

## Development of the late glacial Baltic basin and the succession of vegetation cover as revealed at Palaeolake Haljala, northern Estonia

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**Abstract.** The 4.5 m thick Haljala sequence in North Estonia was studied to provide information on palaeoenvironmental changes between 13 800 and 11 300 cal yr BP. Late glacial environmental history of North Estonia was reconstructed using AMS-dated pollen record, sediment composition, plant macrofossils, and ostracods. The obtained data show environmental fluctuations that are linked to the climate shifts of the Last Termination in the North Atlantic region. Decrease in the arboreal pollen accumulation rate around 13 700–13 600 and 13 300–13 100 cal yr BP refers to short deterioration of climate within the Allerød Interstadial and has been correlated with the cooling of the Greenland Interstadial GI-1c and GI-1b events, respectively. Between 13 100 and 12 850 cal yr BP the pollen accumulation rate of trees, shrubs, and herb as well as organic matter increased, indicating short-term climate amelioration and establishment of pine-birch woods. This change has been correlated with the GI-1a event. Climate deterioration during the Younger Dryas (GS-1) was inferred from the reduction of tree pollen and flourishing of cold-tolerant species, such as *Artemisia*, Chenopodiaceae, and Cyperaceae. New data show that ice cover of the Pandivere Upland started to perish already about 13 800 cal yr BP.

**Key words:** late glacial, pollen, plant macrofossils, LOI, <sup>14</sup>C dates, ostracods, North Estonia.

### INTRODUCTION

The Pandivere ice-marginal formations were shaped by the ice streams of the retreating Scandinavian ice sheet. The proglacial lake systems that developed in front of the decaying ice margin, their formation and configuration were controlled by geology, local topography, and dynamics of the ice sheet as well as climatic fluctuations. The late glacial history of Estonia has been investigated for a long time, yet any palaeogeographical and palaeoenvironmental reconstructions of the area at the closing stage of the last glaciation have been hampered due to lack of chronology. To fill this gap, we revisited the Haljala site and performed multi-proxy studies of sediment cores.

The Haljala overgrown lake was first examined by R. Männil and R. Pirrus, who studied the Holocene lacustrine lime distribution and palynostratigraphy (Männil 1961; Männil & Pirrus 1963). The pollen diagrams by Pirrus (Männil & Pirrus 1963; Pirrus 1965; Pirrus & Sarv 1968) provided a general picture on the vegetation succession and climatic history during the late glacial. On the basis of pollen composition she differentiated the Allerød and the Younger Dryas sediments. However,

the palynological data suffered from simplified taxonomic composition (mostly tree pollen accounts were included), sparse resolution between pollen samples, limited pollen sums, absence of pollen concentration data, and, most importantly, lack of radiocarbon dates, which hindered detailed correlation of the environmental changes.

Late glacial deposits of North Estonia have only been sporadically radiocarbon dated at Kunda, Loobu, Viitna, Äntu, and Räätsma (Table 1). However, according to Pirrus (1976; Karukäpp et al. 1996), dates from Kunda, Viitna, and Loobu were problematic, seemed to be too old and did not match with pollen stratigraphy (Pirrus 1976; Pirrus & Raukas 1996). The AMS <sup>14</sup>C date 10 170 ± 95 (11 885 ± 260 cal yr BP; Ukkonen et al. 2005) from a reindeer antler at Kunda, buried in lacustrine lime, seems to be correct and confirms that lacustrine lime started to deposit at the late glacial/Holocene boundary or even earlier (Sohar & Kalm 2008).

The palaeolake at Haljala was an ancient lagoon of the Baltic Ice Lake (BIL), which isolated from the BIL during the proglacial Lake Kemba (A<sub>2</sub>) phase (Saarse et al. 2007). The former palaeolake, today a bog, which has been drained by numerous ditches and mainly reclaimed and transformed into pasture, is located in the

**Table 1.** Grain size distribution of sediments in the Haljala sequence

Depth, cm	Clay, >0.002 mm	Very fine silt, 0.002–0.004 mm	Fine silt, 0.004–0.006 mm	Medium silt, 0.006–0.02 mm	Coarse silt, 0.02–0.30 mm	Very coarse silt, 0.30–0.63 mm	Sand, 0.63–2 mm	Sediment description
100	3.59	3.73	3.83	10.88	24.25	29.71	24.01	Calcareous sandy silt
140	22.42	22.87	26.23	14.06	4.76	4.67	5.00	Clayey silt
180	10.66	24.18	30.37	16.76	6.14	6.31	5.58	Clayey silt
220	17.08	22.94	27.30	15.51	5.74	5.96	5.47	Clayey silt
260	6.12	19.09	27.73	19.95	8.95	9.84	8.32	Fine-grained silt
320	6.98	23.19	28.96	17.73	7.33	8.06	7.75	Fine-grained silt
360	11.19	25.59	28.57	16.08	5.95	6.24	6.38	Clayey silt
400	20.11	28.42	24.89	12.18	4.41	4.75	5.24	Clayey silt
440	17.77	28.61	27.57	13.35	4.13	4.00	4.57	Clayey silt
460	18.19	24.97	26.70	14.26	5.43	5.05	5.40	Clayey silt
480	11.27	26.47	29.52	15.54	5.62	5.70	5.88	Fine-grained silt

depression above a 20 m deep buried valley. The buried valley is filled in with till, clayey silt, lacustrine lime, and peat. The distribution of lacustrine lime roughly outlines the ancient lake about 4.6 km long and 200 m wide, in the north dammed up by a spit, which was formed during the proglacial lake A<sub>2</sub> phase (Saarse et al. 2007).

The key objective of the present study was to determine the chronology of the late glacial vegetation succession, as well as environmental and climatic changes, and to adjust the timing of ice recession in North Estonia. For this purpose we used the analyses of AMS <sup>14</sup>C dating, lithological composition, pollen stratigraphy, ostracods, and macrofossil remains of plants, mosses, and algae.

## MATERIAL AND METHODS

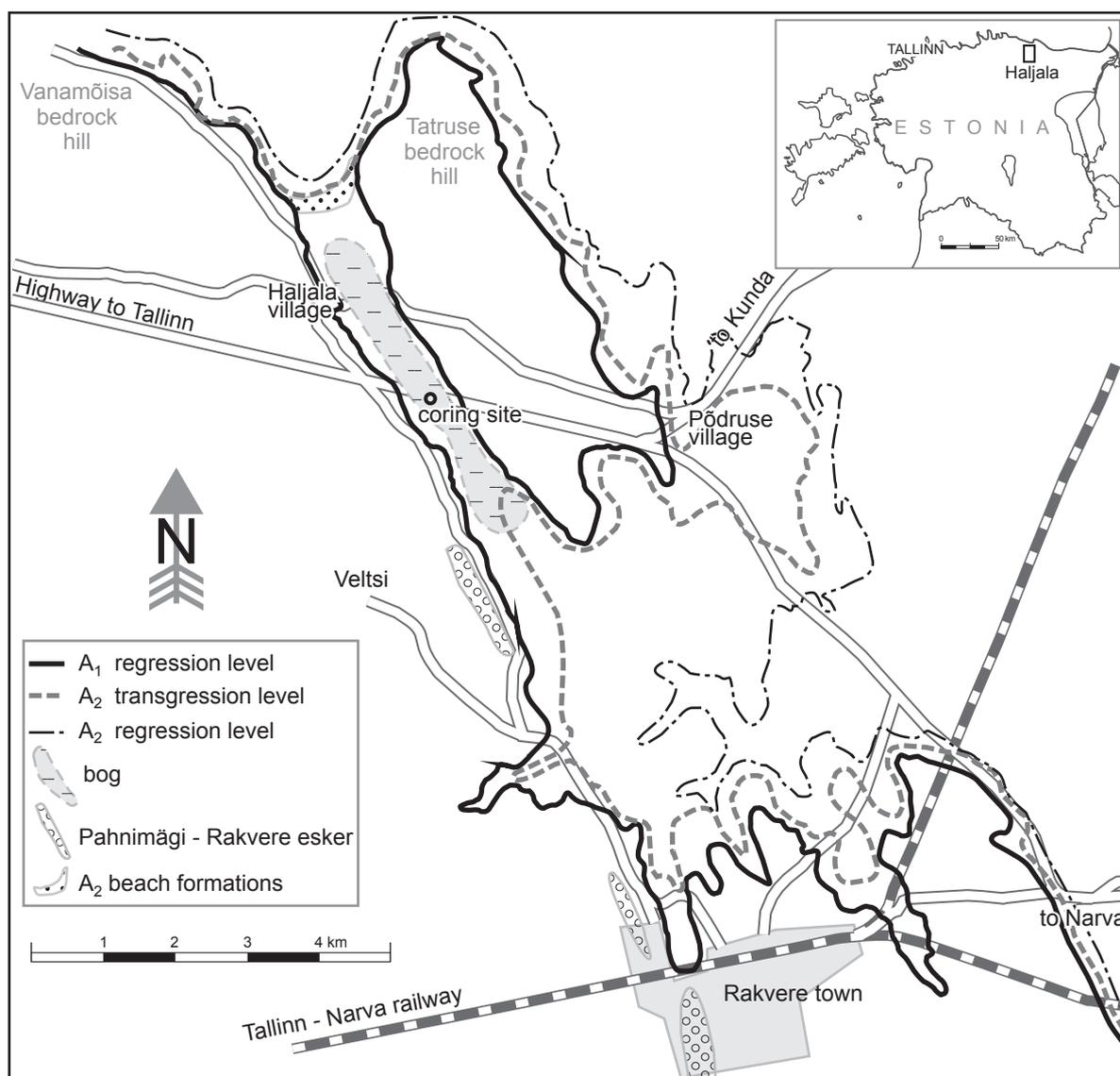
The coring site in Palaeolake Haljala (59°25'27"N, 26°17'42"E) at an elevation of 67.4 m a.s.l is located about 90 km east of Tallinn, near the crossing of Rakvere–Võsu and Tallinn–Narva highways (Fig. 1), just where the road crosses the main draining trench. Multiple 1 m long sediment cores were taken from the central part of the ancient lake with a Belarus peat sampler in 2006 and 2007. One centimetre thick sub-samples for loss-on-ignition (LOI) analyses were taken continuously. Bulk samples were dried at 105°C overnight, and burnt at 525 and 900°C to calculate moisture, organic matter (OM), carbonate, and minerogenic compounds. Loss-on-ignition analyses were performed from all cores and served as a basis for the correlation of cores. Grain size distribution of clayey deposits untreated by chemicals was determined in the Institute of Ecology at Tallinn

