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# On the deglaciation chronology of the Palivere ice-marginal zone, northern Estonia

Leili Saarse[1], Atko Heinsalu[1], Siim Veski[1], Leeli Amon[1] and Andrejus Gaidamavičius[2]

[1] *Institute of Geology at Tallinn University of Technology, Ehitajate tee 5, 19086 Tallinn, Estonia*

[2] *Institute of Geology & Geography, T. Ševčenkos str. 13, LT-03223 Vilnius, Lithuania*

## Abstract

This paper presents new bio-, litho- and chronostratigraphical evidence from two adjacent sediment sequences of the Tõdva and Saku basins, northern Estonia that refine the age estimate of the Palivere ice-marginal zone and the deglaciation history of Estonia. Previous palynological studies demonstrated the presence of late-glacial sediments in the area; however, those sections were not dated, and their ages were poorly constrained. New accelerator mass spectrometry (AMS) $^{14}$C dates show that sedimentation in the Tõdva basin started at approximately 13 200 cal yr BP. Therefore, because the studied sites are located at the distal part of this zone, we infer that this age represents the minimum timing of the ice retreat from the Palivere ice-marginal zone.

**Keywords** (GeoRef Thesaurus, AGI): ice-marginal features, deglaciation, chronology, mires, sediments, stratigraphy, microfossils, absolute age, C-14, Quaternary, Palivere, Tõdva, Estonia

Corresponding author email: saarse@gi.ee

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## 1. Introduction

The reconstruction of the deglaciation history of Estonia is based on the recognition of five ice-marginal zones, of which the Palivere ice marginal is the youngest (Raukas, 1986). The so-called Palivere belt in northern and western Estonia is a complex of glacial, glaciofluvial and glaciolacustrine deposits related to large deltas of ice-dammed lakes (Raukas, 1992; Kalm & Kadastik, 2001). However, the timing of the formation of the Palivere ice-marginal zone remains contentious due to insufficient direct datings and considerable deviations in the available age determinations. Dates of glaciofluvial delta deposits range from 9800 ± 1300 to 21 000 ± 2500 OSL years. Raukas (2009) reported an age of 11 300 ± 1300 OSL years to be realistic for the formation of the Palivere ice-marginal zone. Surface exposure dating of erratic boulders using the cosmogenic $^{10}$Be isotope technique has been applied in studies of the Palivere ice-marginal zone. The ages of 10 erratic boulders ranged from 5200 to 15 200 $^{10}$Be years with a mean of 13 600 ± 1200 $^{10}$Be years (Rinterknecht et al., 2006). Vassiljev et al. (2005) estimated that the Palivere ice-margin re-advance commenced at approximately 13 000–13 100 cal yr BP; however, Kalm (2006) reported a younger age of this advance (12 700 cal yr BP). Clay varve counts at the Vigala site between the Pandivere and Palivere ice-marginal zones showed an age of 11 800 varve years for the Palivere belt (Hang & Sandgren, 1996).

The objective of this study was to use AMS $^{14}$C dating of terrestrial plant macrofossils to track and improve the chronology of the Palivere ice-marginal zone. Radiocarbon dating remains the most prominent method for dating terrestrial macroremains imbedded in late-glacial minerogeneous deposits (Blockley et al., 2007). We selected sediment sections from the Saku and Tõdva mires at the distal region of the Palivere ice-marginal zone, where previous pollen studies confirmed the presence of clayey late-glacial sediments of the Allerød and Younger Dryas age (Veber, 1969).

## 2. Setting

The Saku and Tõdva mires are located 12 km south of the border of Tallinn at an altitude of 37–37.5 m above sea level (a.s.l.) and encompass a total area of 1130 ha (Fig. 1). These mires form a joint complex, the majority of which is currently drained and used as cultural grassland. The threshold of the mires at ca. 37 m a.s.l. is covered by alluvial deposits and was possibly eroded to a certain extent during the isolation. The mires are surrounded by tills and glaciofluvial deposits and are underlain by Ordovician limestone (Teedumäe, 1997). Their outline is characterised as winding bottom topography that is uneven with several deeper hollows, where residual lakes persisted and lacustrine lime was deposited during the early Holocene (Veber, 1969). Both basins were flooded by the Baltic Ice Lake (BIL) and were submerged during the Yoldia Sea stage.

