Changes in the Early Holocene lacustrine environment inferred from the subfossil ostracod record in the Varangu section, northern Estonia

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Abstract. The Varangu section is located on the southern slope of the Pandivere Upland in northern Estonia. A silty clay bed formed in the study area at 11 200–9300 cal yr BP, according to ostracod subfossils (e.g. *Tonnacypris estonica*, *Leucocythere mirabilis*, *Limnocytherina sanctipatricii*) in an oxygen-rich cool and oligotrophic profundal lacustrine environment, with an inflow of surface waters through springs. The record of specific ostracods (e.g. *Cyclocypris ovum*, *Cypridopsis vidua*, *Metacypris cordata*) reflects littoral environments, ongoing eutrophication, temperature increase and a progressive shallowing of the lake in the early Holocene (9300–7400 cal yr BP) when the tufa bed accumulated. A slight cooling and productivity decrease at 9100–8600 cal yr BP preceded further temperature rise and water level lowering, leading to the development of a eutrophic lake and cease of tufa precipitation (8600–7400 cal yr BP).

Key words: ostracods, palaeoecology, tufa, early Holocene, Varangu, northern Estonia.

INTRODUCTION

Reconstructions of early Holocene environmental changes in Estonia are usually based on data on radiocarbon chronology, shoreline displacement, pollen and diatom stratigraphy, and changes in sediment composition (e.g. Saarse & Harrison 1992; Punning et al. 2003; Seppä & Poska 2004; Veski et al. 2004). Ostracod subfossil data have been used in reconstructing the Holocene lake evolution in Estonia in a few cases only (Sohar & Kalm 2008; Niinemets & Hang 2009; Sohar & Meidla 2009). However, this method has been widely used in environmental studies on the Quaternary of Europe (e.g. biostratigraphy and biogeography by Absolon 1973; Walker et al. 1993; Griffiths et al. 1996; Scharf 1998; Schwalb et al. 1998; Wilkinson et al. 2005; stable isotope and trace elements studies by von Grafenstein et al. 1998; Anadón & Gabàs 2009). Calcite carapaces of ostracods, 0.5–2 mm in size, are often well preserved in calcareous sediments and knowledge on ostracod autecology is a valuable tool in palaeoenvironmental interpretations.

Freshwater tufa (lacustrine lime or marl) is an ideal archive for ostracod subfossils. Early Holocene tufas are known from northern Europe and Britain (e.g. Goudie et al. 1993; Walker et al. 1993; Pentecost 2005). Bartosh (1976) has summarized the distribution of Holocene tufas in the Northern Baltic and East European Platform, within and outside the Last Glacial Maximum limit. In the lakes of glaciated areas calcareous sedimentation emerged in the late glacial or early Holocene and typically terminated in the mid-Holocene (Männil 1967; Goudie et al. 1993; Garnett et al. 2006).

Calcareous deposits in a lake form in lentic waters of variable depth and range. Authigenic carbonates are associated with aquatic plants, especially charophytes and phytoplankton, and appear to be the result of plant photosynthesis by CO_2 degassing (Pentecost 2005). Large monogeneric *Chara* phytoherms commonly form in the littoral zone (Pedley 1990; Walker et al. 1993). Evaporation may also change the CO_2 equilibrium in waters. High rates of calcareous deposition are mostly indicative of warm climatic conditions (Pentecost 2005).

The Pandivere Upland is a karstic area in northern Estonia, with spring outflows from the Ordovician limestones. Calcareous sediments accumulated in lake basins of this area in the early Holocene. The Varangu tufa site, a unique area where calcareous sediments are well exposed, has a very good potential for Holocene palaeoecology studies. The first investigation on the site, with sediment description, mollusc and pollen analyses, was performed by Männil (1964, pp. 141–149).

Ostracods are well preserved in tufa and silt layers. Ostracod distribution can be interpreted in the context of hydrological conditions and evolution of the lake, e.g. changes in the water level and regime, trophic status and relative temperature. The aim of the present study is to analyse the early Holocene environmental variations in northern Estonia, as they are reflected in ostracod assemblages of the particular succession, and to discuss the results with respect to earlier information from other palaeoenvironmental proxies. This research is closely related to the stable isotope study of various ostracod species at the Varangu site (Kalm & Sohar 2009).

LOCATION AND GEOLOGICAL SETTING OF THE VARANGU AREA

The studied section at Varangu is located at the eastern edge of an abandoned tufa pit on the southern slope of the Pandivere Upland in northern Estonia (59°02′17″N, 26°07′10″E, ca 91 m a.s.l; Fig. 1). The Pandivere Upland is rich in springs fed by meteoric waters and groundwater. At the Varangu site spring brooks flow out of limestone in the western part of the tufa distribution area. The annual mean debit of springs is ca 400 L s^{-1} and the water is carbonate-rich: the concentration of HCO_3^- is 248.3–322.7 mg L^{-1}, of Ca^{2+} 71.5–94.2 mg L^{-1} (Timm & Järvekülg 1975). The yearly temperature of the upper groundwater layer ranges nowadays from +6.1 to +6.5 °C in northern Estonia (Schmied 1996).

A 100–280 cm thick freshwater tufa bed spreads over an area of about 49 ha and fills in a depression on the surface of Ordovician limestone. The sequence of calcareous sediments is the thickest in the central part of the palaeolake basin (Männil 1964, pp. 141–149). It is underlain by 150–300 cm of silty clay and till of the late Weichselian deglaciation, which terminated in that area 13 550 cal yr BP (Kalm 2006). The tufa distribution area and its vicinity became dry land not later than 12 800 cal yr BP (Rosentau et al. 2009). The tufa layer is overlain by 25–30 cm thick peaty soil (Männil 1964, pp. 141–149). The area is currently covered by paludal forest, whereas its middle part is occupied by an openpit field resulting from the tufa excavation in the 1970s–1990s.

