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Age and duration of a MIS 3 interstadial in the Fennoscandian Ice Sheet core area – implications for ice sheet dynamics

Johan Kleman [a, *], Martina Hättestrand [a], Ingmar Borgström [a], Derek Fabel [b], Frank Preusser [c]

[a] Department of Physical Geography, Stockholm University, 106 91 Stockholm, Sweden

[b] Scottish Universities Environmental Research Centre (SUERC), College of Science and Engineering, University of Glasgow, East Kilbride, United Kingdom

[c] Institute of Earth and Environmental Sciences, University of Freiburg, Alberstraße 23b, 79104 Freiburg, Germany

* Corresponding author

E-mail address: kleman@natgeo.su.se (J. Kleman)

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Abstract

Previous assumptions of continuous ice cover of the core area of the Fennoscandian Ice Sheet, from Marine Isotope Stage 4 (ca. 70 ka) to the end of MIS 2 (ca. 12 ka), have been challenged by the discovery of several sites in central and northern Scandinavia with interstadial sediments of assumed MIS 3 age. The sequences have often been dated by Optically Stimulated Luminescence (OSL) and dates of around 55 ka are present at most sites, indicating ice-free conditions at this time. There is less consensus about the timing of the build-up and advance of the last (Late Weichselian) ice sheet after this ice-free stage. To address the duration of MIS 3 ice-free conditions in central Scandinavia, we reviewed available dating evidence. At the few sites where multiple OSL dates are available, ages indicate around 15 ka of ice-free conditions. Two studies employing cosmogenic nuclide dating of preserved interstadial ground surfaces both indicate a 20 ka long period of ice-free conditions during the last ice-free period before the Holocene. Our interpretation is that central Scandinavia became ice-free around 55 ka and remained so until *c*. 35 ka, when the Scandinavian Ice Sheet started to expand once again. Expansion started from a small-sized remnant ice sheet, or from separate remnant ice caps in Norway. Available data limits the size of any Scandinavian ice sheet remnant surviving the MIS 3 interstadial to less than 1 m of global sea-level equivalent.

1. Introduction

Up until about 2010, it was widely believed that central and northern Scandinavia experienced continuous ice cover from Marine Isotope Stage (MIS) 4 until the final deglaciation around 10 ka (Lagerbäck and Robertsson, 1988; Lundqvist, 1992, Stroeven et al., 2016). This view originated from the lack of dated evidence for MIS 3 interstadials and was much influenced by the biostratigraphical correlation of two interstadials documented from northern Sweden to the Brörup and Odderade interstadials (MIS 5c and 5a) in mainland Europe (Lagerbäck, 1988a; Lagerbäck and Robertsson, 1988). Some indications of ice-free conditions in south-central Norway (Bergersen et al. 1991), were largely ignored or not considered reliable. The documented interstadial sediments were interpreted to postdate and overlie a glacial landscape dating to MIS 5d. This interpretation was based on observations that the tills comprising the preceding glacial landscape are underlain by Eemian sediment (MIS 5e) at both Finnish and Swedish sites (Lundqvist, 1971; Hirvas et al., 1981; Nordkalott Project 1986a, b, c; Hirvas and Neonen, 1987; Lagerbäck and Robertsson, 1988).

Over the last decade, the emergence of new data indicating ice-free conditions in central Scandinavia during MIS 3 has made this view increasingly untenable (Helmens et al., 2000; Hättestrand, 2008; Hättestrand and Robertsson, 2010; Alexanderson et al., 2010, Wohlfarth and Näslund, 2010: Wohlfarth et al., 2011; Ukkonen et al., 2011; Salonen et al., 2014; Möller et al., 2013; Kleman et al., 2020). The new view, which largely rests on Optically Stimulated Luminescence (OSL) dating, but also on radiocarbon dating and cosmogenic nuclide dating, clearly points to ice-free conditions during the early part of MIS 3 (55-44 ka). However, the duration of ice-free conditions is rarely resolved at any single locality. The issue is further complicated by strong evidence for a major ice advance of the western side of a Scandinavian Ice Sheet around 41 - 38 ka (Mangerud et al., 2003, 2010). The location of the eastern margin of the parental ice mass in this time interval is unknown.

In the Scandinavian mountains there is abundant morphological evidence for preservation of interstadial ground surfaces, such as polygonised surfaces and pre-Holocene ventifacts, indicating long periods of cold ice-free climate (Lagerbäck, 1988a). Morphological analyses have long suggested these surfaces and landforms to be older than Late Weichselian (Kleman and Borgström, 1990, 1994) but dating these features has been elusive. The fact that the surfaces were not eroded during the Late Weichselian and are not buried by later glacial sediments is explained by cold based conditions of the ice sheet in its central areas (Lagerbäck, 1988a; Sollid and Sørbel, 1994, Kleman et al., 2008). Cosmogenic nuclide dating, which for locations that have experienced ice burial is an exposure duration method rather than a dating method in the strict sense, has confirmed the antiquity of such surfaces (Fabel et al., 2002). However, this approach requires additional data to place the period of ice-free conditions into a reliable chronology frame.

Reconstructing the Late Weichselian deglaciation is relatively straightforward, because the youngest glacial landforms are well preserved and radiocarbon dating can be efficiently used back to, and somewhat beyond, the Last Glaciation Maximum (LGM). Investigation of former ice sheet core areas, however, poses several challenges. There is still no way to date 'subglacial time' (Kleman et al., 2006), i.e. there is no dating method that can directly determine the time elapsed since, for example, the formation of a subglacial till. All widely applicable dating methods, such as radiocarbon, OSL, and cosmogenic surface exposure dating, are based on atmospheric exchange of living organisms, exposure to sunlight, or exposure to cosmic radiation, all of which are inhibited by ice sheets. Additionally, the last ice-free interval in many ice sheet core areas appears to have occurred during MIS 3, at or beyond the range of reliable radiocarbon dating. Even in the cases of reliable evidence for the occurrence of MIS 3 ice-free conditions, reliable data shedding light on the duration of the ice-free conditions are rare.