Sampling sites in the Saku (59 °17′47′′N, 24 °41′26′′E) and Tõdva mires (59 °16′36′′N, 24°43′55′′E) were chosen in locations where pollen analyses were previously conducted and the thickest late-glacial deposits appeared (Veber, 1969). The coring sites were located on the cultivated meadow (Saku) and on the edge of meadow and birch-pine-spruce wood (Tõdva).

## 3. Material and methods

A total of four parallel 280-cm-long sediment cores from the Saku site and four 520-cm-long sediment cores from the Tõdva site were extracted using a 1-m-long Russian peat sampler. Overlapping cores were macroscopically described and photographed in the field, wrapped in plastic, transported to the laboratory and stored in a cool room. Sub-samples from clayey deposits (1-cm thickness) were taken continuously for loss-on-ignition (LOI) analyses, whereas 1-cm thickness samples were taken at 5–10 cm intervals to determine the grain size distribution. Samples for LOI analyses were weighted, dried overnight at 105 °C and combusted at 525 and 900 °C to calculate the water content, the abundance of organic matter (OM) and carbonate compounds, respectively. The residue containing the siliciclastic and bioclastic components was described as mineral matter and calculated by subtraction based on the sum of OM and carbonates. The lithic grain size distribution was analysed using a Horiba LA-950V2 laser scattering particle size distribution analyser. The magnetic susceptibility (MS) was measured at a 1-cm resolution using a Bartington Instruments high resolution surface scanning sensor MS2E along carefully cleaned flat surfaces of fresh sediments.

Pollen preparation followed a standard method (Berglund & Ralska-Jasiewiczowa, 1986; Fægri et al., 1989). A total of 9 samples were analysed. One tablet of *Lycopodium* spores was added to volume-specific (1 cm$^3$) samples to estimate the pollen con-

