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# Reconstruction of the land–sea changes on the Juminda Peninsula, North Estonia, during the last 10 300 years

***Leili Saarse, Jüri Vassiljev, Atko Heinsalu***

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**Abstract** New results of litho–, bio– and chronostratigraphic data from the Aabla Bog were used for creation of the GIS–based shore displacement model with a grid size of 50 x 50 m. Palaeogeographical maps for the Juminda Peninsula in northern Estonia were constructed for the last 10 300 years. The southern part of the peninsula had emerged from the waters of the Gulf of Finland before the Ancylus Lake transgression. The highest shorelines between 18.5 and 20.5 m above sea level (a.s.l.) formed during the Litorina Sea transgression at about 7800 calibrated years BP (cal. yr BP). After the Litorina Sea transgression the area of the peninsula enlarged mostly northwards and westwards due to land uplift. Diatom stratigraphic analysis indicates deposition of sand in an isolated shallow freshwater lake, not in a lagoon of the Litorina Sea, as was concluded earlier, and suggests that the Litorina Sea maximum water level was below the Aabla basin threshold elevation at 21–21.5 m a.s.l.

***Keywords*** *Litorina Sea, palaeogeography, diatoms, radiocarbon dates, shoreline displacement, North Estonia.*

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## INTRODUCTION

The problems concerning the Baltic Sea shoreline and sea level as well as palaeoenvironmental changes have been in the focus of research for a long time (e.g. Munthe 1910; Berglund 1964, 1971; Kessel, Raukas 1979; Björck 1995; Eronen *et al.* 2001). In the circum–Baltic Sea areas relative sea level rise was primarily governed by global sea–level rise and isostatic uplift (e.g. Fairbridge 1960; Ekman 1996; Uścinowicz 2006) due to melting of the ice–sheet and decrease in the global ice volume (Peltier 2002). Northern areas around the Baltic Sea experienced isostatic uplift and sea level regression, whereas isostatic subsidence in the southern areas caused transgressions. Owning to isostatic uplift ancient beach formations, lagoons and coastal lakes remained at different levels, and their deposits have been widely used to reconstruct the water level changes and shore displacement curves (e.g. Berglund 1971; Kessel, Raukas 1979; Svensson 1989; Björck 1995; Miettinen 2002; Gelumbauskaitė 2009). After deglaciation northern and western Estonia underwent rapid uplift, up to 26 mm $\text{yr}^{-1}$ (Kessel, Miidel 1973), which at present has slowed down to 2–2.8 mm $\text{yr}^{-1}$ (Torim 2004).

In Estonia the early post–glacial history of the Baltic Sea from Baltic Ice Lake through the Yoldia Sea to Ancylus Lake has been discussed in numerous recent publications (e.g. Saarse *et al.* 2003, 2007; Vassiljev *et al.* 2005; Veski *et al.* 2005; Heinsalu, Veski 2007; Rosentau *et al.* 2009), but the development of the Litorina Sea has received little attention (Saarse *et al.* 2009a). Episodic saline water ingression into the Baltic Sea basin started about 9800 cal yr BP (Eronen *et al.* 1990; Andrén *et al.* 2000), however, significant rise in salinity occurred between 8500 and 8000 cal. yr BP, marking the onset of the Litorina Sea (Andrén *et al.* 2000; Berglund *et al.* 2005). The development of fully brackish water conditions in the Baltic Sea basin was a time–transgressive process that lasted several hundred years (Hyvärinen *et al.* 1988; Kunzendorf, Larsen 2009). The onset of the Litorina Sea in the area of the Gulf of Finland coincides with the transgression that resulted from the rising global ocean level. After the Litorina Sea transgression several islands emerged in the southern part of the Gulf of Finland.

Later they joined with the mainland and formed the present winding North Estonian coastline with several peninsulas, which are separated from each other by 'klint' bays[1]. The development of these peninsulas has been discussed in several publications (Tammekann 1940; Kessel 1968; Linkrus 1976). Palaeogeographic maps have been compiled for some of them (Linkrus 1998; Saarse, Vassiljev 2010), however, not for the Juminda Peninsula.

The current study aims to create and provide a 3D model for constructing palaeogeographical maps of the Juminda Peninsula in order to increase our knowledge of the development of North Estonian peninsulas and adjust the start of the Litorina Sea transgression in the study area. For these purposes the sediment core from the Aabla Bog was examined, because earlier studies have considered the Aabla basin as a Litorina Sea lagoon.

## GEOLOGICAL SETTING

Juminda with variegated landscapes is one of the largest and highest peninsulas of North Estonia (Fig. 1). The bedrock is composed by Ediacarian and Cambrian claystones and sandstones and is covered by up to 50-100 m thick Quaternary sediments. The rather uneven bedrock surface is intersected by a 150 m deep ancient valley. Modern landforms are derived from glacial erosion and accumulation and have been reshaped by waters of Ancylus Lake and the Litorina and Limnea seas, which left behind numerous beach ridges, spits, bars, scarps and terraces.

The main beach ridge system is originated from the Litorina Sea transgression in the western part of the peninsula at about 19-20 m a.s.l. Numerous small beach ridges and bars in the south–western corner of the peninsula alternate with swampy hollows running parallel to each other and to the present shoreline. These ridges were most likely formed during the heavy storms when the sea level rose above its usual average level. Beach ridges and dunes are more or less transverse to the direction of drainage, playing thus an important role as a damming factor, described also on the Öland Island (Königsson 1968). Several beach ridges have been reworked by wind and form numerous dunes in the western and southern parts of the peninsula. Picturesque sandy beaches are common in the south–western coast of Juminda, where sand covers also the seafloor forming appreciable resources of bottom sand (Suuroja *et al*. 2007).

