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Water-level changes and palaeogeography of proglacial lakes in eastern Estonia: synthesis of data from the Saadjärve Drumlin Field area

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Abstract. We studied the water-level changes and palaeogeography of Late Weichselian proglacial lakes in eastern Estonia using the shoreline and sediment distribution proxies from the Saadjärve Drumlin Field area together with the geomorphological correlation and GIS-based palaeoreconstructions. Our results show that about 14.0–13.8 cal. kyr BP Glacial Lake Peipsi inundated large areas of the Saadjärve Drumlin Field, Emajõgi River valley and reached the Lake Võrtsjärv basin. In the Saadjärve Drumlin Field area this is reflected in the formation of the highest shoreline and the corresponding rather short period (up to 63 years) of varved clay accumulation. The highest shoreline determined in the Saadjärve Drumlin Field is correlated with the valley terraces in southeastern Estonia, which reflect the water level in Glacial Lake Peipsi and the proglacial lake in the Võrtsjärv basin. The study suggests settling of glacial varved clay in the deepest inter-drumlin basins at the critical (minimal) water depths of about 15–20 m. The proglacial conditions lasted in the Saadjärve Drumlin Field for about 150 years and were interrupted due to the isolation of the lakes from proglacial bodies of water in the Peipsi and Võrtsjärv basins after the formation of the second highest shoreline. In the bottom sediments this isolation is marked by the transition from the laminated sediments to the massive silt interval. The results show that about 14.0–13.8 cal. kyr BP the connection route between Glacial Lake Peipsi and proglacial Lake Strenči, northern Latvia, shifted from the Võhandu–Hargla valley to the Väike-Emajõgi valley and the strait between Glacial Lake Peipsi and large Lake Privalday in northwestern Russia was closed.

Key words: proglacial lakes, palaeogeography, shore displacement, Lake Peipsi, Lake Võrtsjärv, Late Weichselian, eastern Estonia.

INTRODUCTION

Two large proglacial lakes developed in eastern Estonia in the course of the last deglaciation, Glacial Lake Peipsi (Raukas & Rähni 1969; Raukas et al. 1971; Hang 2001) and a proglacial lake in the Lake Võrtsjärv basin (Orviku 1958; Raukas et al. 1971; Moora et al. 2002). Glacial Lake Peipsi was formed together with ice retreat from the Haanja–Luga line to the Otepää line of the ice margin position (Fig. 1a; Hang 2001) and expanded north following the ice recession. At the initial stage, Glacial Lake Peipsi was connected with large Lake Privalday in northwest Russia (Kvasov 1979) and with the proglacial lakes in the Gauja basin in northern Latvia (Aboltynsh 1971; Aboltynsh et al. 1974; Zelčs & Markots 2004). The proglacial lake in the Lake Võrtsjärv basin formed later when the glacier retreated from the Otepää ice margin position to the Laeva–Piirissaar line (Fig. 1b; Raukas et al. 1971; Moora et al. 2002). The proglacial lake in the Võrtsjärv basin was connected with Glacial Lake Peipsi through the Emajõgi River valley while the water level was so high that it flooded also the Saadjärve Drumlin Field area (Fig. 1b; Raukas et al. 1971). However, coastal landforms on the slopes of the drumlins and proglacial deposits in the inter-drumlin depressions as indicators of the distribution and water level of the proglacial lake, have so far been poorly investigated (Pirrus & Rõuk 1979; Pirrus 1983).

In this paper we report new geomorphic and sedimentary data from the Saadjärve Drumlin Field area, interpreted together with previous information in order to reconstruct Late Weichselian water-level changes in eastern Estonia. For this purpose glaciolacustrine sediments from a number of successively isolated small inter-drumlin lake basins were studied and coastal landforms were mapped. The configuration and bathymetry of proglacial lakes were reconstructed using the correlation of shorelines, a digital terrain model (DTM), and GIS analysis in order to understand how proglacial lakes were distributed and related in eastern Estonia.

GEOLOGICAL SETTING AND REGIONAL BACKGROUND

The Saadjärve Drumlin Field is located in eastern Estonia between the Lake Peipsi and Lake Võrtsjärv depressions (Fig. 1b). Silurian dolomites in the north and Devonian sandstones in the south are covered by Weichselian glacial deposits, forming northwest–southeast oriented and morphologically clearly expressed drumlins and drumlinoid ridges (Fig. 2; Rattas 2004). Inter-drumlin

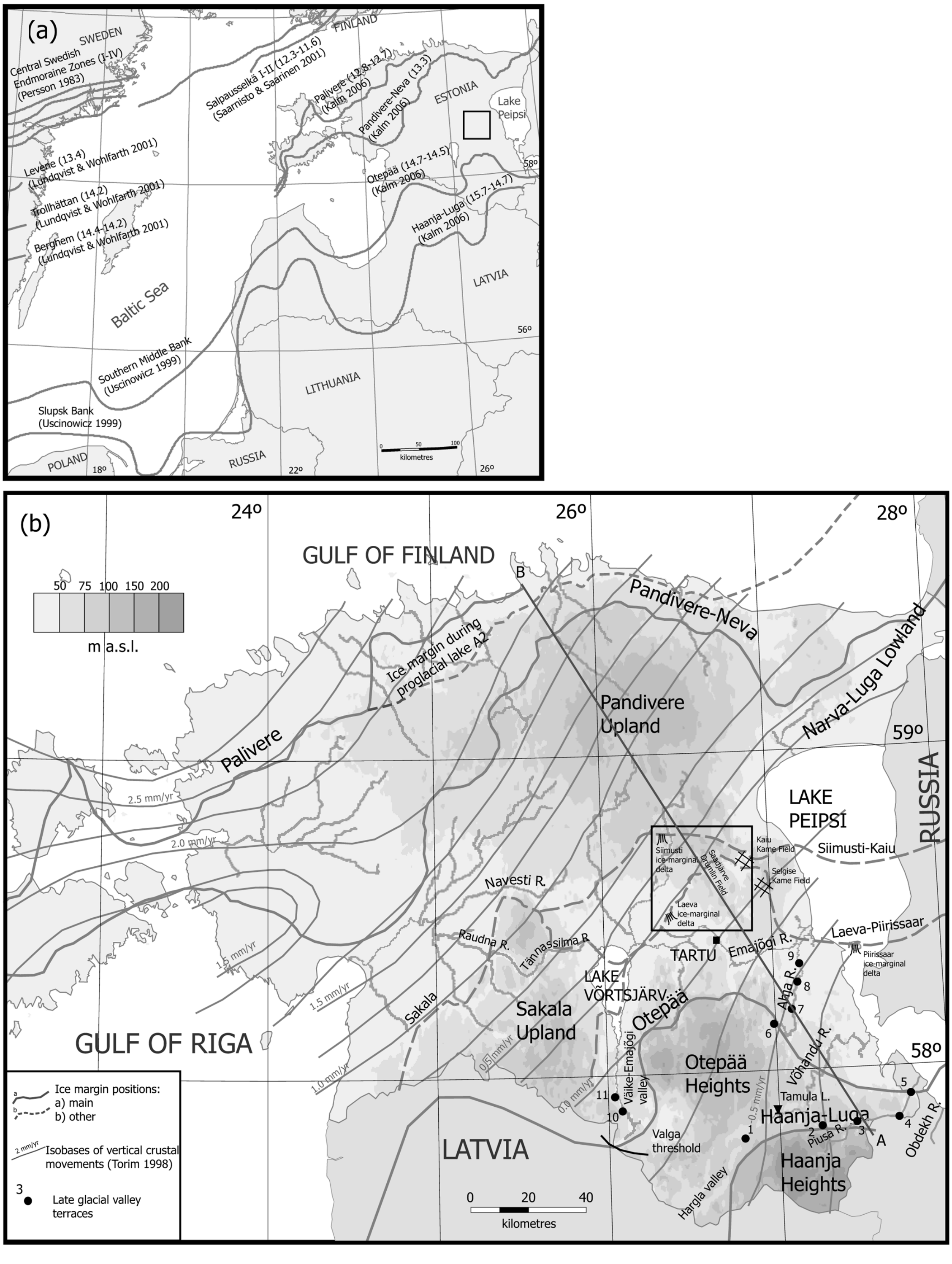


Fig. 1. (a) Index map with location of the study area (rectangle) and main Late Wechselian ice margin positions around the Baltic Sea with ages (cal. kyr BP) according to Kalm (2006), Lundqvist & Wohlfarth (2001), and Saarnisto & Saarinen (2001). (b) Location of the study area (rectangle) in Estonia in relation to the ice margin positions and present-day vertical crustal movements isobases. Dots with numbers refer to the valley terraces reflecting the proglacial lake levels in the southern part of Lake Peipsi (Liblik 1966; Hang et al. 1995) and Lake Võrtsjärv basins (Palusalu 1967): 1, Hargla valley (79–73 m a.s.l.); 2–5, Piusa River valley (95–71.5, 62–60, 51–45, 41–33 m a.s.l.); 6–9, Ahja River valley (62.5–61.5, 54–50, 44–41, 39–34 m a.s.l.); 10, 11, Väike-Emajõgi River valley (61; 61 m a.s.l.). The location of the cross-section in Fig. 6 (line A–B) is shown on the map.