University with a Fritsch Analysette 22 laser particle size analyser.

Sub-samples for pollen analyses (2 cm<sup>3</sup>) were taken at 5 cm intervals and prepared according to Berglund & Ralska-Jasiewiczowa (1986). In addition, minerogenic samples were treated with concentrated hydrofluoric acid. *Lycopodium* tablets were added to calculate pollen concentration (Stockmarr 1971). Up to 350 terrestrial pollen grains were counted. Pollen identification followed Moor et al. (1991). Both the percentage and pollen accumulation rate (PAR) diagrams were constructed using TILIA and TGView programs (Grimm 2000). The zonation of pollen data is based on the constrained cluster analysis by the sum of squares (CONISS) method. Palynological richness was estimated by rarefaction analysis (Birks & Line 1992) using the PSIMPOLL 4.10 program (Bennett 1994, 1998). All identified terrestrial pollen taxa were included and standardized to the lowest pollen sum.

Macrofossils were extracted by soaking 5 cm thick silt samples in water and sieving through a 0.25 mm mesh. Thirteen samples were prepared for fossil seed and moss fragment analysis. The samples were treated according to the method proposed by Birks (2001). Ostracod subfossils were picked out of five sediment samples (sample size ~25 cm<sup>3</sup>) under the binocular microscope using a fine wet brush. Species identification and ecological preferences are based on the monograph by Meisch (2000). Ostracod shells and valves were photographed by the scanning electron microscope at the Natural History Museum, London, UK.

Accelerator mass spectrometry <sup>14</sup>C radiocarbon dating was performed in Poznan and Uppsala Radiocarbon Laboratory and dates were calibrated on the basis of the IntCal04 calibration curve (Reimer et al. 2004) and



**Fig. 1.** Location of the study area, with the configuration of the ancient lake in the Haljala buried valley. The Haljala basin isolated at a sensitive time interval between the regressive phase of A<sub>1</sub> (Voose) and the transgressive phase of A<sub>2</sub> (Kemba), at around 13 000 cal yr BP.

the Calib Rev 5.0.1. program (Stuiver et al. 2005). All ages mentioned in text are calibrated years before AD 1950 (cal yr BP).

## RESULTS

### Sediment lithostratigraphy and grain size distribution

On the basis of grain size composition the sediment sequence was subdivided into five lithological units (Fig. 2; Table 1). The base of the studied sequence

consists of fine-grained grey silt overlain by alternating grey clayey and fine silt, and ends with greenish-grey calcareous sandy silt (Fig. 2). The grain size and LOI results revealed the homogeneous nature of silt, with clay fraction fluctuating within 7–22%, silt within 72–85%, and sand within 5–8%. The mineral matter content was between 90% and 95%. The content of OM in bottom clayey silt was low, around 1–2%, except between core depths of 340–460 cm and 210–225 cm, where it reached 4% and 7.3%, respectively (Fig. 2). The increased moisture, OM, and carbonate content and decreased sedimentation rate at 210–225 cm possibly suggest the

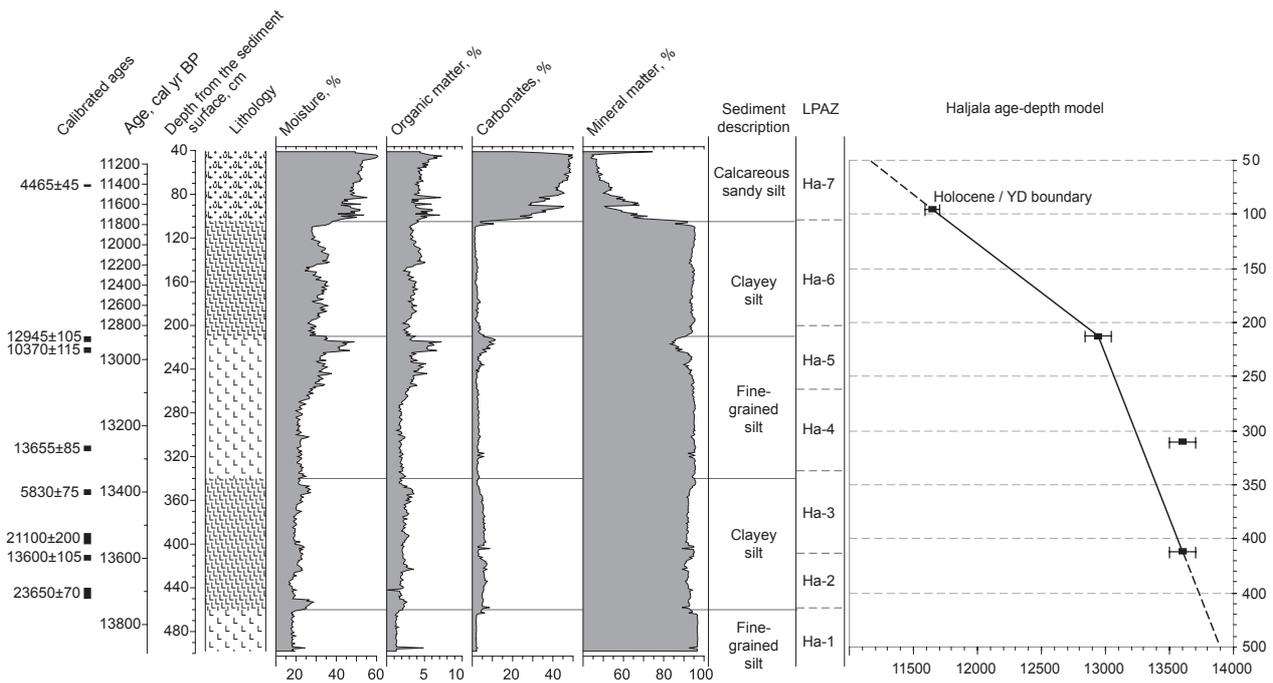


Fig. 2. Vertical distribution of moisture, organic matter, CaCO<sub>3</sub>, and mineral matter in the Haljala sediment core.

isolation of the basin. Transition from silt to calcareous silt was sharp, with carbonates reaching 45% and mineral matter decreasing to 50%. The sediment accumulation rate, ca 3 mm yr<sup>-1</sup> between 13 600 and 12 940 cal BP, indicates rapid influx of minerogenic sediments (Fig. 2). After that the sedimentation rate decreased, being roughly 0.9 mm yr<sup>-1</sup>.

