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Ice-free conditions in Fennoscandia during Marine Oxygen Isotope Stage 3?

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Preface

This document contains information on the Weichselian glacial history, specifically of conditions during Marine Isotope Stage (MIS) 3, the period preceding the Last Glacial Maximum. The information will be used in e.g. the report "Climate and climate-related issues for the safety assessment SR-Site".

Stockholm, April 2009

Jens-Ove Näslund
Person in charge of the SKB climate programme

Contents

1 Introduction

One of the central aims of the climate research conducted by the Swedish Nuclear Fuel and Waste Management Company (SKB) is to investigate the extremes within which climate conditions may vary within a 100,000 year perspective /SKB 2006/. The 100,000 year time perspective corresponds to one glacial cycle during which warm interstadial and cold stadial conditions alternated, leading to ice sheet advance and retreat over Fennoscandia. To address the issue of how extreme climate conditions may impact the deep nuclear waste repository, a climate modelling study was initiated with the aim to investigate the response to different climate scenarios: glacial conditions, permafrost conditions and temperate conditions /Kjellström et al. 2009/. A model set-up for the permafrost and glacial scenario required information on, for example past ice cover, vegetation, and land-sea configuration.

The permafrost climate scenario focussed on a stadial event (Greenland stadial 12) during Marine Oxygen Isotope Stage (MIS) 3, because it was assumed that southern Sweden and the areas of Forsmark and Oskarshamn were not ice covered, but possibly experienced permafrost conditions /Näslund et al. 2008/. This assumption however needed to be validated by paleoenvironmental and paleoclimatic records for MIS 3. Available paleoenvironmental records for this time interval are comparably scarce and due to chronological uncertainties also partly conflicting. Most records are derived from marginal areas of the former Fennoscandian ice sheet and only little and inconsistent information exists for the central part. Geological investigations along the Norwegian coast /Olsen 1997, Olsen et al. 2001ab, Mangerud et al. 2003/, in Denmark, southern Sweden /Houmark-Nielsen and Kjær 2003, Kjær et al. 2006, Houmark-Nielsen 2007/, northern and eastern Finland /Helmens et al. 2007ab, Lunkka et al. 2008/ have for example shown that the Fennoscandian ice sheet margin responded distinctly to some of the warmest middle Weichselian interstadials (MIS 3) (Figure 2-1). Interstadial organic sediments from the central part of the former ice sheet have been described from several localities in Sweden /e.g. Lundqvist 1967, 1978, Hillefors 1974, Miller 1977, Lagerbäck and Robertsson 1988, García Ambrosiani 1990/, but radiocarbon (^{14}C) dates for these deposits provided ages which seemed incompatible with their pollen stratigraphic assignment. Consequently complete ice cover over Fennoscandia was assumed during MIS 3. ^{14}C dated mammoth remains, albeit reworked and transported over some distance, recently suggested ice free conditions over Sweden between ca. 44 and 24 thousand years (kyr) /Ukkonen et al. 2007/. These results are however at odds with the reported ages of interstadial deposits and also with those published for ice sheet advances. A compilation and careful evaluation of all available age measurements therefore seemed necessary in order to assess the extent of the Fennoscandian ice sheet during MIS 3.

^{14}C, Thermoluminescence (TL), Optical Stimulated Luminescence (OSL), and Uranium/Thorium (U/Th) dates which have been published for Norway, Denmark and Sweden for the time interval prior to the Last Glacial Maximum have to some extent been separately compiled by e.g. /Olsen et al. 2001ab, Arnold et al. 2002, Houmark-Nielsen and Kjær 2003/. A compilation of all available dates and a careful evaluation of the quality of these dates, which could potentially provide information regarding ice cover versus ice free conditions in the central part of the former ice sheet prior to the Last Glacial Maximum, has however never been attempted.

This report presents a compilation of published and unpublished ^{14}C, TL/OSL and U/Th dates for Norway, Sweden, Denmark, Estonia and Finland, which were assembled in a data base. This data base is here, with a focus on Sweden, discussed and evaluated in detail, especially in respect to the millennial-scale climate variability which characterized the middle Weichselian or MIS 3.

2 Millennial-scale climate variability during the last glacial period

Millennial-scale climate variability during the last glacial period is a distinct feature seen in ice core records (Figure 2-1), marine sediments, cave speleothems and lake sediment archives, both in the Northern and Southern Hemispheres /Völker et al. 2002, EPICA 2006, Grimm et al. 2006, Hughen et al. 2006, Wang et al. 2008, Clement and Peterson 2008/ (Figure 2-2). These millennial-scale shifts are most pronounced during MIS 3 between 60 and 30 kyr (Figure 2-1), but seem to have also occurred during earlier glacial phases.

Although detailed correlations between different land and marine archives are still unclear, correlations between ice core records from Greenland and Antarctica show that warm and cold phases were in anti-phase with each other /EPICA 2006/. Mechanisms to explain these abrupt climatic shifts include changes in ocean thermohaline circulation /Knutti et al. 2004/, sea ice feedbacks, and tropical processes /Clement and Peterson 2008/.

The signature of millennial-scale climate shifts is most pronounced around the North Atlantic region /Völker et al. 2002/, where temperatures reconstructed from Greenland ice cores indicate amplitude shifts of up to 17°C between warm interstadials (GIS) and cold stadials /Landais et al. 2004/. These estimates are comparable to palaeo-summer and winter sea surface temperature (SST) changes reconstructed for the near-shore mid-North Atlantic /Sánchez-Goñi et al. 2008/. The duration of these millennial-scale events on Greenland varied between ca. 5,000 years for the longest interstadials (GIS 14-13) and ca. 500 years for shorter interstadials (e.g. GIS 4), whereas stadials lasted up to ca. 1,000 years /Krogh Andersen et al. 2006/ (Figure 2-1).

Correlations between Greenland ice core records and North Atlantic marine sequences showed the occurrence of high amounts of ice rafted debris (IRD) coinciding with extremely cold SST prior to GIS 12, 8, 4, 2 and 1 /Bond et al. 1993/. These IRD layers, which were termed Heinrich layers (Figure 2-1), originated from surges of Northern Hemisphere ice sheets /Hemming 2004/. The melt water release during these iceberg surges caused a rise in global sea level /Chappell 2002, Lambeck et al. 2002, Rohling et al. 2004, Arz et al. 2007/, which might have further destabilized the ice sheets, leading to additional ice sheet surging. Provenance analyses of Heinrich layer detritus in North Atlantic marine sediments imply an origin in the Hudson Strait region (Laurentide ice sheet) /Hemming 2004/, although precursor events could possibly have originated from European and Icelandic ice sheets /Grousset et al. 2001/. Melt water events in the Norwegian Sea have lately been associated with Heinrich events and millennial-scale climate variability during MIS 3 /Lekens et al. 2006/ and indicate that the Fennoscandian ice sheet acted as a significant meltwater source, either through the drainage of ice-dammed lakes and/or through sub-glacial meltwater release.

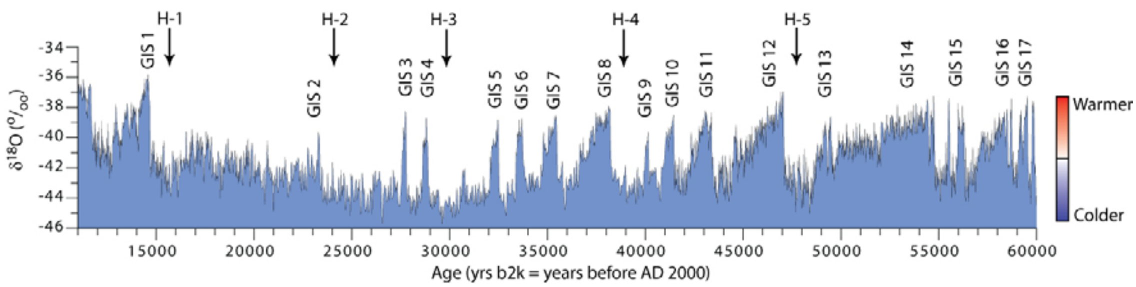

Figure 2-1. *The North GRIP oxygen isotope (δ¹⁸O) stratigraphy for MIS 2 and 3 on the GICC05 timescale. Greenland interstadials (GIS) were succeeded by stadial intervals. Heinrich (H) events 1–5, which have been described from North Atlantic marine sequences, occurred after a series of progressively colder interstadials and in the coldest phase of a stadial. After /Krogh Andersen et al. 2006/.*

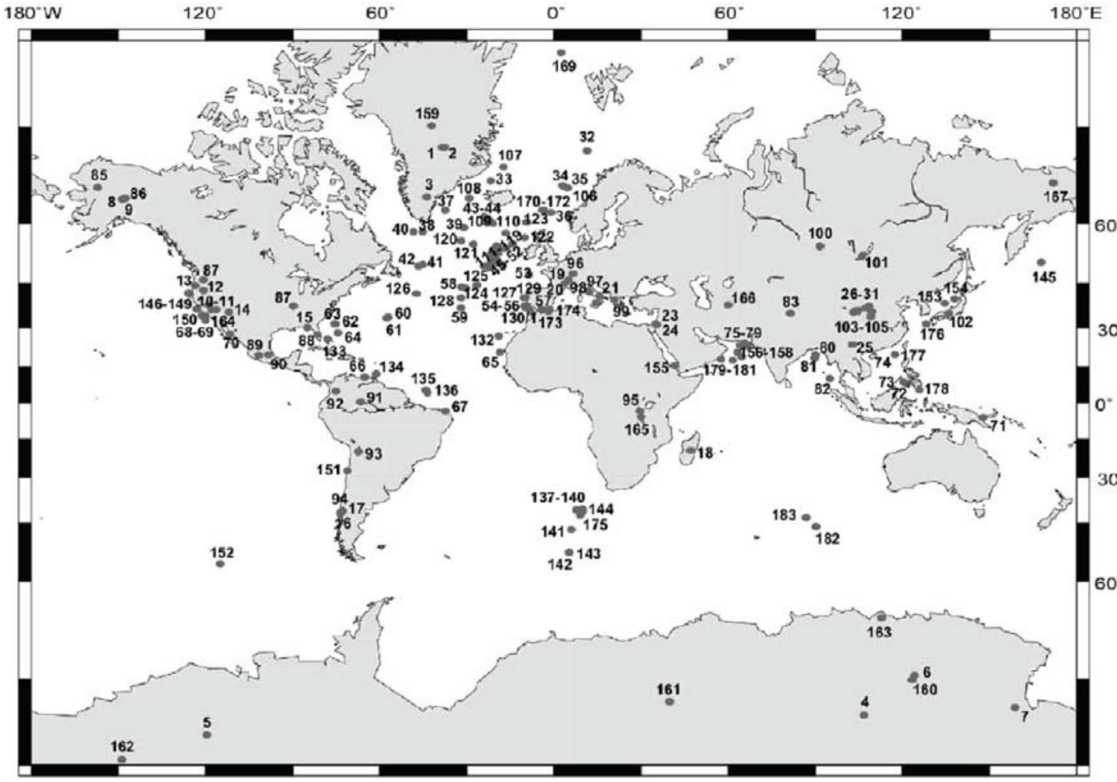

Figure 2-2. *Spatial distribution of ice core, marine, lake and speleothem sequences where millennial-scale climatic shifts have been observed during Marine Isotope Stage 3. After /Völker et al. 2002, figure 2/.*

The effects of millennial-scale climate variability and Heinrich events is strongly seen in areas bordering the North Atlantic /Rasmussen et al. 1996, 2003, Roucoux et al. 2005, Grimm et al. 2006, Sánchez-Goñi et al. 2008/, where the terrestrial vegetation and the lacustrine environment responded in tandem to these rapid temperature fluctuations /Allen et al. 1999, Tzedakis et al. 2004, Grimm et al. 2006, Wohlfarth et al. 2008/. However, the response of the Fennoscandian ice sheet to millennial-scale climatic shifts during MIS 3 has rarely been discussed /Mangerud et al. 2003, Helmens et al. 2007a/.

3 The Fennoscandian Ice Sheet during MIS 3

The simplified picture of the advance and retreat of the Fennoscandian ice sheet during the last glacial cycle /Lundqvist 1992, Donner 1996/ and especially the view that all of Norway, Sweden, Finland, parts of Denmark and the whole Baltic Sea basin had been ice covered between ca. 50 kyr and the start of the last deglaciation at around 17 kyr is now being modified /e.g. Houmark-Nielsen and Kjær 2003, Mangerud 2004, Näslund et al. 2008 and references therein/. Detailed geological investigations along the Norwegian coast /Olsen 1997, Olsen et al. 2001ab, Mangerud et al. 2003/, in Denmark and in southern Sweden /Houmark-Nielsen and Kjær 2003, Kjær et al. 2006, Houmark-Nielsen 2007/ give evidence for a response of the ice sheet margin to some of the warmest MIS 3 interstadials. Studies in northern Finland /Helmens et al. 2007ab, 2009/ and northern Sweden /Hättestrand 2008/ also indicate ice sheet fluctuations during an early part of MIS 3, and /Lunkka et al. 2008/ moreover recently suggested that the eastern part of Finland was ice free between ca. 50 and 25 kyr and that ice advances were restricted to the early Middle Weichselian and to the Late Weichselian.

The latest compilation of the Fennoscandian ice sheet in time and space (Figure 3-1) by (Houmark-Nielsen in prep.) shows a dynamic ice margin with asynchronous advance/retreat during MIS 4-2. According to this compilation, the first major ice advance towards the Norwegian shelf edge (Karmøy) and into the Kattegatt (Norwegian Advance) occurred during MIS 4, at around 75–60 kyr. This was followed by deglaciation along the western and southern ice sheet margin (Bø/Oerel interstadials) and a second advance through the Baltic Basin into Denmark (Ristinge glaciation) and the Polish lowland (Swiecie advance), which seems to have reached its maximum extent around 55–50 kyr /Houmark-Nielsen et al. 2005/ (Figures 3-2 a-b). During the Ristinge advance, the Norwegian shelf edge and fjord coast would have remained ice free, and the western part of the ice sheet would have been confined to the mountain areas.

