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Postglacial palaeoenvironmental changes in the area surrounding Lake Udriku in North Estonia

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Multiproxy data (plant macrofossils, AMS ^{14}C radiocarbon dates, grain-size distribution, loss-on-ignition and magnetic susceptibility) from Lake Udriku Suurjärv in North Estonia were used to interpret local environmental changes during the postglacial period between 13 800 and 11 000 cal yr BP. Sediment lithology is complex but can roughly be described as silt overlain by silty gyttja, gyttja and peat. The macrofossil diagram shows the local vegetation development from Late Glacial pioneer communities to early Holocene communities. The vegetation succession started predominately with *Salix polaris*, which was later replaced by *Dryas octopetala*. The diversity of plant macrofossils increased significantly during the warmer part of the Allerød. Both the diversity and the number of plant macrofossils are low in the Younger Dryas, confirming the severe climatic conditions found during this interval. During the Late Glacial to Holocene transition, aquatic taxa prevail among plant macrofossils. The absence of tree remains among macrofossils of this period suggests that trees were not locally present or were not growing near the studied lake. Proxy data indicate several environmental changes. The sediment composition and vegetation reflect cooler and warmer episodes and confirm that the study area has been free of ice since 13 800 cal yr BP.

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INTRODUCTION

Palaeoecological studies that combine lithological, palaeobotanical and radiocarbon data have successfully determined ice recession chronology and Late Glacial stratigraphy. The Late Glacial stratigraphical subdivision of Estonia comprises two stadials (Older Dryas and Younger Dryas) and one interstadial (Allerød), which are distinguished mainly on the basis of palynological data (Pirrus, 1976; Pirrus and Raukas, 1996). Their chronostratigraphical position has been established by a few radiocarbon dates, thermoluminescence (TL), optically stimulated luminescence (OSL) and ^{10}Be dating of tills and other glacigenic deposits and erratic boulders (Raukas and Stankowski, 2005; Kalm, 2006; Rinterknecht *et al*., 2006; Sohar and Kalm, 2008). Biostratigraphical records in North Estonia have largely dealt with Holocene vegetation dynamics (e.g., Veber, 1961, 1965; Saarse, 1994; Saarse and Liiva, 1995; Saarse *et al*., 1998; Kangur, 2005), while Late Glacial bio- and chronostratigraphy has received limited attention. Up to now only at the Haljala site, 24 km north-east of Udriku, have pollen and chronostratigraphy been studied in detail (Saarse *et al*., 2009). There are two main reasons why radiocarbon dates directly associated with biostratigraphical studies of the Late Glacial are not common. Our Late Glacial deposits are minerogeneous and contain only scarce terrestrial macrofossils suitable for radiocarbon dating. This mostly concerns Northern and Western Estonia where varved clays are widely distributed. At the same time, macrofossil analyses have remained unexploited due to a shortage of analysts and therefore only a few records are currently available from North Estonia for the Late Glacial period (Sohar and Kalm, 2008; Saarse *et al*., 2009). Some random dates from Late Glacial deposits are available, but most are too old as the dating was performed on aquatic mosses (Pirrus, 1976; Saarse and Liiva, 1995; Pirrus and Raukas, 1996).

The present investigation is part of an ongoing project entitled "Environmental and climate changes and their modelling possibilities on the basis of postglacial deposits".The main objective of the present paper is to adjust Late Glacial chronology and examine the local vegetation succession to better understand the regional environmental and climatic variability in

North Estonia. Data on plant macrofossils, loss-on-ignition (LOI) and lithology and AMS ^{14}C dates was used to establish Late Glacial palaeoenvironmental changes.

STUDY AREA

Lake Udriku Suurjärv was examined to adjust the age of the Pandivere ice marginal zone and the chronology of the Late Glacial deposits (Fig. 1). This lake was selected for the study because of the presence of Late Glacial clayey deposits containing plant macrofossils (Saarse, 1994) suitable for AMS ^{14}C dating. The study area is located within the Pandivere ice marginal zone (Fig. 1A) and has an estimated age of 13 300 cal yr BP (Kalm, 2006). Three Udriku lakes (Suurjärv, Väikejärv, and Mudajärv) lie in a V-shaped depression between the Ohepalu–Viitna and Pikassaare–Ohepalu esker ridges (Fig. 1B). These lakes were dammed by esker ridges and their water level was 4 m higher than in Lake Kaanjärv, which is behind the ridge (Fig. 1B).

Udriku Suurjärv is a small (23.7 ha), shallow (6.8 m) lake in NNW Estonia (59°22’17” N, 25°55’50” E) at an altitude of 95.1 m a.s.l. and on the NNW slope of the Pandivere Upland (Fig. 1). The hummocky and rolling landscape on the lake catchment ranges to 115.2 m a.s.l. and mainly composed of sand and gravel, while the surrounding lowland is covered by peat depos-

