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Re-dating the Pilgrimstad Interstadial with OSL: a warmer climate and a smaller ice sheet during the Swedish Middle Weichselian (MIS 3)?

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Pilgrimstad in central Sweden is an important locality for reconstructing environmental changes during the last glacial period (the Weichselian). Its central location has implications for the Scandinavian Ice Sheet as a whole. The site has been assigned an Early Weichselian age (marine isotope stage (MIS) 5 a/c; >74 ka), based on pollen stratigraphic correlations with type sections in continental Europe, but the few absolute dating attempts so far have given uncertain results. We re-excavated the site and collected 10 samples for optically stimulated luminescence (OSL) dating from mineral- and organic-rich sediments within the new Pilgrimstad section. Single aliquots of quartz were analysed using a post-IR blue single aliquot regenerative-dose (SAR) protocol. Dose recovery tests were satisfactory and OSL ages are internally consistent. All, except one from an underlying unit that is older, lie in the range 52–36 ka, which places the interstadial sediments in the Middle Weichselian (MIS 3); this is compatible with existing radiocarbon ages, including two measured with accelerator mass spectrometry (AMS). The mean of the OSL ages is 44 ± 6 ka ($n = 9$). The OSL ages cannot be assigned to the Early Weichselian for all reasonable adjustments to water content estimates and other parameters. The new ages suggest that climate was relatively mild and that the Scandinavian Ice Sheet was absent or restricted to the mountains for at least parts of MIS 3. These results are supported by other recent studies completed in Fennoscandia.

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Pilgrimstad in central Sweden (Fig. 1) is an important site for reconstructing environmental changes during the Weichselian in Scandinavia, since it is situated close to the former ice divide of the Scandinavian Ice Sheet and contains subtill organic and minerogenic sediments (Fig. 2). The site has been investigated and described by a number of authors over the past ~70 years (mainly Kulling 1945; Frödin 1954; Lundqvist 1967; Robertsson 1988a, b; García Ambrosiani 1990), but the absolute chronology of the site is still poorly known. In this study, we present and evaluate results of optically stimulated luminescence (OSL) dating that place the Pilgrimstad Interstadial in marine isotope stage (MIS) 3.

OSL has been used successfully to date Weichselian deposits in, for example, Russia (Svendsen *et al.* 2004; Thomas *et al.* 2006), Greenland (Hansen *et al.* 1999; Adrielsson & Alexanderson 2005), the Himalayas (Spencer & Owen 2004) and New Zealand (Preusser *et al.* 2005), but in Scandinavia results have been of varying quality (Kjær *et al.* 2006; Alexanderson & Murray 2007; Lagerbäck 2007; Houmark-Nielsen 2008). Because of this, and because our results are controversial with respect to previous age determinations of the site, in this article we focus on the methodology and reliability of the OSL ages, while the palaeoglaciological and palaeoecological implications of the dates will be discussed elsewhere.

The Pilgrimstad site

Kulling (1945) recognized three separate series of sand and gravel within the subtill sediments at Pilgrimstad. The lowermost series was interpreted as deposited in a proglacial sub-aquatic environment, while the upper two series represent a transition from glacifluvial to fluvial to lacustrine deposition and contain fine-grained minerogenic and organic material (Lundqvist 1967). A well-sorted sandy bed within the lacustrine sediments has been interpreted as an aeolian deposit (Robertsson 1988a, b). The sediments were exposed at the surface for some time before the most recent ice advance. Detailed descriptions of the stratigraphic units and a review of interpretations are available in Lundqvist (1967).

The palaeoecological interpretation as a cool, subarctic–arctic environment is based on several proxies, mainly from the organic beds. According to pollen and coleoptera, open herb–shrub vegetation was followed by a forest border setting during a climatic optimum (Robertsson 1988a, b). This warm interval was succeeded by a colder climatic phase with periglacial conditions and a subsequent phase of herb–shrub vegetation (Robertsson 1988b). Both diatoms and insects record deposition in a nutrient-rich lake (Lundqvist 1967; Robertsson 1986). The insect fauna also

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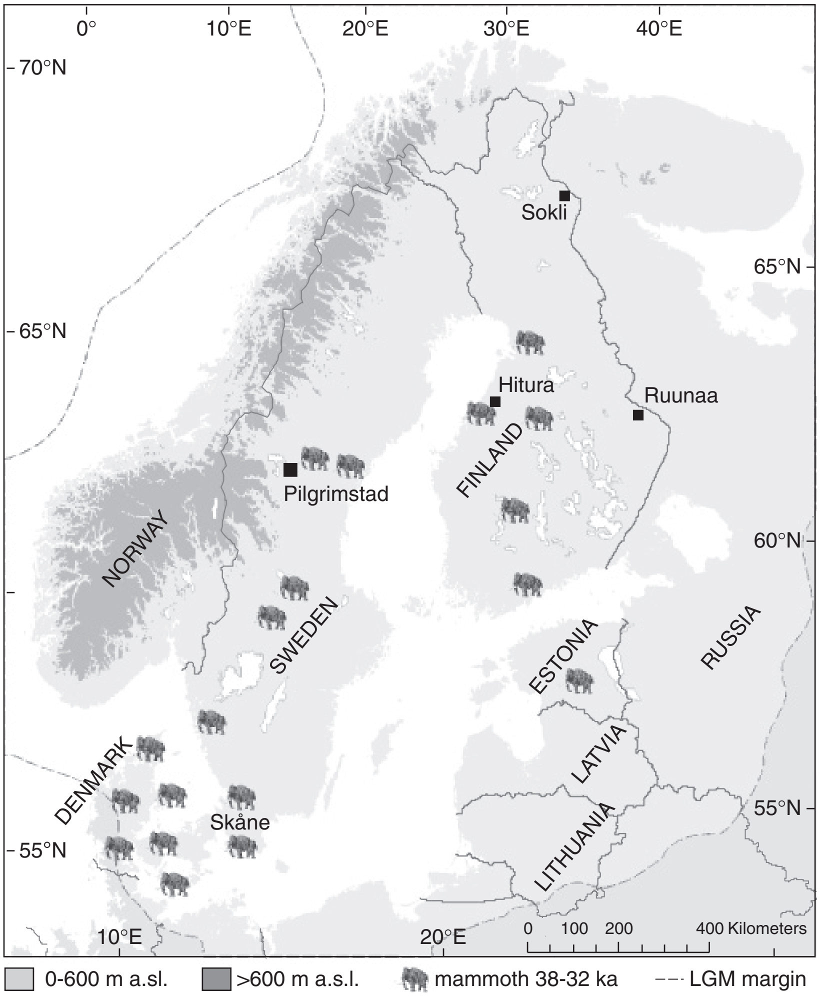