## STUDY SITE AND METHODS

To determine the onset of the Litorina Sea transgression the sediments of the Aabla Bog were sampled in autumn 2009. Aabla is a raised bog (59°34´09´´N, 25°34´38´´E, 356 ha in area) in the central part of the Juminda Peninsula at 24 m a.s.l. bordered by the Litorina Sea beach formations (Fig. 2). The threshold of the basin at 21-21.5 m a.s.l. is covered by sand and can partly be eroded. The catchment of the bog is inhabited, covered by *Pinus–Betula–Picea* stands and dry *Pinus* woods on dunes and beach ridges. Undisturbed one meter long cores were taken from the central part of the bog with

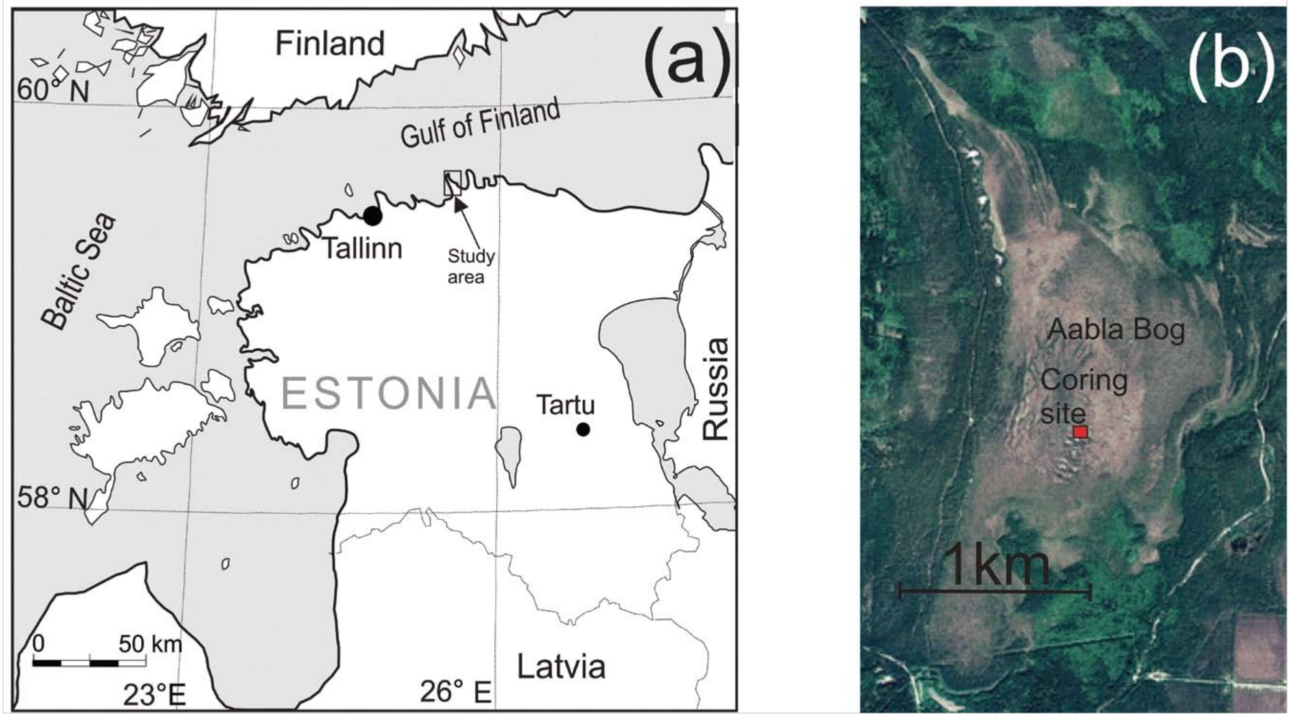

Fig. 1. Location of the study area (a) and sampling site in the Aabla Bog (b). Compiled by L. Saarse.

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[1] The term "klint" bay was suggested by A. Tammekann (1940) to mark bays in the North Estonian klint escarpment which were formed between the klint headlands. Most of them are now fulfilled with sediments.

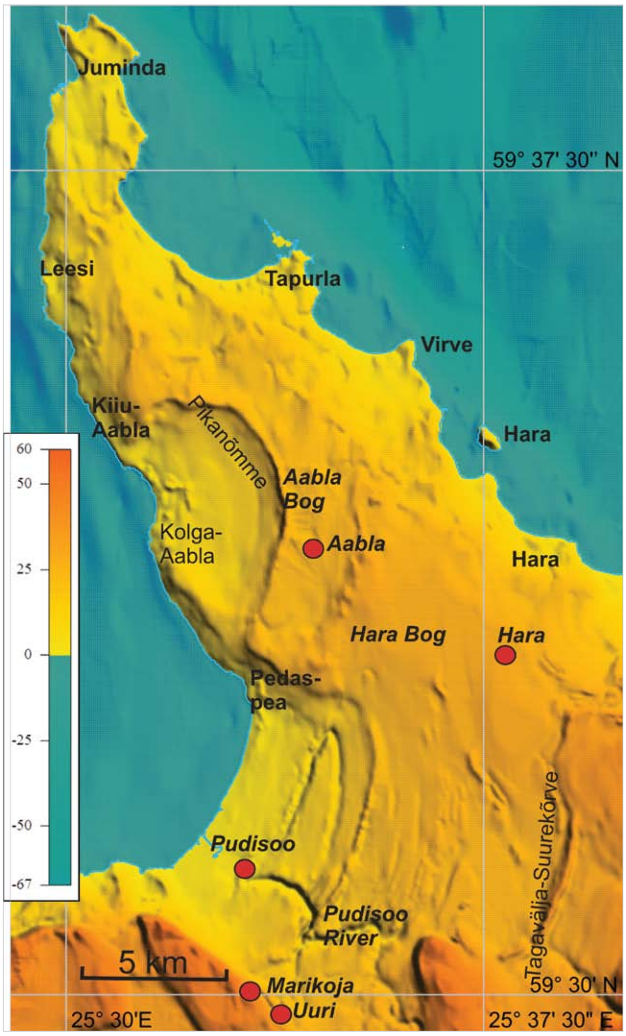

Fig. 2. Modern topography of the Juminda Peninsula with indication of the sites discussed in text (red circles). Compiled by J. Vassiljev.