### Chronology

Altogether eight levels in the Haljala sediment sequence were dated by the AMS <sup>14</sup>C technique (Table 2). Three datings of terrestrial macrofossils (Haljala 2, 4, and 7) gave ages consistent with sediment depth and pollen stratigraphy. However, at an earlier stage of investigations, when only small sediment samples were available, finds of terrestrial plant remains were scarce. Therefore unidentified pieces of organic debris were sent in for AMS dating. Three <sup>14</sup>C dates (Haljala 1, 3, and 5) provided too young ages, perhaps due to contamination

by root penetration from the surface or some other reason. Two dates (Haljala 6 and 8) were apparently too old in comparison with pollen stratigraphy and deglaciation chronology (Kalm 2006). Such discrepancy is not fully understandable, but it seems that selection of the dating material is crucial. Contamination during coring seems not to be an issue, as the obtained cores displayed well-preserved lamination (Fig. 3). Controversial dates were excluded from the age–depth model, which currently is based on three dates. The AMS date Haljala 2 (10 970 ± 150 <sup>14</sup>C yr BP; Poz-22529; 13 050–12 840 cal yr BP) marks the end of the warm episode before the Younger Dryas cooling and increase in arboreal pollen (AP) accumulation and concurrent decrease in non-arboreal pollen (NAP), first of all of *Artemisia*. The AMS dates Haljala 4 (11 780 ± 60 <sup>14</sup>C yr BP; Poz-22530; 13 740–13 570 cal yr BP) and Haljala 7 (11 750 ± 80 <sup>14</sup>C yr BP; Poz-22531; 13 705–13 495 cal yr BP) correspond to the Allerød. By extrapolation of radiocarbon dates the studied 4.5 m core represents

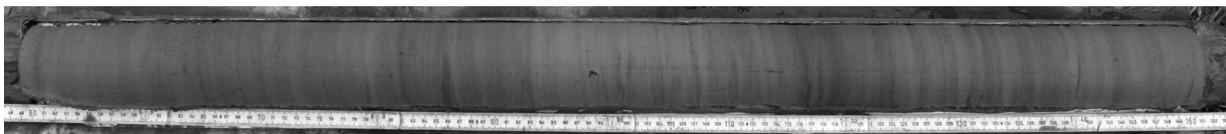


Fig. 3. The Haljala sediment core shows slight lamination. Photo by S. Veski.

**Table 2.** AMS radiocarbon dates calibrated according to Stuiver et al. (2005). Dates used for the age–depth curve reconstruction of the Haljala sediment record are marked with the asterisk. Radiocarbon laboratory codes: Poz, Poznan; Ua, Uppsala; TA, Tartu; Hela, Helsinki; Tln, Tallinn

Site/Sample number	Depth, cm	$^{14}\text{C}$ date, BP	Calibrated age, cal yr BP at 1 sigma	$\Delta^{13}\text{C}$ , ‰ PDB	Laboratory code	Dated material	References
Haljala 1	72–73	3 995 ± 35	4 465 ± 45	–	Poz-27420	Wood	Current study
Haljala 2	210–215	10 970 ± 150	12 945 ± 105*	–	Poz-22529	Terrestrial macrofossil	Current study
Haljala 3	220–225	9 205 ± 90	10 370 ± 115	–24.9	Ua-33185	Moss, leaf fragments	Current study
Haljala 4	310–315	11 780 ± 60	13 655 ± 85*	–	Poz-22530	Terrestrial macrofossil	Current study
Haljala 5	350–355	5 090 ± 35	5 830 ± 75	–	Poz-19615	Aquatic moss	Current study
Haljala 6	390–400	17 860 ± 65	21 100 ± 200	–30.8	Ua-33186	Moss, leaf fragments	Current study
Haljala 7	410–415	11 750 ± 80	13 600 ± 105*	–	Poz-22531	Terrestrial macrofossil	Current study
Haljala 8	440–450	23 650 ± 70	–	–31.1	Ua-33187	Seeds	Current study
Kunda	120–125	11 690 ± 150	13 550 ± 150	–	TA-194	Bryales moss from lacustrine lime	Pirrus 1976; Karukäpp et al. 1996
Kunda	100	10 170 ± 95	11 830 ± 210	–	Hela-597	Reindeer bone	Ukkonen et al. 2005
Viitna	812–822	10 515	12 470 ± 220	–	Tln-2147	Bulk gyttja	Saarse et al. 1998
Viitna	840–850	10 690 ± 100	12 745 ± 95	–	TA-443	Bulk gyttja	Saarse et al. 1998
Äntu	740–750	10 930 ± 200	12 930 ± 160	–	TA-2119	Plant remains	Saarse & Liiva 1995
Äntu	816	10 840 ± 60	12 845 ± 30	–19.6	Poz-19684	Gyttja	Sohar & Kalm 2008
Loobu	180	7 450 ± 40	8 265 ± 65	–	Poz-19616	Plant remains	Saarse unpubl.
Loobu	n.a.	13 070 ± 115	15 440 ± 200	–	TA-137	Plant remains	Pirrus 1976
Loobu	n.a.	14 725 ± 260	17 940 ± 540	–	TA-138	Plant remains	Pirrus 1976
Räätsma 1	540	12 040 ± 100	13 890 ± 100	–	TA-688	Bryales moss from sand	Ilves 1980
Räätsma 2	360–370	12 050 ± 120	13 910 ± 120	–	TA-687	Bryales moss from lacustrine lime	Ilves 1980

n.a., not available; – calibration is not possible.

a time span of ca 13 800–11 300 cal yr BP. Due to the scarcity of radiocarbon dates the sedimentation rate estimations should be considered as a first approximation and the pollen accumulation diagram should be interpreted accordingly. In addition, we used in the current study the event stratigraphic units of Greenland Ice Core 2005 (GICC05) and their ages based on dates as signed to the corresponding boundaries suggested by Lowe et al. (2008), originally put forward by Björck et al. (1998). All these dates are calibrated ages that correspond to AD 2000:

GI-1d – Older Dryas (14 100–13 950 cal yr BP);  
 GI-1c – Allerød warmer period (13 950–13 300 cal yr BP);  
 GI-1b – Allerød colder period (13 300–13 100 cal yr BP);  
 GI-1a – Allerød warmer period (13 100–12 900 cal yr BP);  
 GS-1 – Younger Dryas (12 900–11 700 cal yr BP).

### Palynostratigraphy

A total of 67 samples including 59 terrestrial taxa were analysed. Seven local pollen assemblage zones (LPAZ) were distinguished based on statistical evaluations of pollen spectra.

*LPAZ Ha-1 (498–458 cm; ca 13 800–13 750 cal yr BP; fine-grained silt)*

This LPAZ was characterized by upward increasing *Pinus* and rather stable *Betula* pollen around 20% (Fig. 4). *Juniperus* was present constantly, *Salix* sporadically. The percentage of *Alnus* (4–12%), *Picea* (8–17%), *Ulmus*, *Tilia*, *Populus*, *Fraxinus*, and *Corylus* pollen (QM – up to 7%) was rather high, indicating the redeposition phenomena, obviously from the Eemian deposits, whose outcrops are located on the islands of Prangli and Uhtju in the Gulf of Finland. The NAP content was around 25%, with Cyperaceae, Poaceae, *Artemisia*, and Chenopodiaceae dominating. *Betula nana* was present in low values (1–4%). The concentration of tree and shrub pollen fluctuated between 6000 and 15 000 grains cm<sup>-3</sup>, whereas herb values were over three times smaller (1900–5300 grains cm<sup>-3</sup>). Increase in *Pinus* pollen, together with decrease in *Betula*, *Picea*, *Juniperus*, and *Salix*, marked the upper boundary of the LPAZ. Such a pollen assemblage is characteristic of the late glacial, obviously of the beginning of the Allerød chronozone (Mangerud et al. 1974) and of GI-1c (13 950–13 300 cal yr BP; Lowe et al. 2008).

*LPAZ Ha-2 (458–408 cm; ca 13 750–13 600 cal yr BP, clayey silt)*

The LPAZ was marked by high values of AP (57–74%) and rather low values of herbs (13–21%; Fig. 4). Tree pollen maintained dominance but was fluctuating: *Pinus* within 19–47% and *Betula* within 9–29%. The curve of

*Picea* (2–7%), *Alnus*, and *Quercus* pollen was continuous, whereas the other QM taxa occurred sporadically. Non-arboreal pollen fluctuated between 20% and 40%. Poaceae, Cyperaceae, Chenopodiaceae, and *Artemisia* were present in almost equal amounts. At the *Pinus* peak around 430 cm *Betula nana* pollen disappeared and *Betula*, *Juniperus*, *Artemisia*, and *Cyperaceae* pollen decreased. *Salix* and *Juniperus* made a sporadic appearance throughout the zone. The concentration of tree pollen had decreased (3000–9700 grains cm<sup>-3</sup>), and that of shrubs fluctuated between 0 and 800 and of herbs between 700 and 3900 grains cm<sup>-3</sup>. This LPAZ corresponds to GI-1c, the Allerød warmer period (13 950–13 300 cal yr BP; Lowe et al. 2008), but supports the idea of a slight cooling inside GI-1c.

