

## Ostracod assemblages indicating a low water level episode of Lake Peipsi at the beginning of the Holocene

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**Abstract.** Three sediment cores from the northern part of Lake Peipsi in eastern Estonia were analysed for their ostracod content. The investigated sediments consist of late Weichselian glaciolacustrine varved and homogeneous clay, lake marl, and gyttja. Altogether eight freshwater ostracod species were identified. The distribution of ostracods in L. Peipsi deposits is mostly limited to the lake marl interval. Ostracods made their appearance in shallow-water conditions and were represented by species preferring cold water. The continuous presence of *Ilyocypris bradyi* refers to the existence of a shallow body of water through the whole period of marl accumulation. Two sediment intervals where *Herpetocypris reptans* is present and *Darwinula stevensoni* is absent are interpreted as regressional episodes during the low lake level stage, which were possibly caused by a temporary warming accompanied by increased productivity. Water level in L. Peipsi during the late Weichselian–Early Holocene was ca 10 m lower than at present. According to palynological and radiocarbon data, lake marl with the presence of calcareous fossils started to accumulate at the Younger Dryas–Preboreal transition and continued through the entire Preboreal Chronozone.

**Key words:** Lake Peipsi, ostracods, late Weichselian, early Holocene, lithostratigraphy, lake level changes.

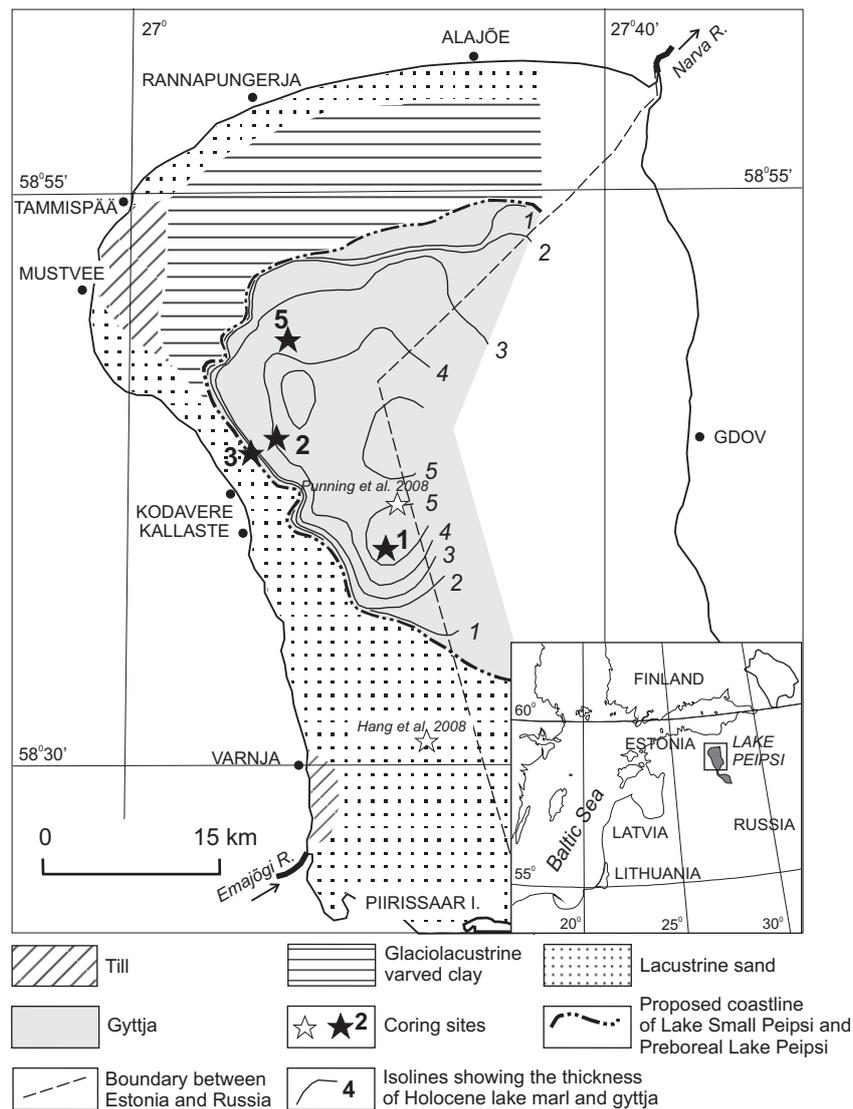
### INTRODUCTION

Lake Peipsi, the fourth largest lake in Europe, located at the border between Estonia and Russia ca 30 m above sea level, is a shallow water body with the mean water depth of about 8 m (max 15 m). The seismic reflection survey (Noormets et al. 1998; Miidel et al. 2001) supported by the lithostratigraphic data (Hang et al. 2001) suggests the glacial origin of the 50–60 m deep bedrock depression which presently holds L. Peipsi. The sediment cover consists of till and glaciolacustrine clay overlain by Holocene lake deposits. The southern part of the lake bottom and narrow foreshore zone close to the northern coast are covered by an up to 2 m thick layer of lacustrine sand (Fig. 1). Proglacial varved clay is outcropping in the northern part of the lake bottom. The distribution of lake marl and gyttja is limited to the deeper central part of the lake (Fig. 1).

The lower portion of the Holocene lacustrine deposits in L. Peipsi is represented by lake marl, which covers the glacial clay. According to palynological data (Hang et al. 2001, 2008), the accumulation of calcareous deposits started at the end of the Younger Dryas Chronozone. Sandy silt, rich in mollusc remains, marks the transition from glacial clay to Holocene lacustrine deposits and is reported here as the transition from the L. Small Peipsi stage to the subsequent Preboreal L. Peipsi stage (Hang et al. 2001).

Despite long-term interdisciplinary research into the geology and palaeogeography of L. Peipsi, many uncertainties still remain regarding the late Weichselian and early Holocene evolution of the lake (Hang & Miidel 1999a; Karukäpp & Raukas 1999; Hang et al. 2001; Hang 2003). Based on geomorphological (Hang et al. 1964; Raukas & Rähni 1969; Hang & Miidel 1999b) and biostratigraphical (Sarv & Ilves 1975; Hang et al. 1995, 2001, 2008; Punning et al. 2008) evidence, the existence of an extremely low water level period in the development of L. Peipsi, the so-called L. Small Peipsi (Orviku 1960), has been recorded at that time. Most of the supporting data originating from the surroundings of the lake suggest that the water level was ca 6 m lower at the beginning of the Preboreal Chronozone (Mangerud et al. 1974) than at present (Sarv & Ilves 1975; Miidel 1981). Studies into the bottom deposits (Hang et al. 2001, 2008) show that the lake level was 8–10 m lower than today. It has also been suggested that this lowest lake level was reached already before the onset of the Holocene (Hang et al. 1995, 2001; Hang & Miidel 1999a). Recent studies have revealed that water level started to rise about 9200–9100 <sup>14</sup>C years BP (Hang et al. 2008; Punning et al. 2008), which corresponds to 10 400–10 300 calendar (cal) years BP.

Ostracods (small bivalved crustaceans) are environmentally sensitive organisms which are readily preserved as fossils because of their calcitic shells. The occurrence



**Fig. 1.** Location of the studied part of Lake Peipsi in eastern Estonia with the distribution of bottom deposits (Hang et al. 2001) based on seismoacoustic profiling (Noormets et al. 1998) and corings (Hang et al. 2001). Lake Small Peipsi and Preboreal L. Peipsi stages are explained in the text.

of ostracods is controlled by hydrochemical parameters, including water composition and salinity, water depth and also the seasonal variability of water temperature. In fact, particular species are very much environment-specific, and therefore ostracods can be used to characterize nearly every possible type of water found on the Earth surface (De Deckker & Forester 1988). Until the current research modern freshwater ostracods in Estonia have been explored systematically by Järvekülg (1959, 1961, 2001, pp. 161–164). Palaeoecological studies on Quaternary subfossil ostracods started in Estonia some years ago (Niinemets 1999; Sohar 2004; Sohar & Kalm 2008).

