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

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Published and unpublished ^{14}C dates for Sweden older than the Last Glacial Maximum ice advance were evaluated. Acceptable ^{14}C dates indicate that age ranges for interstadial organic material in northern and central Sweden are between *c.* 60 and *c.* 35 cal. kyr BP and for similar deposits in southern Sweden are between *c.* 40 and *c.* 25 cal. kyr BP, which is in good agreement with recently derived Optical Stimulated Luminescence ages. ^{14}C dates on mammoth remains show a larger scatter, possibly as a result of incomplete laboratory pretreatment. A possible scenario based on calibrated ^{14}C dates from interstadial deposits is that central and northern Sweden was ice-free during the early and middle part of Marine Oxygen Isotope Stage 3 and that southern Sweden remained ice-free until *c.* 25 cal. kyr BP. A first ice advance into northern and central Sweden might have occurred as late as around 35 cal. kyr BP, more or less coeval with the Last Glacial Maximum ice advance onto the Norwegian shelf. To test the conclusions drawn here, new multi-proxy and high-resolution investigations of several key sites in north, central and south Sweden are required.

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Ocean, land and ice archives in both hemispheres record distinct responses to the millennial-scale climate shifts of the last glacial period (Dansgaard *et al.* 1993; Johnsen *et al.* 2001; Vœlker *et al.* 2002; EPICA 2006; Grimm *et al.* 2006; Hughen *et al.* 2006; Clement & Peterson 2008; Wang *et al.* 2008). The quasi-cyclic alternations between cold stadials and warm interstadials seem to have been most pronounced during Marine Oxygen Isotope Stage (MIS) 3, between 60 and 30 kyr BP, and were most strongly felt around the North Atlantic region (Rasmussen *et al.* 1996, 2003; Allen *et al.* 1999; Shackleton *et al.* 2000; Vœlker *et al.* 2002; Tzedakis *et al.* 2004; Roucoux *et al.* 2005; Grimm *et al.* 2006; Rousseau *et al.* 2007; Sánchez-Goñi *et al.* 2008; Wohlfarth *et al.* 2008). The duration of these millennial-scale events, which are known as Dansgaard-Oeschger or DO events, but are now referred to as Greenland Stadials (GS) and Greenland Interstadials (GIS) (Lowe *et al.* 2008), varied between *c.* 5000 years for the longest interstadials (GIS 14–13) and *c.* 500 years for shorter interstadials (e.g. GIS 4), whereas stadials lasted up to *c.* 1000 years (Krogh Andersen *et al.* 2006) (Fig. 1A).

Temperatures reconstructed from ice cores show amplitude shifts of 8–16 °C over Greenland at the transition from cold stadials to warm interstadials (Landais *et al.* 2004; Huber *et al.* 2006), similar to sea-surface temperature (SST) shift estimates for the near-shore mid-North Atlantic (Sánchez-Goñi *et al.* 2008). However, whereas Greenland temperatures gradually declined during the course of an interstadial, temperatures in the moisture source region decreased much later, which seems to indicate shifts in the position of the Polar Front (Jouzel *et al.* 2007). Mechanisms proposed to explain the underlying causes of these rapid climate shifts include changes in ocean thermohaline circulation (Knutti *et al.* 2004), interactions of wind fields and continental ice sheets (Wunsch 2006), sea-ice feedbacks, and tropical processes (Clement & Peterson 2008). Although the impact of millennial-scale climate variability seems evident in numerous archives, a recent modelling study by Flückiger *et al.* (2008) found that differences in the strength of the Atlantic meridional overturning result in large seasonal and geographical temperature differences. At high northern latitudes the change from cold stadials to warm interstadials was, for example, accompanied by a strong increase in winter temperatures, whereas summer temperatures changed only slightly.

Correlations between North Atlantic marine sequences and Greenland ice-core $\delta^{18}O$ records showed that high amounts of ice-rafted debris (IRD) and extremely cold SSTs occurred prior to GIS 12, 8, 4, 2 and 1 (Bond *et al.* 1993). These so-called Heinrich events (Fig. 1A), which originated from surges of Northern Hemisphere ice sheets (Hemming 2004), caused a rise in global sea level (Chappell 2002; Lambeck *et al.* 2002; Rohling *et al.* 2004; Rohling & Pälike 2005), which in turn could have caused further destabilization of the large ice sheets. Provenance analyses of Heinrich-layer detritus in North Atlantic marine sediments indicate that the IRD is derived from 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.* 2000, 2001). Meltwater peaks in the Norwegian Sea during MIS 3 have been associated with Heinrich events and millennial-scale climate variability (Lekens *et al.* 2006),

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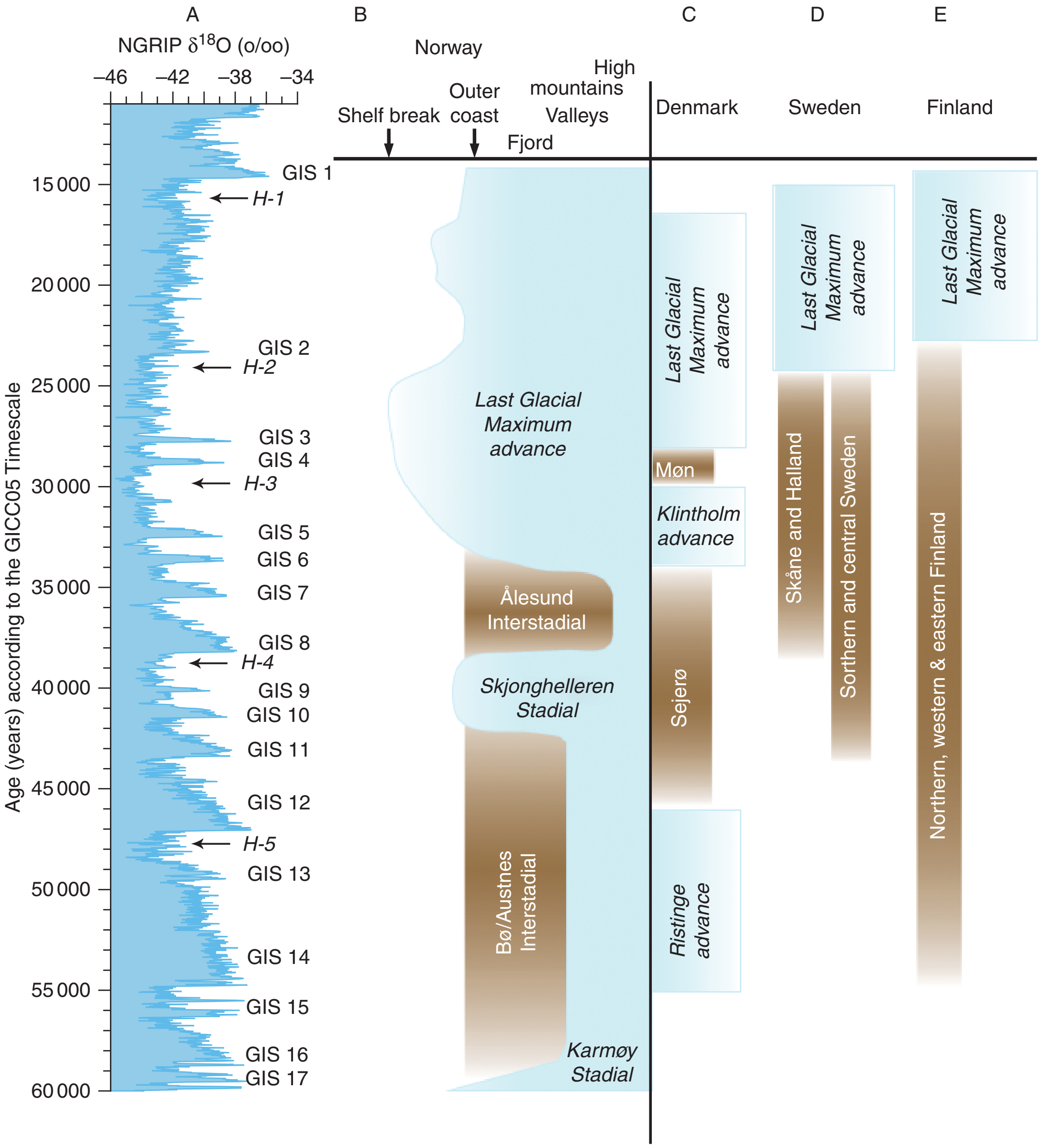

Fig. 1. A. The Greenland ice-core oxygen isotope ($\delta^{18}O$) stratigraphy for MIS 2 and MIS 3 from NGRIP (Krogh Andersen *et al.* 2006). GIS = Greenland interstadials, H = Heinrich events. B. Glaciation curve for Norway according to Vorren & Mangerud (2008), Mangerud (2004) and Mangerud *et al.* (2003, 2009); the correlation between ice advances in Norway and the Greenland $\delta^{18}O$ stratigraphy is based on the detection of the Laschamp and Mono Lake palaeomagnetic excursions in cave sediments. Ice advances and ice-free conditions in Denmark (C) according to Houmark-Nielsen (2007, 2009), in Sweden (D) after Kjær *et al.* (2006) and Ukkonen *et al.* (2007), and in Finland (E) after Mäkinen (2005), Helmens *et al.* (2007a, b) and Lunkka *et al.* (2008). The correlation between ice advances/retreat phases in C–E and the Greenland $\delta^{18}O$ stratigraphy is based on the age assignments provided by the individual authors. Ice-free intervals are shown in brown, and ice advances in blue.

which would imply that the Scandinavian Ice Sheet (SIS) acted as a significant meltwater source, through the drainage of ice-dammed lakes and/or through subglacial meltwater release.

A response of the SIS margin to some of these millennial-scale climate shifts can indeed be inferred from studies along the Norwegian coast (Olsen 1997; Mangerud *et al.* 2003, 2009; Mangerud 2004), and in Denmark (Houmark-Nielsen & Kjær 2003; Houmark-Nielsen 2007) and northern Finland (Helmens *et al.* 2007a, b). The size and the extent of the SIS during MIS 3 are, however, still controversial issues, and several different ice-sheet scenarios exist. The 'larger ice sheet' scenario suggests that the SIS advanced during MIS 4 and subsequently covered Norway, Sweden, Finland, parts of Denmark and the whole Baltic Sea basin (e.g. Donner 1996; J. Lundqvist 2004). Ice-marginal stratigraphies indicate, on the other hand, complex advance and retreat patterns during MIS 3 (Houmark-Nielsen & Kjær 2003; Mangerud *et al.* 2003, 2009, Mangerud 2004; Houmark-Nielsen 2007, 2010; Larsen *et al.* 2009), with ice-free conditions along the Norwegian coast, Denmark and southernmost Sweden alternating with ice advances into Denmark and onto the Norwegian shelf (Fig. 1B, C). Ice retreat along the Norwegian coast (Bø/Austnes, Ålesund) coincided with a series of especially warm Greenland Interstadials (Mangerud *et al.* 2003, 2009; Mangerud 2004) (Fig. 1A, B). However, the advance and retreat phases of the SIS along the Norwegian coast and in southernmost Scandinavia seem to have been partly asynchronous (Fig. 1B, C). The Ristinge advance into Denmark is, for example, dated to the same time interval as the Bø/Austnes interstadial in Norway. The 'small ice sheet' scenario of Arnold *et al.* (2002) suggests a minimum ice sheet centred over southern Norway, or possibly an ice-sheet margin terminating in south-central Sweden. A smaller MIS 3 ice sheet terminating in south-central Sweden (Arnold *et al.* 2002) seems compatible with ice-free conditions in Sweden (Kjær *et al.* 2006; Ukkonen *et al.* 2007) (Fig. 1D), and in Finland (Ukkonen *et al.* 1999, 2007; Mäkinen 2005; Helmens *et al.* 2007a, b; Lunkka *et al.* 2008) (Fig. 1E). Simplified ice-sheet models driven by the temperature record of the Greenland ice cores produce distinct ice-sheet responses to millennial-scale climate shifts (Arnold *et al.* 2002; Näslund *et al.* 2003; Forsström & Greve 2004), which suggest that fast ice flow resulting from wet basal conditions could have played an important role and could easily have influenced ice-sheet dynamics during MIS 3. Ice dynamics as derived from these models would thus have been considerably different from and much more variable than the dynamics reconstructed from geological data.