*LPAZ Ha-3 (408–333 cm, ca 13 600–13 300 cal yr BP, clayey silt)*

This LPAZ was characterized by irregular *Betula* and *Pinus* pollen curves; *Picea* and *Alnus* were present in almost equal values (Fig. 4). Total AP frequency was about 70%. *Salix* and *Juniperus* were more frequent than in the previous LPAZ. At the peak of *Pinus* pollen at 355 cm *Betula nana* and *Salix* pollen was missing and *Betula* had decreased. The proportion of *Artemisia* was decreased and that of Chenopodiaceae increased. The concentration of tree pollen increased and fluctuated between 6000 and 19 800 grains cm<sup>-3</sup>, that of shrubs between 150 and 1000 grains cm<sup>-3</sup>, and herbs between 2900 and 7100 grains cm<sup>-3</sup>.

*LPAZ-4 (333–258 cm, ca 13 300–13 100 cal yr BP, fine-grained silt)*

In LPAZ-4 pollen of *Picea* and thermophilous taxa, especially *Corylus* (Fig. 5), was abundant. *Pinus* was still dominant and *Betula* was subdominant. The percentages of trees and shrubs were high, 70–80. Herb pollen increased by the end of this zone, while tree pollen decreased. Pollen of aquatics was rare, but spores were represented by relatively high values (up to 21%). The concentration of tree pollen increased to 25 000 grains cm<sup>-3</sup> and that of herbs to 12 700 grains cm<sup>-3</sup>. The PAR of trees remained almost at the level of the previous LPAZ (2600–7300 grains cm<sup>-2</sup> yr<sup>-1</sup>), while that of shrubs (50–250 grains cm<sup>-2</sup> yr<sup>-1</sup>) and herbs (700–3800 grains cm<sup>-2</sup> yr<sup>-1</sup>) increased moderately (Fig. 5). This LPAZ correlates well with the Allerød cold event GI-1b (Lowe et al. 2008).

*LPAZ Ha-5 (258–200 cm, ca 13 100–12 800 cal yr BP, upper part of fine-grained silt and lower part of clayey silt)*

The LPAZ was determined by changes in the AP/NAP ratio. Herb pollen percentages had increased, especially

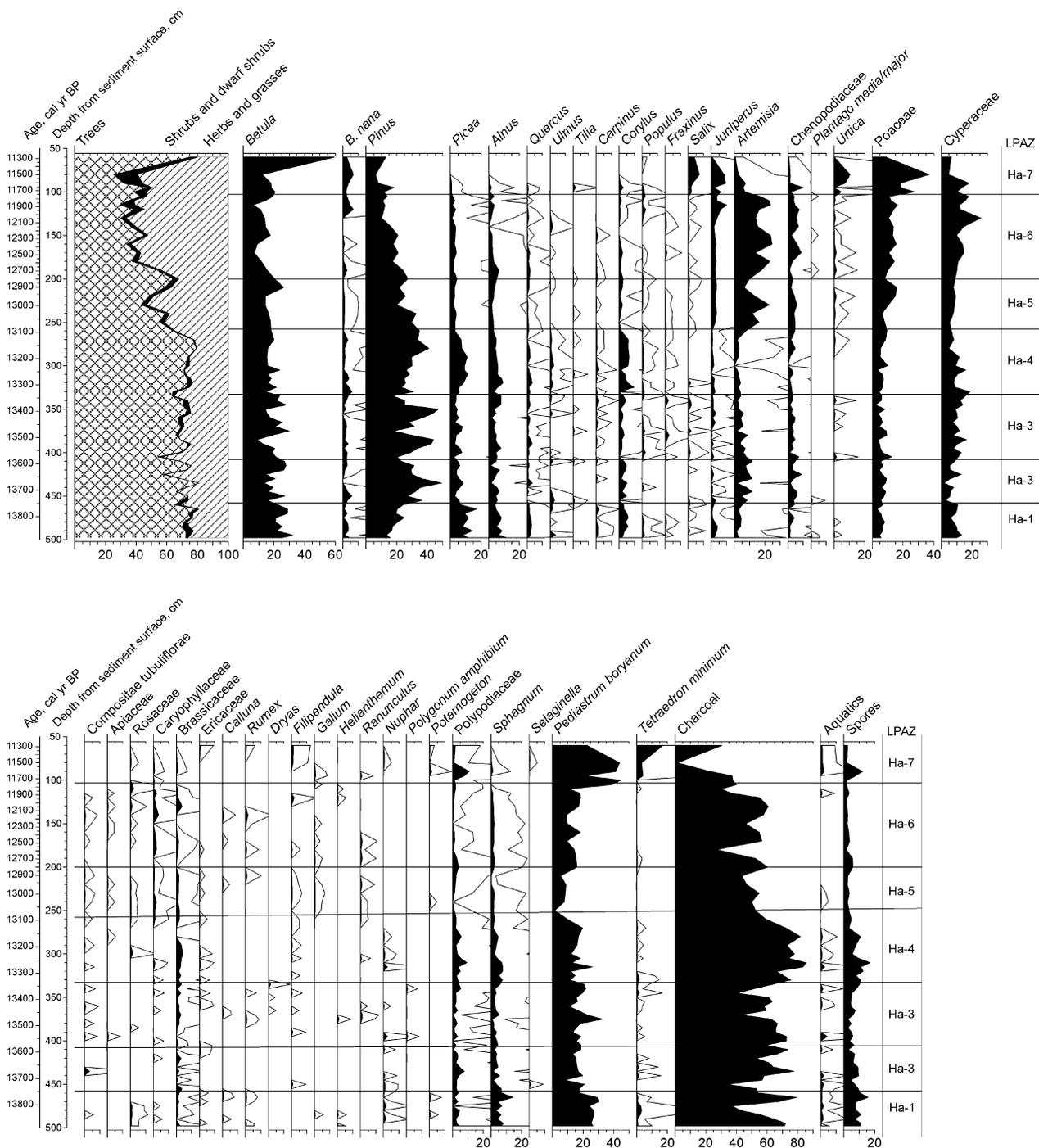


Fig. 4. Pollen diagram from the Haljala sediment core. Analyses by E. Niinemets.

of *Artemisia*, Poaceae, Cyperaceae, and Chenopodiaceae, while tree pollen percentages had decreased, first of all of *Pinus* and *Picea* (Fig. 4). *Juniperus* and *Artemisia* were the main taxa to profit from the decline in AP. They colonized fresh areas around Haljala, which emerged after the isolation of the basin from the

large proglacial lake that occurred between 13 000 and 12 900 cal yr BP. The concentration of tree pollen was high but irregular, reaching up to 22 800 grains cm<sup>-3</sup>, but declined to 11 800 grains cm<sup>-3</sup> at 230 cm. The PARs of trees (3700–6900 grains cm<sup>-2</sup> yr<sup>-1</sup>), shrubs (350–450 grains cm<sup>-2</sup> yr<sup>-1</sup>), and herbs (3500–4800 grains cm<sup>-2</sup> yr<sup>-1</sup>)

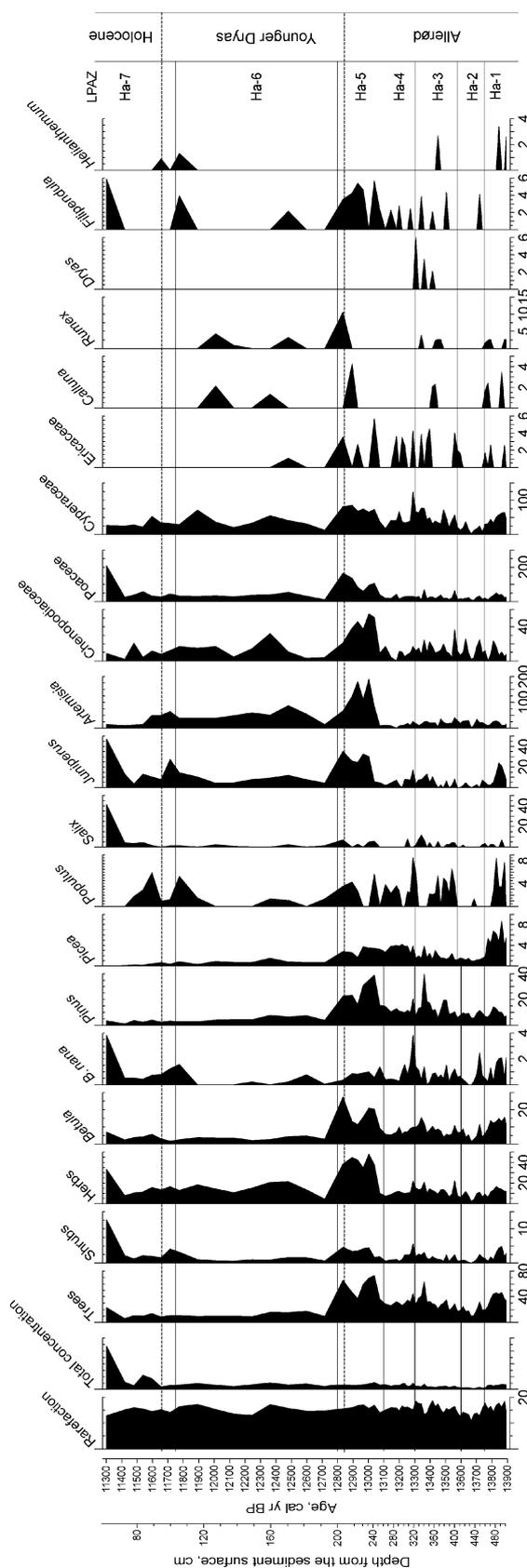


Fig. 5. Diagram of pollen accumulation rates from the Haljala sediment core.

reached their maxima at the LPAZ lower limit around 13 100 cal yr BP and decreased sharply at the LPAZ upper limit (Fig. 5). Pollen concentration remained high up to 12 500 cal yr BP. This LPAZ roughly coincides with GI-1a (13 100–12 900 cal yr BP).