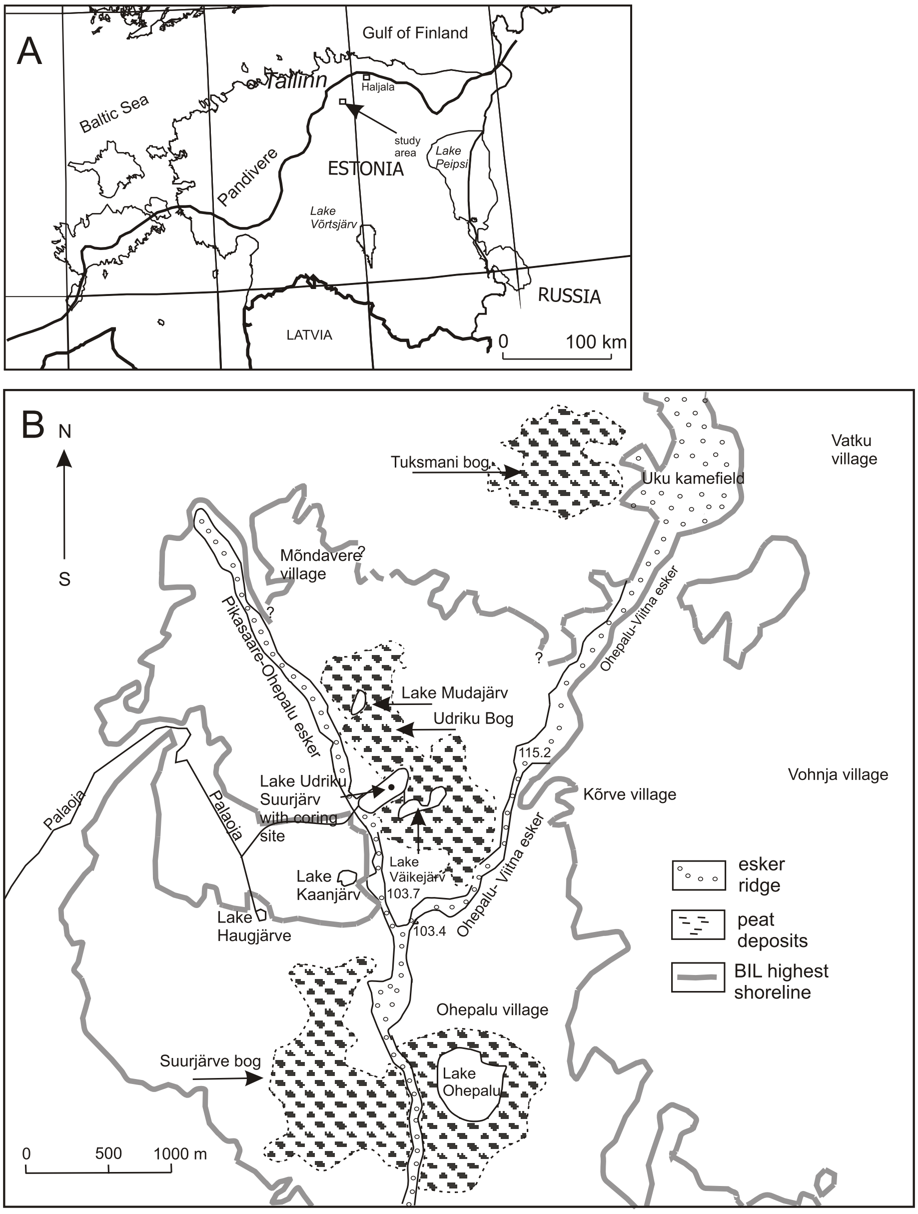

Fig. 1. Location of the study area (A), and coring site (B)

The study site is located within the Pandivere ice marginal zone, indicated by a black line on Figure 1A. The Udriku lakes are located between esker ridges and are surrounded by the Udriku bog. The simulated coastline of the Baltic Ice Lake stage A1 is shown by a thick grey line (B). The question marks point to assumed spillways between Udriku Basin and the Baltic Ice Lake (BIL) its (Fig. 1B). Peaty shores of the lake are strongly abraded and pine trunks and peat cover the narrow NW littoral zone. In the SW part of the region, the Pikassaare–Ohepalu esker borders the coast and forms the sandy shore. This elongated, dystrophic lake is poorly drained. It receives inflow from Lake Udriku Väikejärv and weak temporal outflow occurs via a ditch and the Palaoja Stream (Fig. 1B) to a river in the west. The lake water is reddish-brown, mildly acidic (pH 6.0), rich in organic (33–38 mg $l^{-1}O_2$) compounds and poor in mineral (<10 mg l^{-1}) compounds and water plants (3 taxa; Mäemets, 1968).

The study site belongs to the Boreo-Nemoral Zone, where *Betula pendula*, *Pinus sylvestris* and *Picea abies* are predominant. The esker ridges are covered by a mixed forest of *Picea abies*, *Betula pendula*, *Acer platanoides*, *Populus tremula*, *Fraxinus excelsior*, *etc*. and *Pinus sylvestris* which grows in the bog. The climate in this region is semi-continental. According to the nearest meteorological station, the area has a mean July temperature of 16.5°C, a mean January temperature of –6.7°C and mean annual precipitation of 670 mm yr^{-1} (Jaagus, 2002).

MATERIAL AND METHODS

Studies carried out during the winter of 1989 provided a good understanding of the lacustrine sediment distribution. Coring in the winter of 2009 was performed along a profile described earlier (Saarse, 1994). The sampling site was chosen to be in the middle of the lake at a water depth of 4.4 m (59° 22’17” N, 25°55’50” E), where Late Glacial clayey deposits appeared to be thickest. Five overlapping core segments were extracted using a 1 m long and 10 cm diameter Russian peat sampler. The cores were described and photographed in the field, wrapped in plastic, transported to the laboratory and stored in a cool room. The master core was subject to all analyses. As silt was very poor in macroremains, material from parallel cores, visually correlated with the master core, was used for analyses of plant macrofossils. One-centimetre thick samples for loss-on-ignition (LOI) analyses were taken continuously, while 1 cm thick samples to determine grain-size distribution were taken at 10 cm intervals. Bulk samples for LOI were weighed, dried overnight at 105°C and combusted at 525 and 900°C to calculate moisture, organic matter (OM), carbonate and mineral compounds. The resulting LOI diagram was designed using the *TILIA* and *TGView* programs (Grimm, 1991, 2000). The grain-size distribution for 19 samples was analysed using the *Partica* laser scattering particle size distribution analyser *LA-950V2*. The magnetic susceptibility was measured with a *Bartington MS2E* meter. The sediment surface was cleaned with a microscope glass slide, covered by a thin plastic film and the magnetic susceptibility was measured from the sediment surface at 1 cm resolution.

