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Mid- and late-Holocene shoreline changes along the southern coast of the Gulf of Finland

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Abstract

In response to glacio-isostatic rebound in Estonia, a relative sea level fall occurred during the mid- and late-Holocene, and as a result, lowland regions in northern Estonia have experienced an evolution from sea to land. The mid- and late-Holocene shoreline changes along the southern coast of the Gulf of Finland were reconstructed, using litho-, bio- and chronostratigraphical proxies from four lakes. The lakes are located within the Gulf of Finland drainage system at different altitudes between 18 and 4 m above the present sea level. The isolation from the sea and the onset of freshwater lacustrine sedimentation occurred in Tänavjärv basin at 5400 cal yr BP, in Klooga basin at 4200 cal yr BP, in Lohja basin at 2200 cal yr BP and in Käsmu basin at 1800 cal yr BP. Through the application of GIS-based analysis, a modern digital terrain model and reconstructed past water level surfaces, we present a series of scenarios of shoreline and palaeogeography changes occurring since 7800 cal yr BP. The land uplift rate, which was approximately 2.8 mm yr^{-1} 7800 cal yr BP in the surroundings of Tänavjärv, has decreased to 2.2 mm yr^{-1} at present and that at Lohja from 2.4 to ca 2.0 mm yr^{-1}, respectively. The relative sea level curves show a land uplift decrease, which is nearly linear since the mid-Holocene.

Keywords: lake sediments, stratigraphy, diatoms, absolute age, C-14, paleogeography, sea-level changes, Litorina Sea, Holocene, Estonia

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1. Introduction

Since the deglaciation, the shoreline configuration around the Baltic Sea has been continuous, being controlled by the interaction between local glacio-isostatic recovery and global eustatic sea level rise (Björck, 1995). In Estonia, the latest research on shoreline displacement has been focused on the earliest stages of the Baltic Sea, i.e. the development of the Baltic Ice Lake (Vassiljev et al., 2011; Vassiljev

& Saarse, 2013), Yoldia Sea (Heinsalu & Veski, 2007), Ancylus Lake (Saarse et al., 1999) and Litorina Sea (Saarse et al., 2009, 2010). However, the shoreline development after the Litorina Sea transgression, which formed a comparatively well developed and therefore easily traceable beach formation on the southern coast of the Gulf of Finland, is considerably poorly studied, many disputable aspects exist and the current data are not always consistent with the results from the neighbouring areas (Miettinen, 2002; Sandgren et al., 2004; Miettinen et al., 2007).

Ramsay (1929) was the first, who described the Litorina Sea beach formations at 53 different locations in Estonia and reconstructed its isobases, which are valid up to the present. Kents (1939) distinguished the Litorina Sea shorelines at five different levels, compiled a shoreline diagram and suggested the uplift gradient 15.5 cm km^{-1} for the Litorina Sea, which has been accepted by many later researches (e.g., Kessel & Raukas, 1967). Detailed studies on the post-Litorina sea level changes are highly limited and the shoreline changes for this time window are poorly constrained. To overcome this problem, we studied four basins, using the isolation method that is widely utilised in sea level reconstructions (e.g., Lindén et al., 2006; Miettinen et al., 2007; Lunkka et al., 2012; Saarnisto, 2012).

The main objectives of the current work are to study mid- and late-Holocene shoreline changes in northern Estonia by providing the chronological control on relative sea level changes. Therefore a series of emerged coastal lakes, situated at various elevations between the Litorina Sea transgression limit and the present sea level, were investigated. We also aimed at reconstructing the local palaeogeography, compiling a relative sea level curve and testing the existing age-depth models (Saarse et al., 2007; Rosentau et al., 2011), which claims that the sea level has regressed rather evenly over the last 5000 years due to a linear land uplift (Mörner, 1979; Lindén et al., 2006).

2. Site descriptions

The studied lakes Tänavjärv, Klooga, Lohja and Käsmu are located in northern and northwestern Estonia (Fig. 1), on the terraces of the Litorina and Limnea Sea at 18.4 and 3.9 m above the present sea level (a.s.l.), respectively (Table 1). The glacial

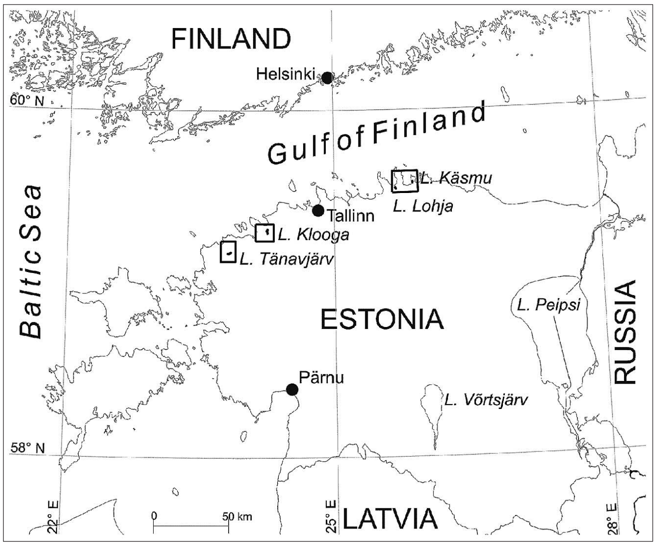


Fig. 1. Location of the studied lakes in northern Estonia, showing the positions of the palaeogeographic maps in Figs. 4-6.

Table 1. Morphometric characteristics of the studied lakes.

Site	Latitude N	Longitude E	Area (ha)	Water depth (m)	Altitude (m a.s.l.)	Catchment area (km^2)	Threshold (m a.s.l.)
Lake Tänavjärv	59°10´54´´	23°48´42´´	138.8	3.0	18.4	4.7	17.4
Lake Klooga	59°18´30´´	24°13´57´´	131.4	2.5	11.8	5.8	11.8
Lake Lohja	59°32´57´´	25°41´23´´	56.8	3.7	5.5	12.3	6.0
Lake Käsmu	59°34´56´´	25°52´51´´	48.5	3.3	3.9	16.5	4.5

deposits covered by marine and aeolian sediments are rather thin, except in buried valleys, where they reach 37–46 m (Kadastik & Ploom, 2000). The relatively flat topography with gentle sloping towards the sea resulted in extensive formation of peat around the investigated lake basins. During the Litorina Sea transgression, all the studied lake basins were inundated by sea water, as the maximum shorelines of the Litorina Sea are recorded at 22.1 m a.s.l. at Tänavjärv, 21.9 m a.s.l. at Klooga, 18.8 m a.s.l. at Lohja and 17.7 m a.s.l. at Käsmu.

Lake Tänavjärv (water level 18.4 m a.s.l., threshold 17.4 m a.s.l.) is an elongated shallow, medium-size semidystrophic lake. The original threshold is located in the southern shore of the lake and is buried under the peat. Prior to AD 1934, Tänavjärv had an outlet to Lake Veskijärv, its area was smaller and water table was lower, (17.9 m a.s.l.; Riikoja, 1934) than at present (Table 1). A ditch between lakes Tänavjärv and Veskijärv has grown over, and consequently, the lake level has been raised about 0.5 m. A set of small beach ridges and dunes has been recognised at 19–21 m a.s.l. in the north and northwest of the lake. The shores of the lake are peaty and partly sandy in the west and east. The catchment is forested by boreal tree species, mostly by *Pinus sylvestris*, and frequently suffers from forest fires (Kangur, 2005).