*LPAZ Ha-6 (200–103 cm, 12 800–11 750 cal yr BP, clayey silt)*

This LPAZ was marked by the abundance of herb pollen, reaching 65% (Fig. 4). Cyperaceae and *Artemisia* had their maxima, 25% and 23%, respectively. *Pinus* pollen percentages decreased, but the frequency of *Picea* remained on the previous level. Shrubs, especially *Juniperus*, were abundantly present. The value of redeposited QM species had also decreased, particularly that of *Corylus*. Apart from NAP increase up to 22 300 grains cm<sup>-3</sup>, AP concentration decreased (7300 and 17 000 grains cm<sup>-3</sup>), referring to cooling in the Younger Dryas. The amounts of *Sphagnum* and *Pediastrum boryanum* spores increased. The concentration of shrubs also reached its maximum (600–4400 grains cm<sup>-3</sup>). The PAR of trees remained between 800 and 1800 grains cm<sup>-2</sup> yr<sup>-1</sup>, of shrubs between 50 and 400 grains cm<sup>-2</sup> yr<sup>-1</sup>, and of herbs between 440 and 2100 grains cm<sup>-2</sup> yr<sup>-1</sup> (Fig. 5). The LPAZ covers the GS-1 cold event of the Younger Dryas (12 900–11 700 cal yr BP; Lowe et al. 2008).

*LPAZ Ha-7 (103–60 cm, 11 750–11 300 cal yr BP, calcareous sandy silt)*

Near the lower limit of the LPAZ tree pollen percentages were the lowest throughout the studied sequence, but shrubs (*Betula nana*, *Juniperus*, and *Salix*) reached their maxima (Fig. 4). The share of *Artemisia* diminished, but Poaceae and *Urtica*, on the other hand, met their maxima. At the top of the LPAZ *Betula* pollen increased sharply to 80% and herb pollen decreased from 50% to 20%. Especially suffered Poaceae, Cyperaceae, *Artemisia*, and Chenopodiaceae; constituents of thermophilous trees *Quercetum mixtum* and *Picea* disappeared from the pollen spectra. The concentration of tree pollen fluctuated between 4000 and 11 500 grains cm<sup>-3</sup>, amounting to 61 500 grains cm<sup>-3</sup> in the topmost sample. The PARs of all taxa increased upwards: of tree pollen from 1000 to 2300 grains cm<sup>-2</sup> yr<sup>-1</sup>, shrubs from 200 to 1200 grains cm<sup>-2</sup> yr<sup>-1</sup>, and herbs from 1100 to 3300 grains cm<sup>-2</sup> yr<sup>-1</sup> (Fig. 5). This LPAZ represents the transition between the Younger Dryas and the Preboreal (Mangerud et al. 1974).

**Plant macroremains**

As silty sediments of Haljala were very poor in macroremains, almost the entire sequence was sieve-washed and macroscopic plant remains were picked out and

identified under the microscope to find suitable material for radiocarbon dating. The content of thirteen samples, prepared specifically for plant macrofossil analysis, is presented in Table 3. The small number of samples and their non-contiguous placement within the core does not allow drawing firm conclusions about the vegetation succession in and around the palaeolake of Haljala based on plant macrofossil analysis only. As the results of plant macrofossil analysis mainly reflect species from local vegetation, it is not surprising that most of the seeds and vegetative parts belonged to the aquatic species: *Ranunculus* sect *Batrachium*, Characeae, *Equisetum* sp., *Potamogeton* sp., and different aquatic mosses (*Drepanocladus* sp., *Scorpidium* sp.). Arctic species, which are characteristic of late glacial vegetation, were represented by *Dryas octopetala*, *Salix polaris*, and *Betula nana*. *Dryas octopetala*, a dwarf shrub indicating Arctic climate conditions, is evenly distributed over the analysed sequence, being present in six samples of thirteen. *Salix polaris*, which nowadays is growing in northern areas, occurs in one sample in the lower part of the sediment core. One *Salix* sp. leaf found was left undetermined to species level because of poor preservation. The cold-tolerate shrub, *Betula nana*, is found rarely in the Haljala sequence. At the same time *B. nana* remains (seeds, leaves, buds, catkin scales)

were present in different late glacial sequences in Europe (e.g. Wohlfarth et al. 2002) and in Estonia (L. Amon, unpublished data). It may be due to the small sample size in case of Haljala, but may also be limited by the lack of ecological conditions *B. nana* needed for spread, growth, and fructification.

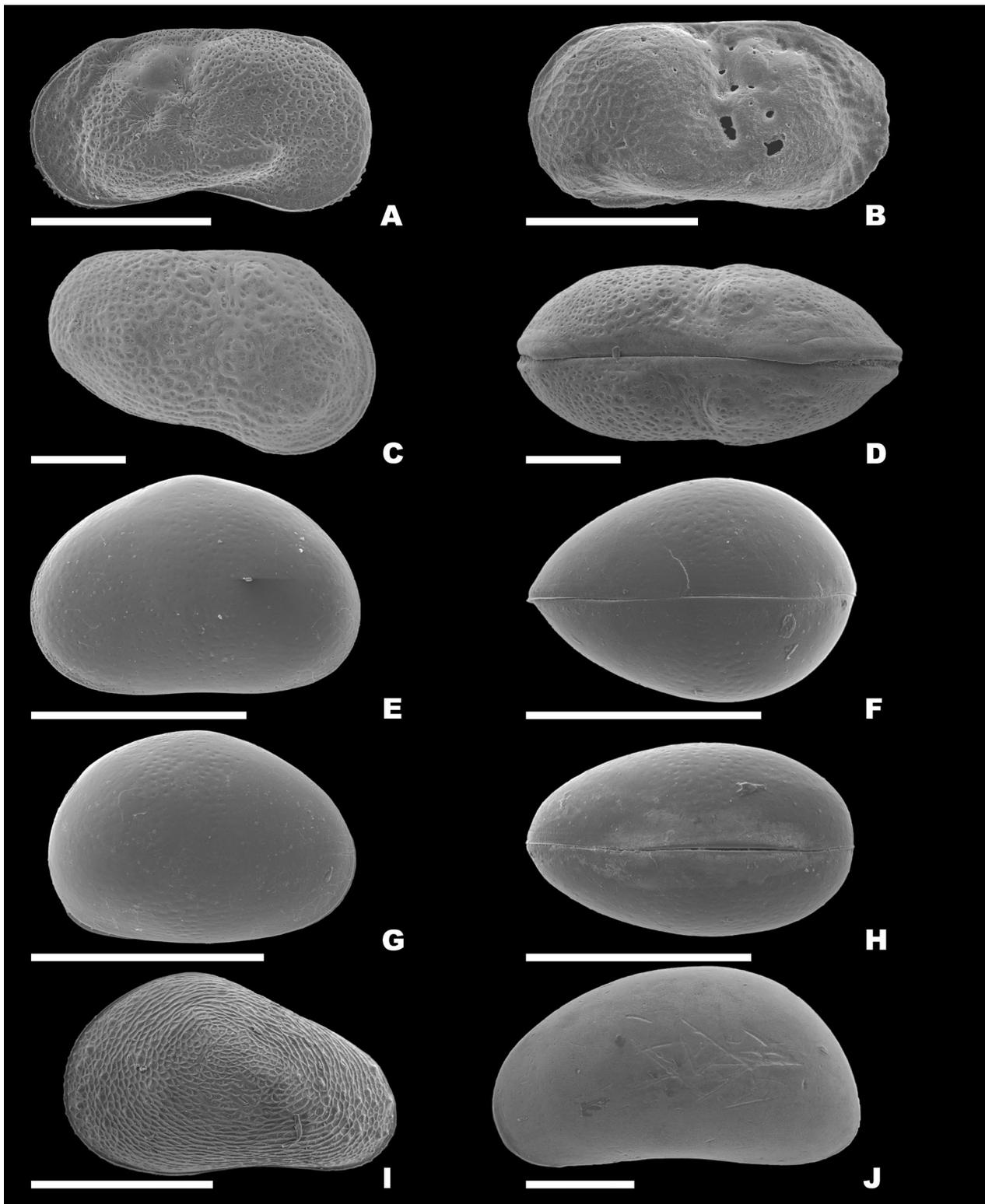
While browsing plant material for radiocarbon dating or identification for plant macrofossil analysis, pyritized and poorly preserved material was observed in several samples. Pyritization is a complex process in palaeobotany (Grimes et al. 2001), linked to decomposition of organic matter in the anoxic and reducing (water) environment (Yansa 1998). Organic material decaying in suitable environment is affected by sulphate-reducing bacteria, which mediates the formation of pyrite aggregates (Tovey & Yim 2002).

