doi: 10.3176/earth.2012.4.09

A palaeocoastline reconstruction for the Käsmu and Pärispea peninsulas (northern Estonia) over the last 4000 years

Ieva Grudzinska, Leili Saarse, Jüri Vassiljev, Atko Heinsalu and Siim Veski

Institute of Geology at Tallinn University of Technology, Ehitajate tee 5, 19086 Tallinn, Estonia; grudzinska@gi.ee, saarse@gi.ee, vassilje@gi.ee, heinsalu@gi.ee, veski@gi.ee

Received 29 June 2012, accepted 28 September 2012

Abstract. The marine-freshwater environmental transition, i.e. basin isolation from the Limnea Sea, has been identified in two short sediment cores with respect to their diatom composition, loss-on-ignition and magnetic susceptibility content. The isolation level of the basins was dated by accelerator mass spectrometry radiocarbon measurements. The basins are situated on the southern coast of the Gulf of Finland between altitudes 5.5 and 3.9 m above sea level. The Lohja basin became isolated from the sea around 2300 cal yr BP and Käsmu basin around 1800 cal yr BP as a result of glacio-isostatic uplift. The total land upheaval rate that has been 2.6 mm yr^{-1} since 2500 cal yr BP has currently decreased to 2.0 mm yr^{-1}. We present a GIS-based 3D palaeogeographic reconstruction of the palaeocoastline changes in northern Estonia for two peninsulas, Pärispea and Käsmu, as well as compose a shoreline displacement curve for the study area, which is a compilation of previous and ongoing investigations.

Key words: shoreline displacement, palaeogeography, Limnea Sea, diatoms, isostatic land uplift, Estonia.

INTRODUCTION

The North Estonian coastline is highly jointed. The post-glacial palaeocoastline formation in the Baltic Sea basin has been ruled by the deglaciation of the Fennoscandian Ice Sheet and resulting isostatic rebound together with eustatic sea level changes. Several peninsulas stretch far out to the sea and bays invade the mainland. These peninsulas are young, formed during the Holocene, when islands started to emerge in the offshore areas of the Gulf of Finland, to become joined with the mainland at a later point and form peninsulas and a winding coast-line. Studies have pursued to define the pattern of post-glacial shoreline displacement of northern Estonia since the early 20th century (e.g. Ramsay 1929; Kents 1939; Kessel & Raukas 1979; Hyvärinen et al. 1988). Contemporary research that has endeavoured to reconstruct the palaeogeographic development of the coastline changes in northern Estonia has centred on the early stages of the Baltic Sea basin, i.e. the development of the Baltic Ice Lake (Rosentau et al. 2007; Vassiljev et al. 2011), Yoldia Sea (Heinsalu & Veski 2007), Ancylus Lake (Veski 1998; Saarse et al. 1999) and Litorina Sea (Saarse et al. 2009, 2010). In general, little is known about the Late Holocene shoreline displacement patterns on the Estonian coast of the Gulf of Finland. Due to lack of dated isolation sequences at lower altitudes, relative sea-level changes for the Limnea Sea are poorly constrained and the lower sections of the shoreline displacement curves are mainly based on extrapolation.

The main objective of the study is to reconstruct palaeogeography for two North Estonian peninsulas, Pärispea and Käsmu. Beach formations of these peninsulas have been examined and levelled earlier (Linkrus 1969, 1971); however, their age has remained uncertain due to lack of radiocarbon dates. In the current study diatoms, loss-on-ignition (LOI), magnetic susceptibility (MS) and radiocarbon dates of the sediment cores of two North Estonian lakes have been examined for the purpose of detecting the age of the isolation of these lakes from the Limnea Sea, acting as a complement to older investigations (Kessel & Linkrus 1979; Heinsalu 2000; Saarse et al. 2006, 2009, 2010; Saarse & Vassiljev 2010) in compiling a new shore displacement curve for the area. Such a methodology has been widely used in relative sea level reconstructions (e.g. Snyder et al. 1997; Miettinen et al. 2007; Long et al. 2009; Watcham et al. 2011; Lunkka et al. 2012; Saarnisto 2012) as well as in studies of isostatic uplift (Risberg et al. 1996).

STUDY AREA

The studied lakes Lohja and Käsmu are located in the North Estonian coastal lowland (Fig. 1), on the terraces of the Limnea Sea. The lakes occupy depressions separated from the sea by beach ridges and dunes and their catchment is mostly covered by sand. According to the water level simulation, the highest shoreline of the Litorina Sea reached 18.8 m a.s.l. at Lohja and 17.7 m

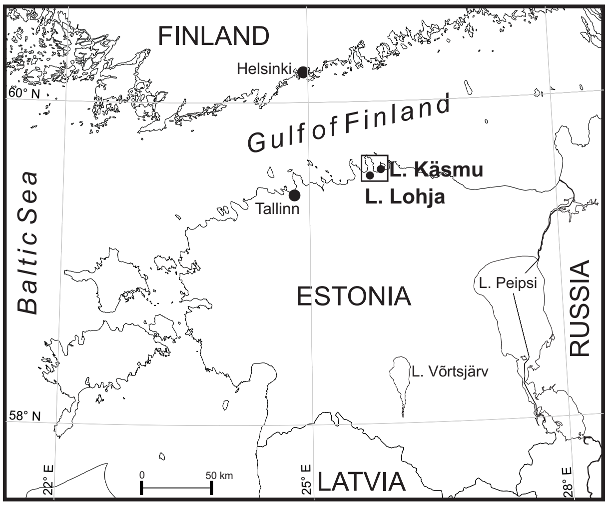

Fig. 1. Location of the study area, marked by a square.

a.s.l. at Käsmu and that of the Limnea Sea 10.7 m and 10.2 m, respectively. The modern land uplift relative to sea level is 2 mm yr^{-1} at Lohja and between 2 and 1.5 mm yr^{-1} at Käsmu (Torim 2004). Prior to isolation, the Lohja basin was located in the rump of Hara Bay that was opened on the northwestern side of the lake, whereas the Käsmu basin formed a lagoon with two narrow passages in the east.