Fig. 1. Location map of Pilgrimstad. Mammoth locations from Ukkonen *et al.* (2007), Last Glacial Maximum (LGM) margin from Svendsen *et al.* (2004). Other sites that also indicate ice-free conditions during MIS 3 are shown: Sokli (~50 ka; Helmens *et al.* 2007a, b), Ruunna (50–25 ka; Lunkka *et al.* 2008), Hitura (deglaciation 62–55 ka; Salonen *et al.* 2008) and several sites in Skåne (39–24 ka; Kjær *et al.* 2006).

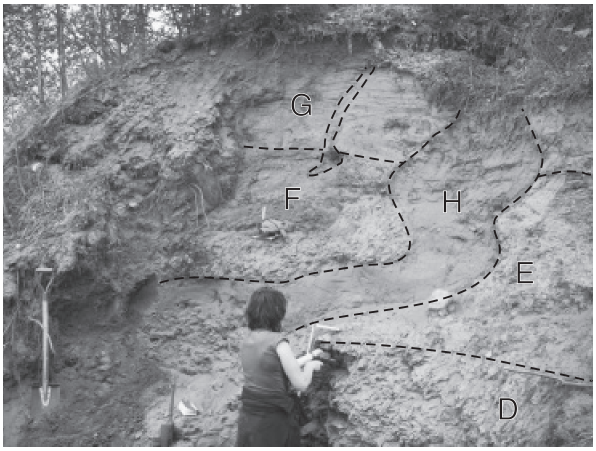
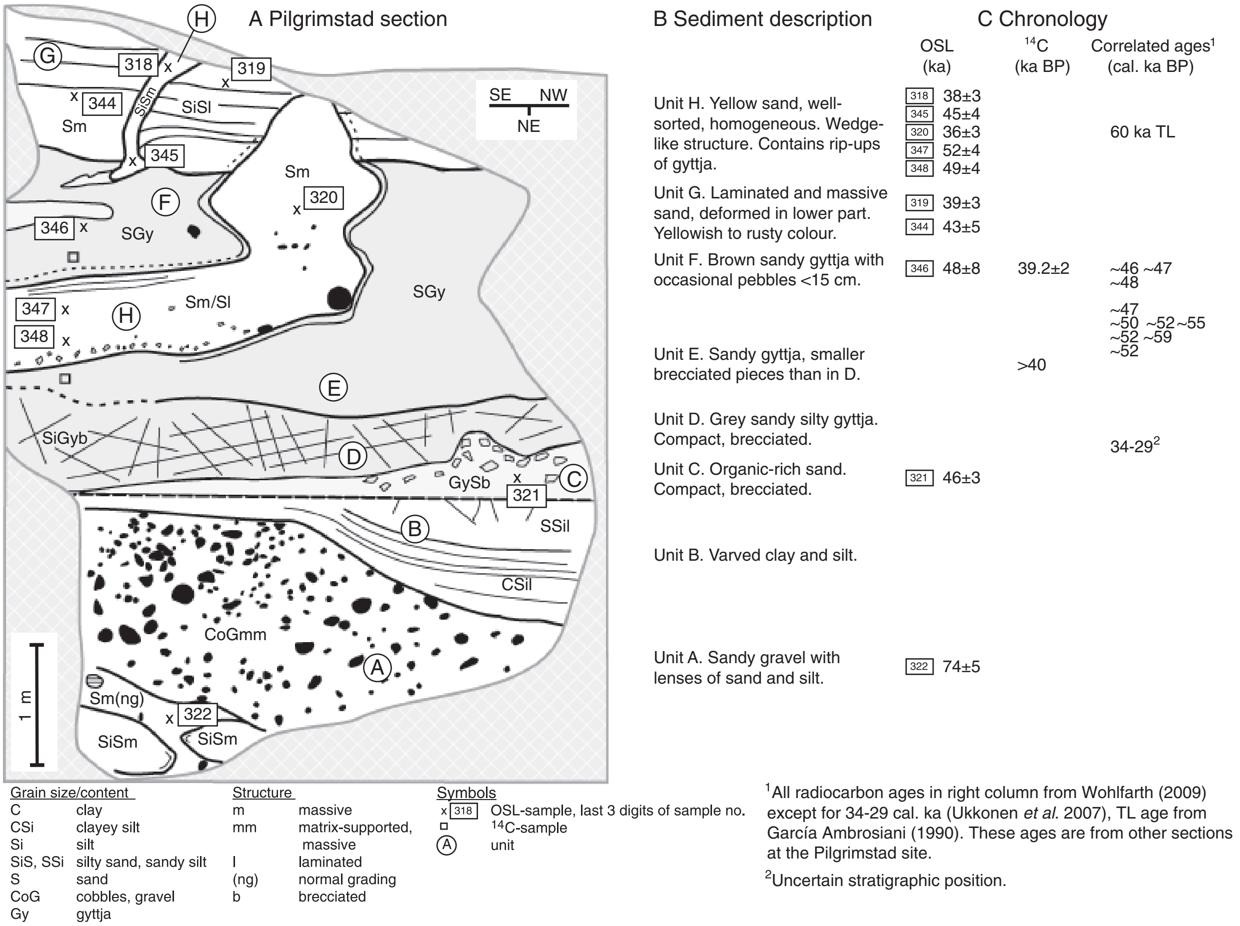


Fig. 2. Photograph of the upper part of the new section at Pilgrimstad (see Fig. 3 for comparisons). D–H represent the lithological units.

indicates a cool, arctic–subarctic climate, consistent with the finds of mammoth (*Mammuthus primigenius*), reindeer (*Rangifer tarandus*) and elk (*Alces alces*) (Lundqvist 1967).