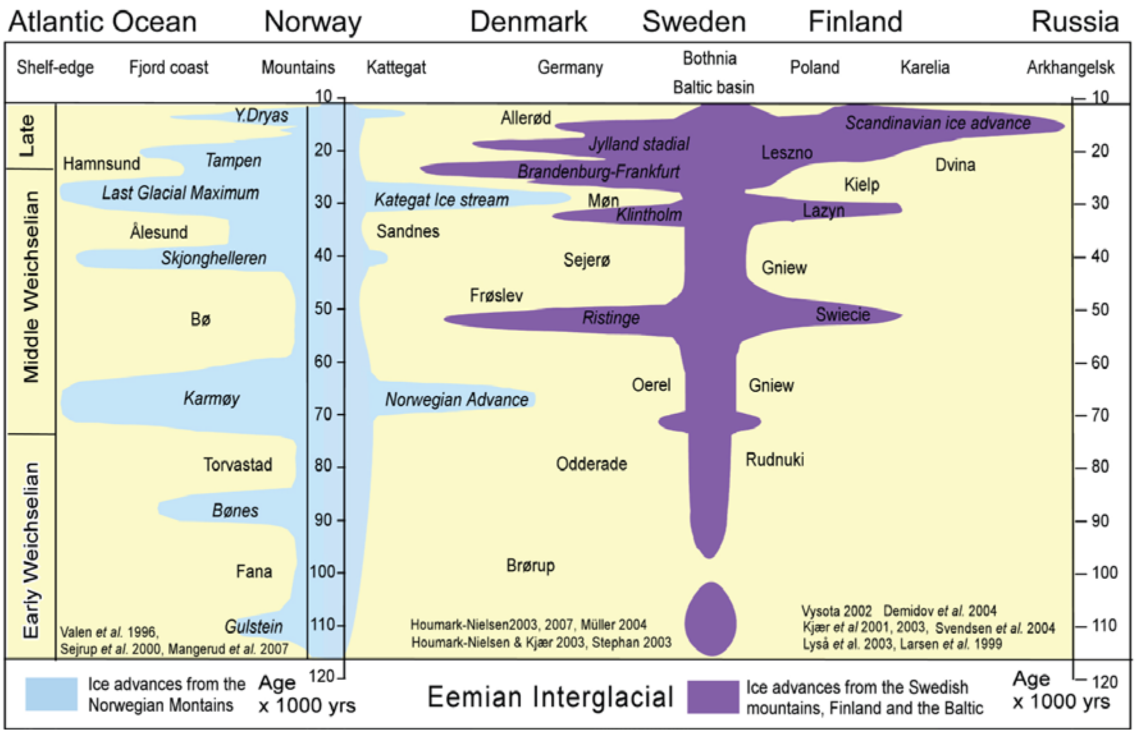

Figure 3-1. *Time-distance diagram showing the advance and retreat of the Fennoscandian ice sheet margin during the Weichselian. This reconstruction assumes more or less continuous ice cover over the Norwegian Mountains, the Baltic basin and central and northern Sweden during the entire Weichselian. See also Figures 3-2 to 3-4. Figure courtesy of Michael Houmark-Nielsen.*

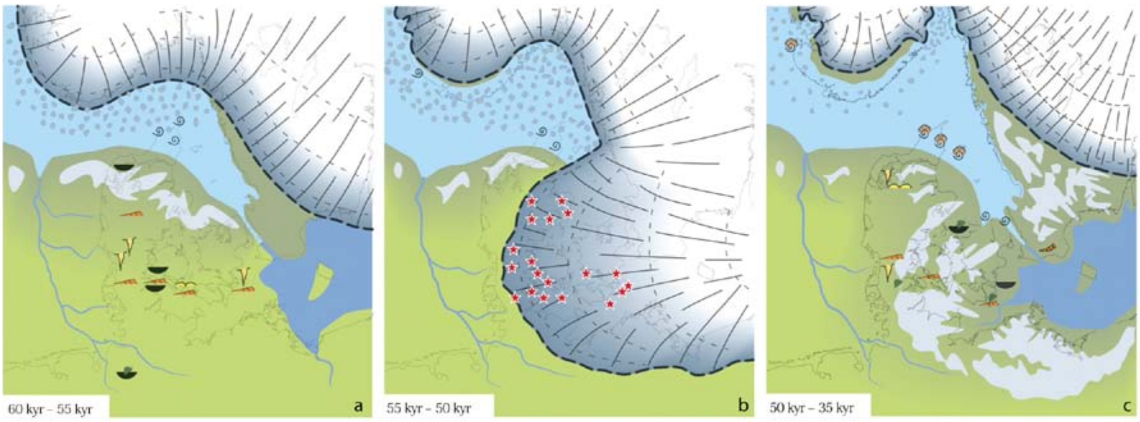

Figure 3-2. *(a, b) The advance of the southern margin of the Fennoscandian ice sheet into Denmark and the Polish lowland (Ristinge advance) between 60–50 kyr seems to have been triggered by an ice stream through the Baltic Basin. (c) The ice margin retreated subsequently and Denmark, southern Sweden and the Norwegian coast became ice free 50–35 kyr. The dashed black line which delimits the ice sheet margin indicates that the exact position of the ice margin is uncertain. From /Houmark-Nielsen et al. 2005/.*

This reconstruction however contrasts with the timing of ice advances and ice retreat presented by /Baumann et al. 1995/ and /Mangerud 2004/, who suggested that the end of the Karmøy advance coincided with an IRD maximum in the Norwegian Sea at around 54 kyr. Melting of the ice sheet (Karmøy advance) along the Norwegian coast might in this latter scenario have occurred during the early part of MIS 3 and more or less synchronously with the Ristinge/Swiecie advances in the south.

Evidence exists for a re-advance along the western and southern margin of the ice sheet (Skjonhelleren) at around 40 kyr /Mangerud et al. 2003, Mangerud 2004/, although Denmark (Sejerø interstadial), southern Sweden and the southern Baltic Sea coast (Gniew interstadial) remained ice free between 50 and 35 kyr /Houmark-Nielsen et al. 2005/. How far north the ice margin receded in southern Sweden is, however, unclear.

During and/or shortly after this time interval, the ice margin also receded from the Norwegian coast (Ålesund interstadial, ca. 35 kyr), but re-advanced in southern Norway, western Sweden and as an ice stream through the Baltic Sea basin into Denmark and Poland (Klintholm/Lazyn advance, ca. 35–33 kyr) (Figures 3-1, 3-3 a) /Houmark-Nielsen et al. 2005/.

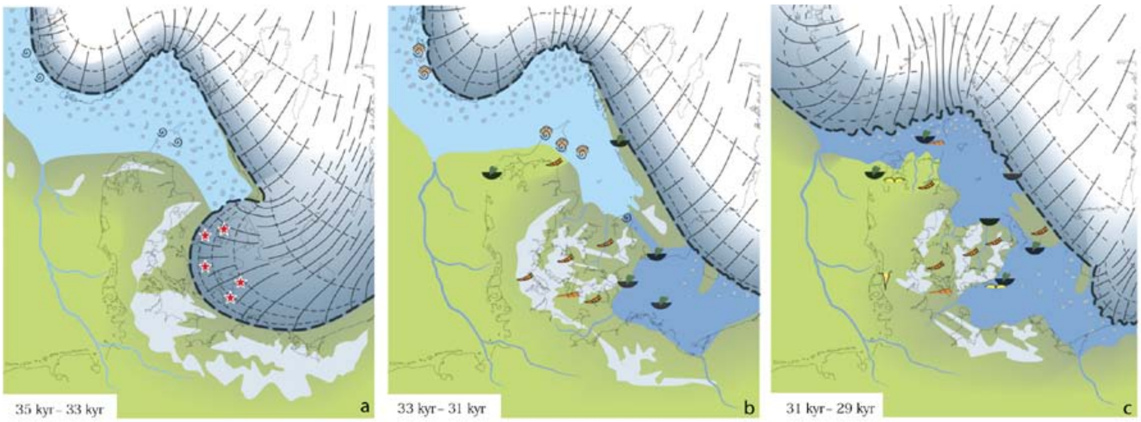

Figure 3-3. *(a) The advance of the southern margin of the Fennoscandian ice sheet into Denmark 35–33 kyr (Klintholm glaciation) and (b, c) subsequent fluctuations of the ice margin in the Kattegat and Baltic Sea basin. The dashed black line which delimits the ice sheet margin indicates that the exact position of the ice margin is uncertain. From /Houmark-Nielsen et al. 2005/.*

The asynchronous and dynamic advance/retreat behavior of the ice margin suggested for MIS 3 seems also to have been characteristic during MIS 2 /Houmark-Nielsen et al. 2005/: while the western and south-western part of the ice sheet advanced onto the Norwegian shelf edge (Last Glacial Maximum) and into the Kattegat (Kategat ice stream) around 30–27 kyr (Figure 3-1), the southern margin receded and south-western Sweden and parts of the western Baltic Sea became again ice free (Møn interstadial, 33–31 kyr) (Figure 3-3 b). The last major Last Glacial Maximum re-advance into Denmark, Germany and Poland (Brandenburg-Frankfurt, Leszno, Jylland, ca. 25 kyr) coincided with ice retreat and only minor re-advances along the Norwegian west coast (Hamnsund interstadial) (Figures 3-1, 3-3 c, 3-4 a-c).

To which extent the ice advances along the western and southern margins of the ice sheet really were separated in time as suggested by /Houmark-Nielsen et al. 2005/ or whether the southern ice advance occurred more or less synchronously with the advance along the Norwegian west coast /Mangerud 2004/ as suggested for the Karmøy/Ristinge/Swiecie advance is up to debate and clearly needs to be resolved. The fairly large error margins of the OSL dates used by /Houmark-Nielsen et al. 2005/ to constrain the ice advance over Denmark, does however not exclude the possibility that both ice advances were more or less synchronous.

The reconstruction of an ice sheet covering most of Sweden and the southern Baltic during MIS 3 and parts of MIS 3 /Houmark-Nielsen et al. 2005, Houmark-Nielsen 2007/ seems at odds with a number of other studies:

- Ice free conditions in northern Sweden and northern Finland during an early part of MIS 3 as suggested by /Helmens et al. 2007ab/ and /Hättestrand 2008/.
- Recent work by /Lunkka et al. 2008/ that points to ice free conditions in eastern Finland between ca. 50 and 25 kyr.
- ^{14}C dates on mammoth remains that suggest ice free conditions in southern and central Sweden and in western Finland between 44 and 24 kyr /Ukkonen et al. 2007/ (Figures 3-5 a, b).
- OSL dates from southern Sweden (Skåne, southern Halland) and the islands of Ven and Bornholm indicate that these areas were ice free between ca. 39 and 24 kyr /Kjær et al. 2006/, i.e. coincident with the Klintholm/Lazyn advance.

This disparity was also partly evident in the reconstruction of the Fennoscandian ice sheet by /Arnold et al. 2002/, who compiled available ^{14}C, U/Th and TL dates within the Stage 3 Project /van Andel 2002/ and presented two versions of a possible ice sheet extent: (i) a minimum ice sheet centred over southern Norway with a lower limit slightly above the present 500 m.a.s.l. elevation line and including a possible second small ice sheet situated north of 68 °N, and (ii) an ice sheet margin terminating in southern Sweden, which approximately resembles the configuration of the ice sheet during the Younger Dryas period.

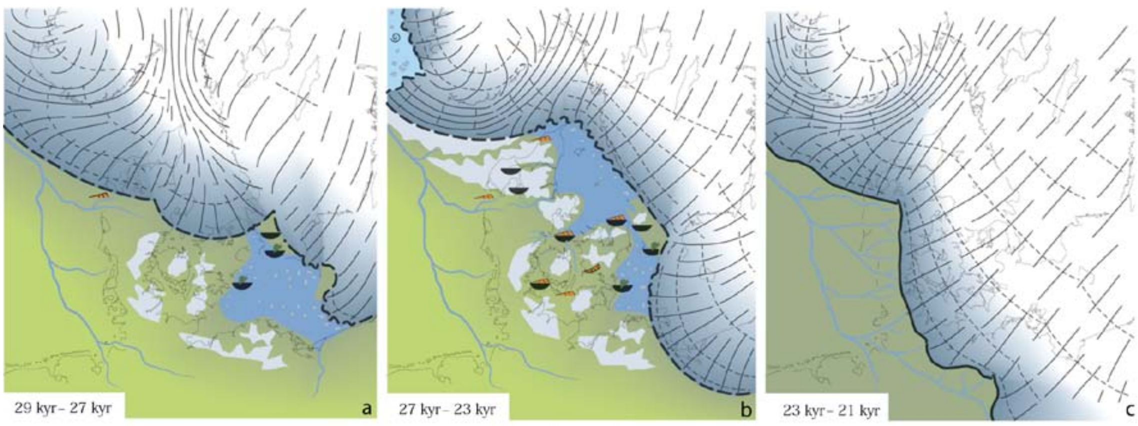

Figure 3-4 a-c. *The advance and retreat of the southern margin of the Fennoscandian ice sheet between 29 and 21 kyr. The dashed black line which delimits the ice sheet margin indicates that the exact position of the ice margin is uncertain. /From Houmark-Nielsen et al. 2005/.*

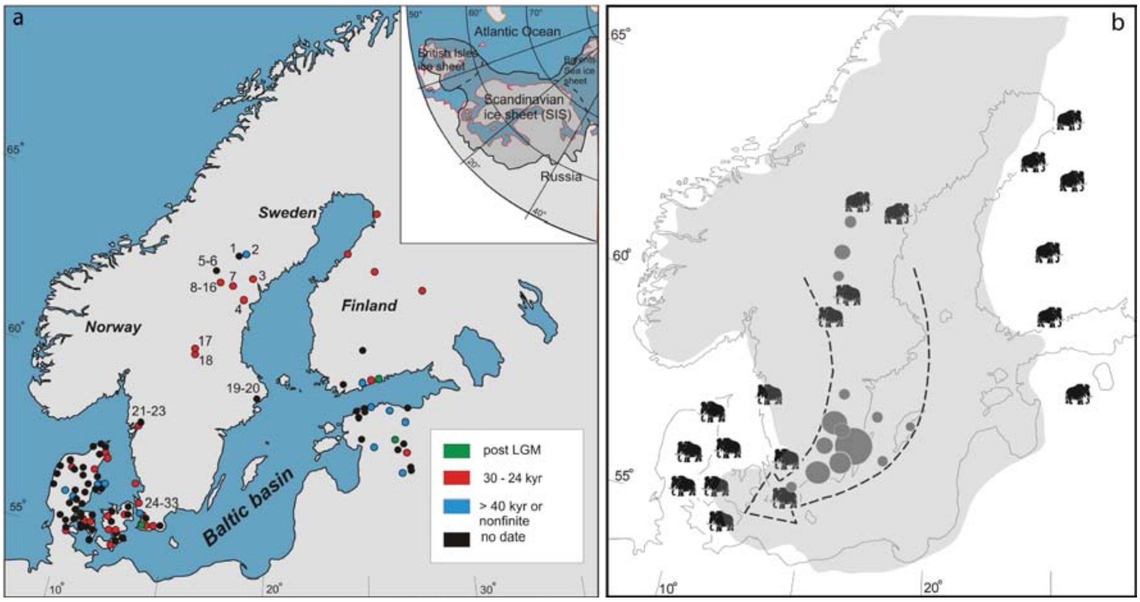

Figure 3-5. (a) Spatial distribution of dated and undated mammoth remains from Sweden, Finland, Estonia and Denmark, from /Ukkonen et al. 2007, Figure 1/. (b) Location of ^{14}C-dated mammoth finds, the ice sheet extent during the Klintholm advance (grey shade) and the provenience of erratic boulders in the Klintholm till (dark grey circles), the ice flow direction is indicated by a dashed arrow. From /Ukkonen et al. 2007, Figure 6/.

Possible explanations for the above cited discrepancies could be that the timing of, for example, the Klintholm advance is not sufficiently constrained by OSL dates (Houmark-Nielsen, personal communication, September 2007), that the OSL ages which delimit the different advance/retreat phases have too large error margins to allow resolving whether events occurred separately from each other or not, and/or that OSL ages have inherent errors and thus not always provide a coherent picture. ^{14}C dates are also prone to many errors, especially if the age determinations on such old organic materials were not performed with great scrutiny (see discussion below). Many of the old ^{14}C dates have very large error margins and may therefore be indistinguishable from OSL ages. Moreover, ^{14}C measurements have been performed on a variety of sediments and/or organic material. Each of these materials has their own specific limitations.

Alternatively, if we assume that all age determinations are correct, the ice sheet response to the abrupt warming of North Atlantic sea surface temperatures (SSTs) at the start of an interstadial /Rasmussen et al. 2003, Sánchez-Goñi et al. 2008/ may have been spatially very different over Fennoscandia. Warmer SSTs likely led to melt and recession along the western and southern ice sheet margins, but also supplied large amounts of precipitation to the centre and eastern part of the ice sheet. This could in turn have led to ice sheet reorganization and/or destabilization along the eastern part and to complicated flow regime changes. Surging ice could have rapidly advanced on the soft sediment and bedrock substrate of the Baltic Sea basin.

Each of the suggested ice sheet advances through the Baltic Sea basin, such as e.g. the Ristinge and Klintholm advances, seem to have occurred during warmer interstadials, when the western part of the ice sheet margin receded to within the Norwegian fjord coast. The simplified ice sheet model presented by /Arnold et al. 2002/ and driven by the temperature record of the GISP 2 ice core, did reproduce distinct ice sheet responses to millennial-scale climate shifts and suggested that fast ice flow due to wet basal conditions could have played an important role and could have easily influenced ice sheet dynamics during MIS 3. Similar findings were obtained by for example /Näslund et al. 2003, SKB 2006, Forsström and Greve 2004/. To which extent such dynamic ice sheet processes could have influenced and/or disturbed the glacial stratigraphies, and thus the sediments which were used for OSL dating and/or the organic material (mammoth bones and teeth) used for ^{14}C measurements, needs to be investigated further.

