Holocene shore displacement in the surroundings of Tallinn, North Estonia

Leili Saarse and Jüri Vassiljev

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

Received 18 June 2009, accepted 23 December 2009

Abstract. The Tallinn area was recovered from the Weichselian ice sheet not later than 13 000–12 800 cal yr BP but remained for ca 1500 years under the waters of the Baltic Ice Lake (BIL). The highest parts of Tallinn emerged from the BIL after its drainage about 11 600 cal yr BP. At the beginning of the Yoldia Sea stage the present city area was submerged by sea water, except for the highest parts of Viimsi, Lasnamäe and Nõmme. At the end of the Yoldia Sea stage the Ülemiste, Pääsküla and Männiku basins isolated from the sea. During the Ancylus Lake transgression about 10 300 cal yr BP the highest coastline at 34–36 m a.s.l. broadly outlined the klint escarpment. The Litorina Sea transgressional coastline at 7800–7600 cal yr BP and beach formations at 21–22 m a.s.l. are less developed than the Ancylus ones and often covered by aeolian deposits. Toompea arched north as a cape in the Litorina Sea and the previous Viimsi Island joined with the mainland. During the Limnea Sea stage (4400 cal yr BP up to the present, the highest coastline at ca 12 m a.s.l.) land increased mostly at the back of Kakumäe and Kopli bays. The Kakumäe Peninsula obtained its outline about 2800 years ago, the Kopli Peninsula ca 1000 years later. The Paljassaar Peninsula was the latest to be formed ca 100 years ago. The attached palaeogeographical maps display shore displacement during the different stages of the Baltic Sea in the vicinity of Tallinn.

Key words: Holocene, Baltic Sea, shore displacement, Tallinn, North Estonia.

INTRODUCTION

Several freshwater to brackish-water stages have been determined in the Baltic Sea history (e.g. Munthe 1910, 1940; Berglund 1964; Kessel & Raukas 1979; Björck 1995). The balance between land uplift and water level rise due to meltwater and river discharge caused connection with the ocean or isolation from it (Lampe 2005). So, the Baltic Sea has largely influenced the development of coastal areas, including the city of Tallinn. Being located on the neotectonically uplifting coast, the highest parts of the Tallinn area started to emerge from the sea after the drainage of the Baltic Ice Lake (BIL) about 11 600 years ago. Several palaeogeographical maps and shoreline reconstructions of the Tallinn area have been compiled (Tammekann 1934, 1940; Künnapuu & Raukas 1976; Kessel 1979; Kessel et al. 1986; Lepland et al. 1995). The proxy data used in these reconstructions originated from various periods and their quality was different. Most of the palaeogeographical maps are hand-made and differ from those presented in the current study.

The aims of the present study were to collect shoreline data available on the Tallinn region, revise the elevation and coordinates of the shoreline sites, and to calculate residual and interpolate water level surfaces for different stages of the Baltic Sea. The statistical approach and the digital terrain model were used to simulate water level surfaces and compile palaeogeographical maps, which more precisely illustrate the land–sea relationship during the evolution of the Baltic Sea. Such maps enable archaeologists to study the colonization pattern and spread of settlements on the retreating coast and offer an improved insight into the development of the Tallinn area.

STUDY AREA

Tallinn, with an area of 156.3 km^2, is situated in northwestern Estonia, on the southern coast of the Gulf of Finland (Fig. 1). Its 46 km long shoreline is indented by bays and peninsulas. The northern part of the city is located on the fore-klint (coastal) lowland, the southern part on the limestone plateau with a steep northern margin known as the North Estonian Klint which runs through the city. The klint was described in detail by Tammekann (1940). The altitude of the southward dipping limestone plateau with a thin Quaternary cover is 40–50 m a.s.l. The carbonaceous bedrock surface is

Fig. 1. Location of the study area.

dissected by ancient valleys filled in with glacial, glaciofluvial, glaciolacustrine and marine deposits of various age and thickness (Künnapuu & Raukas 1976; Künnapuu et al. 1981) and by hills such as Suhkrumägi (47 m) and Lasnamägi (55 m; Fig. 2). Part of the Suhkrumägi cliff has been dug off and its seaward edge artificially altered during road building (Tammekann 1940). The most impressive denudation relief forms are Toompea and Viimsi Lubjamägi, which tower to 47 and 50 m a.s.l., respectively. Sandy plains at Nõmme and Männiku are rather flat, but disjointed due to dunes reaching up to 63.6 m a.s.l. in the northern part of Nõmme.

The fore-klint lowland is cut by several depressions and elevations (Tammekann 1934; Künnapuu 1975). The Harku depression is the westernmost one, followed in the east by the Kakumägi and Veskimägi elevations, Mustjõe depression and a chain of elevations, which continue seawards as the Kopli elevation (Fig. 2). The central part of the city lies on the plateau-like elevation from which Toompea Hill towers, connected with the rest of the plateau by a narrow neck (tombolo). A depression extending to Kadriorg and to the foot of the klint lies east of Toompea. Because of human interference, the initial topography and the shoreline of the city have changed considerably. Urban areas are covered by fillings commonly 0.5–1 m thick, but much thicker in the places of ancient bastions. Most of the Holocene coastal accumulation forms have been removed and destroyed as a result of intensive industrial and building activities and foundation of several harbours.

MATERIAL AND METHODS

Palaeogeographical reconstructions presented in the current paper are based on GIS analysis, by which interpolated surfaces of water levels were removed from the digital terrain model (DTM). The DTM was created, using 1 : 10 000 and 1 : 25 000 Soviet topographic maps. As the initial topography of the city has changed due to human activities, the thickness of the cultural layer was removed, according to maps compiled by Zobel (2008). To correct the DTM elevation and coastline, the Russian maps from the end of the 19th century were also used. Finally the DTM for the Tallinn area was created with a grid size of about 20 m × 20 m.