Lake Lohja (sediment core 59°32′57″N, 25°41′23″E, water depth 2.4 m) is located in the southwestern corner of the Pärispea Peninsula, between the klint escarpment and the sea coast at an elevation of 5.5 m a.s.l. It is a small shallow lake with a surface area of 56 ha, average depth of 2.2 m and maximum depth of 3.7 m (Riikoja 1934; Mäemets 1977). A number of beach ridges and dunes surround the lake in the north and west. Lake Lohja is a dark-coloured soft-water lake with outflow via Lohja Brook to Hara Bay. The water table of the lake is artificially regulated by a dam. The lake has low water transparency due to its brown water (Secchi disc depth <1 m). The total phosphorus (TP) and total nitrogen (TN) concentrations are relatively high, 40 μg L^{-1} and 700–900 μg L^{-1}, respectively.

Lake Käsmu (sediment core 59°34′56″N, 25°52′51″E, water depth 2.4 m), with an area of 48 ha and maximum water depth 3 m, lies on the Käsmu Peninsula 200 m from the sea coast at an altitude of 3.9 m a.s.l. A small outflowing brook joins it with Käsmu Bay. The lake level has been regulated. The ditch west to Eru Bay lowered the water level by almost 1 m, but a rebuilt dam on the ditch elevated the water back to its previous level. The lake is boarded by beach ridges in the west and by a flat slightly paludified marine plain in the east, covered by different types of forest. Lake Käsmu is a dark-coloured soft-water lake, characterized by high concentrations of TP, 50 μg L^{-1}, and TN, 750 μg L^{-1}. The lake water is rich in organic compounds and poor in total dissolved solids.

MATERIALS AND METHODS

Four overlapping cores were obtained in winter 2011 with a Russian peat sampler from the deepest part of the basins. One metre long core sections were described on site, photographed, sealed in plastic half tubes, transported to the laboratory and stored in a cold-room. Continuous 1 cm thick samples were used for LOI analyses. The organic matter (OM) content was measured by LOI at 525 °C for 4 h and expressed in percentages of dry matter. The percentage of carbonates ($CaCO_3$) was calculated after combustion of LOI residue for 2 h at 900 °C. The amount of residue containing terrigenous matter and biogenic silica was described as mineral matter and calculated from the sum of the organic and carbonate compounds. Magnetic susceptibility was measured with a Bartington MS2E high-resolution scanning sensor. The sediment surface was cleaned, covered with a thin plastic film and MS was measured from the sediment surface at 1-cm resolution.

Diatom analyses from Lake Käsmu were made by E. Vishnevskaya several years ago (Kessel et al. 1986). For this reason diatom taxonomy was modified, diagram redrawn and sediment sequence correlated with the new one on the basis of lithostratigraphy and LOI results. The difference between the sediment thickness of the previous and the current core accounts for approximately 20 cm, which has been considered in the correlation of the cores. The diatom preparation was carried out, following the techniques outlined in Battarbee (1986). Diatom samples were digested in hydrogen peroxide until the organic matter was oxidized, followed by removing fine and coarse mineral particles by repeated decantation. A few drops of the remaining residue were dried onto cover slips and permanently mounted onto microscope slides, using Naphrax resin. At least 400 diatom valves were identified and counted from each subsample under Zeiss Axio Imager A1 microscope at ×1000 magnification, using oil immersion and differential interference contrast optics. Diatoms were grouped according to their habitat into plankton and periphyton, and according to their salinity tolerance, to brackish/marine, halophilous and freshwater taxa. Diatom and LOI results were plotted, using the TGView software (Grimm 2007).

Macrofossils for radiocarbon dating were extracted by soaking 1 cm thick samples in water and $Na_4P_2O_7$ solution and then sieving the material through a 0.25 mm mesh. Macrofossil remains were identified under a binocular microscope. Carefully selected terrestrial material was dated in the Poznan Radiocarbon Laboratory. Radiocarbon dates (Table 1) were calibrated at one-

Table 1. AMS radiocarbon dates. The ages have been calibrated according to Reimer et al. (2009)

Lake	Basin altitude, m a.s.l.	Depth, cm	Age, ^{14}C yr BP	Age, cal yr BP with midpoint in brackets	Lab. No.	Dated material
Lohja	5.8	365–370	2275 ± 30	2185–2345 (2270 ± 80)	Poz-42171	*Pinus* bark
Lohja	5.8	395	2490 ± 35	2490–2710 (2600 ± 110)	Poz-42172	*Tilia* wood
Käsmu	3.9	416	1830 ± 30	1730–1815 (1770 ± 40)	Poz-42177	*Pinus* bark
Käsmu	3.9	433	1910 ± 30	1825–1885 (1850 ± 30)	Poz-42166	*Pinus* wood

confidence level, using the Calib Rev 6.0.1 software (Reimer et al. 2009). Alternative chronology was created with an OxCal deposition model (Bronk Ramsey 2008, 2009), where AMS dates were combined with lithological boundaries. Both chronologies differ only slightly and therefore we present here Calib software results. Calibrated ages before present (cal yr BP; 0 = AD 1950) were applied in the present study. Due to the low level of salinity in the Gulf of Finland (Eronen et al. 2001; Miettinen et al. 2007), the marine calibration set was not considered.

Palaeogeograpical maps were reconstructed, using GIS techniques. The interpolated surfaces of water level were derived from the Baltic Sea shoreline database (Saarse et al. 2003, 2006) and earlier published sources (Linkrus 1976, 1988), using a point kriging approach. Topographic maps at a scale of 1 : 10 000 and 1 : 25 000 were used to create a digital terrain model (DTM) with grid size 20 × 20 m. Holocene peat deposits were removed from the DTM. Series of palaeogeographical maps were compiled based on the assumption that during the last 5000 years land uplift diminished linearly (Mörner 1979; Lindén et al. 2006; Yu et al. 2007) and global sea level remained nearly constant (Lambeck & Chappell 2001).