Given the substantial evidence that central Scandinavia was indeed ice-free during MIS 3, we regard it as pertinent to move on to additional questions for understanding ice sheet dynamics in this time interval. Both the age and the duration of ice-free conditions in central Scandinavia are important because they place constraints on the speed of ice-sheet build-up towards the LGM, and they are important parameters for validating numerical ice sheet models. The number of ice-free periods in Scandinavia during MIS 3 is a complex question, strongly dependent on location. It can be assumed that moderate expansion phases of restricted 'Norwegian' ice sheets likely reached temporary standstills somewhere in western Sweden, hence leaving morphological and stratigraphical evidence for two or more interstadials in western Sweden, but for only one further east.

Limiting the duration of ice cover during the MIS 4 to MIS 2 interval has implications for understanding the dynamics and erosional impact of the apparently rather short-lived Late Weichselian ice sheet. New data allows us to assign a maximum size for any MIS 3 ice sheet remnant, thereby facilitating more firm global ice sheet budgeting.

The overall objective of this study is to shed light on the age and duration of a MIS 3 interstadial in central candinavia and to discuss implications for Weichselian ice sheet dynamics. We use an approach that entails:

- review of recent work presenting dating evidence for MIS 3 ice-free conditions in central Scandinavia,
- consideration of the duration of 'ice-free time' based on information from cosmogenic nuclide dating of re-exposed interstadial ground surfaces,
- compilation of a simple spatio-temporal model for advance and retreat of the eastern margin of the Fennoscandian Ice Sheet.

- a discussion on how our findings relate to evidence from the southwestern and western margins, i.e. Denmark and the Norwegian coast.

We focus primarily on the eastern ice sheet margin, because due to the much larger swath between maximum and minimum conditions spatial constraints there more strictly constrain the volume of the ice sheet than evidence from the western margin. However, at least one western-margin event, the Skjonghelleren stadial (Mangerud et al., 2003), which was a major advance of the western margin of the ice sheet during MIS 3, may have consequences for interpretations on the eastern side of the mountains.

2. Data reflecting the age and duration of MIS 3 interstadials in central Scandinavia

Arnold et al. (2002) aimed to establish the minimum Fennoscandian Ice Sheet size during MIS 3. The radiocarbon database they utilise has relatively few sites located centrally in the glaciated area, but still suggests ice-free conditions in northern Sweden 42 – 32 ka. Of considerable importance are their acceptance of the thermoluminescence (TL) ages by Bergersen et al. (1991), which indicate ice-free conditions in central southern Norway at 40 – 37 ka. Their reconstructed MIS 3 minimum ice sheet is of very small area and volume.

The comprehensive reconstruction by Hughes et al. (2016) reaches back to around 38 ka, with one time-slice map showing approximate ice extents 34 -38 ka, the time of the Ålesund interstadial (Mangerud et al., 2003). The reconstruction thus does not fully embrace the entire MIS 3 period we discuss here. For 34 - 38 ka it gives two alternative ice extents, a single elongated ice sheet with its eastern margin approximately 100 km into Sweden, and a minimum alternative with one ice sheet remnant over the high plateaus of southern Norway and a second, narrow ice sheet over the high northern parts of the mountain chain.

In the following, we combine new and relatively recent studies employing OSL dating and novel work employing cosmogenic nuclide dating, with regional overviews summarizing older data. OSL and radiocarbon dates reflect the age of subaerial sediment deposition at ice sheet margins and in ice-free landscapes, while ages received from cosmogenic nuclide dating are a measure of total ice-free time since deposition. The most important data for the scope of this paper are summarized in Tables 1 and 2. Table 2 lists the individual ages and uncertainties for data sets summarised in Table 1. In reviewing this data, two things stand out. The first is that localities with few dates can give clear answers to the ice/no ice question for *some* period in MIS 3. However, only a few have so many dates and such a data structure that they have a bearing on the duration of the ice-free period(s).