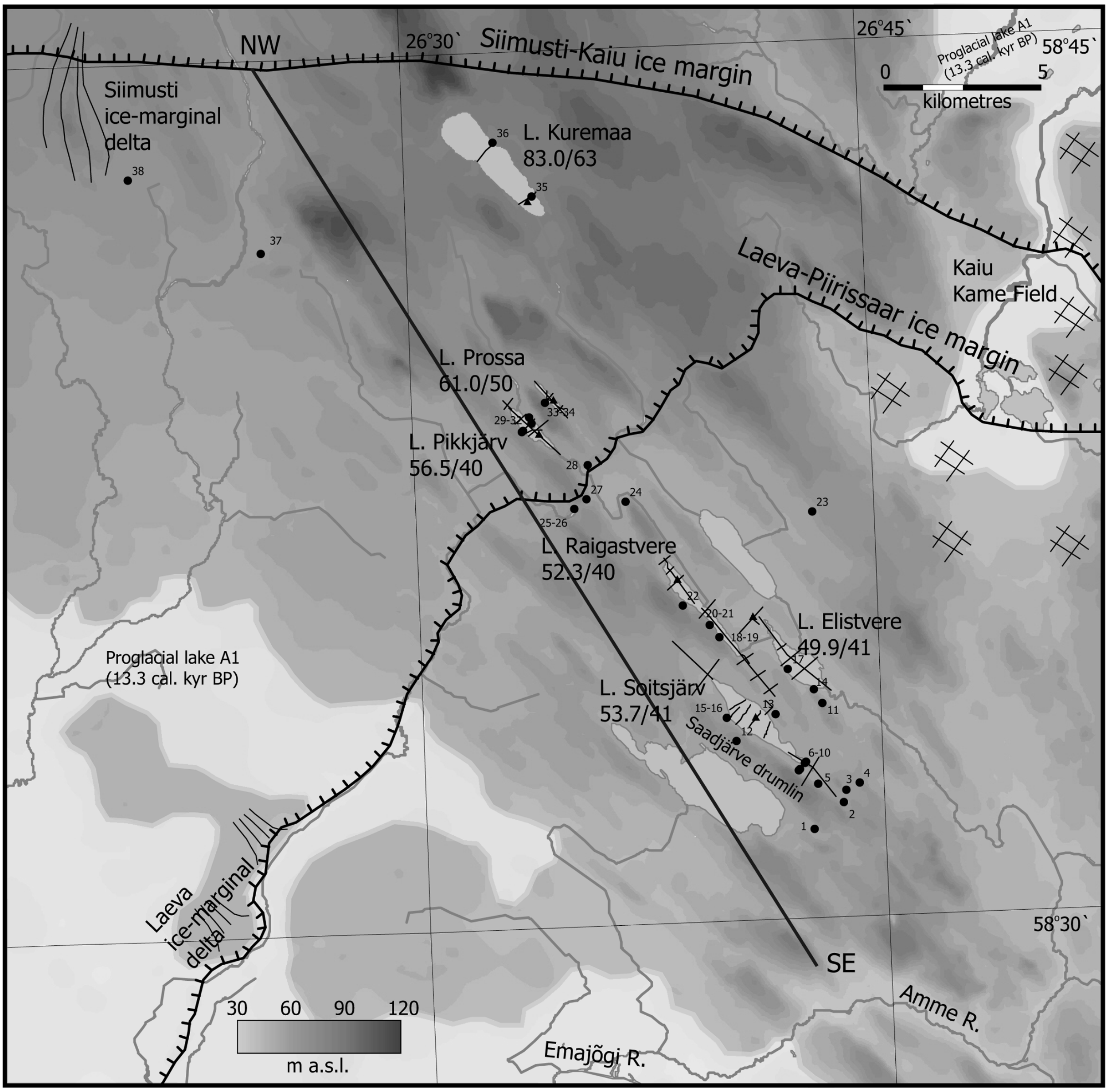


Fig. 2. Modern digital terrain model of the Saadjärve Drumlin Field with indication of ice margin positions (Raukas et al. 1971) and glacial landforms mentioned in the text. Geological profiles (black lines) used for the mapping of glaciolacustrine deposits and location of master cores (triangles) are shown on the map. Dots with numbers refer to the coastal landforms displayed in Table 1 and Fig. 3. The location of the cross-section in Figs 3 and 5 is shown on the map. Numbers below the lake name indicate the present lake level and the lowest recorded altitude of the till surface in the basin. The distribution of the proglacial lake at stage A_1 about 13.3 cal. kyr BP (derived from Rosentau et al. 2007) is shown on the map with light grey colour.

basins contain late glacial glaciolacustrine and Holocene lake deposits and peat. The deepest basins, located at different elevations, are occupied by modern lakes – Kuremaa, Soitsjärv, Raigastvere, Elistvere, Pikkjärv, Prossa, and others (Fig. 2).

The stratigraphy of sediments and morphology of inter-drumlin basins have been studied for many years. Special emphasis has been laid on the Holocene vegetation history and water-level change (Pirrus & Rõuk 1979; Saarse & Kärson 1982; Pirrus 1983). The history of Late Weichselian water-level changes is much less known, and has occasionally been discussed in connection with the development of Glacial Lake Peipsi (Raukas & Rähni 1969; Raukas et al. 1971) or in stratigraphical interpretations (Pirrus 1983; Pirrus & Raukas 1996). On the basis of the flat-topped kames in the Selgise Kame Field (Fig. 1b), the position of the highest shoreline was inferred for the Saadjärve Drumlin Field at an altitude of ca 85–90 m a.s.l. (Raukas & Rähni 1969; Raukas et al. 1971). This level was considered to represent the water level of Glacial Lake Peipsi at the time when the ice margin was positioned at the Laeva–Piirissaar line (Fig. 1b). Later local studies (Pirrus & Rõuk 1979; Pirrus 1983) report that the highest shoreline was located at 75 m a.s.l., which is 10–15 m lower than the earlier suggestions. However, the estimation of the highest shoreline is based only on a single abraded slope at the Saadjärve drumlin (Fig. 2; Pirrus 1983).

The reconstruction of water-level changes and distribution of proglacial lakes in Estonia is closely related to the glacioisostatic movements of the Earth's crust, which results in the tilting of the proglacial lake shorelines. Measurements of present-day vertical crustal movements (Torim 1998) show for the Saadjärve Drumlin Field area a modest land uplift which ranges between 0.75 and 0 mm/yr (Fig. 1b). Correlation of coastal landforms formed during the Pandivere–Neva (proglacial lake at stage A_1) and Palivere stades (proglacial lake at stage A_2) in western Estonia and in the basins of lakes Peipsi and Võrtsjärv in eastern Estonia (Vassiljev et al. 2005; Rosentau et al. 2007) suggests that the NW–SE oriented shoreline tilting in the Saadjärve Drumlin Field area has a gradient of ca 20–30 cm/km. South from the present-day zero uplift line (Fig. 1b) the late glacial shoreline tilting decreases rapidly to the tilting gradient of ca 5–10 cm/km (Vassiljev et al. 2005). A similar low tilting gradient was reported (5 cm/km) from the studies into late glacial river terraces in the Peipsi basin, south-eastern Estonia (Hang et al. 1995; Hang 2001). Nearly horizontal terraces from the same period were also observed in the Väike-Emajõgi River valley (Fig. 1b), reflecting there the proglacial lake level in the Võrtsjärv basin (Kajak 1959; Palusalu 1967; Miidel et al. 2004). Due to the uneven shoreline tilting and difficulties in the dating of late glacial shorelines the reconstruction of proglacial lake-level changes in eastern Estonia is complicated. This has resulted in different views which are summarized in Table 1.