The interpolated water level surfaces were derived from the BIL, Ancylus Lake and Litorina Sea coastal formation databases (Saarse et al. 2003b, 2007), using a point kriging approach. Kriging is useful as it interpolates accurate surfaces from the irregularly spaced data and shows outliers in the data set. Residuals, i.e. the difference of the actual site elevation from the interpolated surface, were calculated to find out the erroneous data and omit sites with residuals more than 1 m.

The BIL water level prior to the final drainage at about 11 600 cal yr BP and the drainage magnitude of about 25 m (Björck & Digerfeldt 1989; Andrén et al. 2002; Jakobsson et al. 2007) were considered in modelling the highest Yoldia Sea water level. The Ancylus Lake water level was the highest at about 10 300 cal yr BP, the Litorina Sea level at 7800–7600 cal yr BP. The regressional levels of the Yoldia Sea and Ancylus Lake were not modelled, as the database does not yet cover those events properly. Palaeoreconstructions for 4400, 3000, 2000 and 1000 cal yr BP were based on the water level fluctuation curve compiled for the Tallinn area (Saarse et al. 2007) assuming that land uplift decreased linearly after the Litorina Sea transgression. Thus, presumably every time slice from the transgression maximum onwards could be modelled considering that the Litorina Sea water level lowered linearly. This assumption is in agreement with Mörner's (1979) opinion that from 7800 cal yr BP up to the present the linear factor was the main cause of the postglacial uplift in Fennoscandia. Studies of Vääna Lagoon also support such a modelling approach (Saarse et al. 2009a). Vääna Lagoon isolated from the Litorina Sea around 6800–6700 cal yr BP when the water level dropped to the threshold elevation at 18.2 m a.s.l. According to our modelling, this event happened at an elevation of 18.4 m a.s.l. So, the error is negligible and our modelling scheme seems to be accurate.

The radiocarbon dates which were used to estimate the age of the different stages of the Baltic Sea are presented in Table 1. The dates were calibrated according

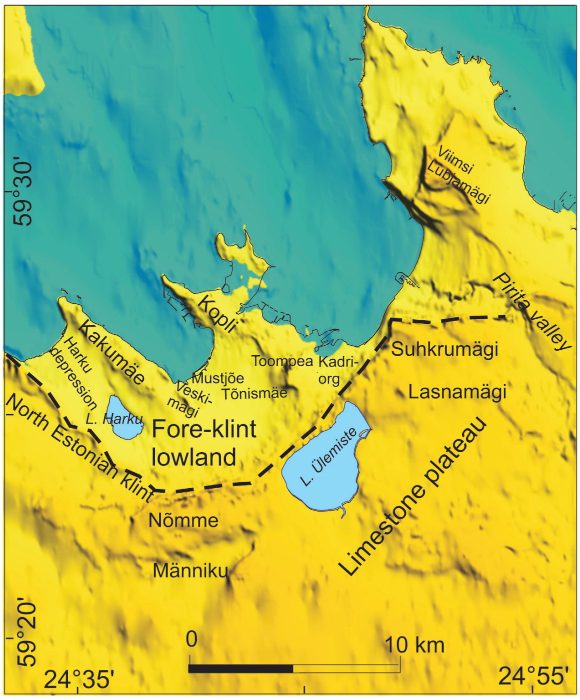

Fig. 2. Modern topography sketch of the Tallinn area.

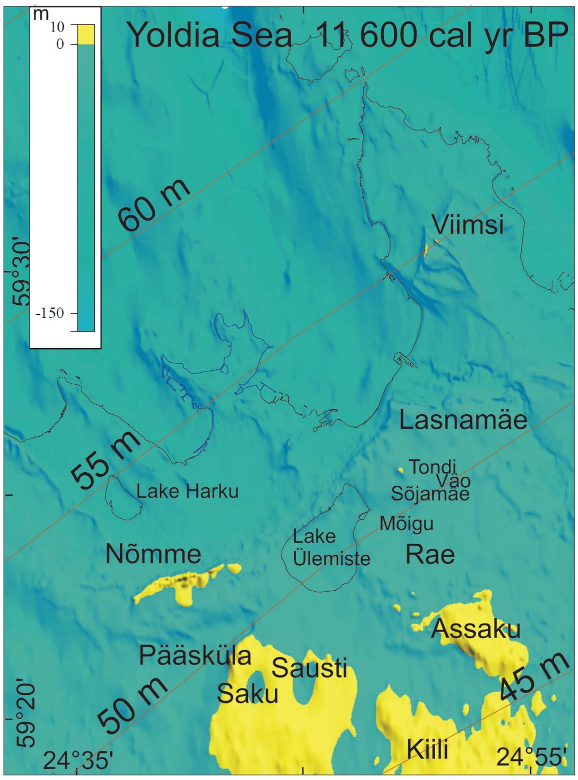

Fig. 3. Palaeogeographic reconstruction of the water level surface isobases (brown lines) and shoreline of the Tallinn area at the beginning of the Yoldia Sea stage about 11 600 cal yr BP. Reconstruction by J. Vassiljev.