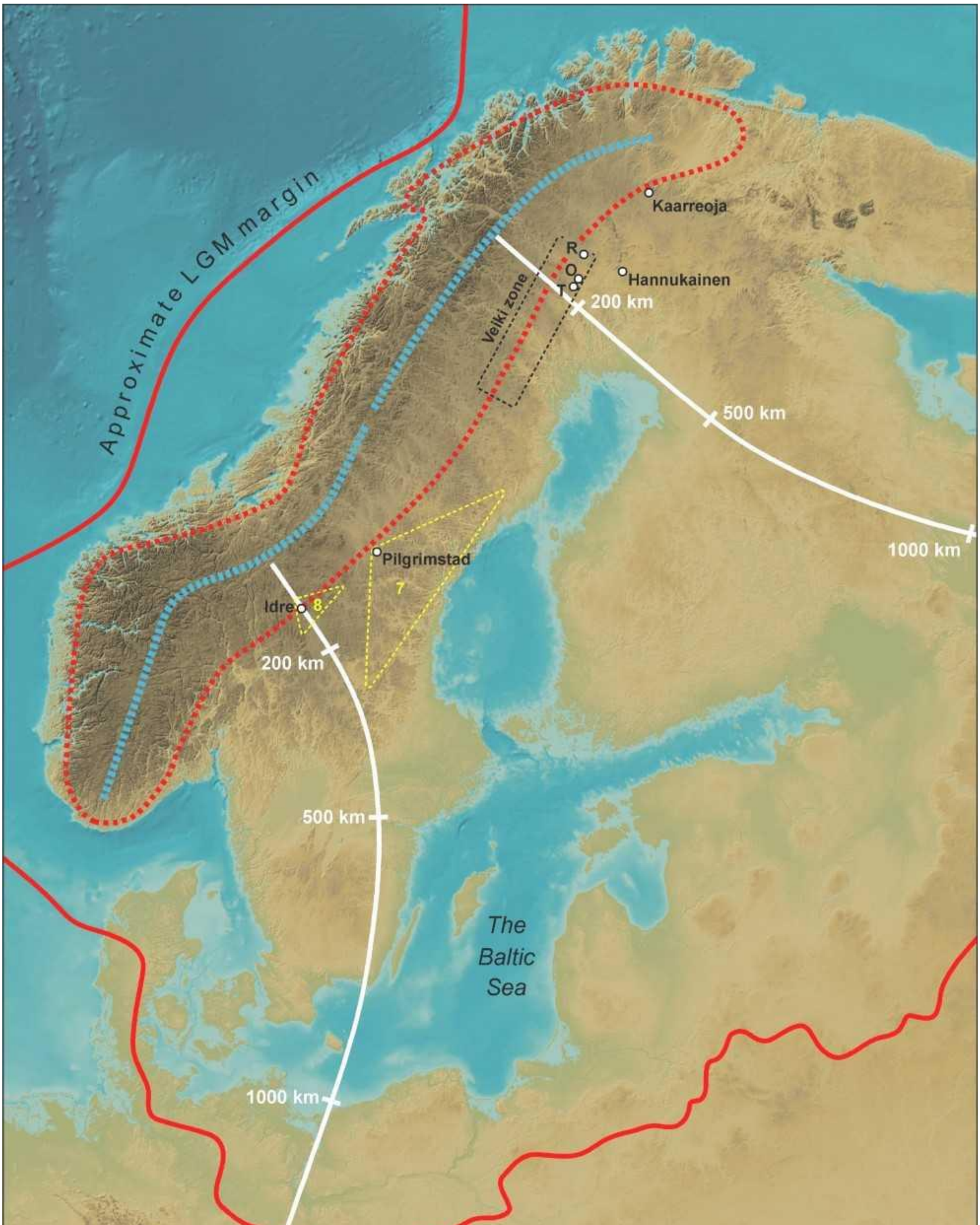

Fig. 1. Locations of interstadial sequences discussed in the text. R (Riipiharju), O (Ontoharjut) and T (Takanenmännikkö) mark sites investigated by Lagerbäck and Robertsson (1988). The location of data from the populations by Ukkonen et al. (2011) and Borgström (2017) are shown by stippled yellow polygons. Illustrated are two 'modes' of glaciation, restricted mountain-centred ice sheet, thought to characterise moderately cold periods throughout the Quaternary (dashed line, Kleman, 1992; Porter, 1989), and sub-continental ice sheets thought to characterize the last few glacial maximum stages (solid line, Kleman et al., 2008). Dotted blue line indicates the approximate elevation axis of the mountain chain. White lines correspond to lines of expansion, along which length from inception areas is indicated in Fig. 3.

2.1 Single-site studies (Fig. 1 and Table 1)

Alexanderson et al. (2010) reinvestigated sandy sub-till sediments in a stratigraphic section at the classical Pilgrimstad site, central Sweden. Nine out of a total of ten OSL dates indicate ice-free conditions during 52 – 36 ka. A sensitivity analysis specifically excluded an Early Weichselian age for this site.

Möller et al. (2013) studied till covered sediments in a river valley at Idre, west-central Sweden. A series of nine OSL dates from one unit (Unit A) range from 54 to 41 ka, supporting ice-free conditions at the site during at least part of MIS 3, even though the ages are not in stratigraphic order. The complicating factor of one date from Unit A of 70 ka and a number of stratigraphically overlying dates in the range 180 – 130 ka was explained by incomplete bleaching of these sediments prior to deposition, so that dating would not give actual ages of deposition, but too old ages. Due to the possible problems with incomplete bleaching of the sediments the interpretation was that the data indicates deposition at the site at or after 41 ka. The mean age of the datings are 44+-7ka. The data and the comments by the author do not allow calculation of interstadial duration.

Kleman et al. (2020) investigated a marginal moraine at an upland site near Idre and on the basis of OSL dates of waterlain sandy sediments within the moraine concluded that it was formed at approximately 55 ka. Six ^{10}Be dates from boulders embedded in the moraine crest indicate an ice-free duration of ca 30 ka since moraine formation. Subtraction of a Holocene exposure of 10.1 ka at this location, derived by analysis of ice retreat maps in Stroeven et al. (2016) and Hughes et al. (2016), leaves 20 ka of exposure before the last glaciation. Hence, this indicates ice-free conditions at this site between 55 and 35 ka. No calculated uncertainty can be assigned to the deglaciation time of 10.1 ka, but we estimate the maximum error in deglaciation time to be 500 a, not materially affecting the 30 ka total duration estimate derived from cosmogenic nuclides.

This upland site is located only 10 km from the lower elevation site of Möller et al. (2013). Pilgrimstad and Idre are at a comparable distance from the main mountain chain and we regard the data by Alexanderson et al. (2010), Möller et al. (2013) and Kleman et al. (2020) as mutually supportive.

Lagerbäck and Robertsson (1988) report 38 radiocarbon dates on humic material, peat, and plant remains from kettle holes in eskers formed by a pre-Late Weichselian ice sheet. 14 of these dates are infinite, >40, >45 or >50 ka respectively. The remaining 24 of the dates are finite, clustering between 30 and 45 ka. Some of the reported errors are very large but a number have 'normal' errors. However, the main part of the dates are not in stratigraphic order. On biostratigraphical grounds, the authors correlated the ice-free events analysed, the Peräpohjola and Tärendö interstadials, to Brörup (MIS 5c) and Odderade (MIS 5a). Partly because of problems with reversed ages, but also based on comparisons with studies of interstadial sites in northern Europe, they argued that *all* dated samples were likely older than MIS 4 and beyond radiocarbon dating range and that the finite ages were artefacts of contamination. 24 of these finite dates were listed by Wohlfarth (2010). She selected seven of the dates, with estimated errors less than 3 ka, and absolute calibrated them. These are the dates reported in Table 2.