MATERIAL AND METHODS

Lake basin and shoreline investigations

Late Weichselian lake sediments from six successively isolated small lake basins (Pikkjärv, Prossa, Soitsjärv, Raigastvere, Elistvere, and Kuremaa) from the Saadjärve Drumlin Field (Fig. 2) were investigated in order to detect the late glacial water-level changes. The lakes were cored from the lake ice and at the shore with the Russian-type peat corer (chamber length 1 m, inside diameters 5 and 2 cm). The distribution (altitude, thickness, spatial distribution) of glaciolacustrine sediments in lake basins was mapped according to our and previously (Pirrus & Rõuk 1979; Saarse & Kärson 1982; Pirrus 1983) compiled cross-sections (Fig. 2). Earlier data were checked in the field at 3–10 locations from each profile to unify the descriptions of sediments. Master cores were taken from each lake for detailed lithostratigraphic description and varve counting at the locations providing the most complete late glacial stratigraphical record. For collecting the master cores we used two parallel sediment sequences with 0.5 m overlap.

Ancient coastal landforms, like terraces, scarps, and outwash plains at the slopes of the drumlins, were investigated by means of their altitude and sediment stratigraphy. A GIS database of previously studied coastal landforms was compiled prior to fieldwork and later complemented with new original data. Previously investigated coastal landforms were checked in the field before they were accepted as water-level indicators. The

Table 1. Water levels (m a.s.l.) of Glacial Lake Peipsi during the deglaciation of the lake basin according to different authors. Water levels are given for the study area at the Saadjärve Drumlin Field (SDF) and for the mouths of the Ahja and Piusa rivers south of the study area. Location of the ice margin, study area, and valley terraces is shown in Fig. 1b

Reference	Otepää Stade	Laeva–Piirissaar Stade			Siimusti–Kaiu Stade			Pandivere–Neva Stade (proglacial lake stage A_1)	
	Piusa River	Piusa River	Ahja River	SDF	Piusa River	Ahja River	SDF	Piusa River	Ahja River
Raukas et al. 1971	70–95	45–51	~60	~85–90	–	~40	~86	~38	~40
Pirrus & Rõuk 1979	–	–	–	~75	–	–	–	–	–
Hang et al. 1995	>75	60–62	62.5–61.5	–	45–51	50–54	–	33–41	41–44
Vassiljev et al. 2005	–	–	–	–	–	–	–	–	41

altitudes of coastal scarps from the Lake Raigastvere and Lake Soitsjärv basins were instrumentally measured during fieldwork. Other geomorphological evidences of water level were observed in the field and their altitudes derived from Soviet topographic maps on a scale of 1 : 10 000 (0.5 m/1 m contour intervals). The positioning of sites was performed by hand GPS.

The ancient coastal landforms were divided into two groups according to altitude: sites above and sites below the highest Holocene shoreline (HHS). It was determined for each lake basin and the surroundings following the available data on sediment distribution, stratigraphy, and radiocarbon datings (Pirrus & Rõuk 1979; Saarse & Kärson 1982; Pirrus 1983). Coastal landforms were projected to the cross-section on the graph and sites above the HHS were first visually correlated. Thereafter, the linear regression gradients of shores and residuals from linear regression were calculated for each site and sites with residuals less than ± 1 m were considered to correspond to the same shores. Finally, in order to describe the shoreline tilting gradient, the linear regression was calculated again using only the sites corresponding to the shores. The cross-section was projected to an azimuth of 326° reflecting the azimuth of the fastest tilting of late Weichselian shorelines (Hang et al. 1995; Rosentau et al. 2004) in eastern Estonia.

Palaeogeographical methods

Reconstruction of the shorelines and bathymetry of proglacial lakes was based on GIS analysis, by which interpolated surfaces of ancient water levels were subtracted from the modern DTM (Rosentau et al. 2004). Water-level surfaces of the proglacial lakes in eastern Estonia were reconstructed on the basis of identified shoreline altitudes from our study area and their correlation with late glacial valley terraces in the Peipsi (Hang et al. 1995) and Võrtsjärv (Palusalu 1967) basins. Reconstruction of water-level surfaces is based on linear solution of natural neighbour interpolation using the constant shoreline tilting direction to an azimuth of 326° (Rosentau et al. 2004). The grid was 5 km × 5 km in size.

The DTM with the grid size of 200 m × 200 m was generated from different elevation data sets:

1. the digital terrain model for Estonia, with the grid size of 200 m × 200 m (Rosentau et al. 2007), based on elevation data from the Digital Base Map of Estonia on a scale of 1 : 50 000 (ELB 1996);
2. Shuttle Radar Topography Mission (SRTM-90) elevation data with the resolution of 3 arc seconds (approx. 90 m × 90 m) for neighbouring areas in Latvia and NW Russia (CIAT 2004);
3. elevation data from Soviet topographic maps on a scale of 1 : 25 000 (2.5 m contour intervals) for the Saadjärve Drumlin Field area (Fig. 2).

Holocene peat deposits were subtracted from the DTM of the Estonian territory, using constant mean thicknesses for three main types of mires: 4 m for raised bogs, 2 m for transitional mires, and 1 m for fens according to data by Orru (1995). In the study area (Fig. 2) the lake water depths and mapped thicknesses of Holocene deposits (peat, gyttja, and lake marl) were subtracted from the DTM according to our and previously published data (Pirrus & Rõuk 1979; Saarse & Kärson 1982; Pirrus 1983). After subtracting Holocene deposits, lake water depths, and the interpolated water-level surface from the DTM, the shoreline and bathymetry were deduced for proglacial lakes and related to the ice margin positions identified by Raukas et al. (1971). All reconstructions were performed in Conformal Transverse Mercator projection: TM-Baltic (ELB 1996).

RESULTS

Correlation of coastal landforms

The identified coastal landforms (Fig. 2) are listed in Table 2 and displayed on the cross-section in Fig. 3. Two best-expressed shore levels can be determined in the study area above the HHS. The highest shore (Shore 1) at an altitude of 68–64 m a.s.l. is represented by 6 sites and is traceable in the central and southern parts of the drumlin field area. Shore 1 is represented in the slopes of the drumlins by short fragments (up to 30 m in length) of coastal terraces and scarps (Table 2). The linear tilting gradient of Shore 1 is 27 cm/km. The position of this, highest, shoreline in the region shows a ca 20 m lower water level than suggested earlier by Raukas et al. (1971) and a ca 10 m lower water level than suggested by Pirrus & Rõuk (1979). The second highest shoreline (Shore 2) is traceable in the northern and southern parts of the drumlin field area and represented by 10 sites at an altitude between 68 and 60 m. This ancient shore is marked by coastal terraces and scarps and by some small outwash plains (Table 2). In the northern part of the study area, south of the Siimusti ice-marginal delta, Shore 2 is marked by two large (ca 1 km × 1 km) coastal plains (sites 37, 38 in Table 2 and Fig. 2), formed in glaciolacustrine sand. The linear tilting gradient of Shore 2 (25 cm/km) displays a similar gradient to Shore 1. Comparison of the tilting gradients of Shore 1 and Shore 2 with the following stages (A_1 and A_2, Vassiljev et al. 2005) in the development of proglacial lakes in Estonia, displays a similar tilting during

Table 2. Mapped coastal landforms in the Saadjärve Drumlin Field area. Location of the sites is shown in Fig. 2