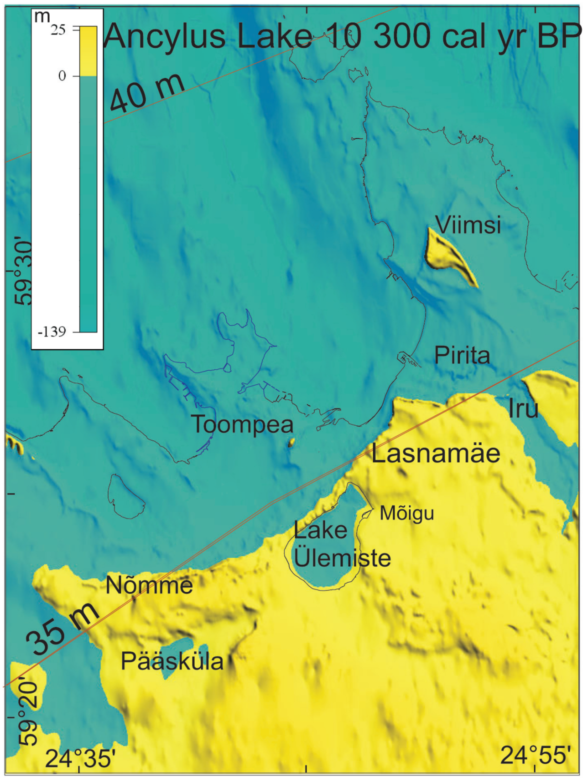

Fig. 4. Palaeogeographic reconstruction of the water level surface isobases (brown lines) and shoreline of the Tallinn area during the Ancylus Lake transgression about 10 300 cal yr BP. Reconstruction by J. Vassiljev.

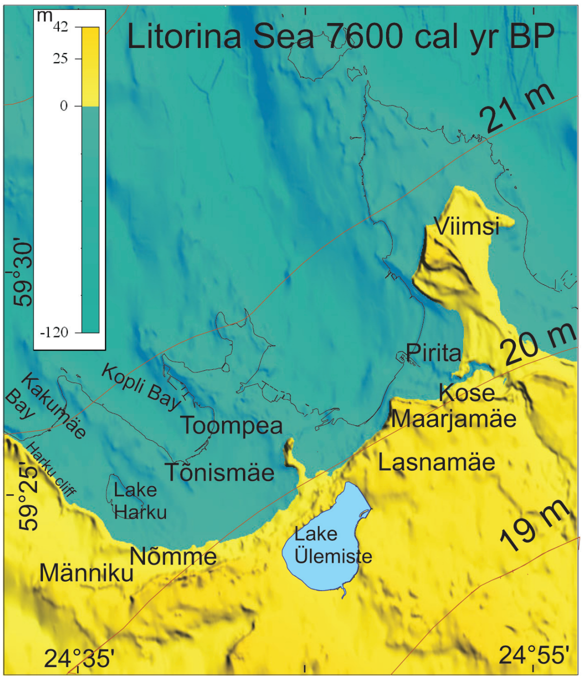

Fig. 5. Palaeogeographic reconstruction of the water level surface isobases (brown lines) and shoreline of the Tallinn area during the Litorina Sea stage about 7600 cal yr BP. Reconstruction by J. Vassiljev.

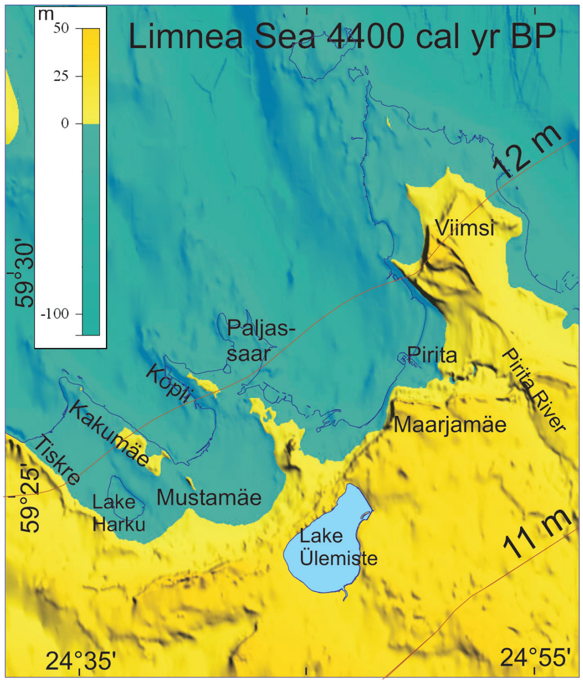

Fig. 6. Palaeogeographic reconstruction of the water level surface isobases (brown lines) and shoreline of the Tallinn area at the beginning of the Limnea Sea stage about 4400 cal yr BP. Reconstruction by J. Vassiljev.

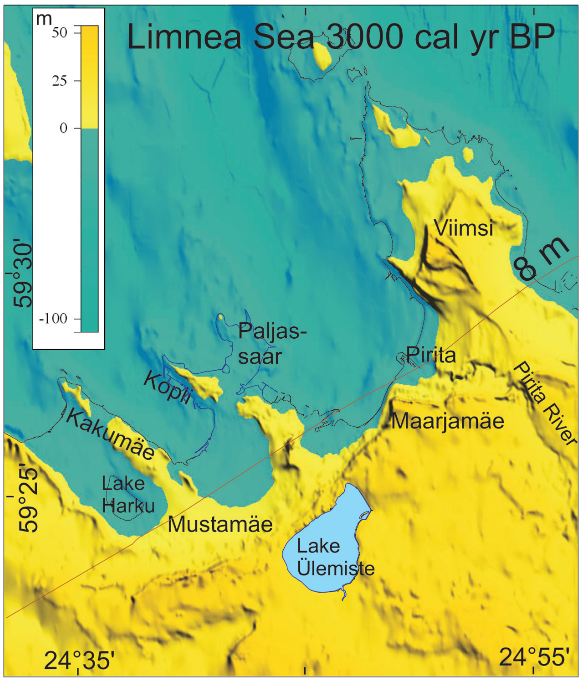

Fig. 7. Palaeogeographic reconstruction of the water level surface isobases (brown lines) and shoreline of the Tallinn area about 3000 cal yr BP. Reconstruction by J. Vassiljev.

