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Ice marginal fluctuations during the Weichselian glaciation in Fennoscandia, a literature review

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Summary

This report presents an overview regarding ice marginal fluctuations during the last glacial, the Weichselian. It is focusing on marginal positions in Sweden with surroundings. The results are used to calibrate a computer simulation of the Weichselian ice sheet. The report also contains some information regarding basal conditions beneath the Swedish part of the Weichselian ice sheet. This information will be used to validate the results of the simulation of the Weichselian ice sheet.

The Weichselian glaciation started 115 ka BP (thousands of years before present) and ended at the transition to the Holocene 11.5 ka BP. Terrestrial and marine records show that ice volumes fluctuated drastically during the Weichselian. The marine isotope record shows the global variations in climate and ice volume during the last ice age and has been divided into Marine Isotope Stages (MIS), which are well dated (MIS5d to MIS 2). Dating of terrestrial records is, however, problematic due to stratigraphical gaps and deposits, which are difficult to date. In many areas the timing of local and regional ice marginal fluctuations, prior to the Last Glacial Maximum (LGM), is therefore poorly understood. Age attribution of terrestrial deposits is often interpreted from bio- and litostratigraphical information, which has been correlated to other records, e.g. marine stratigraphies.

The marine record from Early Weichselian (MIS 5d–5a) shows that two relatively warm periods, interstadials (MIS 5c and 5a), prevailed 105–93 ka BP and 85–74 ka BP. After MIS 5a global ice volume increased and remained large throughout Middle Weichselian (74–24 ka BP). During the LGM (c 21 ka BP), before the onset of the deglaciation, the ice volume was at its largest.

Stratigraphical data indicate at least two periods with ice-free conditions in northern Fennoscandia, which have been correlated with the two early Weichselian interstadials Brørup and Odderade (MIS 5c and 5a). Few absolute dates have, however, been obtained from deposits formed during these interstadials. It has been suggested that two ice advances occurred during the Early Weichselian and covered a large part of northern Fennoscandia. There are, however, different opinions regarding the southernmost extension of these ice sheets. It has also been suggested that large parts of northern Fennoscandia were free of ice from the onset of MIS 5c until the end of 5a.

Several researchers suggest that most of Fennoscandia was covered by an ice sheet from Middle Weichselian until the latest deglaciation. Data from Norway suggests, however, that the youngest of the ice-free interstadials, correlated with MIS 5a, actually occurred during the late part of Middle Weichselian. There are indications of several ice marginal fluctuations along the Norwegian coast during Middle Weichselian. Furthermore, several new data suggest ice-free conditions in large parts of Finland during Middle Weichselian. The timing of the ice oscillations during Early and Middle Weichselian is therefore still an open question, which hopefully will be resolved by better dates of the terrestrial material.

The ice advanced south to its maximum extent during the beginning of the Late Weichselian 24–12 ka BP. The ice reached its maximum position at different times in different regions. After the LGM the ice started to retreat across northern Germany and Poland. The timing of the deglaciation is well dated and the ages have recently been converted into calibrated years. Several readvances took place during the deglaciation of the Danish and Norwegian coast. There are several ice marginal zones in south-west Sweden, which indicate stilltands or readvances of the ice front. These zones have been correlated to other ice marginal zones in Fennoscandia.

The deglaciation was interrupted during the Younger Dryas stadial (12.5–11.5 ka BP) and there were ice readvances and standstills in the middle part of Sweden and southern Finland, whereas coastal areas in the west were characterised by large readvances. The ice marginal deposits formed during Younger Dryas can be followed around the entire Fennoscandia. After the Younger Dryas the ice retreated more or less continuously.

Deep weathered bedrock of Pre-Quaternary age occurs in parts of Småland and in the inner parts of northern Sweden. These deposits indicate low erosion during the Quaternary glacials in these regions. In the inner part of Norrbotten there are morphological features, Veiki moraines, which according to several authors were formed during the first Weichselian ice advance (MIS 5d). In Småland there are till covered eskers, which may have been formed prior to the latest glacial advance. Areas with deep weathered bedrock and those with Quaternary deposits older than the last glaciation coincide to a large extent. These areas are indicators of cold based ice and of low glacial erosion.

Sammanfattning

Syftet med denna rapport är att översiktligt sammanställa kunskapsläget om inlandsisens randlägen under den senaste istiden, Weichsel, med fokus på randlägen i och omkring Sverige. Resultaten ska användas för att kalibrera en datorsimulering av Weichselisen. Rapporten innehåller även information som berör bottenförhållandena under Weichselisen i Sverige. Denna information ska användas för att validera resultat från simuleringen av Weichselisen.

Den senaste istiden började 115 000 år BP (före nutid) och slutade vid övergången till Holocen 11 500 år BP. Det finns både marina och terrestra tidsserier, som visar att isvolymerna fluktuerade kraftigt under Weichselistiden. De marina isotopserierna har delats in i olika marina isotopstadier (MIS) som är daterade och visar de globala variationerna av klimat och isvolymer under den senaste istiden (MIS 5d to MIS2). Det är emellertid svårare att datera de terrestra avlagringarna, pga luckor i stratigrafin och svårdaterade sediment. I många områden är det därför svårt att fastställa när fluktuationer av israndlägen, före den senaste istidens största utbredning (Last Glacial Maximum – LGM), har ägt rum. De terrestra avlagringarnas åldrar har ofta fastställts genom att kalibrera resultat från stratigrafiska undersökningar med andra tidsserier, tex marina stratigrafier.

Marina stratigrafier från Tidigweichsel (MIS 5d–5a) visar att det var två relativt varma interstadialer (MIS 5c och 5a) 105 000–93 000 år BP och 85 000–74 000 år BP. Den globala isvolymen ökade efter MIS 5a och var relativt stor under hela Mittweichsel (74 000–24 000 år BP). Isvolymen var som störst under LGM (ca 21 000 år BP) och därefter inleddes deglaciationen.

I norra Fennoskandia finns det belägg för minst två perioder med isfria förhållanden, vilka har korrelerats med två interstadialer, Brørup och Odderade (MIS 5c och 5a) som ägde rum under Tidigweichsel. Det finns få absoluta dateringar av avlagringar från dessa interstadialer. Under Tidigweichsel täcktes norra Fennoskandia, enligt många forskare, vid två tillfällen av isar. Det råder dock olika uppfattning om hur långt söderut dessa två isar nådde. Det har även föreslagits att norra Fennoskandia var isfritt under hela perioden från början av MIS 5c till slutet av 5a.

Många forskare anser att Fennoskandia till största delen var täckt av en inlandsis från Mittweichsel fram till den senaste deglaciationen. Resultat från Norge indikerar dock att den yngsta av de isfria interstadialerna, korrelerad med MIS 5a, egentligen ägde rum under den senare delen av Mittweichsel. Det finns indikationer på att isfronten oscillerat kraftigt längst den norska kusten under Mittweichsel. Det finns dessutom flera nya resultat som tyder på att isfria förhållanden rått i stora delar av Finland under Mittweichsel. Tidpunkterna för isoscillationerna under Tidig- och Mittweichsel, är en öppen fråga. Förhoppningsvis kommer bättre dateringar av det terrestra materialet att kunna lösa denna fråga.

Under början av Senweichsel (24 000–12 000 år BP) avancerade isen söderut och nådde sin maximala utbredning. Isen nådde sin maximala utbredning vid olika tidpunkter i olika regioner. Efter LGM drog sig isen tillbaka genom de norra delarna av Polen och Tyskland. Isens tillbakadragande genom Sverige är väl daterad och åldrarna har nyligen konverterats till kalibrerade år. Isen ryckte fram vid flera tillfällen under deglaciationen av Danmark och Norges kust. Det finns flera israndlägen i Sydvästsverige vilka indikerar att isen tidvis stått still eller ryckt fram. Dessa zoner har korrelerats med andra israndlägen i Fennoskandia.

Deglaciationen avbröts under Yngre Dryas stadialen (12 500–11 500 år BP) och i Mellansverige och Sydfinland stod isen still eller ryckte fram. De avlagringar som avsattes längst iskanten under Yngre Dryas kan följas runt hela Fennoskandia. Efter Yngre Dryas retirerade isen mer eller mindre kontinuerligt.

Djupvittrad Pre-kvartär berggrund förekommer främst i delar av Småland och i de inre delarna av norra Sverige. Dessa avlagringar antyder att erosionen under de kvartära nedisningarna varit liten i dessa områden. I de inre delarna av Norrbotten finns geomorfologiska företeelser, Veikimoräner, som många forskare anser har bildats under den första isframstöten under Weichsel (under MIS 5d). I Småland finns moräntäckta åsar som kan ha avsatts innan den senaste isframstöten. Områden med djupvittrat berg sammanfaller i stor utsträckning med områden där det finns kvartära avlagringar som är äldre än den senaste nedisningen.

Contents

1 Background and objectives

The deep geological repository for spent nuclear fuel planned by SKB (Swedish Nuclear Fuel and Waste Management Company) shall keep radiotoxic material separated from man and environment for hundreds of thousands years. Within this time perspective the development of ice sheets could alter both the surface and subsurface environment. The repository must thus be designed so that its safety functions can be preserved given these alterations. Some important questions for repository performance are: the maximum hydrostatic pressure, the penetration of glacial melt water to large depth, the maximum permafrost depth, the salinity of the ground water, high groundwater fluxes and alteration of rock stresses.

This study is a subproject of a SKB financed research project called "Basal conditions and hydrology of continental ice sheets". The overall aim of the main project is to give a detailed spatial and temporal view of the hydrological system beneath ice sheets. The project is divided into three subprojects;

1. Glacial geological information and literature reviews.
2. Numerical ice sheet modelling.
3. Ice sheet hydrology – process studies.

This literature review is part of subproject 1. The objectives of this study are to:

- Compile and evaluate geological information on the ice sheet extent during the stadials and interstadials of the Weichselian glaciation, with focus on Sweden and its surroundings.
- Compile and evaluate some of the geological information on basal conditions of the Weichselian ice sheet in Sweden.

The geological information on ice sheet extent will be used to calibrate a numerical computer simulation of the Fennoscandian ice sheet throughout the Weichselian (subproject 2). It includes ice marginal lines, the extent of different kinds of till and localities with interstadial deposits. Thereafter, geological information on basal conditions will be used to validate the results from the ice sheet model. We review a selection of geological features, and their geographical distribution that indicate areas of low glacial erosion. Features discussed in this report are till covered eskers, Veiki moraines and pre-glacially weathered bedrock.

The aim of this report is to give an overview, and not a complete review, of all earlier investigations dealing with the Weichselian ice sheet. The main focus has been to collect information needed for the simulation of the ice sheet. This simulation aims at describing the hydrological conditions at a Swedish deep repository of nuclear waste during a glaciation. Therefore, the review is focusing on Sweden and its near surroundings, and only briefly reports data from other areas.

Since an ice sheet often is erosive there is often a scarcity of documented older oscillations, while more knowledge of the last glacial maximum and deglaciation pattern are at hand. However, there is stratigraphical evidence of ice-free periods within the limit of the Weichselian glaciation. It is, however, difficult to date these warmer interstadials and even more difficult to establish the ice sheet extent during the stadials and interstadials. The timing of the interstadials and stadials is linked to deep-sea oxygen isotope curves /e.g. Martinson et al. 1987, Mangerud 1991/, see Figure 1-1, continental pollen records /e.g. Woillard and

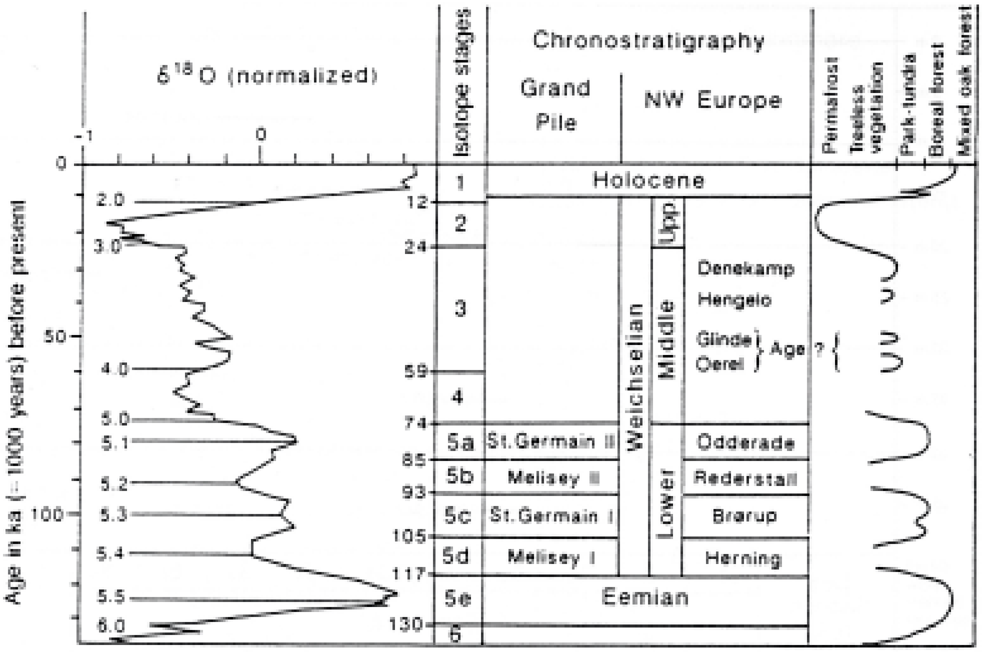


Figure 1-1. *The climate during the last interglacial/glacial cycle (altogether 130,000 years). The marine oxygen isotope curve and the isotope stages are shown to the left. High isotopic values indicate warm climate with relatively small amounts of water bound in glacial ice. The isotope curve has been correlated with climate data from north-eastern France (Grand Pile) and north-western Europe. The interpretations of the climate variations in Europe come from the pollen record, which is shown to the right /from Mangerud 1991/.*

Mook 1982/ see Figure 1-2, or climatological information interpreted from the Greenland ice cores. The timing of the deglaciation has been determined by the use of radiocarbon dates. The radiocarbon ages have been corrected for variations of the past atmospheric concentrations of ^{14}C /Lundqvist and Wohlfarth 2001/. These corrected ages are referred to as calibrated (cal) ages in the forthcoming text. Uncalibrated ^{14}C ages are given as ka (kiloyears) BP. The deglaciation of the Baltic Basin has partly been dated by the use of the clay-varve chronology /e.g. Strömberg 1989/ and are given in the following text as clay varve years BP. That chronology is based on the counting and correlation of glacial and postglacial yearly deposited varves /Cato 1987/. The clay varve chronology has been further correlated with the Greenland ice core chronology /eg. Andrén et al. 1999/ and are referred to in the text as GRIP or GISP yr BP.

In the following text we account for the waxing and waning of ice sheets during the Marine Isotope Stages (MIS) that represent the last glaciation, that is MIS 5d to MIS 2 according to the traditional Emiliani-Shackleton lettering of isotopic stages /Emeliani 1955, Shackleton 1987/. The last glaciation is also commonly divided into Early- Middle- and Late-Weichselian, occurring 115–75 ka BP, 75–25 ka BP and 25–10 ka BP, respectively. We have not tried to explain the climatological and glaciological reasons for waxing and waning of ice sheets. Previous reconstructions and compilations of the glacial history of Fennoscandia have been made by e.g. /Mangerud 1991, Andersen 1992, Lundqvist 1992, Donner 1996, Kleman et al. 1997/ and by /Saarnisto and Lunkka 2004, Svendsen et al. 2004/. The reconstructions made by /Lundqvist 1992/ are shown in Figure 1-3.

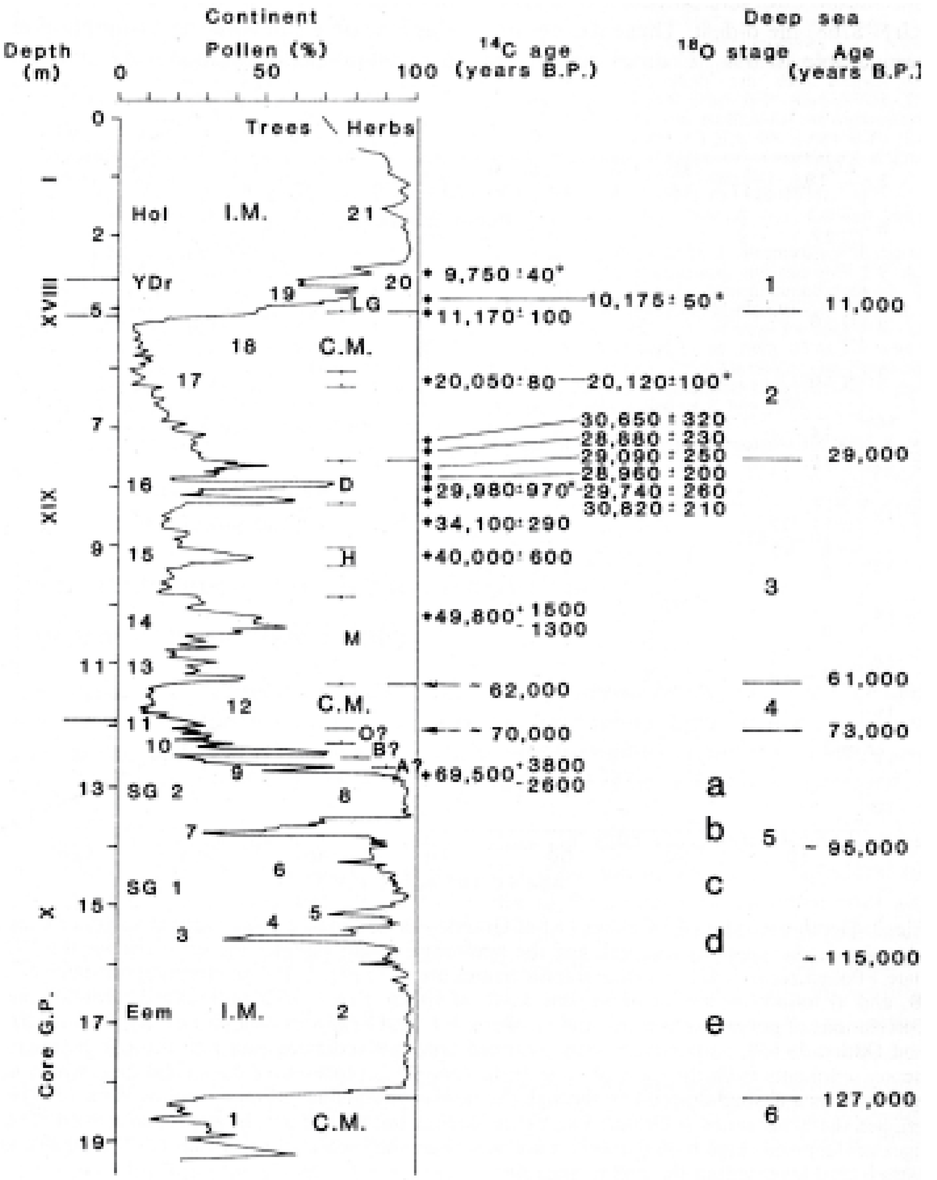


***Figure 1-2.** Correlation between the Grand Pile record (north-eastern France) and the marine isotope record. Isotope stages are shown to the right and the Grand Pile pollen record to the left. The pollen curve shows the relationship between trees and shrub versus herb pollen /from Woillard and Mook 1982/.*