RESULTS

A 195 cm thick sediment core was taken from the central part of Lake Lohja. The basal grey silt (435–375 cm, Lo-1, Fig. 2A) is overlain by greenish-brown silty gyttja (375–365 cm, Lo-2) and dark brown gyttja (365–332 cm, Lo-3). The OM and carbonate content in the silt is low, in silty gyttja OM increases from 10% to 20%. In the lowermost portion of silt (435–390 cm) MS is uniform, about 5–6 × 10^{-5} SI units; between core depths of 390 and 355 cm MS continuously decreases and after that stabilizes, being in good accord with the mineral matter inclination (Fig. 2A). A distinct lithostratigraphical change occurs in between 375 and 365 cm, where the OM content apparently rises and stabilizes afterwards.

The lower part of the core (400–365 cm) contains abundant benthic brackish/marine diatom flora, notably *Planothidium delicatulum* and *Navicula peregrina* (Fig. 3A). Simultaneously, small-sized fragilarioid epipsammic diatoms with brackish-water affinity, such as *Opephora mutabilis*, *O. guenter-grassi* and *Fragilaria gedanensis*, occur with high values, accompanied by freshwater *Pseudostaurosira elliptica*. The absolute dominance of periphytic diatoms suggests shallow-water conditions in the sheltered lagoon-like basin that was connected with the Gulf of Finland through the open strait. The diatom composition shows a relatively abrupt transition from brackish/marine diatom flora to predominantly freshwater species at a core depth of 365 cm, indicating a relatively abrupt isolation contact. The planktonic freshwater diatom *Aulacoseira subarctica* predominates together with *A. ambigua* and *A. granulata*. An AMS radiocarbon date of 2270 ± 80 cal yr BP (Poz-42171, Table 1) obtained from a pine bark fragment represents an approximate date of the isolation of the basin.

Lake Käsmu was cored in its western part, where a 360 cm thick sediment sequence was recovered. The basal sand (600–595 cm, Kä-1), overlain by a silt layer (595–433 cm, Kä-2 and Kä-4) and comprising a thin sand layer at 495–475 cm (Kä-3), is poor in OM (Fig. 2B). From 435 cm upwards the content of OM gradually increases to 35% and of carbonates to 5%. The MS curve is changeable. It has decreased considerably since the isolation of the basin as supply of mineral matter has reduced (Risberg et al. 1996).

The diatom assemblage at the bottom of the core contains abundant taxa with marine and brackish-water affinity (Fig. 3B). Pelagic forms like *Chaetoceros holsaticus*, *Pauliella taeniata* and *Thalassiosira baltica*, as well as periphytic taxa such as *Cocconeis scutellum* and *Tabularia fasciculata* are common, indicating rather open bay-like conditions with brackish-water environment. At a core

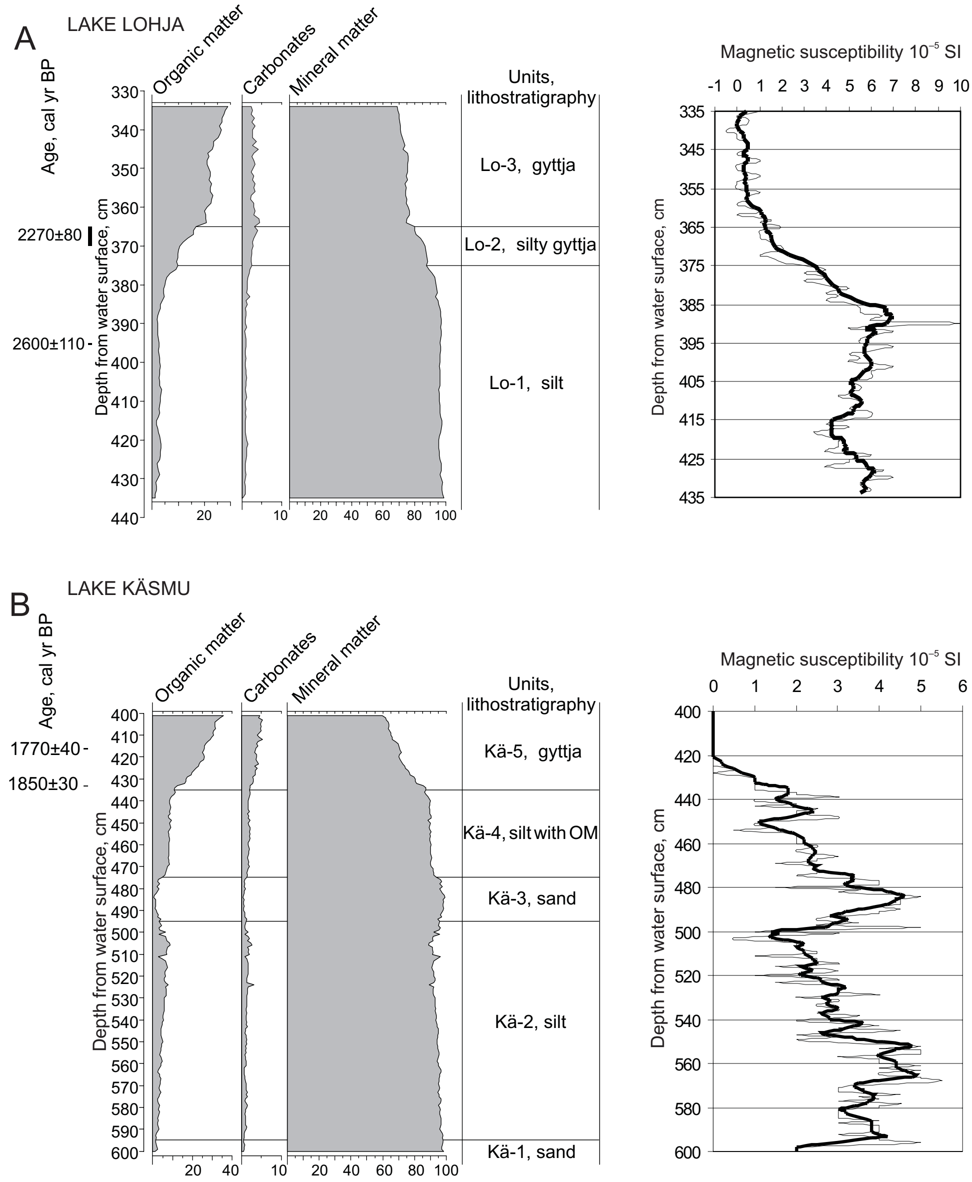

Fig. 2. Loss-on-ignition and magnetic susceptibility of Lake Lohja (A) and Lake Käsmu (B). The thick black line in the magnetic susceptibility graph is 5-sample moving average.