Macrofossils were extracted by soaking 5 cm thick samples (with a volume range of 160–300 cm^3 and a mean volume of 210–220 cm^3) in a water and $Na_4P_2O_7$ solution and then by sieving the material through a 0.25 mm mesh. The sediment volume was measured in water using a graduated cylinder. Thirty one samples were prepared for analysis and were treated according to the method proposed by Birks (2001). Plant remains were identified under a binocular microscope and their abundance was expressed as concentration by volume. The macrofossil diagram with all of the identified taxa was plotted using the *TILIA* and *TGView* programs.

Three AMS radiocarbon dates from terrestrial plant remains and one date from bulk gyttja were obtained via the Poznań radiocarbon laboratory and provide a chronology for the core studied. Taxa occurring in pioneer vegetation were selected for AMS ^{14}C dating to exclude contamination by younger material and to reduce the danger of using reworked material (Ammann and Lotter, 1988). As recent Late Glacial chronostratigraphy is presented in calendar years (Lowe *et al*., 2008), AMS dates are calibrated and then provided in calendar years using the calibration data set from Reimer *et al*. (2004) and the *CALIB 5.0.1* software (Stuiver *et al*., 2005).

RESULTS AND INTERPRETATION

CHRONO- AND LITHOSTRATIGRAPHY

Altogether four levels in the Udriku sediment sequence were dated by the AMS ^{14}C technique. Three datings of terrestrial macrofossils have age consistent with sediment depth. The date determined from bulk gyttja at the top of the sequence (10 190 ±50) was older than the AMS ^{14}C date below (10 ±60) and not in agreement with the Preboreal–Boreal limit fixed by pollen analyses (Veber, 1965; Saarse, 1994). This led to its rejection from the age-depth model (Fig. 2B). Considering the rapid change in the sediment structure and the number of counted laminae, we suggest that the basal portion of the sediment (800–828 cm) was deposited rather quickly, during a roughly 50 year period.

On the basis of LOI and grain-size distribution results, five lithological units have been identified in the Udriku sequence (Fig. 2A). The sediment colour changed from black at the top through brownish black, olive-grey and green-grey, to grey and dark grey at the bottom of the sequence. The brownish, greenish and olive-grey colours indicate oxic conditions, whereas the greyish colour indicates anoxic conditions (Hahne and Melles, 1997).

Unit Ud-1, **828–800 cm**. The base of the sequence studied consists of laminated clayey silt and is shown by the alternation of beige-coloured fine sand with dark grey clayey silt. The lowest portion of sediment (828–820 cm) has a high clay fraction, with values ranging up to 27% (Fig. 3). Upwards in the sequence, the clay fraction decreases to zero. The AMS ^{14}C date (Table 1) shows deposition at the beginning of the Allerød Interstadial (Fig. 2A).

Unit Ud-2, **800–780 cm**. This unit is dark grey sandy silt containing few plant remains, up to 32% sand, 68% silt, and 4–10% OM. The moisture and OM content show peaks at 782 and 790 cm.

Unit Ud-3, **780–755 cm**, is dark grey weakly laminated silt with a lower OM value (3–6%; Fig. 2A) than in the previous unit. The sand fraction decreased to 13–16%, while the silt fraction increased to 83–87% (Fig. 3).