The aim of the present study is to summarize all results of ostracod studies in the L. Peipsi sediments in order to contribute to the knowledge of early Holocene environment and lake level changes.

## MATERIAL AND METHODS

Four sediment cores from the Estonian side of L. Peipsi (Fig. 1) were analysed for this research. Three of them were studied for ostracods. The investigated site PE-1 (58°39'36"N and 27°21'12"E) is located in the central part (water depth during the coring 9.5 m) of the lake.

The coring site PE-2 (58°44'30"N and 27°12'03"E) is situated ca 5 km offshore from Kodavere (water depth 9.5 m) and PE-5 (58°48'50"N and 27°13'30"E) ca 15 km offshore from Mustvee (water depth 10 m). Also the lithology of the sequence from the coring site PE-3 (58°43'22.3"N and 27°10'07"E) is discussed in the text for lake development reconstruction.

Corings were carried out from the lake ice. Positioning of coring sites (Fig. 1) was performed with the satellite-based Global Positioning System (GPS). During the fieldwork, the GPS had an accuracy of approximately  $\pm 20$  m. A Russian-type peat corer with a chamber of 1 m in length and 75 mm in diameter (PE-2, PE-3, and PE-5), and a piston corer with 1.5 m tubes (PE-1) were used to obtain the samples. Samples were packed into PVC tubes for transport. Lithostratigraphical description and subsampling for biostratigraphical analysis were performed later in the laboratory.

Long core magnetic susceptibility of sequences PE-1 and PE-2 was measured at the Department of Geology and Geochemistry of Stockholm University on the Bartington MS2B susceptibility meter, with a 2 cm step before the opening of cores. Magnetic susceptibility, which mainly reflects the concentration of ferrimagnetic minerals (Thompson & Oldfield 1986), was used to correlate two sediment sequences located ca 10 km apart (Fig. 1) at different depths of water.

To determine the water content, the samples were dried to constant weight at 105°C. The organic matter content was measured as loss-on-ignition (LOI) at 500°C for 2 h. The carbonate content was estimated by the 'weight-loss' method according to Blakemore et al. (1987).

Ostracods were analysed by Eve Niinemets (cores PE-1 and PE-2) and Kristi Olt (PE-5). Subsampling for calcareous fossils was performed after a pilot study on ostracod abundance and distribution in different sediment types of the L. Peipsi sequences. First, 10 cm intervals from any represented sediment type (gyttja, lake marl, glaciolacustrine clay of different colour and structure) were collected. Then the samples were sieved through a 63  $\mu\text{m}$  mesh sieve and the amount of ostracods and other subfossils with carbonate shells in sediment was estimated visually. According to the results of this pilot study, it seemed reasonable to take final samples as 5 cm slices from ostracod-rich lake marl and homogeneous clay, and as 10 cm ostracod-poor slices from gyttja and proglacial varved clay.

Before wet sieving the volume of samples was measured for further data unification and sand fraction content calculations. After sieving the samples were dried at 80°C, sediment fraction above 63  $\mu\text{m}$  was weighed and the sand fraction content in grams per litre was calculated.

The ostracod and mollusc shells were picked out under a low magnification binocular microscope with a fine water-wet brush from the whole amount of the samples from the sediment fraction above 63  $\mu\text{m}$ . Ostracods were identified using literature (Zubowicz 1978; Sokolov 1989; Meisch 2000) and consulting with Drs U. v. Grafenstein, H. Griffiths, and C. Meisch (in litt. 1999). All found specimens were counted to analyse the abundance, distribution, and assemblage content in different samples and sediment types. Whole carapaces and single valves were counted separately and the total number of ostracod valves of different species was calculated by the following formula:  $2 \times \text{number of carapaces} + \text{number of valves}$ . The concentration of ostracod carapaces in 100  $\text{cm}^3$  was calculated for sequences PE-1 and PE-2. Ostracod assemblage diagrams were created using the TILIA and TGVIEW software (Grimm 1992). As cluster analyses resulted in unequally spread and wide zones, ostracod assemblage zones (OAZ) were separated visually according to the presence or absence of indicator taxa.

For the reference material all recorded ostracod species were photographed (Fig. 2) under the JEOL scanning electron microscope in the Laboratory of Material Science at Tallinn University of Technology.

Available radiocarbon dates for L. Peipsi concerning the period studied were gathered from published papers. As some dates had already been calibrated into calendar years,  $^{14}\text{C}$  dates were also calibrated with the radiocarbon calibration program CALIB 5.10 (Stuiver & Reimer 1993) for data compatibility.

