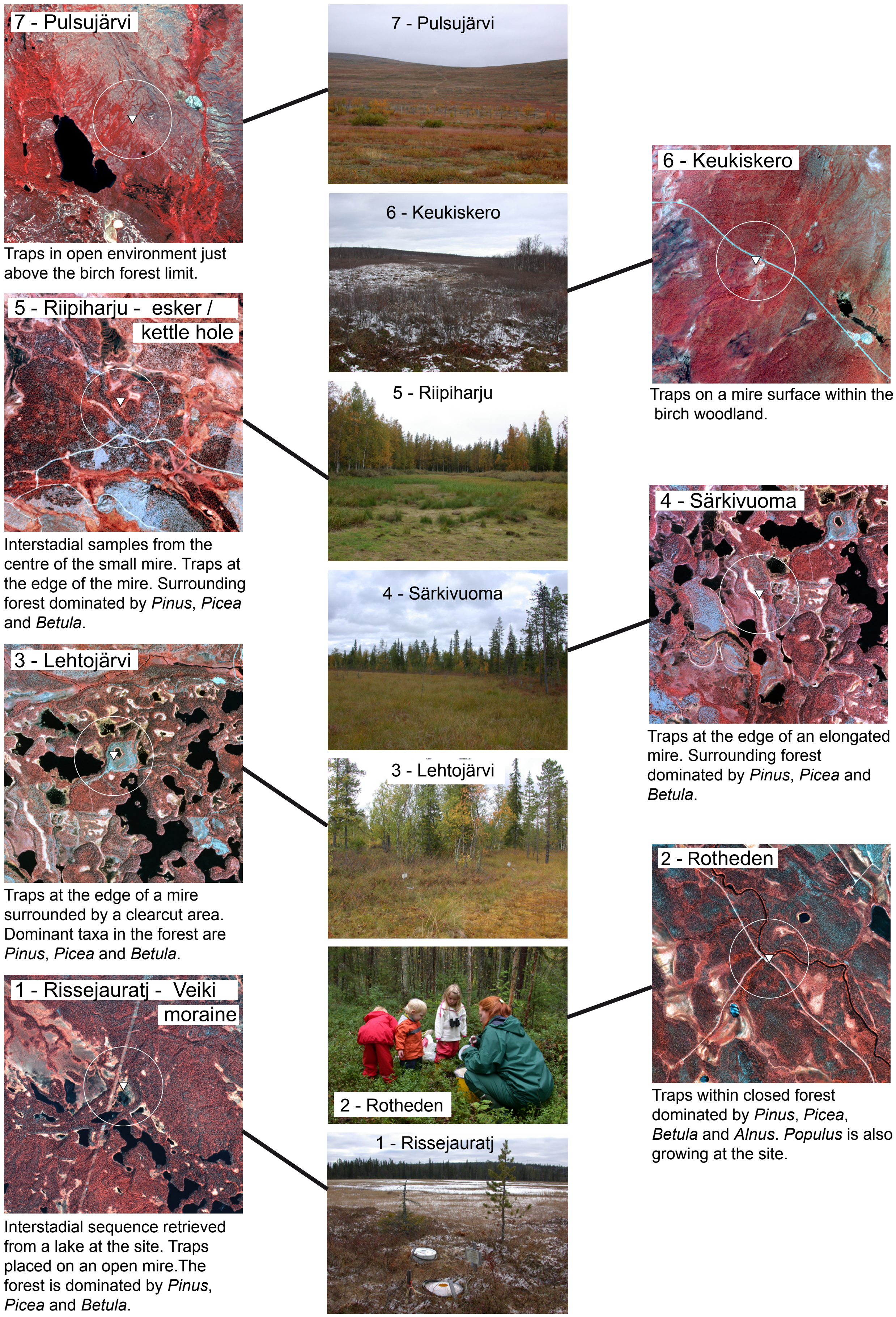

Figure 6. Short description of the studied sites illustrated with field photographs and colour infrared aerial photographs.

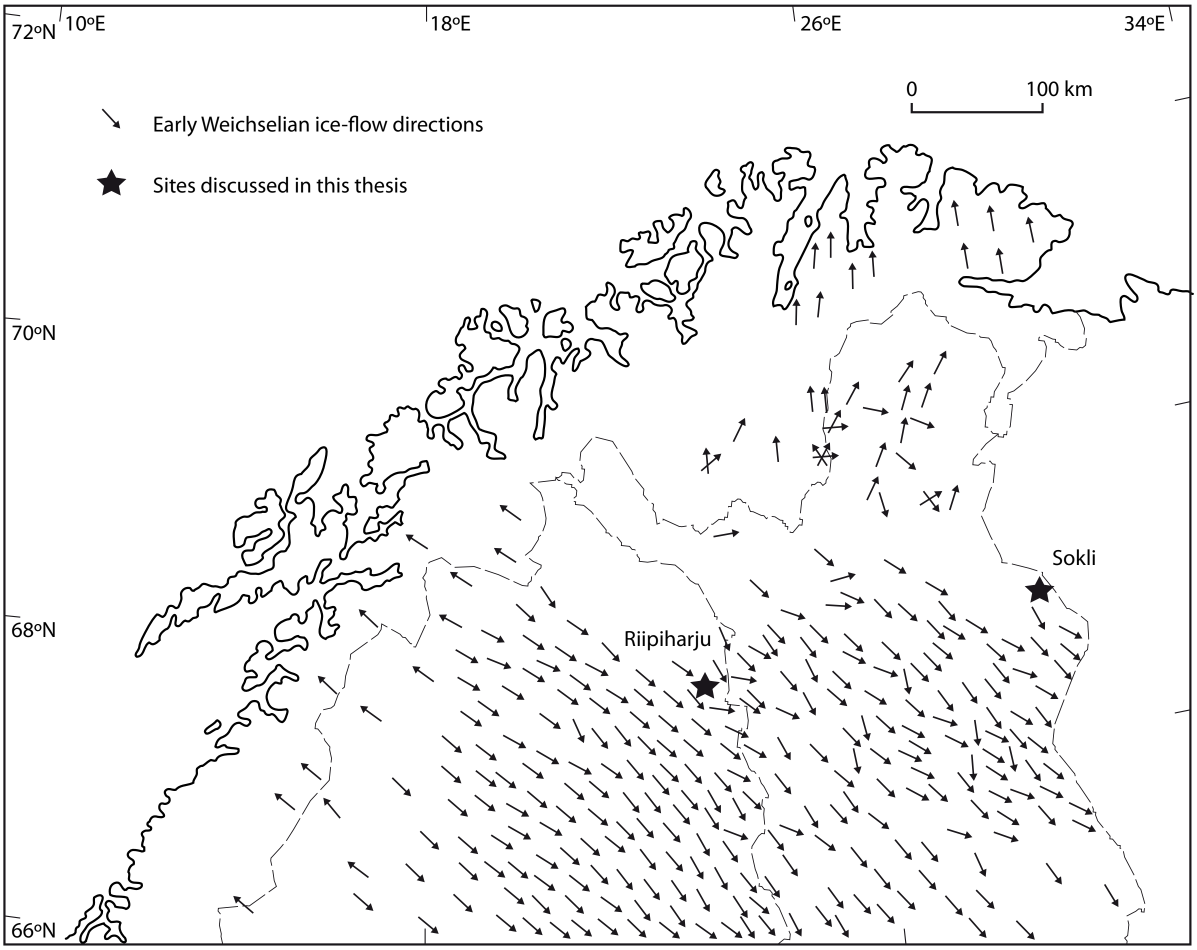

Figure 7. Ice flow directions of the first Weichselian ice sheet in northern Fennoscandia (after Nordkalott Project, 1986) and the location of Riipiharju and Sokli.

Juniperus communis and *Betula nana* and dwarf shrubs of Ericales are growing both in the forests and on the drier parts of the mires. The mire surfaces at the trap sites are commonly dominated by *Rubus chamaemorus*, Cyperaceae and *Sphagnum*. All boreal sites, except Rotheden, were monitored at the edge of mires or on mire surfaces. The Rotheden site is situated within a forest with ground surface vegetation dominated by Ericales. Besides trees of *Betula*, *Pinus* and *Picea*, also trees of *Alnus incana* and *Populus tremula* are growing at the site.

