since 1961

Baltica

BALTICA Volume 27 Number 1 June 2014 : 15–24
doi: 10.5200/baltica.2014.27.02

Biostratigraphy, shoreline changes and origin of the Limnea Sea lagoons in northern Estonia: the case study of Lake Harku

Ieva Grudzinska, Leili Saarse, Jüri Vassiljev, Atko Heinsalu

Grudzinska, I., Saarse, L., Vassiljev, J., Heinsalu, A., 2014. Biostratigraphy, shoreline changes and origin of the Limnea Sea lagoons in northern Estonia: the case study of Lake Harku. *Baltica, 27 (1), 15–24.* Vilnius. EISSN 1648-858X.

Manuscript submitted 15 November 2013 / Accepted 10 April 2014 / Published online 9 June 2014.

Abstract The paper presents diatom, loss-on-ignition, magnetic susceptibility, and radiocarbon data to reconstruct the depositional history and evolution of Lake Harku, a former Limnea Sea lagoon. Harku is one of the youngest isolated lakes that has been studied bio- and chronostratigraphically in Estonia to date. Based on changes in diatom assemblages, four evolutionary stages in basin development have been recognized (lagoon, semi-enclosed lagoon, transitional and closed lake). Shoreline positions at 2000, 1500, 1000 and 800 cal BP have been reconstructed and displayed on 3D palaeogeographic maps. Lake Harku became isolated from the Limnea Sea at ~800 cal BP, followed by occasional seawater incursions over the next 300 years. Plain landscape, low-lying threshold, and proximity to the sea contributed to extended basin isolation.

Keywords *• diatom • radiocarbon dating • loss-on-ignition • 3D palaeogeographic maps • lake isolation*

✉ *Ieva Grudzinska (ieva.grudzinska@ttu.ee), Leili Saarse, Jüri Vassiljev, Atko Heinsalu, Institute of Geology at Tallinn University of Technology, Ehitajate tee 5, 19086 Tallinn, Estonia*

INTRODUCTION

Beginning in the postglacial period, the Baltic Sea underwent a complicated environmental and geological development (e.g. Berglund 1964; Björck 1995; Hyvärinen *et al*. 1988; Miettinen 2002). In northern regions proximal to the Scandinavian Ice Sheet centre, the sea level regressed, whereas it rose in the southern regions due to differences in glacio-isostatic response. This caused spatial and temporal changes in the Baltic Sea coastline. Regional uplift and apparent sea level lowering in the northern regions resulted in the isolation of coastal water bodies, known as residual/isolated lakes, which emerged during the different stages of the Baltic basin. These isolated water bodies are an excellent sedimentary archive of the evolutionary stages of this coastal region, including the Limnea Sea stage (4500 cal BP up to present). To date, the biostratigraphy and shoreline changes of the Limnea Sea are poorly documented in Estonia. Only two lakes in northern Estonia, which became isolated during the Limnea Sea phase, have been studied bio- and chronostratigraphically (Grudzinska *et al*. 2012).

Lake Harku presents a good setting for reconstructing coastal evolution in this region due to fast sedimentation rate (Saarse 1994), which improve the temporal resolution (Fig. 1). The aim of the current study is to examine environmental changes in Lake Harku, a former Limnea Sea lagoon, focusing on its isolation event, and to present 3D palaeogeographic maps of the shoreline.

GEOLOGICAL SETTING AND SITE DESCRIPTION

The North Estonian klint, one of the most impressive geological monuments in Estonia, is intersected by klint bays and peninsulas. Kakumäe Klint Bay to the west of Tallinn is approximately 10 km long and up to 3 km wide, bordered by Suurupi and Kakumäe klint peninsulas (Fig. 1A, B). A buried valley is incised into the limestone down to 140 m below sea level, reaching the Cambrian bedrock, and is faintly traceable in the topography of the klint bay. This buried valley is filled with till, sand, gravel, varved clay, and sandy-silty deposits of the different stages of the Baltic Sea (Kessel, Pork 1971). After the ice recession, the Baltic Ice Lake flooded the Tallinn area, reaching 110 m above present sea level (Saarse *et al.* 2007) and inundating the entire area of the present city. Because of postglacial isostatic uplift, Tallinn began to emerge from the sea, a trend that is ongoing (Torim 2004).

Lake Harku (59°25´N, 24°37´E) on the western border of Tallinn (Fig. 1A) became isolated rather late in the Holocene and offers a possibility to examine the development and environmental changes in the lake over the past 2000 years. It is a medium size, shallow hypereutrophic lake at 1.2 m above mean sea level (a.s.l.) with an area of 163.3×10^{-4} m^2