### Ostracods

Nine freshwater ostracod species were identified from the Haljala late glacial sediments: *Candona candida*, *Cyclocypris* cf. *laevis*, *Cyclocypris ovum*, *Cypridopsis vidua*, *Cytherissa lacustris*, *Eucypris* cf. *virens*, *Limnocythere inopinata*, *Limnocytherina sanctipatricii*, and *Pseudocandona compressa*. The most common species was *C. candida* (Fig. 6J), which tolerates a wide

**Table 3.** Macroremains from the Haljala core. Analyses by L. Amon

Depth, cm	Plant macrofossils and mosses identified in sediment samples
60–62	<i>Carex</i> sp. seed
72–73	Wood of a deciduous tree ( <i>Alnus</i> ?)
205–210	<i>Equisetum</i> sp. remains, <i>Ranunculus</i> sect. <i>Batrachium</i> seeds (six), <i>Trichoptera</i> remains. Mosses: <i>Drepanocladus</i> sp., <i>Scorpidium</i> sp., <i>Tomenthypnum nitens</i> , <i>Rhizomnium punctatum</i>
225–235	<i>Dryas octopetala</i> leaf fragments (six), <i>Betula nana</i> leaf, several <i>Equisetum</i> sp. remains, abundant Characeae oospores (120), remains of limnic animals ( <i>Daphnia ephippia</i> , <i>Plumatella</i> statoplasts). Mosses: <i>Drepanocladus</i> sp., <i>Calliergon giganteum</i>
240–245	Abundant <i>Equisetum</i> sp. fragments, many <i>Dryas octopetala</i> leaves (14 fragments), <i>Carex</i> sp. remains (one leaf, two rootlets). Aquatic mosses ( <i>Drepanocladus</i> sp.)
260–270	Many Characeae oospores (22)
340–350	One <i>Ranunculus</i> sect. <i>Batrachium</i> seed, <i>Dryas octopetala</i> leaves (four), few Characeae oospores
350–360	Pyritized herbs and stems, one <i>Ranunculus</i> sect. <i>Batrachium</i> seed, 20 Characeae oospores
380–390	Pyritized herbs and stems, one <i>Salix</i> sp. leaf, three Characeae oospores
390–400	One <i>Salix polaris</i> leaf fragment, one <i>Potamogeton</i> sp. seed, three Characeae oospores
405–410	<i>Dryas octopetala</i> leaf
440–450	Pyritized macroremains, one <i>Ranunculus</i> sect. <i>Batrachium</i> sp. seed, <i>Urtica dioica</i> seed, <i>Scirpus sylvaticus</i> seed, <i>Dryas octopetala</i> leaves (three), abundant Characeae oospores
450–460	Pyritized macroremains, <i>Betula humilis</i> seed, three <i>Dryas octopetala</i> leaf fragments, 21 Characeae oospores



**Fig. 6.** Ostracod subfossils from Haljala. Scale 0.2 mm. **A**, *Limnocythere inopinata*, left valve, external view; **B**, *Limnocytherina sanctipatricii*, right valve, external view; **C**, *Cytherissa lacustris*, left valve, external view; **D**, *Cytherissa lacustris*, shell, dorsal view; **E**, *Cyclocypris ovum*, left valve, external view; **F**, *Cyclocypris ovum*, shell, dorsal view; **G**, *Cyclocypris* cf. *laevis*, right valve, external view; **H**, *Cyclocypris* cf. *laevis*, shell, dorsal view; **I**, *Eucypris* cf. *virens*, juvenile, right valve, external view; **J**, *Candona candida*, left valve, external view.

**Table 4.** Distribution of ostracod species in the Haljala core. Analyses by K. Sohar

Depth, cm	Species	Number of specimens
225–235	<i>Candona candida</i>	6
	<i>Cyclocypris</i> cf. <i>laevis</i>	8
	<i>Limnocytherina sanctipatricii</i>	3
260–270	<i>Candona candida</i>	1
	<i>Cytherissa lacustris</i>	1
	<i>Limnocytherina sanctipatricii</i>	4
390–400	<i>Cytherissa lacustris</i>	5
	<i>Pseudocandona</i> cf. <i>compressa</i>	1
440–450	<i>Candona candida</i>	14
	<i>Cyclocypris ovum</i>	3
	<i>Cypridopsis vidua</i>	1
	<i>Eucypris</i> cf. <i>virens</i>	4
	<i>Limnocythere inopinata</i>	6
	<i>Pseudocandona</i> cf. <i>compressa</i>	6
450–460	<i>Candona candida</i>	3
	<i>Cyclocypris ovum</i>	7
	<i>Eucypris</i> cf. <i>virens</i>	2
	<i>Pseudocandona</i> cf. <i>compressa</i>	1

range of environmental conditions. Ostracod shells and valves were well preserved, but the number of specimens was low (Table 4). Both adult and juvenile specimens were found (the ratio 80 : 20).

## DISCUSSION AND CONCLUSIONS

### Deglaciation and palaeogeography

The new evidence from Haljala suggests that the area started to deglaciate about 13 800 cal yr BP, thus about 500 years earlier than previously thought (Vassiljev et al. 2005; Saarse et al. 2007). According to Demidov et al. (2006), decay of the ice margin since the Allerød turned from aerial downwasting to frontal-type deglaciation, the ice sheet melted quickly due to the ameliorated climate, and large proglacial lakes appeared at the front of the ice margin. This seems to be valid for Haljala as well, because the sequence reveals deposits that accumulated both in a large proglacial lake and in an isolated lake. Simulation of water level surfaces showed that during the Baltic Ice Lake stage A<sub>1</sub> the water level near Haljala was about 86 m, during A<sub>2</sub> – 69 m, Baltic Ice Lake I (BIL I) – 60 m, BIL II – 57 m, and BIL III – 54 m a.s.l. (Saarse et al. 2003, 2007; Vassiljev et al. 2005). During the A<sub>2</sub> stage, about 13 000–12 900 cal yr BP, a spit formed between Tatruse and Vanamõisa bedrock hillocks at an elevation of 69–70 m a.s.l., which isolated the elongated narrow lagoon in the Haljala depression (Fig. 1). The isolation

contact at 210–220 cm is marked by increased moisture, OM, and carbonate contents and decreased sediment accumulation rate (Fig. 2). Haljala lagoon separated finally between 13 000 and 12 900 cal yr BP, forming a coastal lake where clayey silt deposited. At the Younger Dryas/Holocene transition silt deposition was gradually replaced by calcareous sandy silt and lacustrine lime.

### Palaeoenvironmental events

Based on palaeobotanical, lithological, and chronological data, five main environmental stages have been recognized. These stages coincide rather well with the event stratigraphy proposed by Lowe et al. (2008).

#### 13 800–13 300 cal yr BP

The samples from the basal part of the Haljala sequence between 500 and 330 cm consist of fine-grained and clayey silt, incorporate pollen zones Ha 1–3, and delineate a time span of 13 800–13 300 cal yr BP. These sediments were deposited in a large proglacial lake in the middle of the Allerød–Bølling warming event (GI-1c). The relatively warm climate is supported by rather high OM accumulation, peaking around 13 400 cal yr BP (Fig. 2). The stable representation of the *Pediastrum* algae up to 13 100 cal yr BP suggests that the water/climatic conditions were rather favourable during this late glacial period. Pollen spectra display high and uniform tree pollen percentages (around 60–70%), with a noticeable admixture of *Picea*, *Alnus*, and *Corylus* (Fig. 4). These taxa were not constituents of the flora at that time. Sediment deposition in a proglacial lake with a vast pollen source area and low local pollen production was the main reason why pollen spectra include abundantly redeposited pollen grains (*Picea*, *Alnus*, *Corylus*, QM, etc.), typical of interglacial deposits. Around 435 cm depth (13 700–13 600 cal yr BP) corresponding to Ha-2, a considerable decline in the concentration and palynological richness of pollen is recorded (Fig. 5), which might represent a short-term cooling inside GI-1c. The mentioned decline/cooling could be a result of the ice margin standstill not far from Haljala. The <sup>10</sup>Be exposure ages in the area are somewhat contradictory, but still show ice-free northern Estonia since 13 600 <sup>10</sup>Be yr BP (Rinterknecht et al. 2006). An OSL date of sand from the Pikassaare kame field (21 km west of Haljala) gave a similar age (13 700 yr BP; Raukas & Stankowski 2005), however, the authors considered kame deposits as unpromising material to study the ice recession phenomena.