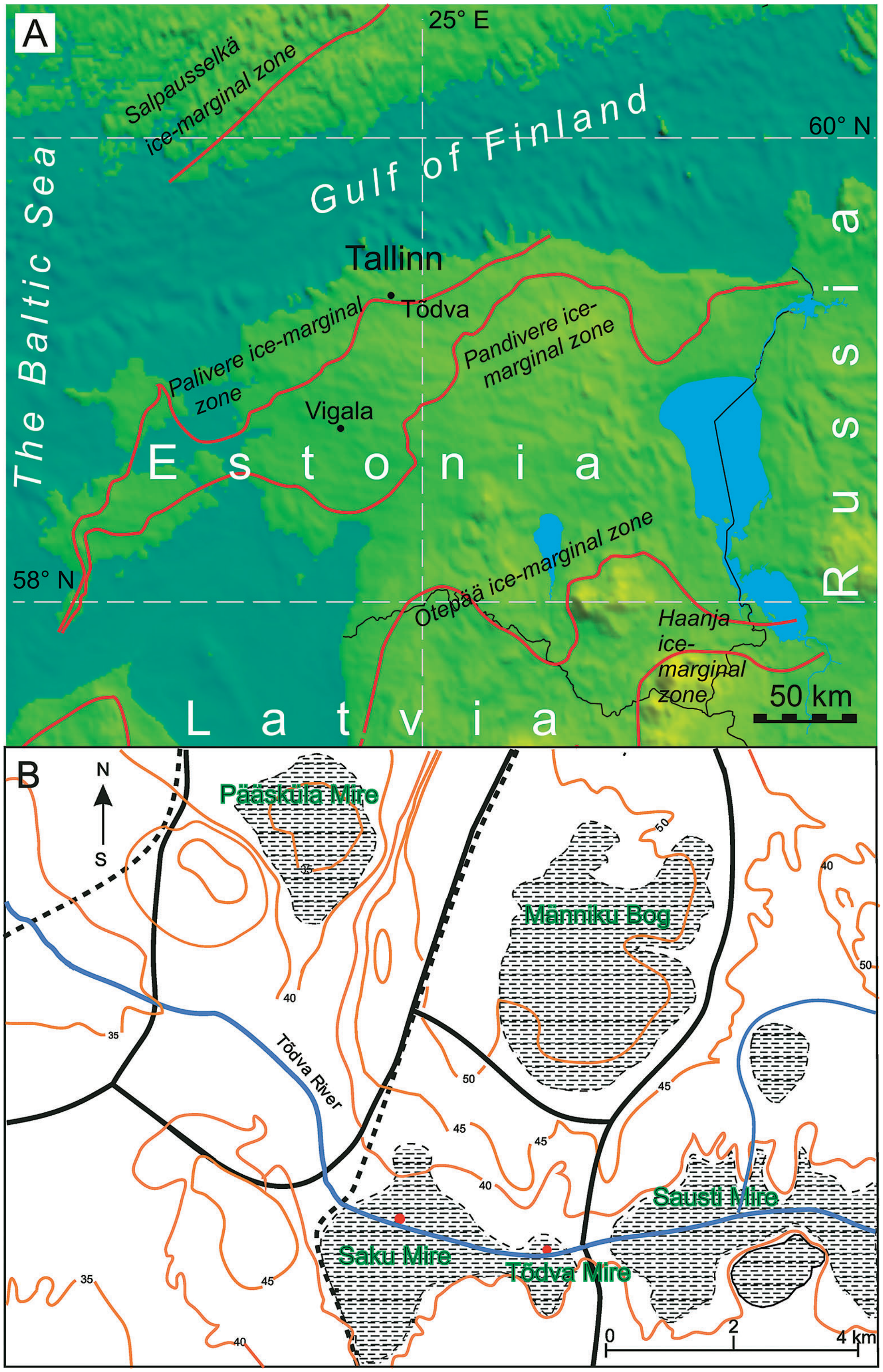


Fig. 1. Location of the study area showing the main ice-marginal zones (A). The Sakala zone is not indicated because it is not clearly defined. Coring sites in the Saku and Tõdva mires indicated by red circles (B). Thick black line marks roads, dotted line – railways, brown colour – isolines.

centration (Stockmarr, 1971). Only 100–200 pollen grains were counted from each sample due to very low pollen concentration. The percentage calculations were based on the sum of terrestrial pollen, and other identified microfossils were calculated based on the basic pollen sum. The pollen accumulation rate (PAR grains $cm^{-2}\,yr^{-1}$) was calculated using the concentration data and a constructed time scale.

For diatom analyses, sediment samples were subjected to sequential treatments with 10 % HCl and 30 % $H_2O_2$ to remove carbonates and OM. Thereafter, fine and coarse mineral particles were removed by repeated decantation (Battarbee et al., 2001). The cleaned sub-samples were dried onto cover slips and permanently mounted onto microscope slides using a Naphrax medium. The analyses were performed using a Zeiss Axio Imager light microscope at x1000 magnification with oil immersion and interference contrast; diatoms were identified using standard floras. Diatoms were grouped according to their habitat into plankton and periphyton, the latter including benthic, epilithic and epiphytic life forms, and into large-lake and small-lake taxa groups. The LOI, PAR and diatom diagrams were constructed using TILIA and TGView software (Grimm, 2007).

To obtain terrestrial macroremains for AMS dating, sediment cores were cut into 5- cm-thick sections and washed through 0.25 mm mesh, and the macroremains were examined under a microscope. Late-glacial sediment sub-samples contained very few terrestrial macroremains, and common *Phragmites* stems and aquatic mosses were present. However, *Dryas octopetala* leaves were present in the Tõdva sediment core, and woody pieces were observed in the Saku sediment sequence. These and several other macrofossils were dated at the Poznan Radiocarbon Laboratory to obtain a chronology for the studied sediment sequences. In addition, conventional radiocarbon dating of Holocene bulk peat samples was performed at the Institute of Geology at Tallinn University of Technology. The chronology in the text and figures is presented according to calendar years prior to 1950 AD derived by the calibration of radiocarbon ages with IntCal98 calibration curve and CALIB 5.1 software at one sigma range (Stuiver et al., 2005).