depth of 500 cm, relative abundance of brackish-water diatoms decreases and that of pelagic diatoms and small-sized fragilarioid taxa increases significantly, which suggests the lowering of water depth and the formation of a shallow sheltered coastal lagoon that was connected with Käsmu Bay through narrow channels. Relative abundance of brackish-water diatoms decreases at 430 cm. These are replaced by periphytic halophilous species and by planktonic *Cyclotella meneghiniana*. *Cyclotella meneghiniana* grows in variable environmental conditions – in brackish waters with elevated nutrient concentration (Weckström & Juggins 2006), lakes with high conductivity (Saros & Fritz 2000) or hypereutrophic lakes (Bradshaw et al. 2002). Diatom-derived isolation is located at a depth of 400 cm, above which the level of brackish-water diatoms has declined and freshwater planktonic diatoms such as *Aulacoseira subarctica*, *A. ambigua* and *A. granulata* dominate, reflecting the development of a small eutrophic lake. An AMS ^{14}C date of the pine bark fragment from a depth of 416 cm yielded an age of 1770 ± 40 cal yr BP (Poz-42177, Table 1), corresponding to a time shortly before the isolation. Therefore the final isolation of Lake Käsmu took place approximately 1800–1700 cal yr BP.

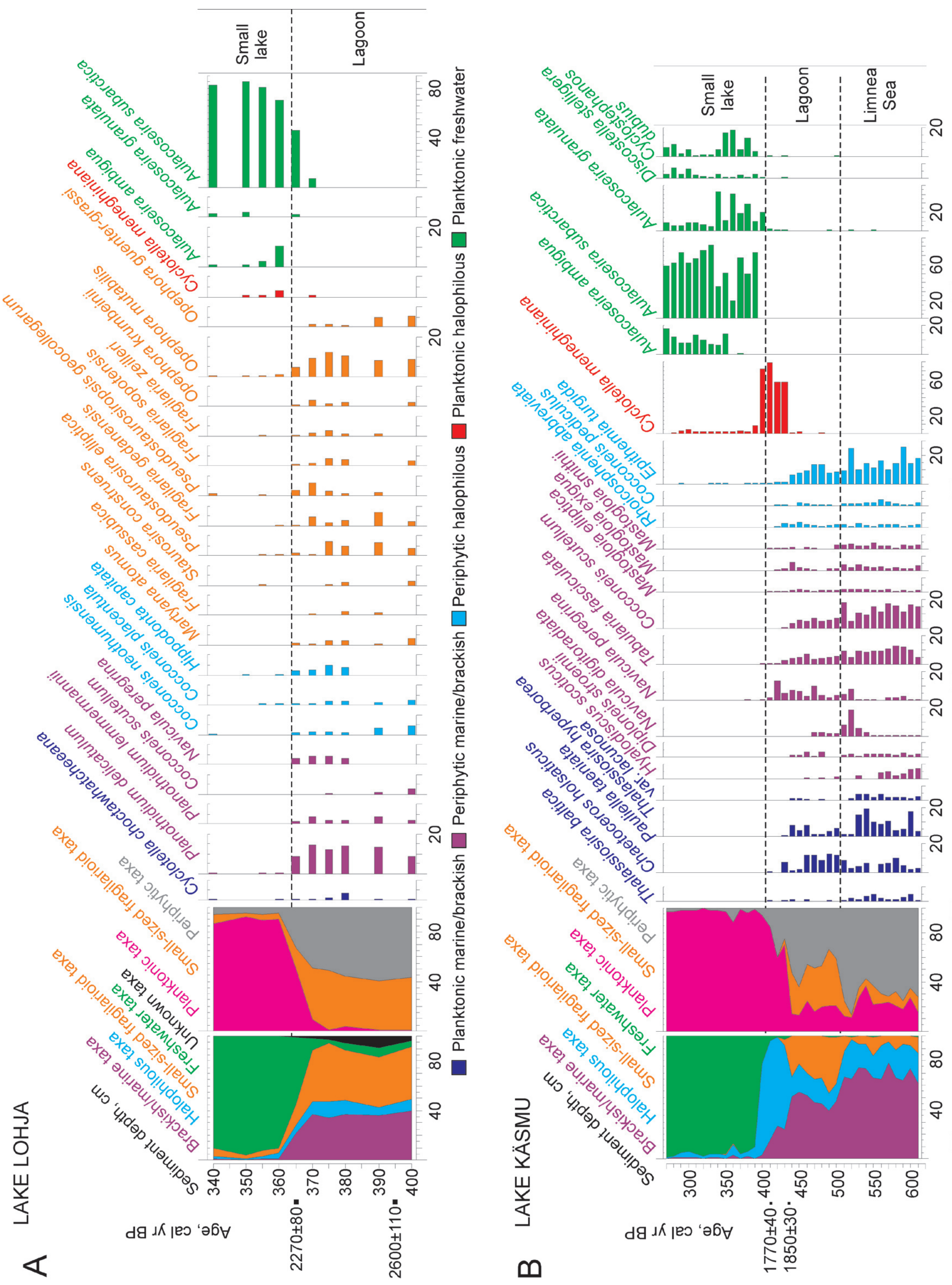

Fig. 3. Diatom diagram from Lake Lohja (A). Analyses by I. Grudzinska. Diatom diagram from Lake Käsmu (B). Analyses by E. Vishnevskaya.