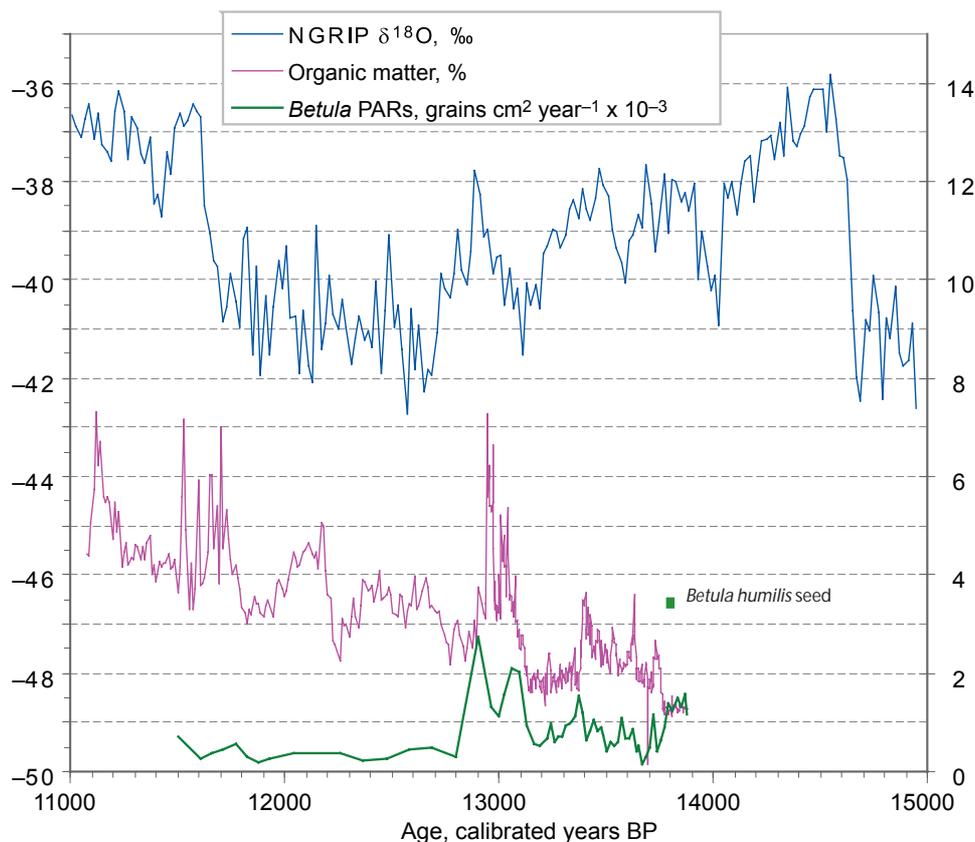
Within this time interval seven sediment samples were analysed for plant macrofossils (Table 3). Characeae

oospores are present in all samples. Other aquatic species found are *Ranunculus* sect. *Batrachium* and *Potamogeton* sp. *Ranunculus* sect. *Batrachium* is a pioneering species often found in late glacial sediments (Birks 2000). The lowermost samples contained seeds indicating mild climate: *Betula humilis*, *Urtica dioica*, and *Scirpus sylvaticus*, suggesting amelioration of climate in GI-1c. However, also two common arctic species are present (*Dryas octopetala* and *Salix polaris*).

Three samples were studied for ostracods. Benthic freshwater ostracods migrated through passive transport, e.g. by wind, drifting vegetation, flowing waters, birds, mammals, fishes, amphibians, and invertebrate animals (Meisch 2000). Ostracod assemblages are typical of shallow lakes at depth intervals 450–460 cm and 440–450 cm and refer to the vegetation of the littoral zone, e.g. *Limnocythere inopinata* (Fig. 6A) and *Cyclocypris ovum* (Fig. 6E, F). *Limnocythere inopinata* preferred a sandy substrate (Scharf 1998). The occurrence of *Eucypris* cf. *virens* (Fig. 6I) may point to a temporary water body, because the species prefers grassy pools that dry up

in summer (Meisch 2000). Climate amelioration in the Allerød was favourable for littoral species. There is no record of mixed ostracod assemblages of species populating deep lake and shore areas; the subfossil material shows littoral derivation. In Scharf (1998) the existence of littoral species in deep lake is explained by limnetic sediment transportation into deeper parts of the lake during storms in the circulation periods. The high sedimentation rate caused the preservation of carapaces of both adult and juvenile specimens. Ostracods became trapped among sediment particles rapidly, which diminishes the opportunity of separation of valves. Anoxic conditions prevented microbial organisms from disarticulating ostracod valves after death (De Deckker 2002). The composition of the ostracod assemblage changed sharply at a depth of 390–400 cm. *Cytherissa lacustris* (Fig. 6C, D), which preferred cool and deep oxygenated lakes, appeared (Meisch 2000).

Decline in the concentration, accumulation rate, and palynological richness of pollen also shows an environmental change around 13 700–13 600 cal yr BP (Ha-2;



**Fig. 7.** Summary environmental evidence from the Haljala sediment core in relation to the NGRIP δ<sup>18</sup>O curve (Lowe et al. 2008). The scale on the left is δ<sup>18</sup>O values in ‰ and on the right, % values for LOI data and 10<sup>-3</sup> PAR values for *Betula*. The first appearance of birch is also denoted.

Figs 5, 7). This change seems to be caused by the emergence of Tatruse Island, which isolated a narrow sound in the Haljala ancient valley (Fig. 1) and protected sediment influx from the large proglacial lake.

Mineral sediments, coupled with low tree pollen concentration (less than 20 000, commonly 6000–8000 grains  $\text{cm}^{-3}$ ) and palynological richness, indicate sparse vegetation (Fig. 4). Xerophilous steppe and tundra assemblages were dominated by *Betula*. *Pinus* was distributed only in favourable habitats characteristic of the open woodland tundra. Still, *Pinus* macrofossils were not found; its pollen may derive from older sediments or may be long-distance transported by winds. The pollen assemblage zones (Ha 1–3) at Haljala are quite similar to that of Visusti (central Estonia): total content of AP about 70%, NAP about 30%, pine pollen dominating over birch, and a notable percentage of thermophilous taxa (Pirrus & Raukas 1996). At Visusti such a pollen composition was correlated with the Older Dryas, in Haljala with the Allerød chronozone GI-1c. In the westernmost part of European Russia cold arid conditions and treeless vegetation have been reconstructed for the time period of 14 000–12 000 cal yr BP (Subetto et al. 2002; Wohlfarth et al. 2002, 2006, 2007). In southern Lithuania macrofossils of *Betula*, *Pinus*, and *Picea* were found before 13 700 cal yr BP (Stančikaite et al. 2008). In northern Estonia birch has been present since 13 800 cal yr BP, as indicated by *Betula* macrofossils and PAR around 1000 grains  $\text{cm}^{-2} \text{yr}^{-1}$  (Fig. 7), which according to Hicks (2001), is the threshold value for the presence of birch forest. Yet, we must bear in mind that in the late glacial environment where the vegetation is sparse, and soils and melting ice are the source for inwash of older sediments and hence pollen to the lakes, sediment focusing and artificially high PARs can be observed (Seppä & Hicks 2006), which may distort our estimations about the existence of *Betula* woods in the early Allerød in northern Estonia.

#### 13 300–13 100 cal yr BP

During this short time span fine-grained silt deposited with lower OM values than during the previous years (Figs 2, 7). In pollen composition (LPAZ Ha-4) *Pinus* and *Picea* percentages reached close to their maxima, up to 41% and 11%, respectively. High percentages of secondary pollen, such as *Picea*, *Alnus*, *Corylus*, and *Ulmus*, together with a low primary pollen accumulation rate and OM content, refer to cold climate and can be correlated with the GI-1b cooling. The interpretation of the elevated *Picea* curve is complicated, as the high pollen percentage (11%) and accumulation rate of *Picea* (300–400 pollen grains  $\text{cm}^{-2} \text{yr}^{-1}$ ) between 13 300 and 13 100 cal yr BP could suggest the presence of *Picea*.