The discrepancies between the ice-sheet scenarios of, for example, Donner (1996), J. Lundqvist (2004), Houmark-Nielsen & Kjær (2003), Mangerud (2004), Mangerud *et al.* (2009) and Houmark-Nielsen (2007) and those suggested by Arnold *et al.* (2002), Näslund *et al.* (2003), Forsström & Greve (2004), Ukkonen *et al.* (2007), Helmens *et al.* (2007a, b) and Lunkka *et al.* (2008) and, to some extent also Kjær *et al.* (2006), are related to the often fragmentary occurrence of interstadial deposits in Fennoscandia, to the lack of multi-proxy studies on stratigraphic sequences from the centre of the former ice sheet, to the limits of the different dating techniques and to the basic assumptions used in ice-sheet models. Stratigraphic sections with good age control are not available from the centre of the former SIS, but a large number of older ^{14}C, TL/OSL (thermoluminescence/Optical Stimulated Luminescence) and Uranium-series (U-series) dates exist for Norway, Denmark, Sweden and Finland for the time interval prior to the Last Glacial Maximum. The quality of many of these older ^{14}C, TL and Uranium-series dates has, however, repeatedly been questioned (e.g. Mangerud 1991; Robertsson 1991; J. Lundqvist 1992, 1997; Donner 1996), and most if not all radiocarbon dates were regarded as too young when compared with pollen-stratigraphic results. Because several of these data points were used by Arnold *et al.* (2002) to constrain the margin of the SIS during MIS 3, and because the different age assignments are often cited, it seemed timely to re-assess the validity of published and unpublished TL/OSL, ^{14}C and U-series dates and to evaluate if and to what extent these data sets can be used to infer ice-sheet presence, ice-sheet absence or ice-sheet fluctuations during MIS 3.

Here I make use of a compilation of published and unpublished TL/OSL, ^{14}C and U-series dates that was commissioned by the Swedish Nuclear Fuel and Waste Management Company (SKB) to support data-model comparisons for different climatic scenarios (Kjellström *et al.* 2009; Wohlfarth 2009). With a focus on Sweden (i.e. the centre of the former SIS), I test the reliability of these dates and discuss whether conclusions can be drawn regarding ice-free conditions during MIS 3.

Compilation and evaluation of MIS 3 age measurements

Age measurements assembled in the database (Fig. 2) include TL/OSL, U/Th- and U-series and ^{14}C dates from Denmark, Sweden, Norway and Estonia, and to some extent also from Finland (a complete data set for Finland is lacking in this database) (Wohlfarth 2009). Most of the TL/OSL data points are from recent studies in Denmark and southern Sweden by Houmark-Nielsen (2003), Houmark-Nielsen & Kjær (2003), Kjær *et al.* (2006) and Houmark-Nielsen (2007), and from investigations in Finland by Helmens *et al.* (2007b). Apart from these new data sets only a few older TL/OSL data points exist for Norway (Larsen & Ward 1992; Olsen & Hammer 2005), Sweden (García Ambrosiani 1990) and Estonia (Kalm 2006). The same is true for U/Th- or U-series dates, there being 19 old data points for Norway (Olsen & Hammer 2005) and only one for Sweden (J. Lundqvist & Miller 1992). Because most recent OSL dates have been extensively discussed in Houmark-Nielsen (2003, 2007), Houmark-Nielsen & Kjær (2003), Kjær *et al.* (2006) and Helmens *et al.* (2007b), the focus will here be on an evaluation of ^{14}C age measurements (Fig. 3A, B). References to published and unpublished ^{14}C, OSL/TL and U/Th dates from Norway, Sweden, Finland, Russia, Estonia and Denmark that have been compiled in the data base for the time intervals prior to the Last Glacial Maximum (Figs 2, 3A, B) are given in Appendix 1.

The material that had been used for ^{14}C dating varied widely in composition and comprised inorganic and organic bulk sediments, plant material of lacustrine, marine and/or terrestrial origin, animal bones and

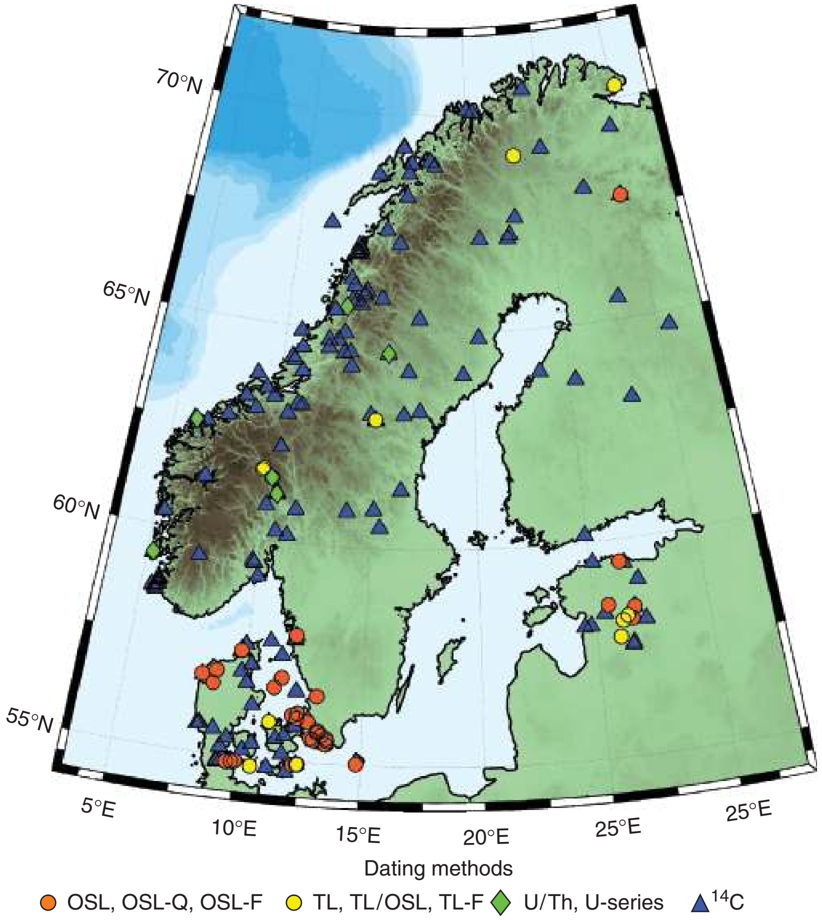

Fig. 2. Data points collected in the database up to May 2008 (note that the data set for Finland is still incomplete), divided into the different types of dating methods (see Appendix 1 for reference list). The data collection is stored at the Swedish Nuclear Fuel and Waste Management Company and at the Department of Geology and Geochemistry, Stockholm University.

teeth, marine shells and foraminifera (Fig. 3A). Each of these types of material is subject to a number of problems, which have been extensively discussed in the literature (e.g. Olsson 1979; Björck & Wohlfarth 2001; Mangerud *et al*. 2006; Hajdas 2007). Important issues when dealing with ^{14}C dates in general and old dates specifically are, for example, the careful selection and treatment of samples prior to sending them to the ^{14}C laboratory; pretreatment procedures in the ^{14}C laboratory and the background of the ^{14}C laboratory. Many of these points are now carefully addressed when sampling, preparing and dating sediments and organic matter, but were or could not be dealt with in earlier studies (Olsson 1979).

Terrestrial plant macrofossils, especially delicate leaves, are generally regarded as 'safe' for ^{14}C dating, provided that the fossil remains are not reworked from older sediments. Reworked peat can, for example, easily become infiltrated by humid acids or roots from overlying younger sediments, and ^{14}C dates of 30–50 kyr BP obtained on Eemian and/or Holsteinian peat in for example Estonia clearly show the danger of accepting these dates as accurate (Kalm 2005, 2006). Sediment samples with low organic carbon content result in erroneous ages because the carbon contained in these samples might be reworked or, if contemporaneous with the sediments, can easily become contaminated during sample handling (Björck & Wohlfarth 2001 and references therein). Organic sediments, such as gyttjas, have been shown to provide both reliable and unreliable ^{14}C ages, depending on the organic matter source. The alkali-soluble (SOL) humic and/or alkali-insoluble (INS) humin fractions extracted from these types of sediments have been tested extensively for ^{14}C dating (Björck & Wohlfarth 2001 and references therein). Usually the SOL fraction results in younger ages than the INS fraction, but, 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, 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, whereas 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 ^{14}C ages that are too old.

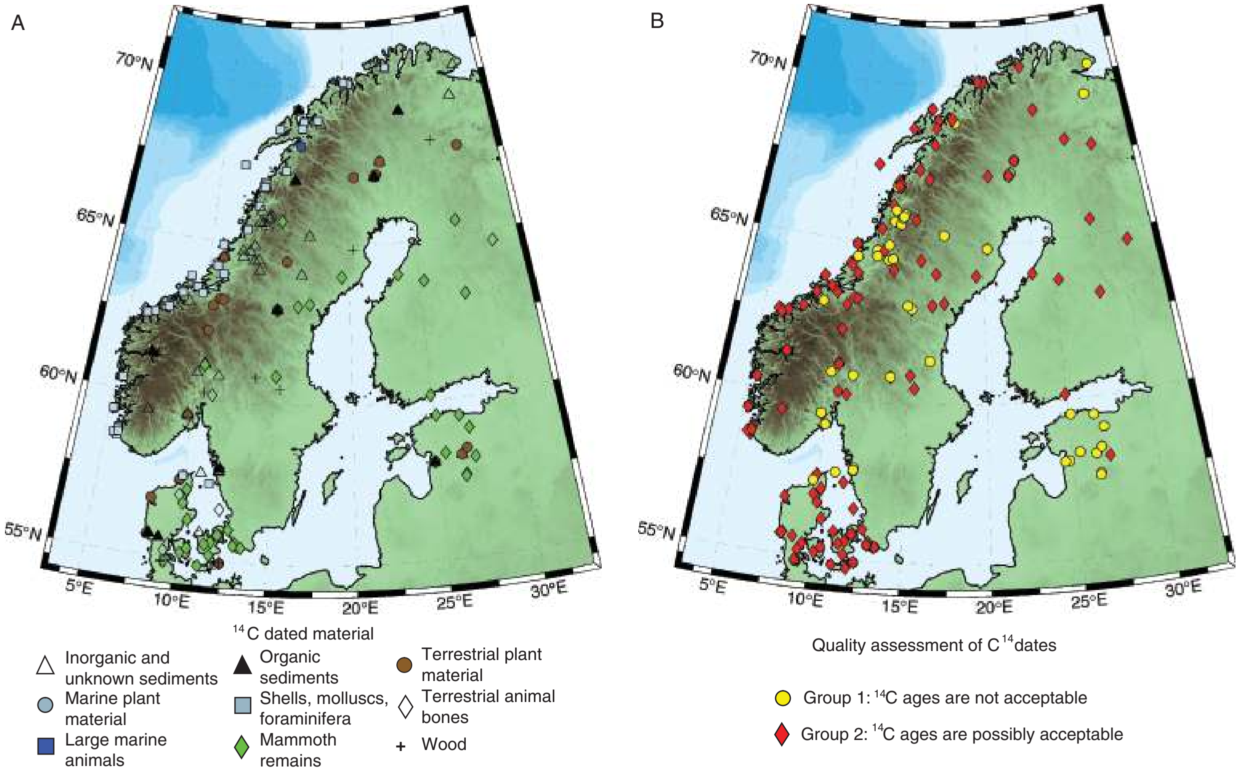

Fig. 3. A. Type of material used for ^{14}C dating of the samples assembled in the database. B. ^{14}C samples for which the reported age cannot be accepted (group 1) and ^{14}C samples for which the reported age can possibly be accepted (group 2). See text for further explanations and Appendix 1for a reference list regarding the data collection. Details on the ^{14}C dates for Sweden are given in Appendix 2.