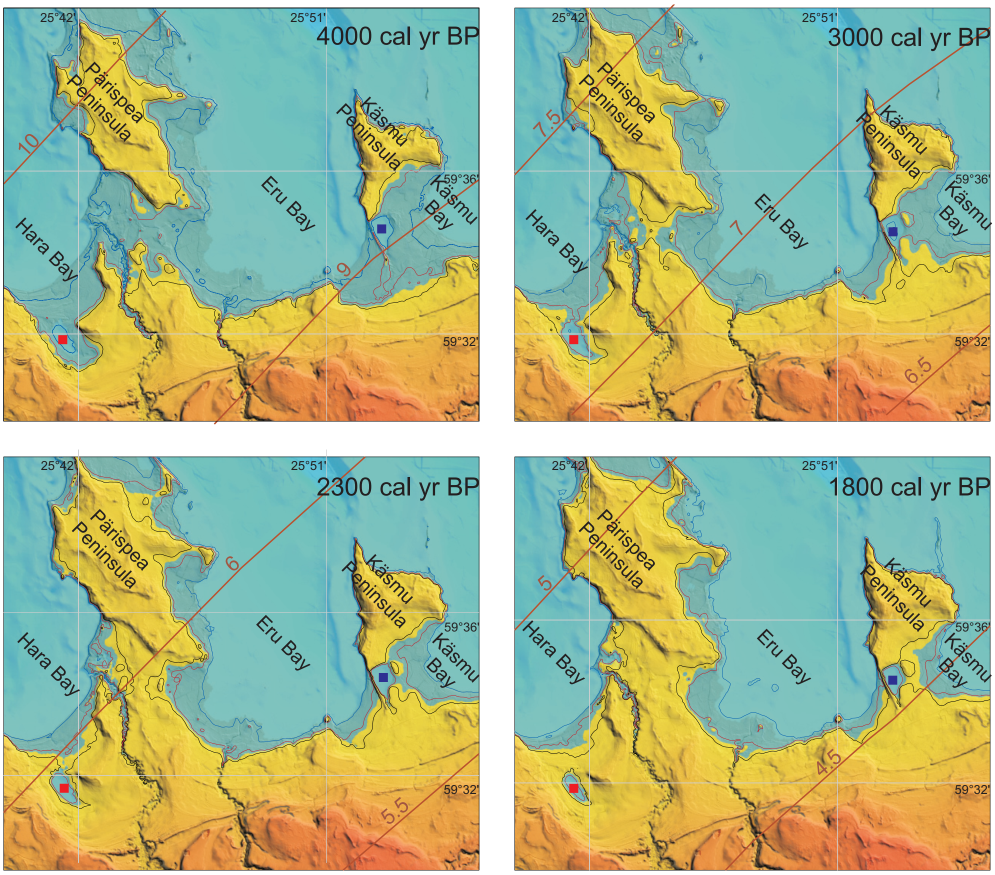

Fig. 4. Palaeogeographic maps for time windows 4000, 3000, 2300 and 1800 cal yr BP. Modelled water level surface isobases are indicated by brown lines together with altitudes in metres a.s.l. The shoreline location is shown together with a possible modelling error in the range of ±1 m (black line +1 m, red line –1 m); the blue line corresponds to the modelled water depth of 5 m. The reconstructions are overlaid by LIDAR elevation data (Estonian Land Board) to visualize the location of the present-day land (greenish) and sea (blue). Lake Lohja is shown by a red square, Lake Käsmu by a blue square. Reconstruction by J. Vassiljev.

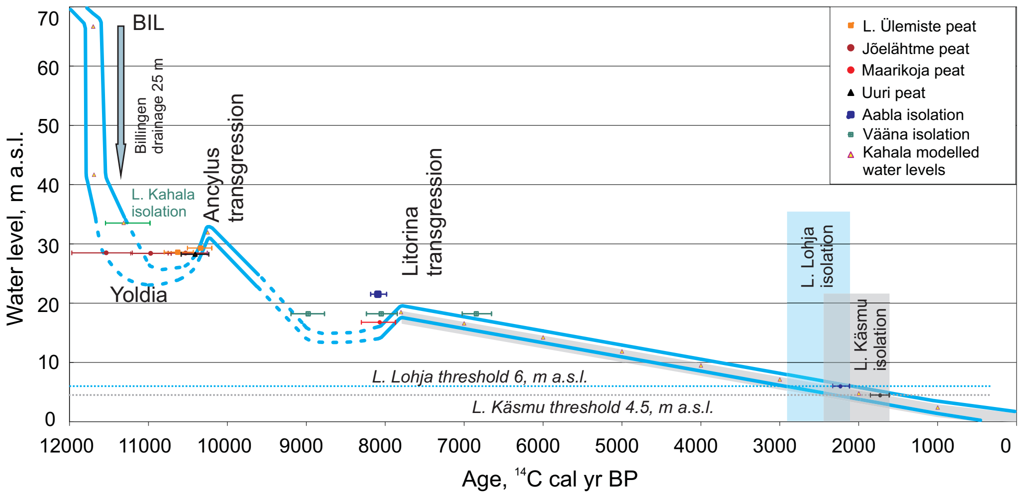

Fig. 5. Shoreline displacement curve for the study area. For the Lohja site blue lines mark the modelled possible minimum and maximum water level changes and for the Käsmu site, the grey area (shown only from the Litorina Sea transgression up to today) marks the modelled possible range of the water level. The reconstruction considers errors in both, modelled water levels (±1 m) and ages. The blue and grey boxes show the possible isolation age according to modelled water level against the isolation age according to the AMS ^{14}C dates (black circles with error bars).