The site has been assigned an Early Weichselian (MIS 5 a/c) age based on a correlation of the palaeoenvironmental reconstruction with type sections in continental Europe and represents the type section for the local Pilgrimstad Interstadial (Kulling 1967; cf. also Jämtland Interstadial; Lundqvist 1967; Lundqvist & Miller 1992). Robertsson (1988a, b), for example, correlated the organic-rich beds with one or possibly two Early Weichselian interstadials (Brørup and/or Odderade) depending on how the climatic cooling in the middle of the section is interpreted – as a phase within one interstadial or as separating two different interstadials.

So far, there have been few absolute dating attempts and these have given uncertain results. According to a recent evaluation of all radiocarbon dates from Pilgrimstad, 10 samples that are acceptable from a quality perspective range between 59 and 46 cal. ka BP in age (Wohlfarth 2009) (Fig. 3). Moreover, a single thermoluminescence measurement resulted in 60 ka for the sandy unit within the organic beds (García Ambrosiani 1990) and one U/Th measurement provided an age of 38±4 ka (Heijnis *in* Robertsson & García Ambrosiani 1992). Recently, Ukkonen *et al.* (2007) also re-dated a



[1] All radiocarbon ages in right column from Wohlfarth (2009) except for 34-29 cal. ka (Ukkonen *et al.* 2007), TL age from García Ambrosiani (1990). These ages are from other sections at the Pilgrimstad site.

[2] Uncertain stratigraphic position.

Fig. 3. A. Sketch of the new section at Pilgrimstad, lithology and position of OSL and ^{14}C samples. B. Brief sediment description. C. Results of OSL and ^{14}C age determination.

mammoth molar from Pilgrimstad to 34–29 cal. ka BP. The exact stratigraphic position of the mammoth remains is not clear, but based on Kulling's (1945) and Robertsson's (1988a) stratigraphic descriptions, it seems to derive from the lower part of the organic beds analysed by Robertsson (1988a).

These ages are all younger than the age estimate based on pollen stratigraphy; a possible correlation of Pilgrimstad with the Moershoofd Interstadial (46–44 ka BP) (Behre & van der Plicht 1992) has therefore been proposed but considered less likely (Robertsson 1988a).

Setting

The study site is located near Pilgrimstad in Jämtland, central Sweden (Fig. 1) and is situated in an abandoned gravel pit located at the edge of a valley floor. Most of the previously described sections have been mined or covered by colluvium or fill. A small hill in the southern part of the pit was the focus of our excavation (Fig. 2). The top (including the till cover) had been removed previously, and for a short time the section had been covered by blast stone (J. Lundqvist, pers. comm. 2007). Thus, we adjusted the sample depths by adding 1 m, corresponding to the general till thickness in the area. The position of the investigated section is 62°57.5′N, 15°01.1′E and its elevation 300 m a.s.l., as measured by a Garmin GPS Vista C and checked against topographic maps.

The beds in the excavated section were correlated to the stratigraphies presented by Kulling (1945) and Robertsson (1988b). Robertsson's original section was situated adjacent to and at right angles to our new section; her stratigraphy is therefore best comparable to the new stratigraphy.

Methods

Sampling, preparation and measurement

Fieldwork was conducted in September 2006 and in July 2007. Five OSL samples were collected during each campaign at the levels marked in Fig. 3 (see also Table 1). The samples were taken in opaque plastic tubes and stored in black bags until opened under darkroom

Table 1. Pilgrimstad OSL sample properties and settings. Listed in order of sample number. For lithofacies codes and stratigraphic unit numbers, see Fig. 3.

Sample	Sampling depth* (m)	Stratigraphic unit	Lithofacies code	Water content (weight %)				Organic content (%)
				w_1	w_2	w_3	w	
061344	1.2	G	Sm	30	29.5	9.1	28	2.2
061345	1.8	H	SiSm	30	29.4	5.2	27	3.9
061346	2.4	F	SGy	150	41.9	16.9	72	9.1
061347	2.9	H	Sm/Sl	40	35.7	8.5	34	2.0
061348	3.1	H	Sm/Sl	35	32.8	8.0	31	1.9
081318	0.5	H	SiSm	35	32.8	5.5	31	1.4
081319	0.5	G	SiSl	40	38.0	4.9	35	1.4
081320	2.1	H	Sm	35	34.6	3.8	32	1.2
081321	4.1	C	GySb	35	34.2	9.0	32	1.1
081322	6.3	A	Sm(ng)	35	32.7	6.2	31	2.7

*Depth used in calculation was sampling depth plus 1 m; see text for explanation.

conditions at Stockholm University (2006) and the Norwegian University of Life Sciences (2007), where the initial preparation was completed. Final preparation, including heavy liquid separation (2.62 g/cm^3) to remove feldspars (081318–22 only), treatment with 10% HCl for 5–30 min, 10% H_2O_2 for 15–30 min, 38% HF for 60–120 min and 10% HCl again for 40 min, was done at the Nordic Laboratory for Luminescence Dating, where the OSL measurements were also undertaken.