Bones, ivory, teeth and wood that have been covered by sediment and/or peat for thousands of years are often prone to contamination by younger carbon (Hajdas 2007). Some of this contamination is routinely removed in the ^{14}C laboratory (e.g. crystallized carbon on bone surfaces), whereas other types of contamination (e.g. post-depositional incorporation of humic substances into the porous bone structure) (van Klinken & Hedges 1995) can only be removed by rigorous laboratory pretreatments. The gradual decomposition process of bones decreases their collagen content, and very old bone samples may therefore contain only a small amount of datable collagen.

The background of the ^{14}C laboratory, adequate pretreatment processes and very low levels of contamination are important prerequisites for obtaining accurate ^{14}C ages for old samples (Hogg *et al.* 2006). ^{14}C laboratories that routinely date old samples employ the ABA or AAA (acid-alkali-acid) method as a chemical pretreatment for wood and peat to remove contamination with old and modern carbon. However, because the alkali step of the ABA method might be responsible for contamination with modern carbon (e.g. Hatté *et al.* 2001 and references therein), the so-called ABOX method (a wet oxidation technique with stepped combustion of samples) is now being used (Bird *et al.* 1999). This procedure is regarded as providing reliable ^{14}C ages (Blockley *et al.* 2008). The most commonly used pretreatment method for ancient bones is the 'Longin method', in which collagen is first isolated by decalcification and then denaturated in weakly acidic water ('gelatinization'). This procedure allows untwisting of the triple-helical collagen molecule and thereby reduces the influence of insoluble residues (Longin 1971). Although this method is generally regarded as a safe approach for obtaining reliable ^{14}C ages, Higham *et al.* (2006) showed that it is not sufficient to remove all possible contaminants in ancient bones. New methods to address these problems include, among others, ultrafiltration, which seems to improve the quality of the extracted collagen for ^{14}C dating (Higham *et al.* 2006 and references therein).

In order to evaluate the ^{14}C data points shown in Fig. 3A, laboratory details were cross-checked in *Radiocarbon* for the years 1960–1996. However, the radiocarbon laboratory at Groningen stopped publishing its dates in *Radiocarbon* in 1971, not all ^{14}C laboratories reported their measurements regularly, and the journal gradually stopped publishing reports from ^{14}C laboratories in the 1980s. ^{14}C laboratories were also directly contacted about details on individual ^{14}C measurements, but as several of these laboratories no longer exist, tracking the details (including pretreatment procedures) for old ^{14}C dates proved rather difficult. Based on the information that could be traced in *Radiocarbon* and that was given by individual ^{14}C laboratories and in the original articles, all ^{14}C dates were assigned to two groups: group 1, ^{14}C ages cannot be accepted; and group 2, ^{14}C ages can possibly be accepted and probably provide reliable age measurements (Fig. 3B).

Group 1 includes ^{14}C samples performed on unknown material, on sediments with low organic carbon content or on reworked interglacial sediments as indicated by pollen stratigraphy. Also included are samples for which the published ages are unreliable according to reports of the ^{14}C laboratory (i.e. very low carbon content, contamination) or when ages were reported without standard errors. Although it is debatable whether samples with ages beyond the background of the ^{14}C dating laboratory (i.e. infinite measurements) should be placed in group 1 or grouped separately, as they may indeed give some indication with respect to other ^{14}C dates from the same sequence, I chose here 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 unsuitable for dating such old samples. Moreover, several of these infinite dates were obtained from stratigraphies that were clearly older than MIS 3. Group 2 is composed of ^{14}C samples derived from *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 and reworked and/or *in situ* terrestrial bones.

Calibration of ^{14}C dates, using the calibration curve of Fairbanks *et al.* (2005), was undertaken only if the reported error was <3000 years and if the dates were within the calibration range of the program. Dates that were too old and thus fell outside the Fairbanks *et al.* (2005) calibration curve were tentatively compared with the curve of Hughen *et al.* (2006). This estimate attributes only an approximate age to the sample and does not provide any errors. Accordingly, the true age of the estimated calibrated age can be considerably younger or older.

Several studies have discussed the implications of published ^{14}C dates for Norway (e.g. Olsen 1997; Olsen *et al.* 2001a, b; Mangerud *et al.* 2003, 2009), Estonia (Kalm 2005, 2006) and Denmark (Houmark-Nielsen 2003, 2007; Houmark-Nielsen & Kjær 2003), and therefore the focus here will be on published and unpublished ^{14}C dates for Sweden, that is, for the central part of the former SIS.

Weichselian interstadials in central and northern Sweden – a short historic overview

Organic sediments that are situated stratigraphically below Last Glacial Maximum till have been known for many decades from localities in mid-central and northern Sweden (e.g. Pilgrimstad, Tåsjö, Borlänge, Vojmå, Juktan, Blajksjön and Gällivare) (J. Lundqvist 1967, 1978; J. Lundqvist & Mook 1981). ^{14}C dates for these sediments have provided both infinite ages and ages ranging from *c.* 40 to around 30 kyr BP, and were initially interpreted as possibly indicating ice-free conditions during parts of MIS 3 in the central and northern parts of Sweden (J. Lundqvist 1967, 1978). Most of these organic deposits were consequently assigned to the 'Jämtland interstadial', during which mean annual temperatures have been reconstructed as being 2–3 °C lower than they are today. Subsequent research on interstadial sediments in central and northern Sweden (^{14}C, U/Th, TL dates; pollenstratigraphy) (Lagerbäck & Robertsson 1988; Robertsson 1988, 1991; Robertsson & Garcia Ambrosiani 1988, 1992; García Ambrosiani 1990; J. Lundqvist & Miller 1992), however, revised this view. All ^{14}C dates were then regarded as unreliable and infinite, and correlations were based entirely on pollen stratigraphy. The pollen-based reconstruction of sparse tree vegetation (including *Betula pubescens* and *Picea*) in central and northern Sweden seemed to correlate better with the forested landscapes of the early Weichselian interstadials Brørup and Odderade of northern Europe (Robertsson 1988, 1991; Robertsson & Garcia Ambrosiani 1988, 1992; García Ambrosiani 1990; Mangerud 1991) than with the treeless mid-Weichselian landscapes of northern Germany (Behre 1989; Behre & van der Plicht 1992). The 'Jämtland interstadial' was consequently not regarded as one interstadial, but as two distinct interstadials, which were correlated with Brørup and Odderade, respectively (Lagerbäck & Robertsson 1988; Robertsson 1991; J. Lundqvist & Miller 1992) (Table 1).

The difficulties of correlating the fragmentary Swedish interstadial deposits with each other and with often incomplete interstadial deposits in northern Europe have been addressed by García Ambrosiani (1990) and recently by Hättestrand (2007, 2008). García Ambrosiani (1990), for example, suggested that the 'Tärendö interstadial' of northern Sweden (Table 1) could be assigned to either Odderade or to a mid-Weichselian interstadial. Hättestrand (2007, 2008), on the other hand, proposed subdividing the 'Tärendö interstadial' into three phases (Tärendö I, IIa, IIb) and presented two alternative correlations between these interstadials and the North European biostratigraphy (Table 1). In alternative 1, Tärendö I could correlate with Brørup and Tärendö II with Odderade; in alternative 2, Tärendö I would correlate with Odderade and Tärendö II with an early mid-Weichselian interstadial. Hättestrand (2008) also speculated whether Tärendö II could be synchronous with the interstadial described at Sokli in northern Finland, which has tentatively been correlated with GIS 12–14 (Helmens *et al.* 2007a).

Table 1. Tentative correlation of early and middle Weichselian interstadials and stadials (shown in italics) in northern Europe with the Greenland ice-core stratigraphy and the marine isotope stratigraphy. GIS = Greenland interstadials; MIS = marine isotope stage; kyr = thousand years. The correlation between the biostratigraphic zones of Behre & 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).

Biostrati-graphy[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		5		3	*LGM advance*			Göta Älv/Dösebacka/Ellesbo/Gärdslöv	
	28–32	6	32–33.5		*LGM advance*				
		7			Ålesund				
Huneborg	??	8	36.5–38.5	3	Ålesund				
		?9		3	*Skjonghelleren*				
Hengelo	36–39	10	41–43.5		*Skjonghelleren*				
		11			Austnes/Bø				
Hasselo-stadial				3					
Moershoofd	44–46	12	45–47	3	Austnes/Bø				
Glinde	48–50	?13/14	49–54.5	3	Austnes/Bø				Alt. 2: Tärendö IIb
Oerel	53–58	15/16	56–59	3	Austnes/Bø				Alt. 2: Tärendö IIa
					Karmøy				
Odderade	61–72	21		5a	Torvastad	Tärendö/Vålbacken	Vålbacken/Tåsjö/Riipiharju	Tärendö/Tåsjö/Pilgrimstad/Norbotten sites	Alt. 1: Tärendö II Alt. 2: Tärendö I
					Bønes				
Brørup/Amersfoort	—	23/24		5c	Fana/Gudbranddalen	Peräpohjola/Pilgrimstad	Stenberget/Slätteröd/Härnösand/Pilgrimstad/Boliden/Gallejaure/Takanenmännikkö	Peräpohjola/Stenberget/Margareteberg/Pilgrimstad/Norbotten sites	Alt. 1: Tärendö I

[1] Behre & van der Plicht (1992).

[2] Huijzer & Vandenberghe (1998). Note that Huijzer & 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, whereas Upton Warren and Riel would be correlative with GIS 12 and 13, respectively.

[3] Greenland interstadials according to EPICA (2006); age assignment of Greenland interstadials is according to GICC05.

[4] Mangerud (2004) and Mangerud *et al.* (in press).

[5] García Ambrosiani (1990).

[6] Robertsson (1991).

[7] Hättestrand (2008).