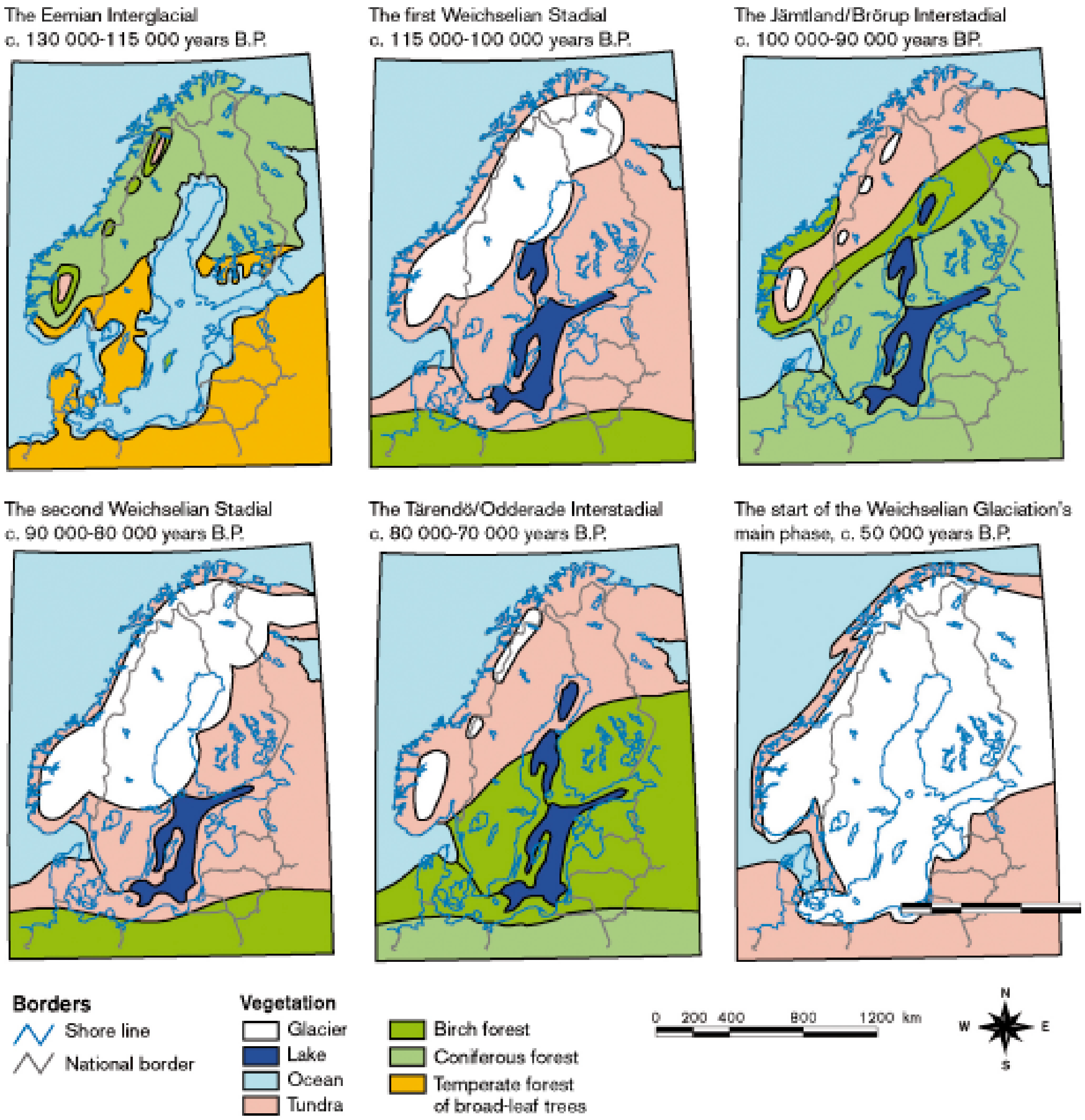


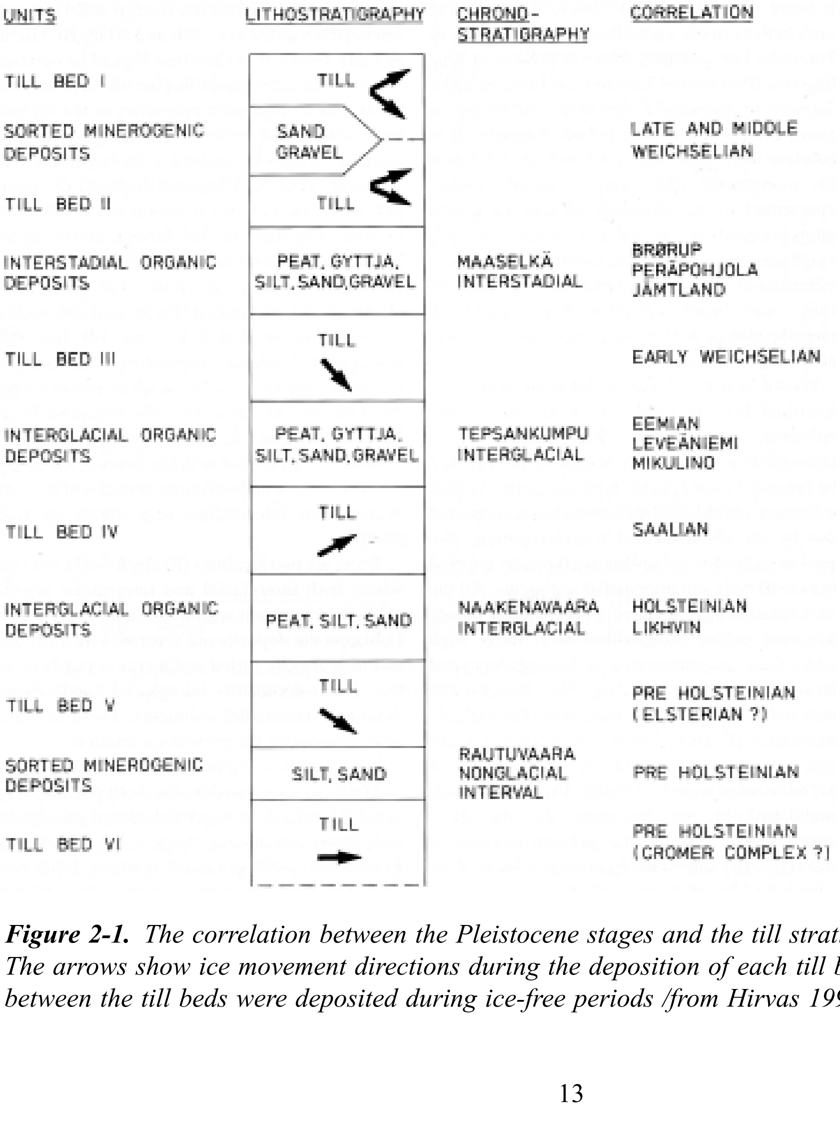
Figure 1-3. The ice sheet and environmental development in northern Europe from the last interglacial (Eemian) to the Middle Weichselian stadial. Each map shows a snapshot of the environment during each isotope stage. According to this model there were two interstadials with ice-free conditions during Early Weichselian (Brørup and Odderade). Most of Fennoscandia was covered by ice from Middle Weichselian until the deglaciation /from Lundqvist 1992 in Fredén 2002/.

2 Weichselian stadials and interstadials

2.1 The Herning Stadial – MIS 5d

This isotope stage (117–105 ka BP) represents the first cold stadial after the warm Eemaian interglacial (MIS 5e). Glacial erosion during subsequent stadials has, probably, to some extent wiped out deposits from the MIS 5d stadial, and knowledge of this ice extent is therefore scarce. There are several alternatives of how to correlate stratigraphical data and the different isotope stages /Hirvas et al. 1988, Garcia Ambrosiani 1990, Helmens et al. 2000/.

It is commonly proposed that the Early Weichselian ice sheet covered the Scandinavian mountain chain, Swedish Norrbotten and Finnish Lapland /Lundqvist 1992, Sutinen 1984/. According to /Lundqvist 1992/ the ice sheet might have reached the southern parts of Swedish Norrland, see Figure 1-3. This interpretation is based on results which suggest that the first Weichselian ice had the largest erosive and morphological effect on the landscape /Lagerbäck 1986/. /Lagerbäck 1988/ has shown that Veiki moraines and related features still found in this region were formed during this first Weichselian stadial. Hence, /Lundqvist 1992/ proposed that the ice extent outside Norrland during this stadial coincided with areas with a relatively thicker till cover, i.e. the proposed ice extent coincides with a line delineating areas of comparatively great till thickness from thinner till cover in the south. In Finland a till bed, called till bed III, has been correlated with MIS 5d, see Figure 2-1 /Hirvas 1991/. Till bed III is stratgraphically overlain by



UNITS	LITHOSTRATIGRAPHY	CHRONO-STRATIGRAPHY	CORRELATION
TILL BED I	TILL		
SORTED MINEROGENIC DEPOSITS	SAND GRAVEL		LATE AND MIDDLE WEICHSELIAN
TILL BED II	TILL		
INTERSTADIAL ORGANIC DEPOSITS	PEAT, GYTTJA, SILT, SAND, GRAVEL	MAASELKÄ INTERSTADIAL	BRØRUP PERÄPOHJOLA JÄMTLAND
TILL BED III	TILL		EARLY WEICHSELIAN
INTERGLACIAL ORGANIC DEPOSITS	PEAT, GYTTJA, SILT, SAND, GRAVEL	TEPSANKUMPU INTERGLACIAL	EEMIAN LEVEÄNIEMI MIKULINO
TILL BED IV	TILL		SAALIAN
INTERGLACIAL ORGANIC DEPOSITS	PEAT, SILT, SAND	NAAKENAVAARA INTERGLACIAL	HOLSTEINIAN LIKHVIN
TILL BED V	TILL		PRE HOLSTEINIAN (ELSTERIAN ?)
SORTED MINEROGENIC DEPOSITS	SILT, SAND	RAUTUVAARA NONGLACIAL INTERVAL	PRE HOLSTEINIAN
TILL BED VI	TILL		PRE HOLSTEINIAN (CROMER COMPLEX ?)

Figure 2-1. *The correlation between the Pleistocene stages and the till stratigraphy in Finish Lapland. The arrows show ice movement directions during the deposition of each till bed. The peat and silt between the till beds were deposited during ice-free periods /from Hirvas 1991/.*

sediments from the Peräpohjola interstadial (Brørup, MIS 5c). According to /Hirvas 1991/ and /Sutinen 1984/ the extent of the Finnish till bed III indicates that the oldest Weichselian ice sheet never reached outside Finnish Lapland. It is, however, possible that till bed III was deposited during the second Weichselian stadial, 5b /Lunkka et al. 2004/. Major parts of Finnish Lapland should then have been free of ice during MIS 5d.

In Finnmark in northern Norway, the first Weichselian stadial is represented by the Gardejokha till /Olsen et al. 1996/ sites 20, 21 in Figure 2-2. This till has characteristics, which indicate deposition by a warm-based ice. /Mangerud 1981, 1991/ argues that the ice almost reached the Norweigian coast, to Fjøsanger close to Bergen, site 27 in Figure 2-2. That is almost the same ice marginal position as during the Younger Dryas (see section 2.7) in Norway. Mangerud proposes that the ice sheet during MIS 5d ought to have been relatively large since the global sea-level was lowered with approximately 70 m after the Eemian /Chappell and Shackleton 1986/. /Olsen 1988/ on the other hand, argues towards a smaller ice sheet extent than that of Younger Dryas. It is possible that one explanation for the low global sea level during MIS 5d

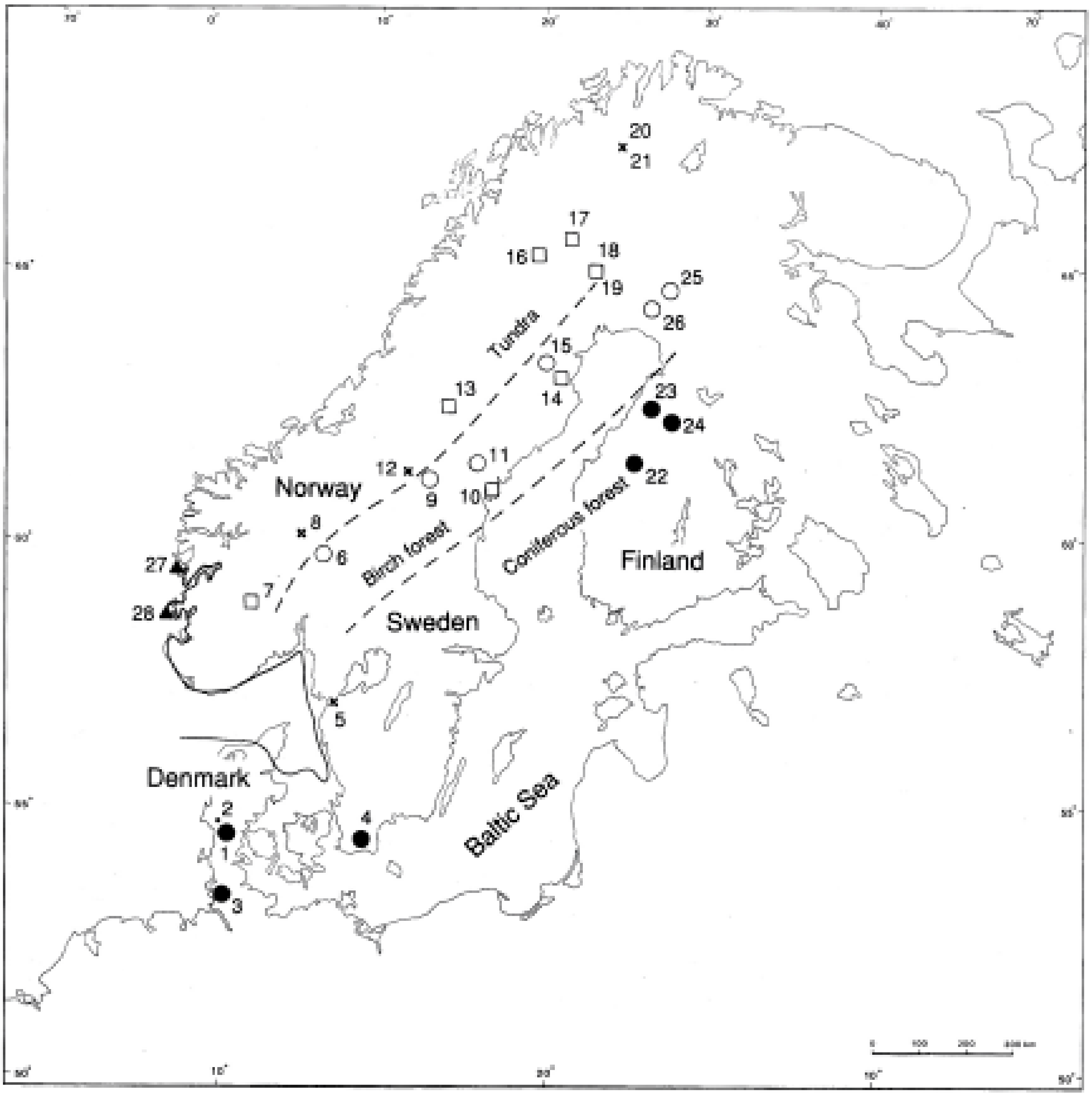


Figure 2-2. Sites with interstadial deposits in Fennoscandia, which have been correlated with the Early Weichselian (Table 2-1). Black dots = pine dominated pollen assemblages, circles = birch dominated pollen assemblages, squares = non arboreal pollen assemblages, crosses = sites with only lithostratigraphical evidence, black triangles = marine sediments /from Donner 1996/.

is the large volume of ice which might have existed in northern Siberia during that time /cf Svendsen et al. 1999, 2004/.

A composite stratigraphy shows that Lithuania was free of ice throughout the Early and Middle Weichselian /Satkunas 1999/. However, it has also been proposed that the Fennoscandian ice sheet reached further south during the Early Weichselian. /Mojski 1992/ advocates ice advances onto the Polish mainland at this time. /Påsse 1998/ has six thermoluminiscence dates of interstadial sediments, overlying till, in the Skrea drumlin in south-western Sweden. These dates vary between 32–136 ka BP, of which three are around 90–105 ka BP. Påsse advocates an Early Weichselian age of the underlying till, which is associated with an ice movement from the north-west. /Forsström and Punkari 1997/ argue that the ice sheet was extensive already during the Early Weichselian and that the ice front during later interstadials never retreated further than the ice position of Younger Dryas (see section 2.7). They chose to regard sites with interstadial sediments of Early Weichselian age inside the Younger Dryas line as misinterpretations. So far, they are alone to embrace this view.

2.2 The Brørup Interstadial – MIS 5c

Isotope stage 5c (93–105 ka BP) represents the oldest Weichselian interstadial. The scientific community commonly agrees that large parts of Fennoscandia were ice-free at least once during the Early Weichselian, presumably during MIS 5c. In northern Sweden, yet another Early Weichselian interstadial is distinguished /Lagerbäck and Robertsson 1988/, which has been correlated with MIS 5a /Lundqvist 1992/. /Donner 1996/ has compiled biostratigraphical data from interstadial sites in Scandinavia (Table 2-1). These interstadial sites (Figure 2-2) have been correlated by the use of a pollen stratigraphy. Since the sediments give infinite ^{14}C ages it is difficult to decide their absolute ages. Results from luminescence dated interstadial sediments from northern Norway indicate, however, ice-free conditions during MIS 5c /Olsen 1988, Olsen et al. 1996/. According to (Lagerbäck pers. comm. 2002) luminescence datings on interstadial sediments from Norrbotten in Sweden yield highly variable ages (sites 18 and 19 in Figure 2-2). On the Swedish west-coast, /Påsse 1998/ has chronostratigraphical data inferring interstadial sediments deposited during Brørup, and in southern Sweden, at Stenberget (site 4 in Figure 2-2), there are sediments that have been correlated with Brørup /Berglund and Lagerlund 1981/.

Most Early Weichselian interstadial sites are situated in the inland areas of Norway, Sweden and Finnish Lapland, see Figure 2-2. In addition there are interstadial localities just inside the maximum limit of the Weichselian ice sheet. Maybe the inland interstadial localities are preserved due to cold-based conditions /Kleman et al. 1997/ and in the peripheral parts of the ice sheet due to short time of glacial cover.