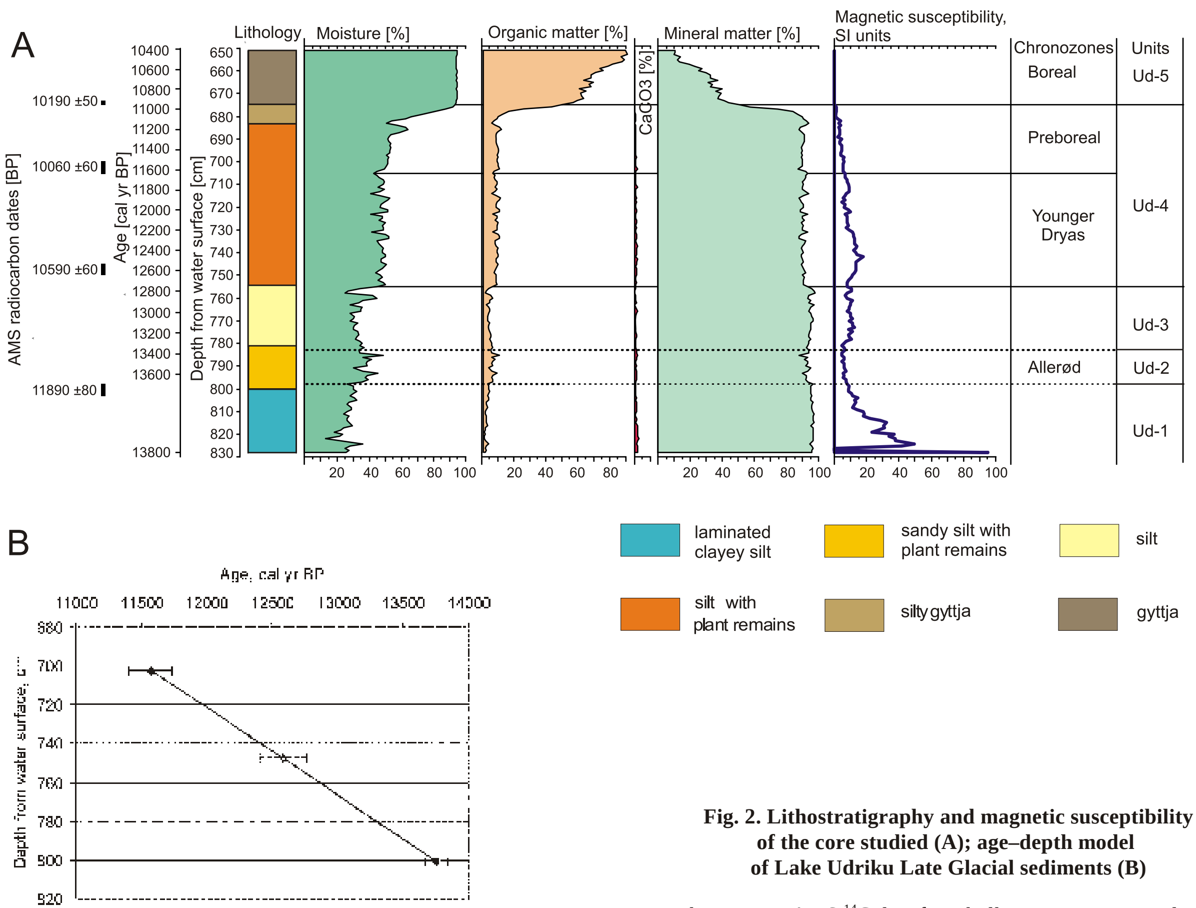

Fig. 2. Lithostratigraphy and magnetic susceptibility of the core studied (A); age–depth model of Lake Udriku Late Glacial sediments (B)

The topmost AMS ^{14}C date from bulk gyttja is not considered, as it does not agree with the following dates

Unit Ud-4, **755–675 cm**, is silt rich in plant remains with 5–10% OM, 17–28% sand and 71–83% silt. Two AMS radiocarbon dates, 12 770–12 410 cal yr BP and 11 750–11 405 cal yr BP (Table 1; Fig. 2B) provide evidence of deposition during the Younger Dryas Stadial. Five beige sandy layers at the basal part of unit Ud-4 coincide with the Allerød/Younger Dryas boundary.

Unit Ud-5, **675–650 cm**, is dark brown gyttja that grades to silt at its lower limit. Sediments in Ud-5 contain 14–20% sand, 80–86% silt (Fig. 3), and up to 90% OM (Fig. 2A).

All samples from the Late Glacial time period were overwhelmingly dominated by high silt fractions, with values ranging from 61 to 86% of the total grain-size distribution (Fig. 3B). The carbonate content was very low, with values of 1–2%, throughout the sediment core studied and the moisture content was in accord with the OM content (Fig. 2A). The average sedimentation rate was about 0.69 mm yr^{-1}during the Allerød Interstadial but decreased to 0.45 mm yr^{-1} during the Younger Dryas.

The magnetic susceptibility values were highest in the basal laminated clayey silt layer (Ud-1), decreased in the uppermost silty deposits and were zero in the gyttja where the mineral particle content decreased from 40 to 20% (Fig. 2A). The most distinct change in magnetic susceptibility was recorded at the transition from laminated clayey silt (glaciolacustrine sediment) to sandy silt (limnic sediment).

MACROFOSSILS

In the current study, attention was paid to macrofossil assemblages in the Late Glacial sediments (Fig. 4), which are a good indicator of local vegetation and water level changes (Digerfeldt, 1988; Gaillard and Birks, 2007). Besides taxa, the content of coarse detritus is a valuable component in macrofossil analyses. This is because sediment deposited in shallow water and close to the shore contains a larger amount of coarse detritus from terrestrial plant remains than deep-water sediments do (Digerfeldt, 1988). The section analysed covers the approximate time span of 13 800–11 000 cal yr BP (Fig. 4). The temporal resolution of plant macrofossil samples was high, especially in the lowermost portion where approximately two hundred years are represented by seven samples (Fig. 4). The plant macrofossil assemblage from Lake Udriku consists of 25 plant species and genera, with the dominant species typically represented by cold-tolerant and boreal plants. Two Charales were also identified. The macrofossil diagram was divided into five zones and displayed several sharp changes (Fig. 4).

In the lowermost zone MA-1 (828–800 cm) five plant taxa were recognized: individual *Silene* sp., *Ranunculus* sect *Batrachium* and *Nitella*, a small number of *Dryas octopetala* and abundant *Salix polaris* leaf fragments (Fig. 4). One sample also contained cladoceran (*Daphnia*) remains. The number of *Salix polaris* decreased sharply and the *Dryas octopetala* curve