MATERIAL AND METHODS

The sediment core (333 cm) was retrieved using a Belarusian-type peat corer. The sediment colour was described according to Munsell soil colour chart (Munsell 1998), the organic matter (OM) and carbonate contents of the sediment were determined by loss-on-ignition analysis at 500 °C and 1000 °C, respectively. A correction factor of 2.27 was used to calculate the amount of carbonate from the weight of CO_2 (Veski 1998; Gedda 2001).

For ostracod analyses sample slices of 5 cm (ca 50 cm^3 in volume) were taken successively from the sediment core. The samples were sieved with slow tap water through a 50 μm sieve and dried at room temperature. Adult and juvenile ostracod specimens were picked from dry sediment samples and cleaned for SEM studies under a stereomicroscope using a fine paintbrush. Figure 2 presents the range chart showing the numbers of collected specimens throughout the Varangu sequence and the calculated Shannon–Wiener diversity index (H′) (details in Hammer & Harper 2006). Both valves and carapaces are counted as specimens.

Ostracod valves and carapaces were photographed with a Zeiss 940D scanning electron microscope at the Department of Geology, University of Tartu, Estonia.

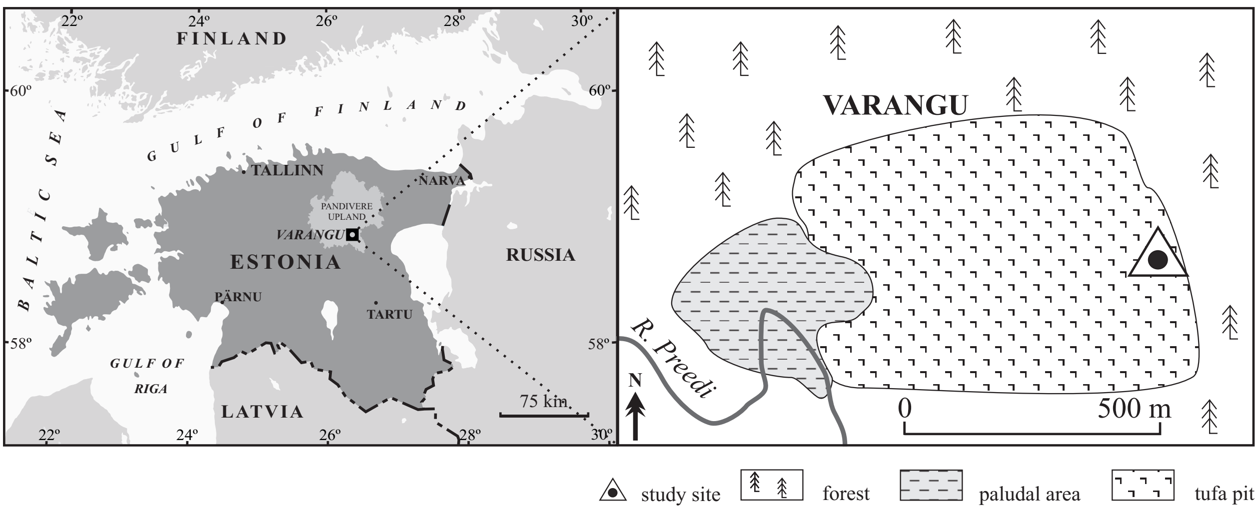


Fig. 1. Location of the Varangu sequence (modified after Kalm & Sohar 2009; Pandivere Upland area after Arold 2005).