# 4. Results

## 4.1 Lithostratigraphy

The Late-glacial and early Holocene sediments of the Tõdva site were divided into four lithostratigraphical units (Table 1). The lowermost beige sandy silt (Tõ-1, 510–520 cm) is overlain by bluish-grey massive clayey silt (Tõ-2, 478–510 cm) with low OM and carbonate content (Fig. 2A, Table 1) and showed the highest MS values (Fig. 3). Unit 3 is sandy silt (Tõ-3, 447–478 cm) with a rhythmic pattern of dark brown banding (slightly organic)

Table 1. Lithology of the Tõdva core.

| Depth, cm with indication unit name | Sediment description |
|---|---|
| 0–220 | Brownish black *Phragmites-Bryales* peat, lower portion well decomposed. |
| 220–421 | Pinkish-beige lacustrine lime distinctly laminated. |
| 421–447/Tõ-4 | Beige lacustrine lime interlayered with bluish silt. |
| 447–478/Tõ-3 | Bluish-grey sandy silt alternation with dark brown layers with scattered mollusc shells. |
| 478–510/Tõ-2 | Bluish-grey clayey silt, massive. |
| 510–520/Tõ-1 | Beige sandy silt. |

and continuously decreasing MS values (Fig. 3). At 478 cm upwards, the carbonate content increases slightly, mainly due to the presence of scattered mollusc shells. In the next studied unit (Tõ-4, 421–447 cm), beige lacustrine lime alternates with bluish silt, which is gradually replaced by lacustrine lime. The OM contents are low throughout the studied sequence, and thus, the mineral matter content is mainly dependent on the amount of carbonate compounds. The sediment grain-size composition is variable and is clayey between 478 and 510 cm with greater amounts of silty and sandy material in the upper portion (Fig. 4).