In the original work of Lagerbäck and Robertsson (1988) it is apparent that at the Riipiharju and Onttuharjut sites, the majority of dates below the till separating the two interstadials are infinite, but all but one date above this till is finite. At face value this sub-set of data therefore supports ice -free conditions in northern Sweden between 35 and 50 ka. The dates could, as the authors suggest, be infinite ages that through contamination erroneously yielded ages in the MIS 3 interval. But we cannot discard the possibility that at least some of the dates are correct. The difficulties surrounding this data set are quite similar to those in the compilation of ^{14}C, TL and OSL dates by Mäkinen (2005) in northwestern Finland. The guiding question for Mäkinen (2005) was the age of Peräpohjola sediments. He reported a large number of both finite and infinite ^{14}C ages. TL and OSL ages were systematically younger than the expected >74 ka, and the difficulty in trusting ^{14}C data so near the limits of the method was noted. Neither Lagerbäck and Robertsson (1988) nor Mäkinen (2005) contradict the conclusions drawn in this article but we hesitate to invoke them as a strong support for long-lasting MIS 3 ice-free conditions.

Salonen et al. (2014) documented interstadial fluvial sediments from the Hannukainen mine, Finland, overlying a MIS 4 till. A thin till was interpreted to indicate that the ice-free interval was interrupted by a glacial event. OSL dates were taken from fairly similar sediments both above and below this thin till and these dates indicate an age for the fluvial sediments of 55 – 35 ka.

Sarala et al. (2016) investigated an interstadial sequence regarded as relatively complete at Kaarreoja, northernmost Finland. Two radiocarbon dates from the same peat bed gave radiocarbon ages of 35 and >45 ka, respectively. An OSL age of 52 ka from fluvial/lacustrine sediments underlying the till was reported. The study lends support to ice-free conditions during MIS 3 but does not allow any conclusions about interstadial duration.

2.2 Overviews, based on multiple dates within a broader region (Table 1)

Ukkonen et al. (2011) compiled and evaluated over 100 radiocarbon dates on mammoth bone material from Northern Europe. They concluded that mammoths were widespread up to 65° N latitude (i.e. north-central Fennoscandia) during MIS 3 (50 – 30 ka). Most of the dated bones are reworked and not in primary position. Seven dates from north central Sweden (see Fig. 1 for area) are of special geographical relevance to the present work and they form the basis for age and duration estimates presented in Table 1. The ages range from 29.7 to 44.6 ka.

Borgström (2017) reported cosmogenic exposure durations for six pre-Holocene polygonised surfaces (Fig. 2) in the southern Swedish mountains (see Fig. 1 for location) These data can illuminate the duration of the last period of ice-free conditions but not its age. We used this data set, which can be regarded as a “floating” (i.e. the absolute age is unknown) measure of ice-free *duration*. We extracted the six samples labelled ‘polygonised surfaces’ from the collection of Borgström (2017). After subtraction of 10.1 ka for Holocene exposure, on the basis of the deglacial retreat maps in Stroeven et al. (2016) and Hughes et al. (2016), a mean ^{10}Be pre-Holocene exposure duration for these polygonised surfaces is 19.5 ka. Errors for the individual dates are notably large. The method and approach cannot resolve whether this accumulated time represents one or more events. Kleman et al. (2020) describe that the flank of the moraine hey dated is covered by sorted boulder polygons, similar to those measured by Borgström (2017). We therefore consider the exposure durations measured by Borgström to have the same first exposure (starting point) as those in Kleman et al. (2020) and have “anchored” Borgströms cosmogenic data to the same start exposure at 54.9 ka.

The data sets of Kleman et al. (2020) and Borgström (2017) rely largely on cosmogenic nuclide dating of surface boulders. The two studies give similar duration estimates of around 20 ka. The cosmogenic nuclide method (Phillips et al., 2008) is a direct and cumulative exposure duration method which , however, requires a substantial set of assumptions, additional data, or modelling, to be used as a dating method (Applegate et al., 2012).

Wohlfarth (2010) focused specifically on the question of MIS 3 interstadials and made a thorough quality analysis and sorting of older, mostly radiocarbon, dates. The majority of dates reported for this area by Wohlfarth are from Lagerbäck and Robertsson (1988), Alexanderson et al. (2009), and Ukkonen et al. (2011). They are here listed under the original publications, but in the analysis and discussion of these dates we have paid attention to Wohlfarths (2010) quality sorting and acceptance of certain data as probably reliable.

Table 1. Age and estimation of duration of MIS 3 ice-free conditions at sites in central Scandinavia, based on retrieved dates from sites east of the mountain range (central and northern Sweden, northwestern Finland). Duration measures are differences between oldest and youngest dates for localities or populations.

		Number of dates			***Youngest***	***Oldest***
	Single–site studies	**OSL**	**^{14}C**	**Cosmo**	**(ka)**	**(ka)**
1	Pilgrimstad, Alexanderson et al. (2010).	9	-	-	36	52
2	Idre airport, Möller et al. (2013.)	9	-	-	41	54
3	Idre/Städjan, Kleman et al. (2020). 15 samples were measured. These were extracted from three field samples obtained in one sedimentary bed. 30 – 45 aliquots were measured per sample. Mean of all 15 samples was 54.9 ±4.1 ka. Mean with three outliers removed 54.9 ±1.7 ka.	3	-	9	Not applicable	
4	Riipiharju, Ontoharjut, Takanenmännikkö, Lagerbäck and Robertsson 1988. We here report the subset of data that was quality assessed and absolute calibrated by Wohlfarth (2010).		7		36	50
5	Hannukainen, Salonen et al. (2014).	5	-	-	35	55
6	Kaarreoja, Sarala et al. (2016).	1	1	-	35	52
	Regional compilations					
7	Central Sweden Ukkonen et al. (2011) (Geographical subset of Ukkonen et al. (2011) data).	-	7	-	30	45
8	West-central Sweden, Borgström (2017).	-	-	6	Not applicable	