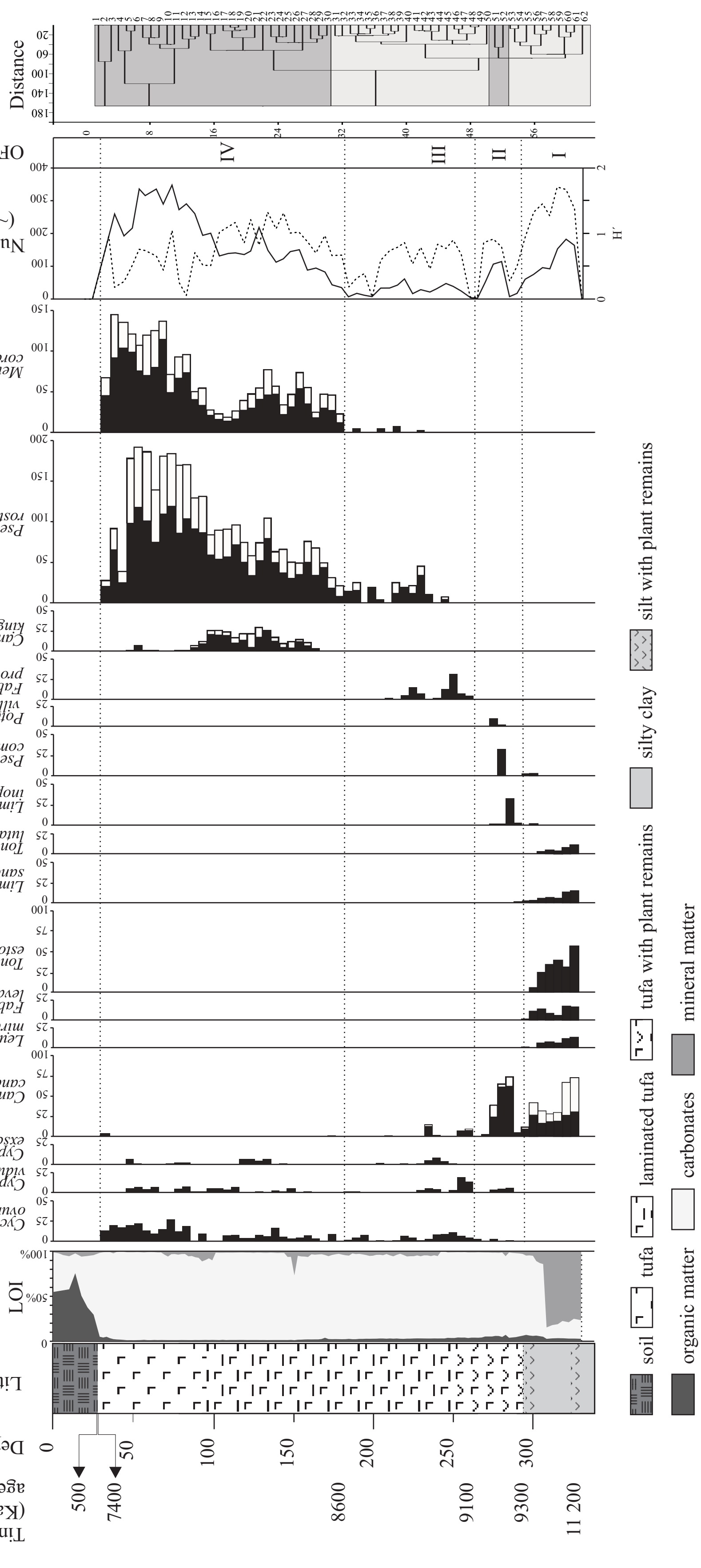


Fig. 2. Age, sedimentology (adapted from Kalm & Sohar 2009), diagram of loss on ignition, ostracod distribution (filled blocks = adults, empty blocks = juveniles), total number of specimens (solid line), Shannon–Wiener faunal diversity index H′ (dotted line), ostracod faunal zones (OFZ), Euclidean distances in the Varangu sequence (borders of OFZ II constrained by the minimal number of specimens).

The Varangu ostracod collection is deposited in the Geological Museum of University of Tartu (collection No. TUG 1370). Statistical analyses were performed with a special software package PAST, designed for palaeontological data analysis (Hammer et al. 2001).

Age control in the Varangu section is based on five calibrated ^{14}C AMS datings from tufa and plant macrofossil samples (Kalm & Sohar 2009) and on the pollen assemblage zones distinguished by Männil (1964, pp. 141–149).

RESULTS

Sediment properties and age

The Varangu section comprises three main sedimentary units (Fig. 2). The lowermost part of the section (333–293 cm) is dark grey (GLAY1 4/1) silty clay with few plant macroremains in its lower half and on the upper surface.

The interval 293–95 cm comprises brown-beige (2.5Y 8/2) pure calcareous tufa. The tufa is massive, light beige (2.5Y 7/3) and very pure (carbonate content up to 98%; Fig. 2). Macroscopic plant fibres occur in the lowermost portion (293–250 cm) of the unit. The interval 250–28 cm is composed of laminated coarse tufa with calcified tubular stems of charophytes. A sharp contact between the tufa and the overlying peaty soil layer (5Y 2.5/1) occurs at a depth of 28 cm. The content of organic matter is high in the soil layer (up to 75%), but low in other parts of the section (ca 3%). Apart from the plant remains, other non-calcareous components are almost lacking in the tufa layer. The proportion of non-carbonaceous minerogenic matter is the highest (ca 80%) in the silty clay layer, in the lowermost part of the section.

The ages of the boundaries of the sedimentary units (Fig. 2) were derived from the age–depth graph by Kalm & Sohar (2009). The age of the youngest tufa layer was derived from the pollen data, suggesting that the tufa precipitated around 7400 cal yr BP, when parent sediments for the soil layer started to accumulate (Männil 1964, pp. 141–149; Männil 1967). Both pollen stratigraphy by Männil (1964, pp. 141–149) and AMS dating (517–485 cal yr BP at the bottom of the soil layer) refer to an extended hiatus or erosion between the end of tufa precipitation and the beginning of soil formation.

Ostracod record and faunal zones

Sixteen ostracod species (57% of the species known in Quaternary sediments of Estonia) were identified from the silty clay and tufa, during the investigation of ca 7200 subfossil specimens. The soil layer did not contain ostracod subfossil material. The identified species are illustrated in Figs 3–5. Both adult and juvenile valves and carapaces were found, but isolated valves were prevailing in the silty clay and bivalved carapaces in the tufa. The ratio of adult to juvenile specimens (ca 70 : 30) suggests that the assemblages are autochthonous in the tufa. Former studies have shown that an assemblage is autochthonous and characteristic of the environment in which it is found when most of ontogenetic stages are present in the material (Whatley 1988; Boomer & Eisenhauer 2002).