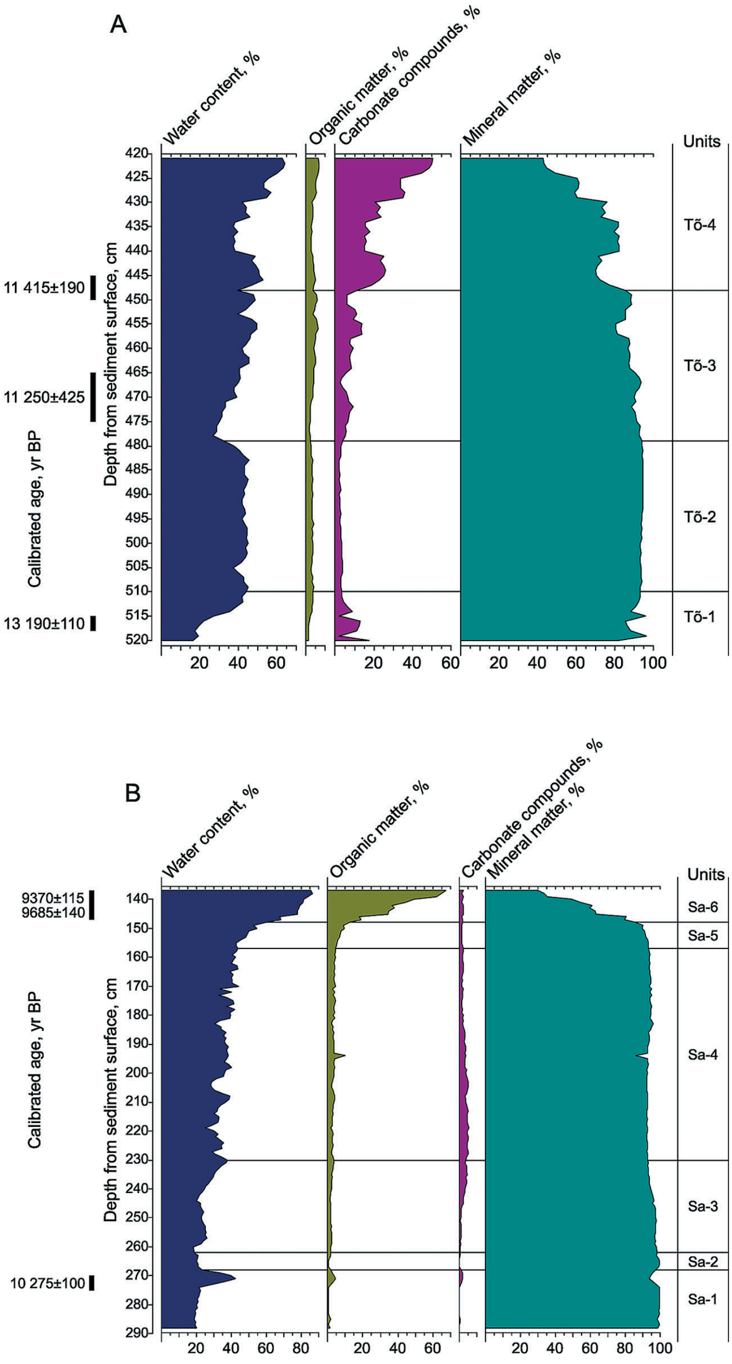


Fig. 2. Distribution of the water content, organic matter, carbonates and mineral matter in the Tõdva (A) and Saku (B) sediment cores.

The lowest unit of the Saku site (Sa-1, 268–288 cm) consisted of medium sand with low OM and carbonate contents (Fig. 2B). At the upper limit of the unit, the OM content increases due to the occurrence of rootlets that penetrated into the sand. This sand is overlain by clayey silt (Sa-2, 262–268 cm) with a clay fraction of up to 25 % and a OM content of less than 2 %. The next unit (Sa-3, 230–262 cm) starts with a thin sand layer (260–262 cm), followed by sandy silt, where clay fraction decreases. At 245 cm the carbonate content begins to increase. Sa-4 unit (157–230 cm) is clayey silt consisting of up to 40 % clay; the OM content is constant at approximately 4 %, although the carbonate content decreases. In the upper-most silty sand (Sa-5, 147–157 m) the sand fraction fluctuates between 50 and 71 %, the OM progressively increases in an upward direction and the mineral matter decreases. In the well-decomposed peat (Sa-6), the OM increased from 19 % to 66 % (Fig. 2B).

## 4.2 Chronostratigraphy

The radiocarbon dates presented in Table 2 are variable, and certain values are not consistent with the lithostratigraphical succession. In the

Tõdva site, *Dryas octopetala* leaves at 445–450 cm were dated to 9920 ± 100 (11 415 ± 190 cal yr BP; Poz-39127). The following AMS date (9830 ± 190; 11 250 ± 425 cal yr BP) at a core depth of 465–475 cm was not considered in the reconstruction of age-depth model because it was dated using unidentified herb leaves and appears slightly younger that the date presented above. The AMS date of 11 310 ±130 (13 190 ± 110 cal yr BP) from the *Dryas octopetala* leaves at the core depth 515–518 cm fits well with the pollen stratigraphy and confirms the deposition of the basal sediment at the end of the Allerød period. In the age-depth model, the Younger Dryas/Preboreal boundary of 11 650 cal yr BP (Lowe et al., 2008) was also considered. All radiocarbon dates for the Saku site demonstrated that the basal clayey deposits, described by Veber (1969) as belonging to the Younger Dryas period, were deposited later in the early Holocene period. Therefore, we presented only the results of the LOI analyses (Fig. 2B) and radiocarbon dates (Table 2).

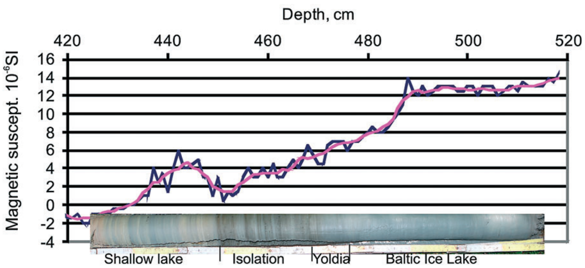


**Fig. 3.** Photo of the studied sediment core with indication of the magnetic susceptibility (units, $10^{-6}$ SI) values and sedimentation environment.

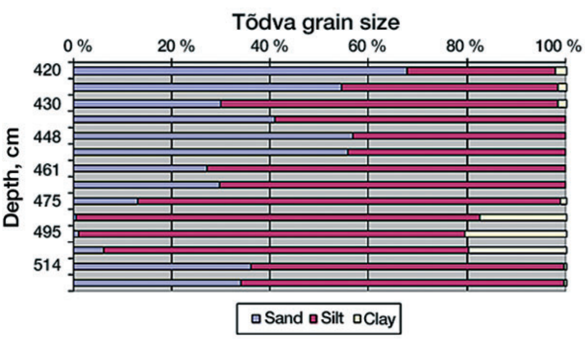


**Fig. 4.** Summary grain size graph for the Tõdva sediment sequence.

## 4.3 Pollen stratigraphy

A total of 36 pollen and spore taxa are identified. Pollen concentrations in the Tõdva minerogenic sediments were very low. However, it was possible to differentiate three local pollen assemblage zones; their description is presented in Table 3 and the PAR diagram in Figure 5. According to the pollen analyses and radiocarbon chronology, the sedimentation of silt began at the end of the Allerød and terminated in the Preboreal period.