Table 2

		ka		
		OSL	**^{14}C**	**Cosmo**
1	Pilgrimstad, Alexanderson et al. (2010).	43 ±5 45 ±4 48±8 52 ±4 49 ±4 38 ±3 39 ±3 36 ±3 46 ±3		
2	Idre airport, Möller et al. (2013).	44 ±3 45 ±3 40 ±2 41 ±2 52 ±5 42 ±4 43 ±2 41±3 48 ±4 54 ±4		
3	Idre/Städjan, Kleman et al. (2020).	56.2 ±3.8 54.1 ±3.6 52.9 ±3.4 52.9 ±3.7 62.4 ±4.2 55.8 ±3.6 54.2 ±3.7 45.4 ±3.0 55.6 ±4.3 54.3 ±3.6 56.6 ±3.7 55.5 ±3.6 53.8 ±3.2 58.8 ±4.0 65.4 ±4.1		36.4 ±1.8 27.6 ±1.3 26.9 ±1.2 32.1 ±1.4 31.7 ±1.5 31.0 ±1.4 29.8 ±1.4 27.6 ±1.3 21.8 ±1.0
4	Dates from Riipiharju, Ontoharjut and Takanenmännikk, Lagerbäck and Robertsson 1988. We here report the subset of data that was quality assessed, found reasonably reliable, and was absolute calibrated by Wohlfarth (2010).		50.0 ±1.0 42.5 ±1.6 35.6 ±1.1 36.0 ±1.0 37.9 ±1.3 39.0 ±1.4 39.2 ±1.7	
5	Hannukainen, Salonen et al. (2014).	35.3 ±4.1 55.7 ±8.7 39.0 ±5.0 50.6 ±6.7 46.8 ±7.2		
6	Kaarreoja, Sarala et al. 2016	52	34.8 ±0,2	
7	Central Sweden Ukkonen et al. (2011) (Geographical subset of Ukkonen et al. (2011) data).		44.6 ±1.0 29.7 ±0.4 34.3 ±0.4 42.3 ±0.4 30.7 ±0.2 34.1 ±0.5 40.7 ±1.4	
8	West-central Sweden, Borgström (2017).			31.5 ±3.6 29.3 ±6.7 24.3 ±2.2 37.4 ±4.5 28.3 ±7.8 27.0 ±2.7

From Table 1 it is evident that there is a clustering of oldest (and only) dates in the 55 – 52 ka interval. We regard the evidence for ice-free conditions in central Scandinavia during the early part of MIS 3 as solid. The late date of 30 ka for renewed ice cover implicit in the data by Ukkonen et al. (2007, 2011) relies on two dates of around 30 ka. We conclude that most studies, including all based on OSL dates, support a start of MIS 3 ice-free conditions at about 55 ka, and most indicate that the ice-free conditions lasted to around 35 ka.

3. Discussion

Existing data from stratigraphic sequences are in good agreement that MIS 3 ice free conditions in central Scandinavia started about 55 ka. The onset of glacial conditions at about 35 ka, after approximately 20 ka of ice-free time, is more uncertain. The support for ice-free conditions as late as 30 ka largely rests on two debated (Wohlfarth 2010) mammoth dates (Ukkonen et al., 2011), whereas other lines of evidence support 35 ka as the approximate time of ice expansion out from the mountains and over central Sweden. Regarding Ukkonen et al. (2011), the problem that the bone material reported (Ukkonen et al., 2007, 2011) was rarely *in situ*, was pointed out by Wohlfarth (2010). In our view, this does not seriously detract from its chronological value for the interstadial duration question in the spatial setting of central Scandinavia. The preservation of identifiable bone material suggests short transport distances. Known ice-flow indicators exclude glacial transport of mammoth bones into north-central Sweden from the east. A more serious problem is the reliability of the youngest dates. Wohlfarth (2010) maintains that inadequate pre-treatment procedures may have made the youngest dates too young, thereby also creating a conflict with their stratigraphic context which indicates higher than reported ages. The data of Borgström (2017) and Kleman et al. (2020) suggest around 20 ka duration of ice-free conditions. The large spread and errors in the two cosmogenic data sets makes the evidence for renewed glaciation at 35 ka temporally more uncertain than the more precise dating of the start of ice-free conditions.

The duration of ice-free conditions can be expected to have been shorter in western Sweden than in more easterly areas. This is a natural consequence of the location of the supposed inception and initial growth area, the mountain chain. It is likely that ice sheets expanded out of Norway on many occasions through the Quaternary. However, they only reached true Fennoscandian dimensions on relatively few occasions (Kleman et al- 2008). An ice-covered westernmost Sweden, with the coast to the Bothnian Bay and the Baltic ice-free must have been a recurring configuration.

Of the two alternatives for ice-sheet size at 38 – 34 ka shown in Hughes et al. (2016) only the smaller one is compatible with the ice-free conditions at Idre documented by Möller et al. (2013) and Kleman et al. (2020), indicating an ice sheet volume of less than 1 m of sea-level equivalent.