Lake Klooga (water level and threshold 11.8 m a.s.l.) is located in a north-south oriented depression on the border of the Lahepera-Kloogaranna buried valley (Kadastik & Ploom, 2000) and Pakri klint headland. The lake is surrounded by abraded limestone terraces and a chain of gravelly beach ridges at 22–20 m a.s.l. in the east, dunes in the north and peatland in the west and south (Tammekann, 1940). Lake Klooga is a shallow drainage lake, largely overgrown by emergent aquatic macrophytes. Due to the overabundance of the macrophyte stand, the lake area has decreased to 7 ha over the last 70 years. Small brooks and bottom springs carry calcareous water to the lake and promote precipitation of lacustrine lime. A ditch outflowing to the Vasalemma River is temporarily dry. The western and southern part of the catchment is paludified and forested; the eastern part is covered by fields and meadows, the northern part by a pine forest. The bottom of the lake is covered by gyttja, calcareous gyttja and silty gyttja with the maximum thickness of 4.5 m in the central part of the basin.

Lake Lohja (water level 5.5 m a.s.l., threshold 6.0 m a.s.l.) is located in a wide Valgejõe-Loobu klint bay which is entirely filled up with sand (Tammekann, 1940). The well-shaped Ancylus Lake beach ridges have formed an arc 2 km to the south of Lake Lohja, while chains of the Litorina Sea and Limnea Sea beach ridges and dunes, which are parallel to the shoreline, occur in low-lying places. The upper limit of the inner beach ridge lies at 9 m in the west and at 8 m a.s.l. in the north. Lake Lohja is a dark-coloured lake with an outflow brook to the Hara Bay.

Lake Käsmu (water level 3.9 m a.s.l., threshold 4.5 m a.s.l.) is located on the Käsmu Peninsula and is a drainage lake with water that is highly rich in nutrients (Table 1). The lake is bordered by beach ridges at 8 m a.s.l. in the west and a slightly paludified marine plain in the east, covered by different types of boreal forest. The transgressional beach ridges of Ancylus Lake and the Litorina Sea run 2–3 km to the south of the lake. The water level of Lake Käsmu is regulated.

3. Material and methods

A series of overlapping cores were obtained with a Russian peat sampler from the deepest parts of the basins. 1-m-long core sections were described in field, photographed, sealed in plastic liners and transported to the laboratory and stored in a cold-room. The organic matter (OM) content was quantified by loss-on-ignition (LOI) at 525 °C. The carbonate content was estimated in terms of the difference between LOI at 900 °C and 525 °C multiplied by 1.36. The ignition residue was estimated as mineral matter content. Magnetic susceptibility (MS) was measured with a Bartington MS2E high-resolution scanning sensor from the sediment surface at 1 cm resolution.

Diatom analyses from Lake Tänavjärv (Saarse et al., 1989) and from Lake Käsmu (Kessel et al., 1986) were made by E. Vishnevskaya several years ago. For this data, diatom taxonomy was modified, diagrams were redrawn and sediment sequences were correlated on the basis of lithostratigraphy and LOI results. For the other sediment records the diatom preparation followed techniques described in Battarbee et al. (2001). Diatom samples were digested in hydrogen peroxide until all OM was removed, hydrochloric acid was added to remove carbonates, and repeated decantation was applied to extract fine and coarse mineral particles. Some drops of the remaining residue were spread over the cover slip, dried overnight and mounted permanently onto microscope slides, using Naphrax medium. At least 400 diatom valves were counted from each subsample under Zeiss Axio Imager A1 microscope at ×1000 magnification and identified to species level. Diatoms were grouped according to their salinity tolerance into brackish/marine, halophilous and freshwater taxa, and according to their habitat into plankton and periphyton. Diatom floras used for the identification and the ecological information were based on the work by Krammer & Lange-Bertalot (1986, 1988, 1991a, 1991b), Witkowski et al. (2000), Snoeijs (1993), Snoeijs & Vilbaste (1994), Snoeijs & Potapova (1995), Snoeijs & Kasperovičien (1996), Snoeijs & Balashova (1998). Sediment LOI and MS, as well as diatom results were plotted, using the TGView software (Grimm, 2007).

The radiocarbon dating of macrofossils was performed partly in the Poznan Radiocarbon Laboratory (AMS dates), partly in the Institute of Geology at Tallinn University of Technology (conventional dates). The chronology of the studied sediment sequences is based on the calibration of the radiocarbon dates, using the IntCal09 calibration dataset (Reimer et al., 2009) and the OxCal 4.1 program (Bronk Ramsey, 2009). Radiocarbon dates and lithological data were combined, using the OxCal deposition model (Bronk Ramsey, 2008). In the present study the calibrated ages (cal yr BP) are provided as weighted averages with 2 sigma. Due to the low level of salinity in the Gulf of Finland (Eronen et al., 2001; Miettinen et al., 2007), the reservoir effect in the coastal sediment of Estonia has not been considered. At the same time, results from an archipelago not far from Stockholm show reservoir ages between 1100 and 400 years (Hedenström & Possnert, 2001), commonly assumed to be in the range of 200 and 400 years (Risberg et al., 2005). The latest studies confirm not only the spatial, but also the temporal difference in the reservoir age since the Litorina Sea (Lougheed et al., 2012).

Palaeogeographical reconstructions are based on GIS analysis in which interpolated water level surfaces were removed from the digital terrain model (DTM; Rosentau et al., 2009). Topographic maps on scales of 1:10 000 and 1:25 000 were used to create a DTM with grid sizes 15×15 m (Tänavjärv, Klooga) and 20×20 m (Lohja, Käsmu). The peat deposits were removed from the DTM, using soil maps on a scale of 1:10 000, whereas the data on peat thickness were obtained from different sources. For the purpose of constructing the relative sea level curve, additional materials from several isolation basins, such as radiocarbon dates and morphometrical data on the raised beaches, were considered (Table 2).

4. Results and discussion

4.1. Environmental conditions

The diatom analysis applied in this study proved to be an effective tool in identifying the position of the isolation contact in the sediment sequence and in defining the related changes in basin salinity and isolation dynamics. The succession of diatom assemblages distinctly records palaeoenvironmental changes induced by the glacio-isostatic uplift and consecutive relative sea level regression through periods of brackish-water environment, isolation from the sea and subsequent lacustrine conditions.

Lake Tänavjärv sediment comprises sand (Tä-1), silt with dispersed OM (Tä-2), silty gyttja (Tä-3) and gyttja (Tä-4; Table 3), and their LOI results are displayed in Figure 2A. MS values are low, even in the silt. Silt with plant remains in core depth between 347 and 342 cm was deposited about 5700–5600 cal yr BP. The basal pre-isolation sediment of the Tänavjärv basin is characterised by

Table 2. Radiocarbon dates considered for the reconstruction of the relative sea level curve.