As shown in Table 1, correlations between the fragmentary Weichselian interstadials in central and northern Sweden, their temporal relationships with other interstadials in Norway, Finland and Denmark, and their link to the northwest European biostratigraphy (Behre & van der Plicht 1992) and to the Greenland ice-core stratigraphy remain highly speculative. Large uncertainties also exist regarding the biostratigraphic intervals during MIS 3 and their possible association with Greenland interstadials and stadials. Calibrated ages of ^{14}C dates published by Behre & van der Plicht (1992) would, for example, suggest that Denekamp is correlative with GIS 5–7, Hengelo with GIS 10/11, Moershoofd with GIS 12, Glinde with GIS 13/14 and Oerel with GIS 15/16. Huijzer & Vandenberghe (1998), on the other hand, expanded the biostratigraphy of Behre & van der Plicht (1992) and included the Huneborg interval between Hengelo and Denekamp, and the Upton Warren and Riel interstadials between Moershoofd and Hengelo. This correlation would lead to an assignment of Huneborg to GIS 8, Moershoofd to GIS 14, whereas Upton Warren and Riel could be correlative with GIS 12 and 13, respectively. Clearly, to resolve these uncertainties, continuous and well-dated land records from different parts of Europe that could unequivocally be compared with the Greenland ice-core stratigraphy are needed.

Evaluation of ^{14}C dates for Sweden

The ^{14}C dates compiled for Sweden (Fig. 4A, B) are derived from published (J. Lundqvist 1955, 1978; Östlund & Engstrand 1960; Engstrand & Östlund 1962; G. Lundqvist 1964; Engstrand 1965; Håkansson 1969, 1970; Hillefors 1974; Berglund *et al.* 1976; Miller 1977; J. Lundqvist & Mook 1981; Lagerbäck & Robertsson 1988; Robertsson 1988; Robertsson & Garcia Ambrosiani 1988; García Ambrosiani 1990; J. Lundqvist & Miller 1992; Aaris-Sørensen 2006; Ukkonen *et al.* 2007) and unpublished (J. Lundqvist; B. Wohlfarth) sources (Appendix 2). For some localities only single ^{14}C dates are available, whereas other sites, such as Riipiharju, Ontoharjut, Takanenmännikkö, Boliden, Tåsjö, Vålbacken, Pilgrimstad, Borlänge, Öje, Dösebacka, Ingebäck, Hisingen, Gärdslöv, Örsjö and Arrie, provided more than one age measurement (Fig. 4B). Detailed litho- and pollen stratigraphies exist for some sites, whereas others lack a stratigraphic context or have vaguely described stratigraphies. The majority of the compiled data set consists of ^{14}C dates that 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 (Fig. 4C).

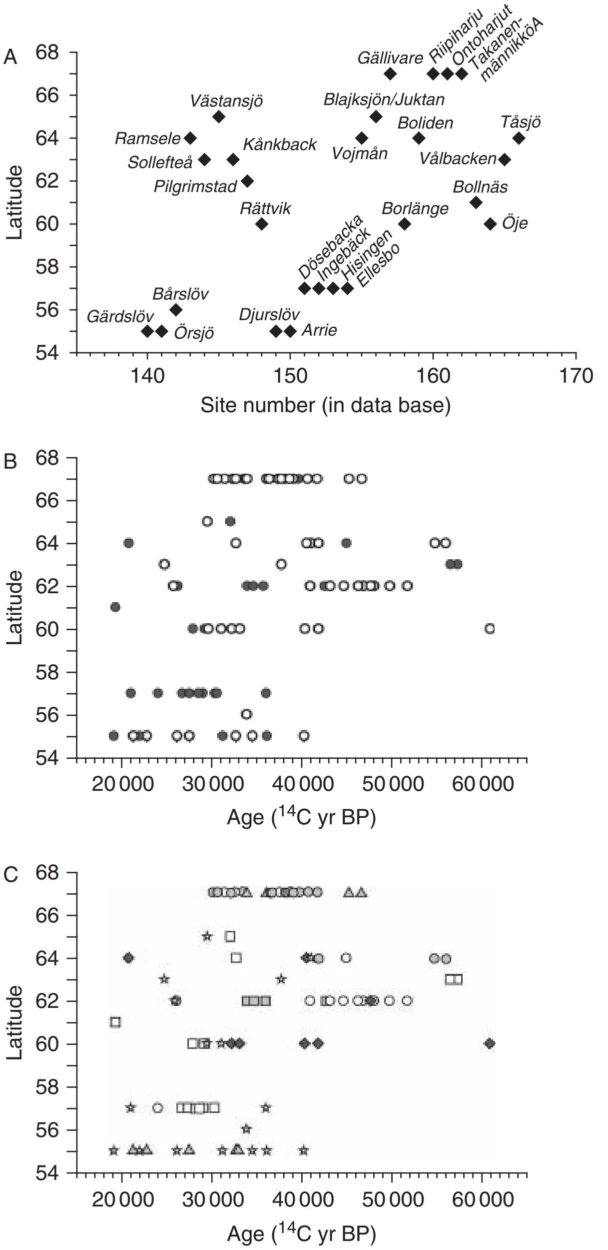

Fig. 4. A. Distribution of sites with ^{14}C dates along a latitudinal transect. B. Quality assessment of all ^{14}C dates: grey filled circles = reported ages that are unreliable (group 1); open circles = reported ages that can possibly be accepted (group 2). C. Characterization of the dated material shown in B: open squares = unknown material; filled grey squares = inorganic sediments; open circles = organic sediments; filled grey circles = organic material; filled grey triangles = terrestrial plant material; filled dark grey diamonds = wood; filled grey stars = mammoth remains.

Sites with detailed litho- and pollen-stratigraphic information

Interstadial sites from Norbotten

The stratigraphies of Riipiharju, Ontoharjut and Takanenmännikkö provided conflicting ^{14}C dates (Fig. 5A–F, Appendix 2), which were consequently regarded

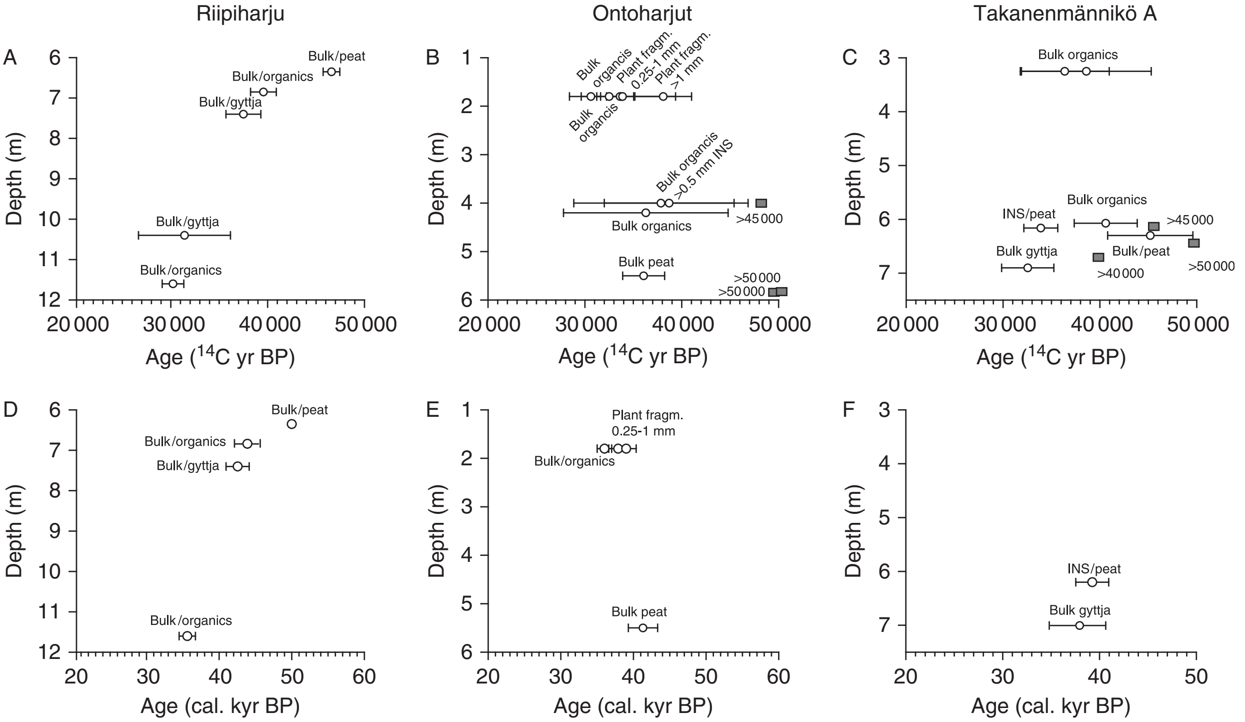

Fig. 5. ^{14}C dates from Riipiharju, Ontoharjut and Takanenmännikö in northern Sweden according to Lagerbäck & Robertsson (1988). A–C. All ^{14}C dates (1σ) according to their depth in the stratigraphy: grey filled circles = group 1 ages; open circles = group 2 ages. D–F. Calibrated age ranges (1σ) of group 2 dates. Note that only dates with error ranges of <3000 years were calibrated.

as unreliable (Lagerbäck & Robertsson 1988). Lagerbäck & Robertsson (1988) and later Robertsson (1991) therefore suggested a correlation of the organic deposits with the early Weichselian interstadials Brørup and Odderade based on their arctic-alpine pollen assemblages.

The five ^{14}C ages (Fig. 5A) for Riipiharju were obtained on bulk organic material or on organic-rich sediments and show a systematic decrease with depth (Fig. 5D). Contamination by younger material would not produce such a non-random distribution of ages, and the possibility therefore exists that mistakes were made when labelling the samples. Disregarding these problems, acceptable calibrated ^{14}C ages for the interstadial deposits of Riipiharju would range between *c.* >50 and 35 cal. kyr BP (Fig. 5D). The pollen stratigraphy on new cores from Riipiharju (Hättestrand 2008) suggests three successive interstadials (Tärendö I, IIa, b) separated by cold phases. Scarce birch forest seems to have been present during all three interstadials, and mean temperatures for the warmest months (MTWM) are estimated to be around 10°C. Hättestrand (2008) proposed a correlation of the three interstadials with Brørup and Odderade, or, alternatively, with Odderade and an early MIS 3 interstadial (Table 1).

The lower peat layer at Ontoharjut contained mosses that today have a distribution in central and northern Sweden, and the pollen spectra indicated the presence of shrubs, herbs and scattered birch trees. Pollen analysed in the overlying laminated sands suggested arctic herb and shrub tundra, periglacial conditions and a continental climate (Lagerbäck & Robertsson 1988). Lagerbäck & Robertsson (1988) dated different sample fractions (e.g. bulk organics; plant remains >1 mm, 0.5–1 mm and <0.5 mm), which provided varying ages, including three infinite age estimates (Fig. 5B). All finite ^{14}C ages are here attributed to group 2, but only three ^{14}C dates at 1.8 m depth and one ^{14}C date at 5.5 m depth have error margins of <3000 years and were therefore calibrated. These provide an age estimate of *c.* 45–35 cal. kyr BP (Fig. 5E).

The pollen stratigraphy of Takanenmännikkö A suggests a development from dwarf birch, ericaceous shrubs, and herbs into a phase with dwarf birch, tree birch, juniper and light-demanding plants (Lagerbäck & Robertsson 1988). This phase was followed by tundra vegetation with a rich herb flora, arctic-alpine pioneer plants, steppe elements, grasses, sedges and willow shrubs. Also here the different fractions of the same sample provided very different age estimates, and the nine dated samples range from infinite to *c.* 30 ^{14}C kyr BP (Fig. 5C). Although all finite ^{14}C ages were classified as group 2, only two had a standard error of <3000 yr, and would translate into a calibrated age of *c.* 40–35 cal. kyr BP (Fig. 5F).