Although new, albeit controversial, geological evidence thus is available for the Fennoscandian ice sheet during MIS 3, based on investigations along its western /Olsen 1997, Olsen et al. 2001ab, Mangerud et al. 2003/, southern /Houmark-Nielsen and Kjær 2003, Kjær et al. 2006, Houmark-Nielsen 2007/ north-eastern /Helmens et al. 2007ab, Helmens 2009/ and eastern /Lunkka et al. 2008/ borders, only scarce information /Ukkonen et al. 2007/ is available from the central part of the former ice sheet. Moreover the ^{14}C dates which have been used to infer ice free conditions in southern and central Sweden and in western Finland between 44 and 24 kyr were obtained on mammoth remains /Ukkonen et al. 2007/ which were not found in situ. Any clear stratigraphic evidence for these is therefore still lacking.

4 Correlation of early and mid-Weichselian interstadials

/Lundqvist 1967, 1978/ described organic sediments in sub-till position from a number of localities in mid-central and northern Sweden (e.g. Pilgrimstad, Tåsjö, Borlänge, Vojmå, Juktan, Blajksjön and Gällivare). ^{14}C dates on sediments and wood provided both infinite ages and ages ranging from 40 to around 30 kyr BP, possibly indicating ice free conditions during parts of MIS 3 in the central and northern part of Sweden. Most of these interstadial deposits were consequently assigned to the *Jämtland interstadial* during which mean annual temperatures were reconstructed as having been 2–3°C lower than today. Subsequent research on interstadial sediments in central and northern Sweden, including ^{14}C, U/Th and TL dates, and pollen stratigraphy /Lagerbäck and Robertsson 1988, Robertsson 1988, 1991, Robertsson and Garcia Ambrosiani 1988, 1992, García Ambrosiani 1990, Lundqvist and Miller 1992/ however revised this view and argued that all ^{14}C dates need to be regarded as infinite ages and that correlations should only be based on pollen stratigraphy. Although /Robertsson 1991/ rejected the ^{14}C dates for central and northern Sweden, she accepted ^{14}C ages of 30–20 kyr, which had been published for interstadial deposits in southern Sweden (Göta Älv, Dösebacka, Ellesbo, Gärdslöv) /Hillefors 1974, Miller 1977/.

The pollen-based conclusion that sparse tree vegetation (including *Betula pubescens* and *Picea*) was present in central and northern Sweden during these interstadials made a correlation to the early Weichselian interstadials Brørup and Odderade more likely /Robertsson 1988, 1991, García Ambrosiani 1990, Robertsson and García Ambrosiani 1992/, especially in comparison to northern Germany /Mangerud 1991/, where sparse shrub and herb vegetation had been reconstructed for the Mid-Weichselian at the site of Oerel /Behre 1989, Behre and van der Plicht 1992/. The fairly large number of ^{14}C dates which had provided Mid-Weichselian ages for these Middle Swedish interstadial organic deposits, and thus contradicted the pollen-based conclusions were explained by sample contamination and unreliable, conventional ^{14}C measurements. The *Jämtland interstadial* (studied for example in great detail at the site Pilgrimstad) was consequently not regarded as one interstadial, but as two different interstadials, which were correlated with Brørup and Odderade, respectively /Robertsson 1991, Lundqvist and Miller 1992/ (Table 4-1).

The difficulties of correlating the partly fragmentary Swedish interstadial deposits with each other and to other interstadial deposits in Fennoscandia and their placement within the North European Weichselian biostratigraphy /Lagerbäck and Robertsson 1988/ was highlighted by /García Ambrosiani 1990/. She discussed different alternatives for possible correlations, i.e. that the so-called *Tärendö interstadial* in northern Sweden could be assigned to either Odderade or to a mid-Weichselian interstadial. Moreover, /Hättestrand 2007, 2008/ recently suggested to subdivide the *Tärendö interstadial* into the two phases, *Tärendö I* and *Tärendö II* and also proposed two alternative correlations between these interstadials and the North European biostratigraphy. In alternative 1, *Tärendö I* which corresponds to the Peräpohjola interstadial of /Lagerbäck and Robertsson 1988/ could correlate to Brørup, and *Tärendö II* to Odderade. In alternative 2, *Tärendö I* would correlate to Odderade and *Tärendö II* to an early mid-Weichselian interstadial (Table 4-1). /Hättestrand 2008/ also interprets *Tärendö II* as being composed of two warmer events, separated by a cold phase and speculates whether this interstadial could be correlated to the interstadial described at Sokli in northern Finland and correlated to GIS 12-14 /Helmens et al. 2007ab/ (Table 4-1).

/Mangerud et al. 2003/ and /Mangerud 2004/ suggested several phases of ice advance and retreat along the Norwegian coast during MIS 3. Of these, the Ålesund interstadial is best constrained by ^{14}C ages and paleomagnetic excursions, which allow a secure correlation to GIS 8-7 /Mangerud et al. 2003/ (Figure 3-2, Table 4-1). However, /Lundqvist 1992/ and /Mangerud 2004/ assumed that most of Sweden was ice covered during the entire middle Weichselian, and that the interstadials described from central and northern Sweden correlate to early Weichselian interstadials (Table 4-1). /García Ambrosiani 1990/ and /Robertsson 1991/ on the other hand proposed that only northern and central Sweden were ice covered, and that southern Sweden remained ice free during all or parts of MIS 3 (Table 4-1). A similar scenario is suggested by /Houmark-Nielsen et al. 2005/ and /Kjær et al. 2006/ i.e. that parts of southern Sweden were ice free during some intervals within MIS 3. These conclusions however contrast with recent investigations by /Helmens et al. 2007ab/, which indicate ice free conditions in northern Finland during an early mid-Weichselian interstadial (Table 4-1) and with ^{14}C dates on mammoth remains presented by /Ukkonen et al. 2007/, which would imply ice free conditions in most of Sweden also during parts of the middle and late Weichselian (i.e. the middle and later part of MIS 3 and the early part of MIS 2).

The correlation between Weichselian interstadials in Fennoscandia shows that large uncertainties and discrepancies exist between the different and often fragmentary interstadial deposits (Table 4-1). The uncertainties become even larger when these interstadial deposits are compared to the northwest European biostratigraphy /Behre and van der Plicht 1992/ and to possible correlatives in the Greenland ice core stratigraphy (Table 4-1).

Uncertainties also exist regarding the biostratigraphic intervals during MIS 3. Published ^{14}C ages by /Behre and van der Plicht 1992/ for the different middle Weichselian interstadials would e.g. suggest that Denekamp correlates to GIS 5-7, Hengelo to GIS 10/11, Moershoofd to GIS 12, Glinde to GIS 13/14 and Oerel to GIS 15/16. /Huijzer and Vandenberghe 1998/ on the other hand expand the biostratigraphy of /Behre and van der Plicht 1992/ and include the Huneborg interval between Hengelo and Denekamp and the Upton Warren and Riel interstadial between Moershoofd and Hengelo. This correlation would lead to an assignment of Huneborg to GIS 8, Moershoofd to GIS 14, while Upton Warren and Riel could be correlative to GIS 12 and 13, respectively. Clearly, to resolve these uncertainties, continuous and well-dated land records which could unequivocally be compared to the Greenland ice core stratigraphy are needed.

Table 4-1. Tentative correlation of early and middle Weichselian interstadials and stadials in northern Europe with the Greenland ice core stratigraphy and the marine isotope stratigraphy. GIS = Greenland interstadials, MIS = Marine Isotope Stage, kyr = thousand years. Blue colors indicate intervals of ice cover in Fennoscandia and red colors indicate ice free conditions. The correlation between the biostratigraphic zones of /Behre and van der Plicht 1992/ and Greenland interstadials is based on a transformation of the ^{14}C ages to calibrated ages using the curve of /Hughen et al. 2006/.

Biostratigraphy[1,2]	Age (^{14}C)[1] (kyr)	GIS[3]	Age of GIS[3] (kyr)	MIS	Norway[4]	Sweden/ Finland[4]	Sweden[5]	Sweden[6]	Sweden[7]
Denekamp	28–32	5–7	32–33.5	3	Ålesund			Göta Älv/ Dösebacka/ Ellesbo/ Gärdslöv	
Huneborg	??	8	36.5–38.5	3	Ålesund				
Hengelo	36–39	10/11	41–43.5	3	Skjong-helleren				
Hasselo-stadial				3	Skjong-helleren				
Moershoofd	44–46	12	45–47	3	Bø				
Glinde	48–50	?13/14	49–54.5	3	Bø				?Tärendö II
Oerel	53–58	15/16	56–59	3	Bø				?Tärendö II
					Karmøy				
Odderade	61–72	21		5a	Tovastad	Tärendö/ Vålbacken	Vålbacken/ Tåsjö/ Riipiharju	Tärendö/Tåsjö/ Pilgrimstad/ Norbotten sites	Tärendö I
					Bønes				
Brørup/ Amersfoort	–	23/24		5c	Fana/ Gudbrand-dalen	Peräpohjola/ Pilgrimstad	Stenberget/ Slätteröd/ Härnösand/ Pilgrimstad/ Boliden/ Gallejaure/ Takanen-männikkö	Peräpohjola/ Stenberget/ Margareteberg/ Pilgrimstad/ Norbotten sites	

[1] /Behre and van der Plicht 1992/ and [2] /Huijzer and Vandenberghe 1998/. Note that /Huijzer and Vandenberghe 1998/ include the Huneborg interval between Hengelo and Denekamp, and the Upton Warren and Riel interstadial between Moershoofd and Hengelo. This correlation would lead to an assignment of Moershoofd to GIS 14, while Upton Warren and Riel would be correlative with GIS 12 and 13, respectively. [3] Greenland interstadials according to /EPICA 2006/, [4] /Mangerud 2004/, [5] /García Ambrosiani 1990/, [6] /Robertsson 1991/ and [7] /Hättestrand 2008/. /Hättestrand 2008/ presented two alternative correlations of the Tärendö I and II interstadials, here only alternative II is shown.

5 Dating pre-LGM sediments and bones in Fennoscandia

A large number of ^{14}C, OSL, TL and U/Th dates have been published for Fennoscandia for the time interval prior to the Last Glacial Maximum. These have been compiled in several studies, i.e. for Norway by /Olsen et al. 2001ab/ and for Denmark and southernmost Sweden by /Houmark-Nielsen and Kjær 2003/. Moreover, several of the older dates, which had been published earlier, were used in the Stage 3 Project /van Andel 2002/ to reconstruct and model the extent of the Fennoscandian ice sheet /Arnold et al. 2002/ during MIS 3. Although the validity of the mainly old ^{14}C dates, but also of older TL and U/Th dates has been repeatedly questioned /Lundqvist and Mook 1981, Robertsson 1988, 1991, García Ambrosiani 1990, Mangerud 1991, Lundqvist and Miller 1992, Lundqvist 1992, 1997/, the quality of the ^{14}C, OSL, TL and U/Th ages used in the compilation and reconstruction by /Arnold et al. 2002/ has never been assessed. To address the controversial issue of ice sheet presence and/or absence, it is however necessary to carefully scrutinize each age determination and to discard all ages, which are clearly unreliable.

6 Compilation and evaluation of MIS 3 age measurements

6.1 Data base compilation

Published and unpublished ^{14}C, TL/OSL and U/Th ages older than ca. 17 ka were compiled for Norway, Sweden, Denmark, Finland, Estonia (Figure 6-1 and Appendix 1, where a list of all references is included) and parts of Russia (not shown in Figure 6-1). This compilation, which has its latest entries from May 2008, is by no means complete and will successively be updated. The data base in its present form (Excel spreadsheet) is available at the Swedish Nuclear Fuel and Waste Management Company (SKB) and will also be made available through a data base which is currently set up at the Department of Geology and Geochemistry, Stockholm University.

Most of the TL/OSL data points are from recent studies in Denmark and southern Sweden by /Houmark-Nielsen 2003, Houmark-Nielsen and Kjær 2003, Kjær et al. 2006, Houmark-Nielsen 2007/ who made a careful evaluation of their results and also compared these to earlier performed TL dates in the same area. Unpublished OSL dates by /Alexanderson et al. 2008/ for southern and central Sweden have not yet been included. Apart from these new data sets only few older TL/OSL data points seem to exist for Norway, Sweden, Finland and Estonia. The same is true for U/Th or U-series dates which amount to 19 data points for Norway and only one for Sweden. The majority of the data points shown in Figure 6-1 are thus based on ^{14}C measurements.

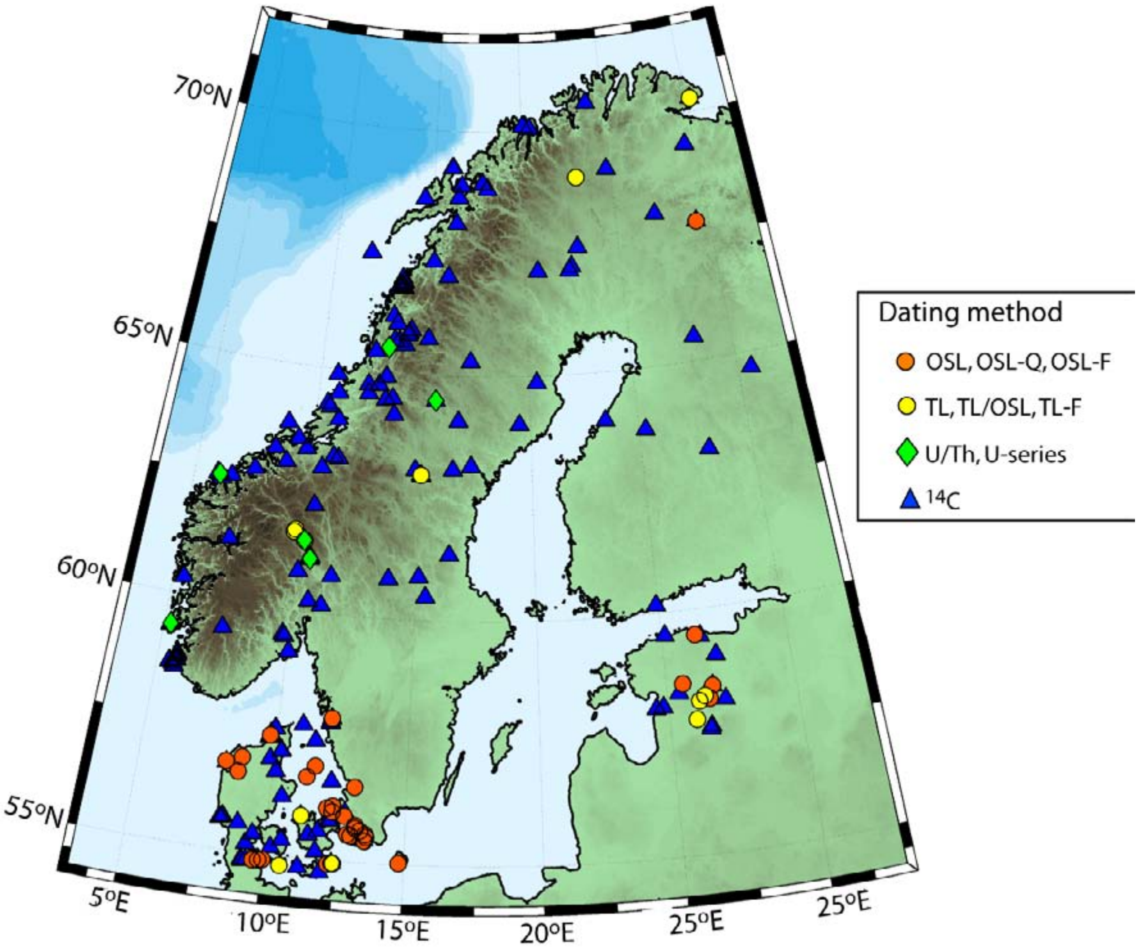

Figure 6-1. *All data points collected in the data base (as of May 2008) divided into the different types of dating methods. OSL-Q=measured on quartz, OSL-F=measured on feldspar, TL-F=measured on feldspar.*

As expected, the material which had been used for ^{14}C dating varied widely and was comprised of inorganic and organic bulk sediment, plant material of limnic, marine and/or terrestrial origin, animal bones and teeth, marine shells and foraminifera (Figure 6-2). ^{14}C measurements of samples derived from these types of material are subject to a number of problems.