Keukiskero is situated above the forest-line of pine and spruce, within the birch woodland. The site is located on a mire surface covered with small trees and shrubs of *Betula pubescens* ssp. *tortuosa*. *Betula nana*, Ericales, *Rubus chamaemorus*, Cyperaceae and *Sphagnum* are dominating the ground surface vegetation at the site.

Pulsujärvi is located above the forest-line on a mountain slope with about 300 m (horizontally) to the closest trees (birch). The ground surface vegetation at the site is dominated by *Betula nana*, Ericales, Cyperaceae, Gramineae, mosses and lichens.

Presentation of the Papers I-IV

The co-authorship of Papers I and IV

Paper I: This paper was planned in collaboration with Ann-Marie Robertsson. Ann-Marie performed the pollen analysis of the fossil material, wrote some of the text, particularly on description of litho- and pollen stratigraphy, and gave valuable comments on the rest of the text. I did the pollen analysis of the modern spectra, processed all data, constructed the figures and wrote most of the text.

Paper IV: This paper was planned and outlined together with Christin Jensen and Margrét Hallsdóttir. Christine Jensen is responsible for the processing of the ordinations and the interpretations of the ordinated data. Margrét Hallsdóttir did most of the writing on the part with the long distance transported pollen. Karl-Dag Vorren provided pollen trap data and useful comments to the manuscript. I coordinated the writing of this paper, did the final data handling and constructed the figures for all parts except for the ordinations and wrote most of the text.

Paper I

Hättestrand, M., Robertsson A-M.: Weichselian ice free intervals at Riipiharju, northern Sweden - interpretations of vegetation and climate from fossil and modern pollen records. *Boreas*, submitted.

Two new pollen records from kettle holes in the northwest/southeast oriented pre-Late Weichselian Riipiharju esker are presented in this paper. In earlier studies the Riipiharju I core, retrieved from the same esker, was analysed. In the Riipiharju I core two Weichselian interstadials, tentatively correlated to Brörup and Odderade, were identified and discussed. Riipiharju was chosen as type site for the second Weichselian interstadial in northern Sweden (Lagerbäck and Robertsson, 1988). The cores presented in this paper, Riipiharju II and III, give new information about the Weichselian glacial period in northern Sweden. Riipiharju II comprises two Weichselian ice free intervals, Tärendö I and II, and part of the Holocene. In Riipiharju III, the early part of Tärendö II is recorded. The fossil pollen assemblages from Riipiharju II and III are interpreted through visual inspection of pollen diagrams and comparisons of samples in a PCA ordination. In the ordination also modern pollen samples from Riipiharju and four other sites in northern Sweden are included. The reference sites are situated from the boreal forest to above the present forest-line of birch. For interpretation of fossil pollen spectra, which are *Artemisia* dominant and very different in composition from the modern reference samples from northern Sweden, comparisons are made with interpretations of similar fossil assemblages from Arctic Russia (Andreev *et al.*, 2002, 2003).

The Riipiharju II core comprises 16 m of sediments in total, and reaches esker gravel at the base. The Weichselian part of the sediments (c. 4-16 m depth) consists mainly of silt and sand with organic remains. The stratigraphy covers a probably late and relatively cold part of the first Weichselian interstadial (Tärendö I), and a long sediment sequence of the second Weichselian ice free interval (Tärendö II). The Tärendö I and II sediments are separated by a diamicton. The results of the analysis indicate that the climate during the Tärendö II ice free interval varied more than earlier suggested (Fig. 8). In Lagerbäck and Robertsson (1988) the Tärendö II ice free interval (then named Peräpohjola) was described as one interstadial, however, according to the present results it is discussed if the Tärendö II sequence rather should be described as two interstadials with a stadial

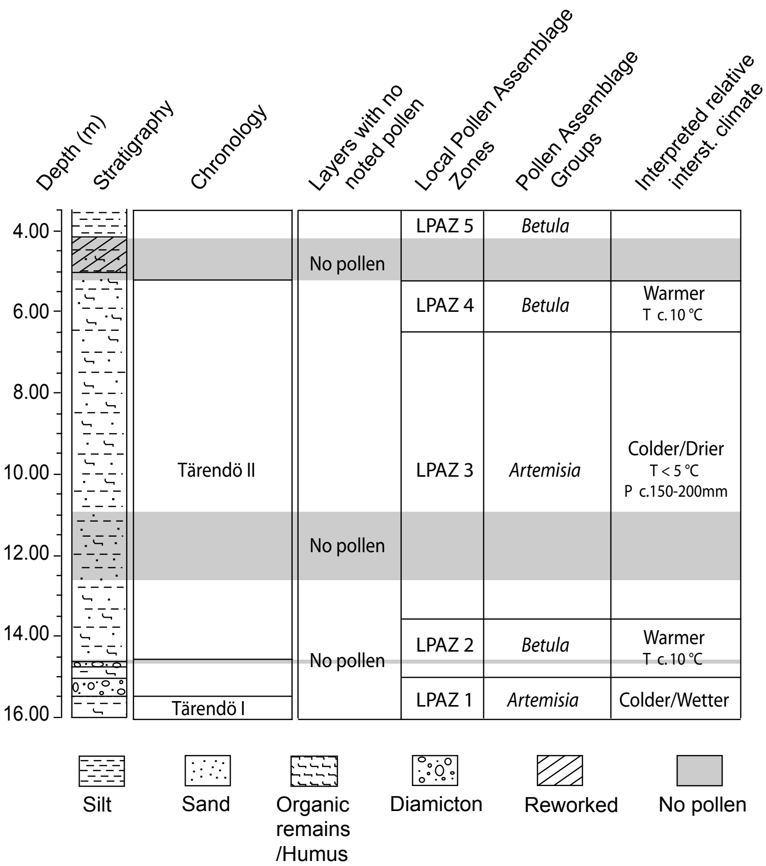

Figure 8. Interpretation of the interstadial stratigraphy of the Riipiharju II core. T = mean July temperature, P = precipitation.