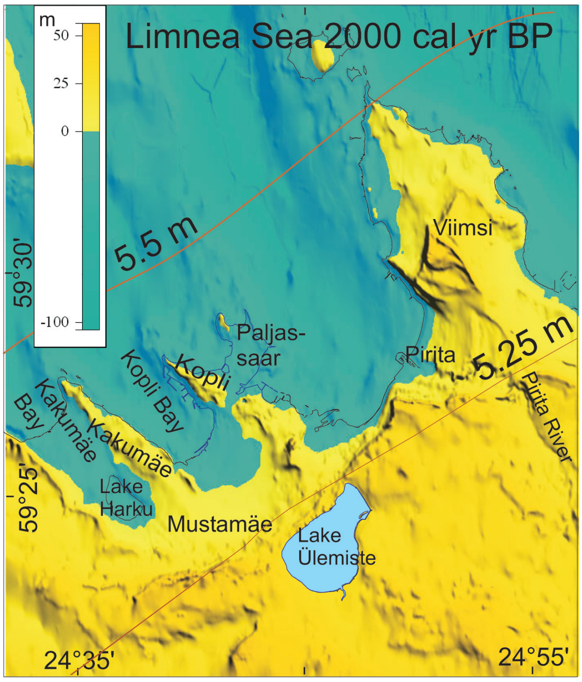

Fig. 8. Palaeogeographic reconstruction of the water level surface isobases (brown lines) and shoreline of the Tallinn area about 2000 cal yr BP. Reconstruction by J. Vassiljev.

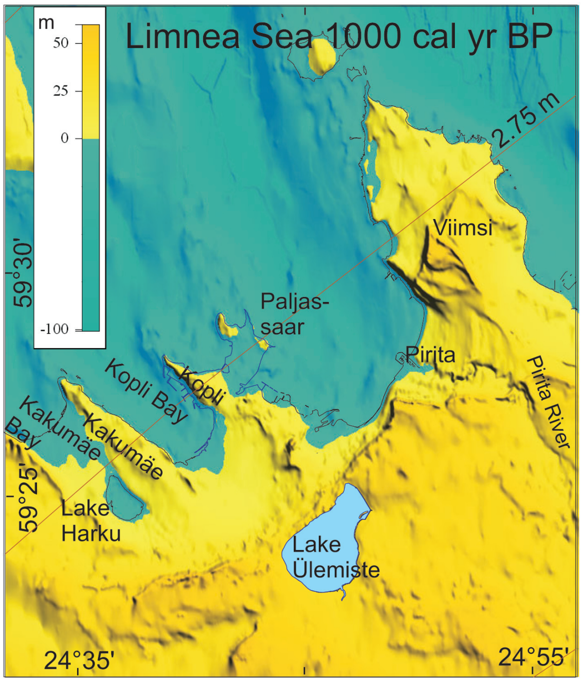

Fig. 9. Palaeogeographic reconstruction of the water level surface isobases (brown lines) and shoreline of the Tallinn area about 1000 cal yr BP. Reconstruction by J. Vassiljev.

Table 1. Radiocarbon dates of Holocene sediments, which have been considered in dating the Baltic Sea stages in the Tallinn region

Site	Depth, cm	^{14}C age	Laboratory No.	Calibrated age, cal BP	Dated material	References
Ülemiste	670–680	9145 ± 75	Tln-1861	10 315 ± 85	Peaty gyttja	Saarse et al. 1997
Ülemiste	720–730	9300 ± 80	Tln-1856	10 470 ± 170	Peaty gyttja	Saarse et al. 1997
Ülemiste	730–741	9480 ± 95	Tln-1858	10 830 ± 240	Peaty gyttja	Saarse et al. 1997
Sõjamäe	430–450	8915 ± 90	Tln-135	10 050 ± 140	Gyttja	Punning et al. 1977
Maardu	535	9490 ± 110	Ua-2390	10 830 ± 240	Wood	Veski 1998
Maardu	580–590	9655 ± 70	Tln-1313	11 000 ± 190	Gyttja	Veski 1998
Vandjala	88–93	8285 ± 75	Tln-1884	9 275 ± 135	Gyttja	Saarse et al. 1997
Saha	128–132	7635 ± 45	Tln-1916	8 445 ± 60	Gyttja	Saarse et al. 1997
Kroodi	140–150?	7730 ± 80	Tln-2668	8 500 ± 75	Buried peat	Saarse et al. 2006
Viadukti tee	145–150	2795 ± 50	Tln-2568	2 885 ± 75	Peat	Saarse et al. 2006
Lepistiku	190–193	180 ± 60	Tln-2441	175 ± 80	Peat	Saarse et al. 2001
Lepistiku	230–233	2790 ± 60	Tln-2719	2 875 ± 80	Peat	Saarse et al. 2001
Lepistiku	250–253	3780 ± 50	Tln-2504	4 160 ± 75	Peat	Saarse et al. 2001
Pääsküla mire	420–425	8640 ± 100	Ua-15322	9 630 ± 110	Seeds	Heinsalu & Veski 2007

to the calibration data set from Reimer et al. (2004) and CALIB5.0.1 software (Stuiver et al. 2005).

RESULTS AND DISCUSSION

Deglaciation pattern

During the last Weichselian glaciation the territory of Estonia was covered by a thick ice sheet, which started to withdraw from North Estonia about 13 800 cal yr BP (Saarse et al. 2009b; Amon & Saarse 2010). Because of climate amelioration in the Allerød, the ice margin retreated rather quickly. The territory of Tallinn was free of ice by 13 000–12 800 cal yr BP, considering the ice recession chronology (Kalm 2006) and the age of proglacial lakes in Estonia (Saarse et al. 2007; Rosentau et al. 2009), but was still covered by the waters of the BIL with the water level at 85–90 m a.s.l. In this large and deep glacial lake varved clays of various thicknesses deposited (up to 12 m at Mustamäe), lying now between 29 and 0 m b.s.l. in buried valleys. Varved clays lacked organic matter and terrestrial macroremains, which hampered their radiocarbon dating, but their pollen composition confirms deposition during the Allerød interstadial (Kessel & Pirrus 1983).