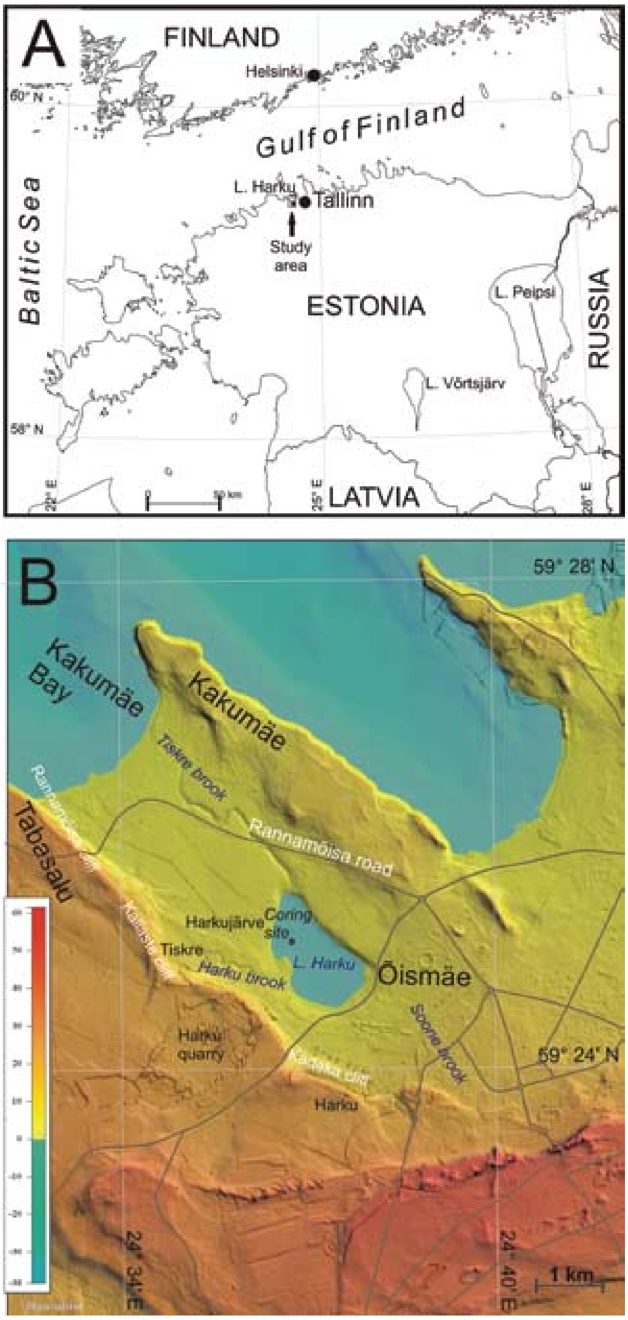

Fig. 1 Location of the study area shown on the overview map (A). Modern topography in the surroundings of Lake Harku with indication of the sampling site (B).

(Tamre 2004), located at the back of the Kakumäe Klint Bay (Fig. 1B). The maximum water depth is only 2.25 m, with an average of 1.7 m. In the 1930s the lake area was smaller – 159×10^{-4} m^2 and the water level only at 0.9 m a.s.l. (Riikoja 1934). Due to the need to irrigate the surrounding fields, a regulator was installed on its outflow (the Tiskre Brook) in 1974, resulting in a water table rise. Water transparency is less than 1 m and pH varies from 9–10 in the summer to 7.2 in winter. Lake catchment, ca 50 km^2 in area, is rather densely settled, resulting in an increasing anthropogenic stress. The large residential area of Õismäe is located directly on the south-eastern shore of the lake, with Harku village farther in south, the new residential areas of Harkujärve and Tiskre in the west, and Tabasalu settlement to the northwest (Fig. 1B).

Lake bottom is flat and mostly covered by gyttja, with the maximum thickness 240 cm. Toward the south, the gyttja becomes thinner and wedges out, becoming absent in the littoral zone where only sand is exposed. Harku is a drainage lake, fed by the Harku and Soone Brooks, flowing out to the Kakumäe Bay through the Tiskre Brook (Fig. 1B). Lake shores are flat, partly paludified and covered by meadows, pastures, and a rim of *Alnus* and *Salix* that provide shelter from the wind. In the 1980s, the southern peaty shore was mantled by glaciofluvial sand to create a sandy beach for the Õismäe residents, an action that has been repeated every year.

Aquatic vegetation is scanty and represented by 13 taxa, among which emergent and floating-leaved macrophytes are the most abundant (Mäemets 1977). Since 1950, phytoplankton dominated by the green algae *Scenedesmus quadricauda* started to flourish, causing frequent "water blooms". To improve the trophic status of the lake, various lake restoration projects have been proposed (Andersen *et al.* 1992), most of which are still awaiting implementation. In 1993–1994, a biomanipulation was carried out for curbing the phytoplankton, but failed to yield the expected results (Leeben *et al.* 2008).

MATERIAL AND METHODS

The bottom deposits of Lake Harku have been examined by several researchers (e.g. Andersen *et al.* 1992; Heinsalu 1993; Saarse 1994; Leeben *et al.* 2008). In winter 2012, series of overlapping cores were obtained with a Russian sampler from the north-western part of the basin (59°25´1.7´´ N, 24°36´35.7´´ E; Fig. 1B). The uppermost loose sediment was sampled by Willner-type sampler. All 1-m-long core sections were described in field, photographed, sealed in plastic liners, and stored in a laboratory cold-room. Sediment taken by the Willner sampler was cut into 1-cm-thick slices for coming analysis. The lithostratigraphy of the core