## 4.4 Diatoms

The massive clayey silts below 478 cm are devoid of diatoms (Fig. 6). At a core depth from 475 to

Table 2. Radiocarbon dates from the Tõdva and Saku sediments.

| Site name | Depth, cm | $^{14}$C date | Laboratory number | Calibrated age range BP (Mean age) | Dated material |
|---|---|---|---|---|---|
| Tõdva | 445–450 | 9920 ± 100 | Poz-39127 | 11 600 – 11 225 (11 415 ± 190) | *Dryas octopetala* leaves |
| Tõdva | 465–475 | 9830 ± 190 | Poz-39129 | 10 825 – 11 675 (11 250 + 425) | Leaves |
| Tõdva | 515–518 | 11310 ± 130 | Poz-39130 | 13 080 – 13 300 (13 190 ± 110) | *Dryas octopetala* leaves |
| Saku | 137–142 | 8350 ± 105 | Tln-3178 | 9255–9485 (9370 ± 115) | Peat |
| Saku | 142–147 | 8700 ± 120 | Tln-3179 | 9545–9825 (9685 ± 140) | Peat |
| Saku | 270–275 | 9070 ± 70 | Poz-33494 | 10 175 – 10 370 (10275 ± 100) | Wood |

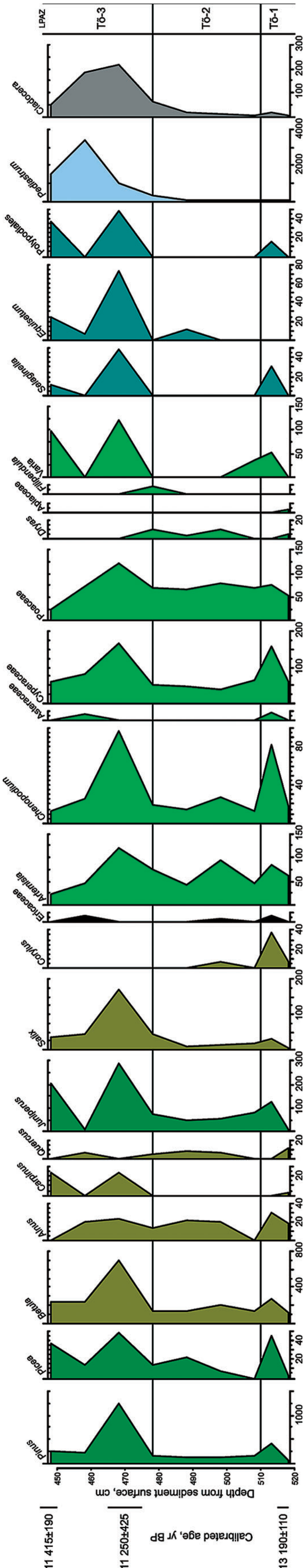


**Fig. 5.** Pollen accumulation rate (grains cm$^{-2}$ yr$^{-1}$) of the Tõdva sediment sequence.

Table 3. Local pollen assemblage zones.

| Depth, cm | Age, cal yr BP | LPAZ index and description |
|---|---|---|
| 440–478 | 11 350–11 650 | Tõ-3: AP up to 65%, *Pinus* reaches 40 % and *Juniperus* to 20 %. PAR of *Pinus* 1250 and *Betula* 700 grains cm$^{-2}$ yr$^{-1}$. |
| 478–510 | 11 650–12 900 | Tõ-2: *Salix* and *Juniperus* are continuously present. NAP dominates by *Artemisia*, Poaceae and Cyperaceae. AP/NAP ratio is about 50/50 %. PAR of *Betula* up to 200 and that of *Pinus* up to 150 grains cm$^{-2}$ yr$^{-1}$. |
| 510–518 | 12 900–13 190 | Tõ-1: AP and NAP accounts ca 50 %. *Pinus* and *Betula* dominate. Relatively high abundance of redeposited pollen. PAR of *Pinus* and *Betula* is less of 400 grains cm$^{-2}$ yr$^{-1}$. |