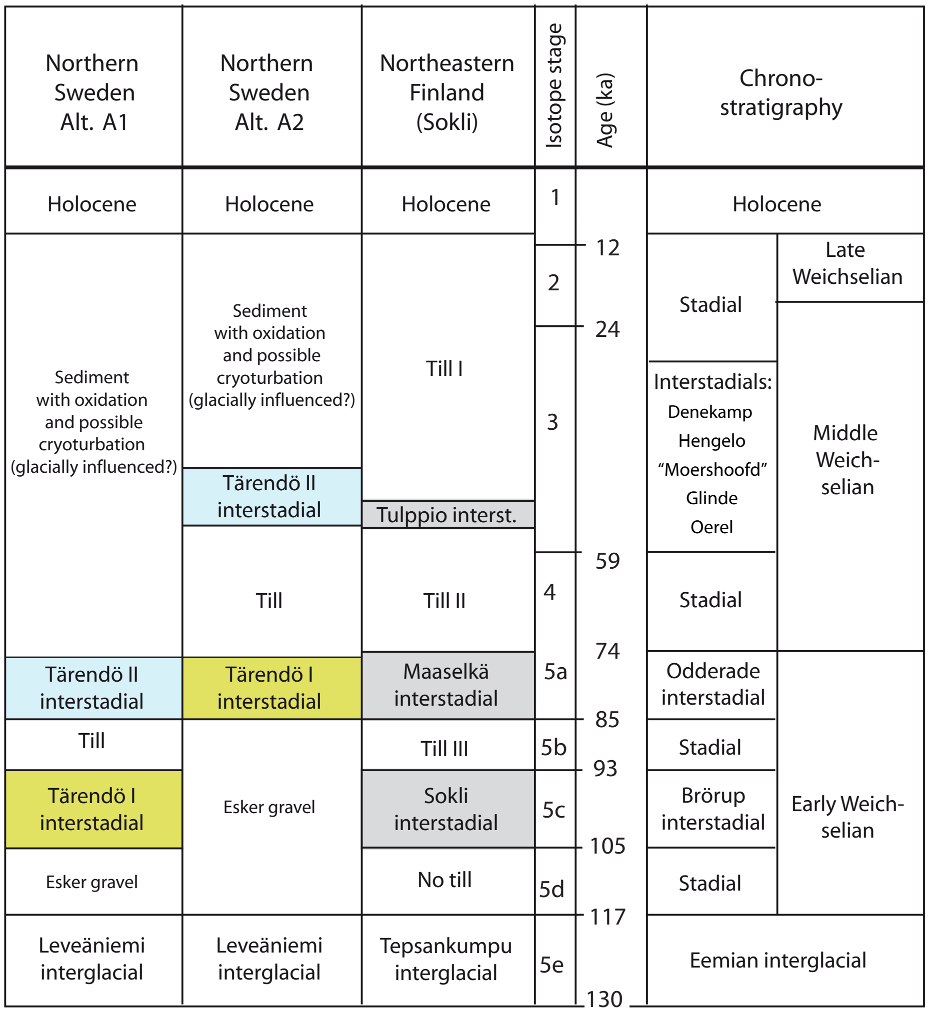

Figure 9. Alternative correlations of the Tärendö I and Tärendö II ice-free Weichselian intervals in northern Sweden. Correlations are made with the Sokli interstadial record in northeastern Finland (Helmens et al., 2000, 2007a, b) and with the Weichselian stratigraphy of northern central Europe (e.g. Caspers and Freund 2001). The time scale follows Mangerud (1991). The esker gravel in the north Swedish stratigraphy is correlated to the Finnish Till III deglaciation (Nordkalott Project 1986).

in between. The *Betula*-dominant pollen spectra in the early part of the recorded Tärendö II interval, indicates rather warm climate with mean July temperatures of c. 10°C. Birch trees probably grew close to Riipiharju at this time and the surrounding vegetation consisted of subarctic birch forests or subarctic shrub tundra. The climate then gradually became colder, which is reflected in the pollen percentages of the Riipiharju III core through a lowering of *Betula* and an increase of *Artemisia*, Gramineae and Cyperaceae. The cold and harsh climate with mean July temperatures of c. < 5°C, reflected through *Artemisia*-dominant pollen spectra indicating arctic steppe vegetation, probably lasted for a relatively long period. However, in the end of the recorded Tärendö II interval the climate once again became as warm as in the beginning of Tärendö II. Dating of the Tärendö I and II sequences have been performed by radiocarbon (^{14}C), Thermoluminescence (TL) and Optical stimulated luminescence (OSL)(Lagerbäck and Robertsson, 1988; Lagerbäck, pers. comm.). The radiocarbon dating of sediments from Weichselian ice free phases are in many cases reversed and have yielded both finite ages, ranging between c. 30 000-45 000 BP and infinite ages for the same sequence (Lagerbäck and Robertsson, 1988). Especially, the dates obtained by the TL and OSL methods are regarded as non-reliable (Lagerbäck, pers. comm.). Based on the radiocarbon dates it is interpreted that the Tärendö I and II sequences are older than 45 000 years, however, it is discussed that ice free conditions could have lasted into younger times. Since there is no firm chronology of the Tärendö I and II ice free intervals at Riipiharju, alternative correlations to Weichselian interstadial records in northern Europe are discussed. Especially important is the comparison with the Sokli record in northern Finland (Helmens *et al.*, 2000, 2007a, b), where three Weichselian interstadials have been identified

(Fig. 9). In the Sokli sediments it is indicated that an open tundra was present during the first Weichselian stadial (MIS 5d) and that the site was not covered by an ice sheet. During the first Weichselian interstadial, correlated to Brörup (MIS 5c), it is likely that pine trees grew in the Sokli area while during the second interstadial correlated to Odderade (MIS 5a), the birch forest-line was probably close to the site. Diamicton separates the interstadials at Sokli. During the third interstadial, correlated to the early part of the Middle Weichselian (MIS 3) it is interpreted that shrub tundra grew in the Sokli area, although pollen percentages of tree birch are rather high (c. 25%). It is discussed that the Sokli site became ice-free during Greenland Interstadial 14, since this probably is the first Middle Weichselian interstadial long and warm enough to allow substantial deglaciation in Fennoscandia (Helmens, 2007a, b).

Two alternative correlations of the Tärendö I and II ice free intervals at Riipiharju are suggested (Fig. 9). Either they are correlated with Brörup (MIS 5c) and Odderade (MIS 5a), or, they are correlated with Odderade and a Middle Weichselian interstadial (MIS 3). The first alternative was considered the most likely by Lagerbäck and Robertsson (1988), because the occurrence of high tree birch values in the Tärendö I and II sequences are seemingly incompatible with the non-forested Middle Weichselian interstadials in northern Germany and the Netherlands (e.g. Behre, 1989; Behre and Van der Plicht, 1992). However, the second alternative is suggested to be likely according to a tentative stratigraphical correlation with the more closely-located Sokli record in northern Finland. Also a Midde Weichelian age of the Tärendö II interval is supported by comparison with climatological records from continental Europe and the Greenland ice cores. In these records Odderade is not interrupted by a cooling event, while the Middle Weichselian (MIS 3) comprises several dramatic climatic shifts. If the Tärendö II sequence correlates to Middle Weichselian time then it is suggested that it Tärendö II correlates to Greenland Interstadials 14 and 12 in the early part of MIS 3.

Paper II

Hättestrand, M., 2007: Weichselian interstadial pollen stratigraphy from a Veiki plateau at Rissejauratj in Norrbotten, northern Sweden. *GFF* 129, 287-294.

In this paper a Weichselian interstadial pollen record from a Veiki moraine plateau at Rissejauratj in north-

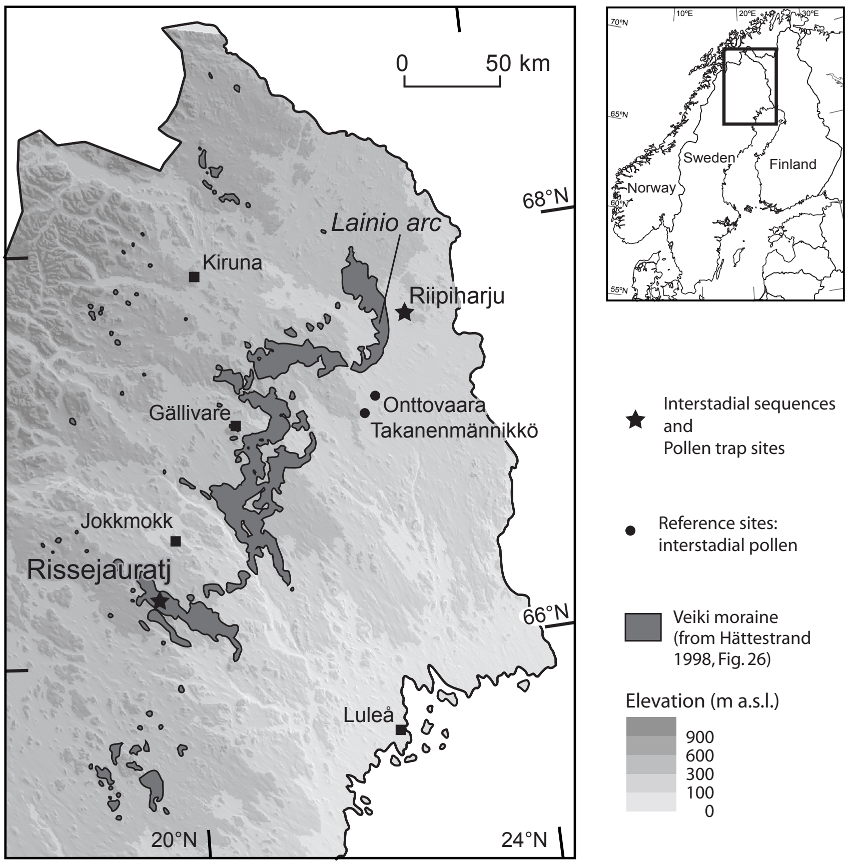

Figure 10. Veiki moraine distribution in northern Sweden (from Hättestrand, 1998) and sites discussed in paper II.

ern Sweden is presented (Fig. 10). Veiki moraine is a type of hummocky moraine suggested to have been formed supraglacially by downwasting of debris-covered stagnant ice. During formation, flow till and lake sediments accumulated within ice-walled lakes. Lamina within the lake sediments indicates that the formation process of the moraines probably continued between 300 and 2000 years (Lagerbäck, 1988). Veiki moraine occurs in an elongated zone in the northern Swedish lowlands (Fig. 10) and the distinct distribution pattern shows the ice margin of a downwasting pre-Late Weichselian ice sheet (Lagerbäck, 1988; Hättestrand, 1998). Radiocarbon dating of sediments from Veiki plateaus has resulted in about half of the dates ranging between 17 000 and 40 000 BP and the other half displaying infinite ages (Lagerbäck, 1988). Because of reversed ages with depth Lagerbäck interpreted the dated organic sediments to be older than 40 000-50 000 years.

