Reworked Middle Pleistocene deposits preserved in the core region of the Fennoscandian Ice Sheet

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1. Introduction

Northern Hemispheric continental interiors that were glaciated during successive Pleistocene ice ages are rarely associated with the preservation of pre-glacial and interglacial deposits much older than the latest glacial-interglacial cycle (e.g., Hägglund et al., 2012). A notable exception is Finnish Lapland on the Fennoscandian Shield which was located near the centre of successive Fennoscandian Ice Sheets (FIS) where permafrost was widespread and ice was cold-based, slow moving and of limited erosive potential. This has resulted in the widespread preservation of pre-glacial weathered bedrock regolith and landforms such as inselbergs and tors (Hall et al., 2013, 2015, Kleman, 1992, 1994), together with in situ pre-glacial placer gold deposits. These features have not survived in more peripheral areas of ice-sheet cover in Fennoscandia that were scoured by vigorous wet-based ice and fast-flowing ice streams (Boulton et al., 2001; Johansson et al., 2011; Hall et al., 2015).

Many sites where older pre-Weichselian sediments are preserved have been described to date (e.g., Lundqvist, 1971; Kleman et al., 1992; Lagerbeck, 1988a,b; Robertson, 1997; Mäkinen, 2005; Hättestrand and Robertsson, 2010; Hall and Ebert, 2013; Lunkka et al., 2015, Fig. 1) but good age control remains elusive. This is a key challenge because better understanding of the age and nature of the pre-Weichselian sedimentary record is a fundamental part of mineral exploration mapping programs across Lapland. In the 1970s the Geological Survey of Finland (GTK) systematically investigated the regional glacial stratigraphy of Lapland and first identified the occurrence of older sediments under and within
Weichselian tills (e.g., Hirvas et al., 1977; Hirvas, 1991; Johansson et al., 2011). During the investigations, some 1400 test pits were dug and examined, and in the process, 240 sites were identified where sub-Weichselian sediments are preserved with an additional 50 sub-till sites that preserve significant pre-Weichselian organic materials sub-till as peat. Other such sites are known from adjacent parts of Sweden, most prominently at Leveäniemi, Rissejaurat and Riipiharju (e.g., Lundqvist, 1971; Lagerbeck, 1988a,b; Robertson, 1997). They have been discovered more recently in the Kola Peninsula of Russia (Lunkka et al., 2018). The most significant discoveries to date have been made in Finnish Lapland, and data from this area is the foundation for current understanding of MIS 6–8 (Saalian) interglacial paleoenvironments occurring prior to the onset of Weichselian glaciation. The glaciation additionally known as the Saalian is a complex of stadials/interstadial and existed from around 300,000 to 130,000 years ago. In this article, we refer the sediments dated within this age range as Saalian. In this paper we use the old terminology that was available for earlier workers in Finnish Lapland. In order to clarify and avoid misunderstandings, we utilize modern Marine Isotope Stages (MIS) alongside the local data. Modern comparison between Finnish Lapland stratigraphy, NW European Pleistocene Stages after Hirvas (1991) and Marine Isotope Stages is given by Lunkka et al. (2015).

The contribution being reported herein is based on new field work at Aaltövittikot identified as one of the most important sites containing pre-Weichselian organic materials exposed in Finnish Lapland (Auri et al., 2008; Sarala, 2008, Fig. 1). This site had been previously described by Hirvas (1991) based on fieldwork done by Hirvas. This paper aims to help the understanding of the important terrestrial paleoenvironmental archive preserved at Aaltövittikot by describing the results of recent re-excavation and facies descriptions by GTK of the stratigraphy, sedimentology and age using optically stimulated luminescence (OSL) dating methods.

2. This paper

This paper commences with a brief overview of what is currently understood of the pre-Weichselian stratigraphic record of Finnish Lapland in order to provide a wider context for observations and interpretations at the Aaltövittikot site. While many organic-bearing deposits lying below Weichselian tills are known from the western (Salonen et al., 2014; Lunkka et al., 2015) and the eastern parts of Finnish Lapland (Helmens et al., 2000, 2007a), the application of OSL dating has been carried out at only 14 of the 9 sites including Aaltövittikot (Fig. 1). In this regard, the principal contribution of this paper is to describe the stratigraphy, sedimentology and report newly-derived OSL ages of facies exposed at the re-excavated Aaltövittikot site. The broader significance of these data is then discussed in the context of geochemical exploration programs across mineral-bearing Paleoproterozoic crystalline rocks of the Fennoscandian Shield that are covered by glacial sediments.