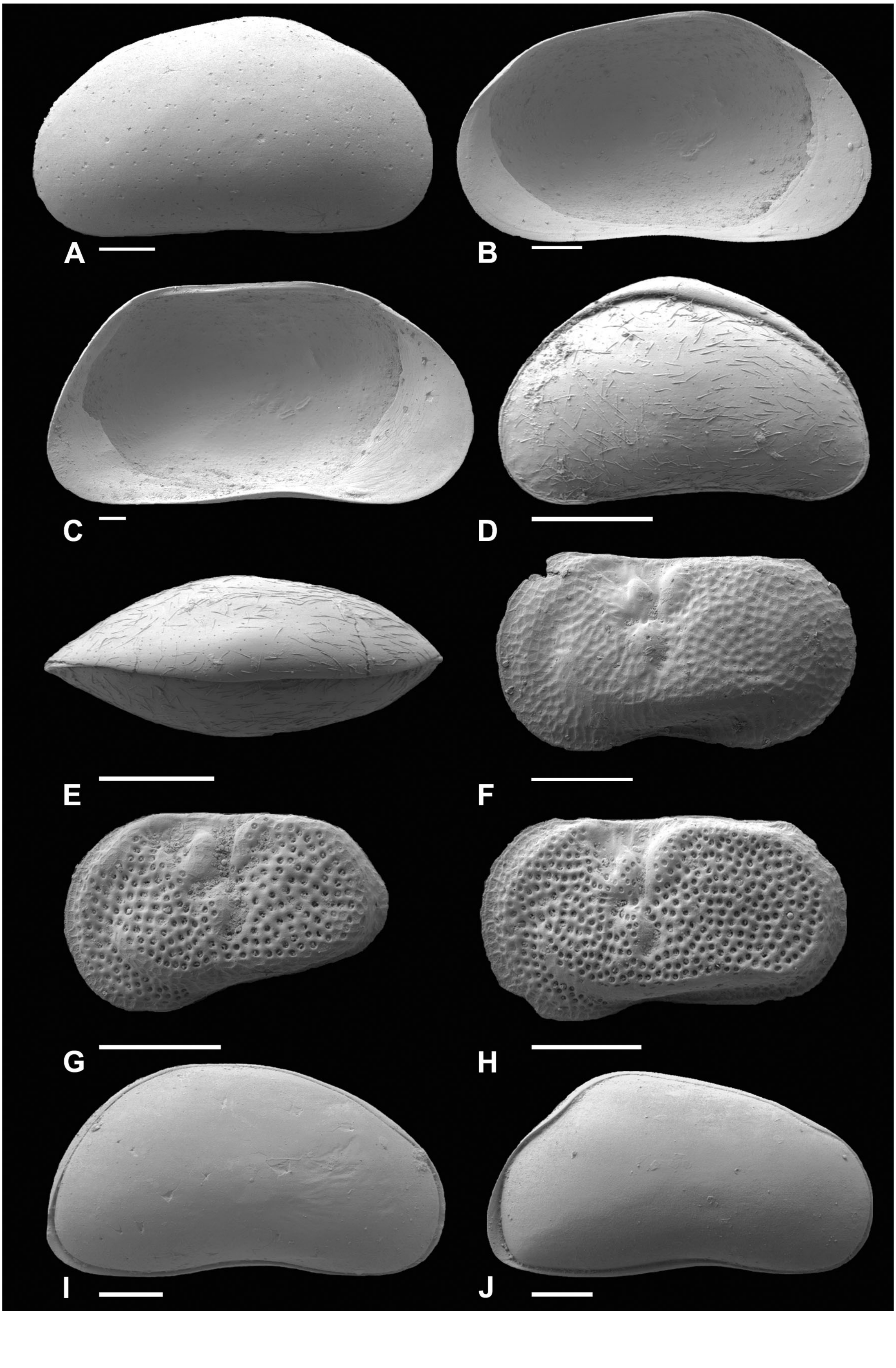
Three species, *Tonnacypris estonica* (Järvekülg) (= *Ilyodromus estonicus* in Järvekülg 1960; Fig. 3A, B), *Tonnacypris* cf. *lutaria* (Koch) (Fig. 3C) and *Potamocypris* cf. *villosa* (Jurine) (Fig. 3D, E), are new in the Quaternary subfossil record of Estonia. Griffiths et al. (1998) considered *T. estonica* fossils unknown. Thus, the material obtained from the Varangu section might be the first subfossil record of *T. estonica*.

The constrained cluster analysis of the data, based on Euclidean distances, resulted in four major clusters that are considered as ostracod assemblages below. Considering these results, the ostracod sequence in the Varangu site is divided into four ostracod faunal zones (OFZ I–IV; Fig. 2) according to the composition of assemblages. The ages of the OFZ boundaries (see Fig. 2) are based on datings by Kalm & Sohar (2009).

The oldest faunal zone (OFZ I, 330–293 cm, 11 200–9300 cal yr BP) in the silty clay layer contains *Limnocytherina sanctipatricii* (Brady & Robertson) (Fig. 3F), *Leucocythere mirabilis* Kaufmann (Fig. 3G, H), *Candona candida* (O. F. Müller) (Fig. 3I), *Fabaeformiscandona levanderi* (Hirschmann) (Fig. 3J, 4A), *T. estonica* and *T.* cf. *lutaria*. Isolated valves of ostracods were mostly recorded in this zone. This kind of disarticulation can be indicative of post-mortem transportation, or slow burial facilitating biological activity and decay of soft tissue (Whatley 1988).

Tonnacypris estonica prefers slowly flowing waters (Järvekülg 1959, 1960, 1995). Timm & Järvekülg (1975)