472 cm, the sandy silt contains broken fragments of the benthic diatom *Gyrosigma attenuatum*, a taxon common in large lakes sediments of Ancylus Lake and the freshwater Yoldia Sea (Heinsalu, 2000, 2001). A common feature of the sediment sequences of small lakes and bogs that were isolated during the freshwater stages of the Baltic Sea is the blooming of *Fragilaria* species around and after the isolation event. The apparent rise of small-size periphytic fragilarioid diatoms from 468 to 450 cm may be explained by the basin isolation. From a core depth of 445 cm *Fragilaria* spp. decrease and are replaced by diatoms that live in small shallow hard-water lakes, i.e. *Mastogloia smithii* var. *lacustris*, *Denticula kuetzingii* and various *Cymbella* spp.

# 5. Discussion

The sedimentation model of the Tõdva basin near the Palivere ice-marginal belt provides a basis to suggest that ice retreated from northern Estonia earlier than was previously reported (Vassiljev et al., 2005; Kalm, 2006; Kalm et al., 2011) and the minimum period when the area became free of ice is 13 200 cal yr BP. Such presumption is in good accordance with estimates from Finland, which indicate that the ice margin reached the northern coast of the Gulf of Finland at approximately 13 000 cal yr BP (Lunkka et al., 2004) and retreated from the

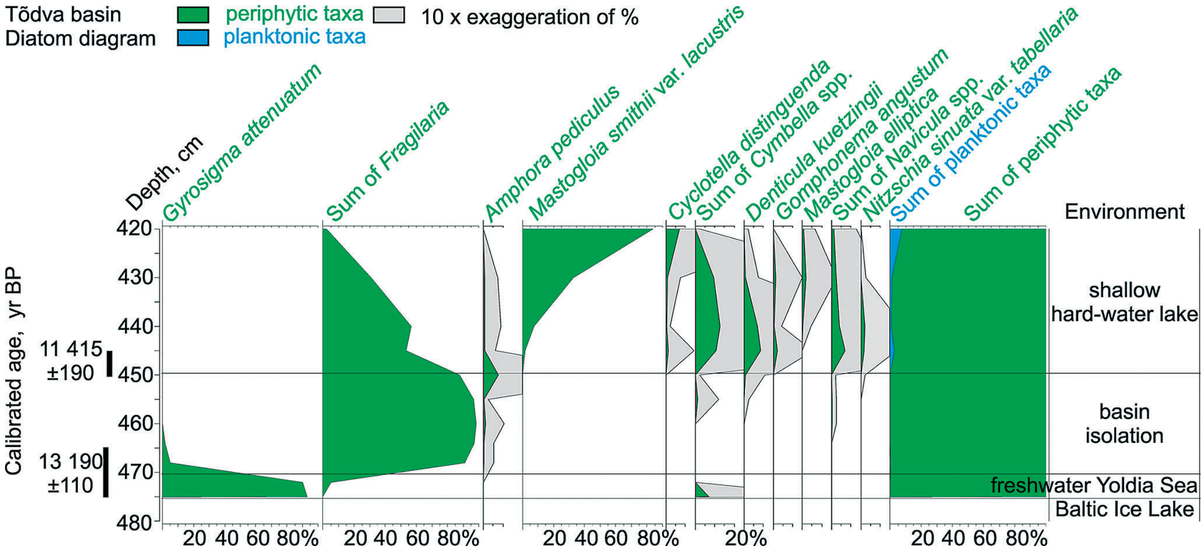


**Fig. 6.** Diatom stratigraphy of the Tõdva sediment sequence with indications of the sedimentation environments.

Salpausselkä I moraine at 12 500±700 $^{10}$Be yr (Rinterknect et al., 2004) or 12 260 cal yr BP (Donner, 2010). Age estimations from the Pandivere ice marginal zone to the south of Palivere show that the ice retreated by at least 13 800–13 900 cal yr BP (Amon & Saarse, 2010; Saarse et al., 2009).