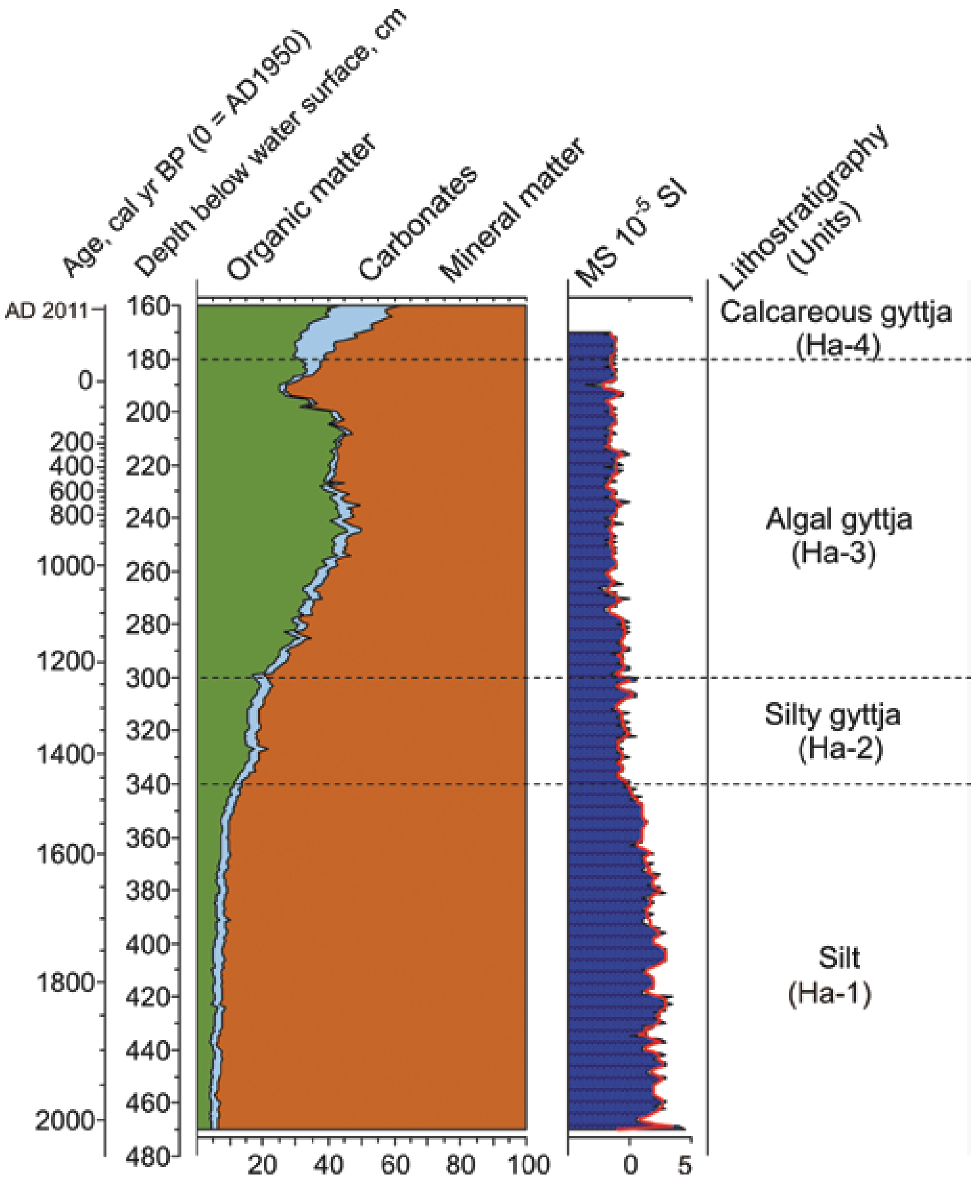

Fig. 2 Loss-on-ignition and magnetic susceptibility from Lake Harku core.

is presented (Fig. 2; Table 1). Continuous 1-cm-thick samples were used for loss-on-ignition (LOI) analysis. The organic matter (OM) was measured at 525°C and expressed in percentages of dry matter. The percentage of carbonates ($CaCO_3$) was calculated after combustion of LOI residue for 2 hours at 900°C. The mineral fraction was calculated based on the sum of organic and carbonates compounds. Low-field bulk magnetic susceptibility (MS) was measured with a Bartington MS2E high-resolution scanning sensor at 1-cm resolution from cleaned sediment surface covered with a thin plastic film (Fig. 2).

The diatom samples were prepared by following techniques described in Battarbee *et al.* (2001). Sediment samples were digested in hydrogen peroxide to remove all OM, hydrochloric acid was added to remove $CaCO_3$, and repeated decantation was applied to extract fine and coarse mineral particles.

Table 1 Lithology of Lake Harku core

Depth, cm	Lithology
0–160	water
160–170	calcareous gyttja, dark greenish grey, loose
170–180	calcareous gyttja, greyish green, loose
180–240	algal gyttja, greenish brown
180–300	algal gyttja, dark brown
300–340	silty gyttja, greyish
340–470+	silt, dark grey

Some drops of the remaining residue were spread over the cover slip, dried overnight and mounted permanently onto microscope slides with Naphrax medium. Between 500 and 600 valves were counted from each sub-sample under Zeiss Axio Imager A1 microscope at ×1000 magnification and identified to species level in order to estimate the percentage abundance of taxa.

Table 2 Radiocarbon measurements of Lake Harku sediments

Depth, cm	Age, ^{14}C BP	Calibrated age, cal BP (average)	Lab. No	Material
275–280	1185±30	1065–1170 (1120±55)	Poz–51453	Plant remains
295–300	1265±30	1175–1260 (1220±45)	Poz–51454	Plant remains
424	1895±35	1750–1890 1820±70	Poz–49185	Wood

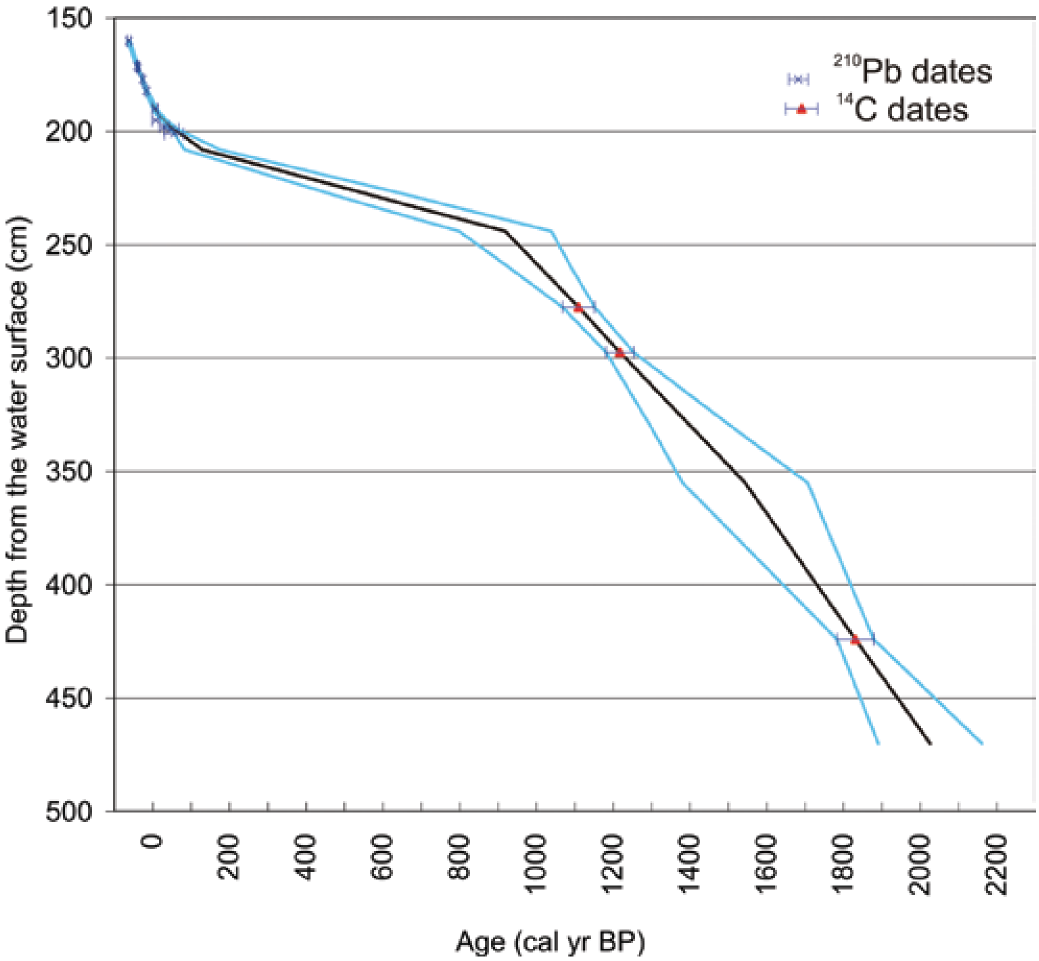

Fig. 3 Age-depth model considering lithological boundaries with respect to loss-on-ignition (see Fig. 2). The black line is weighted average of radiocarbon dates with error bars (blue lines) at one-sigma.