Marine isotope stage 5c is considered to be represented by the Finnish Peräpohjola Interstadial /e.g. Korpela 1969, Hirvas 1991/, sites 25 and 26 in Figure 2-2, the Swedish Jämtland Interstadial /e.g. Lundqvist 1967, Robertsson and Garcia Ambrosiani 1988, Garcia Ambrosiani 1990/, sites 9, 10, 14 and 15 in Figure 2-2, the Eiravarri Interstadial in northern Norway /Olsen 1988, Olsen et al. 1996/, site 20 in Figure 2-2 and maybe the Fana interstadial on the Norwegian west coast /Mangerud 1981, 1991/, site 27 in Figure 2-2. These locally defined interstadials are correlated with the Brørup Interstadial in Denmark /Andersen 1961/, site 1 in Figure 2-2. In Finland /Korpela 1969/ and /Hirvas 1991/ define only one Early Weichselian interstadial, the Peräpohjola. /Helmens et al. 2000/ differently correlate the Peräpohjola interstadial sediments with MIS 5a, i.e. Odderade. That conclusion is based on luminiscence datings from a core taken in Sokli situated in the eastern part of Finnish Lapland, inferring non-glacial conditions between the Eemian interglacial and the Brørup interstadial. /Helmens et al. 2000/ therefore infer that till bed III was deposited, after instead of before, Brørup, as suggested by /Hirvas 1991/ see above. The coring site described by /Helmens et al. 2000/ is, however, situated outside the area that supposedly was glaciated during MIS 5d and may therefore lack any till older than the Brørup interstadial.

Table 2-1. Early Weichselian interstadial and stadial sites compiled by /Donner 1996/ (Figure 2-2).

Sediment	Number	Site	Interstadial
Fresh-water sediments	1	Brørup, Denmark	Brørup-(Rodebaek)
	2	Rodebaek, Denmark	(Rodebaek)
	3	Odderade, Germany	Odderade-Brørup
	4	Stenberget, Sweden	Brørup
	5	Dösebacka-Ellesbo, Sweden	Older Dösebacka-Ellesbo
	6	Brumunddal, Norway	Brumunddal
	7	Førnes, Norway	Førnes
	8	Gudbrandsdalen, Norway	Gudbrandsdalen
	9	Pilgrimstad, Sweden	(Jämtland)
	10	Härnösand, Sweden	(Jämtland)
	11	Långsele, Sweden	(Jämtland)
	12	Vålbacken, Sweden	(Jämtland)
	13	Tåsjö, Sweden	(Jämtland)
	14	Boliden, Sweden	(Jämtland)
	15	Gallejaure, Sweden	(Jämtland)
	16	Seitevare, Sweden	
	17	Leveäniemi, Sweden	
	18	Takanenmännikkö, Sweden	= Brørup
	19	Riipiharju, Sweden	Tärendö = Odderade
	20	Vuoddasjarvi, Norway	Eirivarri = Brørup
	21	Sargejak, Norway	Sargejak = Odderade
	22	Vimpeli I, Finland	
	23	Oulainen, Finland	Oulainen
	24	Marjamurto, Finland	
	25	Permantokoski, Finland	Peräpohjola
	26	Ossauskoski, Finland	Peräpohjola
Marine sediments	27	Fjøsanger, Norway	Fana
	28	Bø, Norway	Torvastad

/Olsen et al. 1996/ argue that the Eiravarri interstadial in northern Norway, site 20 in Figure 2-2, corresponds to both Brørup and Odderade (MIS 5c–5a), and accordingly infer that large parts of northern Norway were ice-free during the stadial MIS 5b. This could mean that the oldest interstadial in Norrbotten, Sweden, reported by /Lagerbäck and Robertsson 1988/, site 18 in Figure 2-2, also span through MIS 5c–5a. The chronostratigraphy presented by /Lagerbäck and Robertsson 1988/ neither confirms or contradict this hypothesis due to unreliable dates.

Most sites with interstadial sediments have remains of only one interstadial and it is difficult to decide whether the sediments were deposited during Brørup (MIS 5c) or Odderade (MIS 5a) or during both these interstadials. Most sites represented by the Jämtland Interstadial have been correlated with Brørup. However, e.g. Vålbacken and Tåsjö, sites 12 and 13 in Figure 2-2, have been correlated with Odderade, i.e. MIS 5a /Lundqvist 1992/. It has also been proposed that Peräpohjola, often correlated with MIS 5c, consists of two interstadials, one with a birch-dominated flora and one with a pine-dominated flora /Garcia Ambrosiani 1990/. During Brørup, coniferous forests grew in southern Norrland in Sweden /Lundqvist 1992/ see Figure 1-3, implying that Brørup was quite warm, probably warmer than the other Weichselian interstadials.

2.3 The Rederstall Stadial – MIS 5b

This isotope stage (93–85 ka BP) represents the second Early Weichselian stadial. Little is known about the glacier extent during this period. A dark clayey till with a fabric indicating ice movement from west has been documented north of the Mälaren Valley in southern Sweden /Lundqvist 1973, Björnbom 1979, Garcia Ambrosiani 1990, Robertsson et al. 1997/. The geographical distribution of that till might correspond to the maximum ice extent during MIS 5b /Lundqvist 1992/. A dark clayey till is also known from many parts of Finland /Rainio and Lahermo 1976/. Moreover /Iisalo 1992/ describe a similar Early Weichselian till in central Ostrobothnia in Finland. However, it is not evident that these tills, although having similar characteristics, were deposited during the same event (Lundqvist oral comm. 2005). It has also been suggested that the dark clayey till was deposited during MIS 4 /Lundqvist 2004/ when large parts of Fennoscandia is thought to have been covered by ice and the ice sheet had a westerly centre /Kleman et al. 1997/.

According to /Olsen et al. 1996/ there was no extensive glaciation between Brørup and Odderade. They mean that the next major ice sheet build-up, represented by the Vuoddasjavri till, site 20 and 21 in Figure 2-2, occurred during the later part of Early Weichselian and early part of Middle Weichselian (MIS 4). This idea is based on luminescence dates from sediments, stratigraphically overlying and underlying the Vuoddasjavri till, yielding ages between 30–40 ka BP and 100 ka BP, respectively, see discussion below and Figure 2-3.

There is a growing consensus that the Fennoscandian ice sheets and Barents- and Kara Sea ice sheets acted out of phase. The most extensive Weichselian glaciation in Russia seems to have occurred during the Early Weichselian /Svendsen et al. 1999, 2004, Thiede et al. 2001/, see Figure 2-4, when the absence of a major Fennoscandian ice sheets allowed transport of moisture-rich air eastwards. The exact timing of the maximum Weichselian ice sheet in Russia is unknown, but it is considered to have occurred around 100–80 ka BP /Svendsen et al. 1999, 2004/.

2.4 The Odderade Interstadial – MIS 5a

Marine Isotope Stage 5a (85–74 ka BP) represents the second interstadial during the Early Weichselian. In Norrbotten in Sweden, /Lagerbäck and Robertsson 1988/ have stratigraphical evidence for two Weichselian interstadials. The younger is called Tärendö, site 19 in Figure 2-2, and has been correlated with Odderade (MIS 5a). The corresponding interstadial sites in Jämtland, Sweden, are Vålbacken and Tåsjö /Lundqvist 1992/, sites 12 and 13 in Figure 2-2. /Påsse 1998/ considers it likely that the older Dösebacka-Ellesbo interstadial on the Swedish west coast /Hillefors 1969/, site 5 in Figure 2-2, is contemporaneous with Odderade. Furthermore /Lundqvist 1992/ infers the possibility that some of the deposits, described by /Berglund and Lagerlund 1981/ at Stenberget, in southern Sweden, site 4 in Figure 2-2, were deposited during Odderade. It is worth mentioning that Tärendö in northern Sweden might represent a Middle Weichselian interstadial /Garcia Ambrosiani 1990/, see Figure 2-5.

/Mangerud 1991/, see Figure 2-6, infers that MIS 5a is represented by Torvastad in western Norway /Andersen et al. 1983/ (site 28 in Figure 2-2). However, there are alternative interpretations. /Sejrup et al. 2000/, see Figure 2-7, infer that Torvastad is contemporaneous with Brørup and that Odderade instead is represented by Bø /Andersen et al. 1983/, site 11 in Figure 2-2. Earlier, /Olsen 1988/ suggested that Sargejohka in northern Norway, site 21 in Figure 2-2, should be correlated with Odderade (MIS 5a). Lately, /Olsen et al. 1996/ have come up with a better chronological control and infer that the Sargejohka interstadial sediments were deposited 35–60 ka BP and correspond to a Middle Weichselian interstadial, see Figure 2-3. Moreover, they suggest that the Tärendö Interstadial is contemporaneous with Sargejokha, meaning that large parts of northern Scandinavia were ice-free during the Middle Weichselian. According to /Olsen et al. 1996/, Odderade is instead represented by the later part of the Eiravarri Interstadial, 85–105 ka BP, in northern Norway.

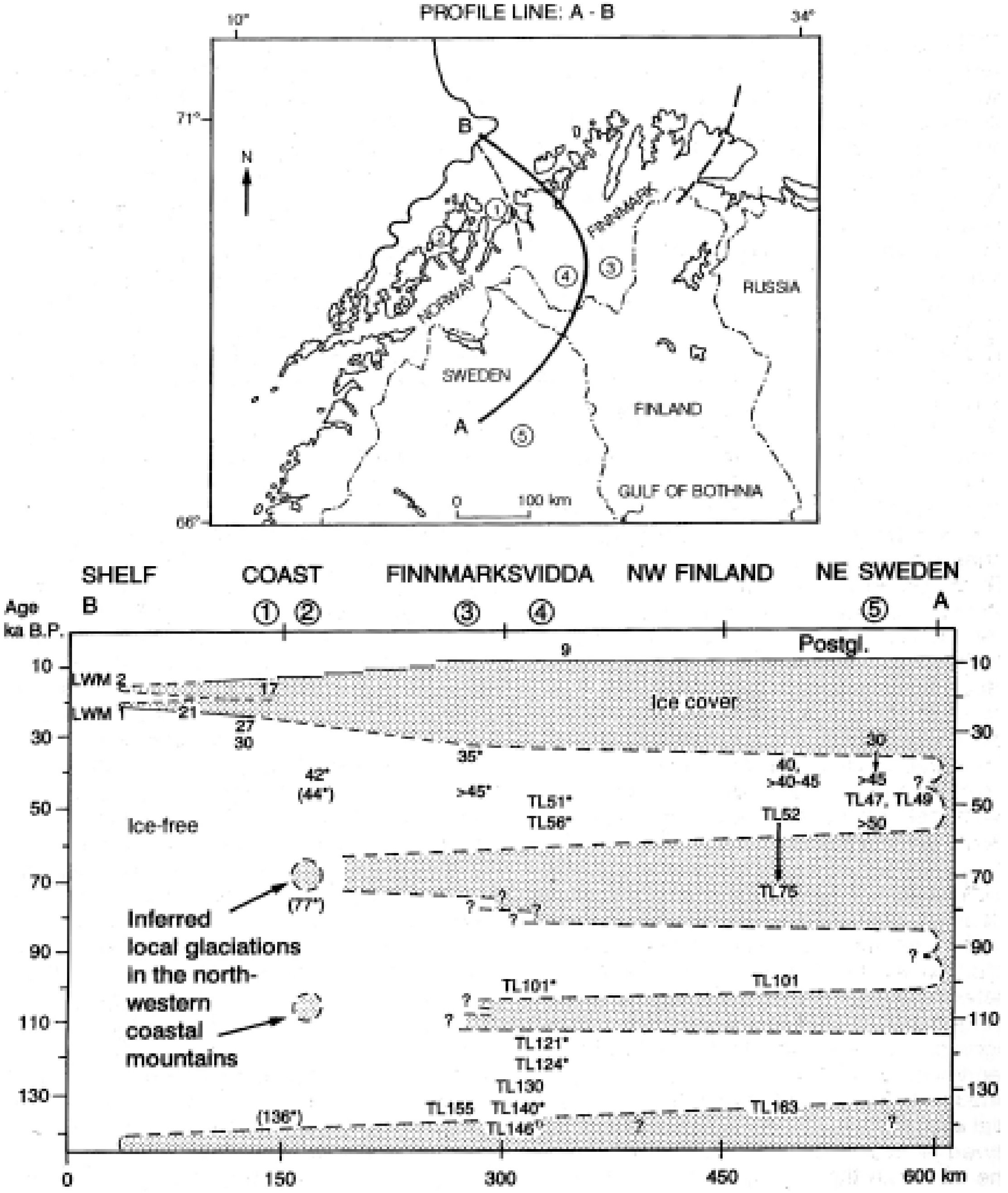
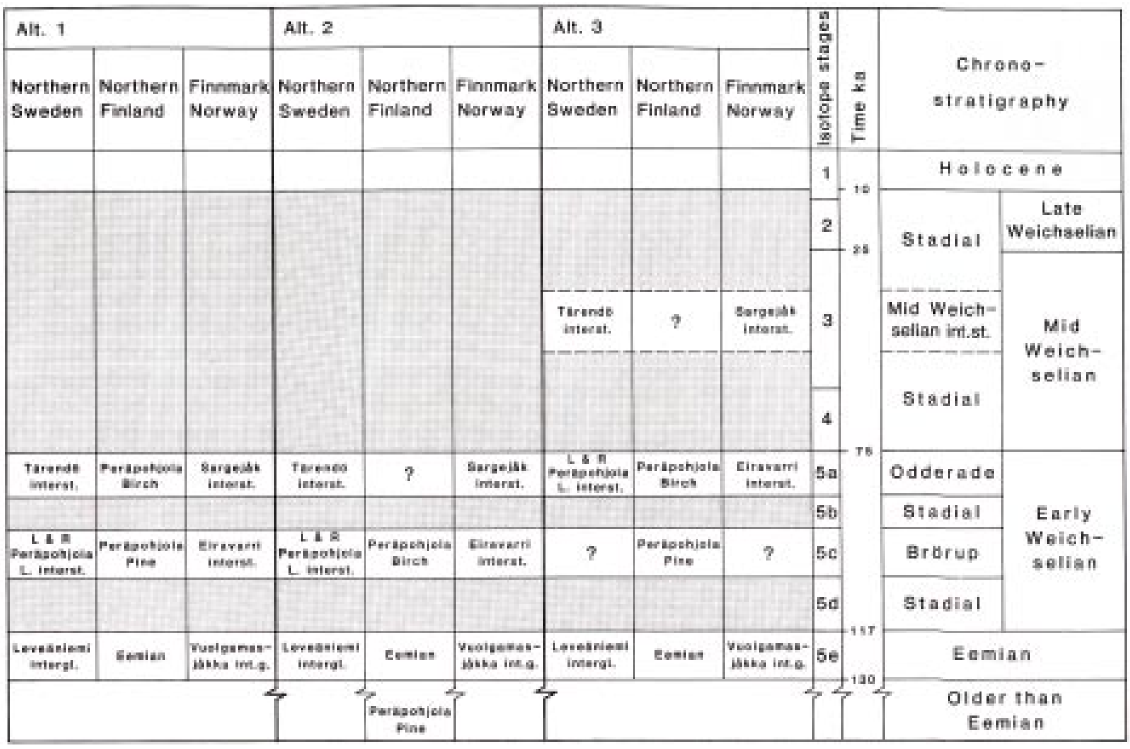


Figure 2-3. *The curve shows ice fluctuations in northern Fennoscandia during the last interglacial/ glacial cycle. The curves follow the line (A–B) which is shown on the map. Examples from localities in areas 1–5 (see map) are projected onto the curve. There was an interstadial with ice-free conditions during Middle Weichselian according to this model. The Late Weichselian Maximum was reached earlier in west (LWM 1, solid line on the map) compared to east (LWM 2, dashed line on the map). The timing of the curve is based on thermoluminescence (TL) and* ^{14}*C dates /from Olsen et al. 1996/.*

Figure 2-4. The maximal extension of the ice sheets during the Quaternary period, Early/Middle Weichselian and Late Weichselian /from Svendsen et al. 1999/.



Alt. 1			Alt. 2			Alt. 3			Isotope stages	Time ka	Chronostratigraphy	
Northern Sweden	Northern Finland	Finnmark Norway	Northern Sweden	Northern Finland	Finnmark Norway	Northern Sweden	Northern Finland	Finnmark Norway				
									1	10	Holocene	
									2	25	Stadial	Late Weichselian
						Tärendö interst.	?	Sargejåk interst.	3		Mid Weichselian int.st.	Mid Weichselian
									4	75	Stadial	
Tärendö interst.	Peräpohjola Birch	Sargejåk interst.	Tärendö interst.	?	Sargejåk interst.	L & R Peräpohjola L. interst.	Peräpohjola Birch	Eiravarri interst.	5a		Odderade	Early Weichselian
									5b		Stadial	
L & R Peräpohjola L. interst.	Peräpohjola Pine	Eiravarri interst.	L & R Peräpohjola L. interst.	Peräpohjola Birch	Eiravarri interst.	?	Peräpohjola Pine	?	5c		Brörup	
									5d	117	Stadial	
Leveäniemi intergl.	Eemian	Vuolgamasjåkka int.g.	Leveäniemi intergl.	Eemian	Vuolgamasjåkka int.g.	Leveäniemi intergl.	Eemian	Vuolgamasjåkka int.g.	5e	130	Eemian	
				Peräpohjola Pine							Older than Eemian	

Figure 2-5. Different possible correlations between Weichselian interstadials, which have been defined in different parts of northernmost Fennoscandia. The figure indicates a possible correlation between the Swedish and Norwegian interstadials and Middle Weichselian /from Garcia Ambrosiani 1990/.

