

Timing of the deglaciation and the late-glacial vegetation development on the Pandivere Upland, North Estonia



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Abstract

In this study, the deglaciation chronology of the Pandivere Upland is defined, and the late-glacial vegetation trends of north-eastern Estonia are summarised. The multi-proxy study includes accelerated mass spectrometry ^{14}C dating, plant macrofossil, magnetic susceptibility, loss-on-ignition and grain-size distribution data of the lacustrine sediment record from one previously unpublished study site (Kursi), and the study discusses the results in combination with five previously published study locations from the area.

The results indicate that the deglaciation of the Pandivere Upland started at approximately 14 200 cal. yr BP and was completed by 13 800 cal. yr BP. The ice recession rate was approximately 180 m yr⁻¹. Based on these new radiocarbon dates, the Baltic Ice Lake stage A₁ submerged the northern and western ice-free areas of Estonia by ca. 13 800 cal. yr BP. The prevalent vegetation type in north-eastern Estonia during the late-glacial period was tundra with local variations in the dominant shrub species. The region remained treeless until the Holocene.

Keywords: deglaciation, lithology, chronology, plant macrofossils, North Estonia

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1. Introduction

Investigation of the spatial pattern and timing of the ice-sheet retreat of the last Scandinavian glaciation, as well as of the postglacial vegetation dynamics in Estonia, has a long history (e.g. Hausen, 1913; Thomson, 1929; Ramsay, 1929; Tammekann, 1938). Hausen (1913) showed that several marginal moraine chains were formed in front of the retreating ice margin, and Tammekann (1938) distinguished five ice-marginal belts (the Haanja, Otepää, Sakala, Pandivere and Palivere). This five-fold structure of ice retreat still holds true today. Ice-marginal belts mark standstills of the ice termini or small-scale readvances (Zelčs & Nartišs, 2014). To date these belts, different methods have been applied, such as optically stimulated luminescence (OSL), cosmogenic ^{10}Be exposure dating, varve chronology, conventional and Accelerator Mass Spectrometry (AMS) radiocarbon dating and pollen analyses (Pirrus, 1965; Pirrus & Raukas, 1996; Sandgren et al., 1997; Raukas, 2004; Raukas & Stankowski, 2005; Kalm, 2006, 2012; Kalm et al., 2011; Rosentau, 2006; Saarse et al., 2012; Lasberg & Kalm, 2013). However, the estimations of the time of the deglaciation vary notably by approach.

Studying varved clays in north-eastern Estonia, Rähni (1963) identified a spatially distributed marker horizon (a so-called drainage varve), and correlated it to an age of 12 080–12 050 years (Raukas et al., 1971). This assessment was considered for several years to be the calendar age of the Pandivere marginal formations (Raukas, 1986; Raukas & Karukäpp, 1993). In later publications Raukas (2009) suggested that ice retreated from Pandivere ca. 12 300 ^{14}C yr BP (calendar age ~14 100–14 300 cal. yr BP). This estimation is older than recently suggested (Kalm, 2012; Saarse et al., 2012; Lasberg & Kalm, 2013; Vassiljev & Saarse, 2013) and does not fit with ^{10}Be -based dates, which indicate that the Pandivere belt formed $13\,100 \pm 1100$ ^{10}Be years BP (Rinterknecht et al., 2006). The varved clay results and their correlation with the Neva ice marginal belt (Saarnisto & Saarinen, 2001) provide grounds for estimating the age of the Pandivere stadial at 12 700 varve years

(Hang, 1997), redefined to 13 300 varve years by Hang (2003) and later to more than 13 300 cal. yr BP (Hang & Kohv, 2013). Saarse et al. (2007) proposed that the proglacial lake A₁, a bay of the Baltic Ice Lake (BIL) formed between the retreating ice margin and the slope of the Pandivere Upland, is approximately 13 300 cal. yr BP old. However, recent AMS radiocarbon dates from the Haljala and Udriku sites (Fig. 1A) indicate ages over 500 years older than 13 300 cal. yr BP (Amon & Saarse, 2010; Saarse et al., 2012).

Despite the long history of palaeobotanical research in Estonia, it has been possible to build a realistic temporal framework to the late-glacial vegetation dynamics only during recent decades through the advances in radiocarbon dating technique. The local late-glacial minerogenic sediments contain very little, but sufficient, organic (terrestrial) material for AMS ^{14}C dating and palaeobotanical studies (e.g. Amon & Saarse, 2010; Amon et al., 2014). So far, the plant macrofossil data indicates that the late-glacial treeline was located in southern Estonia (Amon et al., 2014), but new sites in northern Estonia help to define the detailed dynamics of the treeless tundra.

In this paper, new lithological, palaeobotanical and AMS ^{14}C data from an overgrown Lake Kursi in Savalduma Bog are reported to determine the deglaciation of the Pandivere Upland with particular emphasis on the formation of the ice marginal belt and to describe the late-glacial local vegetation dynamics. For this purpose, the earlier studied and dated sites (Prossa, Räätsma, Äntu, Udriku, Haljala; Fig. 1A; Table 1) are also discussed.

2. Regional Setting and Study Sites

Pandivere is a plinth-type bedrock upland located between the Peipsi–Pihkva and West Estonian ice lobes (Karukäpp, 1997), also known as the Peipsi–Pskov and Võrtsjärv ice streams, respectively (Kalm, 2012). The upland has a carbonaceous bedrock core and thin Quaternary cover. The Pandivere belt was

formed during the ice margin termination at the upland slope and is marked in the east by kames, esker and moraine ridges, in the north mostly by glaciofluvial deltas and kames, and in the west by long chains of esker and moraine ridges. Lakes on the Pandivere Upland occupy basins in the bedrock depressions and hollows of the limestone outcrop, which in some cases were deepened by karst processes and fed by precipitation, inflow streams

and bottom springs. Many of the lakes have alkaline water and calcareous sediments (Saarse, 1994).