The 170–350 cm core interval was used for diatom analysis. Diatoms were grouped according to their salinity tolerance into marine/brackish, halophilous, small-sized fragilarioid taxa with brackish water affinity, small-sized fragilarioid taxa preferring fresh water, indifferent, freshwater, and unidentified taxa. Habitat classification included planktonic, small-sized fragilarioid, and periphytic taxa. Diatom floras used for the identification and ecological information were based on well-established sources (Krammer, Lange-Bertalot 1986, 1988, 1991a, b; Snoeijs 1993; Snoeijs, Vilbaste 1994; Snoeijs, Potapova 1995; Snoeijs, Kasperovičienė 1996; Snoeijs, Balashova 1998; Witkowski *et al*. 2000).

Macrofossils for radiocarbon dating were extracted by soaking 5-cm-thick samples (with a volume of ~250 cm^3) in a solution of water and $Na_4P_2O_7$. After sieving through a 0.20 mm mesh, the material was dried at 70°C. Unfortunately, plant macrofossils were very rare as gyttja largely composed of algae, which was confirmed from measurements of N, C, H concentrations and the C/N ratio (Saarse 1994). An age-depth model was produced based on ^{210}Pb measurements (Leben *et al*. 2008) and AMS radiocarbon dates of macrofossils (Poznan Radiocarbon Laboratory) (Fig. 3; Table 2). Radiocarbon dates were calibrated at one-sigma confidence level using the IntCal09 calibration dataset (Reimer *et al*. 2009) and the OxCal 4.1 program (Bronk Ramsey 2009) and were combined with lithological data according to the OxCal deposition model (Bronk Ramsey 2008). The present study applied calibrated ages as weighted averages before present (cal BP, 0=AD 1950) (Table 2). ^{210}Pb dates permitted extending the chronology up to AD 2011. Diatom, LOI, and MS results were plotted, using the Tilia v.1.7.16 software (Grimm 2011).

Palaeogeographic maps are based on a GIS analysis in which interpolated water level surfaces were removed from the digital terrain model (DTM; Rosentau *et al*. 2009). Topographic maps at scales of 1:2000; 1:10 000, and 1:25 000 were used to create a DTM with grid size of 10×10 m. Palaeogeographical maps for different time windows were compiled based on the assumption that a decrease in the land uplift after the Litorina Sea transgression occurred linearly (Mörner 1979; Yu *et al*. 2007; Rosentau *et al*. 2012) and that global sea level remained nearly constant (Lambeck, Chappell 2001).

RESULTS

Lithostratigraphy and chronology

A lithostratigraphic transect along the lake reveals that the thickness and composition of sediments in Lake Harku is quite similar (Saarse 1994). A comparison of the LOI results of earlier studied cores (Saarse 1994) with the master cores obtained in 2005 and 2012 shows relatively good consistency. The sediment composition changes gradually from silt (Ha-1) to silty gyttja (Ha-2), algal gyttja (Ha-3) and calcareous gyttja (Ha-4; Fig. 2). Silt (core depth of 470–340 cm) contains about 5% OM, in silty gyttja (340–300 cm) the level of OM increases to 20% and in algal gyttja to 40% (Fig. 2). According to the age-depth model (Fig. 3), the silt was deposited between 2030 and 1480 cal BP, silty gyttja between 1480 and 1230 cal BP, algal gyttja from 1230 cal BP to AD 1956, and calcareous gyttja between AD 1956 and 2011. The maximum OM values measured along the 250–200 cm core interval correspond to 950–70 cal BP. The low content of $CaCO_3$ is typical of other fore-klint lakes (Saarse 1994), except for the topmost gyttja where it rapidly increased to 20%, due to the liming of soils in the lake catchment and by the establishment of the Harku quarry in 1954 (R. Voog pers. comm.). As Harku sediment are composed of organic, quartz-rich and carbonate components which are diamagnetic, MS values are low. Bulk MS gradually decreased upsection, from 2–3x10^{-5} SI units between 470–380 cm, decreasing to zero between 380–335 cm, and remaining negative upsection (Fig. 2).

Diatom stratigraphy

A total of 117 diatom taxa representing 51 genera were identified in the 170–350 cm core interval. The most common diatom species are displayed (Fig. 4). The diatom assemblage in the basal part of the core (350–295 cm) is dominated by small fragilarioid taxa with brackish-water affinity (35–50%), primarily represented by *Pseudostaurosira subsalina*, *Opephora mutabilis*, and *Fragilaria sopotensis*. Marine/brackish-water species are represented by the planktonic *Chaetoceros muelleri* var. *subsalsum*, the periphytic *Planothidium delicatulum* and *Navicula peregrina*, whereas the planktonic halophilous *Cyclotella meneghiniana* occurs at 330–310 cm, indicating temporary nutrient enrichment in the embayment (Weckström, Juggins 2006) (Fig. 4).

Around the depth of 295 cm, *Martyana schulzii* and *Opephora guenter-grassi* disappeared, the content of *Pseudostaurosira subsalina* and *Opephora mutabilis* decreased, and that of the *Pseudostaurosiropsis geocollegarum* and *Opephora krumbeinii* increased substantially. Shortly before the marked increase in the freshwater taxon *Stephanodiscus parvus*, the marine/brackish planktonic *Chaetoceros muelleri* var. *subsalsum* reaches its maximum value of 7%.

In the transition zone (265–225 cm), the most significant feature of the diatom flora is the sharp increase in planktonic freshwater taxon *Stephanodiscus parvus* (up to 32%) and halophilous *Cyclotella meneghiniana* (up to 11%), indicating nutrient enrichment (Ander-