Palaeoenvironmental changes during the Holocene

Yoldia Sea stage (11 600–10 700 cal yr BP)

Due to ice margin retreat in central Sweden about 11 600 cal yr BP, the BIL was connected to the ocean (Andrén et al. 2007). This event was accompanied by a drastic water level lowering (25–28 m; Donner 1969, 1982; Björck & Digerfeldt 1989) and formation of the Yoldia Sea, which determines the period between the BIL drainage and the onset of Ancylus Lake. The first phase in the Yoldia Sea history was a freshwater stage due to vast amounts of meltwater supply and narrow straits at Billingen, which protected oceanic water inflow into the Baltic basin (Strömberg 1992). In the Gulf of Finland marine ingression started about 11 300 cal yr BP and lasted to ca 11 200 cal yr BP (Heinsalu & Veski 2007). After that the freshwater environment in the Yoldia Sea was re-established.

The Yoldia Sea beach formations in the Tallinn area have been documented at an altitude of 40–46 m a.s.l. (Kents 1939; Künnapuu 1959; Lepland et al. 1995). Figure 3 illustrates the coastline at the very beginning of the Yoldia Sea stage and shows the island and islets at Nõmme, Lasnamäe, Viimsi and south of the Tallinn border. Because of land uplift, islands and islets slowly enlarged their area and Sõjamäe and Tondi lagoons were outlined on the Lasnamäe limestone plateau (Lepland et al. 1995), with a short spit on the coast of Tondi Lagoon. The other spit was formed on the southeastern tip of Viimsi Island (Kessel 1961). The regressive Yoldia Sea left behind beach ridges at Viimsi, Lasnamäe and Väo and abraded escarpments into Viimsi, Lasnamäe and Harku klint slopes. By the end of the Yoldia Sea stage the water level had lowered to 28–29 m a.s.l. in the Tallinn area (Saarse et al. 1997, 2007) or even lower, considering the altitude of peat in the bottom of Lake Maardu (Veski 1998; Heinsalu 2000). Lake Ülemiste was split into two shallow water bodies (Saarse & Poska 2001) and the Yoldia Sea coastline had retreated to the pre-klint lowland. Radiocarbon-dated wood from L. Maardu and basal peaty gyttja from L. Ülemiste both evidence deposition during this low period at the end of the Yoldia Sea stage about 10 800 cal yr BP (Table 1).

Ancylus Lake stage (10 700–9800 cal yr BP)

At the onset of the Ancylus Lake stage about 10 700 cal yr BP the strait in central Sweden became closed, the connection between the Yoldia Sea and ocean was broken off and the freshwater Ancylus Lake developed in the Baltic basin (Björck 1995). Because of meltwater discharge from the still existing glacier, the water level in Ancylus Lake started to rise, reaching 34–36 m a.s.l. in the surroundings of Tallinn (Ramsay 1929; Tammekann 1934; Kents 1939). The transgression reached its maximum, 8–10 m, around 10 300 cal yr BP. The water level rise resulted in widespread erosional processes and accumulation of beach formations, which consisted of shingle, calcareous gravel and sand containing mollusc shells of *Ancylus fluviatilis*, *Bithynia tentaculata*, *Radix ovata*, etc. (Kessel 1965; Kessel & Raukas 1967). The highest shoreline of Ancylus Lake bordered the Lasnamäe limestone plateau and extended along the dune ridge west of L. Ülemiste and the Nõmme sandy plain slope, in general following the klint escarpment (Fig. 4). Viimsi and Toompea were still islands. The limestone plateau served as dry land with water bodies in the Ülemiste, Männiku and Pääsküla basins (Fig. 4). The coastline was slightly curving, with bays at the Pirita River mouth reaching deep into the mainland and in the depression west of Nõmme and Pääsküla (Fig. 4). By the end of the Ancylus Lake stage these bays were closed and Viimsi and Toompea islands merged with the mainland. The fore-klint lowland was still inundated by deep water, shoaling towards the south.

Litorina Sea stage (9800–4400 cal yr BP)

At 9800–9500 cal yr BP the Baltic Sea obtained a permanent connection with the ocean through the Danish Straits, marking the start of the Litorina Sea stage (Berglund et al. 2005). This phase was earlier named the Mastogloia Sea stage (Hyvärinen 1988; Hyvärinen et al. 1988), later as the Initial Litorina Sea stage with several brackish-water pulses (Andrén et al. 2000) or the Early Litorina Sea (Berglund et al. 2005). From 8500 cal yr BP onwards a truly brackish Litorina Sea developed and the marine gastropod *Littorina littorea* inhabited the Baltic basin. During the transgression maximum the Litorina Sea left behind sediments, escarpments and beach ridges at 21–22 m a.s.l. in the Tallinn area. The exact age of the transgression maximum in the Tallinn area is not known due to lack of appropriate radiocarbon dates. However, peat at Kroodi (12 km east of Tallinn), buried under the Litorina Sea beach ridge (Orviku 1936), was dated to 7730±80 ^{14}C BP (8500±75 cal yr BP; Saarse et al. 2003a; Table 1), which indirectly indicates that the Litorina Sea transgression in the Tallinn area started later than 8500 cal yr BP. In Saaremaa Island the Litorina Sea transgression started about 8200 cal yr BP and culminated between 7800 and 7700 cal yr BP (Saarse et al. 2009c). These ages are similar to that obtained in the eastern part of the Gulf of Finland (Miettinen 2002).

Our modelling scheme assumes one Litorina Sea transgression, however, it is not clear whether there was one (Miettinen 2002; Saarse et al. 2009a, 2009c), two (Sandgren et al. 2004) or several waves (Yu et al. 2007). Still, bio- and chronostratigraphical evidences from the Väana site (25 km west of Tallinn), which lies at a similar isobase to that of Tallinn, suggest the occurrence of only one transgression between 8000 and 7000 cal yr BP (Saarse et al. 2009a). It could be the case that two- or threefold transgressions are not reflected in sites which lie above the 18–20 m Litorina Sea isobase, in contrast to the areas below it, where a threefold Litorina Sea trasgression was suggested (Lepland et al. 1996). However, small-scale water level changes, not transgressions involving the whole Baltic basin, could cause these fluctuations (Eronen 1974; Hyvärinen 1988). The water level curve for the North Sea shows the ocean level rise during the last 7500 cal yr BP with several smaller, 0.5–1 m fluctuations (Behre 2007).