The Pandivere Upland is an important landform associated with the BIL stages (Rosentau et al., 2009; Vassiljev & Saarse, 2013). The highest shoreline of the BIL (stage A₁) formed at the same time as the Pandivere ice marginal zone and the following stage A₂ formed in the front of the next ice marginal zone, Palivere (Vassiljev & Saarse, 2013).

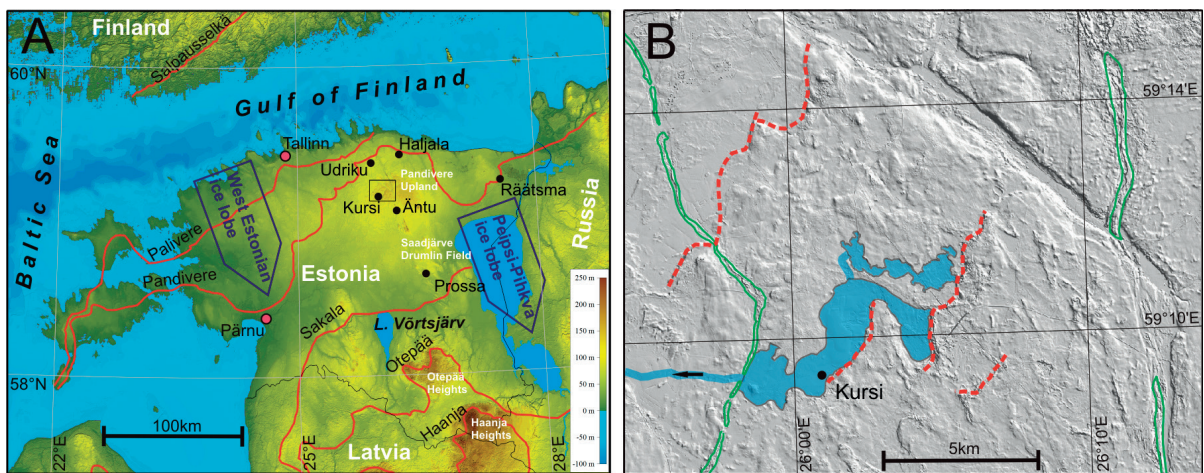


Fig. 1. Overview map of the study area (A) with ice-marginal belts (red lines) and ice lobes (blue arrows). The black rectangle marks the area shown on Fig. 1B. Shaded relief map shows the location of the coring site (black circle) at Lake Kursi (B). The red lines mark the ice contact slopes and the green lines eskers. The blue area indicates the approximate location of the local ice-dammed lake and the black arrow a possible outflow channel.

Table 1. The characteristics of the study sites.

Lakes beyond the Pandivere Upland					
	Coordinates	Size, ha	Depth, m	Height, m a.s.l.	References
Prossa	58°38'57"N, 26°34'40"E	24.2	5	61	Saarse & Kärson, 1982; Rõuk, 1987; Saarse, 1994; Rosentau et al., 2007; Kihno et al., 2011
Räätsma	59°14'16"N, 27°33'21"E	16.4	10.8	45	Saarse et al., 1985; Saarse, 1994
Lakes on Pandivere Upland					
	Coordinates	Size, ha	Depth, m	Height, m a.s.l.	References
Kursi	59°09'21"N 26°00'56"E	-	-	112	Veber, 1961, 1965; present study
Äntu (Sinijärv)	59°03'45.8"N 26°14'24.8"E	2.4	7.3	94.6	Saarse & Liiva, 1995; Sohar & Kalm, 2008, Laumets et al., 2014
Udriku (Suurjärv)	59°22'17"N, 25°55'50"E	23.7	6.8	95	Saarse, 1994; Amon & Saarse, 2010
Haljala paleolake	59°25'27"N, 26°17'42"E	-	-	67.4	Saarse et al., 2007, 2009

The present paper combines the chronologies of lakes beyond (Prossa and Räätsma) and on the Pandivere Upland (Kursi, Äntu, Udriku and Haljala) (Table 1). The previously unpublished study site, Kursi (59°09′21″N, 26°00′56″E), is located in the central part of the Pandivere Upland at the edge of the Savalduma Bog (Fig. 1), where karst is widespread. Limestone of the Tamsalu regional stage outcrops east of the lake, and along the outcrop is a steep cleavage filled with water (Fig. 1B). Lake Kursi is located at the edge of the ancient Porkuni ice-dammed lake whose water level reached 128 m a.s.l. (Rähni, 1961), with a threshold at 112 m a.s.l. (Öpik, 1937) (Fig. 1). The ice margin position during the existence of this glacial lake was reconstructed by Ramsay (1929) and Öpik (1937), but the timing was not determined. In this short-lived ice-dammed lake, up to 1-m-thick glaciolacustrine sediments were deposited. The pollen composition of the sediments was studied by Veber (1961, 1965), and an age was determined in this study based on four AMS ^{14}C dates (Table 2).

3. Materials and Methods

3.1. Coring and lithostratigraphy

Macrofossils, grain-size composition, loss-on-ignition (LOI), magnetic susceptibility (MS) and AMS radiocarbon dates were determined from the overlapping cores, which were extracted from Lake Kursi with a 1-m-long Russian peat sampler. The cores were described and photographed in the field, packed into plastic tubes, wrapped in polyethylene film, transported to the laboratory and stored in a cool room. One-centimetre-thick subsamples were taken continuously for LOI analyses, and 1-cm-thick samples were taken to measure the grain size distribution at 2-cm intervals. Bulk samples for LOI were weighted, dried at 105 °C overnight, and combusted at 525 and 900 °C to calculate

the water, organic matter (OM), carbonate and minerogenic (MM) content (Fig. 2). The grain size was analysed using a Horiba Instruments LA-950 V2 laser scattering particle size distribution analyser (Figs 3A, B). To avoid the effect of OM and carbonates, samples were pre-treated with 30% hydrogen peroxide (H_2O_2) and 10% HCl. Grain size classification follows the Udden-Wentworth scale (Last, 2001). MS was measured with a Bartington Instruments MS2E high-resolution surface scanning sensor at a resolution of 1 cm along carefully cleaned flat surfaces of fresh sediments covered by a thin plastic film.