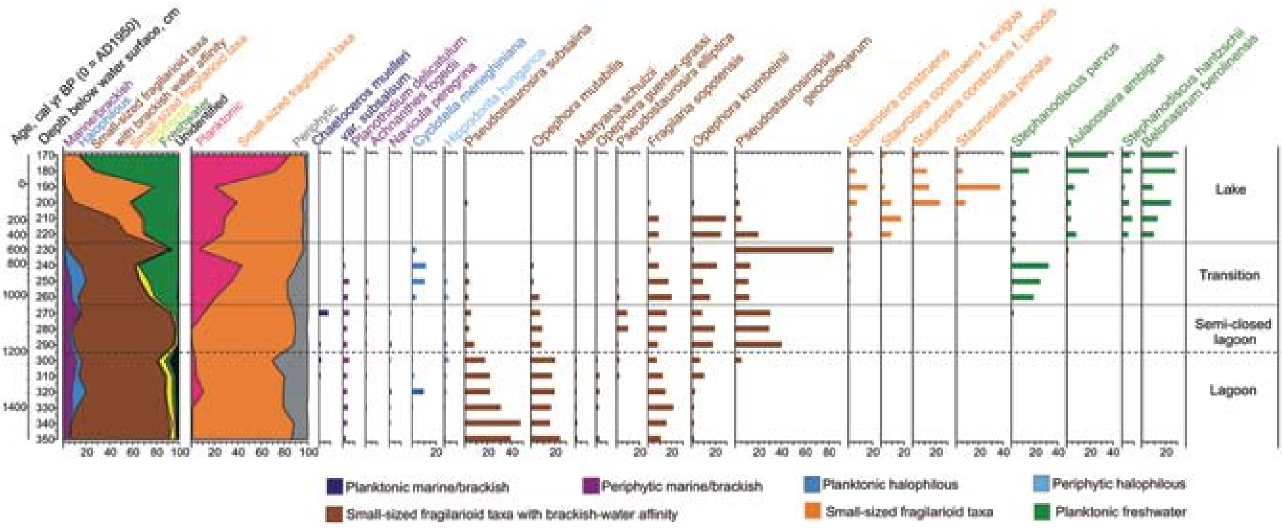

Fig. 4 Percentage diagram of selected diatom taxa from Lake Harku.

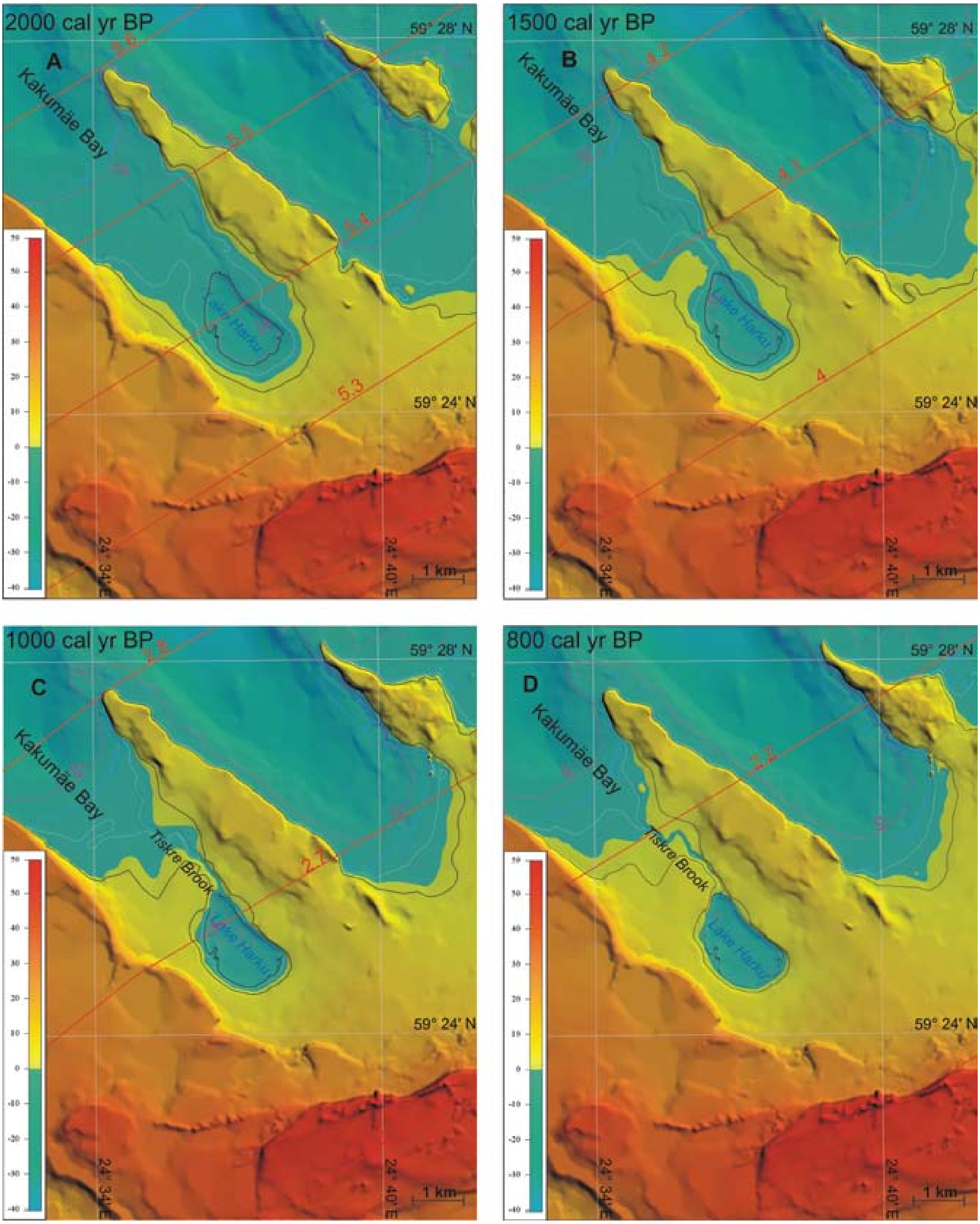

Fig. 5 Palaeogeographic maps of 2000 (A), 1500 (B), 1000 (C) and 800 cal yr BP (D) time windows. Red lines are the water level surface isobases.

son 1990; Witak 2013). These taxa are accompanied by small fragilarioid species with brackish-water affinity, such as *Pseudostaurosiropsis geocollegarum*, *Opephora krumbeinii* and *Fragilaria sopotensis*, and the periphytic marine/brackish-water *Planothidium delicatulum*. Disappearance of *Achnanthes fogedii*, which is a typical species of the Litorina Sea (Snoeijs, Kasperovičienė 1996; Witkowski *et al*. 2000), and the halophilous *Hippodonta hungarica* at the depth of 240 cm indicates reduced influx of brackish water into the basin. Just before the disappearance of marine/brackish and halophilous taxa at 230 cm, there is a sharp decrease of *Stephanodiscus parvus* from 32 to 2% and an increase of *Pseudostaurosiropsis geocollegarum* from 13 to 84%.