The aim of this paper is to study the vegetation and climate during formation of Veiki moraine through pollen analysis of sediments deposited in a lake within a Veiki plateau. The timing of Veiki moraine formation is also discussed based on correlation alternatives of the analysed sediments to Weichselian interstadial records from other sites in northern Sweden (Fig. 11). In a PCA-ordination the Weichselian interstadial pollen assemblages from Rissejauratj are compared to interstadial stratigraphies from the sites Takanenmännikkö, Onttovaara and Riipiharju. They are also compared with Holocene pollen spectra from Rissejauratj and to modern assemblages retrieved by pollen traps at Rissejauratj, Riipiharju and at two sites just below and above the present forest-line of birch in

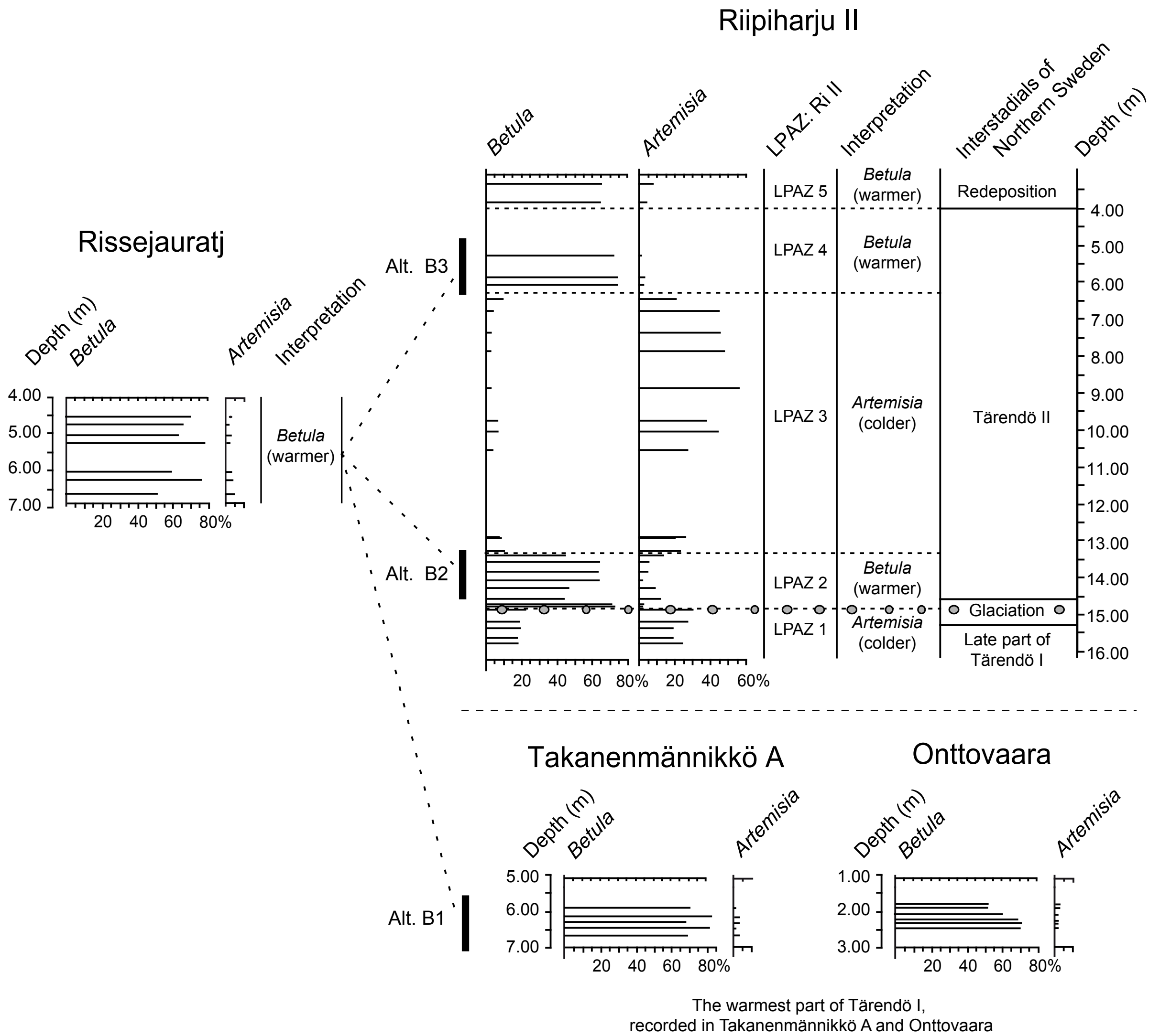

Figure 11. Suggested possible correlations between the interstadial stratigraphy at Rissejauratj and the stratigraphies at Riipiharju (Hättestrand and Robertsson unpublished), Takanenmännikkö and Onttovaara (Lagerbäck and Robertsson 1988). For location, see Figure 10.

northern Sweden. The purpose of including modern pollen samples in the ordination is to compare the interstadial pollen spectra to present day pollen assemblages from sites with known vegetation.

The Rissejauratj core covers 8.35 m of sediments and reaches till at the base. The interstadial sequence (from c. 4 m and downwards) mainly consists of silt with organic content and sand, apart from a 0.7 m layer with disturbed sand and gravel in the upper part of the interstadial stratigraphy. The Weichselian interstadial pollen spectra at Rissejauratj are dominated by *Betula* pollen (Fig. 11) and they represent a relatively warm period, with mean July temperatures of c. 10°C. There are three possible correlations of the Rissejauratj stratigraphy to the stratigraphies of Takanenmännikkö, Onttovaara and Riipiharju (Fig. 11). Either the Rissejauratj interstadial sequence correlates to 1/ the middle part of Tärendö I (recorded at Takanenmännikkö and Onttovaara), 2/ the early warm phase of Tärendö II (recorded in Riipiharju II and III), or, 3/ the late warm phase of Tärendö II (at Riipiharju II). If alternative 3 is correct then the glacial advance preceding the Veiki moraine formation at Rissejauratj is reflected as the cold and harsh climatic period represented during the Tärendö II in the Riipiharju II record.

Paper III

Hättestrand, M.: Eight years of annual pollen monitoring in northern Sweden, from the boreal forest to above the forest-line of birch. Manuscript.

Pollen traps of Tauber type have been used to monitor the annual pollen deposition during 1997-2004 at seven sites in northern Sweden. The main aim is to produce a regional dataset with pollen accumulation rates (PARs) and pollen percentages, which can be used as reference when interpreting fossil pollen records within the boreal-alpine transition. A second aim is to use the dataset for studies of mechanisms of pollen production and deposition of the monitored taxa.

The seven studied pollen monitoring sites are situated from the boreal forest zone to above the present forest-line of birch. Two traps are monitored at each site. A total of 53 pollen taxa are recorded in the traps, of which only 22 taxa are observed in the vegetation surrounding any of the trap sites. Pollen from the remaining 31 taxa are most probably long distance transported. Several of the most common long distance transported herb taxa (*Artemisia*, Chenopodiaceae, *Rumex* and Caryophyllaceae) are also frequent in the Weichselian records of cold and ice free intervals in northern Sweden. It is possible that pollen of these taxa in the Weichselian sequences indicate extremely low local pollen production rather than presence of plants of the taxa in the vegetation surrounding the investigated sites.