The samples were analysed using large aliquots of quartz (180–250 μm) on Risø TL/OSL readers equipped with calibrated ^{90}Sr/^{90}Y beta radiation sources (dose rate 0.14–0.35 Gy/s), blue (470±30 nm; ~ 50 mW/cm^2) and infrared (880 nm, ~100 mW/cm^2) light sources, and detection was through 7 mm of U340 glass filter (Bøtter-Jensen *et al.* 2000). Analyses employed post-IR blue SAR protocols (Murray & Wintle 2000, 2003; Banerjee *et al.* 2001) adapted to suit the samples based on dose recovery and preheat experiments (first batch: preheat 260 °C for 10 s, cut-heat 220 °C; second batch 240°/200 °C). A relatively high test-dose (~50 Gy) was necessary to obtain a statistically precise test signal, and 100 s of illumination at 280 °C between cycles improved recuperation (response to zero dose).

We calculated the dose rates from gamma spectrometry data (Murray *et al.* 1987) (Table 2) and included the cosmic ray contribution (Prescott & Hutton 1994). Natural and saturated water content was measured with pF rings (cylinder volumeters) (Table 1). To account for water content changes through time due mainly to compaction, especially for the organic-rich sediments, we applied a simple three-stage model to all our samples (Table 3). The mean water content ($\bar{w}$) since time of deposition was then calculated as:

$$\bar{w} = w_1 \cdot t_1 + w_2 \cdot t_2 + w_3 \cdot t_3 \tag{1}$$

Two samples were collected for radiocarbon dating. Small twigs (unknown species) were picked out and dated by AMS ^{14}C at the Lund University Radiocarbon Dating Laboratory.

Data analysis

Simple component analysis of the continuous wave OSL data from some aliquots was undertaken using SigmaPlot 10.0 based on the parameters and formulas of Choi *et al.* (2006). The results of the component analysis are discussed further below (Fig. 4), but based on such information from dose recovery measurements (Fig. 5) we chose channels 1–2 (first 0.16 s) and channels 4–6 (0.32–0.56 s) as peak and background integration limits for all aliquots. The equivalent doses were then calculated in Risø Luminescence Analyst 3.24 (exponential curve fitting) and in Microsoft Excel. To be accepted, aliquots had to pass the following rejection criteria: recycling ratio within 20% of unity, recuperation <5%, equivalent dose error <50% and signal more than 3σ above the background. Decay and growth curves also had to be regular. Ages were calculated using the mean and median of the equivalent dose population of accepted aliquots for each sample, as well as using the natural and saturated water contents.

We also did a sensitivity analysis to determine quantitatively which uncertainties have the largest effect on age. Ages were recalculated after adjustments were made to each of the parameters in turn, using reasonable estimates of uncertainty for each parameter. The estimated uncertainties (1 SD) used in these calculations were: depth below surface ±1 m, elevation ±50 m, grain size ±10%, water content (gamma and beta) ±10%, dose rate gamma ±5%, dose rate beta ±5%, internal dose rate ±30%, density ±10%, cosmic ray contribution ±5% and beta source calibration ±2%.

Results

Sedimentology and stratigraphy

We distinguished eight units in the new section at Pilgrimstad (shown and briefly described in Figs 2 and 3).

Table 2. Summary of radionuclide concentrations measured with high-resolution gamma spectrometry on the Pilgrimstad OSL samples. Beta and gamma dose rates refer to dry material; for water contents and final dose rates, see Tables 1 and 3.

Sample	^{238}U (Bq/kg)	^{226}Ra (Bq/kg)	^{232}Th (Bq/kg)	^{40}K (Bq/kg)	Beta (Gy/ka)	Gamma (Gy/ka)
061344	39±6	42.1±0.7	35.4±0.7	642±12	2.18±0.04	1.25±0.04
061345	34±5	42.8±0.6	34.7±0.5	668±9	2.14±0.04	1.15±0.04
061346	178±10	100.8±1.2	45±0.9	675±13	3.19±0.07	1.84±0.09
061347	33±5	49.1±0.7	37±0.5	715±10	2.38±0.04	1.37±0.04
061348	28±3	48.5±0.5	37±0.4	716±7	2.36±0.03	1.36±0.04
081318	40±8	40.2±0.8	34.3±0.8	663±15	2.22±0.05	1.24±0.04
081319	27±6	38.5±0.7	33.2±0.7	670±12	2.17±0.04	1.21±0.03
081320	29±5	31.9±0.5	30.7±0.5	680±12	2.15±0.04	1.14±0.03
081321	41±10	100.3±1.3	35.1±0.9	649±15	2.50±0.07	1.65±0.09
081322	42±7	74.4±0.9	30.7±0.7	614±11	2.26±0.05	1.39±0.06

Table 3. Water-content modelling to calculate average water content since the time of deposition, accounting for compaction and environmental changes. For values, see Table 1.

Assumptions	Three-stage hydrological evolution
The sediments have never been drier than at the time of sampling, and the natural water content is a minimum water content. (The samples were taken within a large gravel pit in which the groundwater table has been lowered.) The saturated water content is the maximum water content for the sediments in their present state. (It is limited by porosity.) The porosity of minerogenic sediments did not change significantly with compaction. Most of the compaction took place early in the sediments' history due to continued sedimentation and, later, pressure from the ice cover.	1. Lake/fluvial stage before the ice advance (sediments loose and saturated). (a) Water content w_1 is the saturated value rounded up to the nearest 5 or 0 for minerogenic samples and an assumed value of 150% for the organic sample (061346), derived from young samples with similar organic content. (b) Duration is ~30% of the time since deposition ($t_1 = 0.3$). 2. Ice cover (sediments compacted and saturated). (a) Water content w_2 is the saturated value. (b) Duration is ~60% of the time since deposition ($t_2 = 0.6$). 3. After deglaciation (sediments compacted and drier). (a) Water content w_3 is the natural value. (b) Duration is ~10% of the time since deposition ($t_3 = 0.1$).