DISCUSSION

A GIS-based palaeogeographical reconstruction visualizes temporal coastline development in northern Estonia during the last 4000 cal yr PB and provides insights into how the area has experienced transition from sea to land (Fig. 4). Our reconstruction shows that a group of small islands had uplifted from the sea already before the Litorina Sea transgression around 9000 cal yr BP. By 4000 cal yr BP a significant part of the Pärispea and Käsmu peninsulas had emerged, however, both still existed as islands and were separated from the mainland by fairly wide and shallow straits. The Lohja basin formed an inner part of Hara Bay, whereas the Käsmu basin was part of a strait. By 3000 cal yr BP a semi-closed lagoon had formed in the area of the present Lohja and Käsmu basins, while the Pärispea Peninsula had joined with the mainland by a narrow neck and the Käsmu Peninsula by an elongated beach ridge. By 2300 cal yr BP the Pärispea Peninsula was exposed from the sea and the coastline was quite similar to the modern seacoast; the Lohja basin was isolated from the sea and formed a small coastal lake, whereas the Käsmu basin still existed as a sheltered lagoon with very narrow open connections to the sea to the east and northeast. Lake Käsmu had become isolated and the Käsmu Peninsula had become rather similar to the present-day configuration by 1800 cal yr BP. Previous studies have claimed that Lake Käsmu became isolated from the sea around 800 years ago (Kessel et al. 1986), however, this conclusion is based solely on palaeoshoreline, lithostratigraphical and pollen evidence without any radiocarbon dates.

The diatom evidence described above indicates diatom succession of the Käsmu basin from marine to lacustrine environment and the Lohja basin from lagoonal to limnic environment. The relatively abundant occurrence of pelagic planktonic diatoms with marine/brackish-water affinity in the Käsmu sediment record infers deeper-water conditions and the basin had a semi-opened connection with the offshore sea. The proportion of pelagic diatoms remained high until the basin connection with the sea narrowed; the basin itself turned shallower and littoral periphytic flora became dominant.

The lagoonal phase of both studied sediment sequences is characterized by apparent high abundance of small-sized fragilarioid diatoms with brackish-water affinity. According to Stabell (1985), *Fragilaria* spp. may predominate before, during or after the isolation and for this reason they have not been considered in interpreting the isolation level (Risberg et al. 2005).

A striking feature in the post-isolation diatom stratigraphy from both studied lakes is distinct increase in freshwater planktonic diatoms that reaches 98% in the Käsmu and 92% in the Lohja record, respectively. Many investigations, which have been based on sediment diatoms, have proceeded from changes in diatom habitat groups (i.e. the ratio of planktonic to periphytic diatoms) as a signal for lake-level oscillations (e.g. Stone & Fritz 2004). Planktonic diatoms contribute frustules to the sediment in deep open-water areas, while periphytic diatoms are primarily associated with shallower littoral habitats closer to shores (Wolin & Duthie 1999). Thus, an increase in the share of planktonic forms is commonly associated with a rise in lake water level (Heinsalu et al. 2008). Alternatively, we assume that post-isolation diatom composition reflects water circulation conditions rather than deeper water depth. Heavily silicified cylindrically shaped and filamentous *Aulacoseira* taxa need turbulence to remain in the water column. Therefore *Aulacoseira* species are common in frequently mixed surface waters, but sink to the lake bottom within long-lasting periods of calm weather. Both isolated lakes were located close to the windy sea coast, thus wind-driven wave motion induced turbulent mixing of the water column and favoured the prevalence of *Aulacoseira*-dominated diatom community.

The shore displacement curve that depicts changes in relative sea level is presented in Fig. 5. In constructing this curve across Ancylus Lake and Litorina Sea high stand, data from the isolation basins and evidences from the raised beaches were considered (Linkrus 1969, 1971; Saarse et al. 2003, 2006, 2010). The reconstructed shoreline displacement curve is relatively regular (Fig. 5) and differs considerably from the previous ones (e.g. Kessel & Raukas 1979). The older curves show up to five transgressional waves during the Litorina Sea and Limnea Sea stages, however, these fluctuations are not radiocarbon dated. Our relative sea-level curve shows regular decrease (Fig. 5) and is in agreement with the curves recently reconstructed around the Gulf of Finland and for the northern part of the Baltic Sea (Seppä et al. 2000; Miettinen 2002, 2004; Lindén et al. 2006; Rosentau et al. 2011; Saarnisto 2012), still differing from the reconstruction carried out in the southern part of the Baltic Sea (e.g. Gelumbauskaitė 2009). Quite regular changes in sea level over the last 5000 years have been reported from different parts of the globe (Murray-Wallace 2007), including the Baltic coast (Lampe et al. 2011). The diagram shows that water level reached 6 m a.s.l. by 2300 cal yr BP. During this time window the land uplift rate at Lohja was 2.6 mm yr^{-1}. These data are in harmony with the current rate of land uplift (Torim 2004), which is still showing a decreasing trend.

CONCLUSIONS

- The formation of the Pärispea and Käsmu peninsulas started prior to the Litorina Sea transgression when small islands emerged. By 3000 cal yr BP these islands had joined with the mainland and formed the core of the present-day peninsulas.
- The studied lake basins yielded isolation contacts between 2300 and 1800 cal yr BP when the shoreline reached 6 m a.s.l. at Lohja and 4.5 m a.s.l. at Käsmu. The results of this study overturn the previous conclusion on the isolation of Lake Käsmu approximately 800 years ago.
- A change in sediment lithology accompanied with a change from brackish-water taxa to freshwater diatom assemblage marks the isolation of lakes.
- Before the isolation both basins were shallow-water lagoons.
- Our data confirm a continuous relative fall of sea level in response to glacio-isostatic rebound without distinct sea level oscillations during the last 4000 years.
- The total land uplift rate at 2300 cal yr BP was 2.6 mm yr^{-1}. At present it is 2 mm yr^{-1}.

Acknowledgements. Our sincere thanks are to J. Risberg and L. Gelumbauskaitė for important suggestions and remarks. We are grateful to M. Märss for improving the language. Financial support was provided by the Estonian Research Council (project SF0140021s12 and ESF Grant 9031) and DoRa Program.

REFERENCES

Battarbee, R. W. 1986. Diatom analyses. In *Handbook of Holocene Palaeoecology and Palaeohydrology* (Berglund, B. E., ed.), pp. 527–570. John Wiley and Sons, Chichester.