a Russian peat sampler. The sediments were described in the field, photographed, put into plastic half tubes and transported to the laboratory.

In the frame of the current study diatoms were analysed, loss–on–ignition (LOI) and grain size composition determined and three radiocarbon dates obtained. Conventional radiocarbon dating of the bulk gyttja sediment sample was performed in the Institute of Geology at Tallinn University of Technology. The accelerator mass spectrometry (AMS) $^{14}$C dates of a wood remain and the date of a bulk sediment sample from organic–rich sand were obtained at the Poznan Radiocarbon Laboratory. The radiocarbon dates were converted to calibrated years before present (cal. yr BP) at one sigma range by using the *IntCal04* calibration curve (Reimer *et al*. 2004) and the *Calib Rev 5.0.1.* programme (Stuiver *et al*. 2005). The organic matter (OM) and carbonate contents were determined by LOI at 525 °C for 4 h and at 900 °C for 2 h, respectively. The residue containing terrigenous matter and biogenic silica was described as mineral matter and calculated against the sum of OM and carbonates. The measurements were performed on continuous one cm thick sub–samples.

For diatom analysis sediment samples were subjected to sequential treatment with 30% $H_2O_2$ and 10% HCl in order to remove OM and carbonates, respectively. Thereafter coarse mineral particles were removed by repeated decantation. A few drops of a cleaned sub–sample were dried onto the cover glass and mounted on slides in *Naphrax* medium and analysed for microfossils under a *Zeiss Axio Imager A1* microscope at × 1000 magnification, using oil immersion and differential interference contrast optics. The LOI and diatom diagrams were constructed with the TGView program (Grimm 2004). Grain size distribution of terrigeneous fraction from eight samples was analysed with the *Partica Laser* scattering particle size distribution analyser LA-950V2.

The construction of palaeogeograpical maps with the grid size of 50 x 50 m was based on the GIS approach that removes the palaeo–water level from the modern digital terrain model (DTM). Topographic maps at a scale of 1:10 000 and 1:25 000 were used to create the DTM. The interpolated water level surfaces for Ancylus Lake and the Litorina Sea were derived from the databases of coastal formations and buried organic deposits (Saarse *et al*. 2003, 2006) and earlier published sources (Linkrus 1976, 1998; Kessel, Linkrus 1979) by using a point–kriging approach. Peat deposits were removed from the DTM, considering the soil maps and thickness of peat in the Hara and Aabla bogs. Assuming that land uplift decreased linearly (Mörner 1979; Yu *et al*. 2007) and global sea level remained nearly constant (Lambeck, Chappell 2001) after the Litorina Sea transgression, palaeogeographical maps from the Litorina Sea up to the present were compiled.

## RESULTS

### Sediment lithostratigraphy

The studied sediment sequence of the Aabla basin was divided into three lithostratigraphic units (Fig. 3).

Unit Aa-1, core depth 580-555 cm. The sediment is medium sand with dispersed OM and abrupt boundary with the overlaying gyttja. In the grain size composition medium and fine sand fraction prevails, forming 42-47% and 18-30%, respectively (relying on the classification of W. Last, 2001). Due to infiltrated humic acids sand is dark brown and contains 1-3% OM.

Unit Aa-2; core depth 555-540 cm. Olive-brown coarse detritus gyttja with woody remains quickly oxidized and obtained black colour. Towards the up-

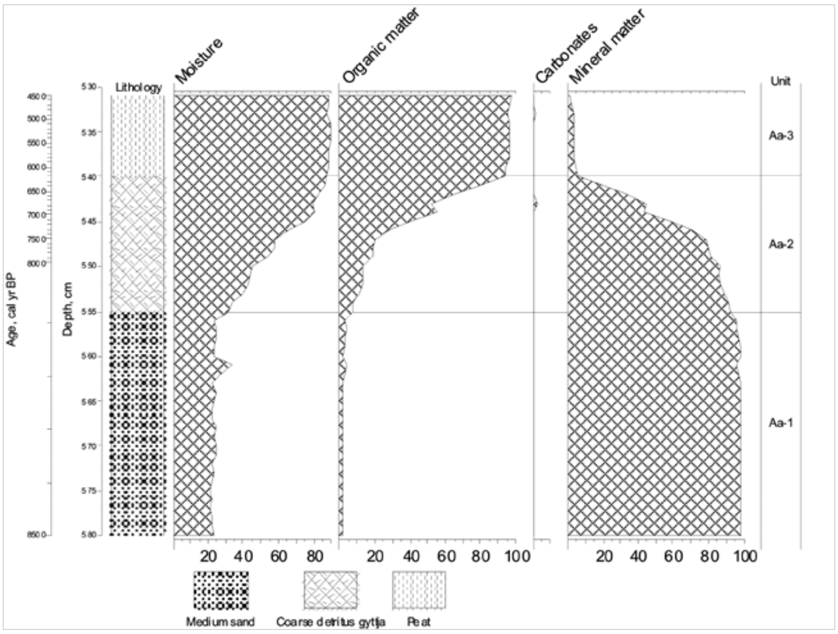

Fig. 3. Loss–on–ignition results from the Aabla sequence. Compiled by L. Saarse.

per limit of the unit OM content increases to 79% and mineral matter decreases to 20%; the content of sand in mineral matter reaches 53-71% and silt 29-47%, respectively.