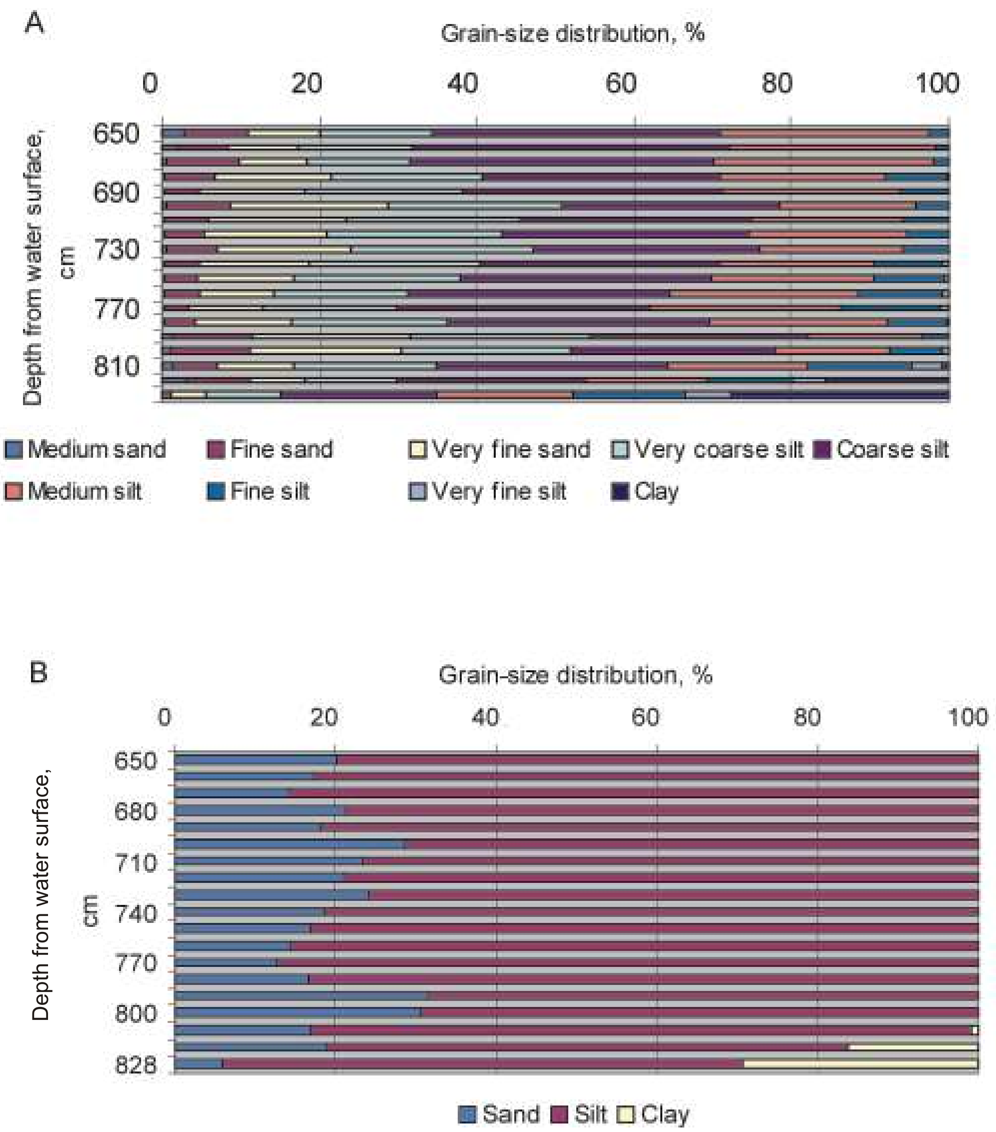

Fig. 3. Grain-size distribution of Lake Udriku sediments (A) with indication of the summary grain-size (B)

increased at the zone upper limit. At the core depth of 822–821 cm increased coarse detritus has been observed.

In zone MA-2 (800–780 cm) seven different plant taxa were recorded, with *Dryas octopetala* leaves and *Daphnia* spp. ephippia being present throughout.

The next zone MA-3 (780–755 cm) was rich in macroremains and a total of 18 taxa were identified. *Dryas octopetala*, *Ranunculus* sect *Batrachium* and *Nitella* were represented continuously and had maxima in this zone, but other taxa (Poaceae, Asteraceae, *Saxifraga etc.*) occurred sporadically and in low amounts. *Daphnia* spp. ephippia was still continuously present.

Zone MA-4 (755–705 cm) was characterized by a low abundance and number of plant remains. Only *Nitella* was present throughout the lower portion of the zone, but it decreased abruptly at a core depth of 740 cm. In the upper portion of the zone (735–705 cm), the light-demanding *Dryas octopetala* reappeared and has a slight peak, whereas *Ranunculus* sect *Batrachium* and *Nitella* oospores disappeared. The total number of identified fossils decreased to six. *Daphnia* occurred only sporadically in this zone.

In the topmost zone MA-5 (705–675 cm) different species of *Potamogeton* appeared and the *Ranunculus* sect *Batrachium* concentration increased slightly. *Potamogeton filiformis* is regarded as an alkaliphilous species, which occurs today in the large Estonian lakes Peipsi and Võrtsjärv as a relic from the Late Glacial period (Mäemets, 2002). The topmost portion of sediment 675–650 cm (unit Ud-5) was not examined.

DISCUSSION

DEGLACIATION PATTERN

The calibrated radiocarbon ages from terrestrial macroremains were in correct stratigraphic order and con-

Table 1

AMS ^{14}C dates from the Lake Udriku sequence

Sample depth [cm]	^{14}C age [yr BP]	Lab. number	Cal. ^{14}C age [yr BP] 68% probability	Dated material
675–673	10 190 +50	Poz-31429	11 990–11 805	Bulk gyttja
705–700	10 060 +60	Poz-30769	11 750–11 405	*Dryas* leaves
750–745	10 590 +60	Poz-30429	12 770–12 410	*Dryas* leaves
803–798	11 890 +80	Poz-30430	13 835–13 665	*Dryas* leaves

strained the start of the lacustrine sedimentation. The age-depth model presented in Figure 2B is in good agreement with the model from the Haljala site (Saarse *et al*., 2009), supporting the idea that ice retreated from the northern slope of the Pandivere Upland not later than 13 800 cal yr BP. This is 300–500 years earlier than previously suggested (Vassiljev *et al*., 2005; Saarse *et al*., 2007; Rosentau *et al*., 2009). The ice recession could have occurred even earlier, as lacustrine sedimentation may be delayed by a hundred years (Warner *et al*., 1991). The AMS ^{14}C dates from Udriku and Haljala were consistent with the ice position chart, which indicates that the Udriku area deglaciated at almost the same time as Haljala (Ramsay, 1929; Rähni, 1961).