No. in Fig. 2	Site	Coordinates, degrees		Elevation, m a.s.l.	Type of landform	Type of measurement	Level	Reference
		Longitude	Latitude					
1	Saadjärv	26.711	58.525	60	Outwash plain	Topographic map	Shore 2	Pirrus 1983
2	Soitsjärv	26.727	58.533	58	Coastal scarp	Instrumental measure	Below HHS	Pirrus 1983
3	Toolamaa	26.729	58.536	60	Coastal scarp	N.a.	Shore 2	Pirrus & Rõuk 1979
4	Toolamaa	26.737	58.538	60	Coastal scarp	N.a.	Shore 2	Pirrus & Rõuk 1979
5	Soitsjärv	26.714	58.538	57	Outwash plain	Topographic map	Below HHS	This study
6	Soitsjärv	26.704	58.542	63.9	Coastal scarp	Instrumental measure	Shore 1	This study
7	Soitsjärv	26.704	58.542	61.1	Coastal scarp	Instrumental measure	Shore 2	This study
8	Soitsjärv	26.704	58.542	57.3	Coastal scarp	Instrumental measure	Below HHS	This study
9	Soitsjärv	26.708	58.544	49	Coastal terrace	Instrumental measure	Below HHS	Pirrus 1983
10	Soitsjärv	26.708	58.544	55	Coastal scarp	Instrumental measure	Below HHS	Pirrus 1983
11	Elistvere	26.720	58.561	60	Outwash plain	Topographic map	Shore 2	This study
12	Saadjärv	26.671	58.551	75	Abraded slope	N.a.	Above HHS	Pirrus 1983
13	Soitsjärv	26.692	58.558	60	Coastal terrace	Topographic map	Shore 2	This study
14	Elistvere	26.714	58.565	55	Coastal scarp	Instrumental measure	Below HHS	Pirrus & Rõuk 1979
15	Soitsjärv	26.665	58.558	56.9	Coastal scarp	Instrumental measure	Below HHS	This study
16	Soitsjärv	26.666	58.558	54.7	Coastal scarp	Instrumental measure	Below HHS	This study
17	Elistvere	26.700	58.571	49	Coastal terrace	Instrumental measure	Below HHS	Saarse & Kärson 1982
18	Raigastvere	26.664	58.581	59.6	Coastal scarp	Instrumental measure	Above HHS	This study
19	Raigastvere	26.664	58.581	54.3	Coastal scarp	Instrumental measure	Below HHS	This study
20	Raigastvere	26.659	58.584	57.3	Coastal scarp	Instrumental measure	Below HHS	This study
21	Raigastvere	26.659	58.585	54.1	Coastal scarp	Instrumental measure	Below HHS	This study
22	Raigastvere	26.644	58.590	65	Coastal scarp	Instrumental measure	Shore 1	Rõuk 1987
23	Kõrenduse	26.717	58.616	62	Outwash plain	Topographic map	Shore 2	This study
24	Nava	26.615	58.621	60.3	Coastal terrace	Topographic map	Below HHS	This study
25	Ilmjärv	26.586	58.617	59	Coastal terrace	Instrumental measure	Below HHS	Pirrus 1983
26	Ilmjärv	26.587	58.619	67	Coastal terrace	Topographic map	Shore 1	This study
27	Ilmjärv	26.594	58.622	66	Coastal terrace	Topographic map	Shore 1	This study
28	Nava	26.595	58.632	66.5	Coastal terrace	Topographic map	Shore 1	This study
29	Pikkjärv	26.560	58.642	68	Coastal terrace	Instrumental measure	Shore 1	Saarse & Kärson 1982
30	Pikkjärv	26.565	58.644	55	Coastal terrace	Instrumental measure	Below HHS	Saarse & Kärson 1982
31	Pikkjärv	26.560	58.642	58	Coastal terrace	Instrumental measure	Below HHS	Saarse & Kärson 1982
32	Pikkjärv	26.564	58.646	57.5	Coastal terrace	Instrumental measure	Below HHS	Saarse & Kärson 1982
33	Prossa	26.575	58.649	61.5 (62–61)	Coastal terrace	Instrumental measure	Below HHS	Saarse & Kärson 1982
34	Prossa	26.573	58.650	63.5 (64–63)	Coastal terrace	Instrumental measure	Shore 2	Saarse & Kärson 1982
35	Kuremaa	26.570	58.709	79	Coastal terrace	Topographic map	Below HHS	This study
36	Kuremaa	26.550	58.724	70	Coastal terrace	Topographic map	Below HHS	This study
37	Pakaste	26.421	58.695	65 (64–66)	Coastal plain	Topographic map	Shore 2	This study
38	Siimusti	26.349	58.717	67.5 (67–68)	Coastal plain	Topographic map	Shore 2	This study

HHS, highest Holocene shoreline; N.a., not available.

stage A_1 (28 cm/km) and a decrease in tilting during stage A_2 (19 cm/km).

A large number of identified coastal landforms are located below the HHS (Fig. 3) and are therefore difficult to distinguish from the Holocene coastal landforms. However, two buried terraces built up of glaciolacustrine sediments, at an altitude of 49 m in the Lake Soitsjärv and Lake Elistvere basins (sites 9, 17 in Table 2 and Fig. 2) are most probably of late glacial age, suggesting that the water level during the Late Weichselian in these lakes might have been even lower than today (Fig. 2).

Distribution of glaciolacustrine sediments

Glaciolacustrine sediments are distributed in inter-drumlin lake basins and represented by clay, silt, and fine sand deposits. Fine sand is common in the shallow parts of these basins, both a few metres above and below the modern lake level. Glaciolacustrine sand is not