A distinct increase in the abundance of diatom taxa that prefer freshwater conditions was observed in the uppermost part of the sediment sequence between 225 and 170 cm. Planktonic freshwater taxa are represented by *Belonastrum berolinensis*, *Stephanodiscus hantzschii*, *Aulacoseira ambigua* and *Stephanodiscus parvus*, whereas the main components of the small fragilarioid taxa are *Staurosira construens* f. *exigua*, *Staurosira construens* f. *binodis*, *Staurosirella pinnata* and *Staurosira construens*.

DISCUSSION

The application of multiple palaeoenvironmental indicators, such as the diatom analysis, LOI, MS, and establishment of lead and AMS-radiocarbon chronology, aided in constraining the timing of basin isolation and reconstructing the palaeoshoreline during the past 2000 years. To exhibit the spatial and temporal shoreline changes, 3D palaeogeographic maps were constructed for the time windows of 2000, 1500, 1000 and 800 cal BP (Fig. 5). The 2000 cal BP situation shows the position of the shoreline during the phase when the palaeo-Harku basin was located at the head of the Kakumäe Klint Bay. The lake depression and northwestern part of its catchment were entirely covered by the seawater (Fig. 5A). By 1500 cal BP, Harku had transformed into a lagoon, connected with the sea via a 300–400-m-wide pass through the present valley of the Tiskre Brook (Fig. 5B). This wide connection maintained brackish conditions in the Harku basin and domination of the marine/brackish diatom assemblage (Fig. 4). Due to land uplift, the connection with the sea continuously narrowed, resulting in a semi-enclosed lagoon and accumulation of OM rich gyttja with very low MS values (Fig. 2). Based on the age-depth model, the semi-enclosed lagoon phase lasted for approximately 160 years. According to a simulation, the passage between the sea and the lagoon was still rather wide, which ensured brackish conditions in Harku basin supported by the dominance of small-sized fragilarioid taxa with brackish water affinity (Fig. 4). By 1000 cal BP, the passage to the sea through the Tiskre valley still existed, narrowing further to 80–100 m (Fig. 5C).

Gradual changes in the diatom assemblages from marine/brackish and halophilous to freshwater indicate the evolution of the basin from a lagoon to a semi-enclosed lagoon, a transition phase (a closing basin with intermittent brackish-water influx) and finally a freshwater lake no longer affected by marine water incursion.

The co-appearance of marine-brackish (e.g. *Planothidium delicatulum*, *Achnanthes fogedii*), halophilous (e.g. *Cyclotella meneghiniana*, *Hippodonta hungarica*) and freshwater (*Stephanodiscus parvus*) diatoms in the transition phase at the core depth of 265–225 cm, (roughly between 1000 and 500 cal BP) demonstrates that the isolation of Harku was a long-lasting event. During this phase, the nutrient load in the lake increased, which can be concluded from diatoms *Stephanodiscus parvus* and *Cyclotella meneghiniana*. Similar changes in the trophic state have been observed in many isolation basins (e.g. Grudzinska *et al.* 2012; Seppä, Tikkanen 1998; Westman, Hedenström *et al.* 2002; Yu *et al*. 2004). The enhanced nutrient content in Lake Harku could be explained by two factors: 1) occasional mixing of brackish and fresh water that promotes biological productivity and enrichment with organic compounds (Head 1976, cited after Bechtel *et al*. 2007), and 2) an intense nutrient input from the sparsely vegetated catchment area (Seppä *et al*. 2000). Long-term influxes of brackish water could be explained by the proximity of the sea to Lake Harku, by the wide and low-lying threshold (~2.5 m a.s.l.) and flat topography. This facilitated seawater inflow during heavy storms, although its infiltration through coastal sand cannot be ruled out. Such circumstances made it difficult to determine the exact age and level of the isolation.

One of the indicators of isolation is the mass occurrence of *Fragilaria* spp. (Seppä *et al*. 2000); however, according to Stabell (1985), the peak in *Fragilaria* spp. could occur before, during or after the isolation of the basin from the sea. In case of Harku, *Fragilaria* spp. are the dominant diatoms down to the core depth of 190 cm (Fig. 4). In order to recognize the transition from the marine-brackish to freshwater environment, small fragilarioid taxa with brackish-water affinity are separated from *Fragilaria* spp. that prefers freshwater conditions. The occurrence of *Fragilaria* spp. with brackish-water affinity showed a sharp decrease at 225 cm (ca 500 cal BP), accompanied by the appearance of several freshwater diatom species (Fig. 4), thereby indicating that the lake ecosystem was no longer affected by saline water.

According to this scenario, the Harku basin became isolated from the sea prior to 800 cal BP (Fig. 5D), which is in disagreement with the diatom assemblages that indicate that the brackish-water conditions lasted longer. This discrepancy has obviously resulted from marine water influxes and other aforementioned factors. Previous studies have claimed that the Harku basin became isolated from the sea considerably earlier, approximately 1500 years ago (Saarse 1994); however, this estimation has been solely based on pollen, lithostratigraphic, and morphologic evidence, in the absence of radiocarbon dates.

During the last 800 years, the shoreline has prograded 2 km in the northeast and 3 km toward northwest and the land has uplifted ca 250 cm with the rate of 0.31 mm per year, which is similar to the value suggested by Künnapuu (1970). However, some scenarios argue that the predicted continuing relative sea-level fall could turn into a relative sea-level rise, even in Estonia (Rosentau *et al*. 2012), based on a considerable acceleration of global sea level rise in the 22nd century (Jevrejeva *et al*. 2012). An average Baltic Sea level rise was calculated 1.4 ± 0.4 mm yr^{-1} for the 20th century (Rosentau *et al*. 2012), consistent with the global sea-level rise 1.48 ± 0.26 mm yr^{-1} between 2003 and 2010 (Jacob *et al*. 2012). In contrast, N.-A. Mörner (2004) predicted that by AD 2100, the Baltic Sea level change will be only $+10 \pm 10$ cm and there will be no fear of massive flooding.

CONCLUSIONS

The development of Lake Harku during the past 2000 years has been a rather complex process, exhibiting a distinct marine phase. Based on diatom assemblages, four evolutionary stages (lagoon, semi-enclosed lagoon, transitional lake, and closed lake) have been identified. The isolation of Harku basin was a long-lasting process due to flat topography, wide and low-lying threshold and proximity to the sea, which promoted the incursion of marine water during heavy storms. According to palaeoenvironmental simulations, the basin became isolated from the Limnea Sea shortly before 800 cal BP, but was influenced by seawater for at least 300 more years, which favoured the survival of brackish water diatoms in the already isolated basin.