For the MIS 3 questions, a key issue is the ice dynamics on the east side of the mountains during the Skjonghelleren stadial. The advance documented by Mangerud et al. (2003, 2010) must have come out of a substantial ice mass. The evidence for the Skjonghelleren advance is solid, and the event was apparently driven by the cold climate of Greenland stadials 10 and 9 (41-38 ka). However, the effects of 3000 years of colder climate, and likely reduced precipitation, on ice volume and frontal advance are difficult to evaluate. Today the ratio in precipitation between the Ålesund area and west-central Sweden is around 3 or 4 to 1. There is no reason to believe that this ratio was radically different in glacial times. Reduction in ablation during 3 ka of cold climate was sufficient for rapid build-up of mass and a major frontal advance in the west, despite likely reduction in precipitation. *Some* advance in the east is likely, but the magnitude is entirely unknown. In this context it should be noted that there are more pre-Late Weichselian end moraines and other evidence of ice marginal positions in west-central Sweden than has previously been known. The only such moraine that is dated, at Idre, is reported in Kleman et al. (2020). It is clearly older than the Skjonghelleren advance. Other moraines at slightly lower elevation are mapped in Kleman et al. (2020), and further examples occur at Långfjället, on the Swedish border to Norway (Borgström, unpublished data). The multitude of glacifluvial channel generations described from the Transtrand Mountains (Kleman et al., 1992) have never been correlated to specific events described elsewhere. It is conceivable that some of them are related to an oscillating MIS 3 ice margin in westernmost Sweden.

The OSL dates reported by Kleman et al. (2020) differ from many interstadial OSL dates in that there is strong evidence that the dated material was deposited and exposed precisely at the ice margin as indicated by the landform, a marginal moraine, to which the dated sand is integral. A key question for this data set is whether it is reasonable to assume a lack of inheritance at the onset of the MIS 3 interstadial, in the boulders sampled for cosmogenic nuclide dating.

At least two factors suggest that exposure of nearly all the boulders sampled in Kleman et al. (2020) indeed started at the onset of the last interstadial. The first is that a content of erratics from the northwest indicates that the material was transported to its present mountain-shoulder position by wet-based and eroding ice (during MIS 4) along a lowland path. The second is the good clustering of dates. Any random collection of previously exposed boulders would likely show a much larger spread. The simplest explanation for the structure of the dates in the study is that the exposure of most of the sampled boulders started at the same time, when the ice withdrew from the newly formed moraine, and that they have received all their exposure in their current position.

The data from Borgström (2017) on polygons in surfaces classified as relict, are potentially associated with additional error sources compared to the data set in Kleman et al. (2020). Sorted polygons, by nature, indicate rotation and vertical and lateral migration of material. This sorting process will take time and we can expect that full exposure to cosmic radiation only started when the boulders reached their present position. The time needed for the sorting, and the degree of positional stability of these boulders over the long durations of an interstadial, the period of ice-sheet coverage, and the present interglacial, is difficult to evaluate. The extreme Holocene stability of these relict surfaces was noted by Kleman and Borgström (1990), but interstadial conditions are unknown.

The morphological integrity of both the marginal moraine and the polygonised surfaces speak against any complex history of burial by sediment and re-exposure of the sampled sites.

Fig. 2. Polygonised relict surface at Fulufjället. Cosmogenic exposure measurement (^{10}Be) indicates that these polygons received 14.2 ka of pre-Holocene exposure (Borgström 2017).

Different methodical approaches to the age and duration questions for the last period of ice-free conditions have been reported here; single site studies relying on OSL dates in a stratigraphical sequence, a combination of OSL (for age) and cosmogenic nuclide dating (for duration), studies relying entirely on ^{14}C-dating, and combinations of OSL and ^{14}C-dating. It is encouraging that these different data sets and approaches give largely convergent results regarding the primary question, the existence of prolonged ice-free conditions in central Scandinavia during MIS 3. Only one of the studies, Salonen et al. (2014), give evidence for more than one ice-free period in this time interval, but it is difficult to judge if this is simply geographical dependence, a restricted advance may have reached their site in the far north, but not more southerly sites.

The data set of Lagerbäck and Robertsson (1988) is enigmatic. They stratigrahically documented two distinct interstadials. However, the glacial advance responsible for the intervening till has never been regionally identified and is therefore of little help for correlations. It also illustrates the uncertainties in interpreting radiocarbon data near the limit of the method. The authors themselves, in basing their correlations and thereby age assessments mostly on biostratigraphic evidence, in effect invalidated all their finite radiocarbon dates, but later authors (Wohlfarth, 2010) have partly "resurrected" them. Hättestrand and Robertsson (2010) suggested that the upper younger interstadial at one of the sites (Riipiharju) would correlate to MIS 3 and that the lower and older interstadial would correlate to Odderade (MIS 5a), based on new interpretations of the Weichselian interstadial conditions in northern Sweden and correlations with the Sokli record in NE Finland (e.g. Helmens et al., 2000). After discussions with Robert Lagerbäck they also renamed the interstadials in order to give both interstadials Swedish local names to avoid problematic and uncertain correlation with interstadial sites in Finland. Now the names Tärendö I and Tärendö II are used where Tärendö I is the older interstadial (previously Peräpohjola) and Tärendö II is the younger interstadial (previously Tärendö). Fluctuating climatic conditions were identified in the Tärendö II interstadial sequence which would fit well with rapid climatic shifts seen in the ice core records during MIS 3.

The application of cosmogenic nuclide dating to pre-Late Weichselian large-scale polygonised surfaces (Fig. 2) opens a new and more direct approach to the study of interstadial ice-free conditions. Polygons, being a subaerial landform, unequivocally demonstrate ice-free conditions and also offer a strong indication of permafrost conditions, while cosmogenic nuclide dating offers a direct method for determining the length of the subaerial exposure. Given the patchy but widespread occurrence of relict polygonised surfaces along the Scandinavian mountain chain (Kleman and Borgström, 1990, 1994, Borgström, 2017), a more complete spatial picture than offered by a small number of stratigraphical sites should be attainable.

3.1 Spatio-temporal model

Figure 3 summarizes our findings, focusing on the advance-retreat history of the eastern FIS margin. Our conceptual model rests on the assumption that every time the FIS grew from small initial ice volumes, it nucleated over, and expanded out from the mountain chain.