Hättestrand (2008) recently correlated the interstadial deposits at Ontoharjut and Takanenmännikkö A with the oldest interstadial at Riipiharju (Tärendö I, i.e. the early Weichselian). Acceptable calibrated ^{14}C age ranges for Riipiharju (*c.* >50–35 kyr BP), and especially for Ontoharjut (*c.* 40–35 kyr BP) and Takanenmännikkö A (*c.* 40–35 kyr BP) (Fig. 5D–F), are however considerably younger than the pollen-stratigraphic correlation suggested by Hättestrand (2008), which prompts the following questions. (1) Is the tentative correlation of the interstadials at Ontoharjut and Takanenmännikkö A with Tärendö I, and as such with the early Weichselian interstadials Brørup and/or Odderade, as proposed by Hättestrand (2008) based on pollenstratigraphy correct? (2) Can pollen-stratigraphic signals of treeless, arctic shrub and tundra environments be used to infer time-synchronicity even between nearby sites where temporally different interstadials with similar vegetation signatures might be present? Are the calibrated ^{14}C ages of group 2 therefore more trustworthy? (3) Should more weight be placed on the infinite ^{14}C dates than on the finite dates of group 2; that is, would the former be indicative of early MIS 3 interstadials or early Weichselian interstadials? The first alternative (time-synchronicity) easily leads to circular reasoning and rejects the validity of all finite ^{14}C dates. The second alternative assumes that group 2 ^{14}C dates are correct and that the infinite ^{14}C ages are a reflection of the laboratory background. The third option leaves open the possibility that the interstadials could date to early MIS 3 or to the early Weichselian. The fact that all acceptable ^{14}C ages from the three sites independently point to a similar age interval of *c.* 50–35 cal. kyr BP (Fig. 5D–F) would lend support to the second option and would suggest ice-free conditions in northern Sweden between *c.* 50 and 35 cal. kyr BP.

Pilgrimstad, Jämtland

The sediment sequence at Pilgrimstad in central Sweden, first described by Kulling (1945) and G. Lundqvist (1964), has been the subject of several subsequent studies, including, among others, lithostratigraphic investigations, pollen, diatom and chironomid analyses, and ^{14}C dating (Kulling 1945; J. Lundqvist 1967; Robertsson 1988 and references therein). Robertsson (1988) suggested, based on pollen stratigraphy, the presence of two separate interstadials, or a three-part interstadial above the macrofossil-rich varved sediments described by Kulling (1945) and G. Lundqvist (1964). A mammoth molar found between the lower part of Robertsson's interstadial sediments and the varved sediments of Kulling (1945) has recently been dated by Ukkonen *et al.* (2007).

The pollen-stratigraphic investigations of Robertsson (1988), which were focused on interstadial deposits situated above those described by Kulling (1945), showed an interstadial vegetation succession with open treeless vegetation, *Juniperus*, herb and shrub communities (e.g. birch, willow), sparse birch forest with *Juniperus*, *Artemisia*, *Thalictrum* and other herbs, and herb and shrub vegetation. Plant macro-remains described from these upper interstadial sediments comprise *Betula nana*, *Salix* sp., *Juniperus* and *Betula* sp. (J. Lundqvist 1967: p. 148 cites *Betula* macro-remains and notes that these are possibly not *Betula nana*). Coleoptera analysis pointed to tundra vegetation and mean temperatures of the warmest and coldest months of 11 °C and −11 °C, respectively (Moseley 1982). Based on these temperature estimates it was assumed that the site was situated close to the border of the forest zone and that sparse birch forest was present in the vicinity (Robertsson 1988). The interstadial/s were therefore correlated with Brørup/Odderade. The main argument against a correlation with the Middle Weichselian was that tree birch could not have been present in central Sweden at the same time as shrub and herb vegetation extended over northern Germany. However, given the fact that it is very difficult to differentiate between pollen of shrub and tree birch, and that plant macrofossils had not been investigated in detail, the presence of tree birch during Robertsson's (1988) interstadial remains unproven. Although coleoptera-based summer temperatures of 11 °C (Moseley 1982) would suggest that tree birch could have become established, Helmens *et al.* (2007a) showed that high summer temperatures in northern Fennoscandia during an early MIS 3 interstadial did not necessarily lead to the immigration and establishment of trees.

^{14}C dates for Pilgrimstad presented in Fig. 6A and B are derived from published (Robertsson 1988; Ukkonen *et al.* 2007) and unpublished (J. Lundqvist, B. Wohlfarth) sources (see Appendix 2 for details). Infinite dates are not included (with the exception of Ua-66 and St 205) because these lack stratigraphic assignment. The age measurements are presented on a schematic depth scale following the summary stratigraphy of Robertsson (1988) and suggest a cluster of group 2 ages at *c.* 55–40 ^{14}C kyr BP (Fig. 6A, B) or c. 60–45 cal. kyr BP (Fig. 6C). This age interval is much older than the mammoth molar dated by Ukkonen *et al.* (2007), which was excavated from below Robertsson's (1988) interstadial and has an age of 25.9±0.2 ^{14}C kyr BP or *c.* 31 cal. kyr BP. If group 2 ages are assumed to be correct, the mammoth molar cannot represent the true age of the sediment unit in which it was found. The age cluster of the group 2 data set of between *c.* 60 and 45 cal. kyr BP compares well, however, with two ^{14}C dates on twigs (39±2 ^{14}C kyr BP or 44±1.8 cal. kyr BP; >40 ^{14}C kyr BP) and with OSL ages of between 52 and 36 kyr BP from a new section at Pilgrimstad (Alexanderson *et al.* 2009) (Fig. 6C) and with a ^{14}C date of 47.6±0.5 kyr BP (UBA-9031). Together these age determinations indicate that the mammoth molar is too young and that the site was ice-free between *c.* 60 and *c.* 36 cal. kyr BP.

Sites with little or no pollen and lithostratigraphic information

Organic material imbedded in clastic sediments has been dated in several sites between 67 and 60°N (J. Lundqvist 1978; J. Lundqvist & Mook 1981; Robertsson & Garcia Ambrosiani 1988; García Ambrosiani 1990; J. Lundqvist & Miller 1992; J. Lundqvist, unpublished) (Fig. 7A). Pollen assemblages of organic sediments from Boliden at 64°N indicate arctic/subarctic conditions with open tundra, willow shrubs and herbs (García Ambrosiani 1990), and pollen and insect remains at Tåsjö, also at 64°N, point to an open tundra landscape, arctic conditions and summer temperatures of <8–10 °C (J. Lundqvist & Miller 1992). Following the scheme of Robertsson (1991), these organic layers were subsequently assigned to an early Weichselian interstadial (Table 1), although ^{14}C ages for Tåsjö range between *c.* 56 and *c.* 42 kyr BP (J. Lundqvist & Mook 1981) and for Borlänge between *c.* 40 and 32 kyr BP (J. Lundqvist 1978) (Fig. 7A).

Samples from Dösebacka, Ingebäck, Hisingen and Ellesbo at 57°N in southwestern Sweden (Östlund & Engstrand 1960; Engstrand & Östlund 1962; Håkansson 1970; Hillefors 1974) contained very little organic carbon and most of these ^{14}C dates were, according to the ^{14}C laboratory, regarded as unreliable (Håkansson 1970). ^{14}C measurements from Gärdslöv/Alnarp at 55°N were obtained on plant remains (Miller 1977), but several of these gave large reported errors of >3000 years (Fig. 7A). Nevertheless, ^{14}C ages from sites in southwestern and southern Sweden have been used to identify ice-free conditions during the later part of MIS 3 (Table 1).

Most of the ^{14}C ages from these sites fall within group 1, whereas there are very few acceptable group 2 dates. These cluster between 45 and 60 cal. kyr BP for the northernmost site Tåsjö, around 35–40 cal. kyr BP for Borlänge at 60°N, and around 25–40 cal. kyr BP for Gärdslöv in southern Sweden (Fig. 7B).

Mammoth dates

^{14}C dates on mammoth finds from Sweden (Fig. 8A) have been published and discussed by Berglund *et al.* (1976), Håkansson (1976), Aaris-Sørensen (2006) and

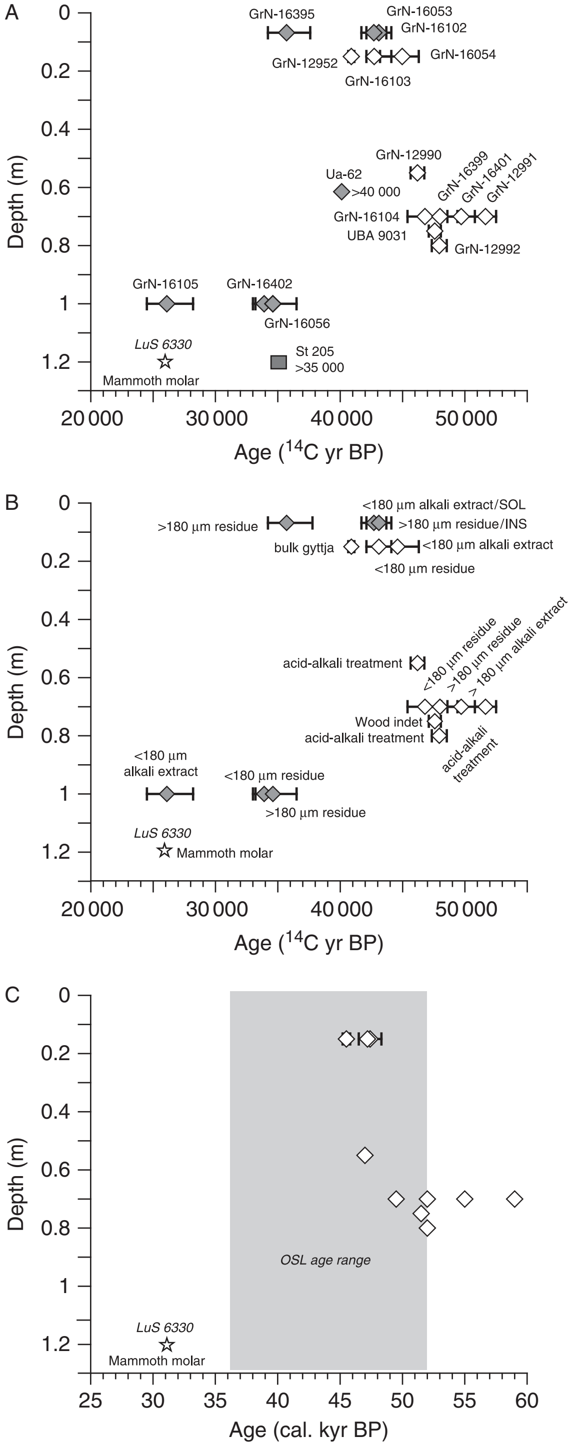

Fig. 6. ^{14}C dates published for Pilgrimstad in central Sweden (Robertsson 1988; Ukkonen *et al.* 2007; and unpublished sources: J. Lundqvist, B. Wohlfarth) shown against a schematic depth. A. All ^{14}C dates (1σ) including their laboratory number; several infinite ^{14}C dates have been reported by Robertsson (1988 and references therein) and Engstrand (1965), but these lack a clear stratigraphic assignment and some also lack a laboratory number (see Appendix 2) and are not shown here. Filled diamonds = group 1 ages; open diamonds = group 2 ages; B. Type of dated material; multiple dates on different fractions were obtained for the same samples: filled diamonds = group 1 ages; open diamonds = group 2 ages. C. Acceptable ages (group 2) in calibrated years (1σ). The depth of the mammoth sample dated by Ukkonen *et al.* (2007) is approximate. Also shown are the age ranges of new OSL dates by Alexanderson *et al.* (2009). Note that only ^{14}C dates with error ranges of <3000 years were calibrated.