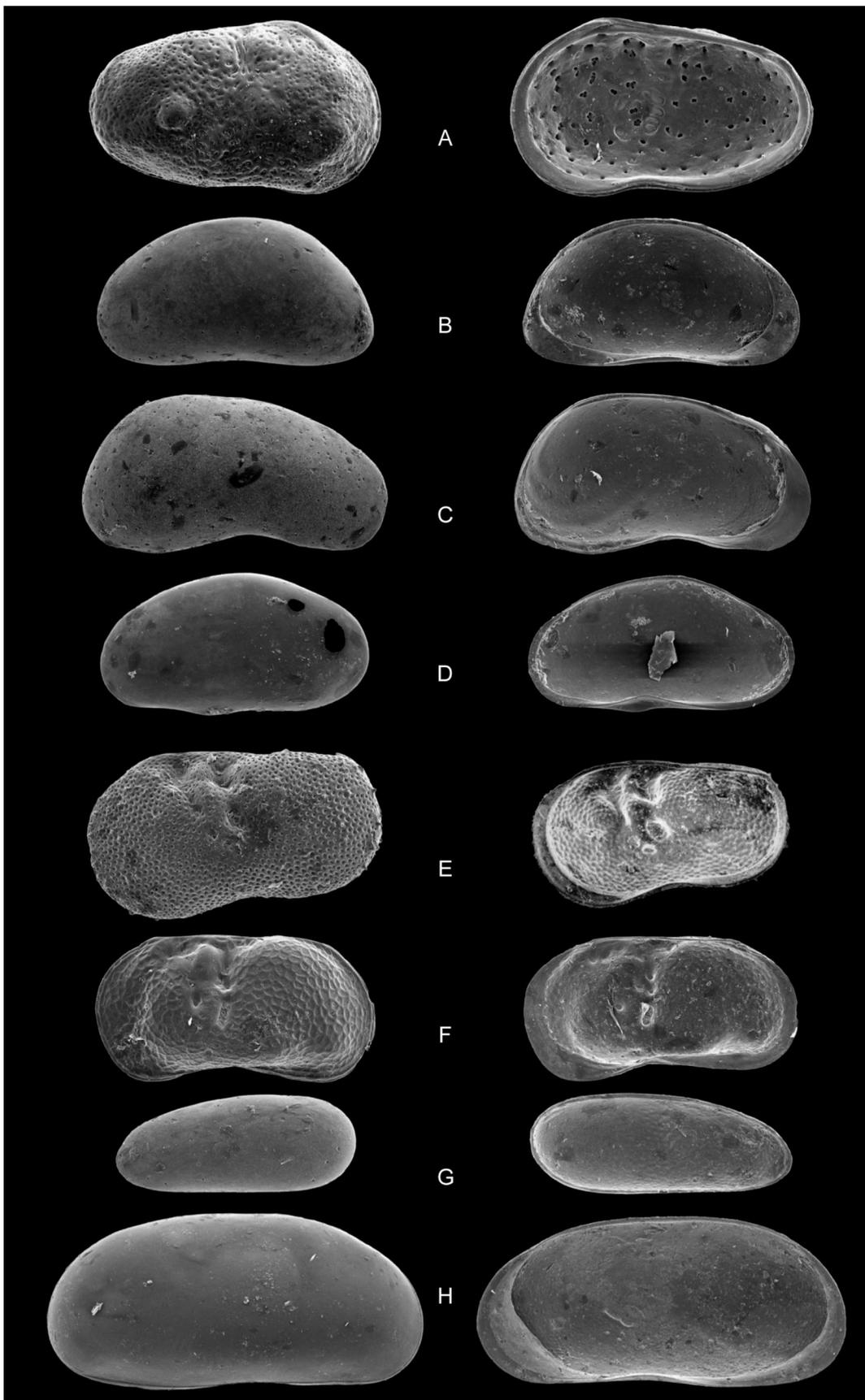
## RESULTS AND DISCUSSION

### Lithostratigraphy

The sediment sequences studied have been divided into five lithostratigraphical units briefly described in Table 1.

The main lithological changes are clear and easy to record and correlate through the investigated sequences (Fig. 3). However, detailed correlation, particularly within similar sediment intervals, is uncertain. It must also be kept in mind that the water level in different sites could have been dissimilar, resulting in differences in sediment type and thickness. For instance, the lake marl interval (Unit 4) probably accumulated at the same time in all sites (before 9200  $^{14}\text{C}$  years BP – 10 400 cal years; Punning et al. 2008) but is of different thickness and character in different cores, reflecting the influence of water column depth and wave action.

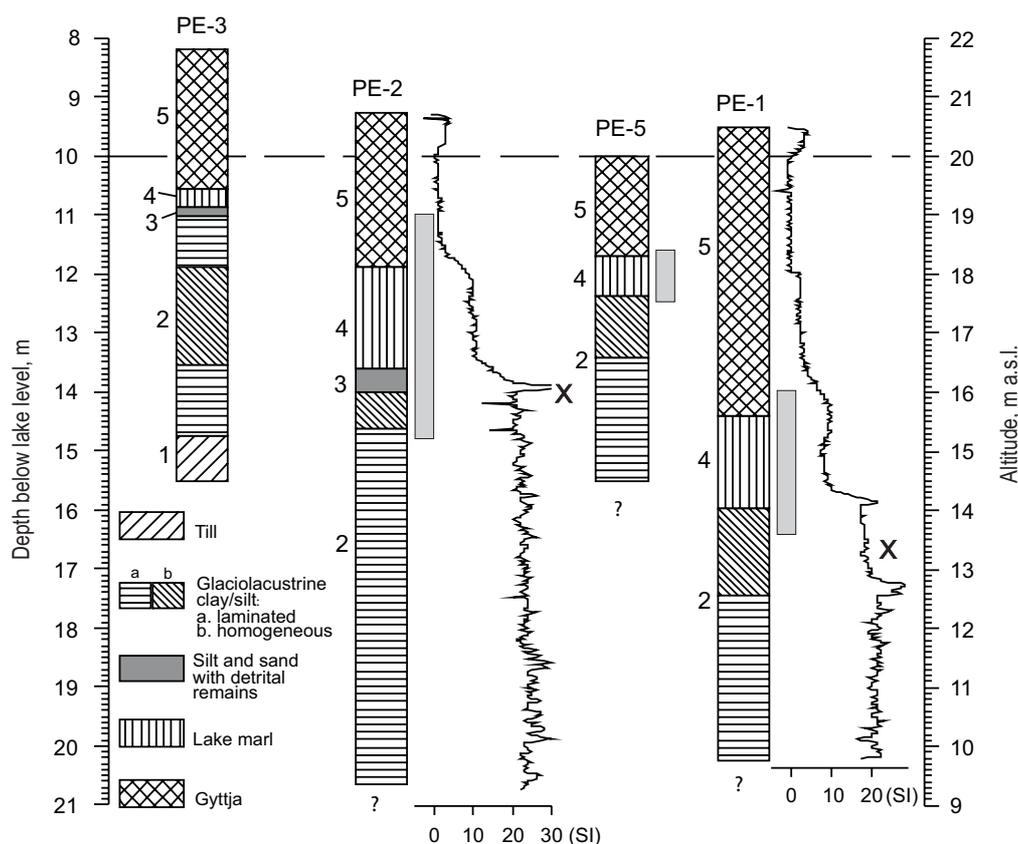
Magnetic susceptibility, which ought to be a good correlation tool between the cores within the same sediment basin, was measured from cores PE-1 and PE-2 (Fig. 3). The morphology of the magnetic susceptibility



**Table 1.** Lithostratigraphic subdivision of sediment sequences from Lake Peipsi

Core No.	Depth below lake level, m	Unit No.	Description
PE-1	0.00–9.50		Water
	9.50–14.40	5	Gyttja: uppermost portion dark brown to black, from ca 12.90 m colour changes to greenish-grey, lower boundary is gradual (14.20–14.40 m)
	14.40–15.95	4	Lake marl: homogeneous, light bluish-grey with shell detritus
	15.95–20.23	2	Glaciolacustrine deposits: 15.95–17.00 m homogeneous reddish-brown silt, 17.00–17.45 m light brown silt with thin chemical lamination in the lower portion, 17.45–20.23 m brownish varved clay, thickness of varves varies from a couple of millimetres to a few centimetres, summer layers consist mainly of coarse silt or fine sand, ripples are common, winter layers consist of reddish-brown homogeneous clay
PE-2	0.00–9.50		Water
	9.50–12.00	5	Gyttja: dark brown to black (9.50–10.00 m), lower portion (10.00–12.00 m) greenish-grey; according to CaCO <sub>3</sub> and organic content the interval could be divided into calcareous silicic gyttja (9.50–11.00 m) and silicic gyttja (11.00–12.00 m), transition from lake marl to gyttja gradual
	12.00–13.60	4	Lake marl: homogeneous, light bluish-grey, sand particles content varies from 5 to 25%, clay content increases (from 35 to 50%) towards the upper boundary of the interval
	13.60–14.02	3	Sandy silt: brownish-grey, lower boundary very sharp, transition to lake marl (13.70–13.85 m) gradual, a distinct layer of mollusc remains (13.82–13.85 m)
	14.02–20.73	2	Glaciolacustrine clayey silt: topmost part (14.02–14.65 m) homogeneous, probably reworked beige varved clay, from 14.65 m brownish-grey varved clay with distinct varves
PE-3	0.00–8.20		Water
	8.20–10.55	5	Gyttja
	10.55–10.85	4	Lake marl: homogeneous, light bluish-grey, contains mollusc remains in the transition from sand
	10.85–11.00	3	Sand: brownish, fine-grained, lower boundary very sharp carrying erosional character, transition to lake marl gradual, in the upper part mollusc remains
	11.00–14.72	2	Glaciolacustrine varved clay: brownish-grey, from 11.00–11.90 m contains 15 varves, 11.90–13.50 m homogeneous with traces of post-sedimentational slides, 13.50–14.72 m contains 20 clearly proximal varves (max thickness 10 cm)
	14.72–15.50	1	Till: brownish-grey loamy till with pebbles
PE-5	0.00–10.00		Water
	10.00–11.70	5	Gyttja: uppermost part greenish, lower portion brownish-green, lower boundary gradual (11.60–11.80 m)
	11.70–12.38	4	Lake marl: homogeneous, light bluish-grey, two intervals with abundance of mollusc remains (12.13–12.17 m; 12.26–12.28 m);
	12.38–13.40	2	Glaciolacustrine homogeneous clay: brown to reddish-brown, transition to lake marl gradual (12.28–12.38 m)
	13.40–15.50	2	Glaciolacustrine varved clay: brownish-grey, thickness of unclear varves from one to a couple of millimetres

**Fig. 2.** **A**, *Cytherissa lacustris* (Sars, 1863); **B**, *Candona candida* (Müller, 1776); **C**, *Fabaeformiscandona levanderi* (Hirschmann, 1912); **D**, *Fabaeformiscandona protzi* (Hartwig, 1898); **E**, *Ilyocypris bradyi* (Sars, 1890); **F**, *Limnocytherina sanctipatricii* (Brady & Robertson, 1869); **G**, *Darwinula stevensoni* (Brady & Robertson, 1870); **H**, *Herpetocypris reptans* (Baird, 1835).