The trees *Pinus*, *Picea* and *Betula* are large pollen producers with high PARs at all sites, also at sites where these trees do not grow. For all other taxa, pollen accumulation rates (PARs) higher than 50 grains cm^{-2} year^{-1} are only recorded when the taxa are growing within 100 m of the trap sites. Traps from just below and above the forest-line of birch can be distinguished from each other and from traps within the boreal forest zone both in the PAR and percentage records. A principle component analysis (PCA) was performed to identify the major trends within the PAR dataset. *Pinus*, *Picea*, *Betula*, *Alnus* and *Juniperus* have high representation within the boreal forest zone while *Trientalis europaea*, Asteraceae, Ericales and *Linnaea borealis* have high representation in the samples from above the forest-line of birch. Mean PARs, based on all recorded traps, were calculated for each of the seven monitoring sites. At sites above the forest-line of pine and spruce, mean PARs are c. 140-620 for *Pinus* and c. 15-65 for *Picea*. For sites within the boreal forest zone mean PARs of *Pinus* and *Picea* are c. 2800-5100 and 400-720 respectively. Just above the forest-line of birch mean *Betula* PARs are c. 980, while at the site within the birch woodland zone the PARs are c. 2400 and at the monitoring sites within the boreal forest the *Betula* PARs are c. 1100-3100. Linear regression analysis of the relation between *Pinus*, *Picea* and *Betula* PARs and mean July temperatures of the year prior to pollen release is performed. A correlation between *Pinus* and *Picea* PARs and mean July temperatures is found, while no correlation is recorded for PARs of *Betula*. Pollen percentages retrieved from pollen traps at Rissejauratj are similar to assemblages from lake surface sediments retrieved from small lakes/pools next to the pollen traps. Moss polster samples from the mire surface, however, are deviating by having higher *Pinus* percentages, lower *Betula* percentages and a smaller number of totally recorded pollen taxa. This indicates that pollen trap data can be suitable for comparisons with pollen data retrieved from small lakes.

Paper IV

Hättestrand, M., Jensen, C., Hallsdóttir, M., Vorren, K.-D., 2008: Modern pollen accumulation rates at the north-western fringe of the European boreal forest. *Review of Palaeobotany and Palynology* 151, 90-109.

In this paper the pollen monitoring data from northern Sweden is analysed together with PAR data from Iceland, Svalbard, Norway and Finland. One aim is to present a synthesis of pollen monitoring data for a large geographical area in which there are wide gradients in vegetation type, climate and amount of background pollen deposition (cf. *sensu* Sugita, 1994). Another aim is to analyse the monitoring data to reveal general information on pollen production and deposition at the north-western fringe of the European boreal forest. The presented dataset can be used as reference when interpreting fossil pollen sequences from boreal/arctic ecotone situations and when discussing correlation between sites.

The monitored sites in the dataset are situated in highly varying environments; from areas with more than 100 km to the nearest tree stands to areas located within forests. The study is concentrated on selected taxa, indicative of the boreal forest-line ecotone, or of the extra-regional pollen component of Iceland and Svalbard. A very strong east-west gradient is recognized in the PARs of the tree pollen taxa, while for *Salix*, Ericales and Gramineae this gradient is less pronounced. The east-west gradient in the dataset is linked to environmental parameters of continentality and oceanity such as for example the temperature difference between the warmest and the coldest month of the year and to absolute temperature of the warmest sum mer month. When comparing monitored samples in a PCA-ordination it is found that *Betula*, *Pinus*, *Picea*, Alnus, *Juniperus*, *Urtica*, Chenopodiaceae and *Artemisia* have high representation at boreal forest sites while *Calluna*, *Empetrum*, *Rumex acetosa* and Gramineae correlate with oceanic heathland sites. Sites with increased elevation are associated with increased PARs of *Salix*, *Juniperus* and Ericales. Tree pollen PARs are generally low in Iceland and western Fennoscandia, even at sites situated below the forest-line. This is likely a result of low amount of deposited background pollen, climatological effects on pollen production and orographic effects on pollen dispersal at the sites. *Pinus* is the most abundant extra-regional pollen taxon recorded on Iceland and Svalbard, however, the recorded PARs of *Pinus* are in all traps less than 14 grains cm^{-2} year^{-1}. The variations in PARs within the studied vegetation formations illustrate that it is important to understand the mechanisms of pollen production and dispersal when interpreting fossil pollen records. Local monitoring datasets are valuable for interpretation of fossil PARs, but it is shown here that also comparisons between monitoring datasets are important for the understanding of differences in pollen deposition between regions.

Discussion

Hypothesis of the Weichselian glacial history in northern Sweden

Paper I presents the most complete record of Weichselian ice free intervals in northern Sweden yet found, and Paper II discusses the timing of the Veiki moraine formation based on analysis of the sediments deposited when the Veiki moraine was formed. Since there are problems with absolute dating of the Weichselian stratigraphies no chronostratigraphy of the Weichselian ice free intervals exists. Therefore, correlation alternatives are discussed in Paper I and II, both for the Weichselian sequence at Riipiharju and for the stratigraphy sampled within the Veiki moraine at Rissejauratj. Below, the correlation alternatives regarded as the most likely will be discussed and put together in a hypothesis of the Weichselian glacial history in northern Sweden.

Numerical ice sheet models indicate that the first Weichselian cold period (MIS 5d) resulted in a significantly smaller ice expansion in Fennoscandia than the second ice advance during MIS 5b (Holmlund and Fastook, 1995; Näslund *et al.*, 2003). This is in accordance with the studies of the sediments from the Sokli and Hitura sites in northeastern and central Finland respectively, that show that the sites were ice free during the MIS 5d stadial (Helmens *et al.*, 2000, 2007a, b; Salonen *et al.*, 2008).

The first Weichselian ice sheet advance reaching the Sokli area is recorded during MIS 5b, following the Brörup interstadial. Based on the observations above, correlation alternative A2 of the Riipiharju sequence appears more likely than alternative A1 (Fig. 9). Correlation alternative A2 implies that the first large Weichselian ice sheet, reaching Sokli, was the same ice sheet that formed the Riipiharju esker and that had a regional ice flow direction from the northwest (Fig. 7). If this is true the sediments recorded within the Riipiharju esker are younger than MIS 5b. Data on till beds and ice flow directions in northern Fennoscandia (e.g. Nordkalott Project, 1986; Hirvas *et al.*, 1988; Lagerbäck and Robertsson, 1988; Hirvas, 1991; Johansson, 1995) are also supporting correlation alternative A2 (see discussion below). Interpretation of the vegetation during Weichselian ice free phases at Riipiharju and Sokli is shown in Figure 12 together with the suggested correlation alternatives A1 and A2.

In the Tärendö II sequence of the Riipiharju II core a severe cold phase is recorded between periods of warmer climate (Fig. 11). It is reasonable to believe that this period included a Fennoscandian ice sheet advance. The ice sheet did, however, probably not reach the Riipiharju site since there is no evidence of ice coverage in the Tärendö II sequences at Riipiharju. Any such ice sheet should have deglaciated during the upper warm period of the Tärendö II interstadial. Correlation alternative B3 (Fig. 11) is based on both the biostratigraphical record and the landform record. Correlation alternative B3 suggests that the cold period recorded during Tärendö II initiated growth of an ice sheet that later, during downwasting, formed the Veiki moraine landscape in the late phase of Tärendö II.

The correlation alternatives presented above are combined as a hypothesis of the Weichselian glacial history in northern Sweden (Fig. 13), being open for discussion and testing in future investigations. The different steps of the hypothesis are discussed below:

1/ MIS 5c: During the Finnish Sokli and Oulainen interstadials, both correlated to Brörup (MIS 5c), it is interpreted that *Pinus* grew close to the Sokli and Oulainen sites (Donner *et al.*, 1986; Donner, 1988; Helmens *et al.*, 2000, 2007a). In the Sokli record *Pinus* percentages reach about 25% during the Sokli interstadial. In the records of Weichselian ice free intervals in northeastern Sweden no sequences have high *Pinus* pollen percentages and therefore no phases when pine could have grown close to the studied sites are recorded.