3. Overview of the pre-Weichselian paleoenvironmental record of Finnish Lapland

There are major uncertainties regarding the number and duration of pre-Weichselian cold and warm episodes recorded in the stratigraphy of northern Finland, the absolute ages of sub-till deposits, and how distant sites are precisely correlated (see recent reviews by Bøe et al., 2012 and Helmens et al., 2015). Currently, it is the case that several sites containing organic-bearing sub-Weichselian age sites in Lapland that had been previously reported as being of Holsteinian interglacial (MIS 11) in
age have been re-evaluated and organic-bearing sediments are now re-assigned to the younger Eemian interglacial. Key location for Holsteinian sediments is Naakenavaara. According to Hirvas (1991), the oldest pre-Weichselian sediments preserved anywhere in Lapland occur in the Kolari region at the Naakenavaara, Kittilä and Rautuvaara sites (Fig. 1). At the Naakenavaara site, peat rests on till of supposed Elsterian age. Pollen analysis had initially suggested a Holsteinian interglacial (MIS 11) palaeoenvironment (Hirvas and Eriksson, 1988; Hirvas, 1991), but recent re-investigation of stratified sediments above and below the peat using OSL-dating indicate a much younger Eemian age (MIS 5e) for the organics (Sarala, 2011, 2014). Based on the known sequence of glacialS and interglacials during the last 50 years ago, the tills and peats found were correlated with these glacials and interglacials in logical stratigraphical order. Gyttjas of the last (Eemian) interglacial (MIS 5e) age occur at Tepsankumpu in Kittilä (Saarnisto et al., 1999) and at Sivakkopalo in Kolari (Hirvas, 1991) and it is possible that ice free conditions occurred for a long period after Saalian glaciation prior to the Late Weichselian. Several sites indicate much of Lapland remained unglaciated during the earlier part of the Weichselian. Specifically, Helmens et al. (2000, 2007a) describe a key location at Sokli with buried tills (Till bed V-VI) occur beneath Holsteinian interglacial (MIS 11) peat using OSL-dating indicate a much younger Eemian age (MIS 5e) for the organics (Sarala et al., 1999) and at Naakenavaara site (Hirvas, 1991). It is still the case which the current till stratigraphy of Finnish Lapland is based on a key exposure at the abandoned mine site of Rautuvaara which shows as many as six distinct till beds (Hirvas et al., 1977; Hirvas, 1991; Salonen et al., 2014; Lukkka et al., 2015). According Hirvas’ previous studies and interpretations of the stratigraphy, the lowermost two tills (Till Beds V-VI) occur beneath Holsteinian interglacial (MIS 11) peat beds (see Hirvas and Eriksson, 1988) and thus represent Elsterian or even pre-Elsterian glacial (MIS 12) deposits with overlying till beds deposited successively during Saalian (MIS 6–8) (Till bed IV) and Weichselian glaciations (MIS 5d, 2–5b) (Till bed III-I) (cf. Hirvas and Nenonen, 1987; Hirvas, 1991). This interpretation has however been recently disputed by Lukkka et al. (2015) who argue that the lowest two till units in Rautuvaara are most likely are of Saalian (MIS 6–8) age, and that all other overlying till units are of Weichselian age. The major limitation on understanding the paleo-glaciological significance of these deposits is once again, the lack of adequate dating control. Salonen et al. (2014) also noted that the till unit at Rautuvaara by Hirvas was previously designated as Till bed VI is sedimentologically and compositionally comparable to Weichselian tills at the nearby Hannukainen exposure which is only 5 km distant from Rautuvaara. Another issue here is that much previous work simply assumed that multiple tills recorded multiple glaciations and could be assigned to various glacial stages simply based on ‘count from the top’ assumptions. Today there is greater recognition of stratigraphic and lithofacies complexity arising from single glacial depositional events and the resulting deposition of complex till stratigraphies. These concerns prompted re-examination of the Aältövittikot study site by GTK to permit new descriptions and analysis of the stratigraphy and absolute-age dating using OSL methods. What follows is a brief description of the physical setting of the site and the field and laboratory methods that were conducted.