During the ice recession, a proglacial lake along the ice margin flooded the study area. Such proglacial lakes have been described and studied in many areas around the world (e.g., Kvasov, 1979; Björck, 1995) and several studies have emphasised their role in the formation of the Younger Dryas climate conditions (Teller et al., 2002; Broecker, 2005). However, the enthusiasm for the flood hypothesis has considerably diminished recently (Broecker et al., 2010; Carlson, 2010).

Recent GIS-based reconstructions have shown that the Palivere ice-marginal zone was linked to the proglacial lake $A_2$, a bay of the BIL (Saarse et al., 2007; Rosentau et al., 2007), and the presence of the $A_3$ phase, as suggested by Pärna (1960), has been questioned. According to water level simulations of the coastline of the BIL located at 71 m in the study area, the coastlines of the Yoldia Sea and Ancylus Lake were present at 44 m and 34 m a.s.l., respectively (Vassiljev, pers. comm.). Rapid drainage of the BIL at 11 600 cal yr BP caused a remarkable lowering of water level and left various traces in the sediment sequences that were recorded in several sites with the Baltic region (Haila et al., 1991; Johnson et al., 2010) and in the Gulf of Finland (Hyttinen et al., 2011). In the Tõdva basin, a clear sedimentary limit is present at 478 cm, which is marked by replacement of clayey silt by sandy silt.

The Yoldia Sea stage led to the ingression of sea water that brought brackish water diatom assemblages into the Baltic basin, which is registered in the Gulf of Finland between 11 300 and 11 200 cal yr BP (Heinsalu & Veski, 2007). Diatom evidence indicates that the Tõdva basin was isolated at the beginning of the Yoldia Sea stage prior to the occurrence of the brief brackish water episode. According to the diatom assemblage, the transition from the freshwater Yoldia Sea to the small isolated lake, i.e., basin isolation, occurred between 468 and 450 cm. This interpretation is supported by sediment litho- and biostratigraphy results, e.g., the increased sand content, changes in diatom assemblages and decreased MS values (Figs 3–6).

The analysis of biostratigraphical materials suggests that the study area was free of ice since the end of the Allerød (Fig. 5). Previous pollen stratigraphical studies from several sites within or behind the Palivere ice-marginal belt described pollen assemblages typical of the Younger Dryas, Allerød and even Older Dryas periods (Pirrus & Sarv, 1968; Kessel & Pirrus, 1983). When comparing these pollen diagrams to the radiocarbon-dated Haljala diagram (Saarse et al., 2009), we can see several similarities. Therefore, we conclude that the pollen spectra, which were previously reported as corresponding to the Older Dryas, were clearly formed considerably later during the cooler Allerød period at 13 300–13 100 cal yr BP (Lowe et al., 2008).

In the basal sediment of the Tõdva site, the frequency of *Pinus* and *Betula* pollen was between 20 and 30 % (Table 3), which likely reflects a long-distance transport or the redeposition of pollen grains from local overburden (till beds). PAR values of less than 400 grains $cm^{-2}$ $yr^{-1}$ suggest treeless tundra-type vegetation at the end of the Allerød and throughout the Younger Dryas period (Fig. 5, Tõ-1, 2). The reason of such an environment is a colder climate, especially during the winter of the Younger Dryas, when the BIL and northern part of the Atlantic Ocean were covered by sea ice (Denton et al., 2005). Such a treeless environment was common to northwestern Estonia (Amon & Saarse, 2010), which is in contrast to southern Estonia where birch and pine forests were present at the second half of the Allerød (Amon et al., 2012). After the drainage of the BIL near the late-glacial/ Holocene boundary and the formation of the Yoldia Sea, emergent areas were rapidly colonised by vegetation. This colonisation can be determined based on the sharp increase in PAR values (Fig. 5, Tõ-3) that confirm the growth of pine and birch trees near the studied site (Hicks, 2001).

## 6. Conclusions

The AMS $^{14}C$ dating and the pollen records from the Tõdva site confirm that the ice advance from the Palivere ice-marginal zone commenced during the Allerød at approximately 13 200 cal yr BP. Additional AMS dates are needed to resolve the ice recession chronology and address problems associated with the formation of the Palivere ice- marginal belt.

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