Unit Aa-3, core depth 540-480 cm. Gyttja gradually grades into dark brown peat rich in OM (94-98%).

The carbonate content is very low throughout the studied sequence, commonly below 1%. The moisture curve is in good accord with OM content (Fig. 3).

## Radiocarbon dating

An unidentified wood remain from the gyttja and sand boundary at a core depth of 556 cm in the Aabla Bog sediment sequence was dated to 7280±50 $^{14}$C yr BP (8095±65 cal. yr BP), which is in good accord with the conventional radiocarbon date (7250±75 $^{14}$C yr BP; 8080±90 cal. yr BP) obtained from the basal part of the overlying gyttja (Table 1). The bulk sediment sample from the sand with dispersed OM at a depth of 571 cm was dated to 6920±40 $^{14}$C (7740±45 cal. yr BP). This age is slightly younger of overlying gyttja and the AMS $^{14}$C measurement might be influenced by penetration of younger rootlets into sand.

In earlier studies on the Juminda Peninsula pollen analyses of the Aabla and Hara raised bogs and Pudisoo ancient valley have been carried out (Kessel 1968; Kessel, Linkrus 1979). In addition, four radiocarbon dates from three different sites have been obtained (Table 1), and these were also considered in our temporal reconstructions. Radiocarbon dates from peat of the Hara Bog and wood from the Marikoja site specify the start of the Litorina Sea transgression (Table 1). Moreover, a sharp rise of the *Picea* pollen curve at the gyttja and peat boundary in the Kahala site about 10 km south–westwards from the Aabla Bog, dated to ca

Table 1. Radiocarbon datings of deposits of the Juminda Peninsula.

| Sampling site | Altitude of sample, m a.s.l. | Age $^{14}$C yr BP | Calibrated age | Lab. No. | Material | References |
|---|---|---|---|---|---|---|
| Aabla Bog | 18.75 | 7280±50 | 8160–8030 | Poz–33490 | Piece of wood | Current study |
| Aabla Bog | 18.85–18.75 | 7250±75 | 8160–8005 | Tln-3195 | Coarse detritus gyttja | Current study |
| Aabla Bog | 18.72–18.70 | 6920±40 | 7785–7695 | Poz–35465 | Sand with organic matter | Current study |
| Hara Bog | 26.5 | 7080±75 | 7975–7835 | TA–61 | Gyttja | Kessel, Linkrus 1979 |
| Uuri | 28.24–28.34 | 9230±80 | 10 390–<br>10 280 | Tln–202 | *Betula* fragment, covered by sand | Kessel , Linkrus 1979 |
| Marikoja | 17.00–17.31 | 6820±70 | 7700–7590 | TA–200 | Buried peat | Kessel, Linkrus 1979 |
| Marikoja | 17.00–17.31 | 7240±90 | 8160–7980 | TA–201 | *Pinus* fragment, covered by sand | Kessel, Linkrus 1979 |

6200 cal. yr BP (Poska, Saarse 1999), was considered to be synchronous with the increase in the *Picea* pollen curve in the Aabla pollen record.

### Diatom stratigraphy

The diatom composition of the sediment sub–samples from the basal sand represents fresh water environment (Fig. 4). Most frequent taxa are epipsammic *Cocconeis disculus* and *Martyana martyi*, epiphytic *Achnanthes clevei* and *Cocconeis placentula*, as well as epipelic *Navicula scutelloides*. All these species have wide ecological amplitude; however, their life–form suggests a very shallow coastal lake with a sandy bottom and abundant aquatic macrophytes. The absence of the brackish water diatom flora indicates that waters of the Litorina Sea did not surpass the threshold of the Aabla basin.