3.2. Palaeoecological methods

Sediment samples for plant macrofossil analysis (80–200 cm^3) and AMS ^{14}C dating were soaked in water and sieved through a 0.2-mm mesh. The plant remains were identified under a binocular microscope. Pollen from the Lake Kursi core was analysed by Veber (1965), and the results are presented in Figure 4B. The LOI, plant macrofossil and pollen diagrams were plotted with the TILIA and TGView programmes (Grimm, 2011).

3.3. Chronology

The AMS radiocarbon ages were determined in the Poznan radiocarbon laboratory from the terrestrial macrofossils *Salix polaris*, *Dryas octopetala* leaves, and bulk gyttja (Table 2). The late-glacial chronostratigraphy is presented in calendar and ice-core years (Lowe et al., 2008) and all ^{14}C dates, including those previously published, were calibrated using IntCal13 calibration data set and Oxcal 4.2 software (Bronk-Ramsey, 2009). In the present study, calibrated ages (cal. yr BP relative to AD 1950) are used (Table 2). Radiocarbon dating from Lake Räätsma and one basal dating from Lake Äntu were performed in the Tartu Radiocarbon Laboratory (index TA).

Table 2. Radiocarbon dates of sites used in setting up deglaciation chronology.

Site name Depth, cm	¹⁴ C date	Radiocarbon lab. no.	Calibrated age (weighted average cal. yr BP)	Material dated	Reference
Lake Udriku					
745-750	10 590±60	Poz-30429	12 420-12 690	<i>Dryas</i> leaves	Amon & Saarse, 2010
768-773	11 240±100	Poz-36168	13 060-13 130	<i>Dryas</i> leaves	Amon & Saarse, 2010
798-803	11 890±80	Poz-30430	13 490-13 970	<i>Dryas</i> leaves	Amon & Saarse, 2010
813-818	12 090 ±80	Poz-36201	13 760-14 140	<i>Dryas</i> leaves	Amon & Saarse, 2010
Palaeolake Haljala					
310-315	11 780±60	Poz-22530	13 470-13 740	Plant remains	Saarse et al., 2009
410-415	11 750±80	Poz-22531	13 440-13 750	Plant remains	Saarse et al., 2009
Lake Äntu					
740-750	10 930±200	TA-2119	12 430-13 240	Plant remains	Saarse & Liiva, 1995
816	10 840±60	Poz-19684	12 670-12 830	Gyttja	Sohar & Kalm, 2008
720-723	10 960±70	Poz-25542	12 710-13 000	Wood	Laumets et al., 2014
Lake Räätsma					
530-540	12 040±100	TA-688	13 620-14 160	<i>Bryales</i> moss	Ilves, 1980
360-370	12 050±120	TA-686	13 580-14 210	Plant remains	Ilves, 1980
Lake Kursi					
258-259	9870±50	Poz-67317	11 200-11 400 (11 290±60)	Bulk gyttja	Current study
299-301	11 800±60	Poz-69661	13 480-13 750 (13 630±70)	<i>Dryas</i> leaves	Current study
307-309	11 970±70	Poz-69556	13 600-14 030 (13 830±110)	<i>Salix polaris</i> leaves	Current study
313-315	12 020±100	Poz-69557	13 600-14 120 (13 880±130)	<i>Salix polaris</i> leaves	Current study
Lake Prossa					
550-555	10 710±50	Poz-35466	12 580-12 730	Plant remains	Kihno et al., 2011
595-600	11 650±50	Poz-35467	13 380-13 580	Plant remains	Kihno et al., 2011
625-630	12 330±60	Poz-35468	14 080-14 700	Plant remains	Kihno et al., 2011
645-650	12 380±70	Poz-36169	14 110-14 850	Plant remains	Kihno et al., 2011

4. Results

4.1. Lithology

The litho-, bio- and chronostratigraphies of Prossa (Kihno et al., 2011), Räätsma (Saarse, 1994), Äntu (Saarse & Liiva, 1995; Laumets et al., 2014), Udriku (Saarse, 1994; Amon & Saarse, 2010) and Haljala (Saarse et al., 2009, 2012) have been previously published. In this study, we focus on the results of the Lake Kursi late-glacial sediments.

The basal unit in Lake Kursi is till (Table 3), which contains approximately 50% crystalline and carbonate clasts. OM accounts for 1% of the sediment, carbonates for 16%, and other mineral matter for 83% (Fig. 2). MS values reach up to 17×10^{-5} . The basal till is overlain by varved clay (333–316 cm) containing a total of 20 varves. The clay content is high, up to 60%, whereas the OM percentage is low, accounting for only 2–3%. The non-carbonate MM increases to 83%, whereas carbonates decrease from 30% to 14%, showing a reverse trend. At a core depth of 330 cm, MS has a clear peak of 90×10^{-5} . Varved clay is overlain by 0.5-cm-thick sand (316–315.5 cm) rich in plant remains and clayey silt with a rhythmic pattern (315.5–299 cm) rich in *Drepanocladus* moss fragments. In the overlying clayey silt, the OM content is low, accounting for 1–3% (Fig. 2). The sand fraction in the mineral portion of the sediment is 9–19%, the clay fraction fluctuates between 3% and 8%, and the silt fraction ranges from 75% and

87% (Fig. 3). The sandy silt at 299–283 cm differs from the underlying clayey silt with a massive texture, increased sand (19–33%) and OM (3–7%) content and decreased carbonate percentages (3–10%). In the next unit (283–259 cm), the sand fraction reaches 50%, clay is present sporadically at low values (0–3%), OM (mostly from water mosses) fluctuates between 4% and 13%, and carbonates decrease to 1–2% (Fig. 2). In gyttja (259–240 cm), OM rapidly reaches 60–70%. Late-glacial lithostratigraphy in Kursi is rather similar to that of the Saadjärv Drumlin Field lake sediments where varved clays are also overlain by silt-clay rhythmites, grey massive silt and greenish grey silt with water mosses (Rosentau et al., 2007).