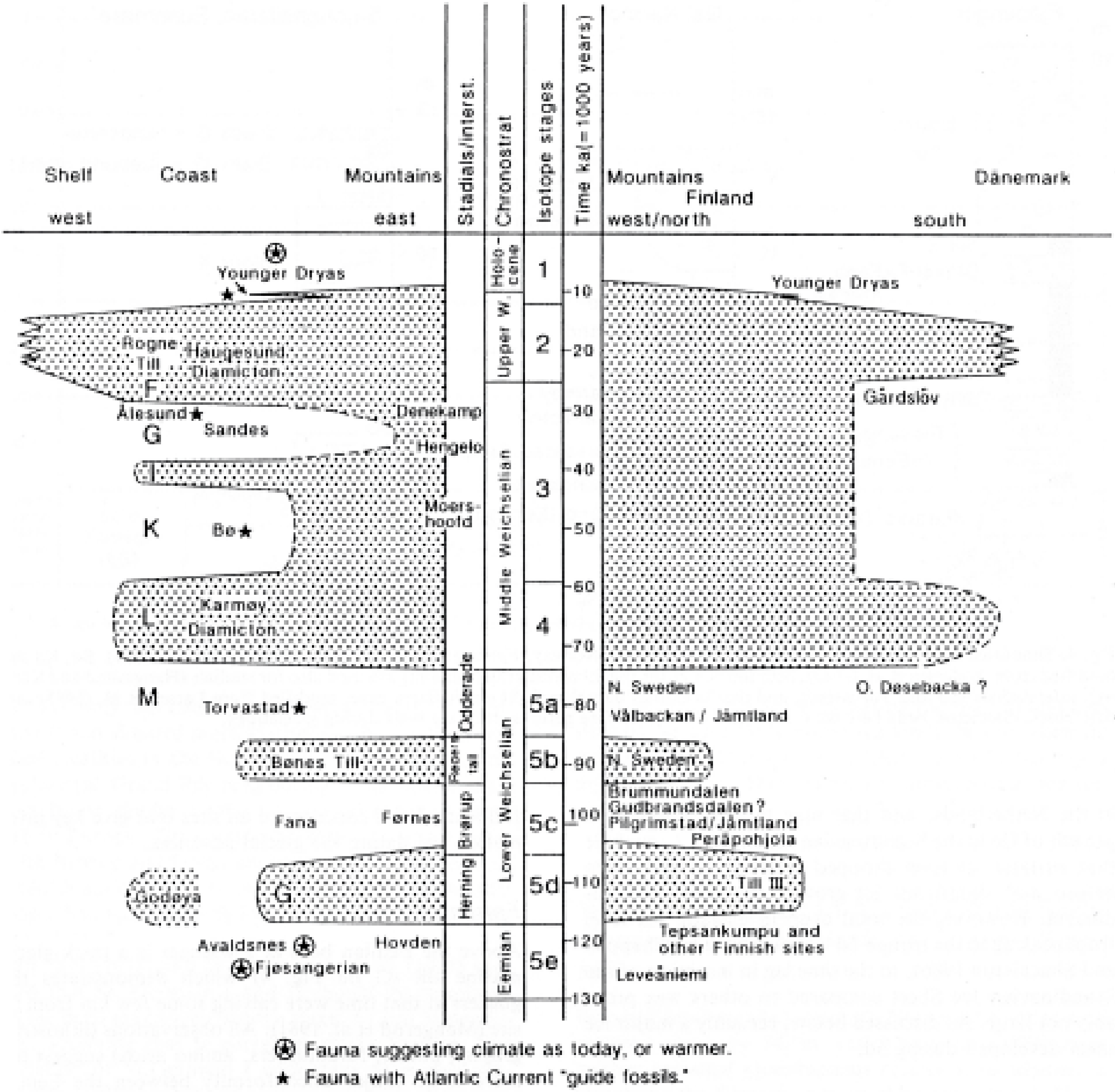


Figure 2-6. *The last interglacial/glacial cycle in Fennoscandia correlated with the different marine isotope stages. The left curve shows the glacial fluctuations on the western side of the Scandinavian mountainrange. The right curve shows the fluctuations on the eastern side of the mountains and towards the south (Denmark). The ages and isotope stages are shown in the middle /from Mangerud 1991/.*

Interstadial sediments from MIS 5a have not been confirmed in Finland /Hirvas et al. 1988/. However, /Olsen 1988/ suggests the possibility that MIS 5a is represented by a sand layer situated between till bed I and II see Figure 2-1 /Hirvas 1991/. According to /Helmens et al. 2000/ the Peräpohjola interstadial should be correlated with Odderade instead of Brørup, as suggested by others. An explanation to this ambiguity is put forward by /Garcia Ambrosiani 1990/ who suggests that Peräpohjola might represent two interstadials, an older and warmer with a pine dominated flora and a younger and colder with birch dominated flora (MIS 5b and 5a).

/Garcia Ambrosiani 1990/ presents several alternative correlations of the interstadial localities in northern Scandinavia with the Weichselian interstadials found further south (Figure 2-5). One of these correlations suggests that large parts of Scandinavia were ice free throughout these two interstadials and the intervening stadial (MIS 5c–5a). This is compatible with /Olsen et al. 1996/ who suggest that the stratigraphically younger interstadial sediments correspond to a Middle Weichselian interstadial. The marine oxygen isotope curve indicates that the climate was colder after MIS 5a compared to the earlier parts of the Weichselian glacial cycle /Martinson et al. 1987/, see Figure 1-1.

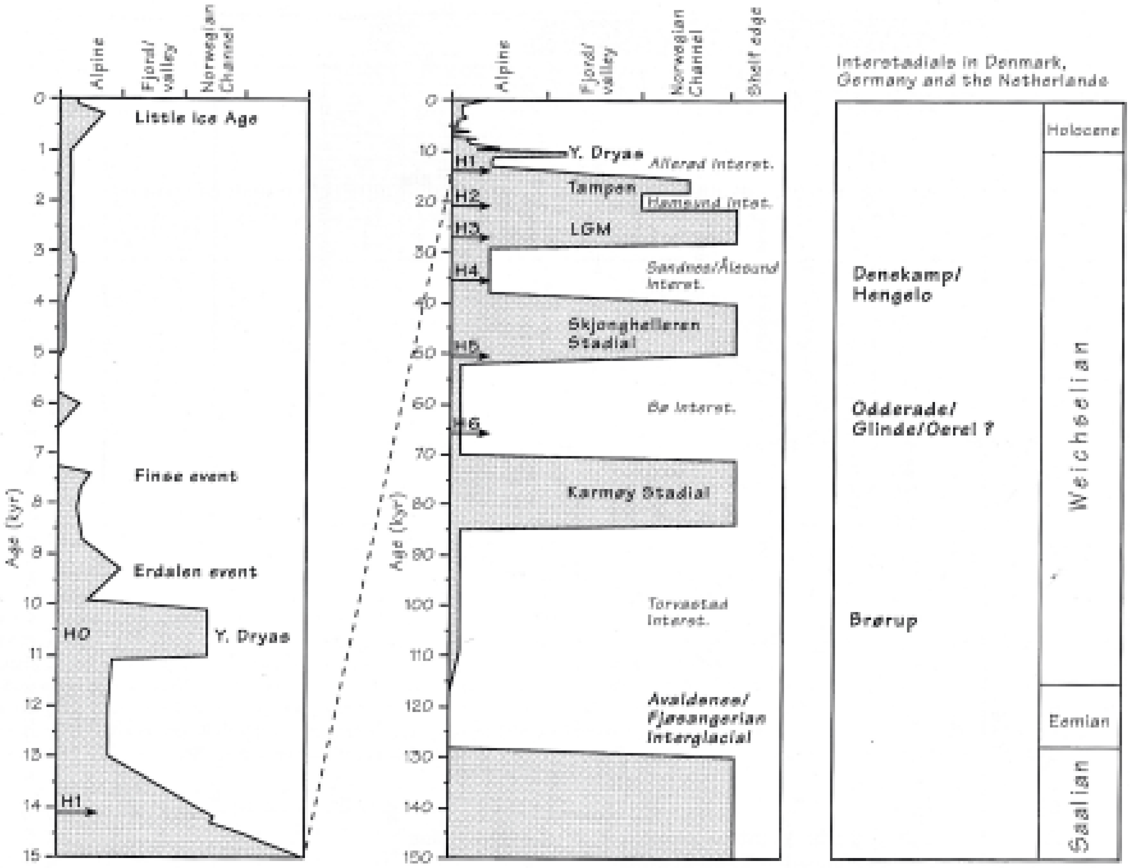


Figure 2-7. Glaciation curve for south-western Fennoscandia during the last 150,000 years. The curve is based on field evidence from western Norway and the North Sea. The timing and length of the oldest stadials/interstadials is uncertain. Heinrich events are marked with H. These events represent periods when large amounts of till material were dropped from icebergs /from Sejrup et al. 2000/.

2.5 The Middle Weichselian – MIS 4–3

According to the marine oxygen isotope record /e.g. Martinson et al. 1987/ the Middle Weichselian (74–24 ka BP) climate was characterised by relatively fast oscillations between warmer and colder conditions, see Figure 1-1. The global ice volume was larger during the Middle Weichselian compared to earlier parts of the glaciation. Marine oxygen isotope stage 4 (74–59 ka BP) was cold while MIS 3 (59–24 ka BP) at times was warmer. On the European continent there is biostratigraphical evidence of five Middle Weichselian interstadials /Behre 1989/. In northern France these Middle Weichselian interstadials were colder than the two Early Weichselian interstadials /Woillard and Mook 1982/, see Figure 1-2. The Fennoscandian interstadial sites dated to early Middle Weichselian are located in the peripheral parts of the assumed maximum ice limit /Donner 1996/, see Figure 2-8. This suggests a relatively stationary ice sheet and deposition of interstadial sediments during minor oscillations.

According to /Lundqvist 1992/ there are few interstadial sites that originate from the Middle Weichselian in southern Sweden and no such localities in northern Sweden. He considers the lack of interstadial deposits as evidence for a complete ice cover in the main part of Fennoscandia throughout the Middle Weichselian. /Miller 1977/ infers that Gärdslöv I, site 2 in Figure 2-8, was deposited during the later part of Middle Weichselian (32–21 ka BP) and she as well as /Berglund and Lagerlund 1981/ suggest that parts of Skåne were not glaciated before 21 ka BP. However, /Berglund and Lagerlund 1981/infers that other parts of Skåne was inundated by an old Baltic ice advance.

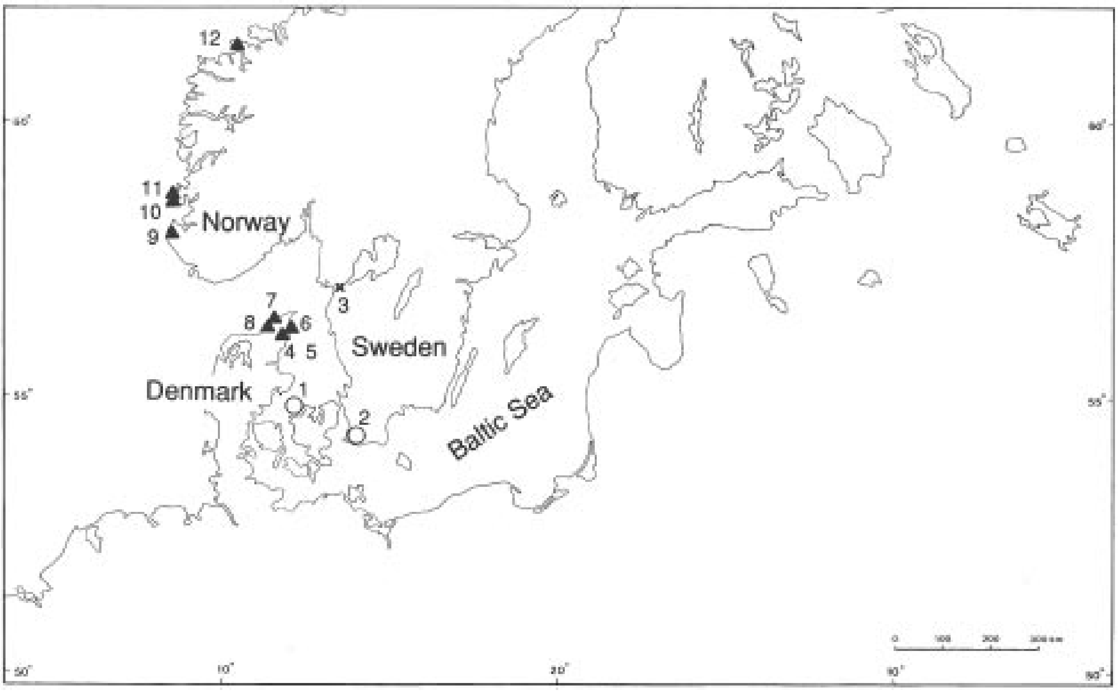


Figure 2-8. Interstadial sites with deposits from Middle Weichselian (Table 2-2). Circles symbolise freshwater deposits, triangles marine sediments and crosses sites with only lithostratigraphical evidences. According to this model most of Fennoscandia was covered by ice during the whole Middle Weichselian /from Donner 1996/.

Table 2-2. Middle Weichselian interstadial sites compiled by /Donner 1996/ (Figure 2-8).

Sediment	Number	Site	Interstadial
Fresh-water sediments	1	Sejerø, Denmark	= Hengelo
	2	Gärdslöv, Sweden	Gärdslöv I
	3	Dösebacka-Ellesbo, Sweden	Younger Dösebacka-Ellesbo
Marine sediments	4	Skaerumhede I, Denmark	
	5	Skaerumhede II, Denmark	
	6	Apholm, Denmark	
	7	Hirtshals, Denmark	
	8	Nørre Lyngby, Denmark	
	9	Jaeren, Norway	Sandnes
	10	Bø, Karmøy, Norway	Nygaard
	11	Bø, Karmøy, Norway	Bø
	11	Nygaard, Karmøy, Norway	Nygaard
	12	Sunnmøre, Norway	Ålesund

The youngest interstadial sediments at Dösebacka and Ellesbo, site 3 in Figure 2-8, yield ages of 24 and 30 ka BP, respectively, inferring deposition during the Middle Weichselian /Hillefors 1974/. Biostratigraphical investigations suggest periglacial conditions at the two sites. /Lundqvist 1992/ has suggested a wedge with ice-free conditions in Skåne during the Middle Weichselian.

The most well-defined Middle Weichselian interstadials on the Norwegian west coast are Bø /Andersen et al. 1983/, site 11 in Figure 2-8, and Sandnes/Ålesund interstadials /Mangerud 1981, Larsen et al. 1987, 2000/, site 9 and 12 in Figure 2-8. The biostratigraphical record indicates a relatively warm and humid climate during these two interstadials. However, there are conflicting views of how to correlate Bø, see Figure 2-6 and Figure 2-7, with occurring interstadials. /Sejrup et al. 2000/ choose to correlate Bø with Odderade (MIS 5a) and the earlier interstadial Torvastad to Brørup. During MIS 3 and 4 the ice sheet might have reached the Norwegian shelf /Olsen 1988, Sejrup et al. 2000/. According to Sejrup these advances occurred during the Karmøy Stadial around 85–70 ka BP and the Skjonghelleren Stadial around 50–35 ka BP, see Figure 2-7.

Stratigraphy on Jæren, south-western Norway /Larsen et al. 2000/ indicates a history of events similar to that described by Sejrup. The oldest glacial advance took place during the Early/Middle Weichselian, about 80–70 ka BP. The area was first inundated by a Norwegian Channel Ice Stream. When the ice stream wasted back, land-based ice advanced into the area at right angles to the flow of the ice stream. Then followed a marine environment. During the Middle Weichselian another glacial event took place, about 50–35 ka BP, again starting with a Norwegian Cannel Ice Stream followed by terrestrial ice. The next ice-free period, indicated by marine clays, is dated to 30–35 ka BP and is correlated with the Sandnes/Ålesund interstadial.

/Houmark-Nielsen 1999, 2003/ and /Houmark-Nielsen and Kjær 2003/ provide litho- and chronostratigraphical data and directional properties of tills suggesting ice streams in the Norwegian Channel, the Kattegat basin and the Baltic depression during the Middle and Late Weichselian, see Figure 2-9. The Ristinge Klint Till is the oldest Weichselian till in eastern Denmark

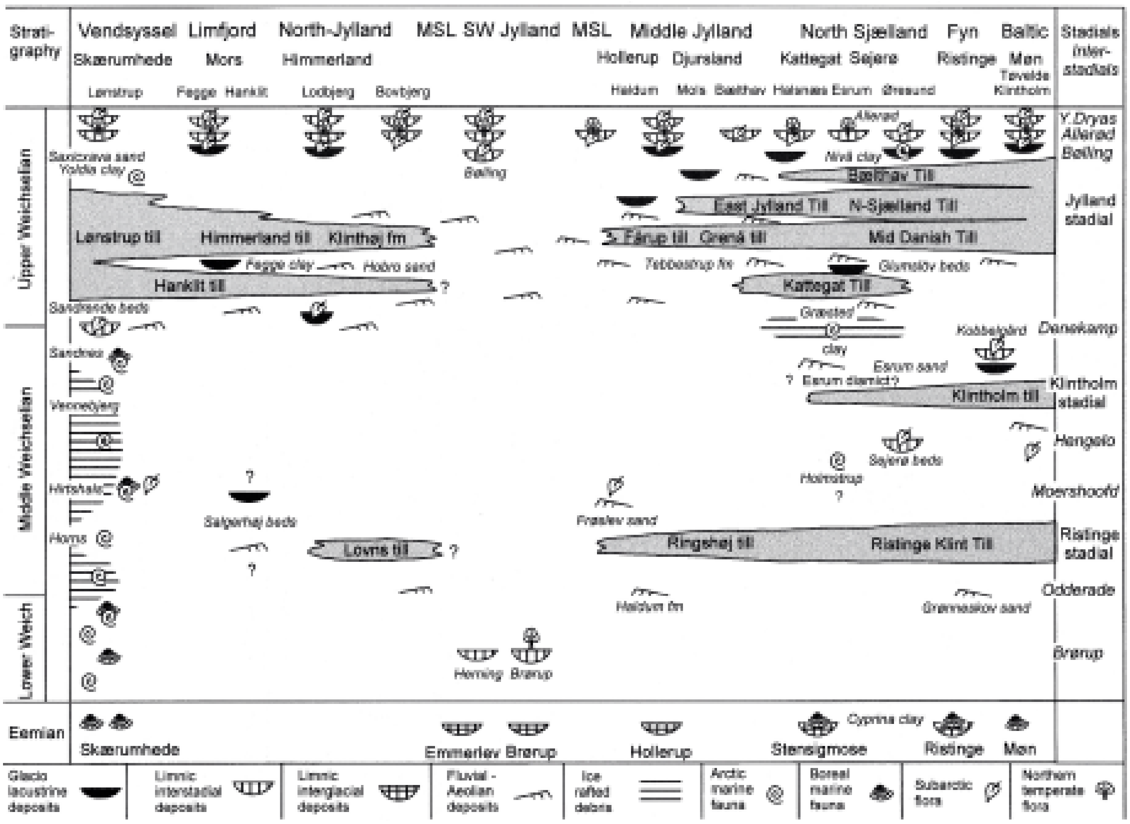


***Figure 2-9.** The last interglacial/glacial cycle in Denmark /from Houmark-Nielsen 1999/. Glacial advances are represented by grey till beds in the figure. The left part of the figure shows sites situated on northern Jylland.*

and is associated with an ice advance from the Baltic during the early Middle Weichselian, MIS 4 /Houmark-Nilsen 1999/. Moreover data from Jylland and northern Sjælland suggest an ice advance from Norway contemporaneous with the Skjonghelleren Stadial in south-west Norway /Houmark-Nielsen 2003/. The coastal regions of Norway were deglaciated during the Sandnes/Ålesund Interstadial /Larsen et al. 2000, Mangerud et al. 2003/. A possible eastward shift of the glaciation centre allowed a glacier advance through the Baltic depression which deposited the Klintholm till in eastern Denmark about 36–33 ka BP /Houmark-Nielsen and Kjær 2003/. Thus the reconstruction of /Houmark-Nielsen and Kjær 2003/ allows ice streams to grow although interstadial conditions prevailed in adjacent areas at times during MIS 3. /Hirvas et al. 1995/ have suggested, based on till stratigraphy, that an early Middle Weichselian (MIS 4) ice reached south of the Helsinki area.