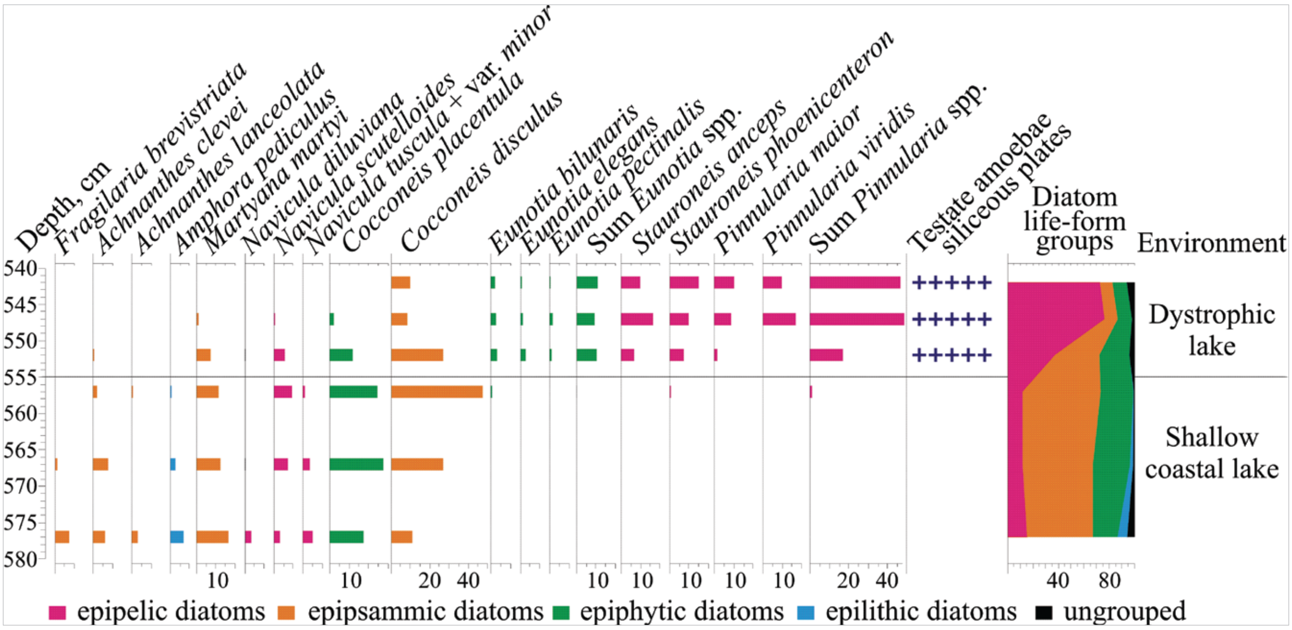

Fig. 4. Siliceous microfossil diagram from the Aabla sediment sequence. Diatoms are grouped according to their habitat. Compiled by A. Heinsalu.

A distinct change in the diatom assemblage takes place at a core depth of 555 cm that coincides with the sediment transition from sand to coarse detritus gyttja. Diatoms are often poorly preserved and part of the valves bear signs of dissolution and fragmentation. The relative abundance of epipsammic diatoms decreases, whereas that of epiphytic *Eunotia* species as well as that of epipelic *Pinnularia* and *Stauroneis* species increases. The latter diatoms prefer oligotrophic, slightly acid, soft–water, dark–coloured lakes. In addition, siliceous plates of testate amoebae appear in abundance. Siliceous protozoan plates are common in sediments associated with the development of bog vegetation, especially *Sphagnum* communities around water bodies and transition from limnic to telmatic environment (Douglas, Smol 2001). The siliceous microfossil evidence indicates that a coarse detritus gyttja layer formed in the dystrophic lake surrounded by fen.

## DISCUSSION

The landscape of the Juminda Peninsula is rather young, as this area was for a long time inundated by the waters of the Baltic Sea. The highest part of the peninsula emerged already before the Ancylus Lake transgression about 10 300 cal. yr BP. This age is deduced from the $^{14}$C date of wood (9230±80 $^{14}$C yr BP; 10 390-10 280 cal. yr BP) collected at Uuri from under the Ancylus Lake sand and gravel (Kessel, Linkrus 1979; Table 1). The shoreline of the peninsula followed the klint escarpment. In klint bays small islets and the Tagavälja–Suurekõrve spit developed, which are now positioned at 31.5 m a.s.l. and higher, isolating lagoons at Pudisoo Bay and in the Kolga River mouth (Fig. 5). Due to the Ancylus Lake regression and land uplift, the surroundings of the present–day Hara Bog emerged and Hara isolated as a coastal lake about 9000 cal. yr BP (Fig. 6). Gyttja with pollen spectra is typical of the Late Boreal chronozone deposited in this lake (Kessel, Linkrus 1979). Numerous beach bars were formed in the SW corner of the peninsula between 27 and 25 m a.s.l. (Fig. 6).

Almost half of the Juminda Peninsula had emerged from the sea by 7800 cal. yr BP. Its coastline ran along the beach ridges and dunes west of the Aabla coastal

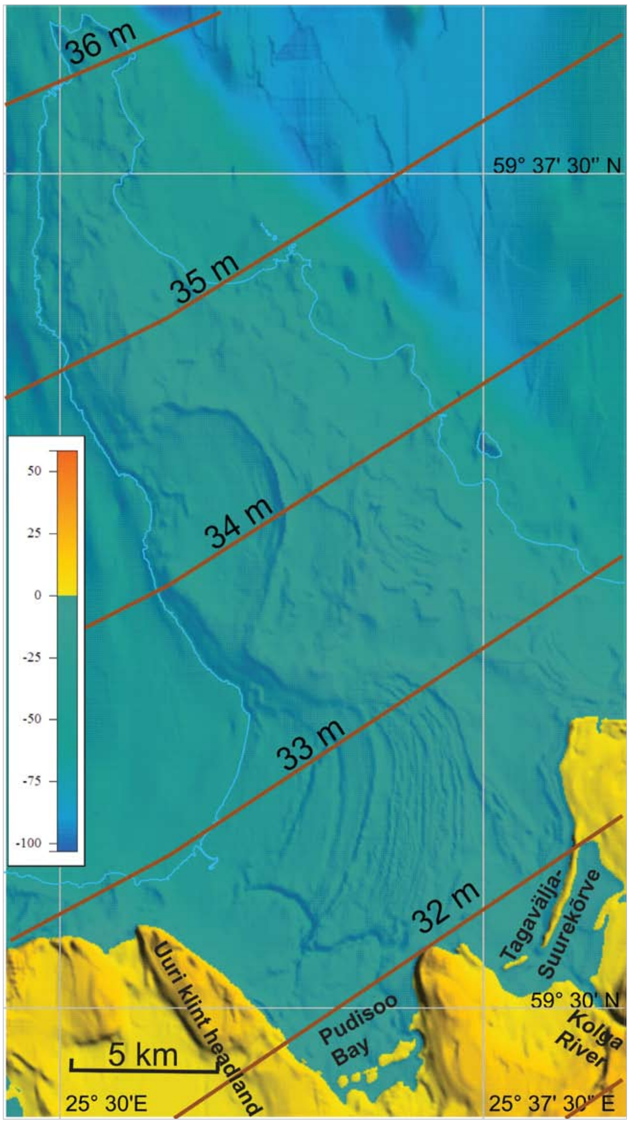

Fig. 5. 3D reconstruction of the Juminda Peninsula during the transgression of Ancylus Lake about 10 300 cal. yr BP. Brown lines are the water level surface isobases. Compiled by J. Vassiljev.