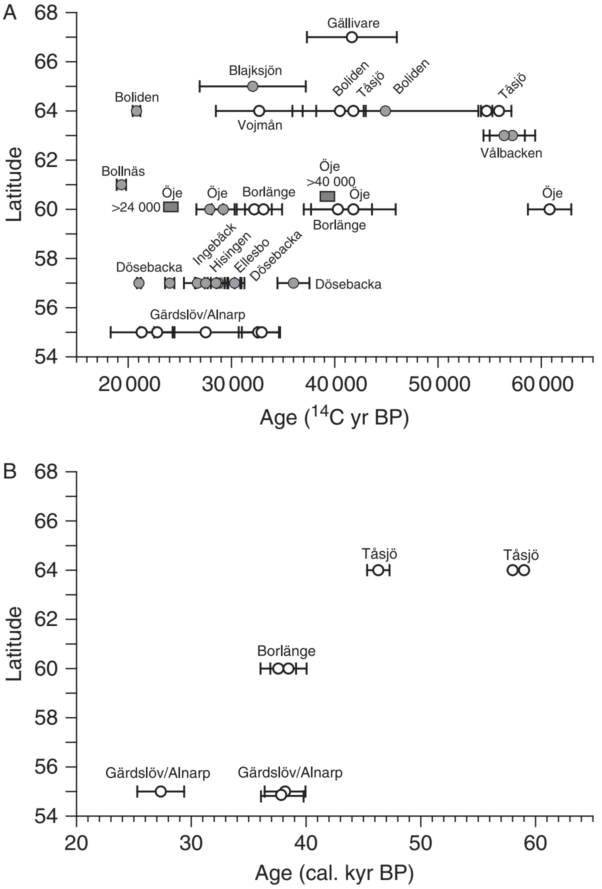

Fig. 7. A. ^{14}C dates (1σ) from sites with little litho- and pollen-stratigraphic information: grey filled circles = group 1 dates; open circles = group 2 dates. B. Calibrated age ranges (1σ) for group 2 dates; note that only ages with a reported standard deviation of < 3000 years were calibrated.

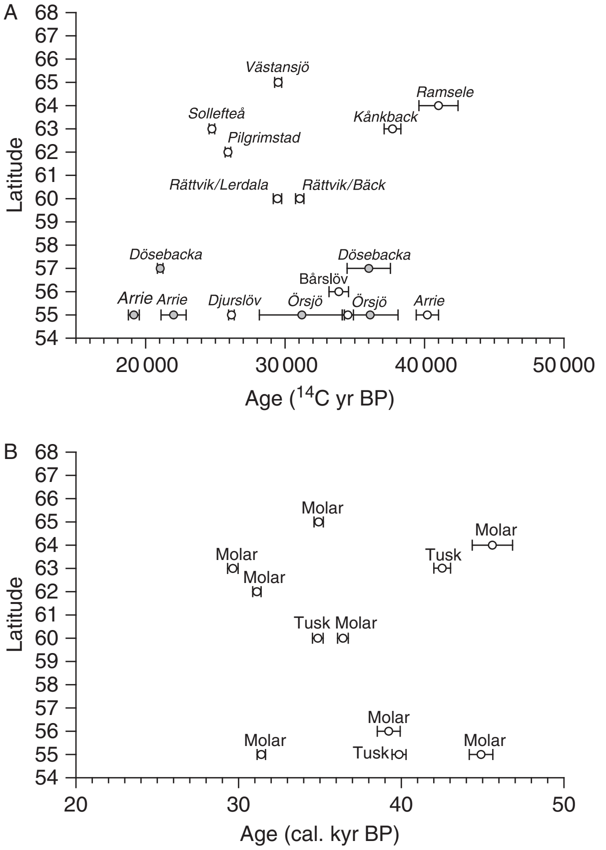

Fig. 8. A. ^{14}C dates (1σ) on mammoth remains from Sweden (Berglund *et al.* 1976; Håkansson 1976; Aaris-Sørensen 2006; Ukkonen *et al.* 2007). Note that Ukkonen *et al.* (2007) re-dated the tusks from Örsjö and Arrie, which had earlier been dated by Håkansson (1976), and the tusk from Kånkback, which had been dated by the Stockholm Radiocarbon Laboratory: filled grey circles = group 1 dates; open circles = group 2 dates. B. Calibrated age ranges (1σ) of group 2 dates.

Ukkonen *et al.* (1999, 2007). Ukkonen *et al.* (2007) re-dated the mammoth tusks from Örsjö and Arrie, which had earlier been dated by Håkansson (1976), and also the tusk from Kånkback, which had been dated at the Stockholm Radiocarbon Laboratory. Using these dates together with new ^{14}C dates on mammoth tusks and molars that had been preserved in museums and at the Geological Survey of Sweden, Ukkonen *et al.* (2007) suggested ice-free conditions in Sweden between 44 and 26 kyr, that is, during a large part of MIS 3 and 2. Moreover, δ^{18}O measured in mammoth enamel implied that mean annual temperatures were *c.* 2–3 °C lower during the middle Weichselian than they are today and that the climate was more homogeneous over Sweden, with moderate north–south gradients (Ukkonen *et al.* 2007).

^{14}C dates performed on mammoth bones, tusks and teeth are controversial and subject to a number of errors, which easily lead to too young ages (e.g. Higham *et al.* 2006; Hajdas 2007), especially if the samples contain too little collagen or are not rigorously pretreated in the laboratory. ^{14}C samples that contained too little collagen and/or dates that were obtained before rigorous laboratory pretreatments became routine are therefore regarded as unreliable (group 1). This is in contrast to recently measured samples (Aaris-Sørensen 2006; Ukkonen *et al.* 2007), which contained enough collagen (G. Skog, pers. comm. 2009) and were carefully handled and pretreated in the radiocarbon laboratories (group 2). These assumptions are, however, not entirely correct, as indicated by the mammoth molar from Pilgrimstad (Ukkonen *et al.* 2007) (LuS 6330; Appendix 2), which gave an age much younger (26±0.2 ^{14}C kyr BP) than that of the overlying organic deposits (> 40 ^{14}C kyr BP). If the ^{14}C ages for these organic deposits are assumed to be valid, sample LuS 6330 must have been contaminated. None of the other recently dated mammoth remains of group 2 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.

The laboratory pretreatment for the mammoth samples measured at the Lund University Radiocarbon Dating Laboratory (Ukkonen *et al.* 2007) included a modified Longin method to extract collagen (i.e. the samples were crushed to a fine powder and acidified under vacuum; G. Skog, pers. comm. 2009). Higham *et al.* (2006 and references therein) showed, however, that sample pretreatment of bones with the Longin method or modifications thereof can result in younger ^{14}C ages as compared to a sample pretreatment that includes ultrafiltration. This latter step allows the removal of low molecular weight contaminants, which can be of a different age from the sample and can therefore influence the age of especially old bone samples (Higham *et al.* 2006). Experiments with split mammoth bones that had been pretreated (a) with the Longin method, and (b) by combining the Longin method with ultrafiltration resulted, for example, in ages of *c.* 38–46 ^{14}C kyr BP and *c.* 45–47 ^{14}C kyr BP, respectively (Hajdas *et al.* 2008), that is, in a difference of several thousand years. The effect of contamination might be randomly distributed, so that some samples may be affected while others are not. Unless different preparation methods have been tested on the same sample, it is therefore not possible to judge whether the obtained age estimates correspond to the true age of the dated sample. The mammoth molars and tusks dated by Ukkonen *et al.* (2007) could very well have resulted in a correct age estimate, they could equally well be too young, or they might have been affected by random contamination. Re-dating these samples after rigorous pretreatment measures have been applied would allow these open issues to be resolved and could provide more secure age estimates.

Discussion

The evaluation of old ^{14}C ages that had been obtained on interstadial organic deposits from Sweden indicates that some of these dates could possibly be regarded as acceptable age range estimates. To further test how well these age ranges match with ^{14}C measurements on mammoth remains (Ukkonen *et al.* 2007) and OSL dates from Pilgrimstad (Alexanderson *et al.* 2009) and southernmost Sweden (Kjær *et al.* 2006), I compare these data sets with each other in Fig. 9.

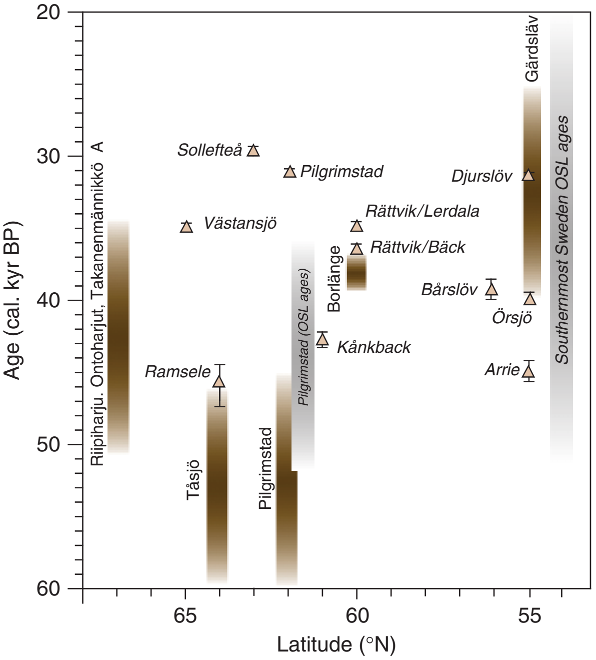

Fig. 9. Calibrated age ranges (1σ) of group 2 dates, which had a reported error of <3000 years, shown along a north–south transect. The dark brown bars give the age range of organic sediments/plant material from Riipiharju, Ontoharjut, Takanenmänniko, Tåsjö, Pilgrimstad, Borlänge and Gärdslöv; the light brown filled triangles represent ages for mammoth molars and tusks, and the grey bars are OSL dates for Pilgrimstad (Alexanderson *et al.* 2009) and southernmost Sweden (Kjær *et al.* 2006).

Age ranges for interstadial deposits and organic material from northern and central Sweden are between *c.* 60 and *c.* 35 cal. kyr BP, and for deposits from southern Sweden they are between *c.* 40 and *c.* 25 cal. kyr BP (Fig. 9). Trusting these ages would lead to the conclusion that northern Sweden was free of ice between *c.* 50 and 35 cal. kyr BP, that central Sweden was ice-free between *c.* 60 and 35 cal. kyr BP, and that southern Sweden was ice-free until possibly *c.* 25 cal. kyr BP. This assumption compares well with the new OSL dates for Pilgrimstad (Alexanderson *et al.* 2009), which suggest ice-free conditions in mid-central Sweden between *c.* 50 and 35 kyr BP. It also compares fairly well with OSL ages from southernmost Sweden (Kjær *et al.* 2006), which indicate ice-free conditions from around 50 to 25 kyr BP (Fig. 9). Most of the mammoth ages also seem to agree with the age ranges attributed to the organic deposits and with those provided by OSL. Exceptions are the samples from Pilgrimstad and Sollefteå, which are considerably younger than the age ranges of interstadial deposits from the same site and/or geographical region (Fig. 9). As discussed above, Ukkonen *et al.'s* (2007) ^{14}C samples contained enough good collagen (G. Skog, pers. comm. 2009) and were not pretreated using ultrafiltration. It is therefore possible that not all contaminating material was removed, which could explain why some of the samples resulted in too young age estimates. Taken together, however, ^{14}C ages on organic deposits, OSL ages and also ^{14}C measurements on mammoth remains seem to be in broad agreement and suggest that ice-free conditions prevailed in Sweden during parts or all of MIS 3.