Site	Basin altitude (m a.s.l.)	Depth (cm)	^{14}C date	Calibrated age range, BP (weighted average)	Laboratory ID	Dated material	Reference
Tänavjärv	18.4	316-321	4490±70	4920-5310 (5130±100)	Tln-3306	Gyttja, bulk	Current study
Tänavjärv	18.4	321-324	4600±100	5050-5450 (5270±110)	Tln-3305	Silty gyttja, bulk	Current study
Tänavjärv	18.4	342-347	4930±40	5600-5730 (5660±40)	Poz-42173	Woody pieces	Current study
Klooga	11.8	335-340	3760±40	3990-4230 (4110±60)	Poz-42168	Terrestrial macro remains	Current study
Klooga	11.8	390-395	3840±50	4150-4420 (4280±80)	Poz-42169	Terrestrial macro remains	Current study
Lohja	5.8	365-370	2280±30	2160-2350 (2270±60)	Poz-42171	*Pinus* bark	Current study
Lohja	5.8	395	2490±35	2440-2730 (2580±80)	Poz-42172	*Tilia* wood	Current study
Käsmu	3.9	416	1830±30	1700-1860 (1770±40)	Poz-42177	*Pinus* bark	Current study
Käsmu	3.9	433	1910±30	1790-1930 (1860±30)	Poz-42166	*Pinus* wood	Current study
Aabla	24	545-555	7250±80	7940-8280 (8080±80)	Tln-3195	Coarse detritus gyttja, bulk	Saarse et al., 2010
Aabla	24	556	7280±50	7990-8190 (8090±50)	Poz-33490	Piece of wood	Saarse et al., 2010
Aabla	24	570-572	6920±40	7670-7840 (7750±50)	Poz-35465	Sand with OM	Saarse et al., 2010
Maarikoja	16.8-17.3		6820±70	7570-7830 (7670±70)	Tln-200	Buried *Carex-Phragmites* peat	Kessel & Linkrus, 1979
Maarikoja	16.8-17.3		7240±90	7870-8300 (8070±90)	Tln-201	Wood	Kessel & Linkrus, 1979
Vääna	24.7	201.5	6240±40	7070-7270 (7200±50)	Poz-24245	Plant remains	Saarse et al., 2009
Vääna	24.7	220-221	7420±40	8170-8340 (8250±50)	Poz-24267	Plant remains	Saarse et al., 2009
Niitvälja	19.5	280-290	7580±70	8210-8540 (8390±70)	Tln-261	Buried gyttja, bulk	Punning et al., 1980

floristic heterogeneity, mixed occurrence of marine and brackish-water species with relatively frequent freshwater forms (Fig. 3A). The dominant part of the assemblage, however, consists of periphytic saline water tolerant species, while euplanktonic forms are absent. Periphytic brackish/marine diatoms, namely *Diploneis didyma*, *Cocconeis scutellum*, *Hyalodiscus scoticus* and *Campylodiscus clypeus* are the diatoms that are most abundant in the silt layer, accounting for 60–80 % of the assemblage (Fig. 3A). This diatom evidence is most likely an indication of a sediment accumulation in a shallow-water lagoon, rather than in an open-sea environment. According to radiocarbon dates, the lagoonal phase of the basin lasted for at least 400 years.

The distinct change in the diatom composition from brackish to freshwater species and sediment lithostratigraphy from silty gyttja to gyttja at the core depth of 327 cm indicates the isolation event. The modelled age of the isolation is 5420±130 cal

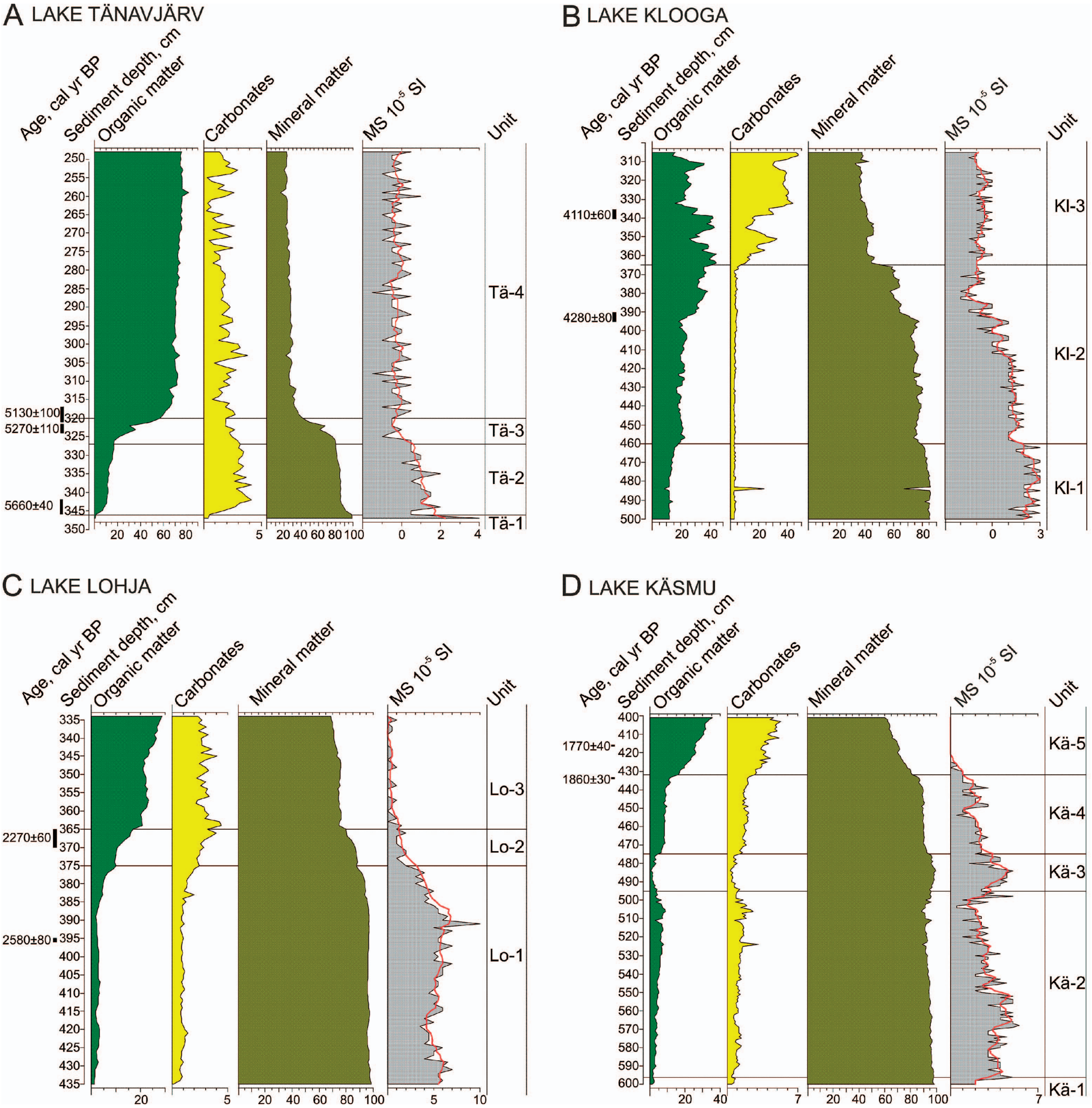


Fig. 2. Sediment organic matter, carbonates and mineral matter content estimated by loss-on-ignition (% of dry weight) and magnetic susceptibility (MS) of Lake Tänavjärv (A), Lake Klooga (B), Lake Lohja (C) and Lake Käsmu (D). The red line in the MS curve is 5-sample moving average.

yr BP (hereafter 5400 cal yr BP). Above the isolation level brackish/marine diatoms disappear, the halophilous taxa decreases and the freshwater taxa, such as *Navicula radiosa*, *Stauroneis phoenicenteron*, *Sellaphora pupula* and *Cymbopleura naviculiformis* increases. The isolation from the sea was probably a rather short-term process.