The sediments have been tectonized, as indicated by brecciation and deformation structures. Within the limited exposure available to us, the sediments nevertheless seem to have a pancake stratigraphy, with the exception of unit H, which cuts units E, F and G.

Unit A in the new section correlates with the 'limestone-rich pebbly gravel series' of Kulling (1945), while units B–H correspond to his 'silt-stratified sand series'. We interpret these sediments as showing an environmental succession from glacifluvial (unit A) to glacilacustrine (unit B) to lacustrine (units C, D, E, F) and back to fluvial or glacifluvial (unit G), in line with previous interpretations. The sandy unit H might represent the aeolian sand of Robertsson (1988a, b). However, the cross-cutting relationship with the other units indicates formation after the deposition of units F and G, and suggests a possible glacitectonic rather than aeolian genesis. We therefore interpret unit H as a clastic dyke formed subglacially during the Late Weichselian ice advance (cf. Larsen & Mangerud 1992; Lindén *et al.* 2008). The sand is thus likely reworked sand from unit G, and the gyttja clasts are rip-ups from the surrounding beds. This has implications for the interpretation of the organic beds as belonging to one or two events, and for the ages of unit H, as discussed below.

OSL characteristics and ages

The major sample properties, settings and results are listed in Tables 1–3 and are shown in Figs 3 and 7. The quartz from Pilgrimstad is insensitive, which necessitated careful selection of peak and background channels to best isolate the fast component (Fig. 4). For the 21 accepted dose recovery experiments (out of 27), the average proportions of the net component signal to the total net signal used for dose calculation were 92±8% (fast), 8±7% (medium) and 0.2±0.3% (slow). When these channels were selected for peak and background integration, the resulting signal was dominated by the fast component. Doses calculated with this channel selection gave good dose recovery (1.05±0.04, $n = 21$) (Fig. 5) and demonstrated that the SAR protocols used were able accurately to recover a known dose administered before any heating. The signals were not close to saturation (Fig. 6).

Equivalent doses range between 89 and 145 Gy and dose rates between 2.5 and 3.1 Gy/ka (Table 4). The nine upper samples are 52–36 ka, while the lowermost is older (74 ka) (Table 4 and Fig. 7). OSL ages from unit H average 44±7 ka ($n = 5$), from unit G 41±3 ka ($n = 2$) and single ages from unit F and C are 48±8 ka and 46±3 ka, respectively. The sensitivity analysis

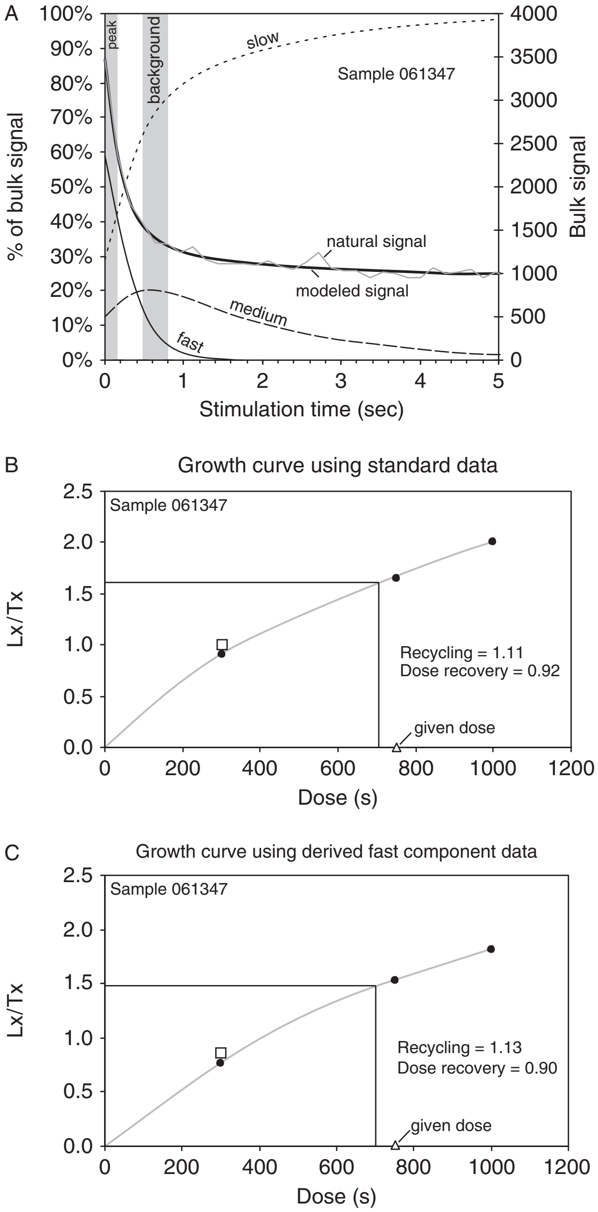


Fig. 4. Data derived from the 27 dose recovery experiments allowed selecting peak and background channels that provided the overall best recycling and dose recovery and a dominance of the fast component after background subtraction. A. Signal component analysis of sample 061347 showing the natural signal which was de-convoluted into fast, medium and slow components (left axis), and the natural and modelled (sum) signal (right axis). Also shown are the peak and background portions of the signal used (0–0.16 s and 0.32–0.56 s). Note that only the first 5 s of the total length of the stimulation (40 s) are shown. B. The upper growth curve uses the standard data (bulk signal) with the selected channels for the same aliquot. C. The lower growth curve is produced by using the derived (de-convoluted) fast component signal data only. The insignificant difference between the growth curves indicates that the channel selection effectively isolated the fast component and that the selection of peak and background channels provided the optimum recycling and dose recovery.

demonstrates that the calculated age is most sensitive to changes in the equivalent dose, beta source calibration and dose rate, followed by water content (Fig. 8).