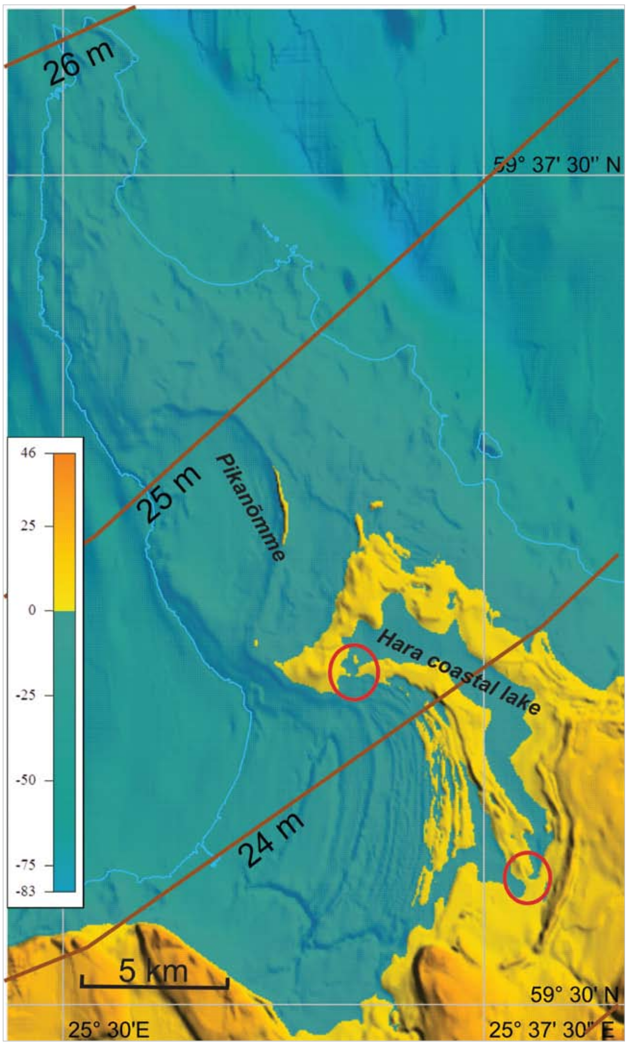

Fig. 6. 3D reconstruction of the Juminda Peninsula during the isolation of the Hara basin about 9000–8900 cal. yr BP before the transgression of the Litorina Sea. Water level surface isobases are indicated by brown lines, the positions of thresholds are shown by red circles. Compiled by J. Vassiljev.

lake and stretched towards the northwest as a long elongated cape that was attached to the main part of the peninsula by a narrow neck (tombolo). The coastline was winding, with small islands and sea arms (Fig. 7). At the highest level of the Litorina Sea around 7800 cal. yr BP, transverse spits were formed in the western part of the peninsula, scarps at 19 m a.s.l. and 20-21 m a.s.l. were abraded and coastal dunes were blown up, now reaching to 33 m a.s.l. at Pikanõmme.

The Aabla basin was a dystrophic lake surrounded by expanding fen. Coarse detritus gyttja accumulated in the lake especially rich in *Alnus* pollen (30-32%; Kessel, Linkrus 1979), probably due to the expansion of water bodies rimmed by *Alnus* stand and the rising Litorina Sea level. The age of the wood 8070±90 cal. yr BP (Table 1) at the buried peat/Litorina sand limit in the Marikoja site evidences that the Litorina Sea transgression started about 8100–8000 cal. yr BP, which agrees well with the results from Saaremaa Island (Saarse *et al*. 2009a). The $^{10}$Be date of 5820±660 yr BP from Kasispea Edelakivi (Rinterknecht *et al*. 2006) at an elevation of 15 m a.s.l. on the neighbouring Pärispea Peninsula also fits well with the age–depth model created for the Juminda Peninsula. Considering beach formations and the marine limit at 18.5-20.5 m a.s.l., the magnitude of the Litorina Sea transgression was about 2-3 m, being thus similar to that on the other peninsulas in northern Estonia (Linkrus 1998; Saarse *et al*. 2009a; Saarse, Vassiljev 2010), but lesser than the transgression east of the Gulf of Finland (Ryabchuk *et al*. 2007).

The diatom composition from the Aabla sediment record confirms that during the Litorina Sea transgression the Aabla basin was already isolated from the Baltic Sea and a small shallow coastal lake with a sandy bottom and abundant macrophyte stands existed