Bradshaw, E. G., Anderson, N. J., Jensen, J. J. & Jeppesen, E. 2002. Phosphorus dynamics in Danish lakes and the implications for diatom ecology and palaeoecology. *Freshwater Biology*, **47**, 1963–1975.

Bronk Ramsey, C. 2008. Deposition models for chronological records. *Quaternary Science Reviews*, **27**, 42–60.

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

Eronen, M., Glückert, G., Hatakka, L., van de Plassche, O., van der Plicht, J. & Rantala, P. 2001. Rates of Holocene isostatic uplift and relative sea-level lowering of the Baltic in SW Finland based on studies of isolation contacts. *Boreas*, **30**, 17–30.

Gelumbauskaitė, L. Ž. 2009. Character of sea level changes in the subsiding south-eastern Baltic Sea during the Late Quaternary. *Baltica*, **22**, 23–36.

Grimm, E. 2007. *Tilia Version 1.0.1*. Illinois State Museum, Research and Collections Center, Springfield.

Heinsalu, A. 2000. Diatom stratigraphy and palaeoenvironment of the Yoldia Sea in northern Estonia. *Proceedings of the Estonian Academy of Sciences, Geology*, **49**, 218–243.

Heinsalu, A. & Veski, S. 2007. The history of the Yoldia Sea in northern Estonia: palaeoenvironmental conditions and climatic oscillations. *Geological Quarterly*, **51**, 295–306.

Heinsalu, A., Luup, H., Alliksaar, T., Nõges, P. & Nõges, T. 2008. Water level changes in a large shallow lake as reflected by the plankton:periphyton-ratio of sedimentary diatoms. *Hydrobiologia*, **599**, 23–30.

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.

Kents, P. 1939. *Postglatsiaalsed Läänemere rannajoone võnkumised Eestis illustreeritud Kõpu poolsaarel* [*Postglacial Shore Displacement Changes of the Baltic Sea in Estonia on the Example of the Kõpu Peninsula*]. Manuscript in Estonian State Archives. Tallinn, 62 pp. [in Estonian].

Kessel, H. & Linkrus, E. 1979. Vanadest rannajärvedest ja nende rannamoodustistest Lahemaa lääneosas [Ancient coastal lakes and coastal formations in the western part of Lahemaa]. In *Eesti NSV saarkõrgustike ja järvenõgude kujunemine* (Raukas, A., ed.), pp. 104–117. Valgus, Tallinn [in Estonian, with English summary].

Kessel, H. & Raukas, A. 1979. The Quaternary history of the Baltic. Estonia. In *The Quaternary History of the Baltic* (Gudelis, V. & Königsson, L.-K., eds), pp. 127–146. Acta Universitatis Upsaliensis, Uppsala.

Kessel, H., Saarse, L. & Vishnevskaya, E. 1986. The development of coastal Lake Käsmu (North Estonia). *Proceedings of the Academy of Sciences of the Estonian SSR, Geology*, **35**, 83–88 [in Russian, with English summary].

Lambeck, K. & Chappell, J. 2001. Sea level change through the last glacial cycle. *Science*, **292**, 679–686.

Lampe, R., Endtmann, E., Janke, W. & Mayer, H. 2011. Relative sea-level development and isostasy along the NE German Baltic Sea coast during the past 9 ka. *E&G – Quaternary Science Journal*, **59**, 3–20.

Lindén, M., Möller, P., Björck, S. & Sandgren, P. 2006. Holocene shore displacement and deglaciation chronology in Norrbotten, Sweden. *Boreas*, **35**, 1–22.

Linkrus, E. 1969. Pärispea poolsaare geomorfoloogiast [Geomorphology of the Pärispea Peninsula]. In *EGS Aastaraamat1967/1968*, pp. 24–49. Valgus, Tallinn [in Estonian, with English summary].

Linkrus, E. 1971. Geomorphology of the Käsmu Peninsula. *Acta et Commentationes Universitatis Tartuensis*, **288**, 3–29 [in Russian, with English summary].

Linkrus, E. 1976. Juminda poolsaare loodusest [About the nature of the Juminda Peninsula]. In *EGS Aastaraamat 1974*, pp. 43–54. Valgus, Tallinn [in Estonian, with English summary].

Linkrus, E. 1988. Suurekõrve reservaat: selle reljeef ja maastikuline struktuur [Suurekõrve reserve: its relief and landscape structure]. In *Lahemaa uurimused III* (Etverk, I., ed.), pp. 16–31. Valgus, Tallinn [in Estonian, with English summary].

Long, A. J., Woodfoffe, S. A., Dawson, S., Roberts, D. H. & Bryant, C. L. 2009. Late Holocene relative sea level rise and the Neoglacial history of the Greenland ice sheet. *Journal of Quaternary Science*, **24**, 345–359.

Lunkka, J.-P., Putkinen, N. & Miettinen, A. 2012. Shoreline displacement in the Belomorsk area, NW Russia during the Younger Dryas Stadial. *Quaternary Science Reviews*, **37**, 26–37.

Mäemets, A. 1977. *Eesti NSV järved ja nende kaitse* [*Estonian Lakes and Their Protection*]. Valgus, Tallinn, 263 pp.

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.

Miettinen, A. 2004. Holocene sea-level changes and glacio-isostasy in the Gulf of Finland, Baltic Sea. *Quaternary International*, **120**, 91–104.

Miettinen, A., Jansson, H., Alenius, T. & Haggrén, G. 2007. Late Holocene sea-level changes along the southern coast of Finland, Baltic Sea. *Marine Geology*, **242**, 27–38.

Mörner, N.-A. 1979. The Fennoscandian uplift and Late Cenozoic geodynamics: geological evidence. *GeoJournal*, **3**, 287–318.

Murray-Wallace, C. V. 2007. Eustatic sea-level changes since the Last Glaciation. In *Encyclopaedia of Quaternary Science* (Elias, S. A., ed.), pp. 3034–3043. Amsterdam, The Netherlands.