6.2 Problems related to ^{14}C measurements of old samples

The errors associated with radiocarbon dating sediments and organic material, have been extensively discussed in the literature /e.g. Olsson 1979, Björck and Wohlfarth 2001 and references therein, Hajdas 2007/. Many of these errors are now carefully taken into account when dating sediments and organic matter, while much of this knowledge was often not taken into consideration for radiocarbon dates obtained during the second half of the last century /Olsson 1979/.

Moreover, ^{14}C dates which are close to the limit of radiocarbon dating (ca. 50 kyr) or had been obtained in radiocarbon laboratories with high background levels, need to be considered carefully. Meaningful dates in this age range can only be obtained if in situ contamination of the sample is reduced to very low levels, and contamination added during handling and processing in the laboratory is minimized /Hogg et al. 2006/. Although finite radiocarbon ages beyond 50 kyr are becoming routinely reported, few attempts have been made to actually demonstrate their accuracy and precision.

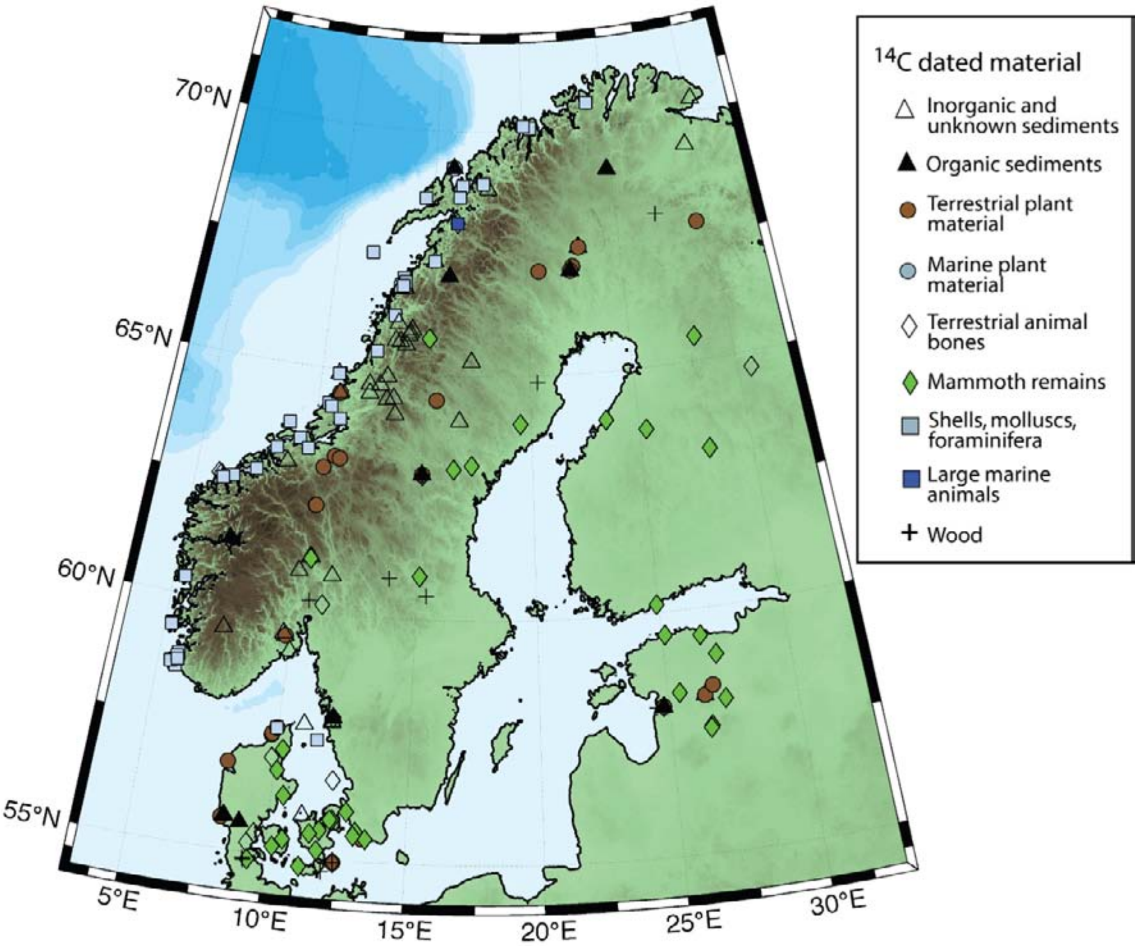

Figure 6-2. *Type of material used for ^{14}C dating of the samples collected in the data base.*

Important issues when dealing with old ^{14}C dates are therefore: (1) Precise knowledge about the geological and stratigraphic setting of the dated material, (2) knowledge about the type of material submitted for ^{14}C dating and careful treatment of samples prior to sending these to the ^{14}C laboratory, and (3) the background of the ^{14}C laboratory and the pretreatment of samples in the ^{14}C laboratory.

1. **Precise knowledge about the geological and stratigraphic setting of the dated material**
   Pure organic plant material, such as peat or carefully identified terrestrial plant macrofossils are generally regarded as "safe" for ^{14}C dating, provided that the plant material grew in the surroundings of its depositional environment and is not reworked from older sediments. Reworked peat can however easily become infiltrated by humid acids or roots from overlying younger sediments and ^{14}C dates of 30–50 kyr obtained on Eemian and/or Holsteinian peat deposits in e.g. Estonia have clearly shown the danger of accepting these dates as providing accurate ages /Kalm 2005, 2006/.
2. **Knowledge about the type of material submitted for ^{14}C dating**
   The difficulties arising from ^{14}C dating of bulk sediment material have been extensively discussed /Olsson 1979, Björck and Wohlfarth 2001 and references therein/. Inorganic sediments with low organic carbon content provide erroneous ages because the carbon contained in these sediments might be derived from older deposits, or if contemporaneous with the sediments, can easily become contaminated during sample handling. Organic sediments, such as gyttjas, have shown to give both reliable and unreliable ^{14}C dates, depending on the organic matter source. The alkali-soluble (SOL) humic and/or alkali-insoluble (INS) humic fractions extracted from these types of sediments have been tested extensively for ^{14}C dating /Björck and Wohlfarth, 2001 and references therein/. Usually the SOL fraction results in younger ages as compared to the INS fraction, and depending on the origin of the dated sediment material either could represent the correct age. It is thus of importance to know if these fractions represent infiltrated organic material or contemporaneous organic material, or old and reworked organic matter. The same holds true when different size fractions of bulk organic material are dated. Fine organic matter may have been recycled several times, while coarse organic matter could originate from plants growing in the immediate surroundings. In addition, organic sediments, such as gyttja may contain both terrestrial and limnic organic material. If derived from hard water lakes, the latter can result in old ^{14}C ages. Bones, ivory, teeth and wood, which had been covered by sediment and/or peat for thousands of years, are often prone to contamination by younger carbon /Hajdas 2007/. One possible source of younger carbon in bones is carbonate which crystallized on the bone surfaces. This contamination is however generally removed during the pretreatment process in the laboratory. Another source of contamination is post depositional incorporation of humic substances into the bone material either due to humification processes occurring in the bone and/or due to an interaction with the burial environment /van Klinken and Hedges 1995/. Younger humic acids which migrate laterally or downwards with groundwater can attach to the porous bone structure and build cross-links within the collagen. If this type of contamination is not carefully removed by rigorous pre-treatment in the radiocarbon laboratory, the resulting ages will become much younger. Dried, defatted fresh bones contain about 20% collagen, but the gradual decomposition process decreases the collagen content of bones /Hajdas 2007/ and very old bone samples may therefore only contain a small amount of datable collagen. Several methods exist to extract the organic bone fraction, or collagen, but if the amount of collagen in a sample is very small and if the sample is not handled with great care, then contamination can easily occur.
3. **Background of the ^{14}C laboratory and pretreatment of samples**
   The background of the ^{14}C laboratory and adequate pre-treatment processes in the ^{14}C laboratory are important prerequisites for obtaining accurate ^{14}C ages for old samples /Hogg et al. 2006/. For AMS ^{14}C measurements of old samples the assurance that the ion source background is negligible via measurements of unprocessed geological graphite is vital. In addition no possible interference from mass-14 molecular ions such as ^{13}CH, or from molecular fragments must occur. Multiple analyses of a suitable background are essential if the extent and variability of contamination are to be accurately defined /Hogg et al. 2006/. The degree of success in eliminating in situ contamination depends on the efficacy of the pretreatment method. α-cellulose extraction is usually used if old wood samples are being dated /Hogg et al. 2006/. Minimizing laboratory contamination requires the use of vacuum lines that are either dedicated to low-background samples, or pre-cleaned by preparation of multiple low-activity samples.

^{14}C laboratories which routinely date old samples employ the ABA or AAA (acid-alkali-acid) method as chemical pre-treatment of wood and peat to remove contamination with old and modern carbon. However several studies /Hatté et al. 2001 and references therein/ have shown that in some materials the alkali step of the ABA method might be responsible for contamination with modern carbon from atmospheric CO_2 dissolved in the base and incorporated in the sample structure /Hajdas 2007/. The effect of contamination becomes highly significant when old material is dated. A modification of the ABA method is ABOX /Bird et al. 1999/ where samples are subjected to "wet oxidation" and pre-combustion at lower temperatures (330–630°C) prior to the final combustion at 850°C. This procedure is regarded as providing reliable ages.

6.3 Evaluation of the ^{14}C measurements assembled in the data base

To evaluate each of the compiled ^{14}C data points (Figure 6-3), laboratory details were cross-checked in the journal *Radiocarbon* for the years 1960–1996. The radiocarbon laboratory at Groningen however stopped publishing its dates in the year 1971 and established an own data base (which is not possible to access). Moreover, not all ^{14}C laboratories regularly reported their measurements in *Radiocarbon* and the journal gradually ended to publish reports of ^{14}C laboratories in the 1980'ies.

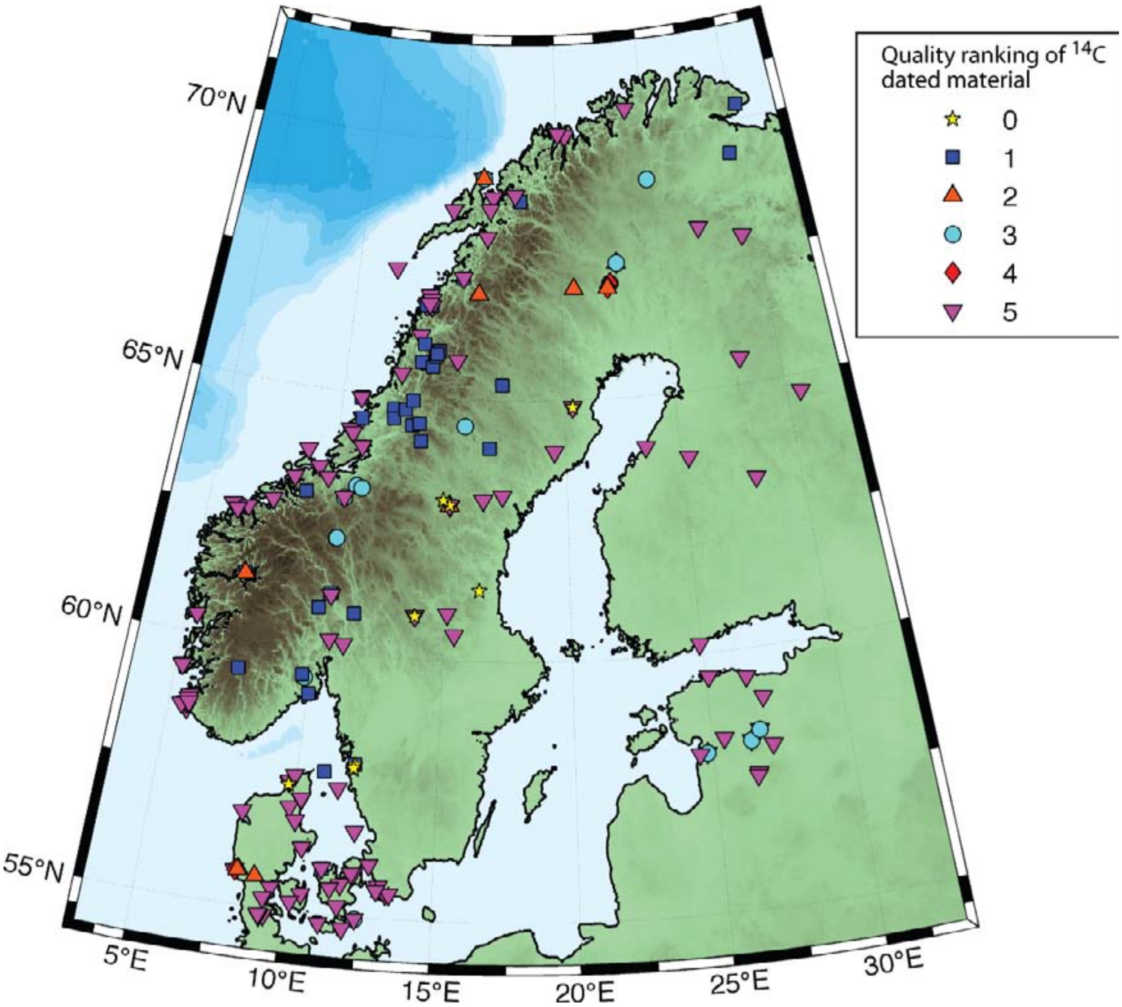

Figure 6-3. *Quality ranking of the ^{14}C dated material. 0 = unreliable because of too little organic material and/or because the origin of the dated material is unknown, 1 = inorganic marine or lacustrine bulk sediment dates, 2 = organic marine or lacustrine bulk sediment dates, 3 = marine or lacustrine bulk organic material (humic substances, plant remains), 4 = peat, 5 = terrestrial material (plant fragments, wood, bones, tusks) and marine shells and bones. Note that not all data points are clearly visible on the figure.*

For the present study, several ^{14}C laboratories were contacted about details on individual ^{14}C measurements, but tracking these details (incl. pretreatment procedures) for old ^{14}C dates proved rather difficult. Some laboratories do not exist anymore and others were not able to provide full sample details. Only ~60–70% of the compiled dates could therefore be assessed.

As a first step, the quality of the ^{14}C dated material was evaluated (Figure 6-3). If too little organic material was present and/or the origin of the dated material was unknown, the date was regarded as unreliable (0). Inorganic marine or lacustrine bulk sediment dates, organic marine or lacustrine bulk sediment dates and marine or lacustrine bulk organic material (humic substances, plant remains) were given lower scores (1–3), while peat, terrestrial material (plant fragments, wood, bones, tusks) and marine shells and bones were given higher scores (4–5). Overall >50% of the dated material obtained scores of between 3 and 5 and thus seemed potentially promising.

In a second step, the quality of the obtained ^{14}C dates was assessed (Figure 6-4). Samples consisting of unknown material, of sediments with low organic carbon content (i.e. inorganic marine or lacustrine bulk sediments, the SOL/INS fraction of inorganic marine or lacustrine sediments) or of reworked sediments (as indicated by pollen stratigraphy) were classified as not acceptable (0). The same classification was used for samples where the published ages were unreliable according to reports of the ^{14}C laboratory (i.e. very low carbon content, contamination), or when ages were reported without standard errors.