**Fig. 3.** Sediment stratigraphy of the sections studied. For location of sites see Fig. 1. The dashed line shows the supposed minimum water level during the L. Small Peipsi stage, light grey rectangles next to the sediment columns indicate the biostratigraphically investigated intervals. Numbers at the sediment columns represent the sediment units described in Table 1. The question mark demonstrates the continuation of the same sediment interval which was not penetrated during the coring. Magnetic susceptibility curves have been placed beside sediment columns of PE-1 and PE-2. The letters X show the correlated intervals of the magnetic susceptibility curves discussed in the text.

curves has a similar character with distinct and easily correlating intervals. The most distinct change in the values of magnetic susceptibility is recorded on the transition from glaciolacustrine (Unit 2) to Holocene lacustrine deposits (Unit 4; Fig. 3). Also transition from lake marl (Unit 4) to greenish-grey gyttja (Unit 5) is easily visible on both susceptibility records. It is somewhat complicated to find a certain correlation between the parts of the curves corresponding to glaciolacustrine (Unit 2) deposits. Excerpts marked with X (Fig. 3), characterized by a sharp peak in the PE-2 curve and two peaks in the PE-1 curve, refer to a possible hiatus in the transition from Unit 2 to Unit 3 in the PE-2 sediment sequence.

### Ostracods

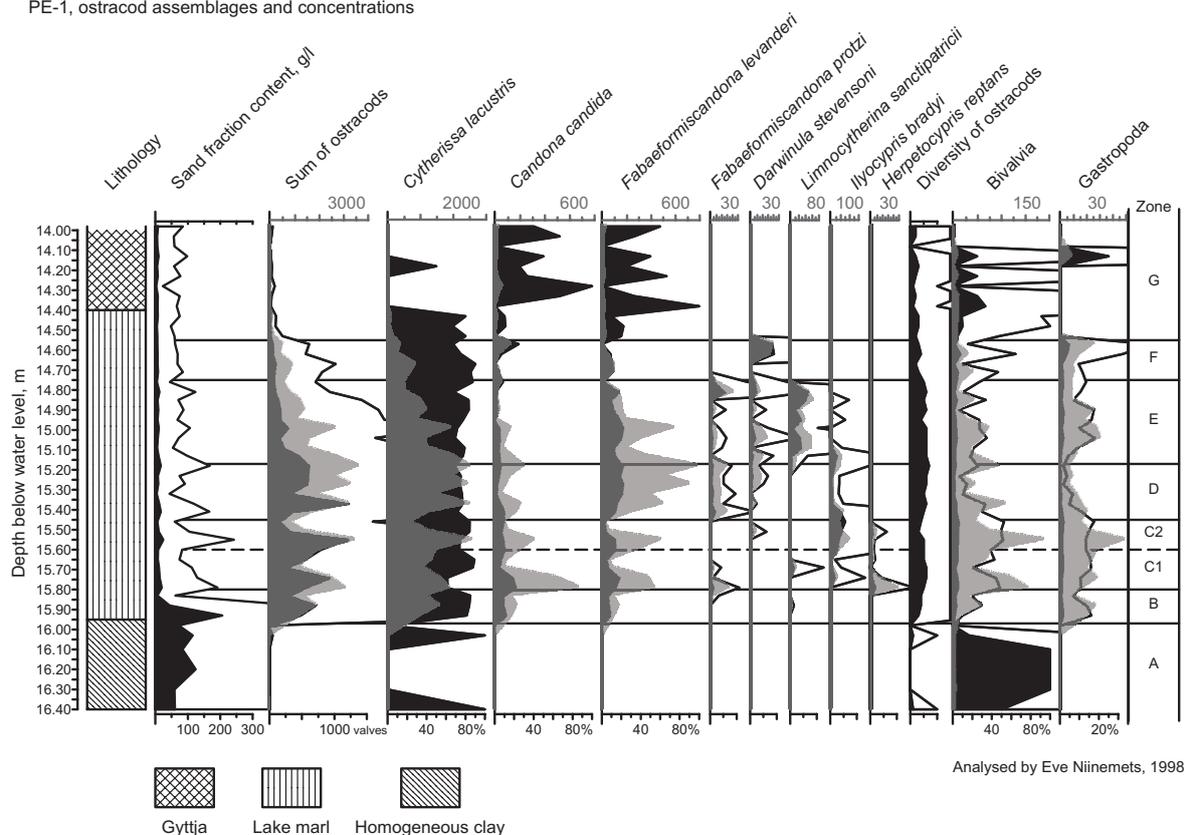
More than 26 000 ostracod valves of 8 different freshwater species were recorded (Figs 4–6) in three

investigated sediment sequences of L. Peipsi (PE-1, PE-2, PE-5). The importance and ecological preferences of these widespread species for the present study have earlier been summarized by Niinemets (1999). The different preservation of ostracods in the samples most likely depends on the thickness of shells. All recognized species are represented by both adult and juvenile specimens demonstrating the autochthonous origin of ostracods. The overall abundance of ostracod valves in 100 cm<sup>3</sup> sediments is less than 3000 in PE-1 and PE-2 cores, being on average less than 1500 in PE-5.

*Cytherissa lacustris* (Sars, 1863) is an ornamented and thick-shelled medium-sized ostracod species (Fig. 2A), which is well preserved in sediment. *Cytherissa lacustris* is a geographically widespread species, being particularly common in waters of 20–30 m (Danielopol et al. 1988). It prefers cool, oligotrophic, and oxygen-rich environments (Schwalb et al. 1998). The species is present in the lake marl and silt intervals, of all studied sequences as the

## Lake Peipsi

PE-1, ostracod assemblages and concentrations



Analysed by Eve Niinemets, 1998

**Fig. 4.** Ostracod and mollusc assemblages with concentrations in sediment sequence PE-1. For location of the site see Fig. 1. Filled curves indicate the percentage of ostracod species in the assemblage; hollow curves show per mils; ostracod and mollusc concentrations (valves/shells in 100 cm<sup>3</sup>) in sediments are presented with grey shadowed curves.

dominant species constituting ca 80% of the ostracod assemblage (Figs 4–6). In 100 cm<sup>3</sup> sediment the abundance of *C. lacustris* reaches ca 2500 valves in PE-1 and ca 1400 valves in PE-2 (Figs 4 and 5), being thus much greater in PE-1 than in PE-2.