Findings of *Picea* wood and high pollen percentages (28%) in Allerød clayey deposits of Kunda (Thomson 1934, p. 103) support the presence of spruce in North Estonia already during the Allerød. The average pollen composition (*Betula* 18.5%, *Pinus* 56%, *Picea* 20%, *Alnus* 5.5%) of Kunda clayey deposits is also similar to that of Haljala clayey deposits at a depth of 280–320 cm, where *Betula* fluctuates within 16–24%, *Pinus* within 25–41%, *Picea* within 6–11%, and *Alnus* within 4–9%. However, considering the size of the sedimentation basin at Haljala and the large pollen source area, redeposition of *Picea* pollen from older sediments, first of all from Eemian deposits, could not be ruled out. As a whole, pollen concentration and accumulation rate values are low for all taxa before 13 100 cal yr BP (Fig. 5), which could be explained by a high sedimentation rate of mineral matter (3  $\text{mm yr}^{-1}$ ). On the basis of pollen composition, open woodland tundra, mostly with birch, pine (?), spruce (?), juniper, and willow, spread in the Haljala basin.

The ostracod assemblage with *Limnocytherina sanctipatricii* (Fig. 6B) and *Cytherissa lacustris* (Fig. 6C) at a depth interval 270–260 cm indicate a cold and deep oligotrophic freshwater lake. The highest densities of *C. lacustris* occur in oligotrophic lakes at depths between 12 and 40 m (Meisch 2000) and the favourable temperature of the species is below 18°C (Geiger 1993). At that time (about 13 100–13 000 cal yr BP) the Haljala basin was a narrow sound in the regressive proglacial lake A<sub>2</sub> (Fig. 1).

#### 13 100–12 850 cal yr BP

Sediments of this interval are represented by fine-grained silt in which OM reached its late glacial maximum (7.3%) at 12 950 cal yr BP (215 cm). At about 13 000–12 900 cal yr BP the Haljala sedimentation basin isolated from the large proglacial water body (A<sub>2</sub>, Kemba). After that sediment transport, mineral matter influx, and consequently the sedimentation rate decreased considerably (0.9  $\text{mm yr}^{-1}$ ). These phenomena could be one reason why pollen accumulation values sharply increased (Figs 5, 7).

A decrease in *Pediastrum* algae might be connected with water level lowering at about 13 100–13 000 cal yr BP. The isolation age of Palaeolake Haljala dates proglacial Lake Kemba to around 13 100 cal yr BP, which agrees with an earlier estimation of 13 150 cal yr BP by Vassiljev et al. (2005), but is somewhat older than the date (12 800 cal yr BP) proposed by Rosentau et al. (2007). Two <sup>10</sup>Be dates from boulders 20 and 30 km west and northwest from Haljala correspond to the approximate level of proglacial Lake Kemba, 12 480±920 (EST-8) and 12 520±890 (EST-11; Rinter-

knecht et al. 2006), however, these boulders are of somewhat lower level and accordingly have younger ages. This suggests ‘not later than’ ages for the Kemba ice lake rather than for the Palivere end moraine these dates were meant for.

Three samples from the period of 13 100–12 850 cal yr BP were analysed for plant and moss macrofossils. Aquatic and mire plant remains were prevalent: abundant *Equisetum* sp. stems and aquatic mosses (*Drepanocladus* sp., *Calliergon giganteum*) were common together with several *Carex* sp. leaves and rootlets. These finds refer to increased growth of moss and mire plants within and in the vicinity of the water body, indirectly suggesting its isolation from a larger proglacial lake. Other features indicative of water environment are abundant Characeae oospores, *Ranunculus* sect. *Batrachium* seeds, and remains of two limnic animals (*Daphnia* and *Plumatella*). *Daphnia* and its ephippia represent the open water component of zooplankton and, together with other cladoceras, have been used in several cases as a palaeoecological (Hoffmann 2003; Feurdean & Bennike 2004) and palaeoclimatological tool (Duigan & Birks 2000). *Trichoptera* remains were recorded but not identified. Moss flora contains besides aquatic species (*Drepanocladus* sp., *Scorpidium* sp., *Calliergon giganteum*) also terrestrial species (*Tomenthypnum nitens*, *Rhizomnium punctatum*). *Tomenthypnum* is presently growing in fens; *Rhizomnium* may occur in shoreline areas but also in forest floors or trees (Ingerpuu & Vellak 1998). In the lower part of the interval the number of *Dryas octopetala* leaves reaches a maximum, suggesting a more severe local climate.

At a depth of 235–225 cm the ostracod assemblage shows a still high water level and cool conditions with sparse aquatic vegetation, because *Cyclocypris* cf. *laevis* (Fig. 6G, H) does not tolerate much vegetation (Meisch 2000). This is in good accord with the pollen record where aquatics are absent (Fig. 4).

The PAR values of *Betula*, *Pinus*, and *Picea* are high, respectively, 1100–2700, 1600–3900, and 160–370 grains cm<sup>-2</sup> yr<sup>-1</sup> (Figs 5, 7). A rather dense forest could be suggested, referring to the threshold values proposed by Hicks (2001). This is contradicted by high PAR values of light-demanding *Juniperus*, *Artemisia*, Chenopodiaceae, and Cyperaceae. On the other hand, these species obviously colonized the new area that emerged from the proglacial lake waters. Taking into account the possible sediment focusing mentioned earlier, we may rephrase the vegetation assemblage to an open pine–birch woodland with sparse spruce (?) stands with shrubs and herbs. An early immigration of *Picea* seems rather likely in the light of *Picea* presence in the Scandinavian Mountains already at 13 000–12 900 cal yr BP (Kullman

2008) and macrofossil finds from Kunda (Thomson 1934). As *Picea* macroremains have not been found in the Haljala sequence, the presence of *Picea* at the end of the Allerød remains still open.

#### 12 850–11 500 cal yr BP

The Allerød was succeeded by the Younger Dryas cold event, caused by a large reduction in the Atlantic thermohaline circulation (Alley 2000; McManus et al. 2004) and/or by Arctic freshwater forcing (Teller et al. 2002; Tarasov & Peltier 2005). The boundary between the Allerød and Younger Dryas stadials at 12 850 cal yr BP (present study) is defined by the increasing content of herb pollen (*Artemisia*, Poaceae, Cyperaceae, and Chenopodiaceae) and decreasing frequency of tree pollen (Fig. 4, Ha-5–7). Deposits of the Younger Dryas stadal (GS-1) are represented by grey and greenish-grey silt with fine-grained sand interlayers and remains of *Bryales* moss corresponding to the *Artemisia–Betula nana* pollen zone defined by Pirrus & Raukas (1996). The accumulation rate of tree and shrub pollen was very low, even lower than in the early Allerød (Figs 5, 7). The percentage of NAP pollen surpassed that of AP as herbs spread in the newly emerged area. Climate cooling resulted in a significant reduction of Sub-Arctic woodlands and their replacement by grass–shrub tundra without birch and other trees, as the PAR values of the latter stay below 500 grains cm<sup>-2</sup> yr<sup>-1</sup>, thus below the level of the forest (Hicks 2001). The closest macrofossil evidence of *Picea* at that time is from the Valdai Highlands and close to the Ural Mountains around 12 000 cal yr BP (Väliranta et al. 2006; Wohlfarth et al. 2007).

#### 11 500–11 300 cal yr BP

A great change in the vegetation community occurred with the start of the Holocene warming. The increased representation of all forest taxa, first of all the percentage of *Betula*, suggests new expansion of the forest, characteristic of the beginning of the Holocene. The PAR of birch still remained rather low (Fig. 7) and shrubs seemed to flourish, with *Salix*, *Betula nana*, and *Juniperus* having their maximum PARs (Fig. 5). Some delay to ameliorated climate occurred in vegetation response, especially reforestation, as was also the case on the Karelian Isthmus (Subetto et al. 2002; Wohlfarth et al. 2002). The delay was caused by the cold water of the Baltic Sea and possible increase in anticyclonic circulation due to the presence of remnants of the Scandinavian ice sheet.

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## **Balti basseini ja taimestiku hilisglatsiaalne areng Haljala paleojärve (Põhja-Eestis) uuringute andmetel**

Leili Saarse, Eve Niinemets, Leeli Amon, Atko Heinsalu, Siim Veski ja Kadri Sohar

Haljala kinnikasvanud järve hilisglatsiaalsest läbilõikest on määratud setete vanus, aineeline koostis, õietolm, taimsed makrojäänused ja ostrakoodid. Hilisglatsiaali sündmusstratigraafias on välja toodud viis perioodi, mis korreleeruvad vastavate keskkonna- ja kliimamuutustega Põhja-Euroopas. Puude ja rohttaimede õietolmu akumulatsiooni vähenemine aastatel 13 700–13 600 ja 13 300–13 100 näitab kliima jahenemist Allerødi interstadiaalis. Puude õietolmu akumulatsiooni järsk tõus 13 100–12 850 aastat tagasi viitab kliima soojenemisele ja kase- ning männimetsade levikule Haljala ümbruses. Jahenemine hilises Dryases põhjustas metsade taandumise ja tundrataimestiku suurema leviku. Uudsete andmete alusel on oletatud, et Pandivere kõrgustiku põhjanõlv vabanes jääkattest seni arvatust märksa varem: umbes 13 800 kalibreeritud radiosüsiniku aastat tagasi.