Minerogenic sedimentation in Harku lasted until ca 1500 cal BP, followed by the deposition of silty gyttja up to ca 1250 cal BP, and culminating in algal gyttja, which became more calcareous over the past 60 years. A sharp increase in calcareous compounds in the upper part of the sequence is attributed to the liming of soils, establishment of the quarry in the lake catchment, and water pollution through rising bioproductivity.

Acknowledgments

The referees Professor Anto Raukas (Tallinn) and Dr. Vaida Šeirienė (Vilnius) are acknowledged for critical remarks and suggestions. Professor Ilya V. Buynevich (Philadelphia) is thanked for constructive comments on the final manuscript. The study was supported by the institutional research funding IUT 1-8, ESF Grant 9031 and Doctoral Studies and Internationalisation Programme DoRa.

References

Andersen, J. M., Liiv, H., Heinsalu, A., Windolf, J., Sondergaard, M., 1992. Harku järv lake restoration. *Technical Report.* Arhus County, 95 pp.

Anderson, N. J., 1990. The biostratigraphy and taxonomy of small Stephanodiscus and Cyclostephanos species (Bacillariophyceae) in a eutrophic lake, and their ecological implications. *British Phycological Journal 25*, 217–235. http://dx.doi.org/10.1080/00071619000650211

Battarbee, R., Jones, V. J., Flower, R. J., Cameron, N. G., Bennion, H., Carvalho, L., Juggins, S., 2001. Diatoms. In J. P. Smol, H. J. B. Birks, W. Last (eds), *Tracking Environmental Change Using Lake Sediments*, Vol. *3*: *Terrestrial, Algal, and Siliceous Indicator*. Kluwer Academic Publishers, Dordrecht, 155–202.

Bechtel, A., Woszczyk, M., Reischenbacher, D., Sachsenhofer, R. F., Gratzer, R., Püttmann, W., Spychalski, W., 2007. Biomarkers and geochemical indicators of Holocene environmental changes in coastal Lake Sarbsko (Poland). *Organic Geochemistry 38*, 1112–1131. http://dx.doi.org/10.1016/j.orggeochem.2007.02.009

Berglund, B. E., 1964. The Postglacial shore displacement in eastern Blekinge, southeastern Sweden. *Sveriges Geologiska Undersökning C 599*, 1–147.

Björck, S., 1995. A review of the history of the Baltic Sea, 13.0–8.0 ka BP. *Quaternary International 27*, 19–40. http://dx.doi.org/10.1016/1040-6182(94)00057-C

Bronk Ramsey, C., 2008. Deposition models for chronological records. *Quaternary Science Reviews 27*, 42–60. http://dx.doi.org/10.1016/j.quascirev.2007.01.019

Bronk Ramsey, C., 2009. Bayesian analysis of radiocarbon dates. *Radiocarbon 51*, 337–360.

Grimm, E., 2011. Tilia software v. 1.7.16. Illinois State Museum. Research and Collection Center, Springfield.

Grudzinska, I., Saarse, L., Vassiljev, J., Heinsalu, A., 2012. A palaeocoastline reconstruction for the Käsmu and Pärispea peninsulas (northern Estonia) over last 4000 years. *Estonian Journal of Earth Sciences 61*, 307–316. http://dx.doi.org/10.3176/earth.2012.4.09

Head, P. C., 1976. Organic processes in estuaries. In J. D. Burton, P. S. Liss, (eds), *Estuarine Chemistry*, Academic Press, London, 54–91.

Heinsalu, A., 1993. Eutrophication history, pollution, internal loading and lake restoration problems on the basis of sediment investigations in Lake Harku, North Estonia. Master Dissertationes Geologicae Universitatis Tartuensis. Manuscript in Geological Institute of Tartu University. Tartu, 84 pp. [In Estonian with English summary].

Hyvärinen, H., Donner, J., Kessel, H., Raukas, A., 1988. The Litorina Sea and Limnea Sea in the northern and central Baltic. Annales Academiae Scientiarum Fennicae A III. *Geologica–Geographica 148*, 25–35.

Jacob, T., Wahr, J., Pfeffer, W. T., Swenson, S., 2012. Recent contributions of glaciers and ice caps to sea level rise. *Nature 482*, *7386*, 514–518. http://dx.doi.org/10.1038/nature10847

Jevrejeva, S., Moore, J. C., Grinsted, A., 2012. Sea level projections to AD 2500 with a new generation of climate change scenarios. *Global and Planetary Change 80*, 14–20. http://dx.doi.org/10.1016/j.gloplacha.2011.09.006

Kessel, H., Pork, M., 1971. On biostratigraphy of bottom deposits of the Balticum in Estonia. In T. Bartosh (Ed.), *Palynological studies in Peribaltic*. Riga, Zinatne, 93–109.

Kramer, K., Lange-Bertalot, H., 1986. Bacillariophyceae 1. Teil Naviculaceae. In H. Ettl, J. Gerloff, H. Heying, D. Mollenhauser (eds), *Süsswasserflora von Mitteleuropa 2/1*. Gustav Fisher Verlag, Stuttgart, 876 pp.

Kramer, K., Lange-Bertalot, H., 1988. Bacillariophyceae 2. Teil Bacillariaceae, Epithemiaceae, Surirellaceae. In H. Ettl, J. Gerloff, H. Heying, D. Mollenhauser (eds), *Süsswasserflora von Mitteleuropa 2*. Gustav Fisher Verlag, Stuttgart, 596 pp.

Kramer, K., Lange-Bertalot, H., 1991a. Bacillariophyceae 3. Teil Centrales, Fragilariceae, Eunotiaceae. In H. Ettl, J. Gerloff, H. Heying, D. Mollenhauser (eds), *Süsswasserflora von Mitteleuropa 2/3*. Gustav Fisher Verlag, Stuttgart, 576 pp.

Kramer, K., Lange-Bertalot, H., 1991b. Bacillariophyceae 4. Teil Achnanthaceae. In H. Ettl, J. Gerloff, H. Heying, D. Mollenhauser (eds), *Süsswasserflora von Mitteleuropa 2/4*. Gustav Fisher Verlag, Stuttgart, 437 pp.

Künnapuu, S. 1970. Sea at the ancient townwalls. *Horisont* 3, 56–58. [In Estonian].