Fig. 3. Ostracod subfossils from the Varangu sequence. Scale 0.2 mm. **A**, *Tonnacypris estonica*, right valve, external view; **B**, *Tonnacypris estonica*, left valve, internal view; **C**, *Tonnacypris* cf. *lutaria*, left valve, internal view; **D**, *Potamocypris* cf. *villosa*, carapace, lateral view; **E**, *Potamocypris* cf. *villosa*, carapace, dorsal view; **F**, *Limnocytherina sanctipatricii*, left valve, external view; **G**, *Leucocythere mirabilis*, female, left valve, external view; **H**, *Leucocythere mirabilis*, male, left valve, external view; **I**, *Candona candida*, carapace, lateral view; **J**, *Fabaeformiscandona levanderi*, carapace, lateral view.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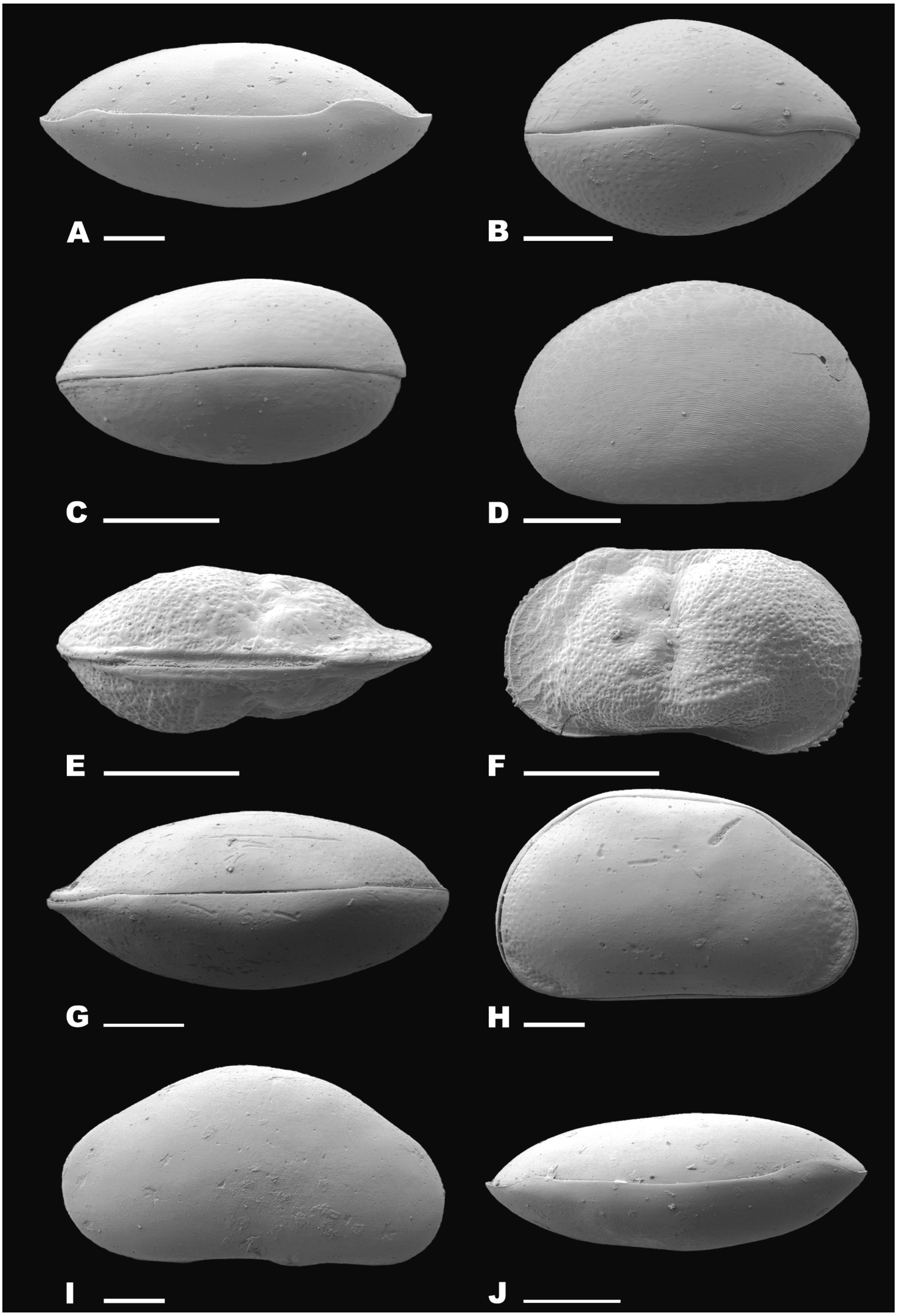