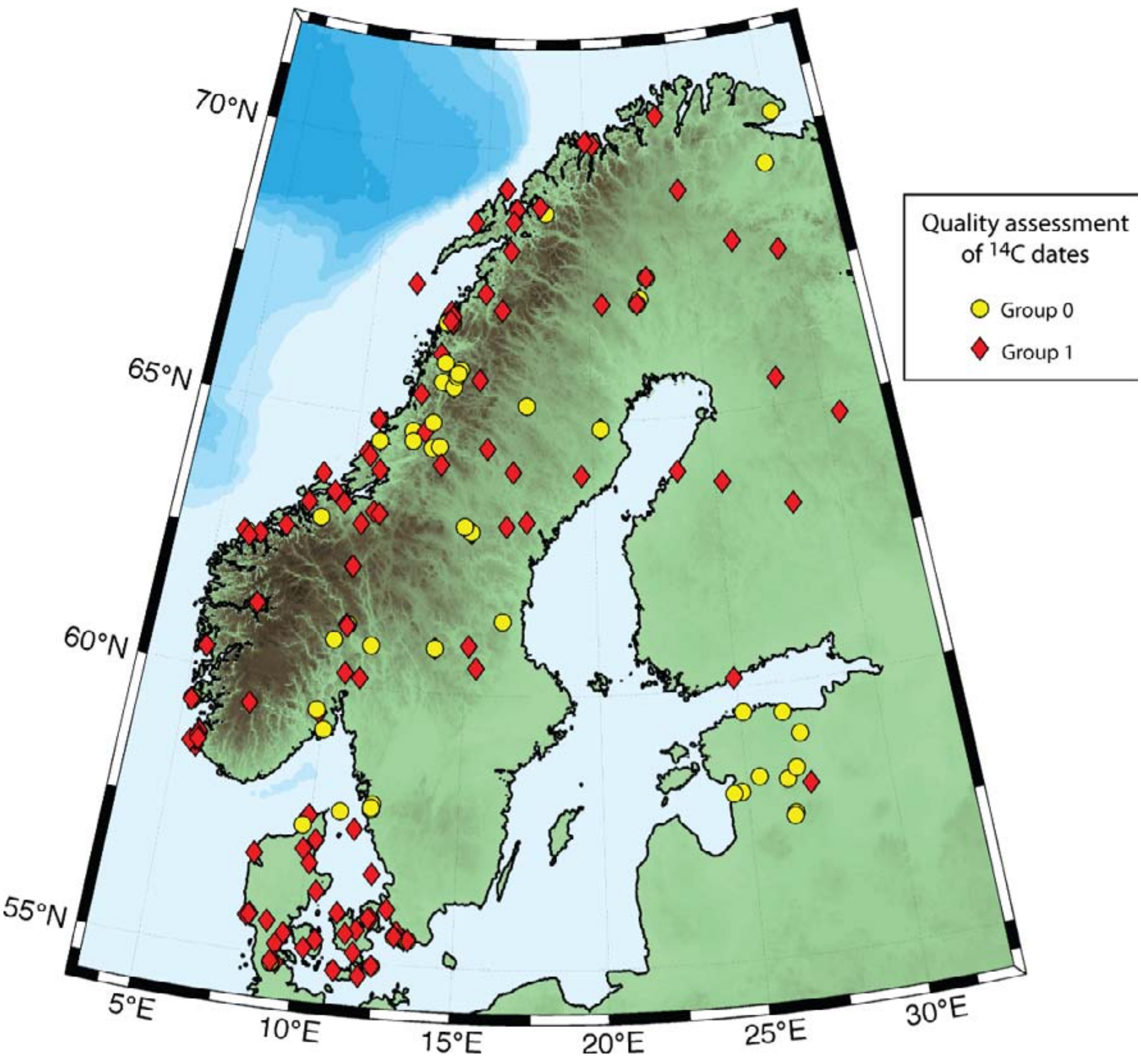

Figure 6-4. *Samples for which the reported age cannot be accepted (group 0) and possibly be accepted (group 1). See text for further explanation.*

Although it is arguable whether samples with ages beyond the background of the ^{14}C dating laboratory (i.e. infinite measurements) should be placed in this category too or whether they should be grouped separately, since they may indeed give some indication in respect to other ^{14}C dates from the same sequence, I chose to classify them as not acceptable. The reason for this is that the background of some of the older and no longer functioning ^{14}C laboratories was clearly not suitable for dating such old samples, in addition, several of these infinite dates were obtained from stratigraphies which were clearly older than MIS 3.

Samples for which the reported age can possibly be accepted and/or which likely provided reliable age measurements were classified as (1). These were in situ and/or reworked bulk organic marine or lacustrine sediments, the SOL/INS fraction of bulk organic material, reworked and/or in situ marine shells, bones and foraminifera, reworked and/or in situ terrestrial plant material, reworked and/or in situ terrestrial bones (Figure 6-4). This approach narrowed the number of presumably good sample material and ^{14}C measurements to about 60%.

Calibration of ^{14}C dates was only made if the reported error was < 2,000 years. ^{14}C dates were calibrated using the calibration curve of /Fairbanks et al. 2005/. Those dates which are too old and thus fall outside the calibration curve, were tentatively compared to the curve of /Hughen et al. 2006/. This latter approach assigns only an approximate age to the sample, but does not provide errors. The true age of the calibrated ^{14}C date can thus be considerably younger or older.

7 Evaluation of ^{14}C dates for Sweden

Several studies have already discussed the implications of the published ^{14}C dates for Norway /Olsen 1997, Olsen et al. 2001ab, Mangerud et al. 2003/, Estonia /Kalm 2005, 2006/ and Denmark /Houmark-Nielsen 2003, 2007, Houmark-Nielsen and Kjær 2003/. Therefore the focus will in the following be on published and unpublished ^{14}C dates for Sweden and their significance for or against ice cover in central areas during MIS 3.

The ^{14}C dates compiled for Sweden (Figure 6-1) are derived from published sources /Lundqvist 1955, Östlund and Engstrand 1960, Engstrand and Östlund 1962, Lundqvist 1964, Engstrand 1965, Håkansson 1969, 1970, Hillefors 1974, Berglund et al. 1976, Miller 1977, Lundqvist 1978, Lundqvist and Mook 1981, Lagerbäck and Robertsson 1988, Robertsson 1988, Robertsson and Garcia Ambrosiani 1988, García Ambrosiani 1990, Lundqvist and Miller 1992, Aaris-Sørensen 2006, Ukkonen et al. 2007/ and unpublished sources (Jan Lundqvist unpublished, Barbara Wohlfarth unpublished). The majority of the compiled data set consists of ^{14}C dates which were obtained on a range of material, such as bulk inorganic sediments, bulk organic sediments, plant remains, peat, bones and tusks, and different fractions thereof (Figure 6-2).

The sites from which ^{14}C dates have been published extend from latitude 55 to 67 °N (Figure 7-1 a). From some localities only single ^{14}C dates are available, whereas other sites, such as for example Riipiharju, Ontoharjutt, Takanenmännikkö, Boliden, Tåsjö, Vålbacken, Pilgrimstad, Borlänge, Öje, Dösebacka, Ingebäck, Hissinge, Gärdslöv, Örsjö and Arrie provided more than one age measurement. Detailed stratigraphies are available for some sites, while others lack a stratigraphic context or have vaguely described stratigraphies. Sites with detailed stratigraphic descriptions are presented in more detail below.

The quality assessment of the different ^{14}C measurements into quality assessment criteria 0–1 (Figure 7-1 b) was made according to:

- 0 = The reported ages are unreliable: the dated material is unknown, the dated material was composed of inorganic marine or lacustrine bulk sediment or of the SOL/INS fraction of inorganic marine or lacustrine sediments, ^{14}C ages are infinite and beyond the background of the dating laboratory, ^{14}C ages are unreliable according to published reports by the ^{14}C laboratory, reworking of the dated layers is indicated by pollen analysis, ^{14}C ages were reported without standard errors.
- 1 = The reported age can possibly be accepted: the dated material was composed of in situ or reworked bulk organic lacustrine sediments of the SOL/INS fraction of bulk organic material, of reworked terrestrial bones, reworked and/or in situ terrestrial plant material.

The data points which qualified as group 1 (Figure 7-1 b) are shown in more detail in Figure 7-2 a–f, where they are separated according to the different type of material used for dating.

7.1 Sites with detailed stratigraphic information

7.1.1 Interstadial sites from Norrbotten

The Norrbotten sites Riipiharju, Ontoharjut and Takanenmännikkö had originally been studied by /Lagerbäck and Robertsson 1988/ and provided rather conflicting ^{14}C dates (Figures 7-3 a–c). /Lagerbäck and Robertsson 1988/ and later /Robertsson 1991/ therefore relied on the pollen assemblages to correlate these stratigraphies to the early Weichselian interstadials Brørup and Odderade.

The stratigraphy of Riipiharju was composed from bottom to top of gravel, silty gyttja, sandy till, laminated organic sand and till. Pollen analyzed in the laminated organic sand suggested that the vegetation surrounding the site consisted of arctic-alpine tundra species and steppic plants.

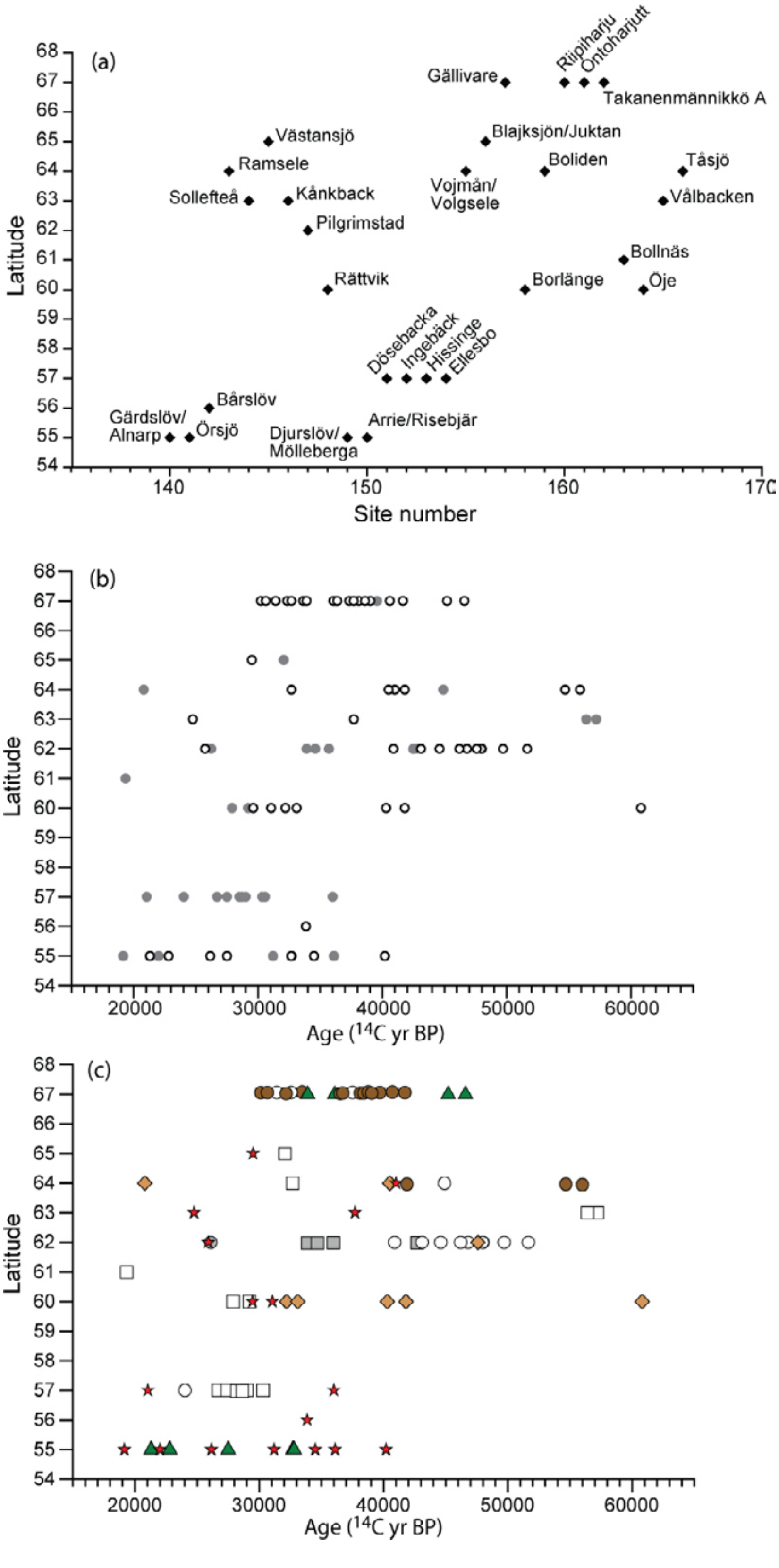

Figure 7-1. *(a) The distribution of sites along a latitudinal transect between 67 and 55 °N, (b) Quality assessment of all* ^{14}*C dates: grey filled circles* = *the reported ages are unreliable (0). Open circles = the reported ages can possibly be accepted (1). See text for an explanation of these quality assessment criteria. (c) Characterization of the dated material shown in (b). Open squares = unknown material or type of sediment, filled grey squares = inorganic lacustrine and marine sediments, open circles = organic lacustrine sediments, filled brown circles = organic material, filled green triangles = terrestrial plant material, filled brown diamonds = wood, red stars = mammoth remains.*

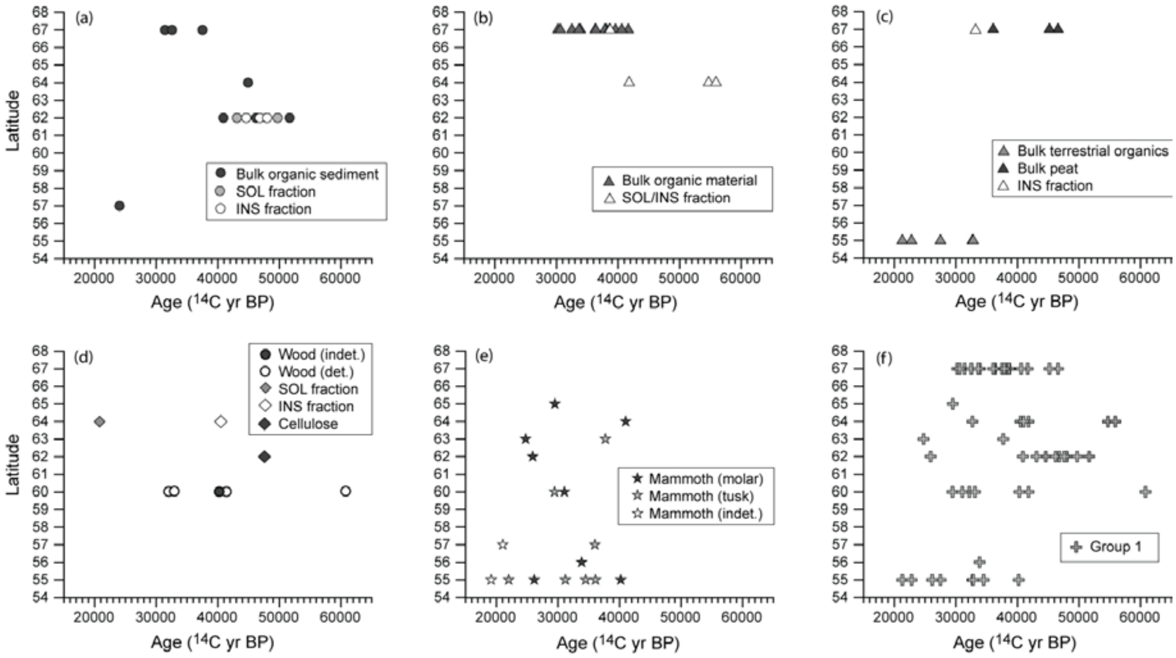

Figure 7-2. *Details on the dated material which qualified as 1 in Figure 7-1b shown along a N-S transect, (a) bulk organic sediments, (b) bulk organic material, (c) bulk terrestrial organic material, (d) wood and wood fractions, (e) mammoth remains, (f) all quality group 1 measurements.*