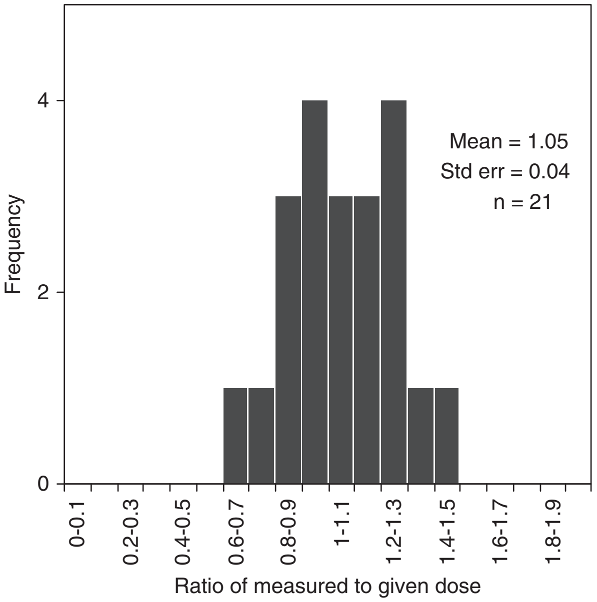


Fig. 5. Histogram of dose recovery tests, excluding aliquots that did not pass rejection criteria. A mean close to unity indicates that the samples can be used for OSL-dating with our analytical protocols.

New radiocarbon ages from twigs are 39.2±2 and >40 ^{14}C ka BP (Table 5).

Discussion

OSL and sediments

From a sedimentological perspective, we can identify two potential problems for OSL-dating at this site: (1) the glacifluvial deposit (unit A) may be incompletely bleached and (2) we cannot properly estimate the original mean water content of the relatively organic-rich unit F.

Incomplete bleaching results in an apparent age overestimation, and is fairly common in glacial settings (e.g. Fuchs & Owen 2008). As we have used only large aliquots for measurements, it is difficult to infer anything about incomplete bleaching from the dose distribution of sample 081322, which is from unit A. In combination with the stratigraphic position of unit A (lowest), we thus consider the OSL age from unit A as providing a maximum age for the overlying organic beds. The good correspondence of ages ($n = 9$) from all the other beds (derived from various depositional settings) suggests that there are no problems with incomplete bleaching for those.

Organic-rich deposits tend to be fairly loose at the time of deposition and may have very high water content, i.e. up to several hundred percent. With time they will become compacted due to sediment loading and the overriding ice sheet; the water content will change significantly, so that what is measured today is not representative of the mean water content since time of deposition (cf. Alexanderson *et al.* 2008). An underestimation of the mean water content results in OSL ages that appear too young, and vice versa. In our case, the OSL ages from the surrounding minerogenic beds can provide some constraints, since these sediments do not suffer to the same degree from water-content variations.

The sandy unit H is the youngest, since it cross-cuts units E, F and G. The OSL ages from unit H should thus be minimum ages for the organic deposits. However, as mentioned above, re-interpretation of the unit as a clastic dyke with remobilized material implies that the sand in unit H could be contemporaneous with unit G and that the OSL ages do not represent the timing of the formation of the dyke. It also implies that the separation into units E and F is secondary.

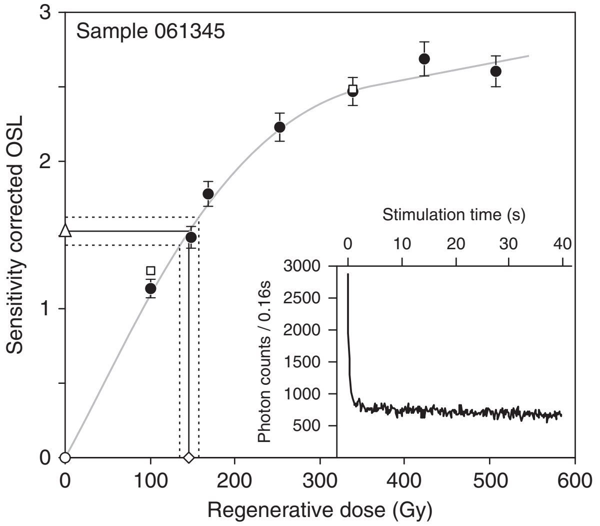


Fig. 6. Single-aliquot regenerative-dose (SAR) OSL growth curve for a single aliquot of sample 061345. The equivalent dose (ED) (open diamond) is obtained by interpolating the corrected natural signal (open triangle) on the growth curve. Repeated dose points (open squares) and a zero dose point (open circle) are also shown. (Inset) The natural decay curve.

Based on the stratigraphic information and on the OSL ages, we consider the OSL ages from units B to H as representing one event, while unit A is older. The OSL ages from units B–H are internally consistent, i.e. all lie in the range 52–36 ka, with a mean of 44±6 ka; this places the interstadial sediments in the Middle Weichselian (MIS 3; 58–24 ka). Taken at face value, the 74 ka age from unit A gives the timing of the preceding deglaciation, but we cannot rule out the possibility that the sediment suffers from some incomplete bleaching, and that the true deposition age is younger.

What is required to make these OSL ages older (MIS 5)?

To capture uncertainties in the ages conservatively, Fig. 7 and Table 4 show the OSL ages calculated under a variety of assumptions. Even when considering the broadest age range for each sample, all upper nine ages fall within the Middle Weichselian (MIS 3) and no reasonable adjustments in assumptions can collectively bring their ages to the Early Weichselian (MIS 5 a/c, > 74 ka). As the sensitivity analysis showed the calculated age to depend most on changes in the equivalent dose and various factors influencing the dose rate (Fig. 8), we tested what those factors would have to be to obtain ~90 ka ages from these samples. To get early Weichselian ages from the current data we would need to double the equivalent doses or half the dose rates; the latter for example by using water contents > 100% by weight, or a combination of these. We consider it unlikely that any of these parameters is in error to this degree.