4. Aältövittikot site

Recent re-evaluation of sub-till stratified sediment deposits with an emphasis on updating the geochronological database of GTK led to re-exca-vation of sub-till sediments described previously at Aältövittikot by Hirvas (1991). The site is situated in central Finnish Lapland and lies at 256 m above sea level just below tree line on the highest point of the hill Kuusilomavaara. The bedrock is depicted by palaeoproterozoic crystallines of the Central Lapland greenstone belt, the Koitelainen layered gabbro intrusion and the Nattanen granite intrusion. The site consists of a 140 m long and 50 m wide gravel pit used for construction of the road from Ivalo-Sodankylä to Lokka (Fig. 2). It is located in an area of low-relief bedrock topography masked by a sporadic but locally thick Pleistocene sediment cover. Deeply weathered bedrock is extensive and tors are frequent on the high ground (see Hirvas, 1991; Hall et al., 2015). The Aältövittikot excavation occurs in a low elongated topographic mound oriented transverse to known Weichselian ice flow directions. The precise origin of the present landform is unclear from its geomor-phology though it is possible that it is a poorly-developed ribbed moraine similar to those that occur in the vicinity of the pit. Streamlined bedforms (drumlins) occur 10 km to the southeast of the site i.e., further down flow (Fig. 2) toward the onset zone of the Salla ice stream and are indicative of faster ice flow velocities (see Discussion below).

5. Field methods

Sediments at Aáltövittikot were systematically excavated along the southern and eastern side walls of the existing aggregate pit. Sections range in height from 3 to 7 m (Fig. 3). Underlying bedrock was not reached. Sedimentary facies were logged at nine stations using the methodology and lithofacies coding system described by Eyles et al. (1983) and widely used by glacial sedimentologists. This detailed work
allowed construction of a series of vertical lithofacies profiles and the drawing of a summary stratigraphic panel showing the distribution of facies around the pit walls (Fig. 3). Facies descriptions were supplemented by analysis of pebble ‘fabric’ together with detailed mapping of glaciotectonic deformation structures in tills and underlying sediments in order to assess former ice flow directions. Clast fabric data (Fig. 4B) is portrayed similarly Hirvas did for comparison. During this work, it became apparent that there are significant differences with the stratigraphy and interpretations reported previously by Hirvas (1991) and recorded in archived GTK Field Notes (1975–1977), underscoring the importance of re-excavation, sediment logging and new OSL age dating.

OSL samples were collected manually from sidewall exposures using black plastic tubes driven horizontally into cleaned sections from the stratified sand deposit lying below till and collected above the water table. Sorted medium to fine-grained sand expected to be well-bleached by exposure during deposition were selected. The field water content of the samples was measured by weighing samples before and after heating at 110 °C for 12 h before transport to the laboratory. Furthermore, two OSL dating samples were collected from boreholes drilled using percussion drilling method.

6. Laboratory methods

OSL samples were submitted to the Nordic Laboratory for Luminescence Dating (NLL, Aarhus University) based at Risø DTU, Denmark (5 samples; Risø 07 34 14, Risø 07 34 15, Risø 07 34 16, Risø 09 34 04 and Risø 10 34 04) and to the Dating Laboratory of the University of Helsinki, Finland (Hel-TL04181 and Hel-TL04201). In both laboratories, the methodology was the same, and quartz equivalent doses were estimated using a Single Aliquot Regenerated (SAR) dose protocol (Murray and Wintle, 2000, 2003) with a preheat of 10 s at 260 °C, cut heat of 220 °C, blue LED (470 ± 30 nm; 50 mW cm⁻²) stimulation with the sample held at 125 °C, and irradiation using a calibrated 90Sr/90Y beta source. Gamma and beta dose rates were derived from high resolution gamma spectrometry (Murray et al., 1987), and cosmic ray dose rates were calculated following Prescott and Hutton (1994). Dose recovery experiments were undertaken at the NLL, in which aliquots of 5 samples were bleached twice at room temperature using blue diode light, with a 10 ks pause between the two stimulations. The aliquots were then given a known beta dose, and this dose was measured in the usual manner. The average ratio of the measured to given dose was 1.01 ± 0.03 (n = 18) confirming that the SAR protocol of Murray and Wintle (2000, 2003)
Fig. 4. A, B. Clast fabric data from unpublished field notes stored in the GTK’s database and from this study of the Weichselian till at Aaitoivistikot identifying a south-eastward direction of ice flow recorded in tills resting on Saalian deposits. OSL sample locations are also indicated in the sidewalls.
used in this study is able to accurately measure a known dose given before any thermal treatment. The list of the OSL dates in the Aältovittikot site is presented in Table 1 and Fig. 4A.