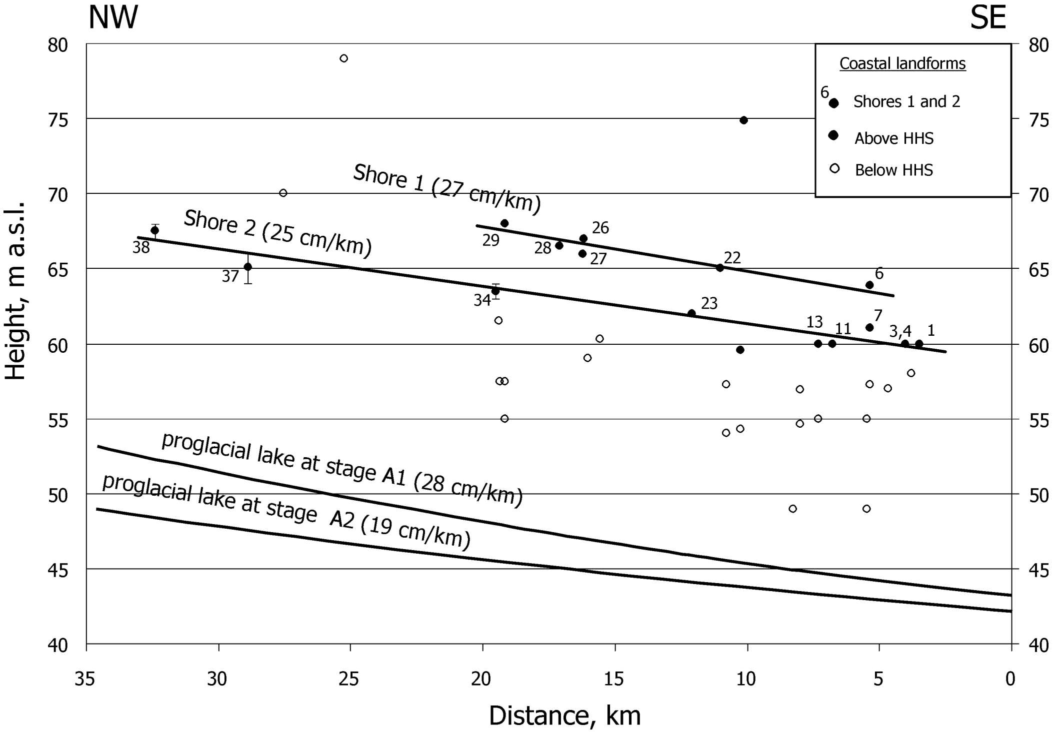


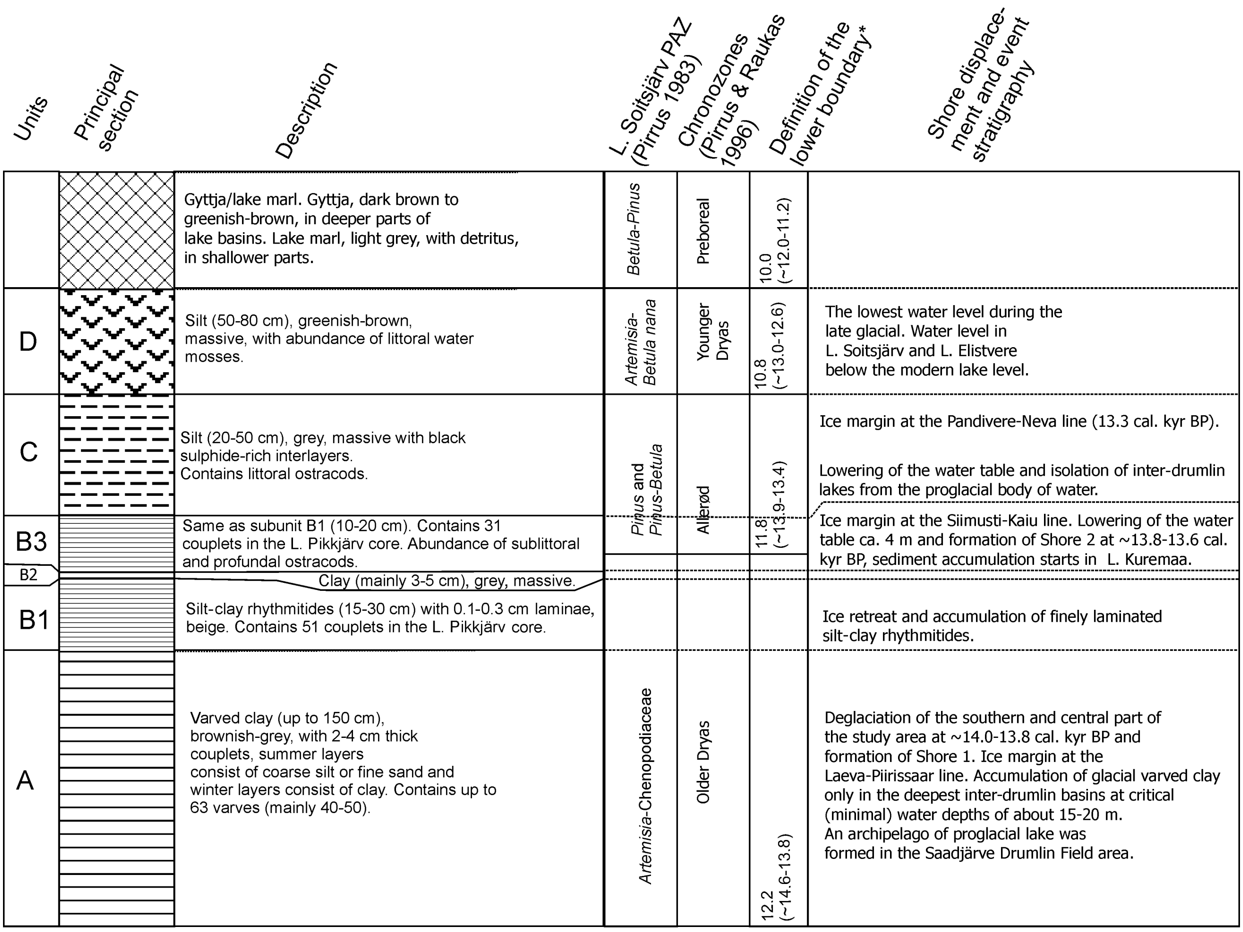
Fig. 3. Height–distance diagram showing the distribution of the studied coastal landforms and identified shorelines above the highest Holocene shoreline (HHS). For comparison the water-level surfaces of proglacial lakes A_1 (~13.3 cal. kyr BP) and A_2 (~12.8 cal. kyr BP) (Vassiljev et al. 2005; Rosentau et al. 2007) are shown on the diagram. Location of the cross-section is shown in Fig. 2 and the description of coastal landforms in Table 1.

distinguishable from the Holocene sand and therefore not applicable in the late glacial water-level estimation. In deeper parts of the lake basins the glaciolacustrine sediments are represented by clay and silt deposits indicating continuous sedimentation during the post-glacial ice-free period. In order to describe the changes in the sedimentary environment, we identified different lithostratigraphic units for the studied glaciolacustrine sediments, designated upwards from unit A to unit D (Fig. 4).

The lowermost unit A consists of brownish-grey proglacial varved clay which lies on top of Late Weichselian till. Varved clay comprises mostly 2–4 cm thick couplets of silt and clay layers, considered as annual varves (Fig. 4). A relatively short period of varved clay accumulation (maximum 63 varves) is common to all studied sequences. The upper surface of the varved clay spreads up to an altitude of 55 m in the central part of the study area (lakes Pikkjärv and Prossa), being about 10 m lower in the southern part (lakes Soitsjärv, Raigastvere, and Elistvere; Fig. 5). The boundary with the following upwards unit B is gradual.

Sediments of unit B are divided into three subunits (B_1–B_3; Fig. 4). Subunits B_1 and B_3 are composed of 0.1–0.3 cm thick couplets of brownish-grey silt and clay layers. In the Lake Pikkjärv basin we counted a total of 81 couplets in these subunits (B_1 and B_3). However, the annual lamination of subunits B_1 and B_3 is not clear as the distinct summer-winter layers are often not clearly visible. Subunit B_3 is rich in profundal ostracods in the Lake Pikkjärv sequence (Sohar 2004). Subunit B_2 contains grey massive clay of variable thickness (mainly 2–5 cm), with sharp transition at its lower and upper boundaries. The upper surface of unit B spreads up to an altitude of 56 m in the central part of the study area (lakes Pikkjärv and Prossa), being ca 10 m lower in its southern part (lakes Soitsjärv, Raigastvere, and Elistvere). In the northernmost of the studied lake basins, Kuremaa (Fig. 2), the sequence of glaciolacustrine deposits starts with subunit B_3, which lies there directly on the till. The upper surface of this subunit is recorded at an altitude of 80 m.

The following upwards unit C, with a total thickness of 20–50 cm, consists of dark grey homogeneous silt with black, probably sulphide-rich interlayers (stripes). Unit C spreads up to an altitude of 77 m in the northern part (Lake Kuremaa), and is between 60 and 51 m a.s.l. in the central and southern parts of the study area. In Pikkjärv sediments unit C is rich in littoral ostracods (Sohar 2004).



* Definition of the lower bounday in uncal. ^{14}C kyr and cal. ^{14}C kyr (in brackets). Radiocarbon ages were calibrated using the OxCal v3.10 calibration programme (Ramsey 2001) based on the atmospheric data for the Northern Hemisphere (Reimer et al. 2004). The uncertainties of ^{14}C dates are reported as 1 sigma.

Fig. 4. Principal lithostratigraphy of the studied lake deposits together with the pollen-, chrono-, and event-stratigraphic interpretations. PAZ, pollen assemblage zone.

The overlying unit D consists of grey homogeneous silt with an abundance of different littoral water mosses (Pirrus & Rõuk 1979). The upper surface of unit D in lakes Soitsjärv and Raigastvere is located ca 1 m above the current lake level, while in Pikkjärv, Prossa, Elistvere, and Kuremaa unit D remains a few metres below it. Unit D is covered by Holocene gyttja, deposited in the deeper parts of the lake basins, or by lake marl/calcareous gyttja in the nearshore parts of the lakes (Fig. 4).

DISCUSSION

Water-level changes in the Saadjärve Drumlin Field area

The Late Weichselian lake-level changes in the study area, deduced from geomorphic and lithological data, are summarized in Figs 4 and 5. Following the ice retreat from the central and southern parts of the study area in the Saadjärve Drumlin Field, the deposition of glacial varved clays took place over a relatively short time period (up to 63 years). Our results show the formation of glacial varved clays only in the deepest parts of the inter-drumlin basins, reaching an altitude of 55 m a.s.l. in the central part and being ca 10 m lower in the southern part of the drumlin field. It has been argued that the critical (minimal) water depth for the formation of clastic annual varves has to be about 15–20 m (Pirrus 1968; Hang 2001). Considering this, the critical water level during the varved clay accumulation in the inter-drumlin basins must have been about 75–70 m in the central part and 65–60 m in the southern part of the study area. These inferred critical water levels are in good agreement with the altitude of the geomorphologically determined highest shoreline (Shore 1; Fig. 5). Thus we argue that the formation of the highest shoreline