Initially, the water in the post-isolated basin was rather nutrient rich, confirmed by benthic diatoms such as *Navicula radiosa* and *Sellaphora pupula*. However, the final takeover of diatoms such as *Pinnularia* spp., *Brachysira serians*, *Eunotia* spp. and *Tabellaria fenestrata* implies that the lake underwent a rapid change from alkaline to acidic nutrient-poor

Table 3. Lithostratigraphy of the studied sediment cores.

Site	Depth, cm	Sediment description	Unit
Lake Tänavjärv	245-320	Gyttja, dark brown, slightly consolidated	Tä-4
	320-327	Silty gyttja, dark grey, limit with gyttja sharp	Tä-3
	327-347	Silt with dispersed OM, dark grey	Tä-2
	347-350+	Sand, fine grained, light grey	Tä-1
Lake Klooga	300-365	Calcareous gyttja, beige, subfossil mollusc shells, fluctuating OM	Kl-3
	365-460	Silty gyttja, dark brown, well decomposed OM	Kl-2
	460-500+	Silt with dispersed OM	Kl-1
Lake Lohja	333-364	Gyttja, brown, loose	Lo-3
	364-375	Silty gyttja, greenish grey, at 363 cm richly plant remains	Lo-2
	375-435+	Silt, grey dispersed OM	Lo-1
Lake Käsmu	400-433	Gyttja, dark brown, soft	Kä-5
	433-475	Silt with OM, dark grey	Kä-4
	475-495	Sand, medium size, at lower limit thin OM rich layer	Kä-3
	495-595	Silt with sparse plant remains, dark grey	Kä-2
	595-600+	Sand, fine grained, grey	Kä-1

conditions (Bigler et al., 2000; Dixit & Dickman, 1986) due to paludification of the catchment.

Lake Klooga sediment lithology differs from that of Lake Tänavjärv, containing more OM rich silt (Kl-1) and silty gyttja (Kl-2) that grades into calcareous gyttja (Kl-3; Table 3). The OM content peaks in the upper part of silty gyttja (Kl-2) and lower part of calcareous gyttja (Kl-3; Fig. 2B). The shift in the MS values in general coincides with sediment lithostratigraphical boundaries and is associated with decrease in mineral matter. The calcareous gyttja that terminates the sediment sequence is characterised by low MS values (Fig. 2B). Silty gyttja in the basal part of the sediment sequence (420–365 cm) contains periphytic brackish/marine diatoms, namely *Achnanthes fogedii*, *Campylodiscus clypeus*, *Planothidium delicatulum* and *Karayevia submarina*, periphytic halophilous taxa, such as *Epithemia turgida*, *E. sorex*, *Hippodonta hungarica* and *Cocconeis placentula*, and small-sized fragilarioid species with brackish water affinity, such as *Pseudostaurosiropsis geocollegarum*, *Pseudostaurosira elliptica* and *Opephora mutabilis* (Fig. 3B). The diatom assemblage suggests brackish water environment, and the AMS ^{14}C dating yielding the age of 4280±80 cal yr BP consequently indicates the period when the basin had been a semi-closed lagoon with a connection to the open sea.

In the interval between 365–350 cm, cosmopolite salinity-indifferent *Fragilaria* spp. predominate after the disappearance of the brackish-water diatom assemblage. Small-sized fragilarioid taxa are considered to be the pioneer diatoms that have an advantage in a rapidly changing environment (Yu et al., 2004) and thus the peak of *Fragilaria* spp. is regarded as the marker of the transition to the final isolation of the Klooga basin. A dominance of periphytic freshwater diatoms, such as *Cymbella-falsa diluviana*, *Sellaphora vitabunda* and *Achnanthidium minutissimum* from the core-depth of 345 cm indicates the isolation from the sea and suggests a shallow hard-water lake environment. An AMS ^{14}C age of 4110±60 cal yr BP corresponds to the time shortly following the isolation and the modelled age of isolation is 4180±50 cal yr BP (hereafter 4200 cal yr BP).

Lake Lohja lithostratigraphy follows the transition from silt (Lo-1) to silty gyttja (Lo-2) and to gyttja (Lo-3; Table 3). The MS of the sequence is rather stable between the core depths of 435 and 390 cm, decreasing successively between 390 and 360 cm and stabilising in the upper part at low values (Fig. 2C).