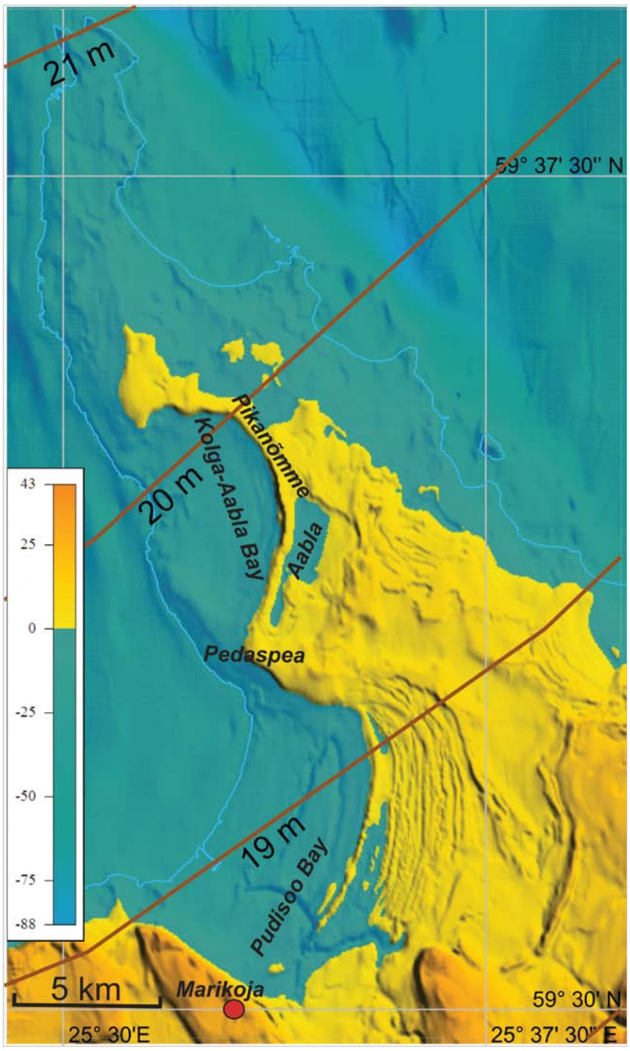

Fig. 7. 3D reconstruction of the Juminda Peninsula during the Litorina Sea transgression about 7800 cal. yr BP. Brown lines are the water level surface isobases. Compiled by J. Vassiljev.

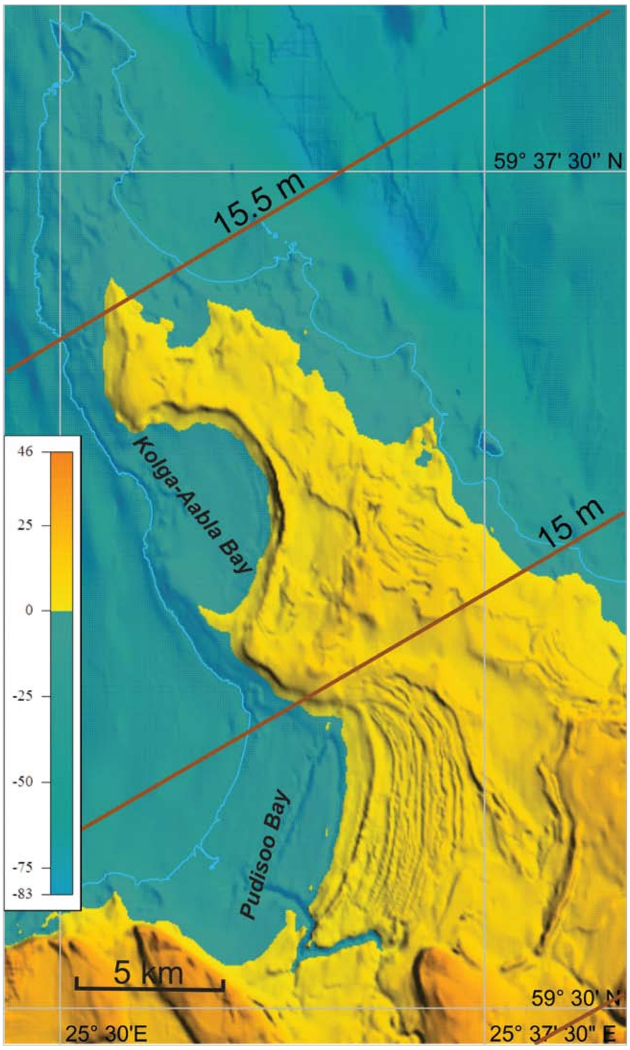

Fig. 8. 3D reconstruction of the Juminda Peninsula at 6000 cal. yr BP after the Litorina Sea trangression. Brown lines are the water level surface isobases. Compiled by J. Vassiljev.

in it. Our new evidence contradicts the earlier conclusion that the Aabla basin was a Litorina lagoon, which isolated at the end of the Atlantic chronozone (Kessel, Linkrus 1979). Moreover, our sea level simulations show that the Litorina level reached close to the Aabla threshold, but did not surpass it. Therefore, it is reasonable to conclude that the culmination of the Litorina Sea transgression on the Juminda Peninsula was not higher than 20.5 m a.s.l.

The shoreline continuously regressed after the Litorina Sea transgression and most of the Juminda Peninsula was exposed from the sea. By 6000 cal. yr BP the coastline was quite similar to the present one with two bays, namely Kolga–Aabla and Pudisoo, in the west (Fig. 8). Since that time the peninsula has stretched ca 4 km towards the north and 1.5 km towards the west in the places of the former bay back and the coastline has straightened up. By the beginning of the Limnea Sea stage about 4400 cal. yr BP, Juminda had obtained a more compact configuration and nearly the present–day outlook as all areas above 12 m had emerged from water (Fig. 9). Being regressive in nature, the Limnea Sea left behind the accumulative terraces. By 1000 cal. yr BP the former bays near Kolga–Aabla and Pudisoo disappeared and the coastline became considerably straighter (Fig. 10). The shoreline reached the capes of Tapurla and Virve in the east and abrasion of scarps into varved clays started. The modern jointed and picturesque landscape has attracted holiday-makes, hikers, berry-pickers and tourists for whom a 7 km long nature trail and boardwalk across the Aabla Bog have been constructed.