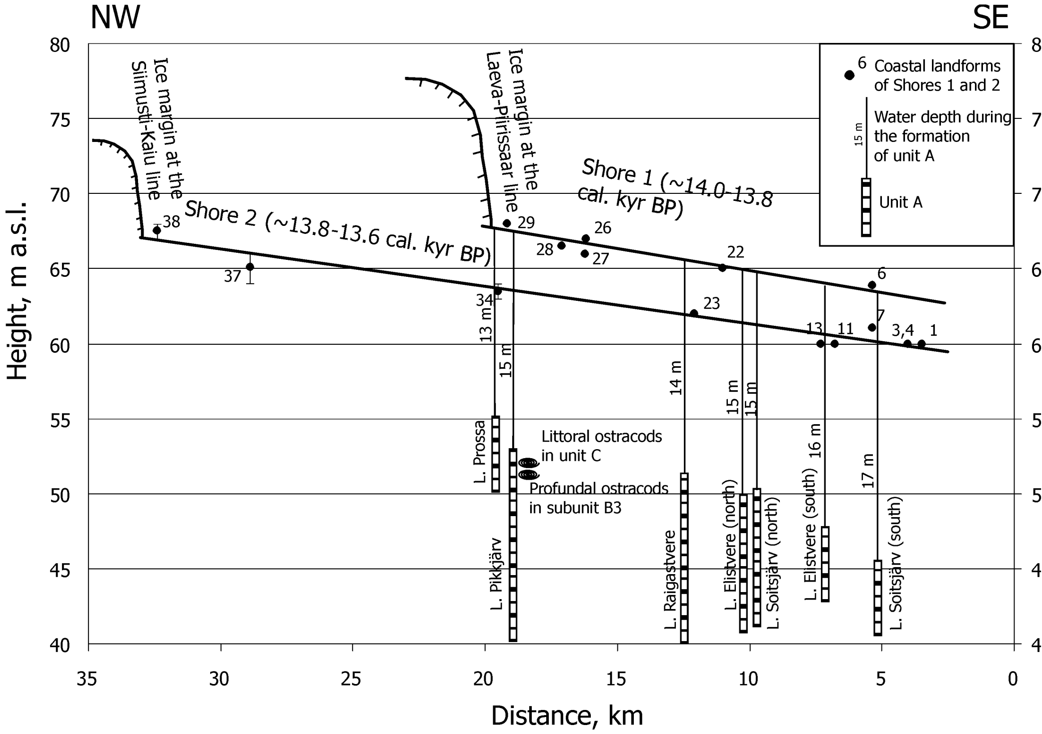


Fig. 5. Relation diagram of elevations of Shore 1 and Shore 2 with the elevation of varved clay intervals (unit A) and ostracod data (Sohar 2004) discussed in the text. For location of the numbered sites see Fig. 2 and description of landforms Table 1.

may have been synchronous with the period of the accumulation of varved clays. Moreover, as the coastal landforms of Shore 1 and varved clays in the lake basins are distributed only in the central and southern parts of the study area approximately in front of the ice margin position at the Laeva–Piirissaar line (Figs 2 and 5), we consider the formation of Shore 1 and varved clay accumulation at the time when the ice margin stagnated at the Laeva–Piirissaar position. The timing of this event could be only tentatively estimated to be 14.0–13.8 cal. kyr BP. This time is derived from the modelled age of the deglaciation of the southern and central parts of the Saadjärve Drumlin Field (about 14.0 cal. kyr BP; Kalm 2006) as well as from the ages of the Piirissaar (about 14.0–13.8 cal. kyr BP; Hang et al. 2001; Fig. 1b) and Laeva ice-marginal deltas (13.8 ± 1.5 OSL kyr; Raukas 2004; Fig. 1b).

The grading transition from varved clay (unit A) to finely laminated silt-clay rhythmitides (unit B; Fig. 4) in the central and southern parts of the drumlin field area reflects the decrease in sediment input due to a change in the sedimentary environment towards more distal conditions. The change was most likely caused by the ice recession from the Laeva–Piirissaar line (Fig. 2). Such a conclusion is supported by the aforementioned delayed start of glaciolacustrine sedimentation in the northernmost, Lake Kuremaa basin (Figs 2, 4). If this is true, the formation of sediment unit B is correlated with the ice recession from the Laeva–Piirissaar line to the Siimusti–Kaiu line of ice terminus position (Fig. 2). The dominance of the ostracods *Cytherissa lacustris* and *Leucochytere mirabilis* in subunit B_3 sediments in the Lake Pikkjärv master core (52 m a.s.l.; Figs 2, 5) refers to the water depth of at least 12 m (Sohar 2004) there, which corresponds to the lake level of ≥64 m a.s.l. during the formation of subunit B_3 (Fig. 5). This estimated proglacial lake level fits well with the altitude of Shore 2 in the same area (64 m a.s.l.; Fig. 5) and suggests that the formation of Shore 2 may have been synchronous with the period of the accumulation of sediments of subunit B_3 (Fig. 4). To sum up, a ca 4 m lowering of the proglacial lake from Shore 1 to Shore 2 in the Saadjärve Drumlin Field area took place during the ice retreat from the Laeva–Piirissaar line to the Siimusti–Kaiu line (Fig. 5) and corresponds to the formation of sediment units A–B within about 150 years (unit A, 63 years + unit B, 81 years).

Our results show the cease of rhythmic sedimentation in the studied lakes since the beginning of deposition of unit C (Fig. 4), which according to palynological data, took place during the Allerød Chronozone (Pirrus 1983; Fig. 4). Changes in ostracod fauna from profundal to littoral species (Sohar 2004) at the transition from unit B to unit C in the Lake Pikkjärv master core (Fig. 2) provide clear evidence of water-level lowering after the formation of Shore 2 (Fig. 5). As derived from the DTM (Fig. 2), the isolation of the lakes in the central and southern parts of the drumlin field must have occurred at the time when the water level lowered 2–5 m below Shore 2. We resume that most probably the lowering of the water level below Shore 2 interrupted the direct sediment supply from the glacier into the lakes and ceased therefore the rhythmic sedimentation.

It is probable that the lowering of the water level in the studied lake basins continued in the course of unit D sedimentation during the Younger Dryas Chronozone (Pirrus 1983; Fig. 4). This assumption is based on the discovery of buried coastal terraces in the bottoms of lakes Soitsjärv and Elistvere. These terraces (49 m a.s.l.), buried under younger Holocene lake deposits, consist of littoral sediments, which contain an abundance of water mosses characteristic of unit D (Fig. 4) and may thus indicate the water level below the modern lake level during the Younger Dryas Chronozone (Table 2; Figs 3, 4). The Younger Dryas low water level has been estimated in many Estonian small lakes (Saarse & Harrisson 1992) as well as in Peipsi (Hang et al. 2001) and Võrtsjärv (Miidel et al. 2004), which is in good agreement with our results.

Correlation of Shore 1 and Shore 2 with the Lake Peipsi and Lake Võrtsjärv basins

According to the altitudes of Shores 1 and 2 projected to the DTM, the strait-like connection between proglacial lakes in our study area and proglacial lakes in the Peipsi and Võrtsjärv basins must have existed in front of the Laeva–Piirissaar and Siimusti–Kaiu ice margins. Therefore it is possible to compare the altitudes of Shores 1 and 2 with proglacial lake water levels in the Peipsi (Hang 2001) and Võrtsjärv (Palusalu 1967) basins, identified according to the correlation of terraces in the Ahja, Piusa, and Väike-Emajõgi river valleys (Fig. 1b).

The correlation of Shores 1 and 2 with aforementioned terraces in southeastern Estonia is achieved through the shoreline tilting pattern. Our results show that the tilting of Shores 1 and 2 is rather similar to the tilting of the shoreline of the younger, proglacial lake of stage A_1 (13.3 cal. kyr BP; Fig. 3). This suggests a comparable pattern also in the adjoining areas further to the south where the A_1 shoreline has been identified (Vassiljev et. al. 2005; Rosentau et al. 2007). If this is true, exploiting of a low tilting gradient similar to A_1 (Fig. 6) south of the study area displays a good correlation of Shore 1 with the altitude of terraces in the Ahja and Piusa river valleys earlier connected with the Glacial Lake Peipsi water level during the Laeva–Piirissaar Stade (Hang 2001). Also, the