2/ MIS 5b: In the Sokli region there is a till unit with fabric indicating ice flow from the northwest,

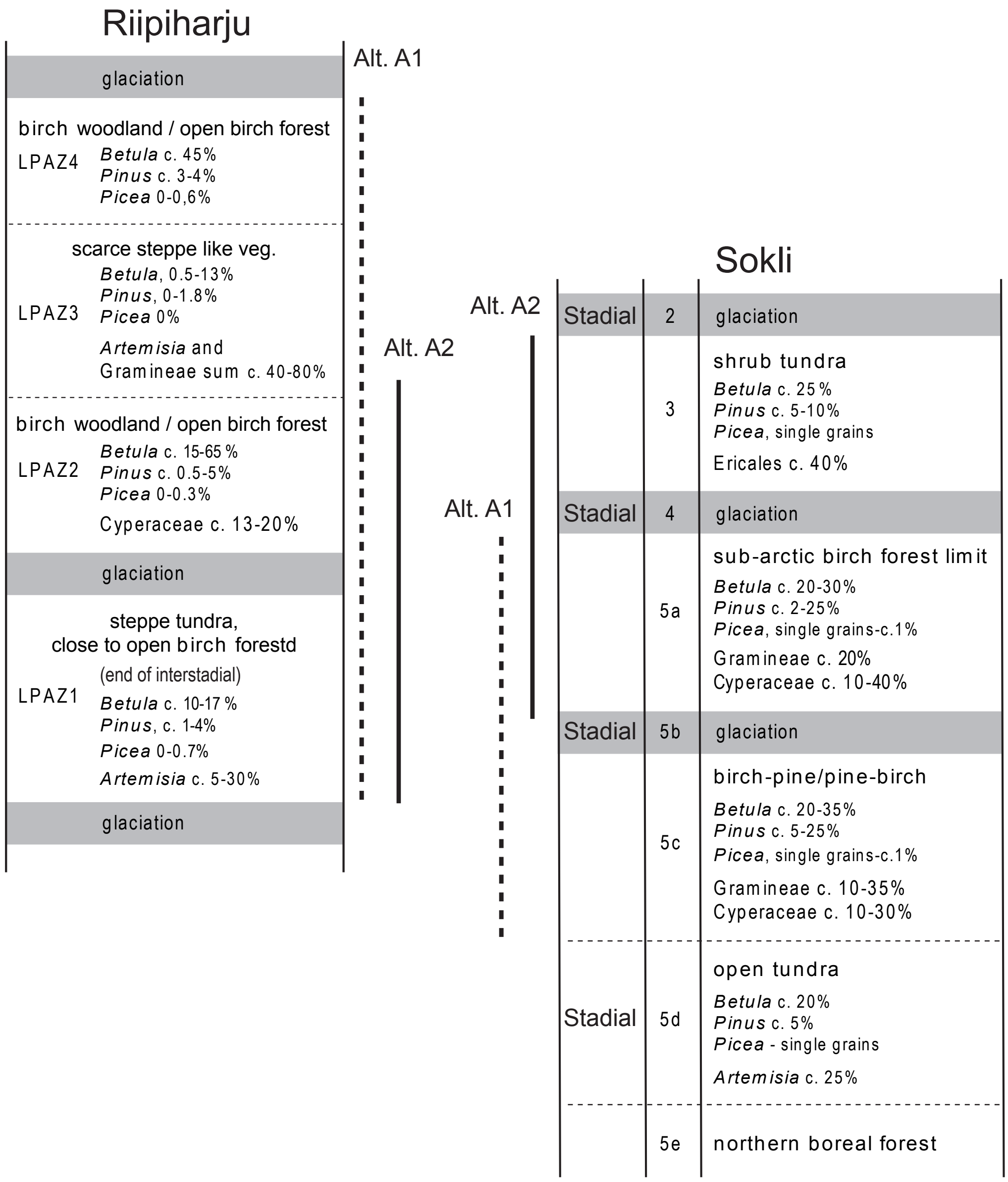

Figure 12. Interpretation of vegetation during Weichselian ice free intervals at Riipiharju and Sokli (Helmens et al., 2007a), and correlation alternatives A1 and A2 of the Riipiharju sequence.

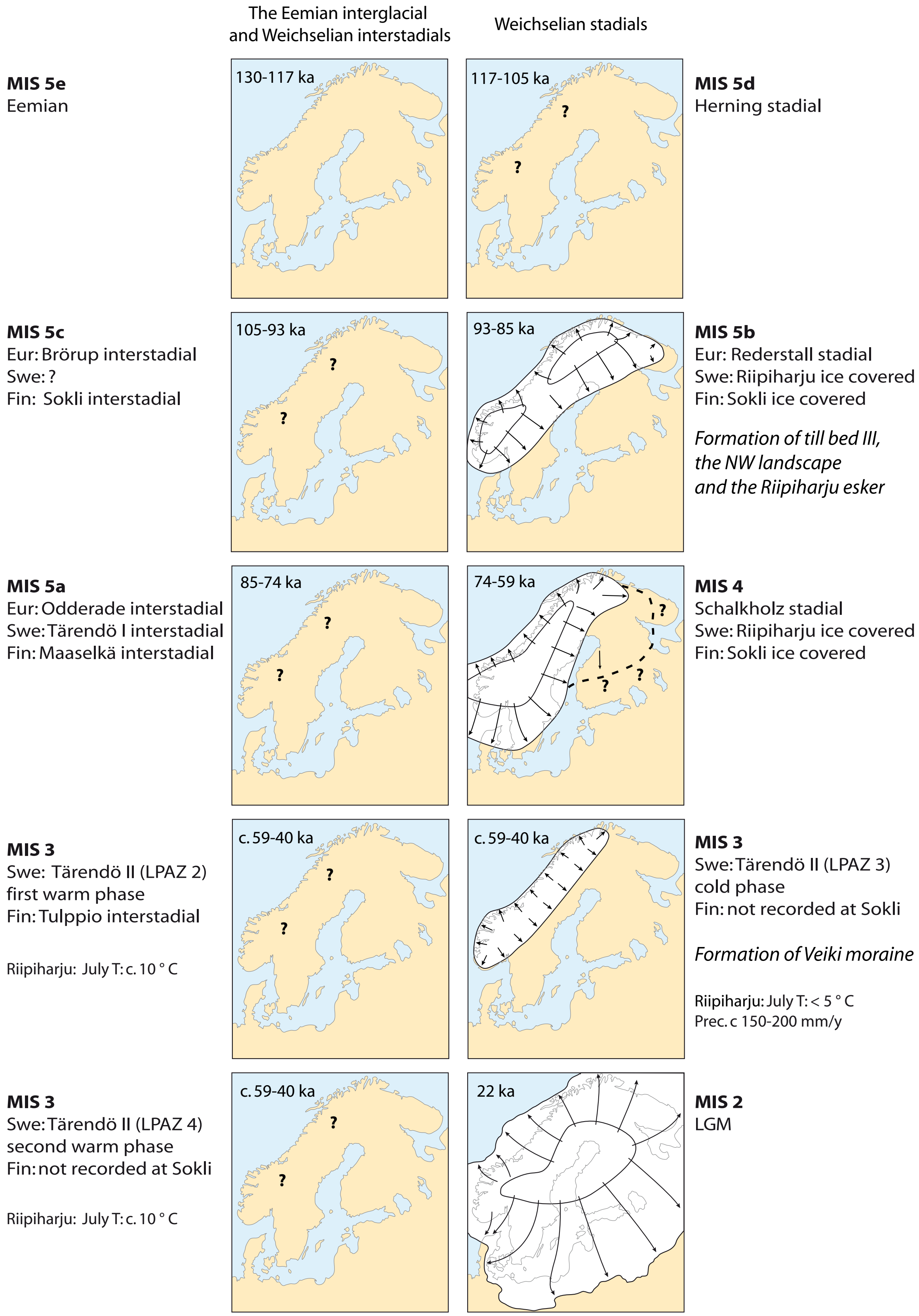

Figure 13. Hypothesis of the Weichselian glacial history in northern Fennoscandia based primarily on results presented in this thesis and comparison with the Sokli record in northern Finland (Helmens et al. 2000, 2007a, b). Ice sheet configuration and flow patterns from Kleman et. al 1997. Hatched ice margin in eastern Fennoscandia during MIS 4 is interpreted from data from recent glacial stratigraphical data from Ostrobothnia in west-central Finland (Salonen et al., 2008). Unknown ice extent in the Scandinavian mountain range during glacial minima is marked by question marks.

the so called "Oldest till unit", which by Johansson (1995) is correlated with till bed III of Hirvas (1991). The fabrics of till bed III are by Hirvas (1991) interpreted as belonging to Flow stage III, which is correlated to the early Weichselian northwest ice-flow direction in the Nordkalott map (Fig. 7; Nordkalott Project, 1986; see also Hirvas *et al.*, 1988), which in turn is interpreted as the ice flow direction that prevailed during the deglaciation when the NW-oriented esker at Riipiharju was formed (Lagerbäck and Robertsson, 1988). According to Helmens *et al.* (2007a, b), the first Weichselian ice sheet expansion reaching Sokli was during MIS 5b. If the Riipiharju esker was formed during MIS 5b the sediments deposited in the kettle holes in the esker must be younger than the stadial following Brörup.