In Poland there are different views of when the Weichselian ice sheet reached the Polish mainland for the first time. /Mojski 1992/ suggests that it occurred already during the Early Weichselian, while /Drozdowski and Fedorowicz 1987/ infer an Early Middle Weichselian age for this event. According to /Wysota et al. 2001/ The Vistula region in Poland was first invaded by Weichselian ice 70 ka BP. /Marks et al. 1995/ infer that northern Germany was reached by Weichselian ice around 50 ka BP. Latvia was ice free until 80 ka BP /Stelle and Savvaitov 2004/.

There are indications that also inland parts of Scandinavia were ice free during the later part of Middle Weichselian (MIS 3). /Olsen et al. 1996/ consider the Sargejokha interstadial in Norwegian Finnmark and Tärendö in northern Sweden, site 20 and 19 in Figure 2-2, to be of Middle Weichselian age (MIS 3) and not Early Weichselian (MIS 5a). These correlations were based on luminiscence and ^{14}C datings of interstadial sediments, yielding ages between 30–40 ka BP /e.g. Thoresen and Bergersen 1983, Rokoengen et al. 1993, Selvik et al. 1993/, see Figure 2-3. /Olsen et al. 2001a–c/ suggest that the Norwegian west coast experienced fast alterations between glacial and ice-free conditions after 45 ka BP. Furthermore, mammoth bones from the southern and middle parts of Finland yield ^{14}C ages between 32–23 ka BP, see Figure 2-10 /Ukkonen et al. 1999/, indicating non-glacial conditions in the south-eastern part of Fennoscandia during parts of the Middle Weichselian (MIS 3). OSL dates by /Nenonen 1995/ suggest that southern Finland was free of ice for most of the period between 50 and 25 ka BP.

2.6 The last glacial maximum – MIS 2

During MIS 2 (24–12 ka BP) the Weichselian ice sheet reached its maximum extent over Fennoscandia /e.g. Lundqvist and Saarnisto 1995, Svendsen et al. 1999/, see Figure 2-4. The Last Glacial Maximum (LGM), indicating the largest global ice sheet volume, occurred at 21 ka BP /Mix et al. 2001/. However, the maximum extent of the Fennoscandian ice sheet in the different marginal areas was non-synchronous and occurred between 28–15 ka BP /e.g. Houmark-Nielsen and Kjær 2003/.

The earliest ice advance to a maximum position occurred around 28 ka B P from a centre in south-west Norway into the North Sea. There was probably a continuous ice sheet between Scandinavia and the British Isles after that advance /Sejrup et al. 1994, 2000/. The ice sheet covered the North Sea between 29–22 ka BP /Sejrup et al. 1994/, and readvanced a short distance out in the North Sea during the Tampen readvance, between 18–15 ka BP /Sejrup et al. 2000/, see Figure 2-7. /Olsen et al. 1996, 2001a–c/ suggest that the ice front was situated inland from the coast at 19 ka BP and suggest an advance onto the shelf around 16 ka BP. They propose that the western fringe of the Fennoscandian ice sheet experienced several advances and readvances during the Late Weichselian.

/Vorren and Laberg 1996/ suggest that the maximum extent of the Fennoscandian ice sheet, as well as the Barent Sea ice sheet, can be separated into two maximum, an older prior to 22 ka BP and younger after 19 ka BP. Debris flows in the Bjørnøya trough indicate that the ice front reached the shelf break during both advances. They infer a deglaciation of the southern Barents Sea around 15 ka BP.

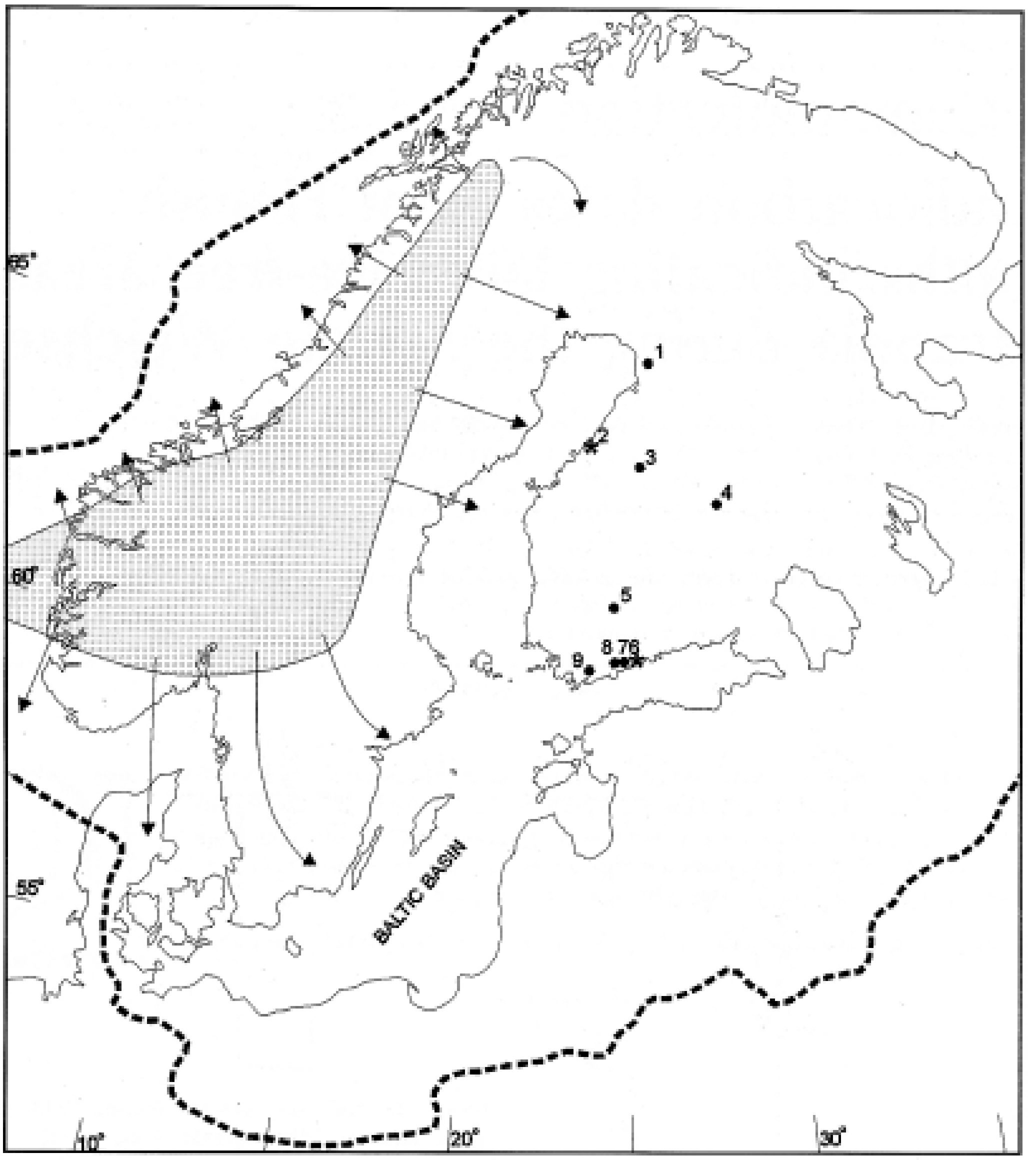


Figure 2-10. *Localities in Finland with Middle Weichselian mammoth bone findings. Black dots show glacially deposited remains, and asterisks remains dropped in the Baltic Sea sediments, probably by icebergs. The dashed line shows the extension of the ice sheet during the LGM, and the shaded area the glaciation centre in the mountains /from Ukkonen et al. 1999/.*

Contemporaneously with the ice advance onto the Norwegian shelf, around 28 ka BP, the Kattegat ice stream invaded northern Denmark and deposited the Kattegat till /Houmark-Nielsen 2003/. Luminescence datings of non-glacial sediments above the Kattegat till suggest deglaciation of northern Denmark around 26 ka BP. In /Houmark-Nielsen 2003/ and /Houmark-Nielsen and Kjær 2003/ ^{14}C ages younger than 25 ka are calibrated into calibrated years. Around 22 ka BP the Fennoscandian ice sheet reached its maximum extent in Denmark, called the Main Stationary Line (MSL), see Figure 2-11, and deposited the Mid-Danish till /Houmark-Nielsen and Kjær 2003/. /Kjær et al. 2003/ have acquired directional and compositional data of Mid-Danish till and the young Baltic till. The latter till was deposited during the deglaciation (see below). Their studies suggest a consistent ice flow from north-east during the deposition of the Mid-Danish till. Findings of an oblique relationship between ice-flow direction and the MSL imply that the ice might have expanded farther west beyond the MSL. The sharp bend of the MSL is explained by an overstepping by an ice stream from the Oslo Fjord, the Tampen readvance. /Houmark-Nielsen and Kjær 2003/ correlate the MSL through Jylland with the Brandenburg-Lezno phase in eastern Germany and Poland /e.g. Kozarski 1988/, see Figure 2-12.

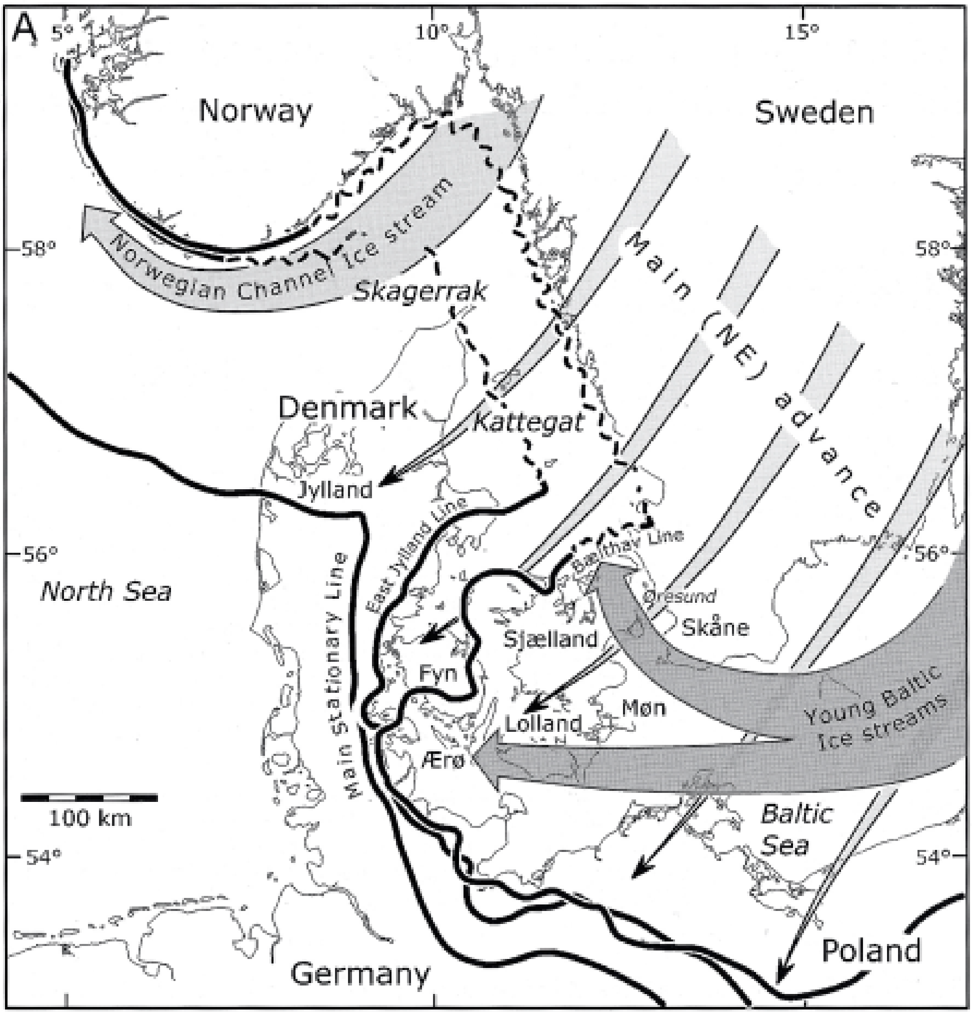


Figure 2-11. *The development during the time interval 28–15 ka BP in south-western Scandinavia. The Main Stationary Line indicates the extension of the ice during LGM. The East Jylland and Bælthav Lines indicate ice readvances which occurred during the latest deglaciation /from Kjær et al. 2003/.*

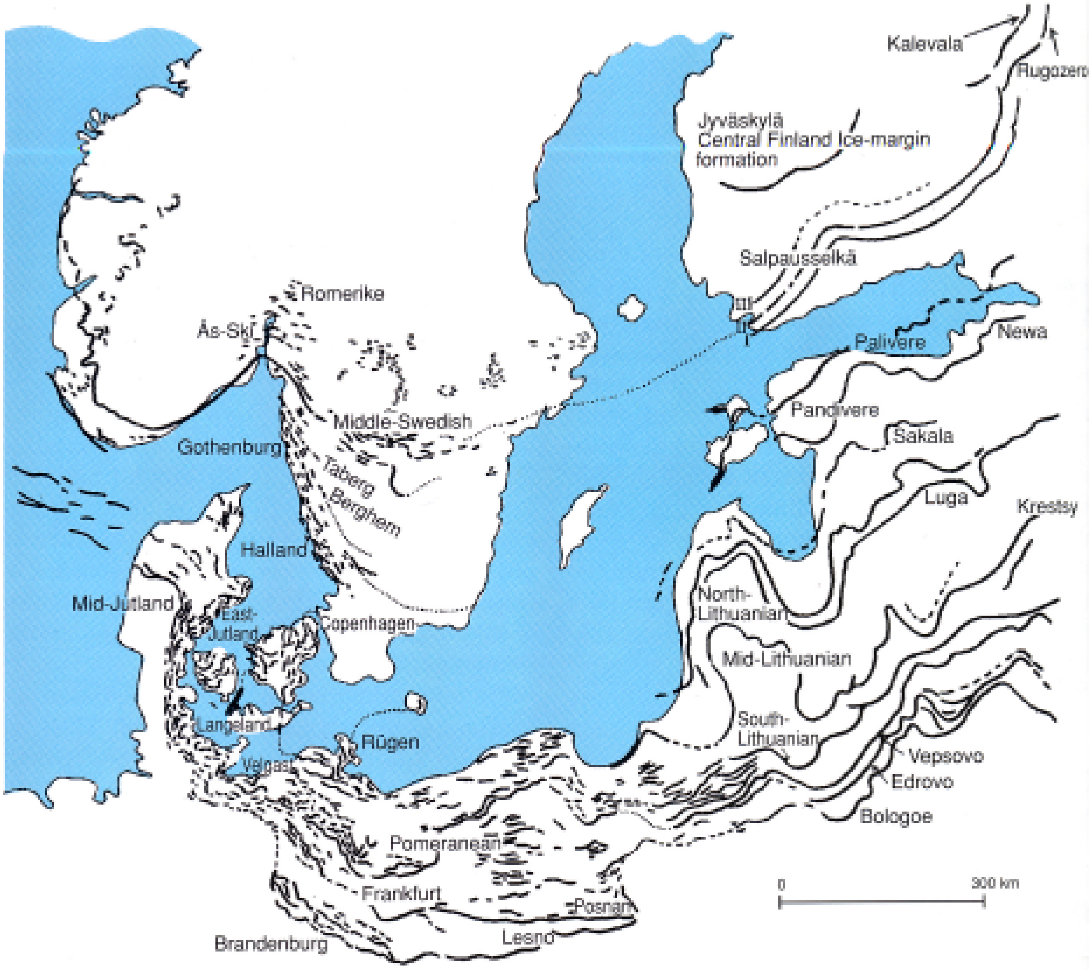


Figure 2-12. *End moraines formed during the Last Glacial Maximum (LGM) and the last deglaciation. The solid lines indicate marginal formations and the dashed lines correlations between known marginal formations. Approximate radiocarbon ages in years BP: Brandenburg-Leszno: 20,000; Frankfurt-Poznan 17,000; Pomeraneian: 15,000; Mid-Lithuaneian-Velgast-Copenhagen: 14,000; Luga-Rügen-Halland-Lista: 13,500; Pandivere-Gothenburg: 12,500; Berghem: 12,300; Taberg: 12,000; Ra-Middle Swedish-Salpausselkä: 11,000–10,300 (10,500); Aas-Ski: 10,500–10,200; Aker: 9,800; Romerike-Jyväskylä: 9,600–9,500. Some of the moraines are not well dated. From /Andersen and Borns 1997/.*

Earlier ice sheet reconstructions of Eurasia during the Late Weichselian usually encompass a large continuous ice cover over Scandinavia and northern Russia /Grosswald 1980, Peltier 1996/. However, more recent litho- and chronostratigaphical data from Siberia and north-western Russia /e.g. Forman et al. 1999, Larsen et al. 1999, Svendsen et al. 1999, Houmark-Nielsen et al. 2001/ show that the Barents and Kara Sea ice sheets never reached the Russian mainland during the Late Weichselian, see Figure 2-4. In Russia and Siberia the extent of glaciers culminated during the Early/Middle Weichselian. The Fennoscandian ice sheet reached its maximum extension in north-western Russia in the Dvina basin around 17 ka BP /Larsen et al. 1999, Lyså et al. 2001/. According to /Lunkka et al. 2001/ the eastern maximal extension was reached east of Lake Onega at 18 cal (calibrated) ka BP (calibrated radiocarbon age), see Figure 2-4. Furthermore, they suggest that since the ice front was situated in southern Finland at 25 ka cal BP /Ukkonen et al. 1999/, it took only 7,000 years for the ice sheet to reach its maximal position in Russia.

2.7 The deglaciation

Reconstructions of the deglaciation pattern and alternative ways to correlate ice marginal zones between different parts of the Fennoscandian ice sheet are shown in Figure 2-12 /Andersen and Borns 1997/ and Figure 2-13 /Lundqvist and Saarnisto 1995/. Further deglaciation patterns are presented by /Lundqvist 1986, Andersen and Pedersen 1998/ and Lundqvist in /Lindström et al. 2000/.