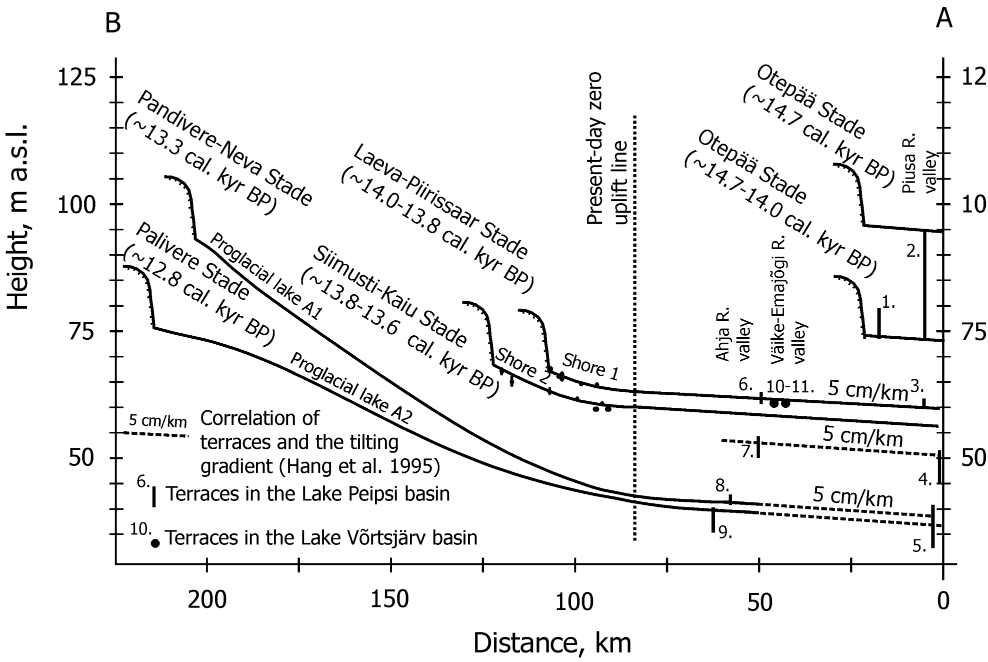


Fig. 6. Correlation of Shore 1 and Shore 2 with the Late Weichselian valley terraces reflecting the water levels in Glacial Lake Peipsi (Hang et al. 1995) and in the Lake Võrtsjärv basin (Palusalu 1967). For comparison the water levels of proglacial lakes of stages A_1 and A_2 are given according to Hang et al. (1995) and Vassiljev et al. (2005).

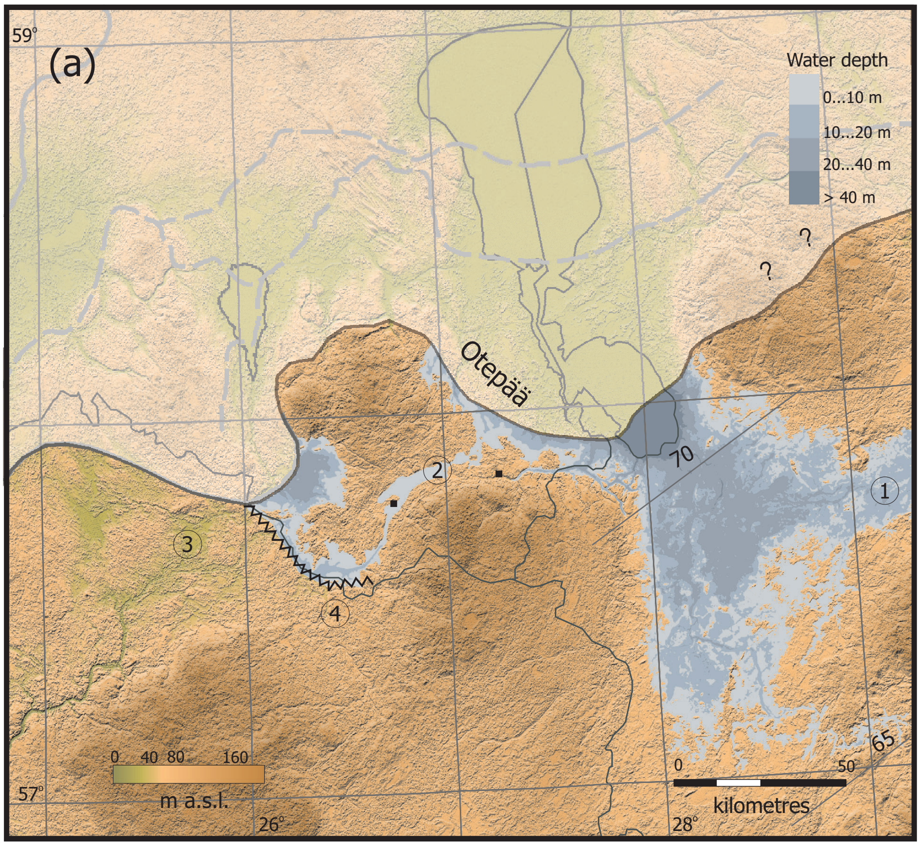


Fig. 7. Palaeogeographic reconstruction of the shoreline and bathymetry of proglacial lakes in eastern Estonia during the (a) Otepää Stade (derived from Rosentau et al. 2004), (b) Laeva–Piirissaar Stade, and (c) Siimusti–Kaiu Stade with indication of water-level surface isobases. Modern DTM (CIAT 2004) and locations discussed in the text are shown on the map: 1, Porkhov Strait; 2, Võhandu–Hargla Strait; 3, location of proglacial Lake Strenči; 4, location of proglacial Lake Middle Gauja; 5, connection route between proglacial lake in the Lake Võrtsjärv basin and proglacial Lake Strenči. Coastal landforms (circles) and valley terraces (squares) used for reconstruction are shown on the maps. Note that reconstructions do not consider the proglacial lakes in northern Latvia (the end of the study area is marked by a zig-zag line). Question marks point to the uncertain location of the ice margin.

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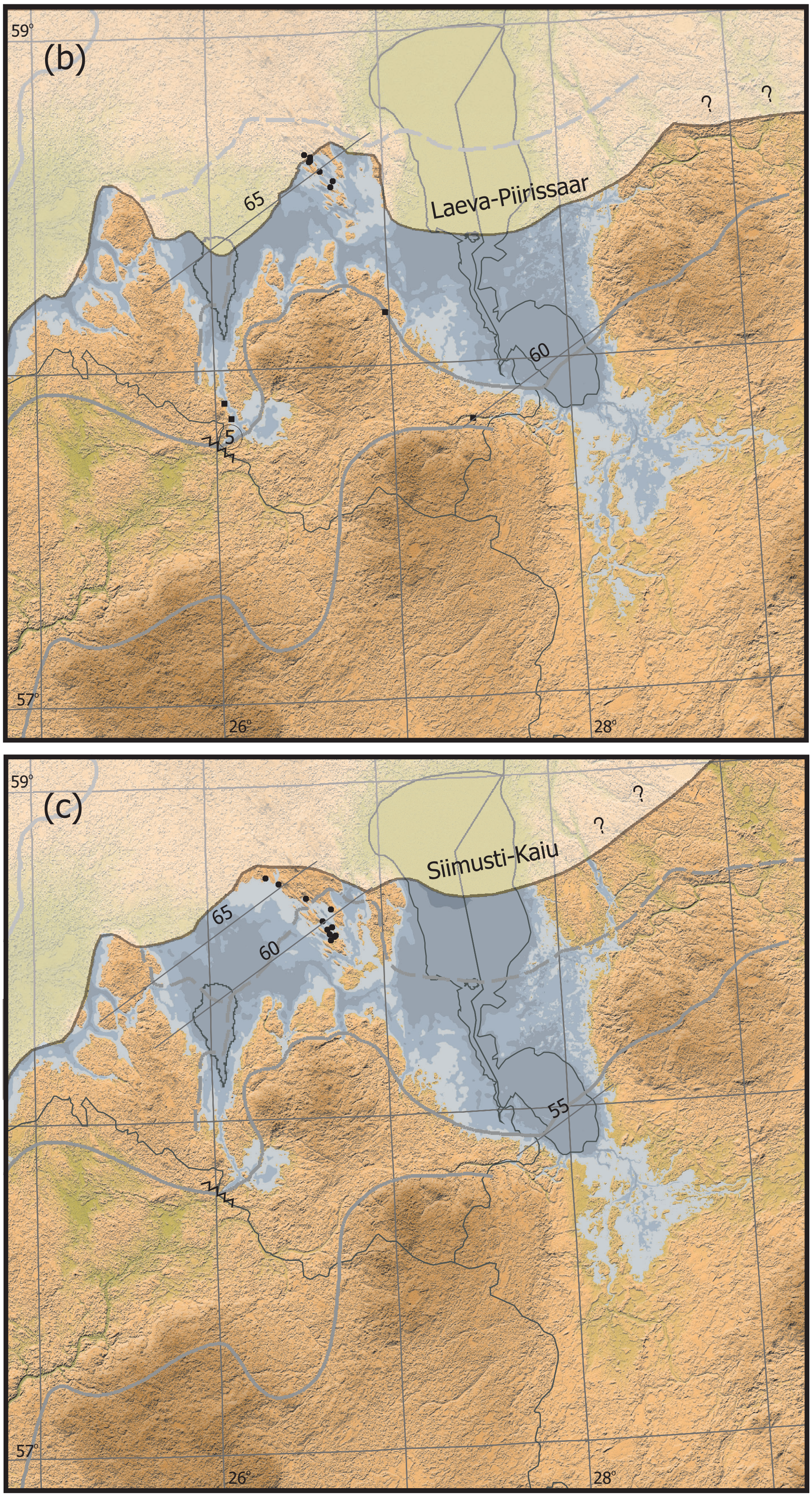

Fig. 7. *Continued.*

highest terraces in the Väike-Emajõgi River valley (61 m a.s.l.; Fig. 6), which reflect the Late Weichselian proglacial lake level in the Lake Võrtsjärv basin (Palusalu 1967; Miidel et al. 2004), exhibit the same altitude of Shore 1 (Fig. 6). Therefore, it is argued that the coastal landforms of Shore 1 were formed synchronously with the aforementioned terraces, suggesting that waters from proglacial lakes in the Lake Peipsi and Lake Võrtsjärv basins reached the Saadjärve Drumlin Field area during the Laeva–Piirissaar Stade.