Lambeck, K., Chapell, J., 2001. Sea level change through the Last Glacial cycle. *Science 292*, 679–686. http://dx.doi.org/10.1126/science.1059549

Leeben, A., Alliksaar, T., Heinsalu, A., Lepane, V., Veski, S., 2008. Tracking changes in the organic matter in a lake palaeoecosystem: a spectrophotometric approach. *Organic Geochemistry 39*, 915–918. http://dx.doi.org/10.1016/j.orggeochem.2008.05.004

Miettinen, A., 2002. Relative sea level changes in the eastern part of the Gulf of Finland during the last 8000 years. *Annales Academiae Scientiarum Fennicae, Geologica-Geographica 162*, 1–102.

Mäemets, A., 1977. Estonian lakes and their protection. Valgus, Tallinn, 263 pp. [In Estonian with English summary].

Mörner, N.-A., 1979. The Fennoscandian uplift and Late Cenozoic geodynamics: geological evidence. *GeoJournal 3*, 287–318. http://dx.doi.org/10.1007/BF00177634

Mörner, N.-A., 2004. Estimating future sea level changes from past records. *Global and Planetary Change 40*, 49–54. http://dx.doi.org/10.1016/S0921-8181-(03)00097-3

Reimer, P.J., Baillie, M.G. L., Bard, E., Bayliss, A., Beck, J.W., Blackwell, P.G., Bronk Ramsey, C., Buck, C.E., Burr, G.S., Edwards, R.L., Friedrich, M., Groots, P.M., Guilderson, T.P., Hajdas, I., Heaton, T.J., Hogg, A.G., Hughen, K.A., Kaiser, K.F., Kromer, B., McCormac, F.G., Manning, S.W., Reimer, R.W., Richards, D.A., Southon, J.R., Talamo, S.,Turney, C.S.M., van der Plicht, J., Weyhenmeyer, C.E., 2009. IntCal09 and Marine09 radiocarbon age calibration curves, 0 - 50,000 years cal BP. *Radiocarbon 51*, 1111–1150.

Riikoja, H., 1934. List of Estonian lakes. *Looduseuurijate Seltsi Aruanded XLI*, 1–192 pp. [In Estonian].

Rosentau, A., Harff, J., Oja, T., Meyer, M., 2012. Postglacial rebound and relative sea level changes on the Baltic Sea since the Litorina transgression. *Baltica 25*, 113–120. http://dx.doi.org/10.5200/baltica.2012.25.11

Rosentau, A., Vassiljev, J., Hang, T., Saarse, L., Kalm, V., 2009. Development of the Baltic Ice Lake in the eastern Baltic. *Quaternary International 206*, 16–23. http://dx.doi.org/10.1016/j.quaint.2008.10.005

Saarse, L., 1994. Bottom deposits of small Estonian lakes. Estonian Academy of Sciences, Institute of Geology, Tallinn, 230 pp. [In Russian with English summary].

Saarse, L., Vassiljev, J., Rosentau, A., Miidel, A., 2007. Reconstructed late glacial shore displacement in Estonia. *Baltica 20*, 35–45.

Seppä. H., Tikkanen, M., 1998. The isolation of Kruunuvuorenlampi, southern Finland, and implication for Holocene shore displacement models of the Finnish south coast. *Journal of Paleolimnology 19*, 385–398. http://dx.doi.org/10.1023/A:1007927921179

Seppä, H., Tikkanen, M., Shemeikka, P., 2000. Late-Holocene shore displacement of the Finnish south coast: diatom, litho- and chemostratigraphic evidence from three isolation basins. *Boreas 29*, 219–231. http://dx.doi.org/10.1111/j.1502-3885.2000.tb00980.x

Snoeijs, P., 1993. Intercalibration and distribution of diatom species in the Baltic Sea 1. Opulus Press, Uppsala, 129 pp.

Snoeijs, P., Balashova, J., 1998. Intercalibration and distribution of diatom species in the Baltic Sea 5. Opulus Press, Uppsala, 144 pp.

Snoeijs, P., Kasperovičienė, J., 1996. Intercalibration and distribution of diatom species, in the Baltic Sea 4. Opulus Press, Uppsala, 126 pp.

Snoeijs, P., Potapova, M., 1995. Intercalibration and distribution of diatom species in the Baltic Sea 3. Opulus Press, Uppsala, 126 pp.

Snoeijs, P., Vilbaste, S., 1994. Intercalibration and distribution of diatom species in the Baltic Sea 2. Opulus Press, Uppsala, 126 pp.

Stabell, B., 1985. The development and succession of taxa, within the diatom genus Fragilaria Lyngbye as a response to basin isolation from the sea. *Boreas 14*, 274–286.

Tamre, R., 2004. List of Estonian lakes. Natural and manmade. Keskkonnaministeeriumi Info- ja Tehnokeskus, Tallinn, 168 pp. [In Estonian].

Torim, A., 2004. On the land uplift and changes in coastline of Estonia. *Geodeet 28*, 57–62 [In Estonian].

Weckström, K., Juggins, S., 2006. Coastal diatom-environment relationships from the Gulf of Finland, Baltic Sea. *Journal of Phycology 42*, 21–35. http://dx.doi.org/10.1111/j.1529-8817.2006.00166.x

Westman, P., Hedenström, A., 2002. Environmental changes during isolation processes from the Litorina Sea as reflected by diatoms and geochemical parameters – a case study. *The Holocene 12*, 497–506. http://dx.doi.org/10.1191/0959683602hl560rp

Witak, M. 2013. A review of the diatom research in the Gulf of Gdansk and Vistula Lagoon (southern Baltic Sea). *Oceanological and Hydrobiological Studies 42*, 3, 336–346. http://dx.doi.org/10.2478/s13545-013-0091-x

Witkowski, A., Lange-Bertalot, H., Metzeltin, D., 2000. Diatom Flora of Marine Coasts I. *Iconographia Diatomologica 7*. A. R. G. Gantner Verlag K. G., Ruggell, Liechtenstein, 925 pp.

Yu, S.-Y., Berglund, B. E., Andrén, E., Sandgren, P., 2004. Mid-Holocene Baltic Sea transgression along the coast of Blekinge, SE Sweden – ancient lagoon correlated with beach ridges. *GFF 126,* 257–272. http://dx.doi.org/10.1080/11035890401263257

Yu, S.-Y., Berglund, B. E., Sandgren, P., Lambeck, K., 2007. Evidence for a rapid sea-level rise 7600 yr ago. *Geology 35*, 891–894. http://dx.doi.org/10.1130/G23859A.1