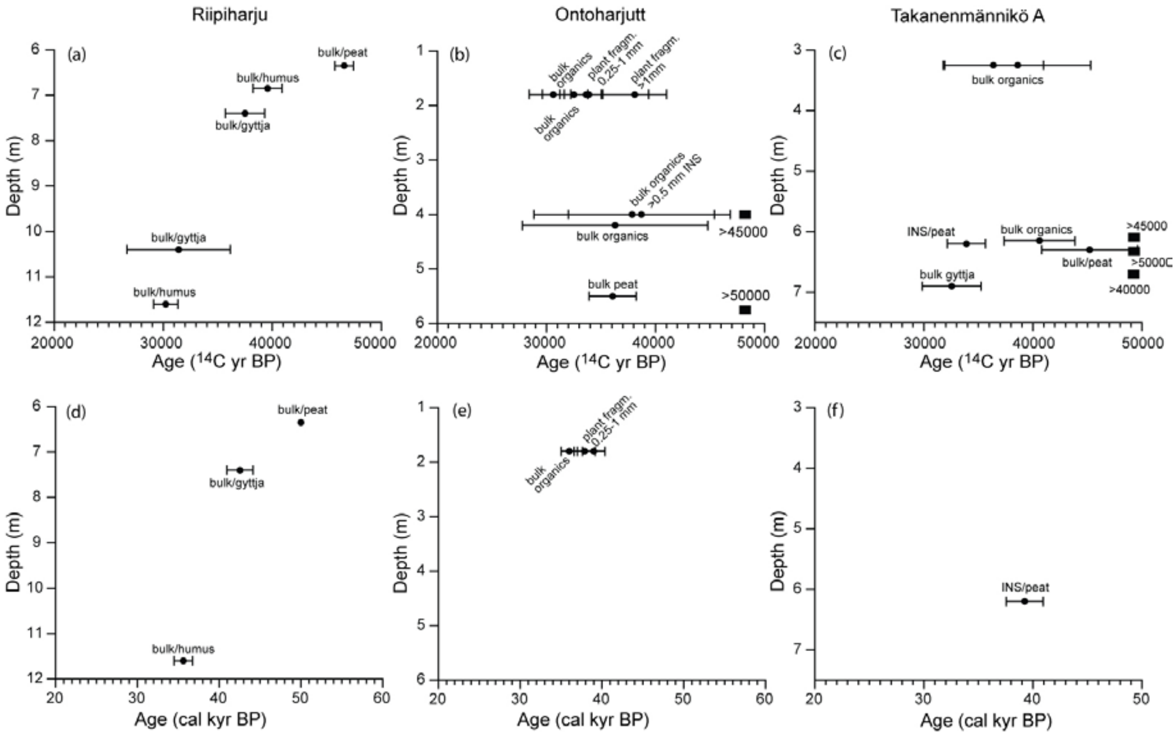

Figure 7-3. *Sites from northern Sweden published by /Lagerbäck and Robertsson 1988/. (a–c) all ^{14}C dates shown with one standard deviation (σ) and placed according to their depth in the stratigraphy. (d–f) calibrated age ranges of those dates which qualified as group 1 are shown with 1σ error ranges.*

Based on the reconstructed vegetation continental climatic conditions were assumed during the deposition of the laminated organic sand /Lagerbäck and Robertsson 1988/. All published ^{14}C ages for Riipiharju, including those ^{14}C dates which qualify as group 1, show a systematic decrease of ages with depth (Figure 7-3 a, d). This is in contrast to the two other sites (Figure 7-3 b, c), which had been studied by /Lagerbäck and Robertsson 1988/ and suggests that mistakes had being made in labeling the samples. Contamination by younger material seems less likely because of the non-random distribution of the ^{14}C ages. Independent of these problems, acceptable ages for the interstadial deposits of Riipiharju may range between ca. 50 and 35 kyr.

The stratigraphy of Ontoharjut shows from bottom to top gravel, peat, sandy till, laminated sands and gyttja layers. The peat layer contained mosses which today have a distribution in central and northern Sweden. The pollen spectra indicated the presence of shrubs, herbs, and scattered birch trees. Pollen samples analyzed in the overlying laminated sands implied arctic vegetation with herb and shrub tundra, periglacial conditions and a continental climate /Lagerbäck and Robertsson 1988/. In the case of Ontoharjut different fractions of the same samples were dated separately, each providing a different age estimate. While one aliquot sample resulted for example in infinite ages, the other aliquots gave finite, but very different ages (Figures 7-3 b). If we accept only those ^{14}C ages which fall within quality category 1, only three dates ranging at ~35–40 kyr would seem acceptable (Figure 7-3 e).

Takanenmännikkö A provided a complicated stratigraphy with sand and gravel in the bottom, overlain by laminated silt and sand, peat, laminated silt and sand with organic matter. On top of the latter layer followed a sandy till, laminated organic sands, and a diamicton. The pollen stratigraphy of the sub-till layers showed the development from dwarf birch, ericaceous shrubs, and herbs into a phase with dwarf birch, tree birch, juniper and light demanding plants. This phase was followed by tundra vegetation with a rich herb flora, arctic-alpine pioneer plants, steppe elements, grasses, sedges, and willow shrubs. For Takanenmännikkö A the different fractions of the same samples provided very different age estimates, ranging from infinite to age estimates of ~30 ^{14}C yr (Figure 7-3 c). Taking only those ^{14}C ages into consideration which fall within quality category 1, one date of ~40 kyr BP would seem acceptable (Figure 7-3 f).

The correlation of the three sites Riipiharju, Ontoharjut and Takanenmännikkö to the early Weichselian interstadials Brørup and Odderade, as proposed by /Lagerbäck and Robertsson 1988/ and /Robertsson 1991/, has recently been questioned by /Hättestrand 2008/, who analyzed the pollen-stratigraphy in two new cores from Kettle holes along the Riipiharju esker. Her pollenstratigraphic interpretation suggests the presence of three interstadials, which were separated by cold stadials. The older interstadial, called Tärendö I, was characterized by the possible presence of scarce birch forest and was separated from the two younger Tärendö II interstadials by an ice sheet advance and retreat phase. Presence of scarce birch forests is also inferred for the two warmer intervals of Tärendö II which were separated by a cold phase during which *Artemisia* pollen percentages increased. Reconstructed mean temperatures of the warmest months (MTWM) are around 10°C when tree birch was present and around 5°C when *Artemisia* dominated. /Hättestrand 2008/ presents two possible correlations for the new Riipiharju pollenstratigraphy: As one alternative she correlates the interstadial events Tärendö I and II with Brørup and Odderade, respectively. As alternative 2, she suggests a correlation of Tärendö I to Odderade and of Tärendö II to an early MIS 3 interstadial (Table 4-1), which could be time-equivalent with the interstadial described by /Helmens et al. 2007ab/ from Sokli and correlated to GIS 12-14. The vegetation and temperature reconstructions of /Hättestrand 2008/ are entirely based on pollen stratigraphy and have not been corroborated by any other independent paleo proxies or new ^{14}C dates.

Following this new correlation scheme, /Hättestrand 2008/ suggests that the interstadials identified at Ontoharjut and Takanenmännikkö A /Lagerbäck and Robertsson 1988, Robertsson 1991/ could tentatively be correlated to Tärendö I, i.e. would represent early Weichselian interstadials. As outlined above, the ^{14}C ages published for Riipiharju range at 35–50 kyr, but show an age reversal with depth, while acceptable ^{14}C ages for Ontoharjut are around 35–40 kyr and for Takanenmännikkö A at around 40 kyr (Figures 7-3 e, f). These estimates are considerably younger than the correlation suggested by /Hättestrand 2008/ and leads to the following questions: (i) Is the tentative correlation of the interstadials at Ontoharjut and Takanenmännikkö A to Tärendö I, and as such to the early Weichselian interstadials Brørup and/or Odderade as suggested by /Hättestrand 2008/ based on pollenstratigraphy correct, and are the too young ages of the "acceptable" ^{14}C measurements due to contamination by younger carbon? (ii) Are correlations which are entirely based on the pollenstratigraphic signals of tree-less, arctic shrub and tundra environments suitable to infer time-synchroneity even between nearby sites where temporally different interstadials with similar vegetation signatures can be expected? Are the "acceptable" ^{14}C ages therefore more trustworthy? Alternative (i) easily leads to circular reasoning, while alternative (ii) assumes the correctness of the ^{14}C dates. The fact that all acceptable ^{14}C ages from the three sites independently point to a similar age interval of ca. 50–30 ^{14}C kyr or 50–35 cal kyr BP (Figure 7-3 d–f) would lend support to alternative (ii) and would suggest ice free conditions in northern Sweden between 50 and 35 cal kyr BP.

7.1.2 Pilgrimstad, Jämtland

The site Pilgrimstad (Figure 7-4) in central Sweden had been the object of several detailed investigations /Kulling 1945, Lundqvist 1967, Robertsson 1988 and references therein/. According to /Robertsson 1988/ two interstadials or one three-parted interstadial are represented in the stratigraphy.

The lower and older interstadial 1 provided pollen spectra which indicate an open tree-less vegetation with grasses and herbs, followed by a transitional phase during which juniper is present, together with herbs and shrub communities (e.g. birch, willow) /Robertsson 1988/. Interstadial 1 ends with a sparse birch forest, which also contained *Juniperus*, *Artemisia*, *Thalictrum* and other herbs. The presence of *Juniperus*, *Filipendula*, and *Selaginella sellaginoides* pollen suggests a MTWM of between 8 and 14°C /Isarin and Bohncke 1999/, while *Armeria* pollen point to coldest month temperatures of –8 to 8°C /Iversen 1954/. Moreover, the presence of *Betula nana* pollen give indications for a MTWM of 4–7°C and a mean temperature of the coldest month (MTCM) of –20°C /Hultén and Fries 1986, Brinkkemper et al. 1987, Ran et al. 1990/, (Bennike personal communication), which would imply slightly colder conditions. Coleoptera analysis on the sediments from interstadial 1 suggested tundra vegetation with dwarf willows and shrub birch close to the site. Temperature estimates, derived from fossil coleoptera suggested mean temperatures of the warmest and coldest months of 11°C and –11°C, respectively /Moseley 1982/ and were interpreted as indicating that the site was situated close to the border of the forest zone /Robertsson 1988/.

According to the pollenstratigraphy, the vegetation during interstadial 2 was dominated by herbs. The presence of *Juniperus*, *Filipendula* and *Selaginella sellaginoides, Armeria, Betula nana* and *Dryas octopetala* pollen would give similar MTWM and MTCM as during interstadial 1.

The inferred presence of sparse birch forest around the site during interstadial 1, albeit based on pollen analysis only, led /Robertsson 1988/ to suggest a correlation of interstadial 1 with Brørup and of interstadial 2 with Odderade. She argued that tree birch could not have been present in central Sweden during the Middle Weichselian, since only shrub and herb vegetation had been reconstructed for this time interval in northern Germany. However, given the fact that it is very difficult to differentiate between pollen of shrub and tree birch, and that no plant macrofossil studies had accompanied the pollenstratigraphic record, the presence of tree birch during interstadial 1 is not proven. Even though coleoptera-based summer temperatures of 11°C /Moseley 1982/ would suggest that tree birch could have been present, the study by /Helmens et al. 2007a/ showed that high summer temperatures in northern Fennoscandia not necessarily led to an immigration and establishment of tree vegetation.

Following the stratigraphic transect presented by /Kulling 1945/, an additional, older interstadial deposit seems to be present in Pilgrimstad, below the stratigraphy described by /Robertsson 1988/. The mammoth molar which had been found by /Kulling 1945/ and which was recently re-dated by /Ukkonen et al. 2007/, seems to have been derived from this lower interstadial (Figure 7-4 a–d).

The ^{14}C dates of Pilgrimstad shown in the Figure 7-4 a–d are presented on an approximate depth scale following the summary stratigraphy of /Robertsson 1988/. The mammoth date of /Ukkonen et al. 2007/ is also shown, since its approximate stratigraphic and depth context was reported in /Robertsson 1988/. The infinite ages reported by /Robertsson 1988/ and /Engstrand 1965/ are however not shown in Figure 7-4 since these lack a stratigraphic context. The data set indicates that ages which were assigned to quality group 1, cluster around 40–55 ^{14}C kyr or 60–45 cal kyr

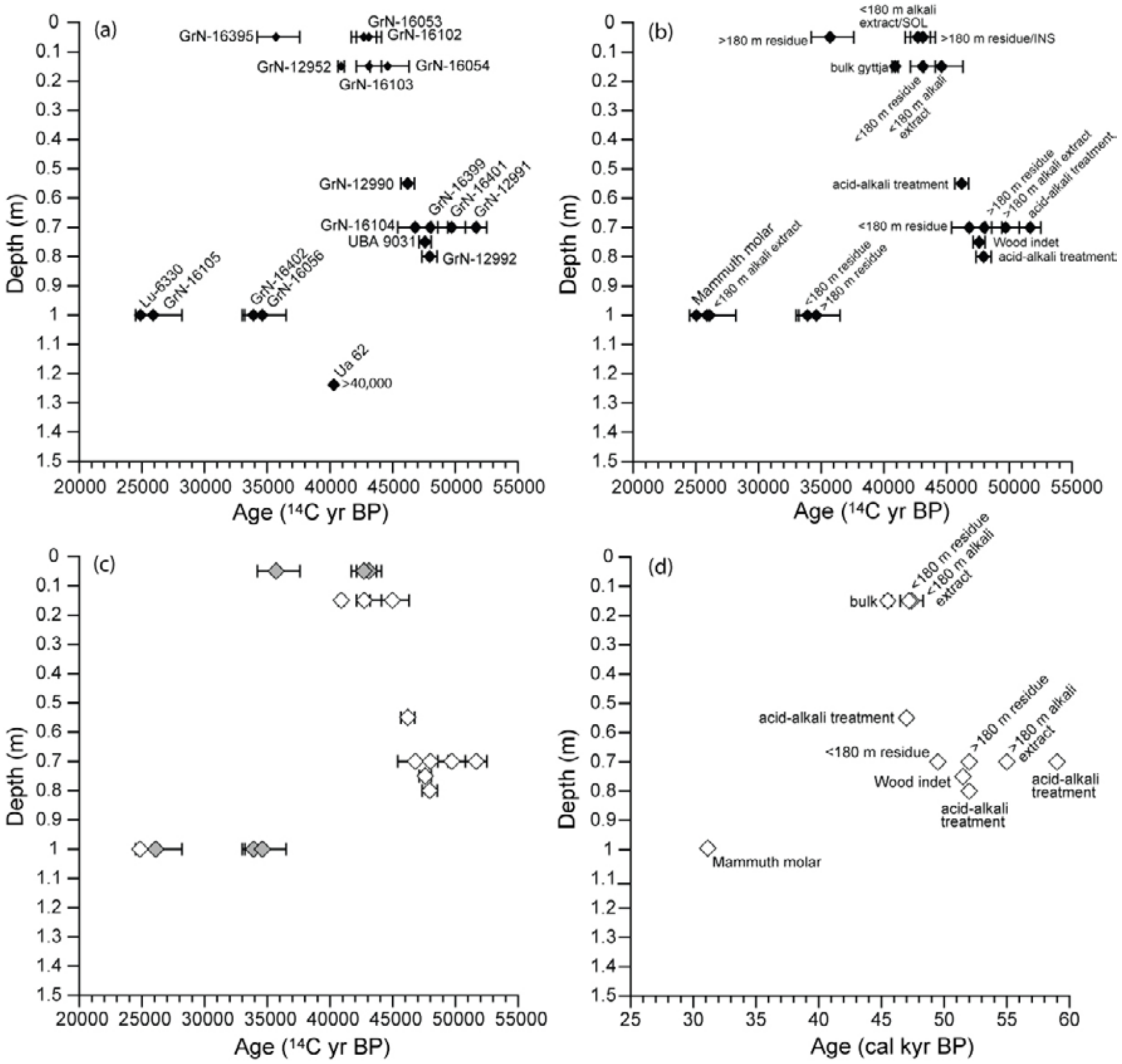

***Figure 7-4.** ^{14}C dates (1σ) published for Pilgrimstad in central Sweden shown against a schematic depth. The ^{14}C dates are derived from /Robertsson 1988, Ukkonen et al. 2007/ and unpublished sources (J. Lundqvist, B. Wohlfarth). (a) All ^{14}C dates including their laboratory number, several infinite ^{14}C dates have been reported by /Robertsson 1988 and references therein/, and /Engstrand 1965/ but these lack a clear stratigraphic assignment and partly also a laboratory number (St 205: >35,000, St 211: >39,000, St 1270: >39,000, >40,000, >40,000). Therefore they are not shown here. (b) Type of dated material: from several samples multiple dates on different fractions of the material were obtained. (c) All dates and their quality ranking (0–1), where group 0 dates are marked by filled diamonds and group 1 dates by open diamonds. (d) Acceptable ages (group 1) in calibrated years (1σ). Note that only ^{14}C dates at 0.15 m could be calibrated using the curve of /Fairbanks et al. 2005/, all other "calibrated" ages were estimated in comparison to the curve by /Hughen et al. 2006/.*

(Figure 7-4 c, d), with the exception of the mammoth date of /Ukkonen et al. 2007/, which is considerably younger. Although no error could be assigned to the calibrated ages below 0.5 m depth, it seems that the dates on plant material are in stratigraphical order, i.e. they become younger towards the top. If the ^{14}C dates on the plant and sediment material are assumed to be correct, the dated mammoth sample must have been contaminated by younger material and does not represent the true age of the sediment unit where it was found. Tentatively, and with the exception of the mammoth date, the data set would indicate deposition of organic material between ca. 60 and 45 cal kyr BP and as such ice free conditions during this time interval at the site.