The assumption of ice-free conditions in Sweden during all or parts of MIS 3 is, however, in conflict with reconstructed ice advances in Norway (Skjonghelleren) (Vorren & Mangerud 2008; Mangerud *et al.* 2009) and with ice advances through the Baltic Basin into Denmark (Ristinge and Klintholm advance) (Houmark-

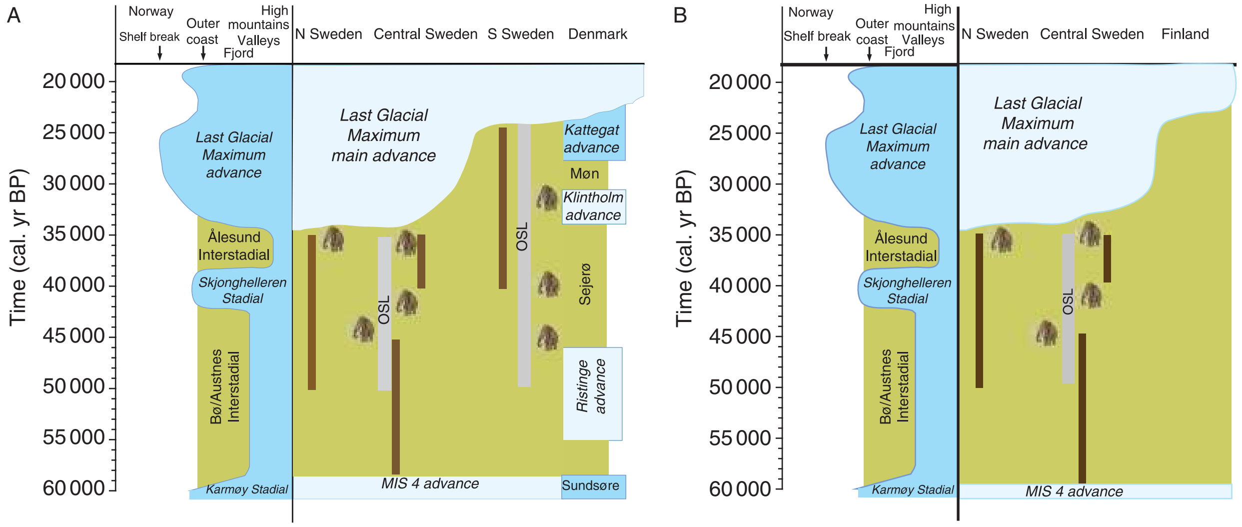

Fig. 10. A possible scenario of ice advance and retreat phases during MIS 3 in Scandinavia along (A) north–south and (B) west–east transects. Scandinavian Ice Sheet advances in Norway are according to Vorren & Mangerud (2008) and Mangerud *et al.* (2003, 2009), and ice advances into Denmark follow Houmark-Nielsen *et al.* (2005) and Houmark-Nielsen (2009). The Kattegat and Sundsøre ice advance reached Denmark from the north, whereas the Klintholm and Ristinge ice advanced through the Baltic Basin (Houmark-Nielsen 2009). Ice-free conditions in Finland are assumed following Mäkinen (2005), Helmens *et al.* (2007a, b) and Lunkka *et al.* (2008). The age range of OSL dates for central Sweden is according to Alexanderson *et al.* (2009), and for southern Sweden is according to Kjær *et al.* (2006). Ages for mammoth remains (Ukkonen *et al.* 2007) that were assigned to group 2, but excluding the samples from Pilgrimstad and Sollefteå, are shown alongside the age ranges for organic deposits in northern, central and southern Sweden.

Nielsen *et al.* 2005; Houmark-Nielsen in press) (Fig. 10A). It does, on the other hand, compare well with the scenario of ice-free conditions in Finland during MIS 3, suggested by, for example, Lunkka *et al.* (2008), Ukkonen *et al.* (1999, 2007), Helmens *et al.* (2007a) and Mäkinen (2005) for different parts of Finland (Fig. 10B). Because the temporal resolution of the Swedish data set is very low, it is not possible to discuss the precise age interval of the various interstadial deposits, nor to decipher whether all sites represent the same time interval or different interstadials within MIS 3. Consequently it cannot be assessed whether ice-free conditions alternated with ice advances during MIS 3. Despite the clear limitations of the presented data set, it seems obvious that the Scandianvian Ice Sheet was smaller and much more dynamic during MIS 3 than hitherto assumed. To corroborate the conclusions drawn here, new multi-proxy investigations of some of the most well-known interstadial deposits from northern, central and southern Sweden are required.

Conclusions

- Published and unpublished ^{14}C, TL/OSL, U/Th dates for Norway, Denmark, Sweden, Estonia, and parts of Finland and Russia older than the LGM ice advance were assembled in a database and evaluated. The database (last data entry May 2008) is in its present form available at the Swedish Nuclear Fuel and Waste Management Company and at the Department of Geology and Geochemistry, Stockholm University.
- The evaluation of ^{14}C dates from Sweden shows that acceptable ages for interstadial organic material in northern and central Sweden range between *c.* 60 and *c.* 35 cal. kyr BP and for similar deposits in southern Sweden between *c.* 40 and *c.* 25 cal. kyr BP.
- ^{14}C dates on mammoth tusks and molars from Pilgrimstad and Sollefteå diverge from the age estimates assigned to organic deposits, which suggests that these ^{14}C dates may be too young and that they should not be used to infer ice-free conditions.
- A possible scenario based on ^{14}C dates from interstadial deposits is that central and northern Sweden was ice-free during the early and middle part of MIS 3 and that southern Sweden remained ice-free until *c.* 25 cal. kyr BP. The first ice advance into northern and central Sweden might have occurred around *c.* 35 cal. kyr BP, more or less contemporaneous with the LGM ice advance onto the Norwegian shelf.
- To resolve the issues addressed here new multi-proxy and high-resolution investigations of several key sites in north, central and south Sweden are required.

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Appendix 2. Published and unpublished ^{14}C dates from Sweden used in the present study.

Locality ID #	Locality	N Lat deg	N Lat min	E Long deg	E Long min	Dated material	Lab ID	^{14}C age BP	^{14}C error+	^{14}C error -	Cal. age (mean) yr BP	Cal. age error (yr)	Quality Group	References
157	Gällivare	67	8	20	38	Organics/bulk	St-5405	41 655	4350	4350			2	Lundqvist (1978)
160	Riipiharju	67	35	22	49	Peat/bulk	St 10074	46 595	860	860	50 000		2	Lagerbäck & Robertsson (1988)
160	Riipiharju	67	35	22	49	Organics/bulk	St 10075	39 570	1330	1330			2	Lagerbäck & Robertsson (1988)
160	Riipiharju	67	35	22	49	Gyttja/bulk	St 10076	37 500	1800	1800	42 549	1595	2	Lagerbäck & Robertsson (1988)
160	Riipiharju	67	35	22	49	Gyttja/bulk	St 10078	31 415	4750	4750			2	Lagerbäck & Robertsson (1988)
160	Riipiharju	67	35	22	49	Organics/bulk	St 10080	30 230	1120	1120	35 620	1122	2	Lagerbäck & Robertsson (1988)
161	Ontoharjutt	67	12	22	25	Organics/bulk	St 10090	30 620	1000	1000	36 006	0.999	2	Lagerbäck & Robertsson (1988)
161	Ontoharjutt	67	12	22	25	Organics/bulk	St 10094	32 505	1280	1280	37 887	1285	2	Lagerbäck & Robertsson (1988)
161	Ontoharjutt	67	12	22	25	Plant remains > 1 mm fraction	St 10091	38 090	2925	2925			2	Lagerbäck & Robertsson (1988)
161	Ontoharjutt	67	12	22	25	Plant remains 0.5–1 mm fraction	St 10092	33 885	5480	5480			2	Lagerbäck & Robertsson (1988)
161	Ontoharjutt	67	12	22	25	Plant remains 0.25–0.5 mm	St 10093	33 630	1400	1400	38 995	1375	2	Lagerbäck & Robertsson (1988)
161	Ontoharjutt	67	12	22	25	Plant remains	St 10098	37 850	9000	9000			2	Lagerbäck & Robertsson (1988)
161	Ontoharjutt	67	12	22	25	INS > 0.5 mm	St 10100	38 700	6700	6700			2	Lagerbäck & Robertsson (1988)
161	Ontoharjutt	67	12	22	25	Plant remains	St 10101	> 45 000					1	Lagerbäck & Robertsson (1988)
161	Ontoharjutt	67	12	22	25	Plant remains	St 10095	36 290	8495	8495			2	Lagerbäck & Robertsson (1988)
161	Ontoharjutt	67	12	22	25	Peat/bulk	St 10097	36 065	2165	2165			2	Lagerbäck & Robertsson (1988)
161	Ontoharjutt	67	12	22	25	Peat/bulk	St 8931	> 50 000					1	Lagerbäck & Robertsson (1988)
161	Ontoharjutt	67	12	22	25	Peat/bulk	St 8931	> 50 000					2	Lagerbäck & Robertsson (1988)
162	Takanenmännikkö	67	7	22	18	Organics/bulk	St 9157	38 600	6700	6700			2	Lagerbäck & Robertsson (1988)
162	Takanenmännikkö	67	7	22	18	Organics/bulk	St 8684	36 370	4590	4590			2	Lagerbäck & Robertsson (1988)
162	Takanenmännikkö	67	7	22	18	Peat/INS	St 8639	33 900	1750	1750	39 244	1697	2	Lagerbäck & Robertsson (1988)
162	Takanenmännikkö	67	7	22	18	Peat/SOL	St 8640	> 45 000					1	Lagerbäck & Robertsson (1988)
162	Takanenmännikkö	67	7	22	18	Organics/bulk	St 9158	40 600	3250	3250			2	Lagerbäck & Robertsson (1988)
162	Takanenmännikkö	67	7	22	18	Peat/bulk	St 9159	45 200	4400	4400			2	Lagerbäck & Robertsson (1988)
162	Takanenmännikkö	67	7	22	18	Peat/bulk	St 9160	> 50 000					1	Lagerbäck & Robertsson (1988)
162	Takanenmännikkö	67	7	22	18	Gyttja/bulk	St 9161	> 40 000					1	Lagerbäck & Robertsson (1988)
162	Takanenmännikkö	67	7	22	18	Gyttja/bulk	St 9162	32 550	2700	2700			2	Lagerbäck & Robertsson (1988)
145	Västansjö, Sättna	65	45	15	5	*Mammuthus primigenius*, molar	LuS 6329	29 500	250	250	34 921	0.284	2	Ukkonen *et al.* (2007)
156	Blajksjön/Juktan	65	18	17	11	Sediment/bulk	St 4814	32 060	5135	5135			1	Lundqvist (1978)
143	Ramsele	64	1	19	30	*Mammuthus primigenius*, molar	LuS 6650	41 000	1400	1400	45 599	1239	2	Ukkonen *et al.* (2007)
155	Vojmån/Volgsele	64	5	16	39	Organic sediment/bulk	St 5178	32 685	4200	4200			2	Lundqvist (1978)
159	Boliden	64	52	20	22	Wood/SOL	U-++++	20 800	370	370	24 994	0.485	1	Robertsson & Garcia Ambrosiani (1988)
159	Boliden	64	52	20	22	Wood/INS	U-++++	40 500	2300	2300			2	Robertsson & Garcia Ambrosiani (1988)
159	Boliden	64	52	20	22	Organic sediment/bulk	St 8949	44 900	9000	4300			1	Robertsson & Garcia Ambrosiani (1988)
166	Tåsjö	64	30	15	33	Organics/bulk	GrN-9394	54 700	550	550	58 000		2	Lundqvist & Mook (1981)
166	Tåsjö	64	30	15	33	Organics/bulk	GrN-9374	41 800	1200	1000	46 297	0.975	2	Lundqvist & Mook (1981)
166	Tåsjö	64	30	15	33	Organics/bulk	GrN-11.010	55 900	1200	1200	59 000		2	Lundqvist & Miller (1992)
166	Tåsjö	64	30	15	33	Peat/bulk	GrN-91-135-138				75 000	6000	2	Lundqvist & Miller (1992)