The esker ridges, kame fields and the Udriku depression between them were formed during the ice retreat from the northern slope of the Pandivere Upland (Fig. 1). Obviously, eskers melted out of the ice first and were followed by kame fields and glaciodepressions. The AMS ^{14}C date from the basal clayey silt (803–798 cm, 13 750 ±85 cal yr BP, Poz-30430) matches the Allerød age and corresponds to the OSL date for sand from the Pikassaare kame field (13 700 yr BP; Raukas and Stankowski, 2005). However, the AMS ^{14}C date is about 700 years older than the ^{10}Be date (13 060 ±1120, EST-12; Rinterknecht *et al*., 2006) of the Kallukse Lodikivi boulder from 7.5 km east of Lake Udriku. Thus, we suggest that the Lake Udriku Basin was established not later than 13 800 cal yr BP as a sheltered bay of the Baltic Ice Lake (BIL), which (according to reconstruction) invaded areas below 90 m a.s.l. (Vassiljev, pers. comm.). The palaeogeographic reconstruction did not firmly establish the connection between the BIL and the Udriku Basin, as the threshold of the latter is covered by peat of unknown thickness. Therefore, peat was not removed from the simulated water surface and the possible spillways in Figure 1B are denoted by a question mark. However, laminated sediments in the bottom of the Udriku Basin, which were deposited when the remnants of the ice melted, indicate a connection between Udriku Basin and the BIL.

PALAEOENVIRONMENTAL CHANGES

ALLERØD

The Lake Udriku sediment record began 13 800 cal yr BP with clayey silt deposition containing low amounts of OM (Fig. 2A). The minerogenic material content, carried into the basin from the melting ice remnants and surrounding esker ridges, was high. The macrofossil diagram is relatively poor in taxa (MA-1, Fig. 4), indicating periglacial conditions with nearly bare ground close to a widespread occurrence of dead ice and permafrost. The dominant species was *Salix polaris*, which has been reported as a pioneering dwarf shrub in studies of northern areas (Birks, 1994) and Southern Sweden and Denmark (Bennike *et al*., 2004). However, these typical snow-bed dwarf shrub leaves may be over-represented in sediments due to their large number and good preservability (Korsager *et al*., 2003). As sedimentation took place in a lagoon of the BIL, the past lake level, the high sedimentation rate and barren soils may have also influenced the macrofossil composition (Väliranta, 2006*a*, *b*).

A sharp increase in the sandy fraction at a core depth 800 cm (*ca*. 13 700 cal yr BP) obviously corresponds to the isolation contact that resulted in the separation of Lake Udriku from the BIL and the formation of different water bodies. At this contact, the sand fraction content increased from 18 to 31% (Fig. 3B) and the magnetic susceptibility decreased considerably (Fig. 2A), indicating a change in the sediment source during the isolation event. At the same time, a notable change in the vegetation assemblages occurred: *Salix polaris* remains disappeared almost completely and were replaced by *Dryas octopetala*, which is another plant species common in Late Glacial sediments (MA-2, Fig. 4). The remainder of the plant assemblages consisted of a few grasses and sedges. According to Lowe *et al*. (2008), this corresponds to GI-1b, a short cooling episode within the so-called Allerød warming.

The next zone (MA-3, Fig. 4) is characterized by a variable vegetation succession. The dominant terrestrial species was still *Dryas octopetala*, occurring among relatively abundant macroremains. The assemblage consisting of *Papaver*, *Rumex* and two species of *Saxifraga* reflects suitable conditions for the development of variable terrestrial plant cover. Conversely, the presence of telmatic species such as *Carex, Juncus* and *Luzula* indicates the proximity of wetland. In this zone, aqueous organisms were also represented in larger numbers. *Ranunculus* sect *Batrachium* seeds were abundant, as were oospores of the stonewort genus *Nitella*. Both of these aquatic species are common colonisers of newly formed water bodies and are usually found in large quantities (Birks, 2000). In the Udriku sequence, *Nitella* was first recorded at about 13 800 cal yr BP and *Ranunculus* sect *Batrachium ca*. 13 750 cal yr BP, but their maxima occurred later: *Nitella* had a peak *ca*. 13 000 cal yr BP, and *Ranunculus* sect *Batrachium* peaked at the end of the Allerød (Fig. 4). As for water plants, *Potamogeton filiformis*