*Candona candida* (Müller, 1776) has smooth thin medium-sized shells (Fig. 2B). The modern species inhabits several arctic and holarctic water bodies (Zubowicz 1978); it occurs in a wide depth interval (0.4–300 m) in stagnant and clean freshwaters, peaty and water-saturated soils, or in fluvial environments (Griffiths 1995). For its wide range of ecological preferences and its worldwide occurrence, the species is considered cosmopolitan (Külköylüoğlu 2004). In the sequences studied, *C. candida* is quite stably present in the lake marl interval, constituting less than 20% of the ostracod assemblage in PE-1 and less than 30% in PE-2 and PE-5 (Figs 4–6). Curves of ostracod abundance in 100 cm<sup>3</sup> sediment have some peaks of *C. candida*, which occur at 15.79 m in PE-1 (672 valves) and at

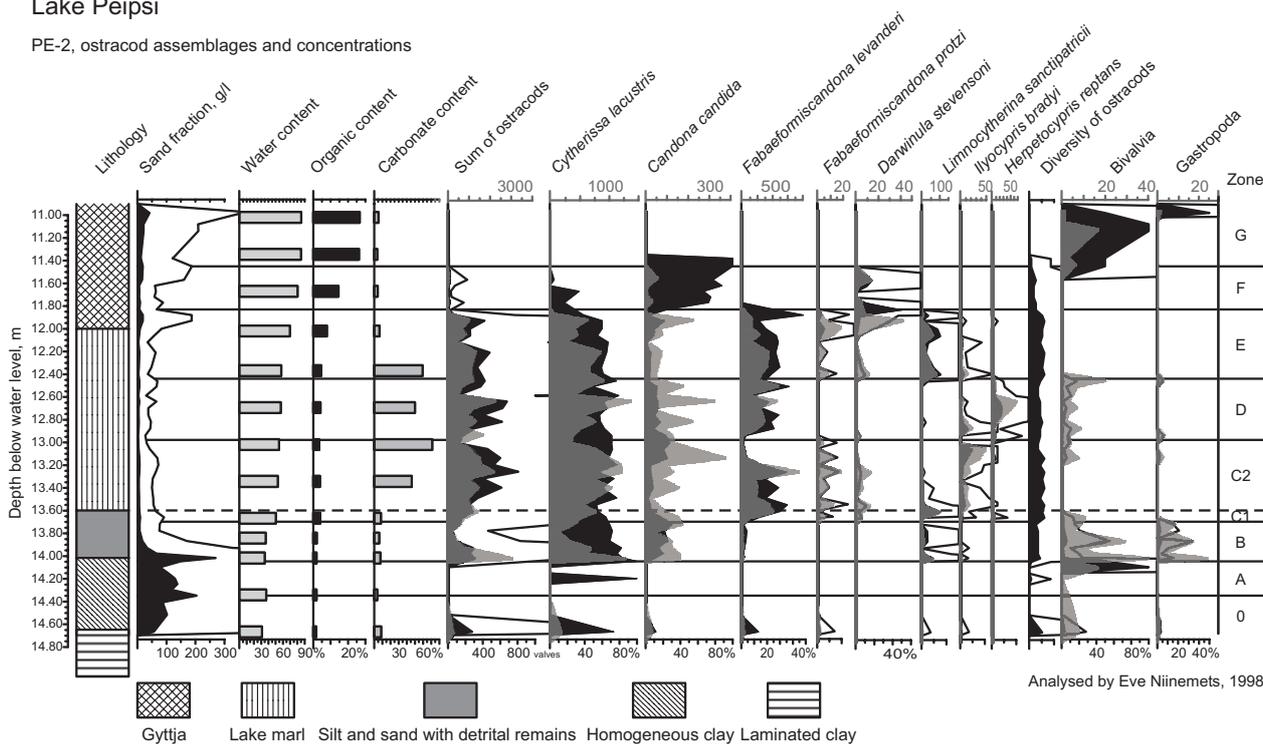
13.14 m (378 valves) in PE-2 (Figs 4 and 5). The abundance of the species is much greater in PE-1 than in PE-2.

*Fabaeformiscandona levanderi* (Hirschmann, 1912) has a little larger than medium-sized smooth valves (Fig. 2C). It prefers cold water and the turbulent littoral zone of lakes (Griffiths 1995). This species is present in the lake marl and silt intervals of the L. Peipsi sequences studied. Its proportion in the ostracod assemblage is less than 20% in PE-1 and less than 35% in PE-2 and PE-5. The percentage curves of *F. levanderi* in PE-2 and PE-5 have major declines in the middle of the lake marl (at 12.95–13.15 m in PE-2 and at 12.08–12.13 m in PE-5) interval (Figs 4–6). The concentration of the species in 100 cm<sup>3</sup> sediment (Figs 4 and 5) is almost equal in cores PE-1 and PE-2 (max 776 valves in PE-1 and max 765 valves in PE-2).

*Fabaeformiscandona protzi* (Hartwig, 1898) (Fig. 2D) has very thin and fragile shells, which accounts for their poor preservation in sediments. It lives in small cold-

Lake Peipsi

PE-2, ostracod assemblages and concentrations



**Fig. 5.** Ostracod and mollusc assemblages with concentrations and LOI results in sediment sequence PE-2. For location of the site see Fig. 1. Filled curves indicate the percentage of ostracod species in the assemblage; hollow curves show per mils; ostracod and mollusc concentrations (valves/shells in 100 cm<sup>3</sup>) in sediments are presented with grey shadowed curves.

water basins and has never been reported from flowing water environments (Griffiths 1995). This species is present in two intervals of the lake marl section in PE-1 and PE-2 and in one interval in PE-5. Its proportion is higher (ca 5%) in the upper part of lake marl and its maximum concentration in 100 cm<sup>3</sup> of sediment is 42 valves in PE-1 and 19 valves in PE-2 (Figs 4 and 5).

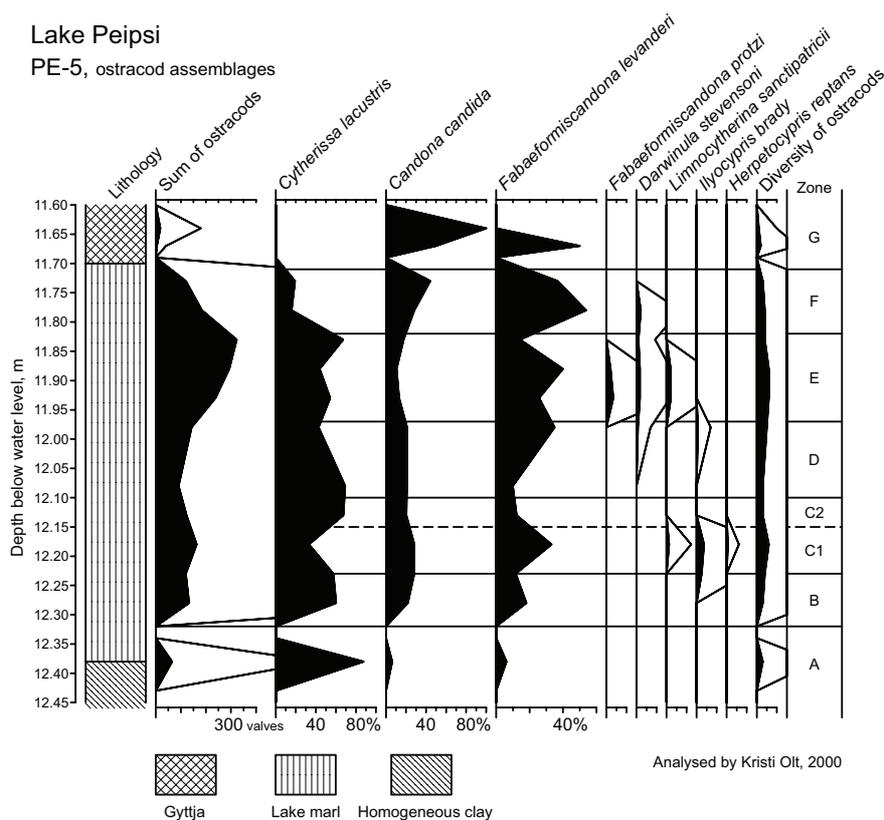
*Ilyocypris bradyi* (Sars, 1890) is a medium-sized thin-shelled ostracod species (Fig. 2E) which generally prefers shallow (0–4 m) moving and cool water but tolerates also a wide temperature range and a high carbonate content of water (Zubowicz 1978; Griffiths 1995; Schwalb et al. 1998). *Ilyocypris bradyi* appears to prefer water bodies fed by springs (Wilkinson et al. 2005). It is widespread in lake marl of PE-1 and PE-2 and is represented by two minor intervals in PE-5 (Figs 4–6). The species is the most abundant in the lower part of lake marl; its concentration per 100 cm<sup>3</sup> of sediment is higher in PE-1 (103 valves) compared to PE-2 (50 valves) (Figs 4 and 5).