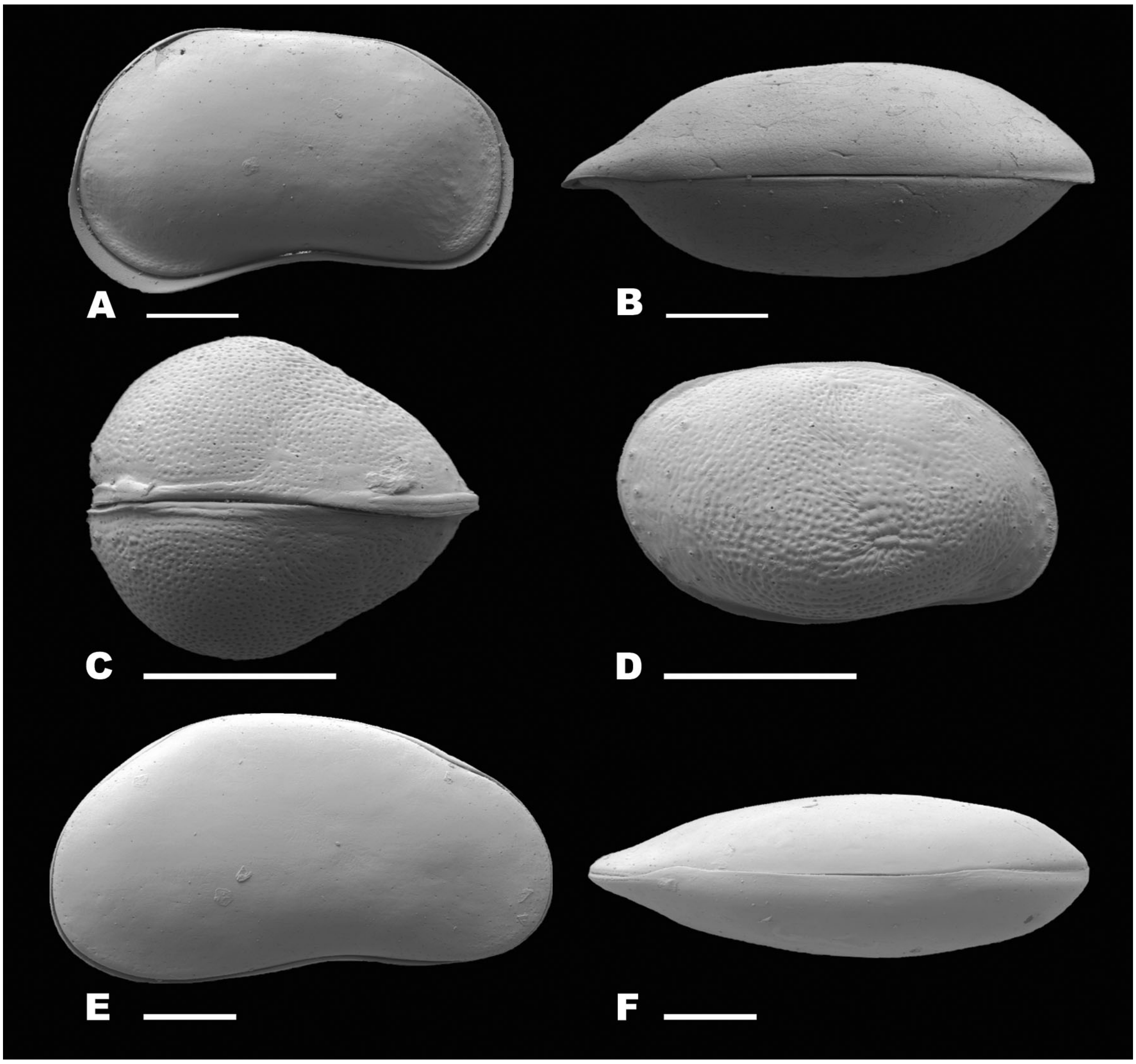

Fig. 5. Ostracod subfossils from the Varangu sequence. Scale 0.2 mm. **A**, *Pseudocandona rostrata*, carapace, lateral view; **B**, *Pseudocandona rostrata*, carapace, dorsal view; **C**, *Metacypris cordata*, female, carapace, dorsal view; **D**, *Metacypris cordata*, female, right valve, external view; **E**, *Candonopsis kingsleii*, carapace, lateral view; **F**, *Candonopsis kingsleii*, carapace, dorsal view.

described high abundance of recent *T. estonica* in cold-water springs of the Pandivere Upland in Estonia. Van der Meeren et al. (2009) refer to findings of *T. estonica* in modern Mongolian shallow slow-running springs with sandy or silty bottom sediments, where the species is characteristic of oligotrophic environment (water temperature 3.5–16.8 °C). *Tonnacypris lutaria* is found in seasonal pools but also in springs in several parts of Europe (Meisch 2000). *Limnocytherina sanctipatricii* occurs mainly in deep lacustrine oligotrophic and cold environs with low organic content (Meisch 2000). *Leucocythere mirabilis* is present in oxygen-rich cold oligotrophic lakes (depth ≥12 m; Scharf 1993; Danielopol et al. 1993; Meisch 2000). *Candona*

Fig. 4. Ostracod subfossils from the Varangu sequence. Scale 0.2 mm. **A**, *Fabaeformiscandona levanderi*, carapace, dorsal view; **B**, *Cypridopsis vidua*, carapace, dorsal view; **C**, *Cyclocypris* cf. *ovum*, carapace, dorsal view; **D**, *Cypria exsculpta*, left valve, external view; **E**, *Limnocythere inopinata*, female, carapace, dorsal view; **F**, *Limnocythere inopinata*, female, left valve, external view; **G**, *Pseudocandona compressa*, carapace, dorsal view; **H**, *Pseudocandona compressa*, carapace, lateral view; **I**, *Fabaeformiscandona protzi*, male, right valve, external view; **J**, *Fabaeformiscandona protzi*, carapace, dorsal view.

candida and *F. levanderi* also prefer lower water temperature (Viehberg 2006; Wetterich et al. 2008).

Three younger ostracod faunal zones (OFZ II–IV) are found in the freshwater tufa sequence at Varangu. The faunal diversity index is rather low in this interval (Fig. 2). The species present in OFZ I disappear in OFZ II (293–262 cm, 9300–9100 cal yr BP), with the only exception of *C. candida*. Specimens of *Cypridopsis vidua* (O. F. Müller) (Fig. 4B), *Cyclocypris* cf. *ovum* (Jurine) (Fig. 4C) and *Cypria exsculpta* (Fischer) (Fig. 4D) occur in low numbers (altogether <35 specimens per sample) in all three faunal zones (OFZ II–IV). Nagorskaya & Keyser (2005) have described those species in all freshwater systems. According to Meisch (2000), *Cyclocypris ovum* is common in the littoral zone of lakes, *Cypridopsis vidua* is an active swimmer in water bodies rich in vegetation and *Cypria exsculpta* is a pure freshwater species in both permanent and temporary water bodies.

New species in OFZ II are *Limnocythere inopinata* (Baird) (Fig. 4E, F), *Potamocypris* cf. *villosa* (Fig. 3D, E) and *Pseudocandona compressa* (Koch) (Fig. 4G, H). *Limnocythere inopinata* and *Ps. compressa* prefer littoral areas in lakes, whereas *P. villosa* is a pure freshwater species known from grassy waters flowing from springs and pools; it also occurs in small numbers in the littoral area of lakes and is tolerant to eutrophic conditions (Meisch 2000).

New species in OFZ III (262–180 cm, 9100–8600 cal yr BP) are *Fabaeformiscandona protzi* (Hartwig) (Fig. 4I, J) and *Ps. rostrata* (Brady & Norman) (Fig. 5A, B). *Fabaeformiscandona protzi* is considered a winter form (Hiller 1972) and a cold-stenothermal ostracod in Estonia according to Järvekülg (1959) and Timm & Järvekülg (1975). This species is known from cold reservoirs in both littoral and profundal zones of lakes. Air temperature estimations by Horne & Mezquita (2008) suggest low temperature ranges for *F. protzi*. *Pseudocandona rostrata* is a benthic cold stenothermal species documented from small lakes, springs and interstitial groundwater, and its adults dominate in the summer period (Meisch 2000 and references therein). Keatings et al. (2002) have found the species from small ponds fed by groundwater springs.