The basal part of the core (400–365 cm) shows

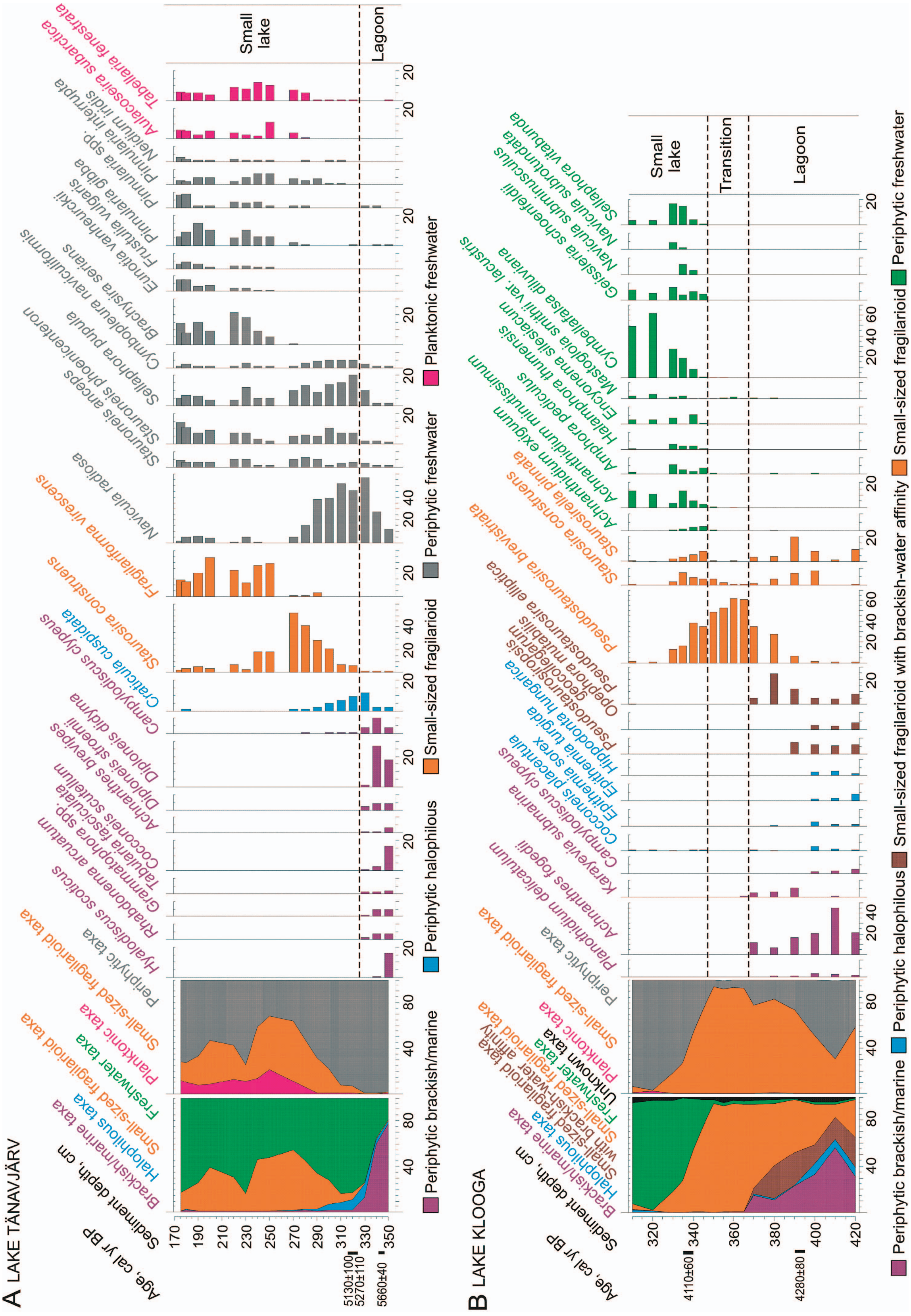
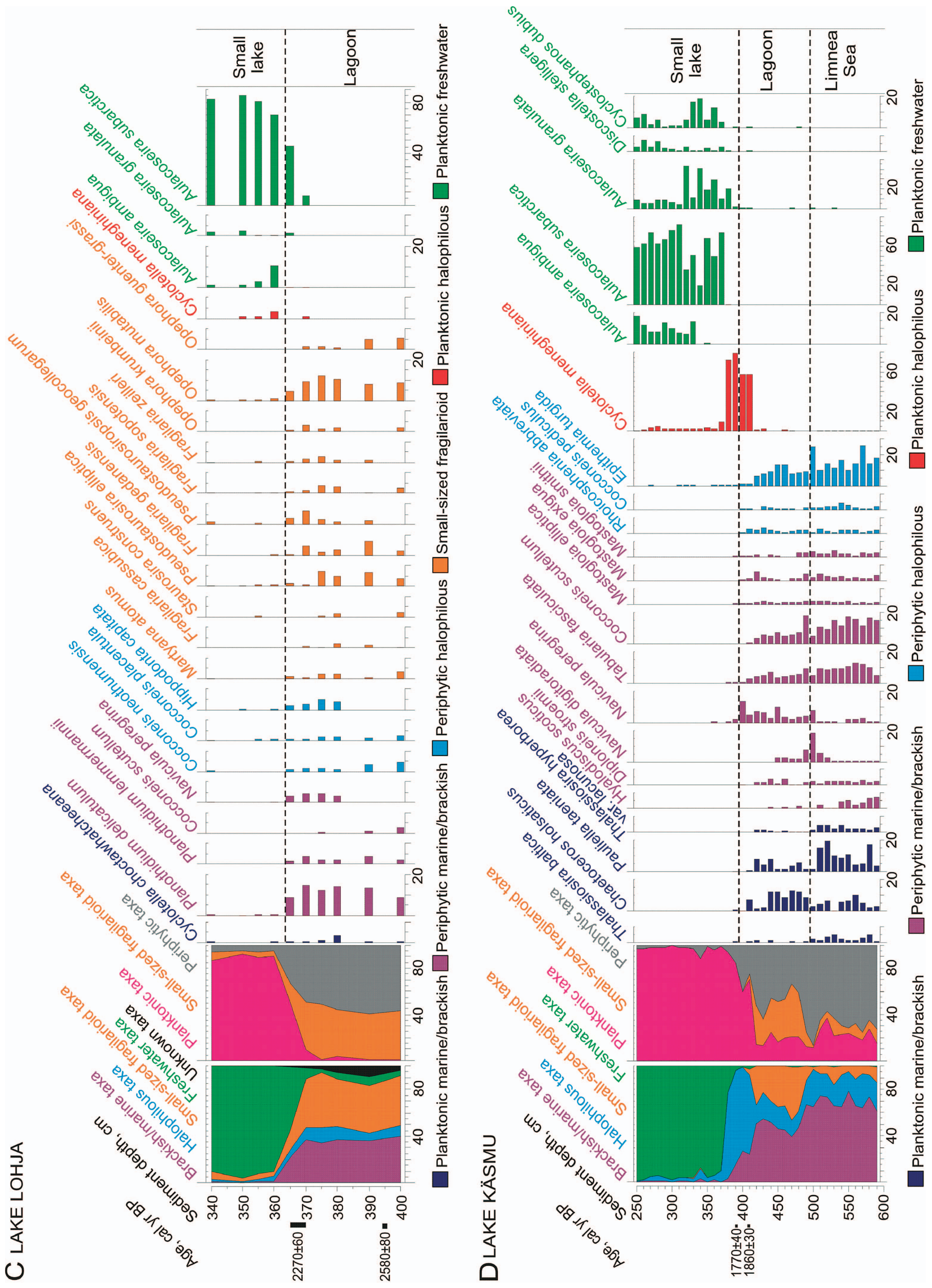


Fig. 3. Diatom diagrams from Lake Tänavjärv (A), Lake Klooga (B), Lake Lohja (C) and Lake Käsmu (D).


C LAKE LOHJA
Age, cal yr BP
Sediment depth, cm
Brackish/marine taxa
Halophilous taxa
Small-sized fragilarioid taxa
Freshwater taxa
Unknown taxa
Planktonic taxa
Small-sized fragilarioid taxa
Periphytic taxa
Cyclotella choctawhatcheeana
Planothidium delicatulum
Cocconeis lemmermannii
Navicula peregrina
Cocconeis neothumensis
Hippodonta capitata
Martyana atomus
Fragilaria cassubica
Staurosira construens
Pseudostaurosira elliptica
Fragilaria gedanensis
Pseudostaurosira brevistriata
Fragilaria sopotensis
Opephora zeilleri
Opephora krumbeinii
Opephora mutabilis
Cyclotella guenter-grassi
Cyclotella meneghiniana
Aulacoseira ambigua
Aulacoseira granulata
Aulacoseira subarctica
Small lake
Lagoon
340
350
360
370
380
390
400
2270±60
2580±80
40
80
20
Planktonic marine/brackish
Periphytic marine/brackish
Periphytic halophilous
Small-sized fragilarioid
Planktonic halophilous
Planktonic freshwater
D LAKE KÄSMU
Age, cal yr BP
Sediment depth, cm
Brackish/marine taxa
Halophilous taxa
Small-sized fragilarioid taxa
Freshwater taxa
Planktonic taxa
Small-sized fragilarioid taxa
Periphytic taxa
Thalassiosira baltica
Chaetoceros holsaticus
Pauliella taeniata
Thalassiosira hyperborea var. lacunosa
Hyalodiscus scoticus
Diploneis stroemii
Navicula digitoradiata
Navicula peregrina
Tabularia fasciculata
Cocconeis scutellum
Mastogloia elliptica
Mastogloia exigua
Mastogloia smithii
Rhoicosphenia abbreviata
Cocconeis pediculus
Epithemia turgida
Cyclotella meneghiniana
Aulacoseira ambigua
Aulacoseira subarctica
Aulacoseira granulata
Discostella stelligera
Cyclostephanos dubius
Small lake
Lagoon
Limnea Sea
250
300
350
400
450
500
550
600
1770±40
1860±30
40
80
20
60
Planktonic marine/brackish
Periphytic marine/brackish
Periphytic halophilous
Planktonic halophilous
Planktonic freshwater