Between 18–17 ka BP, when the western margin of the Fennoscandian ice sheet had started its retreat, Denmark was invaded by two Baltic advances, depositing the Jylland and Bælthav tills /Houmark-Nielsen and Kjær 2003/. /Kjær et al. 2003/ suggest that during the Jylland and Bælthav advances the ice had become successively thinner, allowing ice streams through the Baltic with lobate margins, see Figure 2-11. Thus they adopt a more dynamic view of the ice sheet, which has been discussed earlier by /Lagerlund 1987/.

During the deglaciation of Germany and Poland there were successive halts at the Frankfurt-Poznan and the Pomeranian ice marginal zones. The main stationary lines in the southern Baltic have been described by e.g. /Lagerlund et al. 1995, Uscinowicz 1999/ and /Marks 2002/. /Houmark-Nielsen and Kjaer 2003/ tentatively correlate the Frankfurt-Poznan phase with the Jylland advance and the Pomeranian phase with the Bælthav advance, see Figure 2-11 and Figure 2-12.

/Saarnisto and Saarinen 2001/ have clay varve and paleomagnetic data suggesting that Lake Onega in Russia was deglaciated 14,250–12,750 cal yr BP. Furthermore luminescence datings of glaciolacustrine sediments infer deglaciation of the Dvina basin in north-western Russia at 14.8 ka BP /Larsen et al. 1999/. As already mentioned, the deglaciation of the south-western Barents Sea started around 15 ka BP. /Vorren and Kristoffersen 1986/ have identified moraine ridges on the Norwegian shelf, where shells from overlying glaciomarine sediments yield ages > 13.5 ka BP. This suggests that the minimum age for the deglaciation is 13.5 ka BP.

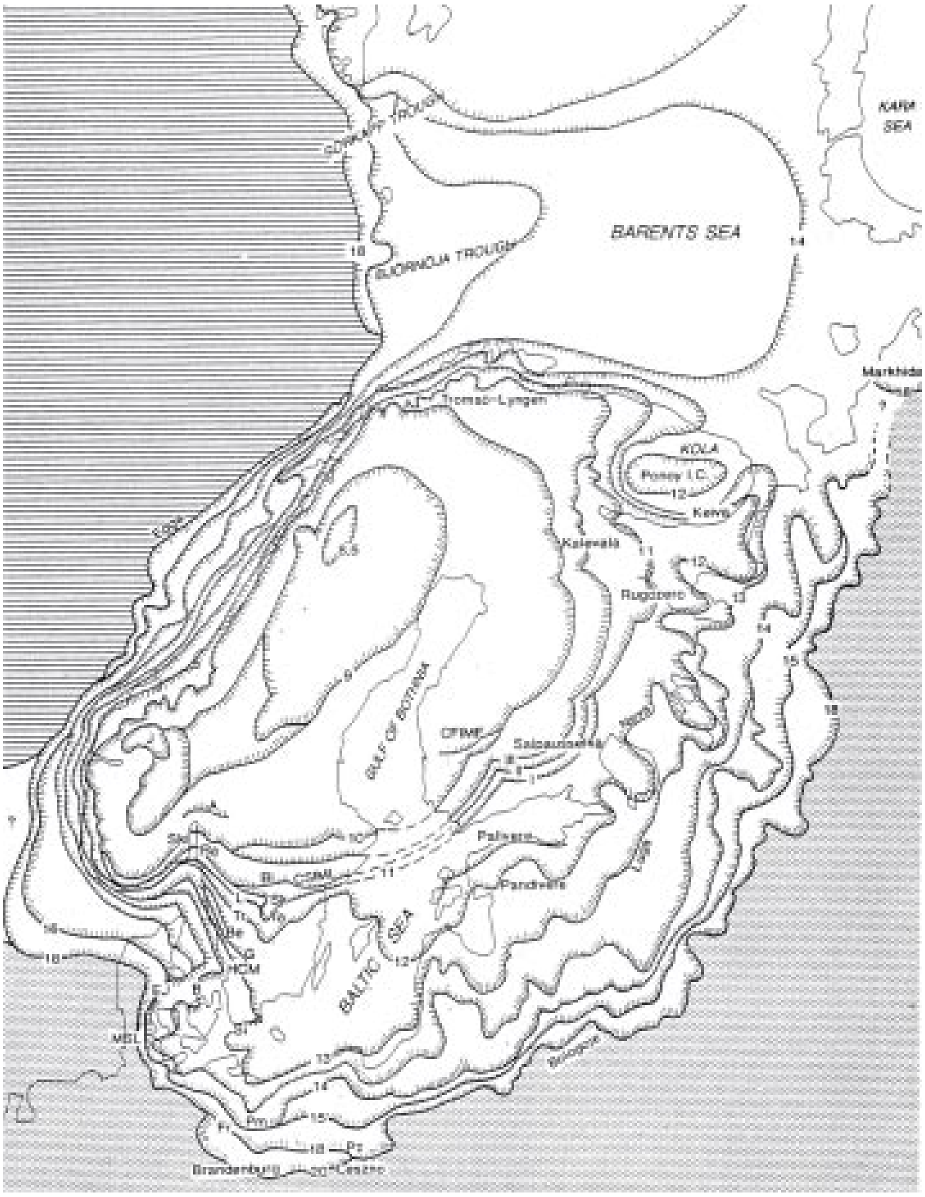


Figure 2-13. The final deglaciation of the Weichselian ice sheet. All dates are shown as uncalibrated radiocarbon years ka BP /from Lundqvist and Saarnisto 1995/.

/Lundqvist and Wohlfarth 2001/ recently revised the timing for the deglaciation of southern Sweden, prior to Younger Dryas, see Figure 2-14. They tried to correlate the moraines across southern Sweden by using calibrated radiocarbon ages from the west coast and compare these with the chronology on the east coast. Along the east coast, the timing of ice recessional stages is mainly based on clay varves and a few ^{14}C dates. The clay varve chronology has recently been revised by /Andrén et al. 1999/ who add some 900 years to the old chronology /e.g. Strömberg 1989, Cato 1987/. The correlations of ice marginal zones across Sweden are problematic. In south-eastern Sweden few end moraines developed. Stagnant ice remained in front of the retreating ice sheet /Björck and Möller 1987, Ising 2001/. According to /Lundqvist and Wohlfarth 2001/ the south-west Swedish moraines are as follows, from oldest to youngest see Figure 2-14; the Halland Coastal Moraines (18–16 cal ka BP), the Göteborg Moraine (15.4–14.5 cal ka BP), the Berghem Moraine (14.4–14.2 cal ka BP), the Trollhättan Moraine (> 14.1 cal ka BP) and the Levene Moraine (13.4 cal ka BP). The Levene Moraine, which is situated south of the Younger Dryas Moraines, is considered to be of Alleröd age /Lundqvist and Wohlfarth 2001/. Glaciotectoninc structures, stratigraphical data and straie show that

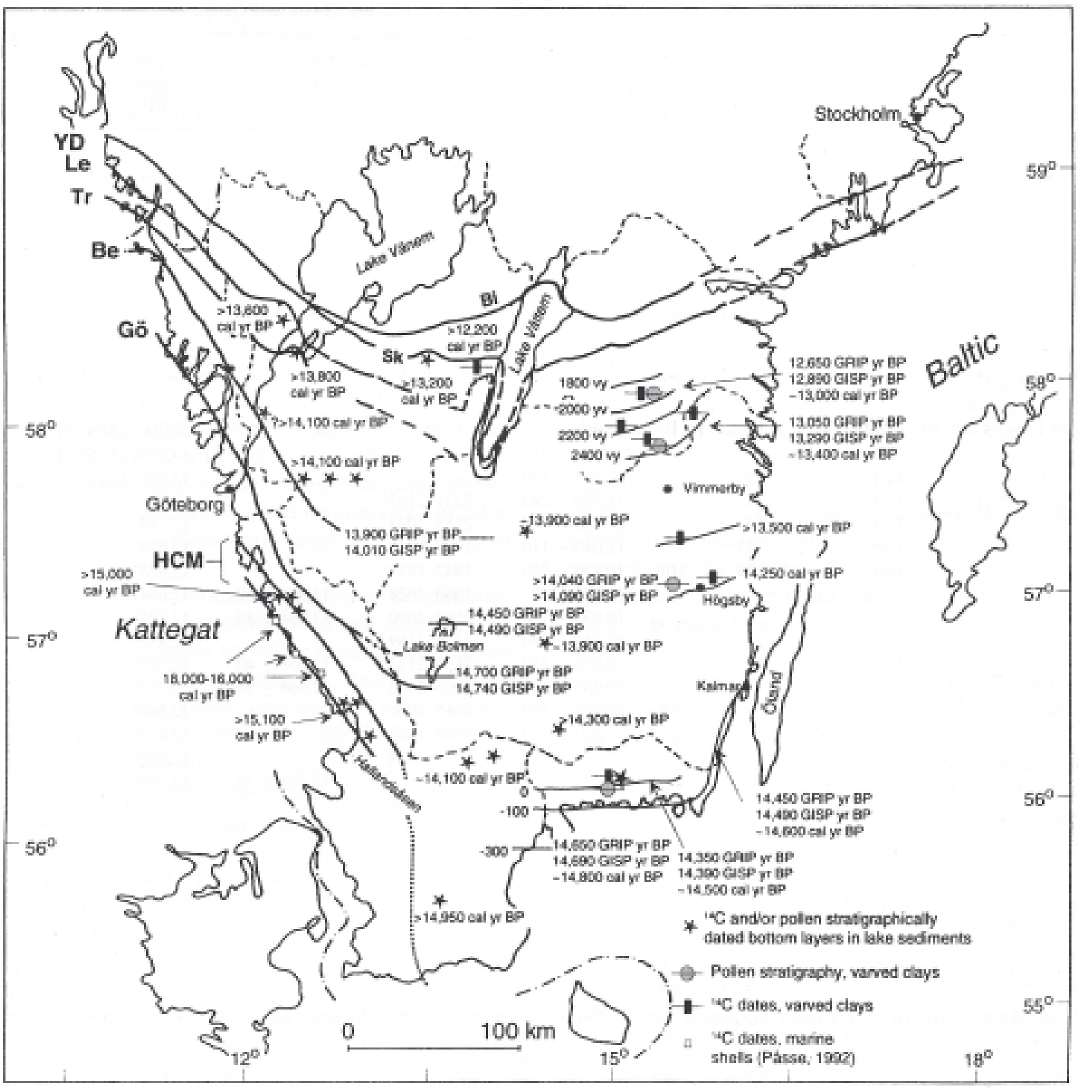


Figure 2-14. Deglaciation of south Sweden with age-equivalent west-east correlations of the ice marginal lines. Ages determined with different techniques have been calibrated to calibrated years BP. GISP and GRIP refers to ages determined in the ice cores sampled on Greenland /from Lundqvist and Wohlfarth 2001/. HCM = Halland coastal moarines, Gö = Göteborg moraine, Be = Berghem moraine, Tr = Trollhättan moraine, Le = Levene moraine, YD = Younger Dryas moraines (constituted by Sk = Skövde moraine, Bi = Billingen moraine).

the Levene Moraine was formed in connection with a readvance in the Lake Vättern basin /Waldemarsson 1986/. This readvance might be correlated with the GI-b event that has been registered in the GRIP ice core /Björck et al. 1998/.

In the Baltic countries there are three successively well-developed ice marginal zones, the Luga, Pandivere and Palivere, see Figure 2-12 and Figure 2-13. Lundqvist in /Lindström et al. 2000/ correlate these end moraines with the Halland Coastal Moraines, the Göteborg Moraine and the Levene Moraine, from the oldest to the youngest. /Noormets and Flodén 2002/ show that the Baltic end moraines continue out in the Baltic Sea towards Gotland.

Earlier, datings from Fennoscandia have shown that Younger Dryas occurred 11–10 thousand uncalibrated radiocarbon years BP /Andersen et al. 1995a/. At present the Younger Dryas event in Fennoscandia has been synchronised with other chronologies, which suggest that Younger Dryas spans between 12.6–11.4 cal ka BP /Björck et al. 1996, 1998/. /Andersen et al. 1995a/ have presented a map showing the correlation of the Younger Dryas moraines in the Nordic countries see Figure 2-15.

Figure 2-15. The margin of the Fennoscandian ice sheet during Younger Dryas. Solid lines represent marginal deposits. Dashed lines represent possible continuations of the marginal deposits. Some of the moraines are named on the map /from Andersen et al. 1995/.

In Sweden, the Skövde line represents Younger Dryas and Billingen Moraines, see Figure 2-14 and Figure 2-15. It is not clear how far south the ice front readvanced, but there seem to have been readvances west of Mt Billingen and Lake Vänern and through the basin of Lake Vättern /Lundqvist and Wohlfarth 2001/. Furthermore it is unclear if the Younger Dryas moraines formed synchronically. East of Mt Billingen the ice recession slowed down between 11.6–10.7 thousand varve years BP /Strömberg 1994/, which corresponds to 12.5–11.6 adjusted ka varve years BP /Andrén et al. 1999/.

In Norway the ice readvanced approximately 10–40 km during Younger Dryas /Andersen et al. 1995b/. According to /Bondevik and Mangerud 2002/ the readvance in western Norway occurred during the late part of Younger Dryas, approximately 11.6–11.7 cal ka BP. The ice stayed at a maximum Younger Dryas position for 100–200 years and started to retreat during the transition to the Holocene, which according to the authors occurred 11.5 cal ka BP.

Three end moraines, the Salpausselkä moraines (SsI, SsII and SsIII) can be followed through southern Finland /Rainio et al. 1995/, see Figure 2-12 and Figure 2-15. The two oldest moraines, SsI and SsII formed in the early and middle part of Younger Dryas, respectively. North of the Ss moraines the Central Finland Ice-Marginal Formation can be observed. This moraine formed during a readvance in the beginning of Holocene. /Saarnisto and Saarinen 2001/ suggest that SsI and SsII formed between 12.2 and 11.6 cal ka BP. Each Salpausselkä moraine is divided into several arcs probably formed by different ice lobes /Andersen and Pedersen 1998, Saarnisto and Saarinen 2001/. Since these ice lobes developed independently it is difficult to make correlations between the different end moraines.

Lundqvist /in Fredén 2002/ accounts for the timing and distribution of ice recessional lines in Sweden, see Figure 2-16a and b. A scarcity of end moraines north of the Younger Dryas line makes it difficult to assess the timing of the deglaciation. Along the coastal areas of Norrland and in the river valleys below the highest coastline the timing for deglaciation is dated by clay-varve chronology. The climate was warm and the deglaciation more or less continuous after Younger Dryas. However, during the Preboreal oscillation 11.2–11.0 ka BP the climate was temporarily colder /Björck et al. 1996/.

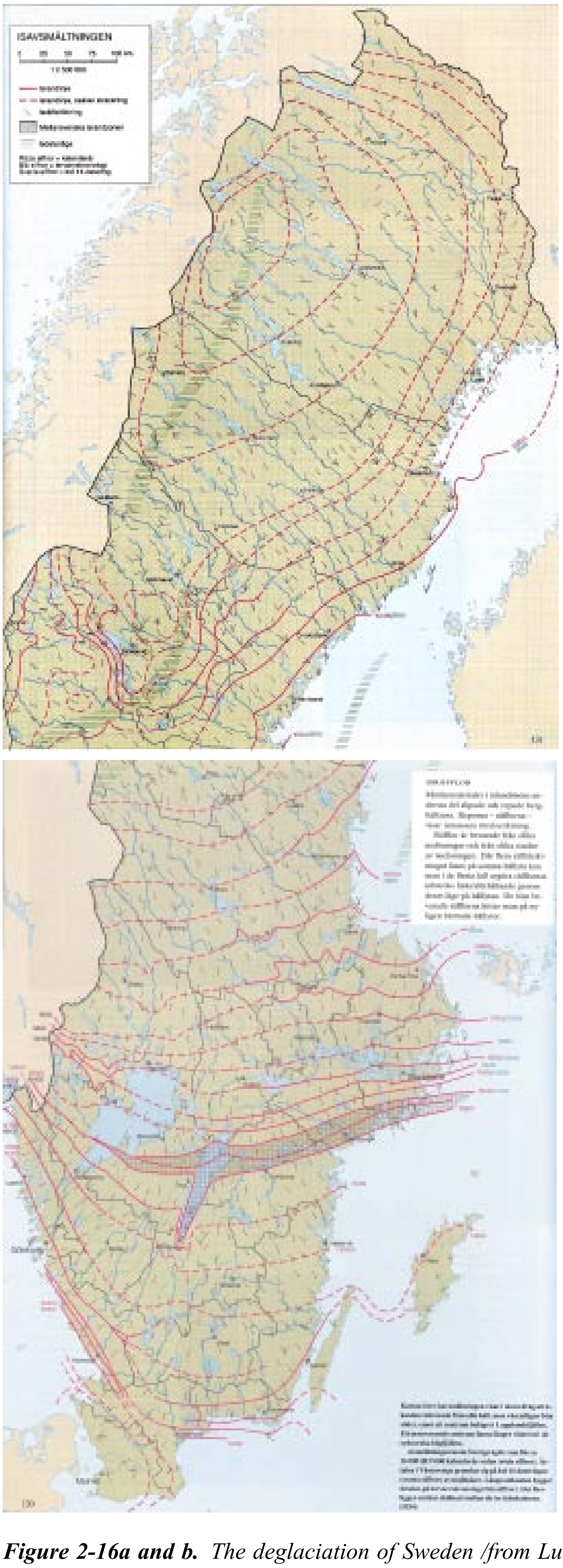


Figure 2-16a and b. *The deglaciation of Sweden /from Lundqvist in Fredén 2002/. The timing of the deglaciation was determined with ^{14}C dates on the west coast and with clay varve chronology on the east coast. The ages have been converted to calibrated years BP. Red numbers = calibrated years BP, blue numbers = clay varve years BP, black numbers = ^{14}C years BP.*

3 Interpretations of basal conditions of the Weichselian ice sheet in Sweden

This chapter discusses the basal conditions of the Weichselian ice sheet in Sweden. The discussion is focusing on field data, which indicates weak glacial erosion or frozen-bed conditions during the whole or parts of the Weichselian glaciation. There are several other publications showing the distribution of frozen-bed conditions during the Weichselian /e.g. Kleman et al. 1997, Kleman and Hättestrand 1999, Fabel et al. 2002/. /Kleman et al. 1997/ presents a map with the distribution of frozen-bed conditions during LGM (Figure 3-1). That map is based on field data from several other publications.