Figure 5 displays the Litorina Sea coastline at 7600 cal yr BP. This time was chosen to show the merger of Toompea Hill with the mainland. At that time the coastline ran parallel to the Lasnamäe klint escarpment in the northeast, encompassed the Toompea and Tõnismäe bedrock hill slopes and turned towards the southwest and west in front of the Nõmme sandy plain (Fig. 5). Toompea with Tõnismäe and Viimsi elevations formed elongate capes in the Litorina Sea (Fig. 5). The Litorina Sea beach ridges are less developed than the Ancylus Lake ones and frequently buried by aeolian sands. In ancient valleys the Litorina Sea sediments are located between 11 and 2 m b.s.l., on the Litorina Sea terrace – between 12 and 22 m a.s.l.

Limnea Sea stage (4400 cal yr BP–present)

Coastal formations at an elevation of 12–13 m a.s.l. have been described in Tallinn by Tammekann (1934) and connected with the Limnea Sea development. The boundary between the Litorina and Limnea seas has been placed at 4000 ^{14}C years (Kessel 1965; Donner 1995; Miettinen 2002), on the basis of the immigration of the freshwater mollusc *Radix peregra* (previously known as *Lymnaea peregra*) into the Baltic basin (Kessel 1965). In the latest publications the last stage of the Baltic Sea was named Post-Litorina stage, which started about 2750 cal yr BP with the decrease in diatom assemblages that require marine environment (Andrén et al. 2000). The Limnea Sea in the Tallinn area was regressive throughout its development, creating a shelving coastal zone. At present the sea intensively abrades the klint escarpment on the tip of the Kakumäe Peninsula which retreats at a rate of 10 cm per year, during stormy years even farther (Suuroja 2006). Fine-grained sand and silt are typical deposits of the Limnea Sea; coastal deposits are coarser. Sands of the Limnea Sea were often removed during construction works or coated by a 0.5–1 m, in several places up to 8–15 m thick cultural layer (Zobel 2008).

The Limnea Sea coastline was modelled at different time slices (Figs 6–9). Kakumäe and Kopli islands and several small islets emerged at the beginning of the Limnea Sea stage (4400 cal yr BP, Fig. 6) and joined with the mainland at different times: Kakumäe Island ca 2800 cal yr BP (Fig. 7) and Kopli Island about 1000 years later (Fig. 8). The last impressive change in the Tallinn coastline occurred about 100 years ago, when Paljassaar Island merged with the Kopli Peninsula (Saarse & Vassiljev 2008). Aeolian processes were rather common on the shelving coast of the Limnea Sea, coating peat in several places of Tallinn. Buried peat deposits at Mustamäe (16.2–17 m a.s.l) started to develop ca 5400 cal yr BP and were covered by sand rather lately, ca 180 years ago, and peat at the Järvevana site was buried by sand about 400 cal yr BP (Saarse et al. 2001, 2006). Aeolian processes are still active at some spots on the Nõmme sandy plain.

CONCLUDING REMARKS

- The Tallinn area has disjointed topography, inherited from the glacial exaration and accumulation, marine abrasion and accumulation and aeolian processes. The altitude of the terrain is between zero and 63.6 m a.s.l.
- The area surrounding Tallinn was recovered from the last ice sheet by 13 000–12 800 cal yr BP, but during the following 1500 years was inundated by the waters of the Baltic Ice Lake (BIL).
- The highest parts of Tallinn emerged from the sea during the drainage of the BIL about 11 600 cal yr BP. Coastal formations related to the Yoldia Sea have been described at an altitude of 40–46 m a.s.l.
- During the Ancylus Lake transgression about 10 300 cal yr BP the highest coastline followed the klint escarpment and slopes of the Nõmme and Männiku sandy plain at 34–36 m a.s.l. During the Ancylus Lake regression Toompea and Viimsi islands merged with the mainland.
- The Litorina Sea coastline runs close to Ancylus Lake, however, at a 12–13 m lower altitude, about 21–22 m a.s.l. The Toompea and Viimsi elevations stretched north as capes. Litorina Sea beach formations are less developed than those of Ancylus Lake and often covered by aeolian deposits.
- During the Limnea Sea stage land increased mostly on the back of Kakumäe and Kopli bays. The area of the Viimsi Peninsula enlarged considerably. Kakumäe Island joined with the mainland about 2800 cal yr BP, Kopli – ca 1000 years later. Paljassaar was the latest peninsula to be formed about 100 years ago.

Acknowledgements. We express our thanks to Siim Veski for reading the manuscript and for valuable comments. T. Hang and R. Guobytė are acknowledged for critical remarks and suggestions. The study was supported by the Estonian Ministry of Education and Research (project SF0332710s06) and the Estonian Science Foundation (grant 6736).

REFERENCES

Amon, L. & Saarse, L. 2010. Late glacial palaeoenvironmental changes in North Estonia. *Geological Quarterly*, **54**, 85–94.

Andrén, E., Andrén, T. & Sohlenius, G. 2000. The Holocene history of the southwestern Baltic Sea as reflected in a sediment core from the Bornholm Basin. *Boreas*, **29**, 233–250.

Andrén, T., Lindeberg, G. & Andrén, E. 2002. Evidence of the final drainage of the Baltic Ice Lake and the brackish phase of the Yoldia Sea in glacial varves from the Baltic Sea. *Boreas*, **31**, 226–238.