high values of benthic brackish/marine diatoms, notably *Planothidium delicatulum* (Fig. 3C). Simultaneously, small-sized fragilarioid epipsammic diatoms with brackish-water affinity, such as *Opephora mutabilis*, *O. guentergrassi* and *Fragilaria gedanensis* are abundant. At the core depth of 360 cm brackish/marine diatoms have declined and planktonic freshwater diatom *Aulacoseira subarctica* predominates together with *A. ambigua* and *A. granulata*, implying a relatively abrupt isolation. An AMS radiocarbon date of 2270±60 cal yr BP, obtained from a pine bark fragment, represents the date that immediately precedes the isolation, and the modelled age of isolation is 2230±70 cal yr BP (hereafter 2200 cal yr BP).

Post-isolation sediments are characterised by the predominance of planktonic freshwater *Aulacoseira* species. The most common diatom *Aulacoseira subarctica* is meroplanktonic and is only present in the water column when there is sufficient turbulence (Gibson et al., 2003), therefore the distinct increase in planktonic diatoms is not related to the lake level rise, but can instead be explained by the location in an open landscape close to a windy sea coast (Grudzinska et al., 2012), where the exposure to wind-induced waves resulted in the turbulent mixing of the water column.

Lake Käsmu lithostratigraphy is rather similar to Lohja site, however, the Käsmu core also includes a sand layer (Kä-3), imbedded into silt (Kä-2, Kä-4; Table 3). The MS shows a wiggly appearance throughout the lithostratigraphical units (Fig. 2D). The diatom composition at the base of the core includes mainly diatoms with marine and brackish-water affinity (Fig. 3D), such as pelagic *Chaetoceros holsaticus*, *Pauliella taeniata* and *Thalassiosira baltica*, as well as periphytic *Cocconeis scutellum* and *Tabularia fasciculata*, indicating rather open bay-like conditions with brackish-water environment. The diatom-derived isolation at the depth of 400 cm is marked by a decline in brackish-water diatoms and dominance of freshwater planktonic *Aulacoseira* taxa, reflecting the development of a small eutrophic lake. The modelled age of isolation is 1840±30 cal yr BP (hereafter 1800 cal yr BP). The high abundance of planktonic *Cyclotella meneghiniana* at the biostratigraphic isolation contact is an interesting feature. A peak of *C. meneghiniana* that 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) presumably suggests highly elevated water conductivity and nutrient concentrations during the final isolation event.

4.2. Palaeogeography

Based on the results of the current study, several palaeogeographical maps were constructed, which correspond to the following time windows: for Tänavjärv area 6500, 6000 and 5400 cal yr BP; for Klooga area 7800, 4500 and 4000 cal yr BP; for Lohja and Käsmu area 7800, 2200 and 1800 cal yr BP (Figs. 4–6). During the peak of the Litorina Sea transgression about 7800 cal yr BP, numerous beach ridge systems formed along an ancient coastline, stretching continuously in the North Estonian klint bays as a well-developed beach ridge arc at 21 m a.s.l. 15 km SE from Tänavjärv and a ridge system at about 17.5 m a.s.l. 2.5 km to the south from Käsmu. At that time only small islets emerged not far from the studied lake basins that were fully inundated by the sea.

The development and isolation of Lake Tänavjärv was determined by the Audevälja-Harju-Risti-Pedase buried endmoraine ridge and a glaciofluvial delta sediment reaching up to Lake Tänavjärv (Kadastik, 2004). By 6500 cal yr BP the delta plain had partly emerged, becoming subject to wave erosion and wind deflation, and forming a beach ridge/dune landscape to the north and northwest of Lake Tänavjärv (Fig. 4A). Due to the shallow sea, the isolation of Lake Tänavjärv was a rather short-lived process: by 6000 cal yr BP a lagoon with a passage in the south was formed, surrounded by beach ridges in the north and southeast and by a reworked esker ridge or spit in the west and southwest (Fig. 4B). According to the palaeoreconstruction, Lake Tänavjärv was fully isolated by 5400 cal yr BP (Fig. 4C). These results are consistent with the conclusions made earlier on the basis of

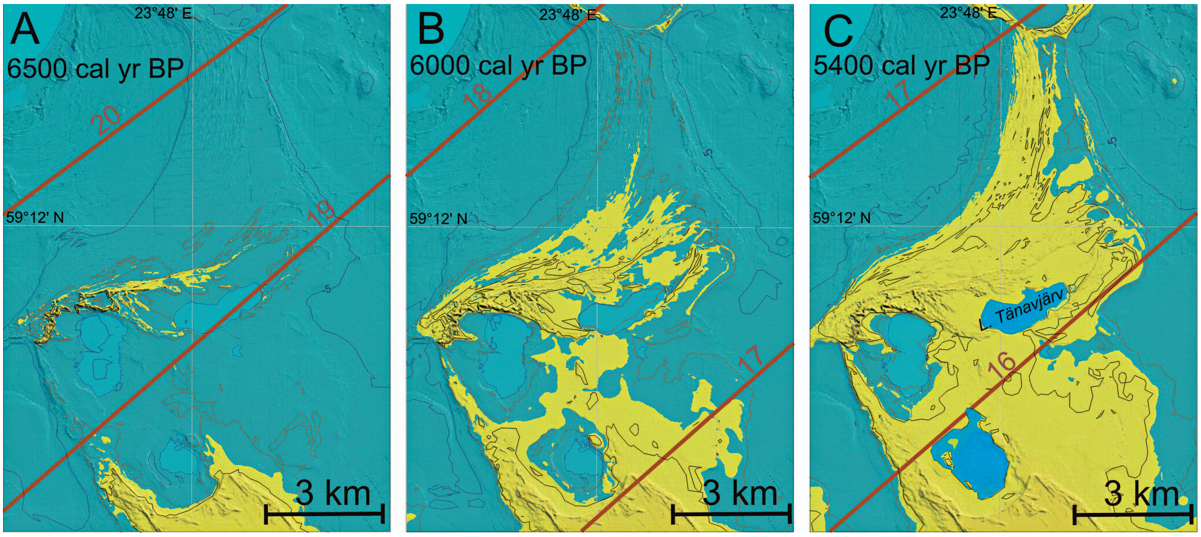


Fig. 4. Palaeogeographic maps of the Tänavjärv area for the time windows of 6500 (A), 6000 (B) and 5400 (C) cal yr BP. Modelled water level surface isobases are indicated by brown lines together with altitudes in meters a.s.l. The shoreline is shown with deviation ±1 m (black line +1 m, brown line -1 m). Blue line corresponds to the 5 m water depth. The reconstructions are compiled with LIDAR elevation data (Estonian Land Board) to visualize the present day land (yellow) and sea (blue) area.

pollen analyses, according to which sediments corresponding to the isolation were deposited in the second half of the Atlantic period (Saarse et al., 1989).