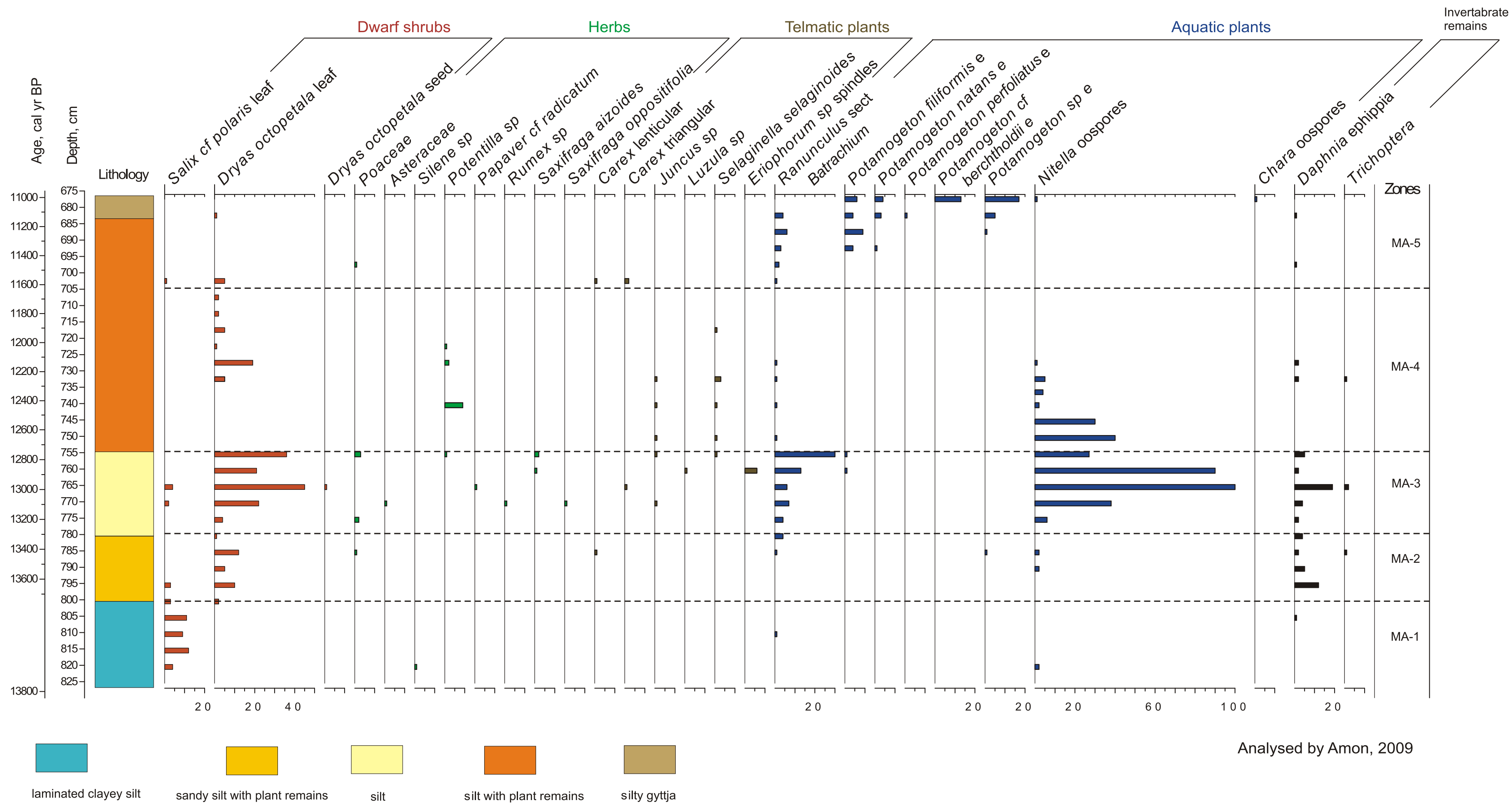

Fig. 4. Plant macrofossil diagram from Lake Udriku, displaying macrofossils (number of specimens per sample)

m – megaspore (*Selaginella selaginoides*), e – endocarp (Potamogetonaceae); sedges (*Carex*) are divided into two types based on their morphology: triangular-shaped and lens-shaped seeds were found, which have a short lag time because they are generated every year, are dispersed by water and are therefore not dependent on soils (Iversen, 1954). The mean July temperature could have been about 8–10°C considering the temperature requirements that allow *Potamogeton filiformis* and *Ranunculus* sect *Batrachium* to generate during this warmer episode (Isarin and Bohncke, 1999; Gaillard and Birks, 2007). In conclusion, the increased temperature during the Allerød warming obviously affected water plant distribution in Lake Udriku and accumulation of organic debris in the sediments. The light-demanding *Dryas octopetala* was present in significant amounts and the landscape around Lake Udriku was likely open during this period.

YOUNGER DRYAS

The temperature decreased during the Younger Dryas stadial (12 700–11 600 cal yr BP), especially in wintertime (Denton *et al*., 2005), due to a shift of the North Atlantic polar front (Bard *et al*., 1987; Alley, 2000), which brought about the dominance of herb and shrub vegetation, at least in the areas surrounding Haljala (Saarse *et al*., 2009). At the Allerød–Younger Dryas lithostratigraphic boundary (755 cm), moisture and OM content slightly increased and mineral compounds decreased (Fig. 2A). Increasing sand fraction proportions (Fig. 3) suggest a lowering of the water level and the erosion of the exposed sandy shores to a greater extent than was previously seen. The abundance and diversity of macroremains declined (MA-4, Fig. 4), as relatively cool climate inhibited the spread of aquatic plants and animals (Birks, 2000).