4.2. Chronostratigraphy

Radiocarbon dates defining the deglaciation age of the Pandivere Upland and the formation of the ice-marginal belt are presented in Table 2. The basal till and varved clay of Kursi was barren of terrestrial macrofossils, containing only a few fragments of the water moss *Drepanocladus*. *Salix polaris* leaves were present in the laminated silt between 315.5 and 308 cm at core depths of 313–315 cm dated to 12020 ± 100 ^{14}C yr BP (13880 ± 130 cal. yr BP) and 307–309 cm dated to 11970 ± 70 ^{14}C yr BP (13830 ± 110 cal. yr BP). The silt between 307 and 299 cm mostly contained *Dryas octopetala* leaves, with the depth interval of 299–301 cm dated to 11800 ± 60 ^{14}C yr BP (13630 ± 70 cal. yr BP). One

Table 3. Sediment lithology of Lake Kursi.

Depth, cm	Sediment description
0–50	sod
50–259	gyttja, dark brown, unconsolidated
259–283	sandy silt, greenish grey, with dispersed OM
283–299	sandy silt, greenish grey, with <i>Drepanocladus</i> fragments
299–315.5	laminated clayey silt, greenish grey, between 308–315.5 cm rich in mosses
315.5–316	sand, grey, with plant remains
316–333	varved clay, brownish grey
333–335+	till, grey, rich in clast

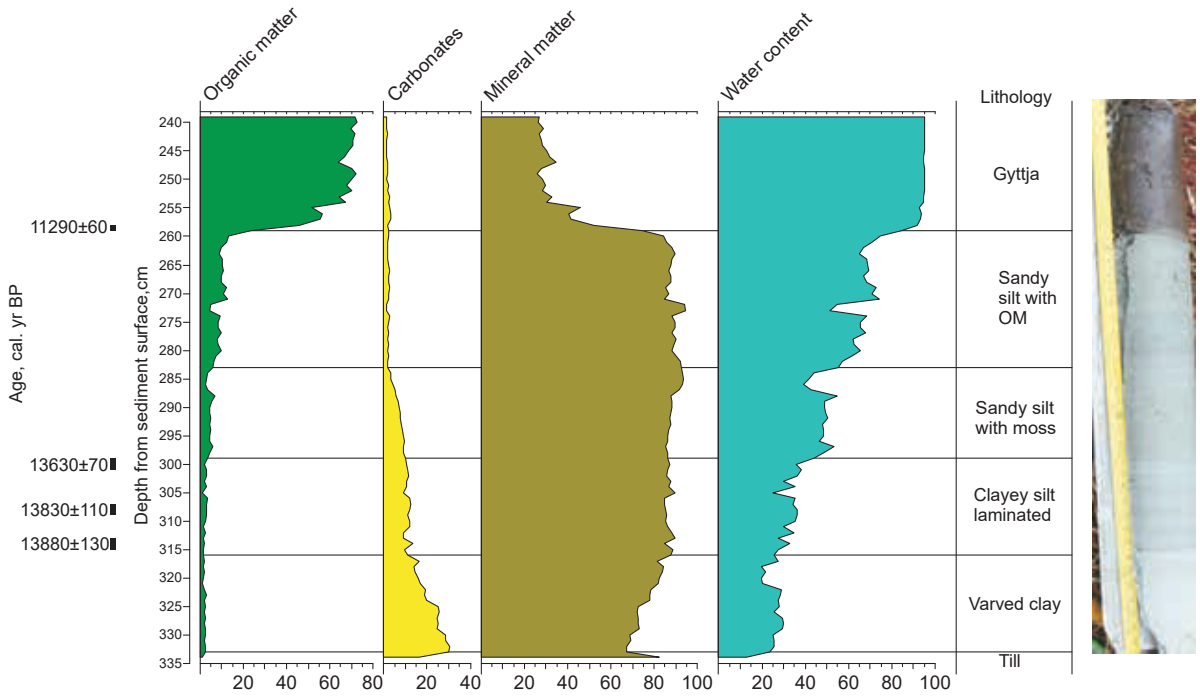


Fig. 2. Lithostratigraphy, loss-on-ignition (OM, MM and carbonates content), calibrated radiocarbon dates and a photograph of the Lake Kursi sediment core.