3/ MIS 5a: After the first Weichselian ice cover at Sokli (MIS 5b), a second Weichselian interstadial, the Maaselkä interstadial (MIS 5a – Odderade), is recorded. If the Riipiharju esker was formed during MIS 5b the sediments deposited in the kettle holes in the esker must be younger, and thus the Tärendö I interstadial can be correlated with MIS 5a. In the Tärendö I sediments recorded in northern Sweden (Lagerbäck and Robertsson, 1988) the *Pinus* percentages are low (<5%) while the *Betula* percentages during the more favourable phases reach 40-60%. These high *Betula* values and low *Pinus* values correlate well with the pollen records of the Maaselkä interstadial described at Maaselkä (Hirvas, 1991) and at Sokli (Helmens *et al.*, 2000, 2007a). In the Sokli record the Maaselkä interstadial is correlated to Odderade (MIS 5a). The Peräpohjola interstadial is also characterized by *Betula* dominant pollen spectra and Forsström (1988) suggested a correlation with Odderade based on the recorded composition of the pollen flora. Till beds underlying sediments of the Maaselkä and Peräpohjola interstadials show ice-flow directions from the northwest (Korpela, 1969; Hirvas, 1991).

4/ MIS 4: During the MIS 4 cold stage the Fennoscandian ice sheet advanced and there is evidence of glaciation both at Riipiharju and Sokli after the Tärendö I and Maaselkä interstadials.

5/ MIS 3 (LPAZ 2): During MIS 3 the climatic conditions became warmer again, but also more variable and according to the present hypothesis the Tärendö II sequence at Riipiharju represents a Middle Weichselian ice free interval, deposited during the early part of MIS 3. The Tärendö II sequence at Riipiharju is 8.4 m thick and because the pollen frequency is high enough to allow quantitative pollen analysis, despite generally sparse vegetation, the sediment accumulation rate during this period was probably relatively low. This ice free interval comprises two warm and one cold phase. Compared to the Middle Weichselian stratigraphies from northern Germany and the Netherlands the Tärendö II sequence at Riipiharju is very thick. In comparison, the peat layers representing the Oerel (58-54 ^{14}C ka BP) and Glinde (51-45 ^{14}C ka BP) interstadials at the Oerel site are 0.8 and 0.25 m respectively (Behre *et al.*, 2005). It is possible that the Riipiharju stratigraphy corresponds to several, or at least two, of the interstadials recorded in the Netherlands and northern Germany. The stratigraphy of the third Weichselian interstadial recorded at Sokli (Helmens *et al.*, 2007a, b) is comparatively thin (c. 2 m), and the microfossil assemblages do not record any large climatic shifts. The pollen spectra of the Tulppio interstadial at Sokli are characterized by high *Betula* percentages (20-25%). Based on pollen content they correlate better with the warm phases of Tärendö II at Riipiharju than with the cold phase during the middle of Tärendö II, characterized by *Artemisia*-dominant pollen spectra (Figs. 9, 12). An AMS-^{14}C date of 54±7/4 ka BP (uncalibrated) on the Middle Weichselian sediments at Sokli indicate that the interstadial sediments were deposited in the early part of MIS 3 and Helmens *et al.* (2007a, b) suggest that they were deposited during Greenland Interstadial 14. This indicates that the Middle Weichselian interstadial at Sokli is better correlated to the warm period in the beginning of the Tärendö II ice free interval than the warm period in the end of Tärendö II. Possibly, LPAZ 2 in the Tärendö II sequence was deposited during Greenland Interstadial 14, in line with the argument presented by Helmens *et al.* (2007a, b), that this was the first phase during MIS 3 when climate was warm enough during a long enough time to allow for substantial deglaciation of the Fennoscandian ice sheet.

6/ MIS 3 (LPAZ 3): A period with cold and harsh climate is recorded in the middle of the Tärendö II sequence at Riipiharju. It is likely that glaciers were growing from the Fennoscandian mountain range at this time. The Riipiharju site is situated just east of the Veiki moraine landscape. It is possible that the cooling in the middle of Tärendö II lead to growth of an ice sheet to a limit just west of Riipiharju, and that Veiki moraine was formed during downwasting of the ice sheet when the climate became warmer again in the late part of Tärendö II. The relatively warm period recorded in the Rissejauratj sediments can, based on pollen composition, be correlated to the warm phase in the end of the Tärendö II. However, it can also be correlated to two other Weichselian warm periods (the middle of Tärendö I and the beginning of Tärendö II). At Sokli, no ice free interval with cold and harsh climate is recorded during the Middle Weichselian.

7/ MIS 3 (LPAZ 4): Towards the upper part of the Tärendö II sequence relatively warm climatic conditions, with mean July temperatures of c. 10°C, occur once again. If the warm interval in the beginning of the Tärendö II sequence (LPAZ 2) corresponded to Greenland Interstadial 14 then this second warm period (LPAZ 4) could correspond to Greenland Interstadial 12. If the Tärendö II sequence comprises both interstadials then it includes a sedimentary record of about 9000 years, based on the assumption that about 2000 years of the second relatively warm period (LPAZ 4) in the upper part of Tärendö II is recorded.

According to the time scale in the GISP2 record (Alley *et al.*, 1995), the Greenland Interstadials 14 and 12 started approximately 52 and 46 ka BP, respectively. If the Tärendö II sequence were deposited during this interval (c. 52-44 ka) it correlates well in timing with the Sargejohka interstadial (60-35 ka) recorded in northernmost Norway (Olsen *et al.*, 1996). It would also correlate with the Bø interstadial (about 55-45 ka), recorded at the western coast of Norway (Andersen *et al.*, 1983; Sejrup, 1987).

Future perspectives of studies of Weichselian ice free intervals in northern Sweden

Accurate absolute dating of the recorded Weichselian ice free phases in northern Sweden would be an important step forward in understanding the climatic shifts of the last glaciation in northern Europe. Climatic fluctuations in Fennoscandia are linked to waxing and waning of ice sheets which in turn affect the climatic system through feedback processes. The hypothesis of the Weichselian glacial history presented above may have some wider implications. If the first large Weichselian glaciation in Fennoscandia occurred during MIS 5b, after the Brörup interstadial (MIS 5c), most of northern Sweden was ice free during the Brörup interstadial. It is therefore possible that sediments of Brörup age are preserved somewhere in northern Sweden. However, if the hypothesis is correct, they can not be found within sediments of the Veiki moraine plateaus or within landforms formed by the northwest oriented pre-Late Weichselian ice-flow system, since these landforms are suggested to be younger than Brörup. Rather, these sediments should be searched for in areas lacking glacial imprint altogether, such as the Parkajoki area in northeasternmost Sweden, where Hättestrand and Stroeven (2002) has shown that the landscape still likely display its Mid-Quaternary character. In addition, only one single Weichselian interstadial warm period, defined through pollen spectra dominated by *Betula*, is to be found in the sediments within Veiki moraines in northern Sweden. The period with a gradually cooling (early part of Tärendö II) recorded in Riipiharju III is, according to the hypothesis presented above, a period when the climate shifted and ice sheets again started to grow large in Fennoscandia. The cold period recorded during Tärendö II is correlated with growth of a Fennoscandian ice sheet of intermediate size with its eastern limit reaching just west of Riipiharju. The cold period as well as the following warming, when the ice sheet was downwasting and Veiki moraine formed is, according to the hypothesis, recorded at Riipiharju. The link between Sokli and Riipiharju based on glacial geology and ice flow directions might be considered incomplete. Hence, future work on these parameters in northern Fennoscandia could strengthen the correlation between the two sites. Both Sokli and Riipiharju contain complex Weichselian stratigraphies and since parts of the sequences at both sites are unique, both records need to be considered when interpreting the Weichselian glacial history in northern Fennoscandia.