The reaction of vegetation during the Younger Dryas stadial (Ma-4) can be separated into two parts. *Dryas octopetala* and *Ranunculus* sect *Batrachium*, two dominant plant species of the previous warming episode, disappeared in the lower part of MA-4 (Fig. 4). The macrofossils that were found consisted of a few species of different herbs and telmatic plants (*Potentilla* sp., *Juncus*, *Selaginella selaginoides*) and a decreased number of *Nitella* oospores. In the upper part of Ma-4, at 12 300 cal yr BP, *Dryas octopetala* reappeared confirming tundra-like conditions. The drop in the abundance of *Nitella* oospores in samples may indicate unfavourable water conditions and prolonged ice cover (Birks, 2000; Kultti *et al*., 2003). The establishment of treeless shrub tundra with herbs, especially open habitat taxa, shows a reversal to colder and drier conditions (Pirrus and Sarv, 1968; Saarse *et al*., 2009) and is described as “steppe tundra” on the Karelian Isthmus (Subetto *et al*., 2002).

EARLY HOLOCENE

The beginning of the Holocene is shown in the Udriku section at 11 600 cal yr BP (705 cm) by a silt layer deposition (Fig. 2A). The transition from the Younger Dryas to the Holocene is distinct in changes in plant community (MA-5, Fig. 4). The characteristic arctic species, *Dryas octopetala*, almost completely disappeared, while *Ranunculus* sect *Batrachium* reappeared together with different species of the genus *Potamogeton*. The mean summer temperature could have been above 9°C, referring to the *Potamogeton perfoliatus* modern range limit at the Arctic tree-line (Bennike *et al*., 2004). *Daphnia* ephippia and the first single oospore of the genus *Chara* were found in this zone.

The sedimentation change in Lake Udriku at the Preboreal–Boreal limit, about 11 000 cal yr BP, coincides with the start of peat accumulation in the bog surrounding the lake (Veber, 1965). The topmost black gyttja in Lake Udriku (Fig. 2A) was mostly formed from decomposed organic debris and humic acids that infiltrated into the lake from the surrounding bog. The elemental composition of gyttja showed organic carbon saturation (C_{org} – 44–58%), but a low content of nitrogen compounds (1.4–2.0%; Saarse, 1994). This elemental composition and C/N ratio is typical of peat and peaty gyttja that is still depositing in the littoral zone of a lake.

TREE-LINE ADVANCES IN NORTHERN ESTONIA

Tree-line dynamics during the Late Quaternary have been discussed in several studies using plant macrofossil data or macroscopic charcoal (Willis and van Andel, 2004; Binney *et al*., 2009). Unfortunately, not much macrofossil data is available from the south-east sector of the last glaciation. Recent data from Latvia (Heikkilä *et al*., 2009) and Southern Estonia adds information about the reintroduction of tree species following the glaciation in the eastern Baltic. Plant macrofossil analysis from two localities of Southern Estonia confirmed the reintroduction of *Betula* sect *Albae* (tree birch) at 13 500–13 400 cal yr BP. The Lake Udriku record (about 200 km north of these localities), however, did not show tree birch immigration during the Late Glacial period and thus suggested local treeless vegetation. As the coring site is located in the central part of the lake, the macrofossil record cannot adequately reflect vegetation on the terrain. In contrast to Udriku, the Haljala pollen record indicated that a woody tundra environment was already present in the Allerød (Saarse *et al*., 2009). The ground layer contained *Artemisia*, Chenopodiaceae, Poaceae, Carophyllaceae and Asteraceae, whereas *Betula* and *Pinus* could have formed sparse woody stands where heliophytic species had developed (Saarse *et al*., 2009). Still, according to Birks and Birks (2000), pollen data should be handled with caution in Late Glacial studies.

In many studies focussing on the Late Glacial period the vegetation record begins with aquatic plants (Birks, 2000; Wohlfarth *et al*., 2002; Subetto *et al*., 2002). This is not the case in Udriku, where *Salix polaris* was the prevalent macrofossil in the lower part of the sequence. Aquatic plants were present in larger quantities later in the Allerød, but disappeared almost completely in the Younger Dryas. Patterns similar to the Udriku macrofossil record and plant succession were described for Russian Karelia (Lake Tambichozero), where lacustrine sedimentation also started 13 700 cal yr BP (Wohlfarth *et al*., 2002). The lower part of the core contained a plant community similar to that of Lake Udriku (dwarf shrubs, grasses, *Nitella* oospores). Another similarity is the absence of trees during the warmest period of the Allerød. The first occurrence of the seeds of *Betula pubescens* (tree birch) in Lake Tambichozero was recorded at approximately 11 000 cal yr BP (Wohlfarth *et al*., 2002), but in the

Llet-Ti site (Usa Basin, northern taiga) it was already seen at approximately 12 700 cal yr BP (Väliranta *et al.*, 2006).

CONCLUSIONS

1. Plant macrofossils, AMS ^{14}C dates and lithological parameters were used to interpret the environmental history of Lake Udriku from the Late Glacial period to the Holocene.

2. Five lithostratigraphical units were differentiated. These units vary in grain-size distribution, LOI results and magnetic susceptibility.

3. The macrofossil diagram shows the local vegetation development from Late Glacial pioneer communities to early Holocene communities.

4. By 13 800 cal yr BP, the surroundings of Lake Udriku were freed of ice. This is confirmed by the age and finds of *Salix polaris* and *Dryas octopetala* remnants in limnoglacial sediments.

5. The diversity of identified plant taxa was highest in the Allerød warm episode between 13 100 and 12 700 cal yr BP and decreased considerably during the Younger Dryas.

6. A distinct change in plant community at about 11 600 cal yr BP indicates the major climatic warming.

7. Both the Haljala and Udriku sites show evidence that the northern slope of the Pandivere Upland deglaciated by 13 800 cal yr BP. This is approximately 500 years earlier than has been previously suggested.

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