7. Results

The stratigraphy exposed at Aältovittikot is characterized by highly variable sediments described in Figs. 3 and 4. A total height of the Quaternary sediment sequence is 10–11 m, of which 3–4 m is exposed on the walls of old aggregate pit. The deepest part of the sediments were examined both from excavated side walls and from a continuous percussion drilling sample. In the borehole, the lowest unit is composed matrix supported sandy diamicton (Unit I) resting directly on the weathered bedrock surface. Above the diamicton a horizontally-laminated deformed sand unit (Unit II) yield an OSL age of 46/6 ka. Rest of the drill core is composed of diamicton (Unit III) and gravel (Unit IV) that is described in detail in the side walls presentation below.

In the excavated sections, the lowermost fine-grained lithostratigraphic unit (Unit II) consisting of laminated silts (facies Fl) and ripple cross-laminated sand (facies Sr) typical of a lacustrine basin subject to sporadic variation in sediment supply. The presence of sporadically-deposited lacustrine sediments on the highest point of hill Kuusilomavaara indicates ponding by ice. The upper part of Unit II is disturbed by glaciotectonic deformations that occur immediately below the base of a sand-rich and grey coloured till that is predominantly massive and structureless (facies Dmm; Eyles et al., 1983). The same till unit in the southeastern part of the pit is crudely stratified (facies Dms) because of the presence of numerous rafts of complexly fractured and folded lacustrine rippled cross-laminated sand and silt facies; these are clearly the same facies that occur under the till. These rafts similarly yielded OSL dates of 218/6 12 ka, 225/6 17 ka consistent with an mid Saalian age recorded by the well-preserved deposits below 218/6 15 ka (Unit II).

Shear planes within glaciotectonized Saalian sands indicate ductile and simple shear resulting from compression (and thus ice flow) from NW to SE, which is confirmed by analysis of the orientation of the a-axis of ~50 prolate pebbles in the overlying till (Fig. 4B). Structural mapping of deformed sands (Figs. 5 and 6) shows a complex system of brittle shear fractures, consisting of SE-dipping primary listric shear fractures with co-sets of secondary syn- as well as antithetic shear fractures. Downward movement of hanging wall segments with off-sets of up to 10 cm indicate

| Lab. no. | Field | Depth (m) | W.c. (%) | Age (ka) | Paleodose (Gy) | Dose rate (Gy/ka) | n |
|---------|-------|-----------|----------|----------|---------------|------------------|---|
| Risø07 34 14 | KUUSSI 1.1 | 2 | 7 | 218 ± 12 | 342 ± 9 | 1.57 ± 0.07 | 25 |
| Risø07 34 15 | KUUSSI 1.2 | 2 | 11 | 225 ± 17 | 399 ± 22 | 1.77 ± 0.08 | 27 |
| Risø07 34 16 | KUUSSI 4.1 | 4.5 | 9 | 218 ± 15 | 381 ± 19 | 1.75 ± 0.08 | 26 |
| Risø09 34 04 | KUUSSI 1.3 | 2.5 | 2 | 235 ± 17 | 567 ± 30 | 2.41 ± 0.11 | 28 |
| Hel-TL04181 | KUUSSI 1.4 | 2.5 | 20 | 190 ± 18.6 | 382 ± 32 | 2.01 ± 0.15 | 6 |
| Risø10 34 04 | RUOSSELKA R1 | 4.50 | 20 | 46 ± 6 | 113 ± 12 | 2.44 ± 0.10 | 26 |
| Hel-TL04201 | RUOSSELKA R2 | 5.25 | 20 | 81 ± 26.3 | 175 ± 53 | 2.17 ± 0.20 | 12 |