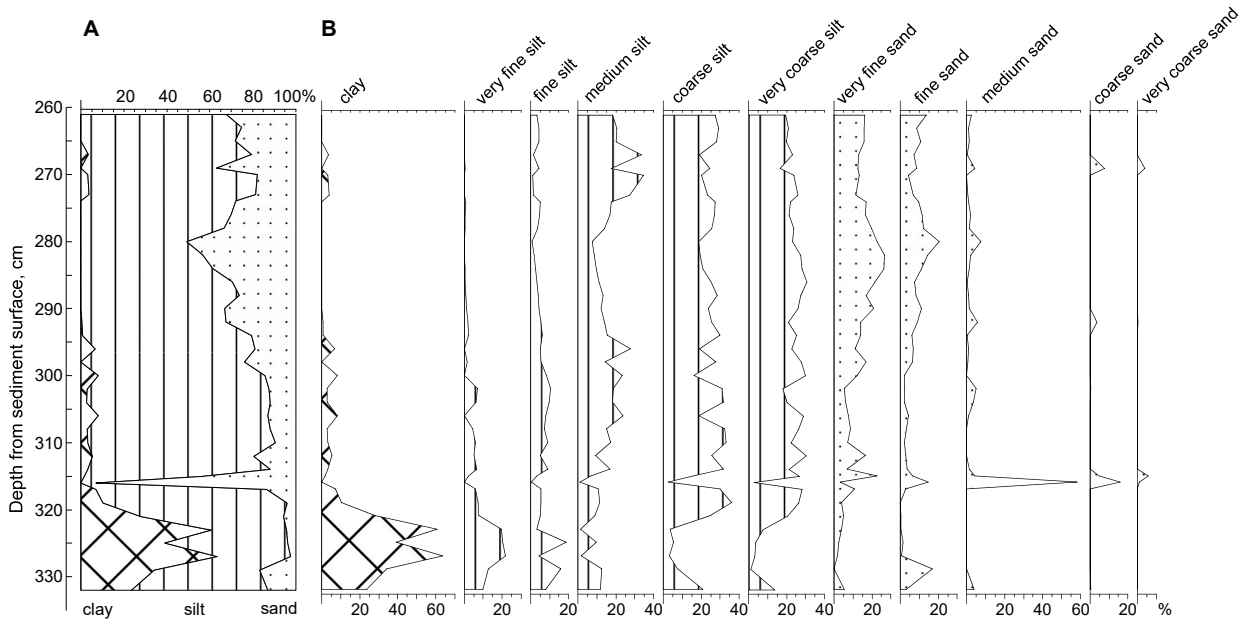


Fig. 3. Diagram showing grain size distribution characteristics of Lake Kursi late-glacial sediments (A) and the detailed grain size distribution of Lake Kursi late-glacial sediments (B).

bulk gyttja at 258–259 cm in contact with clayey strata was dated at 9870 ± 50 ^{14}C yr BP (11290 ± 60 cal. yr BP), which is a Holocene age. Based on the radiocarbon dates and the sediment thickness, the laminated clayey-silt (rhythmites) between 315.5 and 299 cm were deposited over 250 years at an average sedimentation rate of <0.7 mm yr $^{-1}$, and the silt between 299 and 259 cm was deposited over 2340 years at an average sedimentation rate of only <0.2 mm yr $^{-1}$. The low sedimentation rate, the sharp limit between organic and minerogenic sediments and the changes in pollen data obviously indicate a hiatus in the core.

It is important to stress that the AMS ^{14}C date of 13 880 cal. yr BP for Kursi (Table 2) reflects the age when the sedimentary basin was surrounded by vegetation that was deposited into the sediments and thus could be dated. The basal date does not include the age of the varved clays and thus reflects the onset of sedimentation with a delay. The only site where the varved clays contained *Salix polaris* leaves was Udriku, which was dated to 13950 ± 110 cal. yr BP.

4.3. Biostratigraphy

The basal part of the sediment of Lake Kursi, the varved clay, contained no terrestrial macrofossils. *Betula* and *Pinus* pollen are common, accounting for 26–33% and 18–33% of the total pollen, respectively (Veber, 1965, Fig. 4B) – however, the tree pollen grains are not local but were transported over long distances or partially reworked from older sediments.

Willow dwarf shrub (*Salix polaris*) macrofossils appear in the lower portion of the laminated silt (Fig. 4A) with occasional finds of different mosses (*Scorpidium* sp., *Calliergon* sp.). In the upper part of the same portion of sediment, the number of willow dwarf shrub macrofossils declines. Meanwhile, *Dryas octopetala* leaves appear from core depth 303 cm (~ 13700 cal. yr BP) to core depth 280 cm, where their numbers decrease. The other macrofossils found besides *Dryas* include water moss leaves, *Sphagnum*, different herbs (*Poaceae*,

Juncus spp., *Ranunculus* section *Batrachium*) and *Nitella* oospores. At core depth 280 cm, numerous dwarf birch remains are observed in one sample. The samples between depths of 280–260 cm are practically void of terrestrial plant macrofossils except for a fragment of *Dryas* leaf. The Younger Dryas silt in Kursi was characterized by only one pollen sample, in which *Betula* accounted for 1%, *Pinus* for 23%, *Picea* for 3%, and *Alnus* for 2% (Veber, 1965). Among NAP, the same taxa dominated as in the Allerød portion of the sediment, but the ratio of AP to NAP was slightly inclined (51%) towards NAP. Again, the tree pollen is a result of long distance transportation since plant macrofossil results clearly indicate that the local vegetation was typical of treeless tundra. At core depth 260 cm, the sediment type changes distinctively from silt to gyttja. The macrofossils found in gyttja belong to tree-birch and *Menyanthes trifoliata*.