*Limnocytherina sanctipatricii* (Brady & Robertson, 1869) has medium-sized reticular-pattern shells (Fig. 2F). The species lives in cold-water lakes and is limited to oligotrophic environments (Griffiths 1995). *Limnocytherina*

*sanctipatricii* is present in all sequences studied, in two intervals of lake marl (Figs 4–6). Its maximum abundance per 100 cm<sup>3</sup> of sediment is 67 valves in PE-1 and 105 valves in PE-2 (Figs 4 and 5).

*Darwinula stevensoni* (Brady & Robertson, 1870) has tiny elongated smooth shells (Fig. 2G). The species lives all the year round in the bottom of freshwater bodies with the water depth of at least 2 m (Zubowicz 1978) and less than 10–12 m, with preference for depths less than 6 m (Wilkinson et al. 2005). In L. Peipsi, maximum proportions of *D. stevensoni* occur in the upper part of lake marl in all sequences studied but some minor occurrences were registered in the lower part of the lake marl section in PE-2. The maximum abundance per 100 cm<sup>3</sup> of sediment in PE-1 and PE-2 is similar (42 and 43 valves, respectively), although the average abundance is still lower in PE-2.

*Herpetocypris reptans* (Baird, 1835) has very large elongated smooth and quite thin shells (Fig. 2H). The species prefers shallow-water conditions (Sokolov 1989; U. v. Grafenstein in litt. 1999) and lives in water bodies with a muddy bottom and rich vegetation, preferably with high water energy (Griffiths 1995). *Herpetocypris reptans* is present in small amounts in all sequences



**Fig. 6.** Ostracod assemblages in sediment sequence PE-5. For location of the site see Fig. 1. Filled curves indicate the percentage of ostracod species in the assemblage; hollow curves show per mils.

studied, being limited to short intervals within the lake marl section (Figs 4–6). In the PE-2 sequence some occurrences of *H. reptans* were recorded also outside the main interval. Maximum abundances in 100 cm<sup>3</sup> of sediment are 50 valves in PE-1 and 67 valves in PE-2 (Figs 4 and 5).

Some other calcareous shells were collected from the PE-1 and PE-2 sediment sequences and identified by A. Järvekülg (pers. comm. 2000) as the bivalves *Pisidium amnicum* (Müller, 1774) and the snails *Valvata profunda* (Clessin, 1887) and *Valvata depressa* (Pfeiffer, 1828). These species are widespread in European freshwater lakes and rivers and prefer fine-grained bottom deposits or aquatic plants in the upper littoral zone with hard water. In the PE-1 sequence molluscs are present in the whole lake marl interval, being somewhat less abundant in the upper part (Fig. 4). In PE-2 molluscs are less spread than in PE-1 and are concentrated to three intervals (in the upper part of glaciolacustrine sediments, in the middle of lake marl, and in the lower part of gyttja; Fig. 5). Due to the wide range of their ecological thresholds, molluscs are hardly usable in the reconstruction of the L. Peipsi development.

Based on the distribution of ostracod species and molluscs, nine **ostracod assemblage zones** (OAZ) were distinguished (Figs 4–6; Table 2). Three dominating ostracod species (*Cytherissa lacustris*, *Candona candida*, and *Fabaeformiscandona levanderi*) of permanently high distribution constitute about 90% of the whole ostracod assemblage along the investigated cores. The presence or absence of ecologically more restricted minor species in the assemblage referring to different palaeoecological conditions is the basis for distinguishing OAZs.

The **distribution** of ostracods in the L. Peipsi sediments is closely related to the sediment type as most of the ostracods occur in the lake marl (Unit 4) and sandy silt (Unit 3). The anomalous level in the glaciolacustrine clay of PE-2 (OAZ 0) is characterized by a high faunal diversity and ostracod content (Fig. 5). We explain it with sediment disturbances most likely caused by post-sedimentary slides in the shallow lake bottom, which could have mixed younger sediments into glaciolacustrine clays.

The interval of high abundance of ostracods in the sediment sequences of PE-1 and PE-2 starts in sandy silt deposits (OAZ B, Figs 4 and 5), although generally the

Table 2. Ostracod assemblage zones

Depth below lake level, m			OAZ	Description
PE-1	PE-2	PE-5		
13.98–14.55	10.90–11.35	11.60–11.71	G	<i>Candona</i> – <i>F. levanderi</i> zone in PE-1 and PE-5 where the proportion of ostracods has decreased nearly to zero. The zone is also characterized by a high mollusc content, mostly <i>Bivalvia</i> ; there are a few gastropods only at the top of the zone
14.55–14.75	11.35–11.83	11.71–11.82	F	The <i>Darwinula</i> zone represents an interval where <i>Darwinula</i> is the only minor ostracod species. In PE-2 the ostracod proportion has dramatically decreased, the proportion of <i>Candona</i> reaches nearly 95%
14.75–15.10	11.83–12.44	11.82–12.10	E	<i>Limnocytherina</i> (– <i>F. protzi</i> – <i>Darwinula</i> ) zone. Three minor species: <i>Limnocytherina</i> (upper maximum), <i>F. protzi</i> , and <i>Darwinula</i> constitute an assemblage. The proportion of <i>F. levanderi</i> is high again and that of <i>Candona</i> reaches its minimum
	12.44–12.98	12.15–12.20	D	Zero-zone of <i>Limnocytherina</i> . Also the rise of the <i>F. levanderi</i> curve is characteristic. In PE-2, the zone is represented by the maximum concentration of <i>H. reptans</i>
15.10–15.48	12.98–13.60	12.10–12.28	C2	<i>Ilyocypris</i> (– <i>F. protzi</i> ) zone. <i>Ilyocypris</i> is dominating among minor species. <i>H. reptans</i> occurs in PE-1, but in lesser numbers also in PE-2. The proportion of <i>F. levanderi</i> declines substantially at the upper limit of the zone
15.48–15.80	13.60–13.70		C1	<i>Herpetocypris</i> – <i>Ilyocypris</i> – <i>Limnocytherina</i> zone
15.80–15.97	13.70–14.05	12.28–12.45	B	<i>Candona</i> – <i>F. levanderi</i> – <i>Cytherissa</i> zone. OAZ is represented by three main ostracod species, <i>Cytherissa</i> is highly dominating (more than 80%). There can also be some specimens of <i>Limnocytherina</i> (in PE-2 even about 5%) and <i>Ilyocypris</i> in this zone. The gastropod curve begins in PE-1, while in PE-2 a high number of gastropods is limited to this zone
15.97–16.40	14.05–14.35		A	The <i>Cytherissa lacustris</i> – <i>Bivalvia</i> zone indicates the very fossil-poor or even empty part of the core, which lithologically corresponds to glacio-lacustrine clay or silt
	14.35–14.70		0	This zone is present only in PE-2 and indicates probably a post-sedimentational slide and is therefore labelled out of the alphabetical order. Its composition most resembles OAZ D or E

high sand fraction content related to a higher sedimentation rate seems to dilute the actual microfaunal content. The abundance of *C. lacustris*, *C. candida*, *F. levanderi*, *L. sanctipatricii*, and *I. bradyi* – the species of cold and shallow water preference – refers to the cool climate at that time.