Fig. 5. A–C. Glaciotectonic structures in the Saalian sediments at vertical profile #7 (Fig. 3) recording ductile and simple shear conditions consistent with ice flow to the southeast as indicated by clast fabric data (Fig. 4). a) Overview of grey till subunits seen at vertical profile #7. b) Close-up of upper subunit of grey till showing P, R and Y type shears as part of a northwest-dipping sinistral deformation zone (shear zone boundaries indicated by dashed black lines). The sinistral and reverse sense of movement along the shear planes results in the sigmoidal shape of grey coloured sand/silt inclusions.
thermic shear fractures. The downward movement of hanging wall segments with offsets of up to 10 cm, indicates normal fault movement along the shear fractures in the direction of ice flow.

Panel c) shows the complex system of brittle shear fractures, consisting of SE-dipping listric shear fractures (primary) and sets of secondary syn-as well as anti-Saalian Stage (Table 1; Fig. 4A; B old i.e., identifying that they likely bleached during some part of the dating of sand (Unit V) indicates an age of 235 ka (Table 1).

The sediment sequence at Ääntöjävittikot is formed of complex of 6–7 glacigenic and/or lacustrine/glaciofluvial, glaciotectonic units. The agreement of NW to SE ice flow direction, glaciotectonic deformations and pebble fabrics for the thick till (Unit II) containing rafts of Saalian deposits suggests that the entire succession of glacial (tills) and proglacial sediments (outwash) that rest on early/middle Weichselian deposits at Ääntöjävittikot are all Weichselian age. The southeasterly ice flow direction recorded in both overlying tills (Fig. 4A and B, 5, 6) is fully consistent with what is known of the overall regional pattern of ice flow during ice sheet build up and decay in Lapland and the emerging history of the Salla Ice Stream (e.g., Hirvas, 1991; Johansson et al., 2011; Lunkka et al., 2015; Putkinen et al., 2017).

In the borehole that was drilled on bottom of the quarry, 10 m north from section 7, horizontally-laminated sands below the grey till (Unit III) yield an OSL age of 46 ± 6 ka indicating deposition during the Weichselian age for overlying units. Based on stratigraphical interpretation, it seems to be the case that the drilled sands belong to the same unit which was observed in the excavated sections 7 and 8. However, having the totally different ages (225–218 ka vs. 46 ka) may lead to speculation about the presence of separate stratified unit inside or on top of the lowermost till (Unit I). This sand unit represents Middle Weichselian stage that was reported in many targets in northern Finland (e.g., Helmens et al., 2007b; Alexanderson et al., 2008; Sarala et al., 2010, 2016; Sarala and Patisson, 2011; Sarala and Eskola, 2011; Howett et al., 2015). Based on partly disturbed borehole core an exact estimation of the original position of the horizontally-laminated sands is dubious.

Above, the Unit V on the top of the Ääntöjävittikot sediment sequence has been demonstrated to be Saalian age. However, at present stratigraphy position and sedimentary environment interpretation of the topmost units (Units IV–VI), Unit V material must be completely subglacially reworked and redeposited consisting of old, incompletely bleached material originally belonged to the Unit II. A similar analogy for old sediment redeposition can be found in Rautuvaara, western Finnish Lapland, were the oldest sands (171 ka) exists on the top of 25 m thick glacigenic sediment complex (cf. Lunkka et al., 2015). However,
Saalian-aged sediment data deposited in an ice marginal lake presented here is favourable for OSL dating, even though these ages are within the limits of the applicability of the method (Alexanderson et al., 2011). According to Alexanderson and Murray (2012) studies in this type depositional environment is well suited to the method.

8. Discussion

MIS 7 sediments age reported herein from Älätövittikot in Finnish Lapland are rarely preserved in terrestrial continental settings that experienced Middle Pleistocene glaciations (see reviews by Kukla, 2005; Böse et al., 2012). Alexanderson et al. (2011) report Saalian marine sediments (239 ± 17 ka and 196 ± 15 ka) from Svalbard; Rattas et al. (2010) described lacustrine sands and silts dated at 234 ± 14 ka and 231 ± 13 ka in Estonia. Saalian marine sediments as from the Belvedère interglacial complex on the Dutch-Belgian border area near Maastricht have OSL ages of 219 and 231 ka (de Warrimont, 2007), with comparable ages 231 ± 25, 220 ± 20 and 219 ± 21 ka reported from the Netherlands (Meijer and Cleveringa, 2009).