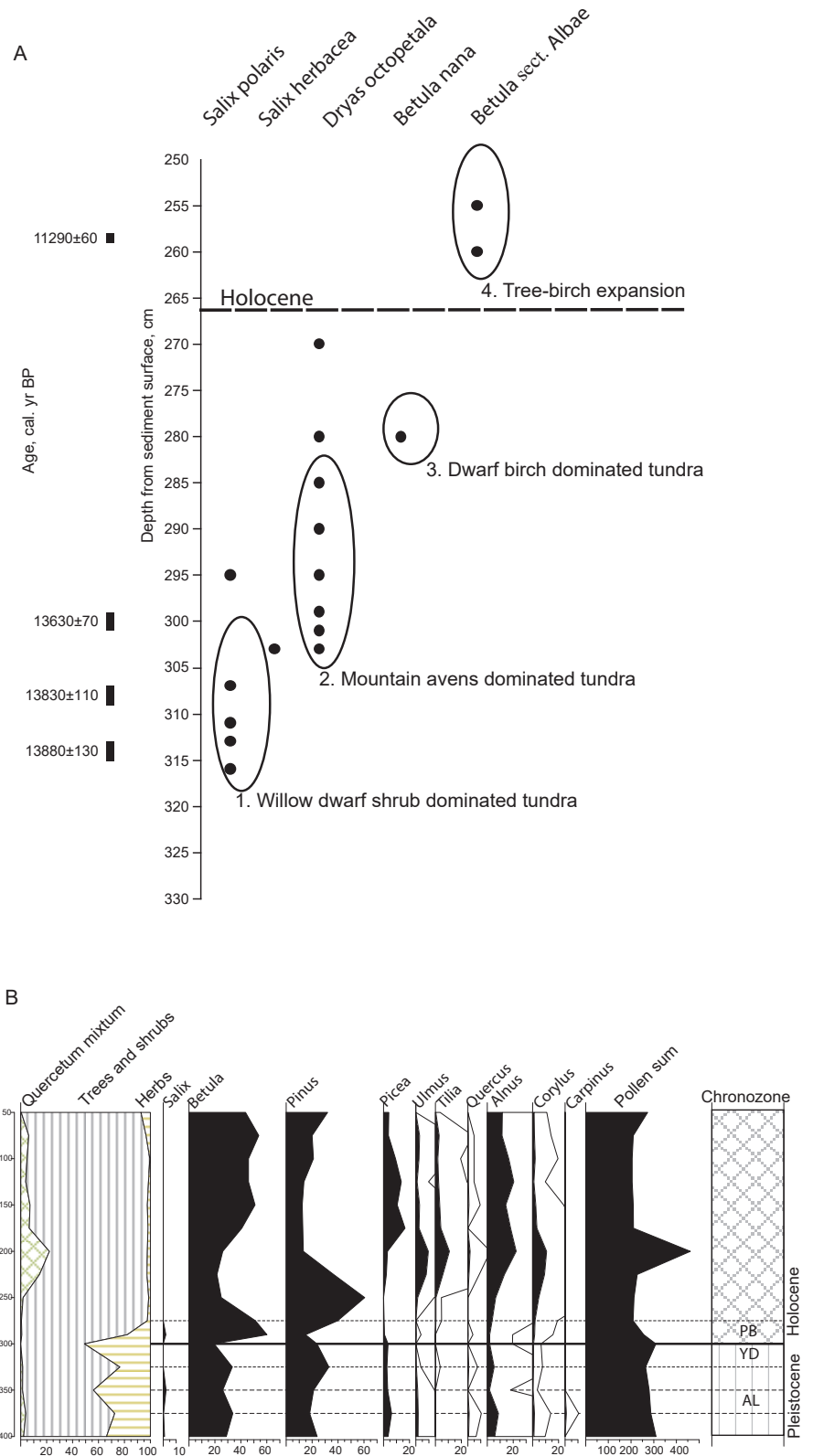
5. Discussion

5.1. Timing of the deglaciation of the Pandivere Upland

The chronologies from the present study sites help to clarify the timing of the deglaciation of the Pandivere Upland. The southernmost study site, Lake Prossa, is located between the Otepää and Pandivere marginal belts. Based on previous studies, the surroundings of Lake Prossa became ice-free approximately 14 400 cal. yr BP (Kihno et al., 2011, Table 2), which is consistent with the proposed age of the Otepää zone (14 700–14 500 cal. yr BP; Lasberg & Kalm, 2013). Over the next 150 years, the area around Prossa was submerged by waters of a proglacial lake deduced from ca. 5-m-thick varved clay and clayey rhythmites occurring in lakes of the Saadjärv Drumlin Field (Rosentau et al., 2007).

The distance between the Otepää marginal belt and Prossa is ca. 45 km and the deglaciation age differs by 300 years. From this, we estimate the calculated annual ice recession rate was ~ 150 m yr $^{-1}$,

Fig. 4. The scheme of the dynamics of the late-glacial local vegetation types around Lake Kursi (A) and the modified tree pollen diagram from Lake Kursi (after Veber 1965) (B).