In OFZ IV (180–28 cm, 8600–7400 cal yr BP) *F. protzi* disappears and *Ps. rostrata* is gradually gaining the dominant position in the ostracod assemblage. *Metacypris cordata* Brady & Robertson (Fig. 5C, D) is a new species in this assemblage. Its abundance increases together with the increase in *Ps. rostrata*. Another new species in this faunal zone is *Candonopsis kingsleii* (Brady & Robertson) (Fig. 5E, F).

Metacypris cordata is a warm stenothermal summer form, known from shallow, macrophyte-rich freshwater environs, which is considered an indicator of lake ageing (Hiller 1972; Griffiths & Evans 1995; Danielopol et al. 1996; Meisch 2000; Viehberg 2004). It populates mainly littoral vegetation in eutrophic lake margins or floating vegetation masses, avoiding groundwater outflows (Danielopol & Vespremeanu 1964; Danielopol et al. 1996; Meisch 2000). *Candonopsis kingsleii*, which is also present in OFZ IV, prefers the littoral zone of lakes with paludal substrate. This species may co-occur with *M. cordata* and is known from small vegetation-rich lakes (Meisch 2000).

DISCUSSION

Palaeogeographic reconstructions show that the Pandivere Upland and its vicinity became free of local proglacial lakes (turned into dry land) 12 800 cal yr BP at the latest (Rosentau et al. 2009). Water level studies of lakes in the Viitna area in the northwestern slope of the Pandivere Upland refer to a water level rise during 11 400–8900 cal yr BP, where a notable lake water decrease was established at ca 8000 cal yr BP (Punning et al. 2003). Trophic status studies suggest that most of the lakes were oligotrophic in the early Holocene in Estonia (Mäemets & Saarse 1995).

The mean annual air temperature was rather low at the beginning of the early Holocene in northern Europe (reconstructions based on pollen data by Heikkilä & Seppä 2003). The air temperature was increasing rapidly during the early Holocene in the area, achieving the thermal maximum at 8000–4500 cal yr BP. Pollen data indicate progressively warmer and drier summers during the Holocene thermal maximum in Estonia (Seppä & Poska 2004).

A short transient cool ‘8200 yr event’ is recorded against the background of temperature increase in the early Holocene of Europe (e.g. von Grafenstein et al. 1998; Seppä & Poska 2004; Veski et al. 2004; Prasad et al. 2006). It is suggested that the environment was dry in northern Europe during cool Holocene phases (Magny et al. 2003; Prasad et al. 2006). Seppä & Poska (2004) interpret the pollen data in favour of a cooling in the early Holocene (ca 8400 cal yr BP) and point at the following temperature increase ca 8000 cal yr BP in northern Estonia. Saarse et al. (1998) recorded the cool periods of 9600–9500 and 8700–8400 cal yr BP in northern Estonia as well.

The ostracod assemblage in OFZ I, at 11 200–9300 cal yr BP, is indicative of lacustrine conditions, probably with a limited inflow. This is inferred from the ecological preferences of the species present in that interval. The occurrence of deep-water ostracods, such as *Leucocythere mirabilis* and *Limnocytherina sanctripatricii*, suggest a profundal area and some inflow from the nearby cold springs into the cold oxygen-rich oligotrophic lake (depth ≥12 m). The sedimentation took place in open-water environment, as silt- and clay-sized particles dominate in pelagic sediments (Cohen 2003). Minerogenic sediments are related to oligotrophic lakes (Håkanson & Jansson 1983). Pollen data show that herbs, e.g. *Artemisia*, occupied the surroundings of the lake. The dominance of *Betula nana* refers to an open landscape and arctic cold-tolerant plant community (Männil 1964, pp. 141–149).

The silt unit contains an assemblage that is ecologically heterogeneous and probably mixed, judging from the co-occurrence of *Tonnacypris estonica* and *T.* cf. *lutaria* in this OFZ. Most of the subfossil material of OFZ I is represented by single uncrushed valves, whereas *T. estonica* and *T.* cf. *lutaria* are represented by adult specimens only. This is probably due to sediment transportation and water movement sorting the ostracod valves.

Tufa formation in the Pandivere Upland and its surroundings started in the early Holocene (Männil 1967). Terrigenous sedimentation (silty clay) was replaced by tufa precipitation at ca 9300 cal yr BP at Varangu. The information attained from the ostracod fauna reflects successive changes in the lake marginal environments in the early Holocene.

At ca 9300 cal yr BP cool oligotrophic environment turned mesotrophic. *Cyclocypris ovum*, *Cypria exsculpta* and *Cypridopsis vidua*, taxa of a wide ecological range, are common throughout the tufa unit. The appearance of these species suggests that water level lowered in the lake. The disappearance of species preferring cold waters suggests a temperature rise. Ostracod faunal zone II reflects an environmental succession from an initial open-water stage, with some hint of flowing water, into a littoral stage of a richly vegetated large lake margin. The increasing density of vegetation can be suggested from the occurrence of *Cypridopsis vidua*. The assumption gains further support from the presence of macroremains (films) of plants. Carapaces prevail in subfossil material from OFZ II, which suggests more stagnant water, although the occurrence of *Potamocypris villosa* suggests an at least temporary (seasonal) slow flowing water regime.

At 9100–8600 cal yr BP the water temperature decreased slightly at the Varangu site. This agrees roughly with the data by Seppä & Poska (2004) which suggest a cooling period at 9000–8400 cal yr BP in northern Estonia. Cooling at Varangu is derived from the record of *Fabaeformiscandona protzi*, a diagnostic species of cold conditions. The appearance of *Pseudocandona rostrata* was also recorded in OFZ III, along with the disappearance of *Limnocythere inopinata*, *P.* cf. *villosa* and *Pseudocandona compressa* and decrease in the abundance of *Candona candida*. However, there was no marked water level rise, judging from the absence of profundal species in OFZ III. Additionally, water level lowering can be suggested, probably due to drier conditions in a cooling phase.