7.2 Sites with little or no stratigraphic information

The sites for which only few dates were available and/or where dates where reported without detailed stratigraphic context, are shown in Figure 7-5 a, b along a north-south transect.

The northernmost sites, between 64 and 65° N, comprise Vojmån, Blajksjön and Boliden where organic and sediment material had been obtained from drill holes. At Boliden, organic sediments were intercalated in till and the pollen flora on these indicated arctic/subarctic conditions with open tundra, willow shrubs, herbs and a possible interglacial or interstadial origin /Robertsson and García Ambrosiani 1988, García Ambrosiani 1990/. Tåsjö in Jämtland, also at 64° N, provided organic material in a gravel pit and both insects and pollen pointed to an open tundra landscape, arctic conditions and summer temperatures of < 8–10°C /Lundqvist and Miller 1992/. Borlänge at 60° N was a drill hole, where wood and macrofossils (*Juniperus*, *Picea*) found in glacial silt and sand had been dated (Figure 7-5 b). Pollen spectra on these sediments indicate redeposited interglacial or interstadial sediments.

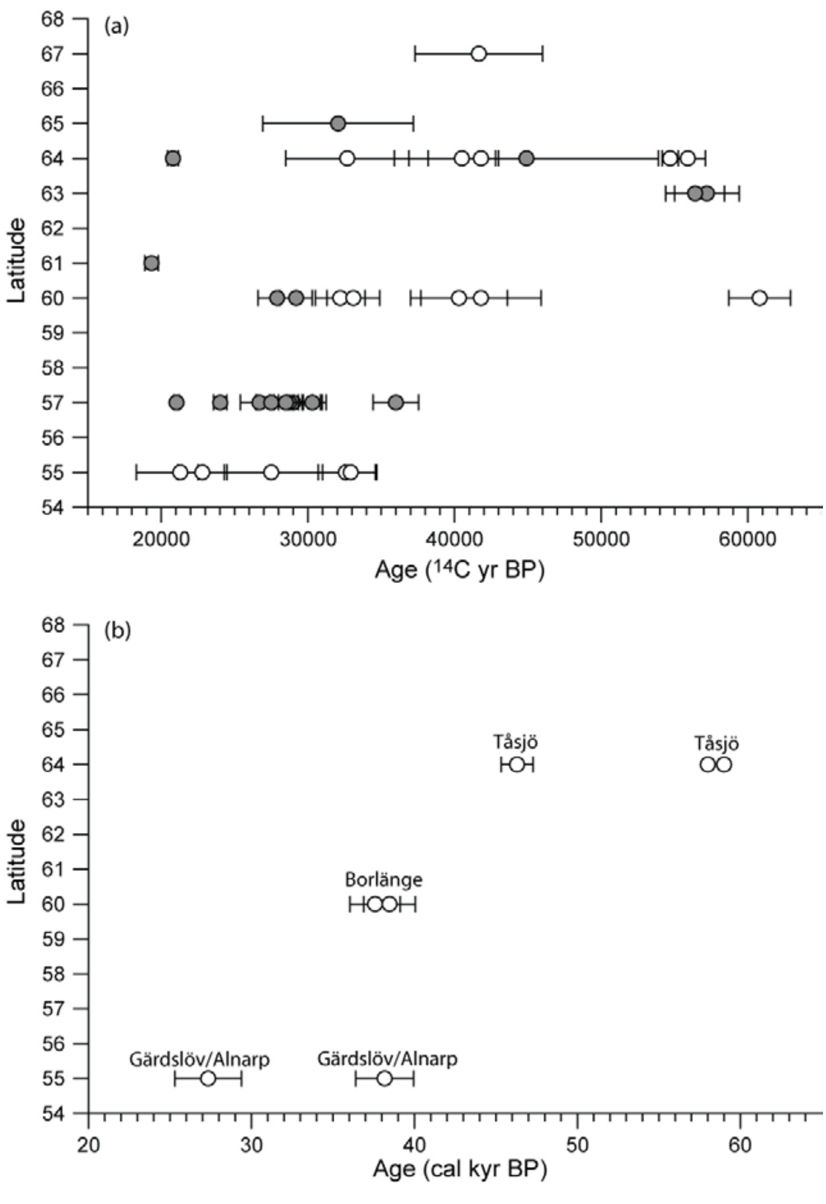

Figure 7-5. *^{14}C dates (1σ) from sites for which no or little stratigraphic information was available. (a) All dates (1σ) and their quality assignment 0–1. Grey filled circles = group 0 dates and open circles group 1 dates. (b) Calibrated age ranges (1σ) for those dates which were ranked in group 1. Note that only ages with a reported standard deviation of < 2,000 years were calibrated, and that the "calibrated" age of the oldest dates was estimated in comparison to /Hughen et al. 2006/, while the younger dates were calibrated according to /Fairbanks et al. 2005/.*

Dösebacka, Hissinge, Ellesbo at 57° N in south-western Sweden /Hillefors 1974/, sites which are often referred to as indicating ice free conditions, provided samples with very low organic carbon content and, according to the ^{14}C laboratory, unreliable ages. ^{14}C measurements from Gärdslöv/Alnarp at 55° N were obtained on plant remains /Miller 1977/, but several of these measurements resulted in very large reported errors of >2,000 years and could therefore not be calibrated.

Acceptable dates are thus very few and cluster between 45 and 60 cal kyr for the northernmost sites, around 35–40 cal kyr for those at 60° N and around 25–40 cal kyr for sites in southern Sweden.

7.2.1 Mammoth dates

^{14}C dates on mammoth finds from Sweden (Figure 7-6 and Table 7-1) and neighboring countries have been published and discussed by /Ukkonen et al. 1999, 2007, Arppe and Karhu 2006, Aaris-Sørensen 2006/.

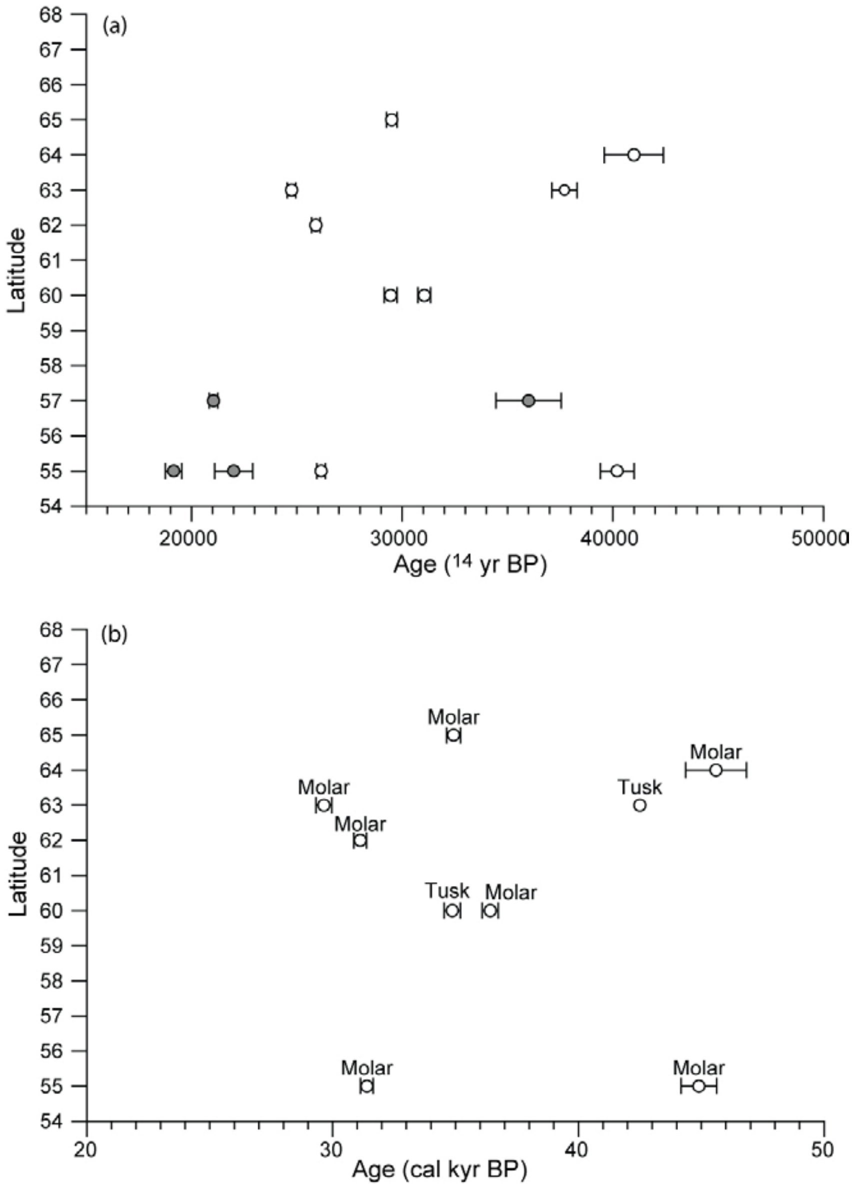

Figure 7-6. *^{14}C dates (1σ) on mammoth remains from Sweden published by /Håkansson 1976, Berglund et al. 1976, Aaris-Sørensen 2006, Ukkonen et al. 2007/. (a) ^{14}C dates of all finds. Note that /Ukkonen et al. 2007/ re-dated the same tusks from Örsjö and Arrie, which had earlier been dated by /Håkansson 1976/, as well as the tusk from Kånkback which had been dated by the Stockholm Radiocarbon Laboratory. Filled grey circles = group 0 dates, open circles = group 1 dates. (b) Calibrated age ranges (1σ) of the ^{14}C dates which were classified as acceptable (see text).*

Table 7-1. Radiocarbon dates on mammoth remains from Sweden. LuS 6649 = new date for the tusk earlier dated (St 5331), LuS 6342 = new date for the tusk earlier dated (Lu 746, Lu 880), LuS 6651 = new date for the finds at Arrie (Lu 887, Lu 887:E).

Site name	Lab number	Material	^{14}C age (1σ)	Reference	Quality group
Västansjö	LuS 6329	Molar	29,500 ±250	Ukkonen et al. 2007	1
Ramsele	LuS 6650	Molar	41,000 ±1,400	Ukkonen et al. 2007	1
Sollefteå	LuS 6328	Molar	24,750 ±200	Ukkonen et al. 2007	1
Kånkback	St 5331	Tusk	>43,000	?	0
Kånkback	LuS 6649	Tusk	37,700 ±600	Ukkonen et al. 2007	1
Pilgrimstad	LuS 6330	Molar	25,900 ±200	Ukkonen et al. 2007	1/0
Rättvik/Bäck	LuS 6331	Tusk	29,450 ±300	Ukkonen et al. 2007	1
Rättvik/Lerdala	LuS 6332	Molar	31,050 ±300	Ukkonen et al. 2007	1
Dösebacka	Lu 879	Tusk	36,000 +1,550/–1,300	Håkansson 1976	0
Dösebacka	Lu 795	?	21,040 ±200	Håkansson 1976	0
Bårslöv	OxA-10193	Molar	33,850 ±700	Aaris-Sørensen 2006	1
Örsjö	Lu 746	Tusk	31,200 +3,050/–2,650	Håkansson 1976	0
Örsjö	Lu 880	Tusk	36,100 +2,000/–1,600	Håkansson 1976	0
Örsjö	LuS 6342	Tusk	34,500 ±400	Ukkonen et al. 2007	1
Arrie	Lu 887	Tusk	22,000 +900/–800	Håkansson 1976	0
Arrie	Lu 887:E	Tusk	19,150 ±390	Håkansson 1976	0
Arrie	LuS 6651	Molar	40,200 ±800	Ukkonen et al. 2007	1

/Ukkonen et al. 2007/ re-dated the mammoth tusks from Örsjö and Arrie, which had earlier been dated by /Håkansson 1976/, and the tusk from Kånkback which had been dated at the Stockholm Radiocarbon Laboratory and also presented new ^{14}C dates on mammoth tusks and molars which had been preserved in museums and at the Swedish Geological Survey. Based on these new ^{14}C dates /Ukkonen et al. 2007/ suggested ice free conditions in Sweden between 44 and 26 kyr, i.e. during a large part of the middle and late Weichselian (i.e. parts of MIS 3 and 2). Moreover, δ^{18}O measured in mammoth enamel implied that mean annual temperatures were ~2–3°C lower during the middle Weichselian as compared to today and that climate was more homogenous over Sweden, with moderate north-south gradients /Ukkonen et al. 2007/.

Given the complications which can arise when old tusks are dated (see Section 6.2), I choose to classify those ^{14}C dates which had been made by /Håkansson 1976/ and by the Stockholm Radiocarbon laboratory as unreliable, while I assume that recently measured samples /Aaris-Sørensen 2006, Ukkonen et al. 2007/ contained enough collagen, were carefully handled and correctly pretreated in the radiocarbon laboratories. This reasoning is however not entirely correct as shown by the recently dated mammoth molar from Pilgrimstad by /Ukkonen et al. 2007/ (LuS 6330, Table 7-1, see also Section 7.1), which resulted in a much younger age than the overlying organic deposits. If the ^{14}C ages of these organic deposits are regarded as correct, then sample LuS 6330 was certainly contaminated.

None of the other, recently dated mammoth remains (quality group 1, Table 7-1) was found in a stratigraphic context, which makes it impossible to corroborate their ^{14}C ages in relation to dated contemporaneous deposits and/or older and younger layers.

8 Discussion

All ^{14}C dates which passed quality criteria 1 and which could be calibrated (reported error < 2,000 years) are shown in Figures 8-1 a and b along a west-east and north-south transect, respectively. The calibrated ages for all dates range between ~60 and ~25 cal kyr. Some of the mammoth dates compare well with ages attributed to organic deposits, while others clearly diverge. The mammoth dates of ~30 cal kyr from Pilgrimstad and Sollefteå (15–17° E, 62–63° N) are for example considerably younger than the age ranges of interstadial deposits from the same site and geographical region. Moreover, mammoth