## CONCLUSIONS

The highest part of the Juminda Peninsula emerged from the water before the Ancylus Lake transgression about 10 300 cal. yr BP. Diatom stratigraphy indicates that the Litorina Sea water did not inundate the Aabla basin, since the diatom composition represents fresh–water taxa. The Litorina Sea limit in the Juminda

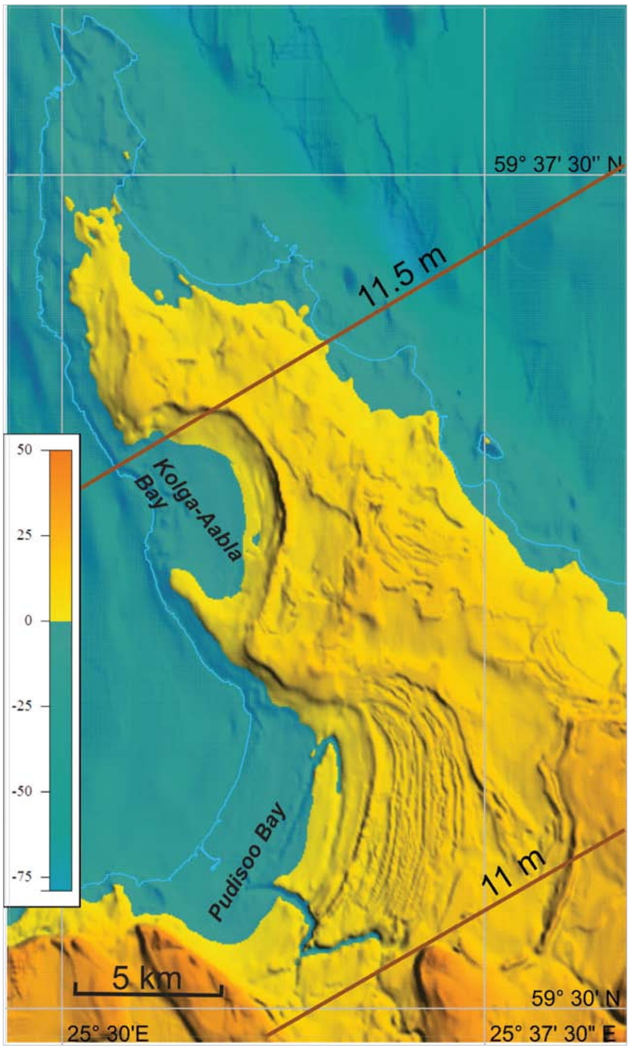

Fig. 9. 3D reconstruction of the Juminda Peninsula at the beginning of the Limnea Sea at 4400 cal. yr BP. Brown lines are the water level surface isobases. Compiled by J. Vassiljev.

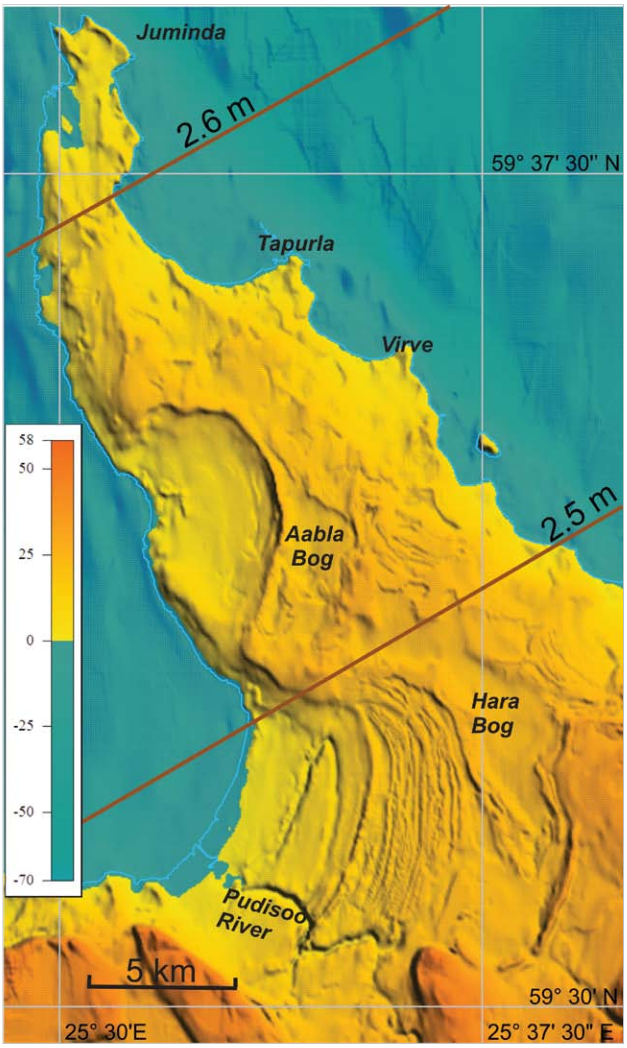

Fig. 10. 3D reconstruction of the Juminda Peninsula at 1000 cal. yr BP. Brown lines are the water level surface isobases. Compiled by J. Vassiljev.

Peninsula is at 20.5 m a.s.l. in the north–western and 18.5 m a.s.l. in the south–eastern part, due to a different land uplift rate, which decreases towards the southeast. Comparison of the threshold elevation and marine limit confirms that the Litorina Sea transgression waters reached close to the Aabla threshold elevation at 21-21.5 m a.s.l., but did not surpass it.

The highest coastline of the Litorina Sea stretched north as a long cape and was connected with the main peninsula by a narrow neck. The Litorina Sea transgression formations are best developed in the western part of the peninsula often covered by aeolian sands. From the Limnea Sea stage onwards land increased mostly in the north and west, on the back of the former bays.

## Acknowledgements

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