During the Litorina Sea transgression, a spit was formed in the area to the east of Lake Klooga, isolating a small lagoon. In the surroundings of Niitvälja, a costal lake was formed (Fig. 5A), where gyttja deposited until 8390±70 cal yr BP (Table 2), later buried by deposits of marine and terrestrial deposits. At 5000 cal yr BP, a beach ridge system developed to the east of the lake, while a tombolo started to form north of the lake, closing the northern connection with the sea by 4000 cal yr BP (Fig. 5C), and only a small passage in the west through the Vasalemma River valley provided the connection with the sea. Obviously, the lake level was slightly higher than the sea level and the passage functioned as a drainage canal of the lake, because the diatom record confirms an isolation around 4200 cal yr BP, which compared to Lake Tänavjärv was tardy due to the depth of the surrounding sea. Therefore, the isolation of Lake Klooga was contingent not only on the land uplift, but also on the development of different beach formations.

At 7800 cal yr BP the coastline of northern Estonia mostly followed the klint escarpment (Fig. 6A) and both Lohja and Käsmu lakes acted as offshore basins with small nearby islets. They maintained their broad connection with the sea until 4000 cal yr BP (Grudzinska et al., 2012). At 3000 cal yr BP, semi-closed lagoons formed in the place of Lohja and Käsmu lakes, with narrow passages between the sea and the lagoons. Lohja and Käsmu lakes became isolated by 2200 cal yr BP and 1800 cal yr BP, respectively, and developed into isolated coastal lakes (Fig. 6). This evidence confirms that Lake Käsmu isolated about 1000 years earlier than previously suggested (Kessel et al., 1986). The isolation history of Lake Lohja in the rump of the klint bay was mainly determined by the post-glacial relief-forming processes, primarily by the beach ridges and dunes. The isolation of Lake Käsmu on the drumlin-like peninsula (Karukäpp, 2004) was also controlled by glacial formations, primarily by a buried esker ridge to the west of the lake. LIDAR maps show that the surface of these drumlin-like forms was jointed by several esker-like ridges orientated to the ice flow direction as can be seen on the Pärispea Peninsula (Fig. 6).

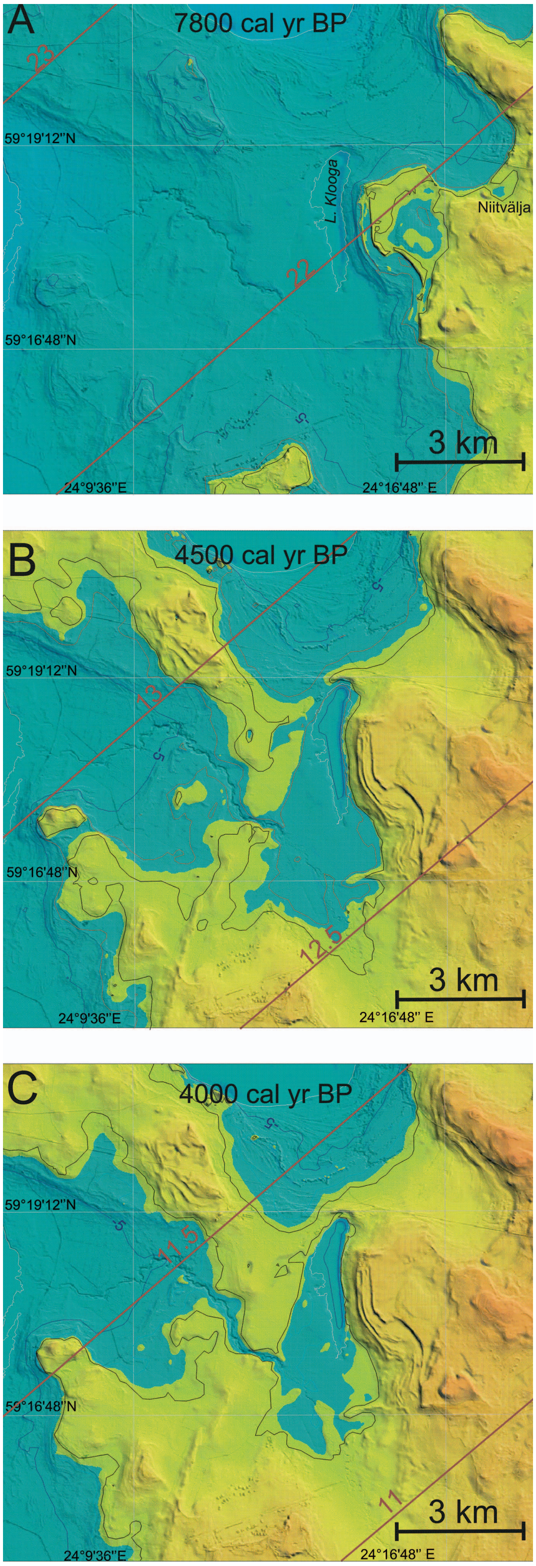


Fig. 5. Palaeogeographic maps of the Klooga area for the time windows of 7800 (A), 4500 (B) and 4000 (C) cal yr BP. For legend explanations see Fig. 4.