144	Sollefteå	63	10	17	15	*Mammuthus primigenius*, molar	LuS 6328	24 750	200	200	29 645	0.321	2	Ukkonen *et al.* (2007)
165	Vålbacken	63	4	14	45	—	GrN-12949	57 200	2200	1700			1	J. Lundqvist (unpublished)
165	Vålbacken	63	4	14	45	—	GrN-12950	56 400	2000	1600			1	J. Lundqvist (unpublished)
146	Kånkback	63	5	16	26	*Mammuthus primigenius*, tusk	LuS 6649 (#7)	37 700	600	600	42 736	0.543	2	Ukkonen *et al.* (2007)
147	Pilgrimstad	62	58	15	1	Sediment > 180 µ residue/INS	GrN-16053	43 100	1000	1000	47 408	0.910	1	J. Lundqvist (unpublished)
147	Pilgrimstad	62	58	15	1	Sediment < 180 µ alkali extract/SOL	GrN-16102	42 700	1000	1000	47 071	0.884	1	J. Lundqvist (unpublished)
147	Pilgrimstad	62	58	15	1	Sediment > 180 µ residue	GrN-16395	35 700	1900	1500	40 941	1.568	1	J. Lundqvist (unpublished)
147	Pilgrimstad	62	58	15	1	Organic sediment < 180 µ residue	GrN-16054	44 600	1700	1400	47 500		2	J. Lundqvist (unpublished)
147	Pilgrimstad	62	58	15	1	Organic sediment < 180 µ alkali extract	GrN-16103	43 100	1000	1000	47 408	0.910	2	J. Lundqvist (unpublished)
147	Pilgrimstad	62	58	15	1	Organic sediment < 180 µ residue	GrN-16104	46 800	1800	1400	49 500		2	J. Lundqvist (unpublished)
147	Pilgrimstad	62	58	15	1	Organic sediment > 180 µ residue	GrN-16399	48 000	1400	1200	52 000		2	J. Lundqvist (unpublished)
147	Pilgrimstad	62	58	15	1	Organic sediment > 180 µ alkali extract	GrN-16401	49 700	2000	1600	55 000		2	J. Lundqvist (unpublished)
147	Pilgrimstad	62	58	15	1	Sediment < 180 µ residue	GrN-16056	33 900	700	700	39 275	0.703	1	J. Lundqvist (unpublished)
147	Pilgrimstad	62	58	15	1	Sediment < 180 µ alkali extract	GrN-16105	26 000	2100	1600	31 232	2.106	1	J. Lundqvist (unpublished)
147	Pilgrimstad	62	58	15	1	Sediment > 180 µ residue	GrN-16402	34 600	1900	1600	39913	1.668	1	J. Lundqvist (unpublished)
147	Pilgrimstad	62	58	15	1	Organic sediment/bulk	GrN-12952	40 890	250	250	45 508	0.301	2	Robertsson (1988)
147	Pilgrimstad	62	58	15	1	Organic sediment AA-pretreatment	GrN-12990	46 200	550	550	48 000		2	Robertsson (1988)
147	Pilgrimstad	62	58	15	1	Organic sediment AA-pretreatment	GrN-12991	51 650	850	850	59 000		2	Robertsson (1988)
147	Pilgrimstad	62	58	15	1	Organic sediment AA-pretreatment	GrN-12992	47 950	600	600	52 000		2	Robertsson (1988)
147	Pilgrimstad	62	58	15	1	*Drepanocladus*	St 211	> 39 000					1	Engstrand (1965)
147	Pilgrimstad	62	58	15	1	*Juniperus communis*	St-1270	> 39 000					1	Engstrand (1965)
147	Pilgrimstad	62	58	15	1	—	St-205	> 35 000						Robertsson (1988)
147	Pilgrimstad	62	58	15	1	—	??	> 40 000						Robertsson (1988)
147	Pilgrimstad	62	58	15	1	—	??	> 40 000						Robertsson (1988)
147	Pilgrimstad	62	58	15	1	*Mammuthus primigenius*, molar	LuS 6330	25 900	200	200	31 123	255	2	Ukkonen *et al.* (2007)
147	Pilgrimstad	62	58	15	1	Wood indet	UBA 9031	47 587	485	485	51 500		2	B. Wohlfarth (unpublished)
147	Pilgrimstad	62	58	15	1	Organic sediment/bulk	Ua-62	> 40 000					1	Robertsson (1988)
147	Pilgrimstad	62	58	15	1	Twigs	LuS 6957	39 200	200	200	44 000	1.800		Alexanderson *et al.* (2009)
147	Pilgrimstad	62	58	15	1	Twigs	LuS 6958	> 40 000						Alexanderson *et al.* (2009)
163	Bollnäs	61	21	16	22	Sediment/SOL	????	19 340	450	450	23 051	0.570	1	unpublished
148	Rättvik, Lerdala	60	53	15	7	*Mammuthus primigenius*, tusk	LuS 6331	29 450	300	300	34 869	0.327	2	Ukkonen *et al.* (2007)
148	Rättvik, Bäck	60	53	15	7	*Mammuthus primigenius*, molar	LuS 6332	31 050	300	300	36 414	0.328	2	Ukkonen *et al.* (2007)
158	Borlänge	60	29	15	25	*Picea*	U-4000	32 200	1700	1400	37 581	1.548	2	Lundqvist (1978)
158	Borlänge	60	29	15	25	*Picea*	??	33 100	1800	1400	38 470	1.580	2	Lundqvist (1978)
158	Borlänge	60	29	15	25	*Juniperus*	U-2667	41 800	4100	2800			2	Lundqvist (1978)
164	Öje	60	49	13	51	Sediment/INS	U-++++	27 900	1300	1300	33 240	1.379	1	unpublished
164	Öje	60	49	13	51	Sediment/INS	U-++++	29 200	1100	1100	34 590	1.123	1	unpublished

164	Öje	60	49	13	51	Sediment/SOL	U-++++	>40 000					1	unpublished
164	Öje	60	49	13	51	Cellulosa	U-++++	40 300	3300	3300			2	unpublished
164	Öje	60	49	13	51	*Picea*	GrN-12951	60 800	2100	1700			2	Robertsson (1988)
164	Öje	60	49	13	51	—	St 11	>24 000					1	Lundqvist (1955)
164	Öje	60	49	13	51	—	St 181	>40 000					1	G. Lundqvist (1964)
151	Dösebacka, Romelanda	57	54	12	2	*Mammuthus primigenius*, tusk	Lu-879	36 000	1550	1300	41 226	1.302	1	Håkansson (1976), Berglund *et al*. (1976)
151	Dösebacka	57	54	12	2	*Mammuthus primigenius*	Lu-795	21 040	200	200	25 273	0.327	1	Håkansson (1976)
151	Dösebacka	57	54	12	2	—	—	30 330	640	640	35 718	0.635	1	Hillefors (1974)
151	Dösebacka	57	54	12	2	Sediment/bulk	Lu 104 (#1)	24 020	450	425	28 763	0.524	1	Håkansson (1976)
152	Ingebäck	57	48	12	0	Sediment/bulk	St-448 (#2)	26 700	1300	1000	31 957	1.278	1	Östlund & Engstrand (1960)
152	Ingebäck	57	48	12	0	Sediment/bulk	St-449 (#2)	29 000	1300	1000	34 385	1.180	1	Östlund & Engstrand (1960)
153	Hissinge Tunnel	57	43	10	58	Sediment/bulk	St-607	28 700	2150	1670			1	Engstrand & Östlund (1962)
153	Hissinge Tunnel	57	43	10	58	Sediment/bulk	St-610	27 500	1050	900	32 829	1.046	1	Engstrand & Östlund (1962)
153	Hissinge Tunnel	57	43	10	58	Sediment/bulk	St-609	28 500	1100	1000	33 875	1.097	1	Engstrand & Östlund (1962)
154	Ellesbo	57	50	12	0	Sediment/SOL	Lu-280 (#3)	30 300	950	850	35 690	0.897	1	Håkansson (1970), Hillefors (1974)
142	Bårslöv	56	0	12	48	*Mammuthus primigenius*, molar	OxA-10193	33 850	700	700	39 226	0.703	2	Aaris-Sørensen (2006)
140	Gärdslöv, Alnarp	55	28	13	25	Plant remains/bulk	St-4273	21 300	3000	3000			2	Miller (1977)
140	Gärdslöv, Alnarp	55	28	13	25	Plant remains/bulk	St-4938	22 800	1680	1680	27 340	2.041	2	Miller (1977)
140	Gärdslöv, Alnarp	55	28	13	25	Plant remains/bulk	St-4271	27 500	5000	5000			2	Miller (1977)
140	Gärdslöv, Alnarp	55	28	13	25	Plant remains/bulk	St-4946	32 700	2000	2000			2	Miller (1977)
140	Gärdslöv, Alnarp	55	28	13	25	Plant remains/bulk	St-3158	32 800	1800	1800	38 170	1.779	2	Miller (1977)
141	Örsjö	55	28	13	32	*Mammuthus primigenius*, tusk	Lu-746 (#4)	31 200	3050	2650			1	Håkansson (1976)
141	Örsjö	55	28	13	32	*Mammuthus primigenius*, tusk	Lu-880 (#5)	36 100	2000	1600	41 301	1.641	1	Håkansson (1976), Berglund *et al*. (1976)
141	Örsjö	55	28	13	32	*Mammuthus primigenius*, tusk	LuS 6342 (#6)	34 500	400	400	39 863	0.429	2	Ukkonen *et al*. (2007)
149	Djurslöv	55	36	13	10	*Mammuthus primigenius*, molar	LuS 6336	26 150	200	200	31 394	0.258	2	Ukkonen *et al*. (2007)
150	Arrie, Risebjär	55	31	13	6	*Mammuthus primigenius*, tusk	Lu-887	22 000	900	800	26 408	1.057	1	Håkansson (1976), Berglund *et al*. (1976)
150	Arrie, Risebjär	55	31	13	6	*Mammuthus primigenius*	Lu-887:E	19 150	390	390	22 845	0.507	1	Berglund *et al*. (1976)
150	Arrie, Risebjär	55	31	13	6	*Mammuthus primigenius*, molar	Lu 6651	40 200	800	800	44 902	0.725	2	Ukkonen *et al*. (2007)

(#1) Sample undersized, diluted with ‘dead’’ carbon.

(#2*c*.) 0.5 kg of sediment, no pretreatment.

(#3*c*.) 4.4 kg of sediment, no pretreatment.

(#4) Collagen, C_{org}: 1%.

(#5) Collagen C_{org}: 4.75%.

(#6) Same tusk as Lu-746.

(#7) Same tusk as St-5331.