Correlation of most OAZs in the sequences studied is quite easy because of the remarkable similarity of ostracod distribution, particularly in PE-1 and PE-5. Sediments of PE-2 have most likely accumulated in foreshore conditions and have, therefore, minor differences in the ostracod assemblage succession. However, a good marker in all sediment columns is a major decline in the *F. levanderi* curve between OAZs C and D (Figs 4–6), which correlates also with the decline in the ostracod

concentration (Figs 4 and 5). This decline could possibly be explained by climate amelioration (maybe only a few very hot summers causing draughts), which triggered intensive lake marl accumulation, thus ‘diluting’ ostracods (decrease in cold water preferring species) in sediments. The idea is also supported by the highest CaCO<sub>3</sub> content coinciding with the decline in ostracod concentration (at 13.00 m in the PE-2 sequence; Fig. 5). Another marker interval in the sequences studied starts with the spreading of *L. sanctipatricii* in the upper portion of lake marl distinguished here also as a boundary between OAZs D and E (Figs 4–6). This supports the conception of simultaneous accumulation of lake marl with different intensity in the sediment sequences represented, due to the varying water depth in different parts of the lake.

Three most abundant species (*C. lacustris*, *F. levanderi*, and *C. candida*) being tolerant to different ecological conditions (Griffiths 1995; Meisch 2000) are widespread along the studied cores (Figs 4–6). The rarely occurring species (*I. bradyi*, *H. reptans*, *D. darwinula*) provide much more information on palaeoecological conditions. The presence of *I. bradyi*, which is believed to be a very shallow-water species (Zubowicz 1978; Griffiths 1995), in most of the lake marl interval in the sections studied refers to the water depth of no more than 4 m during the time of carbonate precipitation. This is also supported by the fact that all the species present can live in shallow well oxygenated lakes.

In all cores there are intervals with another shallow-water species (*H. reptans*) coinciding with the absence of the fragile species *F. protzi* and *D. stevensoni*. These intervals refer to even shallower water than 4 m (less than 2 m according to Zubowicz 1978, 1983) and possible warming accompanied by increased productivity. The lowering of water level, indicated by the presence of *H. reptans* preferring higher water energy, has obviously occurred twice, first during the period when sandy silt accumulated in PE-2 (OAZ C1), and secondly in the middle of the lake marl interval where *H. reptans* maximum is recorded in the PE-2 sequence (OAZ E; Fig. 5). A major low water level period of about 12 800–10 500 cal years BP indicated by ostracod data has been reported also in small L. Sinijärvi (Sohar & Kalm 2008), proving the sensitivity of ostracods to climate changes both in small and large water bodies.

### Sediment accumulation chronology

Age assignment for the L. Peipsi deglaciation chronology is based on palaeomagnetic (Sandgren et al. 1997) and varve chronological data (Hang 2003). The commencement of the glaciolacustrine environment in the southern part of the L. Peipsi depression can be dated to about 14 400 cal years BP. Glaciolacustrine varved clays in the northern part of the lake depression were deposited approximately between 13 500 and 13 100 cal years BP. The deglaciation of the L. Peipsi depression was completed around 13 300 cal years BP with the ice withdrawal from the Pandivere–Neva ice marginal formations in NE Estonia (Hang 2003). Shore displacement curves for the southern part of L. Peipsi proper (Hang et al. 1995; Rosentau 2006) display a rapid regression between 12 500 and 10 200 <sup>14</sup>C years BP (between 14 700 and 11 800 cal years BP; with the minimum water level of about 10 200 <sup>14</sup>C years BP (11 800 cal years BP)).

According to pollen stratigraphy of core PE-2 (Hang et al. 2001), local pollen assemblage zones PAZ Pe-1 and PAZ Pe-2, identified at the transition from glaciolacustrine clay to lake marl, could be correlated with the

Younger Dryas Chronozone (YDr) (Hang et al. 2001). Thus, the fossil-rich interval of the lake marl started to accumulate at the very end of the YDr and continued through the entire PAZ Pe-3, which is correlated with the Preboreal Chronozone (PB) (Hang et al. 2001). Lake marl accumulation continued also in the lower part of PAZ Pe-4, which is correlated with the beginning of the Boreal Chronozone (BO). This is in good accordance with the earlier studies into the calcareous lake sediments from the areas adjoining the lake (Männil 1961). The lake marl accumulation in L. Peipsi terminated about 9200 <sup>14</sup>C years BP (10 400 cal years BP; Punning et al. 2008), most likely due to lake level rise. This is in good accordance with the start of sand deposition onto the gyttja around 9100 <sup>14</sup>C years BP (10 300 cal years BP) in the southern part of L. Peipsi proper (Hang et al. 2008).

### Evolution of the lake

After the retreat of the late Weichselian inland ice from the L. Peipsi depression into the Gulf of Finland (Fig. 1), the water level dropped and Peipsi was isolated from the proglacial lake (Rosentau et al. 2009). The isolation is considered as the initial stage of L. Small Peipsi. Outside the study area, in the mouth of the Optjok River (southern part of the L. Peipsi depression) an abrupt change in sediments from silt to fen peat containing silt indicates an at least 10 m lower water level at the YDr/PB transition than at present (Hang et al. 1995). At the same time the accumulation of peat at the mouth of the Emajõgi River (Fig. 1) started, showing that the water level there was ca 6 m lower than at present (Sarv & Ilves 1975). Hang et al. (2001) suggest that the water level in L. Small Peipsi reached its lowest stand after the final drainage of the Baltic Ice Lake at the end of the YDr, which is recorded in the bottom sediments by a thin sand or sandy-silt layer (Unit 3; Fig. 3) indicating the water level ca 10 m lower than at present (Hang et al. 2001).

The idea of a low water level at the beginning of lake marl accumulation is also supported by the results of the current study. Thus, the occurrence of ostracods in the bottom deposits starts from the sandy-silt interval (Unit 3; Figs 4–6). The presence of shallow-water species *H. reptans*, which coincides with the absence of *D. stevensoni* at the beginning of lime accumulation in PE-1 and PE-5 (OAZ C1), refers to the possible water depth shallower than 4 m (Niinemets 1999). As *H. reptans* is almost absent in the lower portion of the lake marl in the PE-2 sequence, the water level has probably been so low in the area represented by PE-2 that the water energy was too high for carbonate accumulation or the area was emerged, supporting thus the possible hiatus in sedimentation in PE-2. The corresponding level in the

PE-3 sequence shows an erosional transition from glaciolacustrine clay to sandy silt (Fig. 3). The glaciolacustrine clay there is varved with clearly distinguishable thick proximal varves, indicating that the upper portion of clay with thin distal varves could be eroded. This, together with a relatively thin lake marl interval in PE-3, which possibly started to precipitate later than in other sequences studied, might also mean that the lake did not reach the area during its lowest stand. A possible hiatus in PE-2 under the lake marl interval is also inferred from magnetic susceptibility curves in Fig. 3, where the excerpt X is only marked as one single peak in PE-2, while in PE-1 the excerpt X covers a ca 1 m interval and has two peaks. At present, it is not possible to determine very precisely the water level of L. Small Peipsi, although there is strong evidence to believe that the water level could have been even a couple of metres lower than previously suggested (8–10 m lower than at present, Hang et al. 2001, 2008). Due to the steep coastal slope of L. Small Peipsi, the contour of the lake did not change markedly even in the conditions of a few metres lower water level and is approximately demonstrated in Fig. 1.