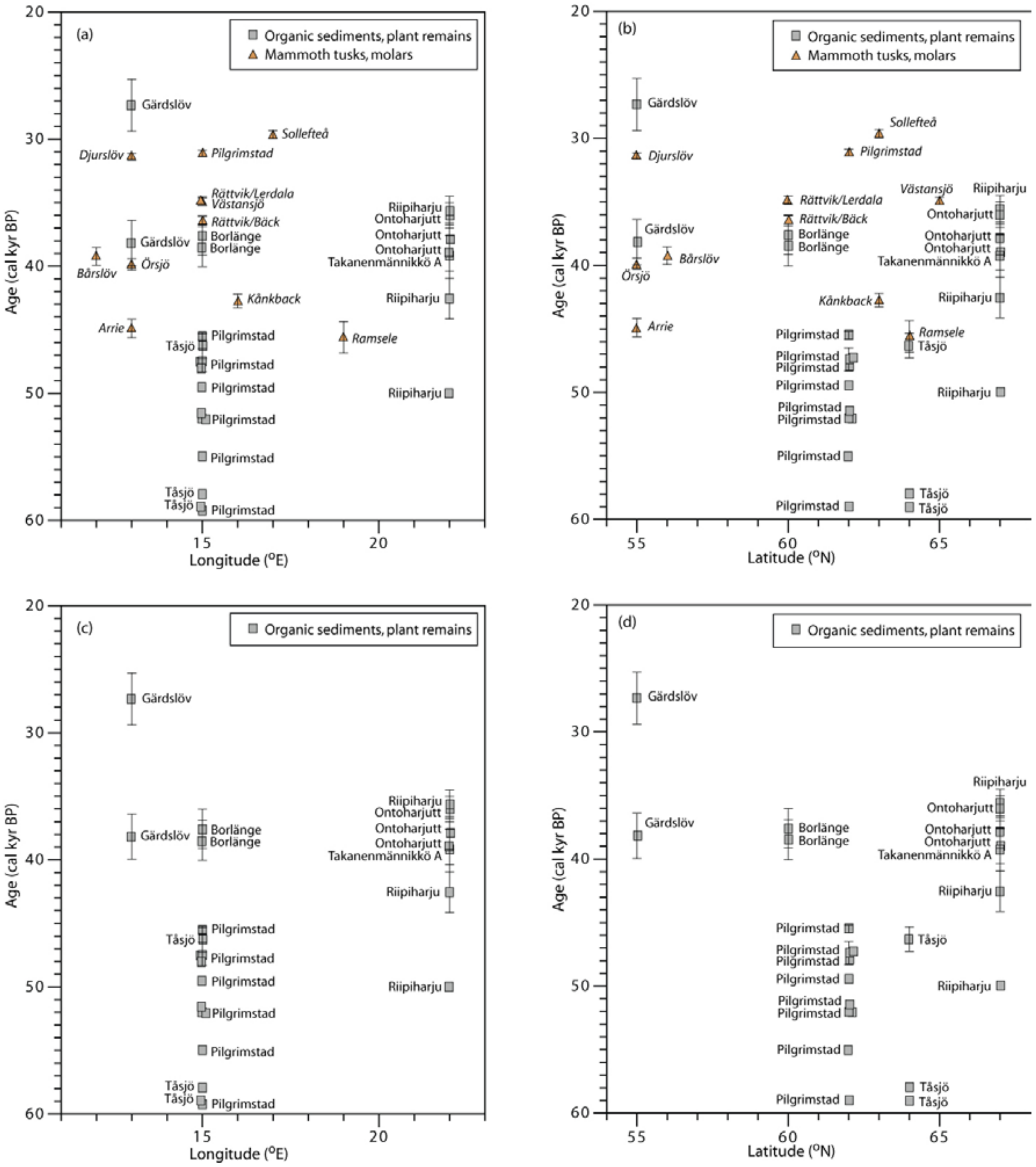

Figure 8-1. Calibrated ^{14}C ages (1σ) of group 1 samples, which had a reported error of >2000 years shown (a) along a west-east transect and (b) along a north-south transect. Note that the ages of the mammoth dates from Pilgrimstad and Sollefteå are considerably younger than the age range of other sites in the same geographical region. Calibrated ^{14}C dates of group 1, except for those obtained on mammoth remains, are shown in (c) along a west-east transect and in (d) along a north-south transect.

dates from Arrie, Bårslöv and Örsjö in southernmost Sweden are up to several thousand years older than the age of the Gärdslöv sediments and mammoth dates from Rättvik and Västansjö in south-central Sweden are younger than interstadial deposits from sites at the same latitude.

As discussed above, the age of the mammoth from Pilgrimstad (LuS 6330) is younger than overlying organic deposits from the same site (Figure 7-4). If the ^{14}C ages of the organic sediments from Pilgrimstad are accepted then sample LuS 6330 (Table 7-1) must have been contaminated and cannot be regarded as a valid age estimate. No information is available for sample LuS 6328 from Sollefteå, but the most plausible conclusion for this young date would be that also this sample had been contaminated by younger carbon. Both samples should thus be excluded from the data set. The discrepancy between the age of several other mammoth dates and those on organic sediments/plant remains from geographically close interstadials, furthermore suggests that most, if not all mammoth dates, have serious problems and that they should probably not be included in group 1.

If all mammoth dates are excluded, acceptable ages (Figure 8-1 c, d) would indicate ice free conditions in northern and central Sweden between ~60 and ~35 cal kyr and in southern Sweden between ~40 and ~25 cal kyr. An ice advance would in this scenario only have occurred in central and northern Sweden during the later part of MIS 3, i.e. after ~35 cal kyr and in southern Sweden during MIS 2, i.e. after ~25 cal kyr. The validity of this conclusion needs however to be tested by comparing this data set against other records which have been used to constrain ice free/ice covered intervals in Fennoscandia.

Figures 8-2 a and b show a comparison between group 1 dates (excluding the mammoth dates) and OSL ages obtained in southern Sweden by /Kjær et al. 2006/. The OSL ages have been used to infer ice free conditions in southernmost Sweden between ca. 39–24 kyr, i.e. prior to the last ice sheet advance /Kjær et al. 2006/. The group 1 ages at 13°E and 55°N fall well within the range of the OSL ages, which could be taken as an independent confirmation for the validity of the ^{14}C dates.

There is clear evidence from numerous ^{14}C dates and, palaeomagnetic measurements that the Fennoscandian ice sheet advanced beyond the Norwegian coast at around 40 cal kyr /Mangerud et al. 2003/. This advance is older than the ice advance into Denmark at ~34 cal kyr which has been suggested by /Houmark-Nielsen et al. 2005/. However, given the large error margins of the OSL dates

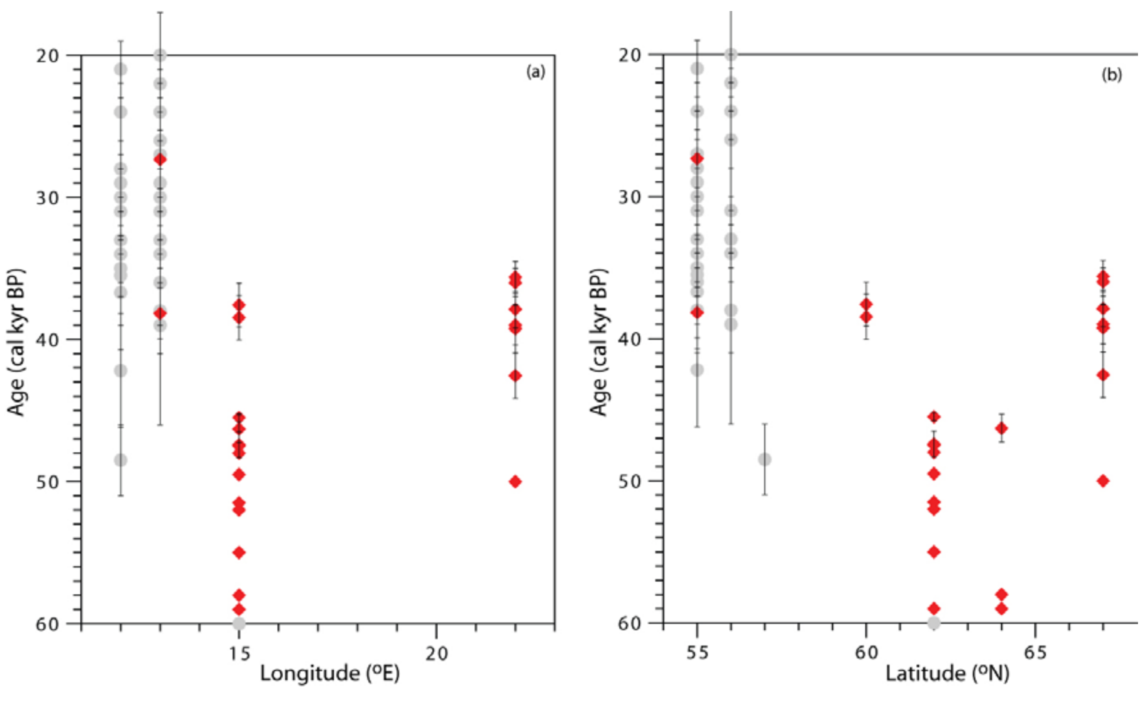

Figure 8-2. *OSL ages (filled grey circles) for southernmost Sweden /Kjær et al. 2006/ and calibrated ^{14}C dates (group 1) (red filled diamonds) shown according to longitude (a) and latitude (b). All mammoth dates are excluded.*

for this ice advance, it is possible that it predates the ice free interval inferred by /Kjær et al. 2006/. It could therefore, as discussed earlier, be contemporaneous with the Norwegian advance. Should these assumptions be correct, an ice advance covering southernmost Sweden would have occurred before ~39–40 cal kyr and was followed by ice free conditions in southern Sweden after ca. 39 cal kyr.

Although the uncertainties of the group 1 ages are considerable, the approximate time span covered by the interstadials at Pilgrimstad and Tåsjö falls within a similar time span as that reported for the Norwegian Bø Interstadial and for the Sokli interstadial in Finland (Figure 8-3, Table 8-1). The interstadial deposits at Ontoharjutt, Takanenmännikö and Riipiharju indicate a slightly younger age range, similar to Borlänge, which seems to correspond in time more closely to the Sejerø interstadial in Denmark (Figures 8-1 c, d, 8-3). Although tentatively, this could be interpreted as ice free conditions in south-central and northern Sweden around and prior to 40 cal kyr and ice cover thereafter.

The large error uncertainties inherent in the Swedish data set do not allow any conclusions regarding the duration of the interstadials or whether shorter ice free intervals alternated with ice covered intervals. The only conclusion that may be drawn with sufficient confidence is that southern, central, and northern Sweden likely remained ice free during the early and middle part of MIS 3. The ice sheet advance beyond the Norwegian coast ~40 cal kyr /Mangerud et al. 2003/, which is possibly also synchronous with that suggested for Denmark /Houmark-Nielsen et al. 2005/ and southernmost Sweden /Kjær et al. 2006/ would have certainly also led to ice cover in northern, central and southern Sweden. How far north in Sweden the ice retreated during the following ice free phase remains unclear, although it could be speculated that the interstadial deposits from Borlänge at 60 °N could represent an ice free interstadial between ~40 and 35 cal kyr (Figure 8-2 a, b).

If we assume that Sweden remained ice free during the early and middle part of MIS 3, summer temperature estimates derived from interstadial deposits should then be comparable with each other. Summer temperature estimates and vegetation reconstructions have been made for the interstadials from Riipiharju /Hättestrand 2008/, Tåsjö /Lundqvist and Miller 1992/ and Pilgrimstad /Robertsson 1988/, and also for Middle Weichselian deposits from Finland and Denmark (Table 8-1). The Danish interstadials correlate to the middle and younger part of MIS 3 or to GIS 11/10 and GIS 8-5, respectively /Houmark-Nielsen and Kolstrup 1981, Bennike et al. 1994, 2006, Houmark-Nielsen et al. 1996/, while the youngest interstadial at Sokli in northern Finland probably dates to the earlier part of MIS 3 and is correlative with GIS 14 /Helmens et al. 2007ab, Helmens 2009/ (Figure 8-3, Table 8-1). The large age ranges for the organic deposits at Riipiharju of ~50–35 cal kyr and at Tåjö and Pilgrimstad of ~60–45 cal kyr do not allow any precise assignment to Greenland interstadials, but could tentatively compare to GIS 14-8 and GIS 17-12, respectively (Figure 8-3, Table 8-1).

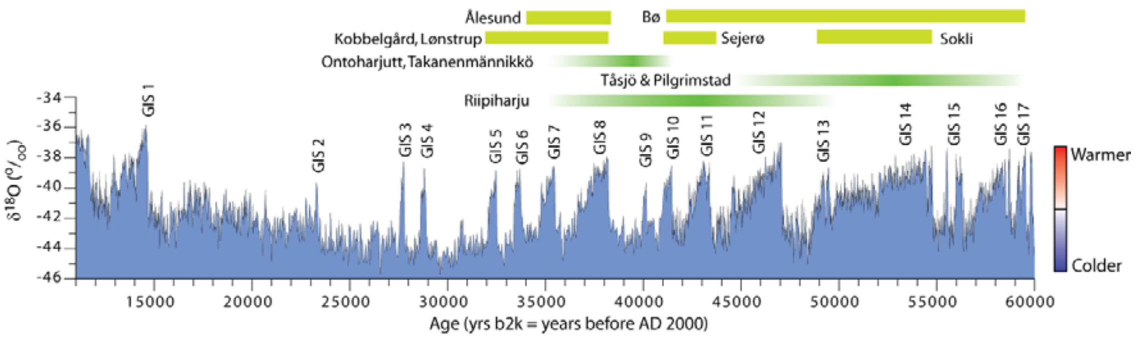

Figure 8-3. *Tentative correlation of interstadial deposits in Norway, Finland, Sweden and Denmark to the Greenland interstadials (GIS) recognized in the North GRIP ice core /Krogh Andersen et al. 2006/. See Table 8-1 for references to the Finnish, Swedish and Danish interstadial sites and /Mangerud et al. 2003/ for the age assignment of the Norwegian interstadials.*

Table 8-1. Interstadial intervals in northern Finland, Sweden and Denmark and their possible correlation to the Greenland ice core stratigraphy (see Figure 2-1). Plant remains from Kobbelgård indicate that winters were cold, but that enough precipitation was available to provide a snow cover. MTWM = mean temperature of the warmest month.

Site name	Time interval	Vegetation	MTWM	Reference
Sokli	?GIS 14	Arctic shrubs & herbs	10–14°C (multi-proxy)	Helmens et al. 2007a, 2007b
Riipiharju/ Tärendö II	?GIS 14-GIS 8	Arctic shrubs & herbs, scarce birch forest	10°C (pollen)	Hättestrand 2008
Tåsjö	?GIS 17-12	Arctic shrubs & herbs	<8–10°C (insects)	Lundqvist and Miller 1992
Pilgrimstad	?GIS 17-12	Open tree less, sparse birch forest	<11–14°C (pollen, insects)	Robertsson 1988, this work
Sejerø	Hengelo GIS 11/10	Arctic shrubs & herbs	8–10°C (multi-proxy)	Houmark-Nielsen and Kolstrup 1981, Bennike et al. 2006
Kobbelgård	Ålesund-Sandnes Interstadial GIS 8-5	Treeless subarctic and low arctic	11°C (multi-proxy)	Bennike et al. 1994
Lønstrup/ Lodbjerg	GIS 8-5	Open, tree less, herbs, scattered shrubs and scarce tree birch	10°C (multi-proxy)	Houmark-Nielsen et al. 1996

Arctic shrub and herb vegetation have been reconstructed for all sites, although the environment at Riipiharju, Pilgrimstad and Lønstrup/Lodbjerg and Riipiharju may also have contained sparse tree birch (Table 8-1). However these latter findings are only corroborated by plant macrofossil evidence at Lønstrup/Lodbjerg. Mean summer temperature estimates for all sites are between ~8 and 14°C, with Sokli and Pilgrimstad giving highest estimates and Tåsjö, Riipiharju and the younger Danish interstadials providing slightly lower summer temperature reconstructions. If we only consider sites with multi-proxy based temperature reconstructions (pollen, beetles, chironomids, plant macrofossils), such as Sokli, Pilgrimstad, Sejerø, Kobbelgård and Lønstrup/Lodbjerg, summer temperatures could have been higher during the earlier part of MIS 3 and lower during the later part of MIS 3.

The temporal resolution of the Swedish data set is far too coarse to allow for any detailed correlations to Sokli or the Danish sites. However it seems that the temperature estimates for Pilgrimstad compare reasonably well to those of Sokli, while summer temperature estimates for Riipiharju and Tåsjö have a similar range than those reconstructed for the younger Danish sites.

9 Conclusions

- Published and unpublished ^{14}C, TL/OSL, U/Th dates for Norway, Denmark, Sweden, Estonia, Finland and parts of Russia >17,000 years old were assembled in a data base and evaluated. The data base is in its present form available at the Swedish Nuclear Fuel and Waste Management Company.
- Special focus was placed on assessing if ice free conditions prevailed in Sweden during the middle Weichselian, i.e. Marine Isotope Stage 3. The careful assessment of mainly ^{14}C dates shows that ages for acceptable datings of interstadial organic material in northern and central Sweden range between ~60 and ~35 cal kyr and for similar deposits in southern Sweden between ~40 and ~25 cal kyr.
- ^{14}C dates on mammoth tusks and molars diverge in several cases from the age estimates assigned to organic deposits, which indicates that most, if not all ^{14}C dates on mammoth remains are too young and should likely be regarded as unreliable.
- A possible scenario, based only on ^{14}C dates from interstadial deposits, is that central, northern and southern Sweden remained ice free during the early and middle part of MIS 3.
- Ice cover likely occurred around ~40 cal kyr, more or less contemporaneous with the ice advance to the Norwegian shelf and into Denmark.
- During an ice free period after ~40 cal kyr southern Sweden and possibly also south-central Sweden may have been ice free.

10 Acknowledgements

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Appendix 1

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