Comparison with other chronologies and records

A mean age of 44±6 ka (n = 9) for the Pilgrimstad sediments agrees with the bulk of previous age determinations from the site, which fall between 60 and 45 ka

Table 4. Pilgrimstad OSL sample results and ages. Listed in order of sample number.

Sample	Age (ka)				Equivalent dose (Gy)	n	Dose rate (Gy/ka)	Recycling ratio
	Mean	Median	Dry[1]	Saturated[2]				
061344	43±5	37	36±4	43±5	116±12	18	2.72±0.10	1.14±0.24
061345	45±4	44	37±4	46±4	118±10	19	2.62±0.10	1.06±0.26
061346	48±8	49	32±5	39±7	134±23	18	2.82±0.09	1.06±0.31
061347	52±4	50	42±4	53±4	145±10	16	2.77±0.10	1.08±0.25
061348	49±4	49	40±3	50±4	139±10	22	2.83±0.10	1.03±0.20
081318	38±3	36	30±3	38±3	101±7	28	2.69±0.10	1.17±0.09
081319	39±3	34	29±3	40±3	97±7	31	2.51±0.09	1.07±0.12
081320	36±3	35	27±2	36±3	89±7	32	2.52±0.09	1.05±0.17
081321	46±3	44	37±3	47±3	143±6	30	3.10±0.13	1.10±0.12
081322	74±5	72	58±4	75±5	202±9	30	2.74±0.11	1.07±0.12

[1] Age calculated with water content at time of sampling.

[2] Age calculated with saturated water content.

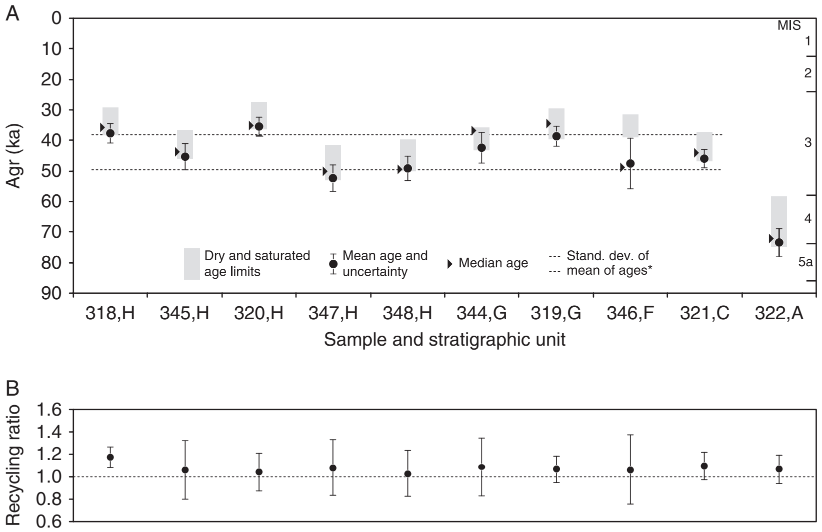


Fig. 7. A. Graphical summary of ages for all samples. B. Corresponding recycling ratios. OSL ages are shown in stratigraphic order with youngest ages to the left and oldest to the right. H–A refers to the stratigraphic units in Fig. 3. Age calculated from the population of accepted aliquots using the mean and median, and for natural water content at sampling (dry) and saturated water content (range shown by grey square). Error bars represent 1 SD. The SD of mean of ages excludes the older, stratigraphically lower sample (081)322. Note that the water content for organic-rich sample (061)346 has been adjusted to compensate for compression. Marine isotope stages (MIS) indicated on the right.

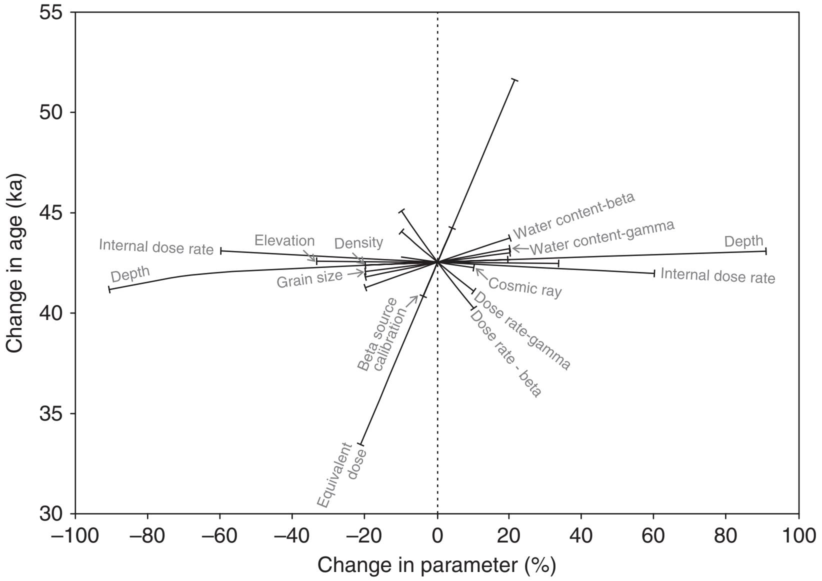


Fig. 8. Sensitivity analysis showing by how much the age will change (percentage change) in a given parameter for sample (061)344 (age = 43 ka). Steeper slopes indicate that the age is more sensitive to changes in the given parameter. The age is most sensitive to changes in the equivalent dose, beta source calibration and dose rate, followed by water content; very large changes in these parameters are needed to make the age consistent with MIS 5. The range of x-axis parameter values corresponds to our estimate of 2 SD in that parameter. Similar results were obtained for the other samples.