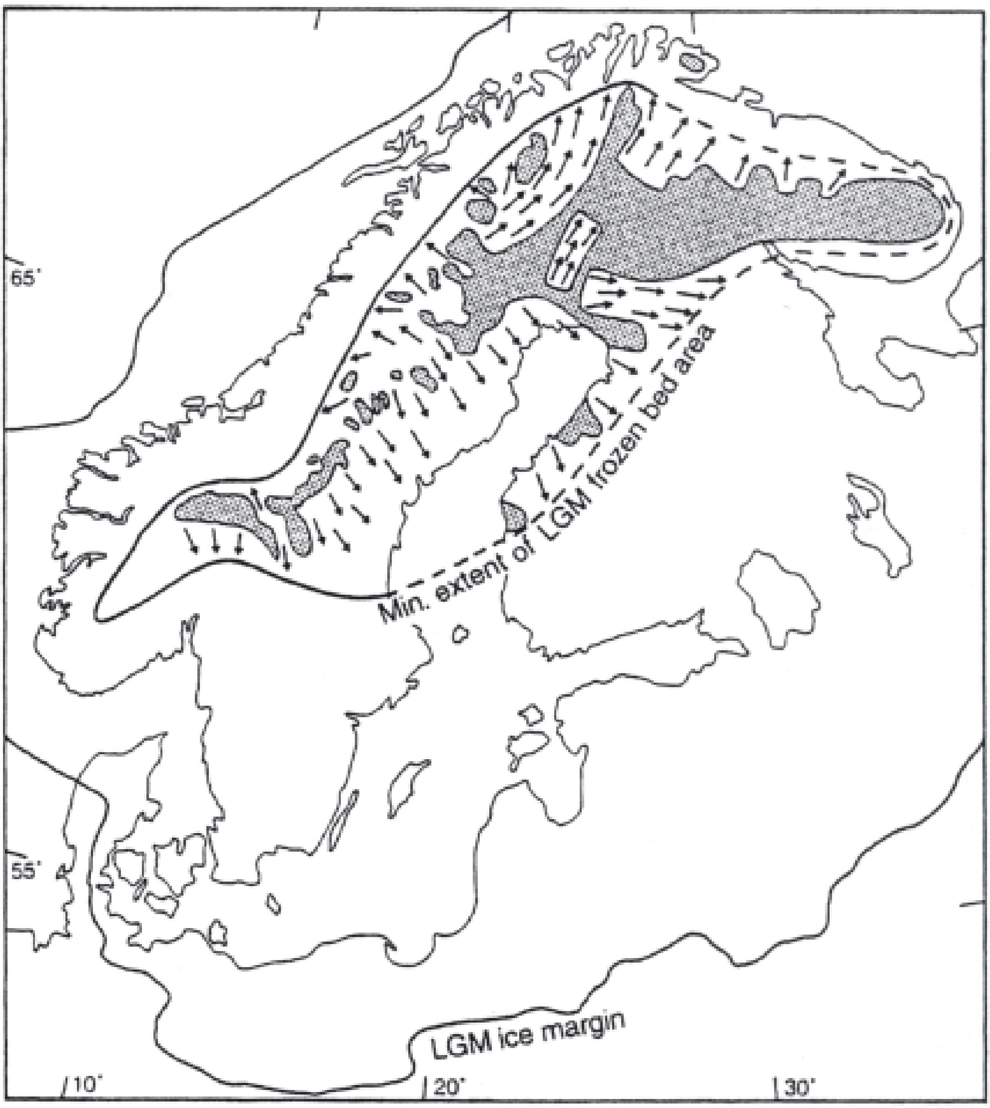


***Figure 3-1.** Distribution of areas with frozen bed during the deglaciation (shaded areas). The interpreted minimum distribution of frozen bed during LGM is also shown on the map /from Kleman et al. 1997/.*

3.1 Areas with deep weathered bedrock

3.1.1 Introduction

Here we aim at defining areas in Sweden where the occurrence of deep weathered bedrock indicates weak or absent glacial erosion. The compilation also contains some information regarding weathered bedrock in Norway and Finland. At certain sites in Sweden, deep weathered bedrock occurs below sedimentary rock or in fracture zones in the crystalline bedrock. Such places are often well protected from erosion and can not be used to make conclusions about the erosional capacity of Quaternary ice sheets. These sites are therefore not included in this report.

It is not always possible to tell if deep weathered bedrock is of pre- or postglacial origin. In some areas there is easily weathered bedrock (e.g. shale) and it is possible that the weathering deposits in such areas were formed after the latest deglaciation. The preglacial weathered bedrock is also found in association with certain types of bedrock. It is possible that thick layers of weathered bedrock were formed in areas with such bedrock before the onset of the Quaternary glaciations.

A large part of the present knowledge of sites with deep weathered bedrock comes from observations made by the Geological Survey of Sweden (SGU). It should be pointed out that there are probably numerous unknown localities with weathered bedrock. Compared to southern Sweden, less intensive fieldwork has been carried out by SGU in the inland of northern Sweden and almost no work has been carried out in the northernmost parts of the Swedish mountains.

Thick layers of glacial and/or postglacial sediments cover the bedrock in large parts of Sweden, which makes it difficult to observe possible occurrences of weathered material. One such example is the areas around Lake Mälaren where the valleys often are covered by thick layers of clay. This is, however, a general problem, which makes it impossible to use the absence of weathered bedrock as an absolute proof of the non-existence of such deposits.

3.1.2 Observations of deep weathered bedrock

Information regarding deep weathered bedrock in Sweden has been reviewed by e.g. /Lundqvist 1985/ and /Migoń and Lidmar-Bergström 2001/. Many sites with weathered bedrock occur in areas that were covered by cold based ice during the glacial cycles. Deep weathered bedrock also occurs in areas situated close to the earlier ice divides and in areas, which have been covered by ice during short periods of time, such as Skåne.

Kaolin-weathered bedrock is the most developed form of weathered bedrock found in Sweden. Kaolin-weathered material in bedrock fractures is known from several places in Sweden. Large areas with kaolin weathered bedrock occur at the border between Skåne and Småland, see Figure 3-2. The kaolin-weathered deposits in southern Sweden are partly covered by Cretaceous sedimentary rock /e.g. Migoń and Lidmar-Bergström 2001/. There are, however, sites with kaolin weathered bedrock, which are not sheltered by sedimentary rock. It is therefore likely that the occurrence of these deposits indicates weak erosional capacity of Quaternary ice sheets. The kaolin rich deposits in southern Sweden were formed in a warm climate prior to the Cretaceous period. /e.g. Lidmar-Bergström et al. 1997/. Kaolin deposits have also been found in northernmost Sweden. These deposits were probably formed by processes in bedrock fractures and not by chemical weathering close to the ground surface (Robert Lagerbäck SGU oral comm.).

Granular weathered bedrock is mostly formed by physical processes and is not as far developed as kaolin weathering. The granular weathered bedrock is in most cases older than the Quaternary period but is regarded as younger than the kaolin weathered bedrock /Lidmar-Bergström et al. 1997/. Examples of granular weathered bedrock can be found in areas that, during the glacial cycles, has been situated close to the ice divide, see Figure 3-2, e.g. in Jämtland and in parts of

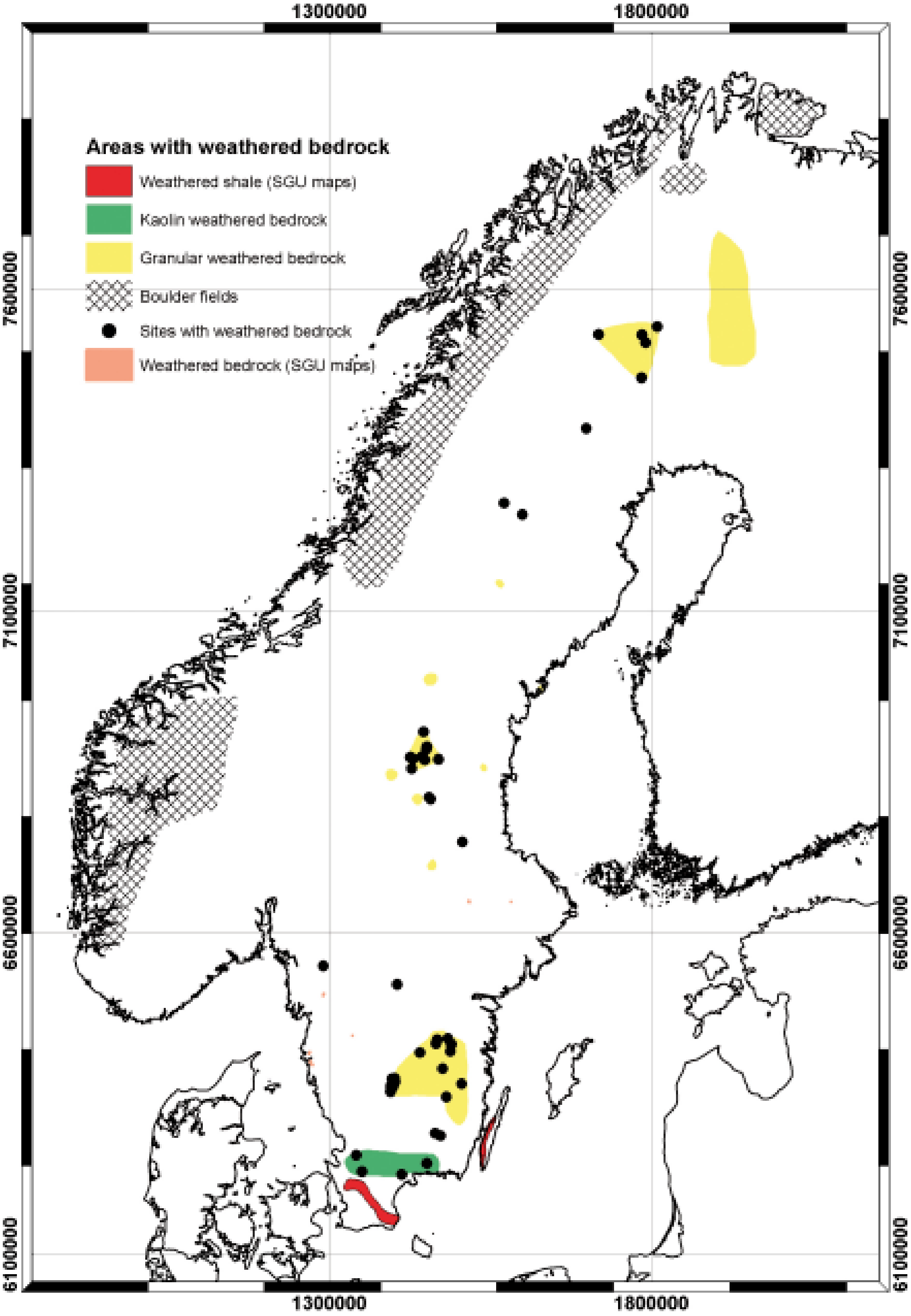


Figure 3-2. *The distribution of areas and sites with different kinds of deep weathered bedrock in Fennoscandia.*

Norrbotten /Lundqvist 1985/. This type of weathered bedrock occurs, however, also in other areas such as on the Swedish west coast, in north-eastern Småland and southern Östergötland /Agrell 1973, Hillefors 1985, Lidmar-Bergström et al. 1997/. /Lidmar-Bergström et al. 1997/ distinguished an area in eastern Småland and southern Östergötland, Figure 3-2, where granular weathered bedrock is common. /Hillefors 1985/ describes localities on the Swedish West Coast where deeply weathered bedrock occur, see Figure 3-2. All these sites are, however, situated in lee positions in relation to the movement of the ice sheet.

/Malmström 1991/ has reviewed the occurrences of boulder fields in Scandinavia, see Figure 3-2. In that work the boulder fields were identified by interpretation of satellite images. Boulder fields are common at high altitudes in large parts of the Swedish and Norwegian mountains. The glacial erosion has been more intense in the valleys and boulder fields are therefore uncommon in such positions.

Tor formations, which were formed due to deep weathering, occur in certain parts of Sweden, especially in northern Sweden. These formations are probably more common in areas where the glacial erosion has been weak. /Johansson 2003/ has compiled sites with tor formations in the western parts of Norrbotten.

The distribution of weathered bedrock coincides largely with areas which according to /Kleman et al. 1997/ were characterised by frozen-bed conditions during LGM. /Kleman et al. 1997/ has, however, not interpreted the occurrence of weathered bedrock in southern Sweden as an effect of frozen-bed conditions.

3.1.3 Observations of deep weathered bedrock made by SGU

Deep weathered bedrock has been observed at a large numbers of localities during SGU's fieldwork. Most of these observations have been made during SGU's regular mapping activities. This information has, however, not been compiled earlier.

Several geologists at SGU have made observation of weathered bedrock in the same area on the South Swedish highland where Lidmar-Bergström and Agrell have found several localities with deep weathered bedrock /e.g. Agrell 1973, Lidmar-Bergström et al. 1997/. There is an area with granular weathered bedrock (mainly syenite) south of Vättern in Småland shown in Figure 3-2. These sites are often situated in positions, which have been exposed to ice movement. The weathered material has most probably been formed prior to the onset of the Quaternary period and it is therefore likely that these deposits can be used as indicators of weak glacial erosion in parts of Småland and Östergötland. In addition several geologists at SGU have made numerous observations of granular weathered bedrock in an area situated close to the former ice divide in Hälsingland and Härjedalen, see Figure 3-2.

Geologists from the Geological Surveys in Norway, Sweden and Finland have described a large number of localities with weathered bedrock in northernmost Finland and Sweden /Hirvas et al. 1986/. The occurrence of the weathered deposits indicates that those parts of Norrbotten and northern Finland only to a small extent have been affected by glacial erosion.

There are sporadic occurrences of weathered bedrock in many parts of Sweden, e.g. at the High Coast in Ångermanland and in south-west Sweden, Figure 3-2. It is difficult to conclude if these deposits have been preserved due to generally weak glacial erosion or due to protection in lee-side positions.

Up to 1.5 metres thick layers of weathered shale were found during the mapping of Quaternary deposits on Öland /Rudmark 1983/. These deposits were, according to Rudmark, formed prior to the latest glaciation. There are large areas of weathered shale in the south-eastern part of Skåne /Daniel 1992/. The age of these deposits has, however, not been discussed in the litterature. The occurrence of weathered shale was also observed during the mapping of Västergötland /Johansson et al. 1943/. Shale is easily affected by physical weathering and it is therefore likely that these weathered deposits have been formed after the latest deglaciation.

3.1.4 Conclusions

The results from the compilation of weathered bedrock are summarised in Figure 3-2. There are four regions where a large number of sites with weathered bedrock indicate that the glacial erosion probably has been weak throughout the Quaternary Period:

1) Kaolin weathered bedrock has been observed at several sites at the border between Skåne and Småland and in easternmost Blekinge.
2) There are a large number of localities with granular weathered bedrock on the central and eastern parts of the South Swedish Highland.
3) There are numerous localities with granular weathered bedrock in the central part of Sweden, in the area where the ice sheet divide was situated at times.
4) There are several localities with granular weathered bedrock in northernmost Sweden and Finland.

In certain areas it is uncertain if the occurrences of weathered bedrock indicate weak glacial erosion:

1) Weathered material formed in areas with shale (e.g. on Öland and in Skåne and Västergötland).
2) Single occurrences of granular weathered bedrock (e.g. on the Swedish west coast and on the High Coast in Ångermanland).

3.2 Areas with till-covered eskers and Veiki moraine

Areas with Veiki moraine indicate where there are remnants from Early Weichselian glaciations /Lagerbäck 1988a/. Also areas with till-covered eskers may indicate remnants from earlier glaciations. These eskers may have been deposited during a previous glaciation and covered by till during a following glaciation. These deposits can therefore give information of where the last Weichselian glaciation had weak erosive effect on the landscape, and may be used to distinguish between areas where the ice was cold-based and warm-based.

/Hättestrand 1998/ and /Lagerbäck 1988a/ have compiled areas with Veiki moraine. The distribution of Veiki moraine in the two publications agrees fairly well, with the difference that /Lagerbäck 1988a/ has a more widespread distribution since he also includes features that are related to Veiki moraines. We chose to outline the distribution of Veiki moraines according to /Hättestrand 1998/, Figure 3-3.

Till-covered eskers have been reported from many parts of Sweden, Figure 3-3. The distribution of till-covered eskers has been compiled through studies of literature and oral communication with colleagues at SGU who have been involved in the mapping of the Quaternary deposits in Sweden. There is a problem, however, to distinguish eskers with a till cover of a later glaciation from those with a till of the same glaciation. Therefore, till-covered eskers with chronostratigraphical control /Lagerbäck 1988b/ are presented with a different colour than till covered eskers that are presumed to be of a pre-Late Weichselian age, but lack chronostratigraphical control /Lundqvist 1967, Eklund et al. 1989, Svedlund and Wiberg 1990, Ek 1999, 2003, in press, Norrlin and Sundh 2003/. Additionally, presumed pre-Weichselian till-covered deltas /Rydström 1971, Daniel 1989, 1994/ (Harald Agrell oral comm. 2003, Gunnel Ransed oral comm. 2003) are included in Figure 3-3. The distribution of sites with till-covered glaciofluvial sediments and Veiki moraines covered in this report may agree with areas that have been mapped more thoroughly. However, since most of Sweden has been mapped to some extent, we regard it likely that the achieved distribution of the referred features closely represent the true picture.