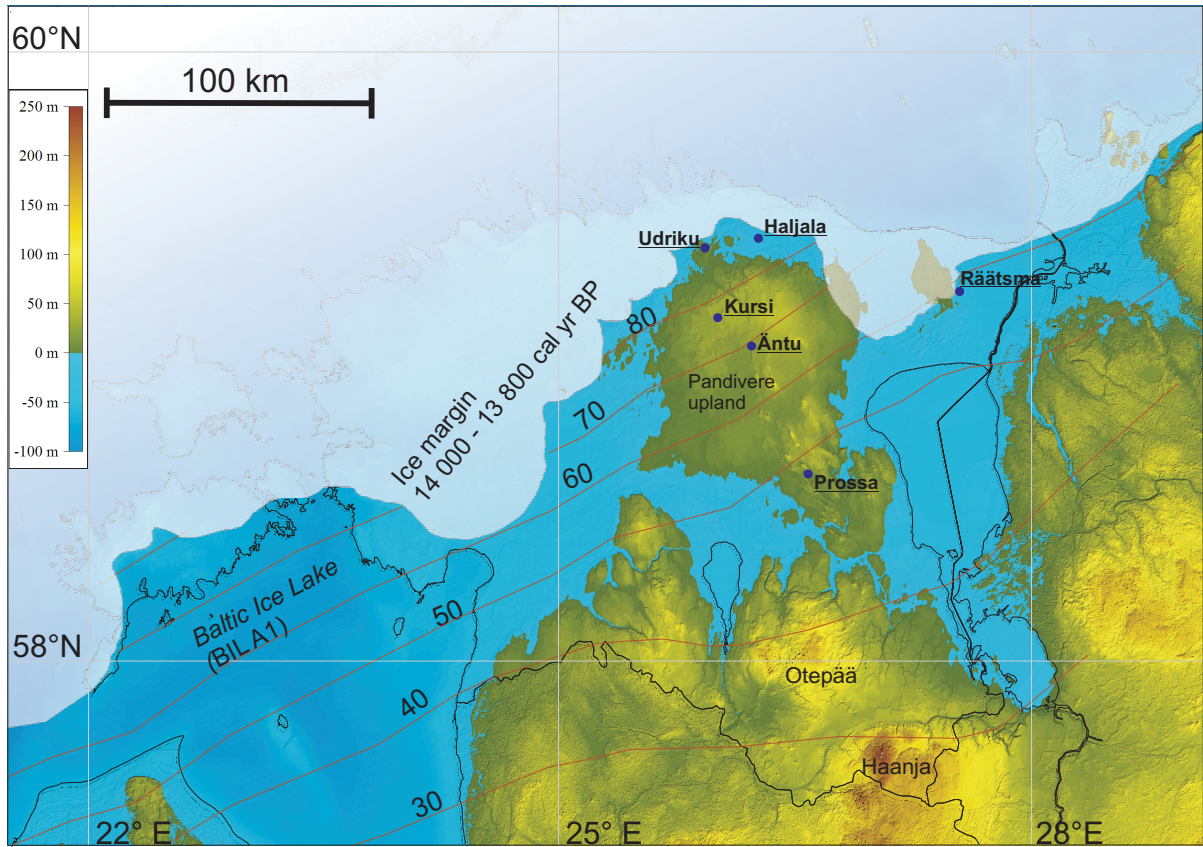


Fig. 5. Palaeogeography during the Pandivere stadal 14 000–13 800 cal. yr BP. The ice marginal position and the BIL stage A_1 are based on Vassiljev & Saarse (2013). Blue circles show the locations of the study sites discussed in the text.

consistent with that suggested for the Peipsi depression, which deglaciated simultaneously with the drumlin field area (Hang, 2001). The ice sheet decay at the Pandivere Upland proceeded under conditions of active and dead ice (Raukas, 2009) and was completed in the Allerød chronozone. In the depressions, the hollows and gullies of dead ice obviously remained longer based on the start of deposition in Äntu Sinijärv (Saarse & Liiva, 1995; Laumets et al., 2014) and several mires (Veber, 1965). An ice front reached and stagnated at the Pandivere marginal belt no later than 13 800 cal. yr BP, forming the shoreline of BIL stage A_1 (Fig. 5). It is demonstrated by the bio- and chronostratigraphy from the Udriku, Haljala and Räätsmä lakes (Table 2) and pollen records from the Lusiku, Auvere and Loobu mires located in the adjacent areas (Pirrus,

1965; Veber, 1965). In all abovementioned sites, the Allerød clayey deposits contained herb pollen characteristic of the late-glacial period. After that period, the ice receded to the coastal lowland and reached the southern coast of the Gulf of Finland at approximately 13 100 cal. yr BP (Lunkka et al., 2004; Johansson et al., 2011).

Based on the distance between the Prossa and Udriku sites (ca 90 km) and the AMS ^{14}C ages (ca 14 400 and 13 900 cal. yr BP), the ice recession rate was 180 m a^{-1} , which is almost half of that calculated for the Pärnu area based on varve chronology (340 m yr^{-1}) (Hang & Kohv, 2013). The same discrepancy is also observed in Sweden, where the varved clay chronology shows a considerably faster ice recession rate than other dating methods (Ringberg & Erlström, 1999). Calculated for

the Pandivere Upland, the ice recession rate is comparable with that suggested for the Onega area (ca 200 m yr⁻¹) (Saarnisto & Saarinen, 2001).

However, the obtained AMS radiocarbon dates do not reflect the exact timing of the deglaciation, but rather the start of terrestrial vegetation colonisation. The AMS ages are determined from plant remains and therefore include gaps between the deglaciation itself and suitable conditions for vegetation to sprout. Late-glacial vegetation development is restricted by several factors, including the harsh climate and species migration. One such factor is the vegetation colonisation period. Previous studies have shown that the colonisation of pioneer vegetation took only a few decades after the land became ice-free (Jones & Henry, 2003; Heikkilä et al., 2009; Amon et al., 2014), which is within the error limits of the AMS age determination. Another factor for terrestrial floral development is connected with palaeo-hydrology and landscape. In the Baltic area, the late-glacial palaeo-landscape was mosaic and flooded by different ice-dammed lakes (Amon et al., 2014). During the initial stage presently overgrown Lake Kursi was a local ice-dammed lake (Fig. 1B, Öpik, 1937) and the ice margin was located within ten kilometres north of Lake Kursi. Varved clay deposited into this water body. A distinct sand layer (316–315.5 cm, Fig. 3) overlying a set of 20 varves has an erosional lower contact and, therefore, probably represents the drainage of the local ice-dammed lake from 128 m a.s.l. to 112 m a.s.l. The age obtained at the top of this layer is ~13 600–14 000 cal. yr BP (Table 2). The first terrestrial plant remains are sedges (*Carex* spp.) and polar willows (*Salix polaris*) (Fig. 4A) and found in the drainage layer. This suggests that the terrestrial area around Lake Kursi already had a vegetation cover by that time and that the shoreline was sufficiently close to the coring point for macrofossils to be found in the sediments.