(Fig. 3) (Wohlfarth 2009). These radiocarbon dates are considered to be of acceptable quality, although close to the methodological limit (Wohlfarth 2009). The mean OSL age also agrees with the finite of our two AMS ^{14}C ages (39.2±2 ^{14}C ka BP; Table 5) and is not contradicted by the non-finite one.

Oxygen isotope curves from the Greenland Ice Sheet provide estimates of temperature variations during the Weichselian in the North Atlantic region (e.g. Johnsen *et al.* 2001). If the sediments at Pilgrimstad are of MIS 3 age, as the OSL and other ages suggest, we would expect a correlation with one of the warmest and/or longest interstadials during this time – with duration long enough to allow for the subarctic–arctic flora and fauna to become established. Taking the OSL ages at face value leads to a correlation with Greenland interstadials 12–10 (47–41 ka), but considering the uncertainties and the actual spread in ages, interstadials 17–10 are also possible options (cf. Walker *et al.* 1999).

This is in agreement with Wohlfarth (2009), who tentatively places the Pilgrimstad site within Greenland interstadials 17–12. Hättestrand (2008) proposes a similar age shift of the Tärendö II Interstadial in northern Sweden, i.e. from the Early Weichselian (MIS 5 a) to the Middle Weichselian (MIS 3). Our OSL data, from a critical location in the former central area of the ice sheet, thus support the documented ice-free conditions reported elsewhere in Fennoscandia during MIS 3 (e.g. Olsen *et al.* 2001; Arnold *et al.* 2002; Kjær *et al.* 2006; Helmens *et al.* 2007a, b; Ukkonen *et al.* 2007; Lunkka *et al.* 2008; Salonen *et al.* 2008) (see also Fig. 1).

Table 5. ^{14}C ages from twigs.

Sample	Stratigraphic unit	^{14}C age years BP
LuS 6957	F	39 200±2000
LuS 6958	E	>40 000

Implications for Weichselian history

Moving the age of the Pilgrimstad Interstadial from Early to Middle Weichselian (MIS 5 a/c to MIS 3) has implications for the understanding of glacial history and environmental change in Scandinavia during the Weichselian. An ice-free Pilgrimstad at ∼50–40 ka requires that the Scandinavian Ice Sheet at that time was restricted, possibly limited to the highest mountains (cf. Arnold *et al.* 2002), i.e. much smaller than previously believed (Lundqvist 2002; Mangerud 2004; Houmark-Nielsen 2007) (Fig. 1). It also implies that the ice sheet must have expanded rapidly thereafter to reach south-eastern Denmark just prior to 30 ka (the Klintholm advance; Houmark-Nielsen & Kjær 2003; Ukkonen *et al.* 2007).

Although the vegetation reconstruction for Pilgrimstad (Robertsson 1988b) still largely holds true, recent studies indicate that forest may not have been as close as suggested (Helmens *et al.* 2007a). Nevertheless, a reconciliation of the Pilgrimstad record with contemporaneous records of tundra in northern continental Europe (Behre 1989) requires alternative migration routes for vegetation, and/or possible tree refugia, during previous stadials and different climate gradients and conditions compared to today (e.g. Nilsson 1972: p. 225; Ukkonen *et al.* 2007).

Conclusions

- A new exposure at the Pilgrimstad site in central Sweden shows >4 m thick subtill minerogenic and organic sediments; these have been OSL-dated.
- The OSL ages from the lacustrine and fluvial sediments range from 52 to 36 ka, while the underlying glacifluvial deposit is probably younger than ∼74 ka.
- The OSL samples passed appropriate methodological checks and the ages are internally consistent. We therefore consider the results reliable.
- From sedimentological and chronological points of view, we favour deposition during a single but variable event, rather than two separate interstadials.
- The OSL ages assign the Pilgrimstad Interstadial site to MIS 3; the organic deposits could possibly correspond to one or more of Greenland interstadials 17–10.
- The central location of the site, together with results from other studies in Fennoscandia, indicates that for at least parts of MIS 3 the ice sheet was absent, or at least restricted to the highest Scandinavian mountains.

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Dissertations from the Department of Physical
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Late Quaternary ice sheet history and dynamics in central and southern Scandinavia

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Doctoral Thesis in Quaternary Geology at Stockholm University, Sweden 2010

Part of the key to predicting the future behaviour of the Earth is linked to our understanding of how ice sheets have operated in the past. Recent work suggests an emerging new paradigm for the Scandinavian ice sheet (SIS); one of a dynamically fluctuating ice sheet. This doctoral research project explicitly examines the history and dynamics of the SIS at four sites within Sweden and Norway, and provides results covering different time periods of glacial history. Two relatively new dating techniques are used to constrain the ice sheet history.

Dating of sub-till sediments in central Sweden and central Norway indicate ice-free conditions during times when it was previously inferred the sites were occupied by the SIS. Consistent exposure ages of boulders from the Vimmerby moraine in southern Sweden indicate that the southern margin of the SIS was at the Vimmerby moraine ~14 kyr ago. In central Sweden, consistent exposure ages for boulders at high elevation agree with previous estimates for the timing of deglaciation around 10 ka ago, and indicate rapid thinning of the SIS during deglaciation.

Altogether this research conducted in different areas, covering different time periods, and using comparative geochronological methods demonstrates that the SIS was highly dynamic and sensitive to environmental change.

I was born and raised on Vancouver Island on the west coast of Canada surrounded by beautiful mountains and coastline, where I developed a deep curiosity and passion for understanding the workings of nature. I completed a Bachelor of Science degree with distinction in Geography 1998 at the University of Victoria, Canada. Then I completed a Masters of Science degree in Geography 2004 at Simon Fraser University, Canada, for which I was awarded the Canadian Association of Geographers Starkey-Robinson Award 2005. I began a PhD in 2004 in Stockholm, Sweden investigating the dynamics of the Scandinavian ice sheet, and eating brown cheese with waffles under the midnight sun.

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