Andrén, T., Andrén, E., Berglund, B. E. & Yu, S.-Y. 2007. New insight on the Yoldia Sea low stand in the Blekinge archipelago, southern Baltic Sea. *GFF*, **129**, 277–285.

Behre, K.-E. 2007. A new Holocene sea-level curve for the southern North Sea. *Boreas*, **36**, 82–102.

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

Berglund, B. E., Sandgren, P., Barnekow, L., Hannon, G., Jiang, H., Skog, G. & Yu, S.-Y. 2005. Early Holocene history of the Baltic Sea, as reflected in coastal sediments in Blekinge, southeastern Sweden. *Quaternary International*, **130**, 111–139.

Björck, S. 1995. A review of the history of the Baltic Sea, 13.0–8.0 ka BP. *Quaternary International*, **27**, 19–40.

Björck, S. & Digerfeldt, G. 1989. Lake Mullsjön – A key site for understanding the final stage of the Baltic Ice Lake east of Mt. Billingen. *Boreas*, **18**, 209–219.

Donner, J. 1969. Land/sea level changes in southern Finland during the formation of the Salpausselkä endmoraines. *Bulletin, Geological Society of Finland*, **41**, 135–150.

Donner, J. 1982. Fluctuations in water level of the Baltic Ice Lake. *Annales Academiae Scientiarum Fennicae, AIII*, **134**, 13–28.

Donner, J. 1995. *The Quaternary History of Scandinavia*. Cambridge University Press, Cambridge, 200 pp.

Eronen, M. 1974. The history of the Litorina Sea and associated Holocene events. *Societas Scientiarum Fennica, Commentationes Physico-Matematicae*, **44**, 79–195.

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 climate oscillations. *Geological Quarterly*, **51**, 295–306.

Hyvärinen, H. 1988. Definition of the Baltic stages. *Annales Academiae Scientiarum Fennicae, AIII, Geologica-Geographica*, **148**, 7–11.

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, AIII, Geologica-Geographica*, **148**, 25–35.

Jakobsson, M., Björck, S., Alm, G., Andrén, T., Lindeberg, G. & Svensson, N.-O. 2007. Reconstructing the Younger Dryas ice dammed lake in the Baltic Basin: bathymetry, area and volume. *Global and Planetary Change*, **57**, 355–370.

Kalm, V. 2006. Pleistocene chronostratigraphy in Estonia, southeastern sector of the Scandinavian glaciation. *Quaternary Science Reviews*, **8**, 960–975.

Kents, P. 1939. *Postglatsiaalsed Läänemere randjoone võnkumised 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, 60 pp. [in Estonian].

Kessel, H. 1961. Über die Entwicklung der Ostsee in Bereich des Territoriums der Estnischen SSR im Holozän. *Eesti NSV Geoloogia Instituudi Uurimused*, **VII**, 167–185 [in Estonian, with German summary].

Kessel, H. 1965. History of the study of the Limnea and Mya stages of the Baltic and the stratigraphy of the Limnea stage on the territory of the Estonian S.S.R. *Baltica*, **2**, 21–45 [in Russian, with English summary].

Kessel, H. 1979. Ülemiste järve geoloogilisest arengust ja tema setete vanusest [Geological development of the Ülemiste Lake and the age of its deposits]. In *Eesti NSV saarkõrgustike ja järvenõgude kujunemine* [*Formation of Insular Heights and Lake Depressions of the Estonian SSR*] (Raukas, A., ed.), pp. 154–160. Valgus, Tallinn [in Estonian, with English summary].

Kessel, H. & Pirrus, R. 1983. Some problems concerning stratigraphic subdivision of Estonian late glacial sediments on the basis of palynologic data. In *Palynologiya v geologicheskikh issledovaniyakh Pribaltiki i Baltijskogo morya* [*Palynologic Researches in Geologic Studies of the Baltic Region and the Baltic Sea*] (Bartosh, T., ed.), pp. 14–17. Zinatne, Riga [in Russian, with English summary].

Kessel, H. & Raukas, A. 1967. *The Deposits of Ancylus Lake and Littorina Sea in Estonia*. Valgus, Tallinn, 134 pp. [in Russian, 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., Vishnevskaja, E. & Sinisalu, R. 1986. Geological development of Lake Ülemiste (Tallinn, Estonian SSR). *Eesti NSV Teaduste Akadeemia Toimetised, Geoloogia*, **35**, 35–41 [in Russian, with English summary].

Künnapuu, S. 1959. Rannamoodustused Tallinnas [The coast configurations at Tallinn]. *Loodusuurijate Seltsi Aastaraamat 1958*, **51**, 301–314 [in Estonian, with English summary].

Künnapuu, S. 1975. Tallinna ja selle ümbruse geomorfoloogiline liigestus. [The geomorphological subdivision of Tallinn and its environs into districts]. *Loodusuurijate Seltsi Aastaraamat*, **63**, 18–39 [in Estonian, with English summary].

Künnapuu, S. & Raukas, A. 1976. Pinnamood ja pinnakate [Relief and Quaternary cover]. In *Tallinna ajalugu 1860-ndate aastateni* [*The History of Tallinn up to the 1860s*] (Pullat, R., ed.), pp. 20–36. Eesti Raamat, Tallinn [in Estonian].

Künnapuu, S., Raukas, A. & Tavast, E. 1981. The bedrock relief of Tallinn and its vicinity. *Eesti NSV Teaduste Akadeemia Toimetised, Geoloogia*, **30**, 167–172 [in Russian, with English summary].

Lampe, T. 2005. Lateglacial and Holocene water-level variations along the NE German Baltic coast: review and new results. *Quaternary International*, **133–134**, 121–126.

Lepland, A., Miller, U. & Sakson, M. 1995. Palaeoenvironmental conditions during the Baltic Yoldia stage in Tallinn area, northern Estonia. *Quaternary International*, **27**, 83–94.