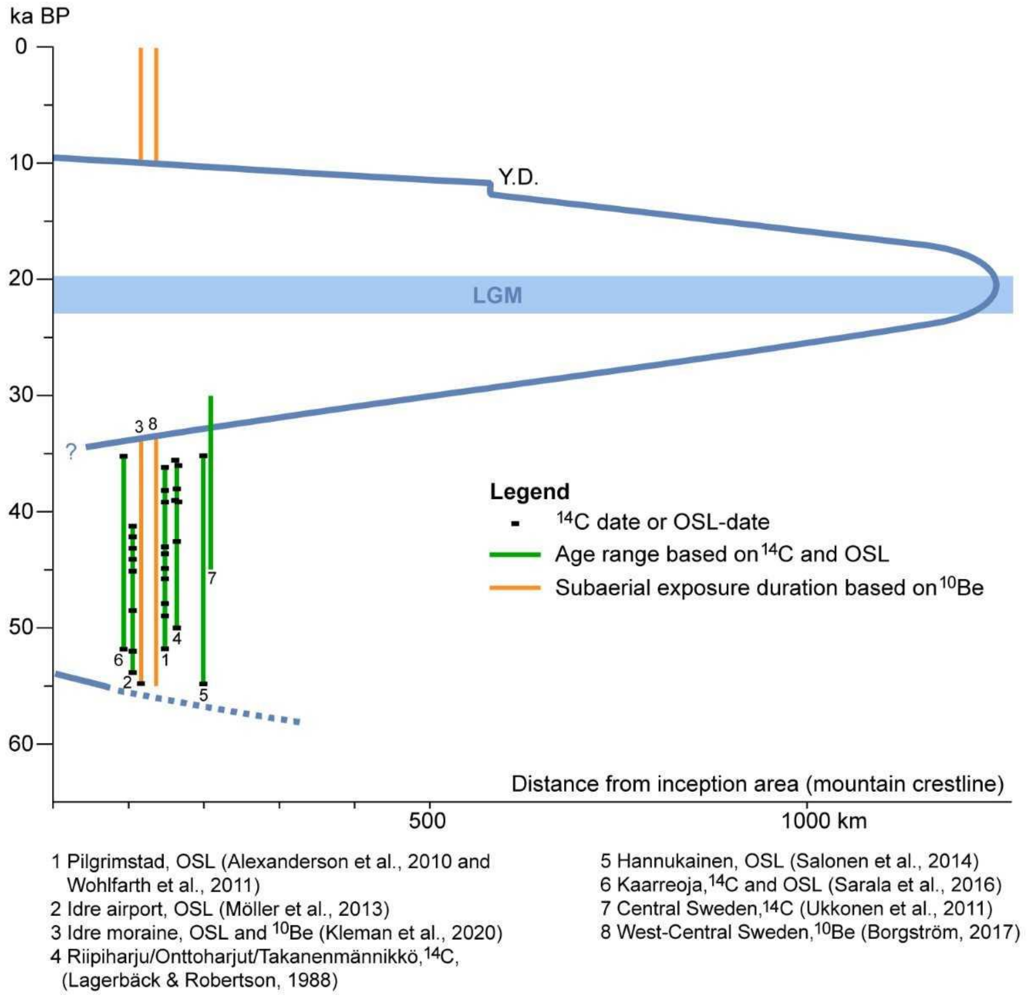

Fig. 3. Date ranges and duration estimates for the MIS 3 interstadial in central Scandinavia (see Table 1). Data are plotted at their approximate distance from the nucleating grounds in the mountain range, shown in Fig. 1.

3.2 Glacial dynamics

Our results have profound effects for our understanding of the dynamics of the ice sheet. The most striking feature in Fig. 3 is that build-up from a very small ice volume at 35 ka to the LGM size and volume was achieved in less than 15 ka, depending on the definition and age of the LGM (Hughes et al., 2013). This is surprisingly fast, given that the event was driven by an insolation minimum that was less extreme than those driving build-up during MIS 5d and 4. We acknowledge major uncertainties on two points. The first is that although OSL dates are well dispersed over the 55 – 38 ka period, it is possible that the interstadial was interrupted by advances also east of the mountains. There must be a sizable parental ice mass for the documented Skjonghelleren 41 – 38 ka advance (Mangerud et al., 2003), but the location and dynamics of the eastern margin in this time interval is unknown.

Also, we cannot ignore the possibility of abortive 'instantaneous glacierization' in the sense of Ives et al. (1974), i.e. the accumulation of thin and short-lived ice fields outside the coherent perimeter of a mountain ice sheet. Climatic candidates for such events are the time periods 49 – 47 ka, and 42 – 38 ka (Fig. 4). It is not known if such events occurred but if they did, they would complicate the interpretation of the cosmogenic results due to their shielding effects. Specifically, they would push back in time the onset of exposure to prior to the time when OSL data suggest the start of the interstadial. Similarly, they would reduce the available time for ice build-up towards the LGM even more.