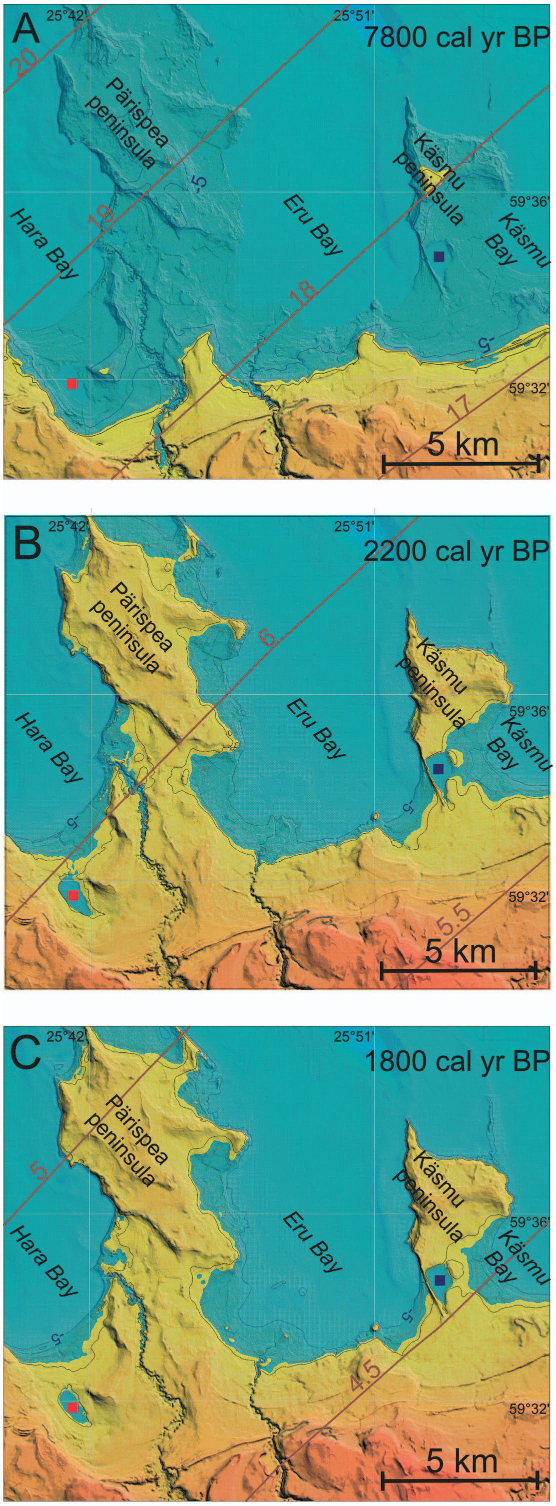


Fig. 6. Palaeogeographic maps of the Lohja and Käsmu area for the time windows of 7800 (A), 2200 (B) and 1800 cal yr BP (C). For legend explanations see Fig. 4. Lake Lohja is shown by a red square and Lake Käsmu by a blue square.

4.3. Relative sea level curve

Despite several studies conducted in northern and western Estonia, the relative sea level curves that are based on both bio- and chronostratigraphical data have not been constructed until only recently. The relative sea level curves for the Tänavjärv, Klooga, Lohja and Käsmu area were compiled, considering the diatom evidence, lithostratigraphy, ^{14}C dates and geomorphological markers. The presented relative sea level curves are regular from the onset of the Litorina Sea regression (Fig. 7), showing smoothly falling sea level from 22 m a.s.l. down to the present level. The isolation horizon provides regular upwards-younger radiocarbon ages, and biostratigraphic proxies do not show evidence of transgression after 6000 cal yr BP. The smoothly falling relative sea level does not rule out changes in local water level during heavy storms that have been rather frequent over the last century and have caused remarkable damages on the coast (Orviku et al., 2009). In general, the reconstructed sea level curves show a linear trend of sea level lowering that is similar to the reconstructed curves around the Gulf of Botnia (Lindén et al., 2006; Widerlund & Andresson, 2011) and the Gulf of Finland (Hyvärinen, 1982; Miettinen, 2002; Miettinen et al., 1999; Saarnisto, 2012), but differs from the previously presented ones concerning the southern coast of the Gulf of Finland (Kents, 1939; Kessel & Raukas, 1979; Raukas & Ratas, 1995) and southern Sweden (Berglund et al., 2005) that displayed several water level fluctuations during the Litorina Sea. Based on recent studies, the Litorina Sea transgression peaked about 7800 cal yr BP (Saarse et al., 2010). The amplitude of the transgression was about 3–4 m, which is compatible with studies carried out in southern Finland in areas with the similar isobase of the land uplift (Miettinen, 2002; Miettinen & Hyvärinen, 1997). Considerably higher magnitude of the Litorina Sea transgression occurred in areas of low uplift, being about 7 m in the surroundings of Pärnu (Fig. 1; Veski et al., 2005). As the Baltic Sea shorelines are widely distributed in northern and western Estonia, they also provide the possibility to examine the pattern of the uplift which they are indicative of (Smith et al., 2000). While the average apparent uplift today in the Tänavjärv-Klooga area is about 2.2 mm yr^{-1} and in Käsmu-Lohja area 2.0 mm yr^{-1} (Torim, 2004), then

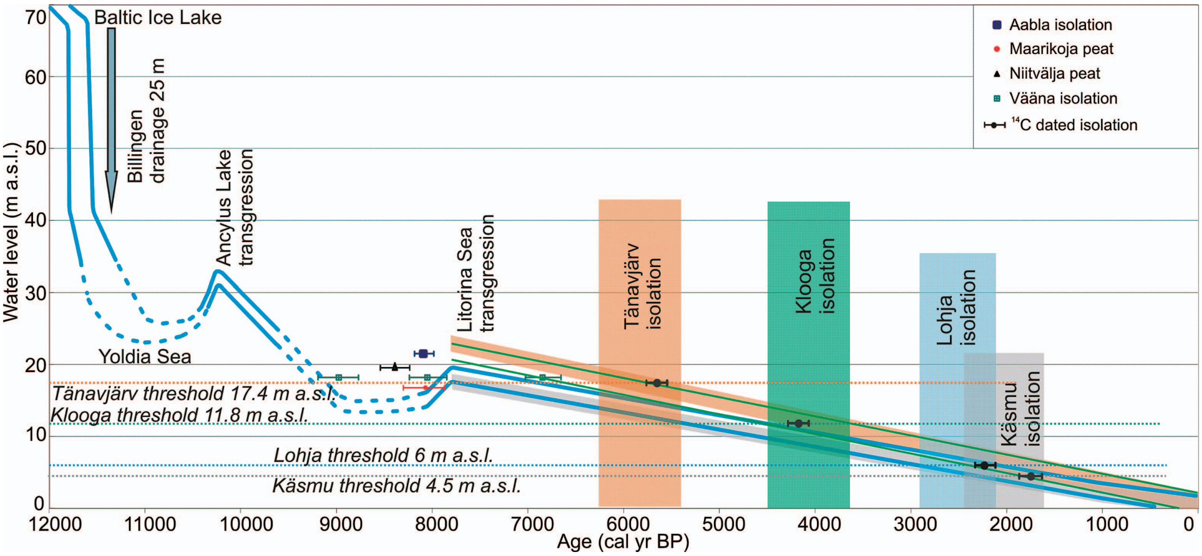


Fig. 7. The relative sea level curves for study areas. Lines mark the modelled possible minimum and maximum water level (green for Lake Klooga, blue for Lake Lohja) and areas mark the modelled possible range of the water level (orange for Lake Tänavjärv and grey for Lake Käsmu). Reconstruction considers errors both in the modelled water levels ±1 m and in the ages. Boxes in different colours show the isolation age range according to modelled water level. Black circles with error bars indicate the radiocarbon-dated age of the isolation.

according to our calculations the land uplift rates were higher in the mid-Holocene, 2.8 and 2.4 yr^{-1}, respectively, showing a continuous decreasing trend towards the present. If there will not be any rapid rise in the ocean level, the lowering trend of the sea level and apparent uplift in northern Estonia will continue.

5. Conclusions

Threshold elevation and marine limit comparison confirmed that the Litorina Sea water reached 22.1 m a.s.l. at Tänavjärv, 21.9 m a.s.l. at Klooga, 18.8 m a.s.l. at Lohja and 17.7 m a.s.l. at Käsmu in northern Estonia.

In all four sediment records the succession of diatom assemblages marks distinctly the palaeoenvironmental changes induced by glacio-isostatic uplift and consecutive relative sea level regression through periods of brackish-water environment, isolation from the sea and subsequent lacustrine conditions.

The final isolation contact of the lakes occurred between 5400 and 1800 cal yr BP without notable sea level oscillations during the post-Litorina period.

The isolation of lakes was dependent on the land uplift rate, determined also by the glacial and post-glacial relief forms, such as eskers, limestone terraces, beach ridges and dunes.

The relative sea level curves show a land uplift decrease for the last 6000 years and a smoothly falling sea level.

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