Ramsay, W. 1929. Niveaurschiebungen, Eisgestaute Seen und Rezession des Inlandeises in Estland. *Fennia*, **52**, 1–48.

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. Eesti järvede nimestik [List of Estonian lakes]. *Looduseuurijate Seltsi Aruanded*, XLI, 1–192 [in Estonian].

Risberg, J., Sandgren, P. & Andrén, E. 1996. Early Holocene shore displacement and evidence of irregular isostatic uplift northwest of Lake Vänern, western Sweden. *Journal of Paleolimnology*, **15**, 47–63.

Risberg, J., Alm, G. & Goslar, T. 2005. Variable isostatic uplift patterns during the Holocene in southeast Sweden, based on high-resolution AMS radiocarbon datings of lake isolations. *The Holocene*, **15**, 847–857.

Rosentau, A., Vassiljev, J., Saarse, L. & Miidel, A. 2007. Palaeogeographic reconstruction of proglacial lakes in Estonia. *Boreas*, **36**, 211–221.

Rosentau, A., Veski, S., Kriiska, A., Aunap, R., Vassiljev, J., Saarse, L., Hang, T., Heinsalu, A. & Oja, T. 2011. Palaeogeographic model for the SW Estonian coastal zone of the Baltic Sea. In *The Baltic Sea Basin* (Harff, J., Björck, S. & Hoth, P., eds), pp. 165–188. Springer-Verlag, Berlin.

Saarnisto, M. 2012. Late Holocene land uplift/neotectonics on the island of Valamo (Valaam), Lake Ladoga, NW Russia. *Quaternary International*, **260**, 143–152.

Saarse, L. & Vassiljev, J. 2010. Holocene shore displacement in the surroundings of Tallinn, North Estonia. *Estonian Journal of Earth Sciences*, **59**, 207–215.

Saarse, L., Heinsalu, A., Poska, A., Veski, S. & Rajamäe, R. 1999. Palaeoecology and human impact in the vicinity of Lake Kahala, North Estonia. *PACT*, **57**, 373–403.

Saarse, L., Vassiljev, J. & Miidel, A. 2003. Simulation of the Baltic Sea shorelines in Estonia and neighbouring areas. *Journal of Coastal Research*, **19**, 261–268.

Saarse, L., Vassiljev, J., Miidel, A. & Niinemets, E. 2006. Holocene buried organic sediments in Estonia. *Proceedings of the Estonian Academy of Sciences, Geology*, **55**, 296–320.

Saarse, L., Heinsalu, A. & Veski, S. 2009. Litorina Sea sediments of ancient Väana Lagoon, northwestern Estonia. *Estonian Journal of Earth Sciences*, **58**, 85–93.

Saarse, L., Vassiljev, J. & Heinsalu, A. 2010. Reconstruction of the land-sea changes on the Juminda peninsula, North Estonia, during the last 10 300 years. *Baltica*, **23**, 117–126.

Saros, J. E. & Fritz, S. C. 2000. Nutrients as a link between ionic concentration/composition and diatom distributions in saline lakes. *Journal of Paleolimnology*, **23**, 449–453.

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.

Snyder, J. A., Forman, S. L., Mode, W. N. & Tarasov, G. A. 1997. Postglacial relative sea-level history: sediment and diatom records of emerged coastal lakes, north-central Kola Peninsula, Russia. *Boreas*, **26**, 329–346.

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.

Stone, J. R. & Fritz, S. C. 2004. Three-dimensional modelling of lacustrine diatom habitat areas: improving paleo-limnological interpretation of planktic:benthic ratios. *Limnology and Oceanography*, **49**, 1540–1548.

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

Vassiljev, J., Saarse, L. & Rosentau, A. 2011. Palaeo-reconstruction of the Baltic Ice Lake in the Eastern Baltic. In *The Baltic Sea Basin* (Harff, J., Björck, S. & Hoth, P., eds), pp. 189–202. Springer-Verlag, Berlin.

Veski, S. 1998. Vegetation history, human impact and palaeo-geography of West Estonia. Pollen analytical studies of lake and bog sediments. *Striae*, **38**, 1–119.

Watcham, E. P., Bentley, M. J., Hodgson, D. A., Roberts, S. J., Fretwell, P. T., Lloyd, J. M., Larter, R. D., Whitehouse, P. L., Leng, M. J., Monien, P. & Moreton, S. G. 2011. A new Holocene relative sea level curve for the South Shetland Islands, Antarctica. *Quaternary Science Reviews*, **30**, 3152–3170.

Weckström, K. & Juggins, S. 2006. Coastal diatom-environ-ment relationships from the Gulf of Finland, Baltic Sea. *Journal of Phycology*, **42**, 21–35.

Wolin, J. A. & Duthie, H. C. 1999. Diatoms as indicators of water level changes in freshwater lakes. In *The Diatoms: Application for the Environmental and Earth Sciences* (Stoermer, E. F. & Smol, J. P., eds), pp. 183–202. University Press, Cambridge.

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.

Estonian Journal of Earth Sciences, 2012, **61**, 4, 307–316

Käsmu ja Pärispea poolsaare paleorannajoone rekonstruktsioonid

Ieva Grudzinska, Leili Saarse, Jüri Vassiljev, Atko Heinsalu ja Siim Veski

Lohja ja Käsmu järvesetete litoloogilise koostise, ränivetikate, magnetilise vastuvõtlikkuse ning AMS ^{14}C dateeringute abil selgitati nende järvede isoleerumine Limneamerest. Nimetatud järved asuvad Põhja-Eestis, vastavalt 5,5 ja 3,9 m üle merepinna. Lohja isoleerus Limneamerest umbes 2300, Käsmu ligikaudu 1800 aastat tagasi. Koostati uuringuala rannasiirde kõver. Rekonstrueeriti Käsmu ja Pärispea poolsaare paleogeograafilised kaardid nelja erineva ajahetke kohta (4000, 3000, 2300 ning 1800 kalibreeritud aastat tagasi), kasutades modelleerimiseks rannamoodustiste andmebaasi ja digitaalset reljeefimudelit.