Lake marl accumulation was characteristic of the Preboreal L. Peipsi stage following the stage of L. Small Peipsi. If the suggestion about the lake level and possible sedimentation hiatus in foreshore areas holds true, the carbonate accumulation started first in the central part of the lake represented by PE-1 and PE-5 sequences already at the end of the YDr (Fig. 1). More gradual transition from the sandy-silt and clay layer to lake marl in PE-1 and PE-5 sequences compared to PE-2 and PE-3 is due to greater water depth and possible wave erosion close to the coastline (PE-2, PE-3) areas (Fig. 1). The presence of *I. bradyi*, which is believed to be a very shallow-water species, in both PE-1 and PE-2 sections throughout almost the entire interval of lake marl, refers to the water depth of no more than 4 m during the whole period of carbonate precipitation. If this is true, the altitude of lake marl interval in the sequences studied points to the lake level between 18 and 22 m a.s.l. during marl accumulation. This correlates rather well with the water level (22 m a.s.l.) derived from the studies of buried gyttja in the bottom of southern L. Peipsi proper (Hang et al. 2008), as well as with the modelling of the water level in L. Small Peipsi during its isolation (Rosentau 2006).

An exceptional interval (OAZ D) could be distinguished in the PE-2 sediment sequence where the presence of *H. reptans* coincides with the absence of *F. protzi* and *D. stevensoni*, which refers to water having been temporarily even shallower than 4 m. Thus, an event of lake regression could be concluded. This is in good accordance with Punning et al. (2008) who found that during the accumulation of the lake marl, the

water depth in the lake was around 2–4 m. Comparison of ostracod distribution and the sediment grain-size distribution (fig. 7 in Hang et al. 2001) at the same level supports this idea. Moreover, increase in sand fraction (sediment grain-size between 63 and 500 µm) occurring twice (at depths of 13.0 and 12.4 m) suggests even two minor regressions of the lake. However, there is no *H. reptans* present in OAZ D in PE-1 and PE-5, which could be explained with the water having been deep enough (>4 m) in these points and with the fact that the aforementioned regression did not affect the ostracod assemblage in the deeper central parts of the lake. Sedimentary environment suitable for carbonate precipitation lasted throughout the Preboreal Chronozone and terminated probably at the beginning of the Boreal Chronozone, when moderate lake level rise has been interpreted from the bottom sediments in the southern L. Peipsi depression (Davydova & Kimmel 1991; Hang et al. 1995), gyttja started to accumulate in the central part of L. Peipsi proper (Punning et al. 2008), and sand accumulation onto the gyttja deposits started in the southern L. Peipsi proper (Hang et al. 2008).

## CONCLUSIONS

The most important conclusions drawn from the project reported here could be listed as follows.

1. In the bottom deposits of L. Peipsi, eight recent freshwater ostracod species were recorded (Figs 2, 4–6). The dominant species in the ostracod assemblage is *C. lacustris*, with the abundance of over 50%. The next species in abundance are *F. levanderi* and *C. candida*, both making up nearly 20%. The total relative abundance of the other five species is about 10%.
2. The distribution pattern of ostracods depends on the type of sediments and is limited mostly to the lake marl interval (Figs 4–6). Exceptions to this are: (a) PE-2 – OAZ 0 containing rich ostracod fauna between empty samples of varved clay, which is explained by redeposition of sediments; (b) PE-1 and PE-2 – the oldest fossil-rich samples contain the highest amount of sand fraction, which is explained by increased productivity of ostracods in shallow-water conditions.
3. Correlation of ostracod assemblages (OAZs) between the cores within the lake marl interval refers to simultaneous accumulation of lake marl with a different accumulation rate in foreshore areas compared to the central part of the lake, being the fastest in the PE-2 sequence. The shortest marl interval represented by the PE-3 sequence started to accumulate after the transgression had reached the foreshore area.

4. As concluded from ostracod studies, the L. Peipsi water level during the late Weichselian–Early Holocene low stand was approximately 20 m a.s.l., which is ca 10 m lower than at present.
5. The water depth of around 4 m during the Preboreal L. Peipsi stage is concluded from the continuous presence of *Ilyocypris bradyi* in the lake marl interval of bottom deposits.
6. A steep recession in the *Fabaeformiscandona levanderi* content at the end of OAZ C2 in all sequences, coinciding with the decline in ostracod abundance in PE-1 and PE-2 (Figs 4–6) sequences, is connected to the amelioration of climate followed by warm water conditions, which accelerated the carbonate precipitation and ‘diluted’ the ostracod valve content in the sediment. The conclusion is supported by a decrease in the distribution of cold water preferring species at the same level.
7. According to ostracod assemblages in the bottom deposits, two regressional episodes could be distinguished during the low stand period in the history of L. Peipsi from the late Weichselian to early Holocene period: one at the beginning of carbonate accumulation at the YDr/PB transition (OAZ C1, the end of the L. Small Peipsi stage) and the other in the middle of the calcareous interval (OAZ D), which was formed during the Preboreal L. Peipsi stage.
8. The accumulation of fossil-rich lake marl ceased at about 9200 <sup>14</sup>C years BP (10 400 cal years BP) due to lake level rise.

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## Ostrakoodikooslused Peipsi põhjasetetes kinnitavad järve arengu madalaveelist perioodi Holotseeni algul

Eve Niinemets ja Tiit Hang

On kokku võetud Peipsi järve põhjasetete ostrakoodiuringute tulemused. Ostrakoodide levikut uuriti kolmest Peipsi järve põhjaosa setteläbilõikest. Uuritud setted olid peamiselt Hilis-Weichseli-aegsed jääpaisjärve viirkihilised ja/või homogeensed savid, järvelubi ning jütja. Kokku identifitseeriti kaheksa ostrakoodiliiki, mis levivad Peipsi järve setetes peamiselt järvelubja intervallis. Ostrakoode sisaldavad setted peegeldavad madalaveelisi tingimusi ja ostrakoodi-

kooslused on esindatud jahedat elukeskkonda eelistavate liikidega. Ostrakoodikoosluste korrelatsioon eri puursüdamike vahel näitab järvelubja samaaegset, kuid erineva kiirusega settimist järve keskel ja rannavööndis. *Ilyocypris bradyi* pidev levik viitab sellele, et järvelubi settis suhteliselt madalas (kuni 4 m sügavuses) vees. Kaht setteintervalli, kus esineb madalamaveelist elukeskkonda eelistav *Herpetocypris reptans* ja puudub sügavamale veele iseloomulik *Darwinula stevensoni*, on interpreteeritud järve niigi madala veetaseme taustal regressiooniepisoodidena. Peipsi järve Hilis-Weichseli/Vara-Holotseeni üleminekuperioodi veetaseme täpne mõõtmine ei osutunud võimalikuks. Ostrakoodikoosluste alusel võib järeldada veetaset 18–22 m üle merepinna, mis on tänapäevases 8–12 m madalam. Vastavalt õietolmu- ja radiosüsinikuandmetele hakkas kaltsiitseid fossiile sisaldav järvelubi järve põhjas kuhjuma Noorema Drüüase/Preboreaali üleminekuajal ning jätkus kogu Preboreaali vältel kuni ajani umbes 9200 <sup>14</sup>C aastat tagasi (10 400–10 300 kalendriaastat tagasi), mil algas järve veetaseme tõus.