At 8600–7400 cal yr BP the ostracod sequence reflects a new ecological shift. The community in OFZ IV represents warm stagnant waters in lacustrine littoral environment. Conditions became favourable for *Metacypris cordata*, a characteristic species of eutrophic lakes. Many isolated tufa basins occurred in the Pandivere area in the early Holocene (Männil 1964, pp. 141–149). This viewpoint gains further support from the ostracod record at Varangu – no species characteristic of flowing waters are present in the assemblage of OFZ IV, indicating that there was no surface spring inflow to the lake. The dynamics of *M. cordata* suggests a lake environment, with a lowering water level. The species probably colonized and crawled among the mats of *Chara* algae, which were common, judging from the abundance of algal calcified tubular stems. Terrestrial mollusc records from the upper part of the tufa suggest a notable water level lowering (Männil 1964, pp. 141–149).

Although *M. cordata* is considered exobenthic and avoiding groundwater-fed water bodies (Danielopol et al. 1996), it co-occurs with *Ps. rostrata* in the Varangu sequence. *Pseudocandona rostrata* is a cold-water stenothermal benthic species inhabiting small lakes, springs and interstitial groundwater and groundwater-fed ponds. Co-occurrence of these species deserves special attention. In the groundwater-fed Lake Sinijärv, 7.7 km northeast of the Varangu site, these two species do not co-occur in the sediments. *Metacypris cordata* is recorded from late glacial to early Holocene sediments, whereas *Ps. rostrata* is known from late Holocene calcareous sediments when the lake turned to the oligotrophic state (Sohar & Kalm 2008). Co-existence of these summer-forms at Varangu suggests that the lake was likely fed by bottom springs, whilst upper water masses warmed up during the summer season. The ostracod assemblage is autochthonous, with both juvenile and adult specimens being present in the fossil material, which is considered indicative of still waters. The warming climate and drier conditions in the early Holocene (Seppä & Poska 2004) most likely affected the lake level. The inflow to the lake was reduced and water level lowering ended tufa formation. Water level lowered further during the Holocene thermal maximum, and the lacustrine basin ceased to exist at the Varangu site.

The often-cited Absolon's (1973) synthesized succession of ostracod fauna is divided into the late glacial '*candida* fauna' and Holocene '*cordata* fauna', with a transitional community between them. The transition from a '*candida* fauna' to '*cordata* fauna' refers to a particular series of changes in lake development

(Griffiths & Evans 1995). At Varangu, OFZ I–III can be interpreted as Absolon's (1973) late glacial/Holocene transitional phase in the ostracod fauna that in OFZ IV was gradually replaced by typical Holocene '*cordata* fauna'. Calcareous sediments were suitable for ostracods, especially for *M. cordata*, which is rather often related to humic deposits (Griffiths & Evans 1995). Environmental changes in the ostracod assemblage structures follow lake evolution from a deep oligotrophic lake (at 11 200–9300 cal yr BP) to an overgrown lake basin (at ca 7400 cal yr BP) in the Varangu area.

CONCLUSIONS

The ostracod data from Varangu provide a good basis for detailed reconstruction of environmental changes in this part of the Pandivere Upland during the early Holocene. The ostracod subfossil record from the silty clay and tufa at Varangu, on the southern slope of the Pandivere Upland, indicates changing lacustrine conditions. The earliest ostracod record in OFZ I, with dominant *Tonnacypris estonica*, *Candona candida*, *Fabaeformiscandona levanderi*, *Leucocythere mirabilis* and *Limnocytherina sanctripatricii* at 11 200–9300 cal yr PB, suggests a cool and oligotrophic environment and possibly represents a mixed subfossil assemblage (due to spring water influx). Calcareous sedimentation began at ca 9300 cal yr BP in a shallowing lake. Temperature increase and water level lowering were deduced from the ostracod assemblage structure: profundal species were replaced by littoral ostracod taxa (*Limnocythere inopinata*, *Pseudocandona compressa*, *Potamocypris* cf. *villosa*) in OFZ II (9300–9100 cal yr BP). An episode of slight temperature decrease in OFZ III, recorded by the appearance of *Fabaeformiscandona protzi* in OFZ III (ca 9100 cal yr BP), was followed by a warming at ca 8600 cal yr BP. The occurrence of *Metacypris cordata* in OFZ IV refers to eutrophic conditions, temperature rise and water level lowering at the Holocene thermal maximum. Still, the water body was continuously fed by cold bottom springs, as oligothermophilic *Pseudocandona rostrata* co-occurs with exobenthic *Metacypris cordata*. Around 7400 cal yr BP lacustrine sedimentation ceased at the Varangu site.

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Vara-Holotseenis toimunud järvelise basseini ja keskkonna muutused Põhja-Eestis ostrakoodide subfossiilileidude põhjal Varangu läbilõikest

Kadri Sohar ja Tõnu Meidla

Varangu läbilõige asub Pandivere kõrgustiku lõunanõlval. Ligikaudu 11 200–9300 aastat tagasi settis uuritud alal aleuriitne savi ja ostrakoodide (nt *Tonnacypris estonica*, *Leucocythere mirabilis*, *Limnocytherina sanctipatricii*) subfossiilid setetes viitavad hapnikurikkale jahedaveelisele sügavale oligotroofsele järvelisele keskkonnale, kuhu voolasid ka külmaveelised allikad. Ligikaudu 9300–7400 aastat tagasi settis järvenõos lubi, milles on säilinud litoraali piirkonnale iseloomulikud ostrakoodiliigid (nt *Cyclocypris ovum*, *Cypridopsis vidua*, *Metacypris cordata*), mis viitavad veekogu järkjärgulisele madaldumisele, soojenemisele, eutrofeerumisele ja taimestiku kasvule kaldapiirkonnas. 7400 aastat tagasi lakkas järvesetete kuhjumine Varangu järvenõos.