Current bio- and chronostratigraphical data confirm that the Pandivere Upland deglaciated between 14 200 and 13 800 cal. yr BP. However, other dating methods, such as ¹⁰Be (Rinterknecht et

al., 2006), OSL (Raukas & Stankowski, 2005) and varve chronology (Hang & Kohv, 2013), suggest an age of 300–500 years younger compared to the AMS ¹⁴C dates, which provide a minimum age of deglaciation. Cosmogenic nucleid ¹⁰Be might show a younger age due to a post-exposure relocation of boulders (Lüthgens & Böse, 2012) or delayed exposure to cosmic rays (Heyman et al., 2011), but why there is almost a half-thousand year difference compared to the varve chronology and the slower ice retreat rate is a problem that requires future study.

5.2. Late-glacial flora beyond and on the Pandivere Upland

The first recognised vegetation development stage around Lake Kursi was a willow dwarf shrub-dominated tundra, at approximately 13 880–13 700 cal. yr BP (Fig. 4A). The next vegetation type was a mountain avens (*Dryas octopetala*)-dominated tundra at ~13 700 cal. yr BP. The landscape was treeless throughout the late-glacial period, but vegetation was probably more diverse and productive. The third notable change was the migration of dwarf birch. The first tree macrofossils found in Kursi core belong to tree-birch but due to the sedimentary gap their age is clearly within the Holocene. This conclusion is also supported by the rise in birch pollen at the beginning of the Preboreal (Fig. 4B).

The similarities of the plant macrofossil data between the study locations suggest that the prevalent late-glacial vegetation type in north-eastern Estonia was treeless tundra until the Holocene, however, the dominant shrub and herb species vary between the sites. In Haljala, the mountain avens (*Dryas octopetala*)-dominated tundra was prevalent with occasional finds of dwarf shrub willow (*Salix polaris*) in the basal part and one dwarf birch (*Betula nana*) leaf in the upper part of the late-glacial sediment. In Udriku, the basal part of late-glacial sediments reveals the *Salix polaris* tundra completely replaced by mountain avens dominated tundra at ~13 600 cal. yr BP, with no findings of dwarf birch macrofossils until the Holocene. The

late-glacial sediments of Äntu confirm the local presence of *Dryas* and dwarf birch tundra. The palaeobotanical data of the present study site, Lake Kursi, suggest treeless tundra conditions until the Holocene. The late-glacial plant macrofossil data from Lake Prossa started with *Salix polaris* tundra and was followed by *Dryas* tundra that later turned to dwarf birch dominated tundra with a *Dryas* component.

In general, the north-eastern late-glacial vegetation show the following succession of vegetation development: the first stage was dwarf shrub willow-dominated tundra replaced by (or mixed with) mountain avens-dominated tundra. The next stage was dwarf birch-dominated tundra: the further south, the more occurrences of *B. nana* macrofossils (abundant in Prossa and Äntu, some in Kursi, one find in Haljala and none in Udriku). The generalised late-glacial tundra dynamics correspond well with modern high- and mid-arctic vegetation zones – Rønning (1996) defines the *Salix polaris* zone as a high-arctic vegetation unit and the *Dryas octopetala* zone as a mid-arctic vegetation unit.

The treeless tundra vegetation with arctic shrubs (*Salix polaris*, *Dryas*) clearly suggest severe late-glacial palaeoclimatic conditions in north-eastern Estonia. Recent pollen-based temperature reconstructions from Lake Udriku show summer temperatures of 10.2–12.6 °C (Veski et al., 2015), but the results are biased due to the long transport of pollen over the treeless landscape and therefore overestimate the temperature range. The first pioneer tree species in the Baltic area is tree-birch (Amon et al., 2014) and the local presence of tree-birch requires summer temperatures of ~10–12 °C (Paus, 1995) or >13.2 °C (Odland, 1996), so the temperature in Pandivere probably did not reach these values.

6. Conclusions

Lithological proxies, plant macrofossils and AMS ¹⁴C dates were employed to investigate the ice recession history, the age of the Pandivere ice-marginal belt and the late-glacial vegetation development in the region.

- The dates from Lake Prossa, located between the Otepää and Pandivere ice-marginal zones, indicate that this area was ice-free by approximately 14 400 cal. yr BP, and support the age proposed for the Otepää zone (14 700–14 500 cal. yr BP). Taking into account the distance between Prossa and the Pandivere Upland as well as the ice recession rate, the deglaciation of the Pandivere Upland started at approximately 14 200 cal. yr BP. This is a minimum age because the AMS radiocarbon dates were determined from plant remains and there is a lag between ice decay and vegetation colonisation.
- The Pandivere stadial lasted ca. 400 years, from 14 200 to 13 800 cal. yr BP, as confirmed by AMS ¹⁴C dates. In hollows and depressions, dead ice obviously melted later.
- The ice recession rate was ca. 180 m yr⁻¹ and stagnation at the ice-marginal zone could have lasted approximately 20 years, as concluded from the varve chronology of the Pärnu area (Hang & Kohv, 2013).
- Deglaciation of the northern slope of the upland and formation of the Pandivere marginal formations are closely connected with the appearance of the proglacial lake A₁, a bay of the BIL (Saarse et al., 2007; Rosentau et al., 2009). New radiocarbon data supports reassessing the onset of the proglacial lake A₁ from 13 300 cal. yr BP (Rosentau et al., 2009) to 13 800–14 000 cal. yr BP (Vassiljev and Saarse, 2013). More records are required to clarify how proglacial lake waters affected ice melting and retreat and why the other dating methods show a younger age for the Pandivere ice-marginal belt.

- The late-glacial vegetation type around the Pandivere Upland was tundra with local variation of dominant cold-tolerant shrub species. The generalised scheme for the vegetation development in the studied area is as follows: willow dwarf shrub-dominated tundra – mountain avens-dominated tundra – dwarf birch-dominated tundra, which indicates that north-eastern Estonia remained treeless until the Holocene.

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