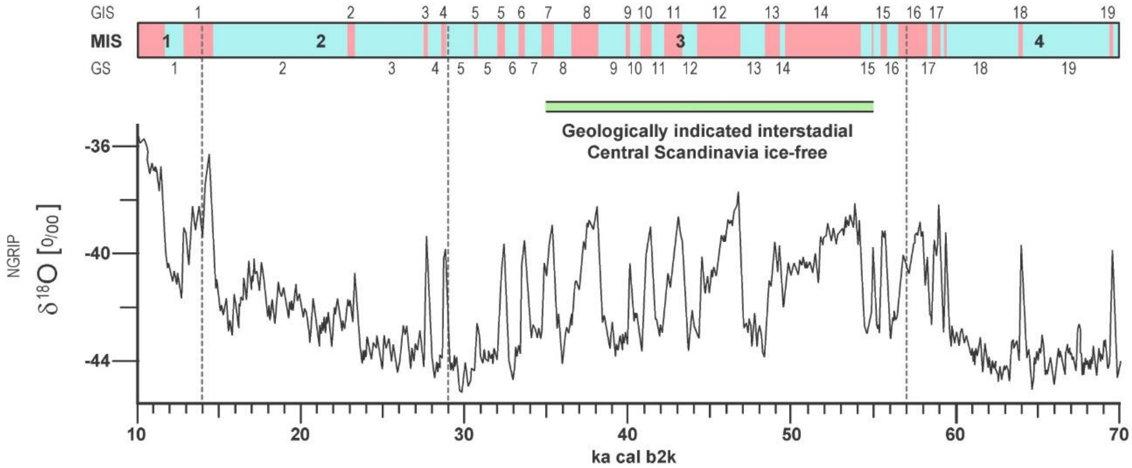

Fig. 4. Climate evolution as reflected in the NGRIP oxygen isotope curve for the 10 – 70 ka interval (Seierstad et al., 2014). GIS/MIS bars according to Rasmussen et al. (2014). The green crossbar indicates our preferred interpretation of ice-free conditions in central Scandinavia. The time interval 55 – 35 ka was characterized by long climatic interstadials, in which time was sufficient to efficiently reduce ice sheet size. Only after 35 ka was climate dominated by long stadials and infrequent and short interstadials, the state necessary for ice sheet growth. The figure also illustrates the general problem of correlating interstadials in the climatic sense with ice-free periods (interstadials in the geological sense). The large number of climatic interstadials (as directly reflected in ice core data), cannot be directly correlated with individual ‘ice-free events’.

In central and northern Scandinavia, the predominantly ice-free but highly variable climate of MIS 3, is recorded in some stratigraphic sequences (Helmens et al., 2000; Wohlfarth, 2010, and possibly at the Veiki moraine zone which defines a former ice marginal position during the Early Weichselian according to Lagerbäck (1988)). If reassigned to MIS 3, as previously suggested by Hättestrand (2007) and Hättestrand and Robertsson (2010), the Veikizone likely indicates a period of climate-induced standstill or readvance within the MIS 3 interstadial.

Our results are at odds with the reconstructed MIS 3 evolution in the southwestern part of the ice sheet (Houmark-Nielsen, 2010; Lüthgens et al., 2020). Two advances (figure 8 in Houmark-Nielsen 2010) are proposed to have occurred at time intervals which are problematic given our evidence for ice-free conditions in the central Scandinavia.

The earlier advance, at 54-46 ka should have occurred at a time when the data reported here gives strong evidence for major deglaciation from the MIS 4 ice sheet, and a very small remnant ice sheet with no Swedish – Finnish extent. We regard FIS advances reaching Denmark during the time interval 55-49 ka as climatically implausible (Fig. 4), dynamically highly unlikely, and not supported by data from the ice source area. Difficulties also surround the younger advance postulated to have occurred at 35-30 ka. This advance is inferred to have passed through the Baltic Basin. Such an advance dynamically requires an ice sheet with a large eastward extent, otherwise a Baltic trajectory cannot be explained. This advance would have occurred at a time when an eastern ice sheet margin at the Swedish-Norwegian border or in north-central Sweden is indicated (Alexanderson et al., 2010). Further, itis also difficult to reconcile with the mammoth data of Ukkonen et al. (2011). The two advances (Fig. 8 in Houmark-Nielsen, 2010) are proposed to have occurred at time intervals that are not in phase with climatic forcing as reflected in NGRIP data and are out-of-phase with advances reconstructed in Norway (Mangerud, 2004).

In this context it is important to note that Houmark-Nielsen (2010) based the chronology entirely on OSL dating, using large multigrain aliquots, where the OSL signal was averaged from *c*. 5000 grains. As discussed by Wallinga (2002a), the use of a large number of grains on an aliquot may cause masking the spread of individual palaeodose values that are used to identify the effect of partial bleaching (cf. Wallinga, 2002b). Partial bleaching represents the incomplete resetting of the OSL signal prior to deposition and will cause overestimation of the calculated OSL age. It is expected to be a common problem in the dating of glaciofluvial sediments (cf. Fuchs and Owen, 2008; Thrasher et al., 2009) and it can be avoided by using small aliquot or ideally single-grain techniques (Duller, 2008).

The picture of the Late Weichselian Fennoscandian Ice Sheet that emerges is that of an ice sheet that in its advance-retreat behaviour was more dynamic than previously thought, with rates of ice sheet growth prior to the LGM possibly rivalling rates of ice sheet retreat during deglaciation. In terms of another aspect of ice sheet dynamics, erosional capacity, we postulate that it was probably less efficient than has been thought. The total life span of the Late Weichselian Fennoscandian Ice Sheet was only 25 ka at most, and this short duration together with evidence for a partially cold-based ice sheet (Kleman and Hättestrand, 1999), makes the rather restricted erosion of landforms and older glacial deposits less surprising.

4. Conclusions

A substantial body of OSL data, with radiocarbon and cosmogenic nuclide data in supporting roles, indicate that central Scandinavia was ice free between 55 ka and ca. 35 ka. The age range is near or at the limit of reliable radiocarbon dating, and our conclusions are mostly based on OSL data. The evidence comprises stratigraphic sites dated with OSL dating, as well as cosmogenic nuclide dating of delicate subaerially formed landforms that were not eroded by the last ice sheet in the area.

The duration of ice-free conditions experienced by the latter far exceeds the Holocene, with the excess exposure, around 20 ka, interpreted to reflect interstadial subaerial exposure, dovetailing with and supporting evidence provided by sediments dated with OSL and radiocarbon techniques. A simple spatio-temporal model indicates that ice sheet build-up from fully ice-free conditions, or from a small alpine ice caps in Norway, towards ice sheet maximum conditions at the LGM (21ka, acknowledging non-synchroneity of margins and dating uncertainty of the LGM) was achieved in less than about 15 ka. Hence, the speed of ice sheet build-up after a long MIS 3 interstadial matched the speed of deglaciation. During the warmest MIS 3 phases, any possible Scandinavian ice sheet remnant was likely equivalent to less than 1 m of global sea-level.

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