Lepland, Aivo, Hang, T., Kihno, K., Sakson, M., Sandgren, P. & Lepland, Aave. 1996. Holocene sea-level changes and environmental history in the Narva area, North-Eastern Estonia. *PACT*, **51**, 313–358.

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.

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

Munthe, H. 1910. Studies in the Late-Quaternary history of southern Sweden. *Geologiska Föreningens I Stockholm Förhandlingar*, **32**, 1197–1292.

Munthe, H. 1940. *On the Late-Quaternary Development and the Stone Age Settlement of North Europe, Primarily to the Baltic*. Almquist & Wiksell, Stockholm, 242 pp.

Orviku, K. 1936. Litoriina randvalli geoloogiast Kroodi oru kohal [On the geology of the beach ridge above the Kroodi valley]. *Eesti Loodus*, 2, 61–63 [in Estonian].

Punning, J.-M., Rajamäe, R., Ehrenpreis, M. & Sarv, L. 1977. Tallinn radiocarbon dates IV. *Radiocarbon*, **19**, 111–117.

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., Bertrand, C., Blackwell, P. G., Buck, C. E., Burr, G., Cutler, K. B., Damon, P. E., Edwards, R. L., Fairbanks, R. G., Friedrich, M., Guilderson, T. P., Hughen, K. A., Kromer, B., McCormac, F. G., Manning, S., Bronk Ramsey, C., Reimer, R. W., Remmele, S., Southon, J. R., Stuiver, M., Talamo, S., Taylor, F. W., van der Plicht, J. & Weyhenmeyer, C. E. 2004. IntCal04 terrestrial radiocarbon age calibration, 0–26 cal kyr BP. *Radiocarbon*, **46**, 1029–1058.

Rosentau, A., Vassiljev, J., Hang, T., Saarse, L. & Kalm, V. 2009. Development of the Baltic Ice Lake in eastern Baltic. *Quaternary International*, **206**, 16–23.

Saarse, L. & Poska, A. 2001. Ülemiste järve tekke- ja arengulugu [The story of the formation and development of

Lake Ülemiste]. In *Inimmõju Tallinna keskkonnale IV* [*Human Impact on the Environment of Tallinn IV*] (Eensaar, A., ed.), pp. 39–46. Teaduslik-rakendusliku konverentsi materjalid. Tallinna Botaanikaaed, Tallinn [in Estonian].

Saarse, L. & Vassiljev, J. 2008. Kopli ja Paljassaare poolsaar olid veel hiljaaegu saared [Kopli and Paljassaar were lately islands]. *Eesti Loodus*, 10, 16–19 [in Estonian].

Saarse, L., Heinsalu, A., Poska, A., Veski, S., Rajamäe, R., Hiie, S., Kihno, K. & Martma, T. 1997. Early Holocene shore displacement of the Baltic Sea east of Tallinn (N Estonia). *Baltica*, **10**, 13–24.

Saarse, L., Veski, S. & Miidel, A. 2001. Lepistiku buried peat, Tallinn, Estonia. *Proceedings of the Estonian Academy of Sciences, Geology*, **50**, 128–134.

Saarse, L., Miidel, A. & Vassiljev, J. 2003a. The role of K. Orviku in the studies of the Litorina transgression in Estonia. In *Human Impact and Geological Heritage. Excursion Guide and Abstracts* (Raukas, A. & Kukk, H., eds), pp. 115–117. Institute of Geology at Tallinn Technical University, Tallinn.

Saarse, L. Vassiljev, J. & Miidel, A. 2003b. 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., Vassiljev, J., Rosentau, A. & Miidel, A. 2007. Reconstructed late glacial shore displacement in Estonia. *Baltica*, **20**, 35–45.

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

Saarse, L., Niinemets, E., Amon, L., Heinsalu, A., Veski, S. & Sohar, K. 2009b. Development of the late glacial Baltic basin and the succession of vegetation cover as revealed at Palaeolake Haljala, northern Estonia. *Estonian Journal of Earth Sciences*, **58**, 317–333.

Saarse, L., Vassiljev, J. & Rosentau, A. 2009c. Ancylus Lake and Litorina Sea transition on the Island of Saaremaa, Estonia: a pilot study. *Baltica*, **22**, 51–62.

Sandgren, P., Subetto, D. A., Berglund, B., Davydova, N. N. & Savelieva, L. A. 2004. Mid-Holocene Littorina Sea transgressions based on stratigraphic studies in coastal lakes of NW Russia. *GFF*, **126**, 363–380.

Strömberg, B. 1992. The final drainage of the Baltic Ice Lake. *Sveriges Geologiska Undersökningar*, **Ca 81**, 347–353.

Stuiver, M., Reimer, P. J. & Reimer, R. 2005. *CALIB Radiocarbon Calibration (HTML Version 5.0)*. http://radiocarbon.pa.qub.ac.uk/calib/

Suuroja, K. 2006. *Baltic Klint in North Estonia as a Symbol of Estonian Nature*. Ministry of Environment, Tallinn, 224 pp.

Tammekann, A. 1934. Tallinna aseme pinnamoest [On the topography of Tallinn]. *Eesti Loodus*, 2, 34–37 [in Estonian].

Tammekann, A. 1940. *The Baltic Glint*. Eesti Loodusteaduste Arhiiv, **XI**, 3–4, Tartu, 103 pp.

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

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.

Zobel, R. 2008. *Tallinn (Reval) in the Middle Ages: Town Building in the 13th–14th Centuries*. Tallinn Academy of Arts. Tallinn, 190 pp.

Tallinna linnaaseme holotseensed rannajooned

Leili Saarse ja Jüri Vassiljev

Maakoore neotektoonilise kerke ja veetaseme muutuste tõttu Läänemeres on Tallinna linnaaseme rannajoon oluliselt muutunud. Neid muutusi on illustreeritud seitsme paleogeograafilise kaardiga.