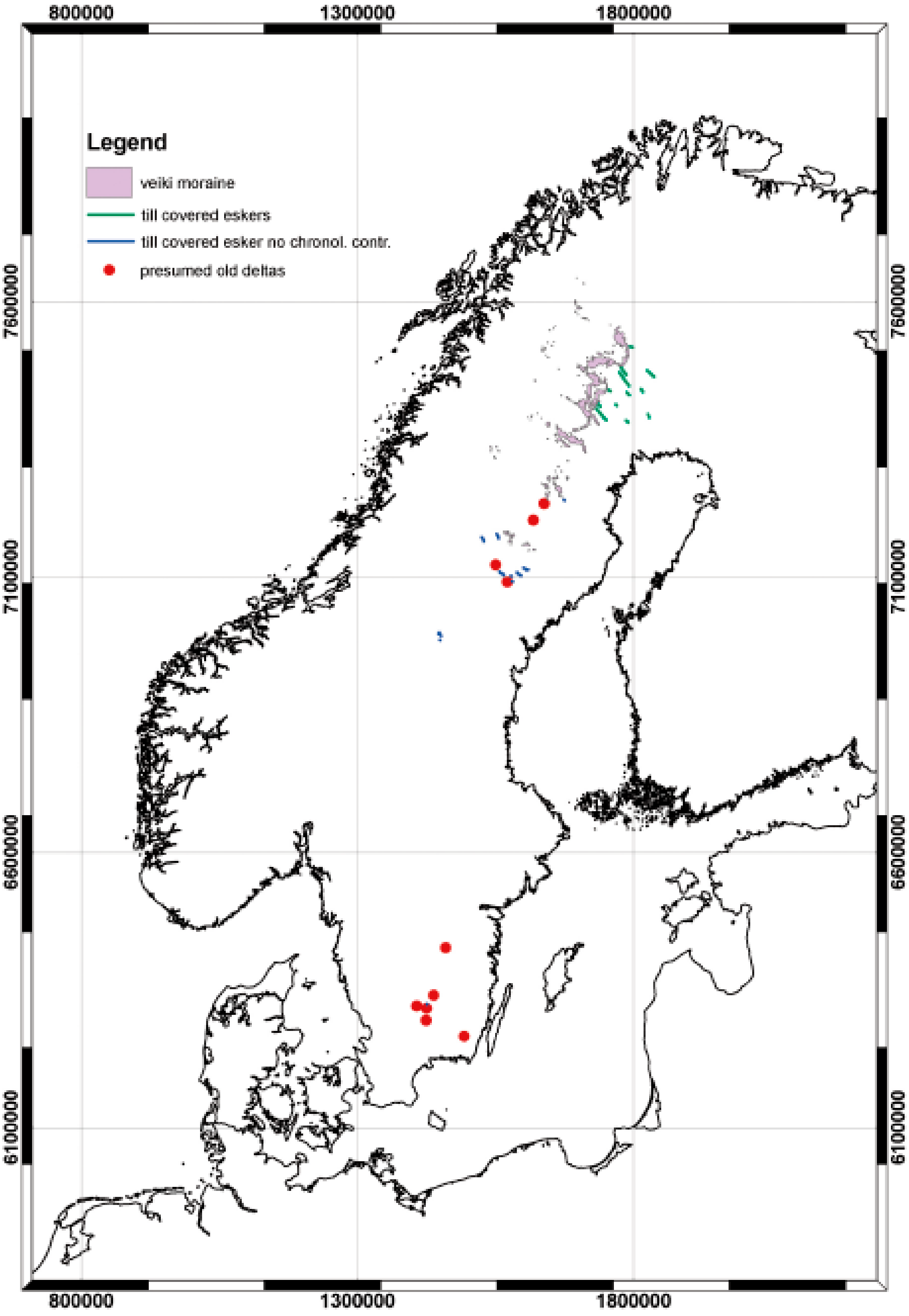


Figure 3-3. *Sites with Veiki moraine, till-covered eskers and presumed old deltas (from Hättestrand 1998 and SGU's databases).*

4 Conclusions

General variations of the global climate and ice volumes during the Weichselian glaciation are well established from the marine record. The timing of local and regional ice-marginal fluctuations in terrestrial areas, which were glaciated, are less well established.

There have been at least two interstadials during the Weichselian with ice-free conditions in most parts of Fennoscandia. The exact timing of these interstadials is, however, under debate. Some researchers suggest that two interstadials took place during the Early Weichselian. Other suggest one ice-free interstadial during the Early Weichselian and one during the late part of Middle Weichselian.

Northern Fennoscandia was covered by ice sheets once or twice during the Early Weichselian. The southernmost extension of these ice sheets is not established.

Some researchers suggest that most of Fennoscandia was covered by an ice sheet throughout the Middle Weichselian. Alternatively, it is suggested that large parts of this area were free of ice during a part of this time period.

The Weichselian ice sheet had its largest extent during the later part of the glaciation. The timing of the final deglaciation is well established and several readvances of the ice front are documented from that period. The erosional effect of Quaternary ice sheets has probably been weak in large parts of Småland and in the inner parts of northern Sweden, indicating that cold-based conditions has been the dominating basal regime of the ice sheet in these areas.

5 Notes from a Workshop on Weichselian glacial history

Stockholm University, March 15 2005

A workshop was held at Stockholm University on Mars 15th 2005. The objectives of the workshop were to identify and discuss the most debatable – but also the indisputable – ice fluctuations during the Weichselian and to explain the underlying reasons for different interpretations. Most uncertainties concern the glacial history prior to the Last Glacial Maximum (LGM) and therefore the discussions were focusing on this period.

Altogether 29 researchers, from all Nordic countrys, took part in the meeting.

The workshop was opened by Lena Morén (Swedish Nuclear Management Company, SKB) who talked about the need for taking climate and climate related processes into account when analyzing the safety performance of a deep geological repository for nuclear waste.

Jens-Ove Näslund (Stockholm University) gave a background on the ice sheet modelling approach used by SKB. He also talked about why it is important with dated information on the glacial history of Fennoscandia, from geological stratigraphy and morphology, in such modelling studies.

Lars O. Ericsson (Chalmers University of Technology) acted as a chairman during the meeting.

5.1 Panel member talks

5.1.1 Jan Lundqvist (Stockholm University)

Title: Weichselian glacial history of Sweden

Poor and few dates make it difficult to say anything about the earlier parts of the Weichselian glaciation in Sweden. Traditional stratigraphical sites with sediments showing ice-free conditions have earlier been straightforwardly correlated to the Brørup and Odderade interstadials but absolute dates are lacking. In the search for the glaciation history between MIS 5d to MIS 3 we need more dates. Lundqvist suggests five potential sites in Mid-Sweden for further studies. Pollen studies by Ann-Marie Robertsson (Stockholm University) suggest that the extent of "the old blue till" might represent the ice sheet coverage during MIS 4 rather than 5b, which has been suggested earlier /Robertsson et al. 2005/. From the distribution of the old blue till, the centre of the ice sheet might have been located far south, similar to the picture around 65 ka BP (thousand years before present) from /Kleman et al. 1997/.

5.1.2 Lars Olsen (Geological Survey of Norway)

Title: Rapid adjustments of the western part of the Scandinavian Ice Sheet during the Middle and Late Weichselian

In Norway stratigraphical data from caves, coastal sites and inland sites show frequent and large ice sheet fluctuations, with advances culminating around 40, 30, 22 and 15 ka ^{14}C BP (i.e. c 44, 34, 25 and 17 ka calibrated BP). Age control is based on 280 dates (^{14}C, thermoluminescence (TL) and optically stimulated luminescence (OSL) dates). In four of the caves, the Lake Mungo paleomagnetic excursion at 28 ka ^{14}C BP (i.e. 32 ka calibrated BP) has been found in the sediments. Many stratigraphical localities indicate relatively little ice around 32 ka ^{14}C BP (i.e. 36 ka calibrated BP), but significant ice retreats, almost as large as at 32 ka are also recorded around

26 and 19 ka ^{14}C BP (i.e. 30 and 22 ka calibrated BP). The ice advances in different geographical regions are not supposed to have been fully synchronous, but rather of time transgressive nature, whereas the ice retreats were synchronised, partly due to climatic variations, but mainly because of sea-level changes which influenced the stability of all of the marine based western and north-western margins of the Fennoscandian ice-sheet. Luminescence ages uncorrected for shallow traps fits better than uncorrected ages to other dating methods and ^{18}O stratigraphy from Greenland.

Comments: *Eiliv Larsen* (Geological Survey of Norway) comments on the time transgressive nature of the last glacial maximum. The maximum glacial extent in the Archangels region was reached 8 ka later than in south-western Scandinavia. Then there was potential and enough moisture to build ice in the north-eastern part of ice sheet. *Jens-Ove Näslund* (Stockholm University) points out that you may see a non-synchronic behaviour in the ice sheet model simulations as well.

5.1.3 Mikael Houmark-Nielsen (University of Copenhagen)

Title: South-western Scandinavian during the Weichselian

The time transgressive nature of LGM (Last Glacial Maximum) was emphasised. A composite stratigraphy from sections in northern Jylland, south-western Jylland and south-eastern Denmark infers the following early-middle Weichselian glaciation history: Northern Denmark was invaded by an ice following the Norwegian channel around 70–60 ka BP. Around 50 ka BP Denmark was reached by an ice sheet coming from the east, from the Baltic Sea. A second fast flowing Baltic ice advance inundated Denmark around 35 ka cal BP. The time control is based on OSL dates that have been compared to ^{14}C dates, and the dates make a good matching /Murray and Olley 2001/. Furthermore a lot of the stratigraphical sites have Eemian marker beds. Optically stimulated luminescence dates of Eemian sediments from Stensig mosse average 119 ka BP /Murray and Funder 2003/.

/Marks et al. 1995/ infer that northern Germany was reached by a Baltic ice around 50 ka BP. The Vistula region in Poland was ice free during the Early Weichselian and was according to /Wysota et al. 2001/ first invaded by ice 70 ka BP. Houmark-Nielsen suggests a subtraction of 10 ka which give an ice in the Vistula region around 60 ka. Latvia was ice free until 60–40 ka BP.

Comments: *Eiliv Larsen* asks about the distribution of tills and the differences between them? *Mikael Houmark Nielsen* replies that it is the erratic content that distinguishes the different tills apart and shows the direction of ice movement. The keys to understand when Denmark was covered by ice from either Norway or Sweden are:

- Migration of ice divides.
- Climate systems (cyclones etc).
- Breaking-up of Norwegian Channel Ice stream (glacioisostatic loading of trough).

5.1.4 Pirkko Ukkonen (Lund University)

Title: Large ice-free areas in Fennoscandia during the Middle Weichselian

Mammoth bones found in Finland, Norway, Denmark and Estonia have been ^{14}C-dated since 1960. Many dates come out as infinite suggesting mammoths of Early Weichselian age or older. Some dates of mammoths from Finland and Norway come out as 36–20 ka ^{14}C BP, inferring ice-free conditions some time during the Middle Weichselian. Another group of dates are from mammoths yielding finite ages younger than 20 ka ^{14}C BP, with the youngest dating, 10 ka^{14}C BP, from Estonia.

There are some uncertainties regarding the datings and collection sites. Most bones are stored in museums and might have been contaminated by the treatment with preserves. There are also scientists that address the anomalies of bones as a dating problem. As for the collection sites there are only very few mammoths that have been found *in situ*. Thus, to avoid long transport distances Ukkonen uses mostly bones and tusks and well preserved molars.

In the near future, Ukkonen will try to collect bones from central Sweden. In addition to ^{14}C datings she will analyse the ^{18}O composition on the molars, giving temperatures.

Comments: *Mikael Houmark-Nielsen* embraces the idea of how the mammoths wandered between ice-free areas, thus showing the dynamics of the Weichselian ice sheet. Olsen refer to a U/Th date of a mammoth-bone from Lillehammer, Norway, yielding an age of 43 ka cal BP, which agrees fairly well with the ^{14}C ages.

Discussion

Lars O. Ericsson starts the discussion. The oxygen isotope data indicates a large global ice volume during MIS 3. If large areas in Fennoscandia were ice-free during MIS 3, where was the ice?

Johan Kleman (Stockholm University) suggests a residual ice dome in north-eastern Sweden during MIS 3. He makes the comparison to Baffin Island in north-eastern Canada. On Baffin Island there is at present an ice dome that has lingered there for 10,000 years, throughout the Holocene. Such an ice dome could explain the quick subsequent ice sheet build-up to a maximal position in Europe. He also proposes that dynamic lobes and thin ice probably had their source from multiple ice domes.

Jan Lundqvist likes Kleman's idea with a residual ice dome in the eastern part of Sweden, suggesting that the ice sheet build-up started from the lowland and not from the mountains. Lundqvist also rejects some of the Swedish Middle Weichselian dates that he suspects are too young.

Juha-Pekka Lunkka (University of Oulu) presents five new OSL dates sampled from a sand layer, sandwiched between two tills, in SW Finland. The sand yields ages between 40–34 ka cal BP inferring ice-free conditions at this time.

Mikael Houmark-Nielsen urges all of us to stop trying to come up with a picture that fits the one we have in our minds or otherwise reject it. With any possible ice configuration there were probably not a continuous ice cover during MIS 3. It was probably a dynamic system with fast and short ice advances, lasting for a couple of 1,000 years.

Karin Helmens (Stockholm University) presented results from a core from central Sokli in Finnish Lapland, which confirms the stratigraphy presented from that site by /Helmens et al. 2000/. It includes a nearly continuous sediment record from the central Sokli basin with only minor coring gaps in the coarsest layers. OSL dates on single quartz grains has supported an earlier correlation with the marine oxygen isotope record /Helmens et al. 2000/. The core covers the period from the Eemian to the Holocene, showing open tundra during MIS 5d, birch forest during MIS 5c, glaciation during MIS 5b, close to tree line environment during MIS 5a, glaciation during MIS 4, shrub tundra during part of MIS 3 and glaciation during MIS 2/3. Thus, no glacial trace was recorded during MIS 5d–5c and MIS 5a. Furthermore, there were ice-free conditions around 45 ka cal BP. The stage 3 deposit includes a laminated minerogenic clay-silt sequence indicating glacio-lacustrine conditions; surrounding ice-free areas were covered with shrub tundra vegetation. She emphasises the importance of correlating data concentrated to certain sectors within the Fennoscandian ice sheet. The long and continuous Sokli record could serve as a type-section for the north-east sector of the former ice-sheet.

Juha-Pekka Lunkka considers /Helmens et al. 2000/ data from eastern Finnish Lapland to be consistent with his data from south-western Finland. However, since /Helmens et al. 2000/ observations are made from borehole material he stresses that caution should be exercised not to over-interpret the results from the Sokli boreholes.

Regarding luminescence dates from Finmark *Lars Olsen* prefers TL or OSL dates, uncorrected for shallow traps. The uncorrected age (average of several dates) of interstadial sediments (Peräpohjola), overlying till bed III, is 87 ka BP, which corresponds well with the data of /Helmens et al. 2000/.

Jan Lundqvist comments that the data of Helmens, inferring that MIS 5c was warmer than MIS 5a, is consistent with other data from northern Sweden. However, data from the European continent suggest the contrary. *Karin Helmens* answers that one problem is the delay of signals using pollenstratigraphy. She furthermore promotes the use of the more quickly responding chironomids instead.

Juha-Pekka Lunkka presents new data from Osterbothnia where 48 samples have been OSL-dated, using both quartz and feldspar. Both methods imply ice-free conditions in Osterbothnia during the Early (MIS 5c, 5e) and Middle Weichselian (MIS 3).

Johan Kleman thinks that the marine oxygen isotope record exaggerates ice volumes, for example inferring large ice volumes during Early Weichselian when there probably was little ice in Europe. He thinks we should use the latest data from coral reefs.

Michael Houmark-Nielsen comments that there probably were ice sheets in the Kara and Barents Sea during the Early Weichselian.

Jens-Ove Näslund says that his models usually do not grow a lot of ice during the Early Weichselian. However, at certain times during Early Weichselian there was thin ice covering extensive areas in northern Fennoscandia, which may or may not be a model artefact.

Robert Lagerbäck (Geological Survey of Sweden) presents his experience of luminescence dating and shows some selected examples. TL and OSL dates from the same sample material differ dramatically. Several OSL dates are also highly contradictory to ^{14}C dates obtained from the same stratigraphies and in complete conflict with the generally accepted glacial development during MIS 2. He is consequently very sceptical to many of his dates.

Lars Olsen comments that a significant part of the apparent age discrepancies disappear when the TL dates are used uncorrected (i.e. not corrected for shallow traps). Such dates give ages that are only c 73% of the corrected ones (e.g. a dating of 55 ka BP, corrected age, equals c 40 ka BP, uncorrected age).

Eiliv Larsen means that lacustrine sediments have proven to be problematic for the luminescence method.

Barbara Wohlfarth (Stockholm University) as well as *Karin Helmens* suggests that Lagerbäck should try to date single grains instead of bulk samples.

Helena Alexandersson (Stockholm University) presents new OSL dates from delta sand in Småland. The sands yield ages around 20 ka, suggesting ice-free conditions at a time when it is generally believed that Sweden was covered by ice. She also presents dates from till covered glaciofluvial sediments, yielding ages around 60–70 ka. This data is new and still unpublished.

5.2 Tentative answers to workshop questions

Several questions concerning the Weichselian glacial history were sent out to the invited participants before the workshop. The answers to these questions as summarised in the text below.

Interstadials

I) Was there only one interstadial interval with ice-free conditions in northern Fennoscandia during MIS 5d–a?

There are several possibilities:

1) There are indications of ice-free conditions throughout 5d–c (at least in Finnish Lapland and SW Finland). The first Weichselian ice (5d) may therefore have had a small geographical extension.
2) Northern Fennoscandia was ice covered during 5d and 5b and ice-free during 5c and 5a.
3) One long interstadial with ice-free conditions persisted in northern Fennoscandia in early Weichselian, during 5c, 5b and 5a.

To answer this question more correlations between sites are necessary.

II) Were large parts of Fennoscandia ice free during a part of Middle Weichselian (around MIS 3)?

There are plenty of results indicating ice-free conditions in large parts of Fennoscandia during MIS 3. Everyone agrees that Finland and Norway may have been partly free of ice during MIS 3. Northern Sweden may also have been ice-free. Many luminescence dates support this hypothesis, but some are less straightforward to interpret.

Stadials

III) How far south did the Early Weichselian ice sheet/s reach?

The ice did not reach Denmark, Poland or Latvia during the Early Weichselian. The southernmost extension of ice in Sweden and Finland is not known.

IV) How far south did the Middle Weichselian ice sheet reach?

Ice streams during MIS 4 reached Denmark, Poland (Vistula) and Latvia. The western part of the ice margin was oscillating throughout Middle Weichselian.

Methods

V) Are the different interpretations a result of poor dating, and can new dating techniques and data contribute to more reliable interpretations?

Different interpretations may partly be due to different glacial histories (event stratigraphies) at the investigated sites and the ice sheets were probably more dynamic than previously thought. We need more thorough data concentrated on certain sectors within the Fennoscandian ice-sheet.

The accuracy of the different dating methods is a problem. There are sometimes large differences between ages achieved from different dating techniques. Single-grain OSL dating may prove to be a useful tool when interpreting the Weichselian glacial.

Approaches for the future

How can the current discrepancies be resolved?

Karin Helmens will try to do tephra-chronology on her Sokli cores and *Barbara Wohlfarth* states that tephras from the interesting periods have been found in the North Grip ice core.

Johan Kleman push forward cosmogenic dating and *Arjen Stroeven* (Stockholm University) confirms that it is a promising tool for estimating the length of ice cover periods.

Jan Lundqvist suggests that one should date sediments from good sites in Swedish Jämtland.

Robert Lagerbäck recommends an active search for good stratigraphical sites (as complex and complete as possible) along a transect from northern to southern Sweden. These sites should be bio- and lithostratigraphically correlated among themselves and linked to the well-established stratigraphy of Northern Europe (Brørup, Odderade etc).

Johan Kleman suggests chronostratigraphical investigations of Veiki moraines, using OSL, tephra etc.

Per Möller lacks data on when southern Sweden first was glaciated during the Weichselian. We know reasonably well when Denmark first was glaciated, what about the white spot in Småland.

5.3 Conclusions from the workshop

- A lot of data presented at the workshop points towards extensive areas of ice-free conditions in Fennoscandia during MIS 3. None of the workshop participants wanted to exclude the possibility of restricted MIS 3 ice-coverage.
- The Weichselian glaciation was characterised by variable climate conditions.
- The Fennoscandian ice sheet was dynamic and probably corresponded relatively quickly to changes in climate.
- The southern and eastern parts of Scandinavia were ice-free during large parts of the Weichselian glaciation.

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