To date, there is only one other locality where Saalian Stage inter-till sand deposit was observed in Finland. It locates at Sihatuna, Tervola in southern Finnish Lapland and has been dated at 201 ± 16 ka using the OSL method (Auri et al., 2008). Consequently, an occurrence of older Saalian sediments below and within Weichselian tills at Älätövittikot have a great contribution to the debate on the limits of OSL dating methods, because the oldest OSL dates range between 235 ± 17 ka and 190 ± 19 ka in this target. The key factor in the preservation of Saalian deposits at Älätövittikot and other old deposits such as Naakenvaara, Rautuvaara and Sokli can be related to their paleoglaciological setting which is located in the central ice divide area of the FIS where ice flow velocities were much reduced and ice was possibly cold-based until final deglaciation thereby minimizing erosion of the underlying bed. Älätövittikot as well as Sokli are located just upstream of the onset zone of the south-eastward flowing Late Weichselian Salla ice lobe now recognized as an ice stream on the basis of newly mapped subglacial bedforms indicative of fast ice flow (glacial lineations: Putkinnen et al., 2017). The area thus lay under sluggish-flowing ice likely moving over permafrost upstream of more faster flowing erosive-based fast flowing ice that developed towards the wet-based margins of the ice sheet (Figs. 1 and 2). It is also noted that the preservation of pre-Weichselian sediments through the wide area is explained by ice-divide zone location in the central Lapland during successive glaciations.

The data presented herein in regard to the presence of older sub-till sediments below last glaciation tills has considerable practical importance for mineral exploration programs being presently conducted across the Fennoscandian Shield of northern Finland. Recent work by Törmänen et al. (2016) and others from GTK shows that the extensive Central Lapland Greystone Belt is highly favourable for komatiite-hosted Ni-Cu-PGE deposits enriched in platinum and palladium. There is also strong potential for REE and Au occurrences due to an intense chemical weathering of different types of rocks with suitable strong structural connection (Sarapää et al., 2013; Sarapää and Sarala, 2013). Much of the bedrock in the area however is covered by glacial sediments deposited under the central slow-moving parts of successive FIS where the potential for preserving older sediments would appear to be high. As is clearly evident at Älätövittikot, later overlying Weichselian tills are likely to have been derived to varying degrees from the glaciectonism and reworking of antecedent non-glacial sediments. The presence of older recycled material within younger tills complicate interpretation of till geochemistry and determination of glacial dispersal patterns in mineral exploration programs. Again, this underscores the need for further analysis of the likely geographic extent of such antecedent deposits across the central divide of FIS. Mapping of paleo-ice streams within the ice sheet (Putkinnen et al., 2017) is an important first step in constraining the geographic boundaries of those areas lying upstream of ice stream pathways and where antecedent sediments are likely to be preserved within Weichselian subglacial bedforms such as transverse (ribbed) moraines (Sarala, 2006).

9. Conclusions

Re-excavation of the Älätövittikot site in central Lapland previously reported in the early 1990’s and based on earlier field work in the 1970’s, has allowed new sedimentological description, paleoenvironmental analysis and age dating of Weichselian tills and inter- and sub-till deposits preserved within a transverse moraine hill composed of complex glacialic deposits. OSL dating of antecedent cross-laminated sand and laminated silt deposits indicates an mid Saalian Stage (MIS 7) age; they have been partially glaciectonized and incorporated as rafts into overlying Weichselian till. Preservation of old antecedent sediment at this site and others across the Fennoscandian Shield of central Lapland appears to be the result of their paleoglaciological setting; they are located under the innermost central portions of former Fennoscandian ice sheets where slow-moving cold-based ice prevented fast ice flow and glacial scour of older deposits and weathered bedrock. Incorporation and recycling of antecedent pre-Weichselian sediment into younger near-surface Weichselian tills as shown at Älätövittikot highlights the need for care in evaluating the results of provenance studies based on till geochemistry of Weichselian tills across this mineral-rich area of the Fennoscandian Shield.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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