The use of pollen monitoring data

In the present thesis pollen monitoring records have been used as reference data when interpreting pollen records from north Swedish Weichselian sequences (Paper I and II). Often, interpretation of pollen percentages from fossil records is not a straight forward process, since the relation between pollen percentages and percentage of vegetation coverage is certainly not 1:1. Plants that grow in abundance in the area surrounding a site might have very low representation in the pollen record and the opposite is also common (see for example Paper III). Comparison of past pollen assemblages to modern pollen spectra from sites with known present day vegetation, as in the PCA-analysis in Paper I and II, can be a useful tool for interpretation of past vegetation. The ordination analysis objectively illustrates the similarity and difference between all studied samples and the relation between samples and analysed taxa. The ordination can bring new ideas to the interpretation of fossil data that were not thought of during visual inspection of ordinary pollen diagrams. In the present study the division of the Weichselian pollen samples into a *Betula* and *Artemisia* pollen assemblage group was made after studying the PCA-ordination where the samples were clearly separated into two main groups. This division was later used in the description of the stratigraphy and in the interpretation of past vegetation and climate. The modern pollen samples included in the PCA-ordinations showed that the spectra within the *Betula* pollen assemblage group are fairly similar to present day assemblages from sites close to the forest-line of birch, except that the *Pinus* and *Picea* values are much lower in the Weichselian samples. This indicates that birch woodland or open birch forest grew close to the sites during the studied ice free intervals, but that *Pinus* and *Picea* grew far away. However, when the fossil pollen assemblages differ largely from the modern reference data, as the samples within the *Artemisia* pollen assemblage group do, other references are needed for vegetation interpretation. Therefore, the *Artemisia* dominant pollen spectra are in Paper I compared to similar fossil pollen assemblages from the Levinson-Lessing core from the Taymyr Peninsula in Arctic Russia (Andreev *et al.*, 2002, 2003). The interpretation of the fossil pollen records from the Levinson-Lessing core are based on quantitative reconstructions of temperature and precipitation through comparison with 1110 modern samples collected in the former USSR and Mongolia. The reconstructed values of temperature and precipitation obtained for the *Artemisia* dominant pollen spectra in the Levinson-Lessing core (c. 30-12.5 ka BP) are inferred also for the *Artemisia* dominant pollen assemblages recorded in the Tärendö II sequence in northern Sweden. The comparison of pollen monitoring data from the north-western fringe of the European boreal forest (Paper IV) show that oceanity/continentality is a parameter largely influencing pollen deposition. It is possible that the climate became more continental in northern Sweden during the Weichselian ice free intervals, partly due to a lowering of the sea level, as more global water became bound in terrestrial ice sheets. It is therefore reasonable to believe that the pollen assemblages from the cold ice free intervals recorded at Riipiharju in northern Sweden are comparable to assemblages further east, as in the fossil samples from the Taymyr Peninsula and in the reference data set of Andreev *et al.* (2003).

In Paper III it is indicated that pollen assemblages retrieved from pollen traps on a mire surface resemble spectra from small lakes/pools within the same mire, while nearby samples from moss polsters are deviating through higher *Pinus* percentages and lower *Betula* values. This suggests that modern pollen samples retrieved from pollen traps are suitable to use as reference for pollen samples deposited in lakes (as in Paper I and II), and that using moss polster samples as reference data would have been less appropriate. Pollen monitoring is time consuming, and therefore, lake surface sediment sampling is more time effective for producing a large reference data set for interpretation of fossil pollen percentages retrieved from lakes. The advantage in using pollen traps is that they can be positioned almost everywhere and that the data has a high resolution in both time and space. Also, the received data can be used for additional studies on mechanisms of pollen production and dispersal which, in turn, can increase the possibility for future development of pollen analysis as a tool for reconstruction of past environments. The combination of pollen monitoring and vegetation mapping can further increase the reliability for how fossil pollen records are interpreted, at least if the fossil environments was similar to the present around the monitored sites.

Future perspectives of studies of pollen deposition

In Paper III it is shown that PARs of *Pinus* and *Picea* relate to mean July temperatures of the year prior to pollen deposition. In Autio and Hicks (2004) and Barnekow *et al.* (2007) a relation is recorded also between *Betula* ssp. pollen deposition and mean temperatures of July and July-August, respectively. In future studies it would be interesting to analyse laminated sediments and compare annual PARs of *Pinus*, *Picea* and *Betula* to mean July temperatures at the studied lake sites. Such a study would clarify if PARs from laminated sediments can be used in detailed climatic reconstructions back in time.

Conclusions

- Two Weichselian ice free periods, given the local names Tärendö I and II (earlier described as the Tärendö and Peräpohjola interstadials), are recorded in northern Sweden. The pollen stratigraphy of the younger ice free interval, Tärendö II, show larger climatic fluctuations than earlier recognized in sediments deposited during this time period. The Tärendö II sequence can be interpreted as either one three-parted interstadial, or as two separate interstadials with a stadial in between.
- In the early part of Tärendö II, pollen spectra are dominated by *Betula* pollen, interpreted as representing relatively warm climatic conditions with mean July temperatures of c. 10° C. Thereafter, *Betula* percentages gradually decrease and *Artemisia* and Gramineae become the dominant pollen taxa. This is interpreted as representing a cooling

phase, resulting in climatic conditions with mean July temperatures of c. <5° C. In the upper part of the Tärendö II sequence the pollen spectra are again dominated by *Betula*, which is interpreted as representing a climatic shift back into warmer climate.

- It is likely that the period with cold and harsh climate during the Tärendö II ice free interval represents a period of ice sheet growth in northern Fennoscandia. It is suggested that an ice sheet of intermediate size grew during Tärendö II, and that Veiki moraine was formed during regional downwasting of the marginal zone of this ice sheet, when climate became warmer in the end of Tärendö II. It is also suggested that the eastern limit of this ice sheet is marked by the eastern limit of Veiki moraine distribution, since no signs of glaciation is found in the Tärendö II sediments at Riipiharju, located just outside the eastern margin of the Veiki moraine landscape.
- The Tärendö I and II ice free intervals can be correlated with either Brörup (MIS 5c; c. 105-93 ka BP) and Odderade (MIS 5a; c. 85-74 ka BP), respectively, or 2/ Odderade and early Middle Weichselian time (MIS 3; c. 59-40 ka BP). According to new data presented in this thesis, correlation alternative 2 is considered more likely. This alternative implies that the first major Weichselian ice sheet expansion in northern Fennoscandia occurred after the Brörup interstadial (MIS 5c), i.e. during the Rederstall stadial (MIS 5b; c. 93-85 ka BP).
- Comparison between fossil pollen assemblages and modern spectra from sites with known present day vegetation can give new insights to the interpretation of fossil pollen spectra. Ordination analysis is a suitable method for comparing modern and fossil assemblages statistically, and the method can aid in performing more objective interpretations.
- Pollen monitoring is a good method to produce modern analogue data since both PARs and percentages can be retrieved and since monitoring can be performed almost everywhere. It is indicated that assemblages retrieved from monitoring on mire surfaces are similar to spectra retrieved from lake surface sediments from small lakes/pools on the mire.
- Since PARs can vary largely in different areas within the same vegetation formation, it is useful to have monitoring datasets in different regions as reference data for interpretation of fossil pollen assemblages.

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