Using the same approach for Shore 2, no correlation with the river terraces south of the study area was achieved (Fig. 6). The terraces in the Ahja River valley, earlier connected with the Glacial Lake Peipsi water level during the Siimusti–Kaiu ice margin position (Fig. 6), remain ca 5 m below the expected extension of the Shore 2 level. This suggests that the valley terraces of the Siimusti–Kaiu Stade and Shore 2 are slightly metachronous. Considering the proglacial lake regression rates between Shore 1 and proglacial lake A_1 (ca 2 m/100 yrs; Fig. 6), Shore 2 might have formed a few hundred years earlier than the discussed valley terraces.

Palaeogeography of proglacial lakes in eastern Estonia

In order to examine the palaeogeography of proglacial lakes in eastern Estonia, two reconstructions of the lake distribution and water depth were performed (Fig. 7b, c), based on the altitudes of Shores 1 and 2 and their extension to southeastern Estonia (Fig. 6). For comparison, the previously reconstructed distribution and water depth of Glacial Lake Peipsi during the preceding Otepää Stade (Rosentau et al. 2004) is also presented (Figs 6, 7a).

Start of terrace formation (Fig. 6) and varved clay accumulation in the Piusa–Hargla valley (dated in Lake Tamula at 14.7 cal. kyr BP in Kalm 2006; after Sandgren et al. 1997) reflects the beginning of the development of Glacial Lake Peipsi during the Otepää Stade. This lake had a connection with Privalday Lake in the east via the Porkhov Strait and with westward proglacial lakes Strenči and Middle Gauja in northern Latvia (Fig. 7a) via the Piusa–Hargla Strait and later via the Võhandu–Hargla Strait (Hang 2001; Rosentau et al. 2004). At the time when the ice margin retreated form the Otepää line to the Laeva–Piirissaar line, Glacial Lake Peipsi extended north, inundating the Emajõgi River valley and large areas of the Saadjärve Drumlin Field, and reached the Lake Võrtsjärv basin (Fig. 7a, b). This is recorded in the Saadjärve Drumlin Field area by the formation of the shallow-water archipelago (with the water depth dominantly below 10 m) about 14.0–13.8 cal. kyr BP and formation of the highest shoreline (Shore 1), which shows the same water level as in Glacial Lake Peipsi and in the proglacial lake in the Lake Võrtsjärv basin (Fig. 7b). The archipelago expanded when ice retreated from the Laeva–Piirissaar ice-marginal position to the Siimusti–Kaiu line (Fig. 7c). The Saadjärve Drumlin Field area emerged thereafter as dry land, with small isolated lakes in the inter-drumlin depressions. Separation of the lakes is marked by the end of laminated proglacial sediments, and the duration of proglacial lake conditions is estimated to have been about 150 years in this area.

Due to the extension of the lake to the Laeva–Piirissaar line and the corresponding lowering of the water level, the earlier connection between proglacial Lake Strenči and Glacial Lake Peipsi was shifted from the Võhandu–Hargla valley (Fig. 7a) to the Väike-Emajõgi valley (Fig. 7b). This conclusion is derived from the location of the highest late glacial terraces in the Väike-Emajõgi valley (61 m a.s.l.) above the critical threshold in the Valga depression (ca 50 m a.s.l.; Kajak 1959). It differs from the view of Moora et al. (2002) who suggested the existence of an isolated proglacial lake in the Võrtsjärv basin. According to reconstructions in Fig. 7b, c, there is also the possibility of a connection between the proglacial lakes in the Võrtsjärv and Peipsi basins and the proglacial lake at the western slope of the Sakala Upland (Lõokene 1959). However, this connection depends on the ice recession pattern in the Sakala Upland, whose palaeogeography and timing are unclear (Kalm 2006).

Our reconstructions show that during the ice retreat from the Otepää ice margin position to the Laeva–Piirissaar line, the Porkhov Strait between Glacial Lake Peipsi and large Lake Privalday in NW Russia was closed (Fig. 7a, b). Separation of these lakes was considered as an important palaeogeographic event, which marks the end of the Lake Privalday stage in NW Russia (Kvasov 1979; Mangerud et al. 2004).

CONCLUSIONS

- Two Late Weichselian shorelines were determined in the Saadjärve Drumlin Field area using correlation of identified coastal landforms. The highest shoreline at an altitude of 68–64 m a.s.l. was formed when the ice margin was at the Laeva–Piirissaar line about 14.0–13.8 cal. kyr BP, and the second highest shoreline was formed at a 4 m lower level when the ice margin was at the Siimusti–Kaiu line. The position of the highest shoreline reported here is 10–20 m lower than suggested in earlier studies.

- The linear tilting gradients for the two highest shorelines in the Saadjärve Drumlin Field area were calculated to be 27 and 25 cm/km, respectively. Comparison of our results with the shoreline tilting gradient data on younger proglacial lake stages A_1 (ca 28 cm/km about 13.3 cal. kyr BP) and A_2 (ca 19 cm/km about 12.8 cal. kyr BP) suggests that shoreline tilting in the Saadjärve Drumlin Field area was rather similar about 14.0–13.3 cal. kyr BP and decreased about 13.3–12.8 cal. kyr BP.
- The highest shoreline in the Saadjärve Drumlin Field area correlates with the valley terraces reflecting the water level of Glacial Lake Peipsi during the Laeva–Piirissaar Stade and with the highest late glacial terraces (61 m a.s.l.) in the Väike-Emajõgi River valley reflecting the proglacial lake level in the Lake Võrtsjärv basin.
- Palaeogeographical reconstruction suggests that during the ice stagnation at the Laeva–Piirissaar line about 14.0–13.8 cal. kyr BP, Glacial Lake Peipsi inundated large areas of the Saadjärve Drumlin Field and the Emajõgi River valley and also reached the Lake Võrtsjärv basin. In the Saadjärve Drumlin Field area this event is reflected in the formation of the highest shoreline and simultaneous varved clay accumulation. Our study suggests that suitable conditions for the settling of glacial varved clay existed only in the deepest inter-drumlin basins at critical (minimal) water depths of about 15–20 m.
- Proglacial conditions in the Saadjärve Drumlin Field lasted for about 150 years and were interrupted due to the isolation of the inter-drumlin lakes from proglacial lakes in the Peipsi and Võrtsjärv basins after the formation of the second highest shoreline. In bottom sediments this isolation is marked by the transition from laminated sediments to a massive silt interval.
- About 14.0–13.8 cal. kyr BP the connection route between Glacial Lake Peipsi and proglacial Lake Strenči in Latvia shifted from the Võhandu–Hargla valley to the Väike-Emajõgi valley and the strait between Glacial Lake Peipsi and large Lake Privalday in NW Russia closed.

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Ida-Eesti jääpaisjärvede veetaseme muutused ja paleogeograafia: uusi andmeid Saadjärve voorestiku piirkonnast

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On esitatud Ida-Eestis eksisteerinud hilisjääaegsete jääpaisjärvede paleogeograafilised rekonstruktsioonid. Uuringu tulemused näitavad, et ligikaudu 14 000–13 800 kalendriaastat tagasi, kui mandrijää serv oli taandunud Laeva-Piirissaare servamoodustiste vööndini, kujunes Emajõe oru ja Saadjärve voorestiku kaudu ühendus Peipsi ning Võrtsjärve nõos eksisteerinud jääpaisjärvede vahel. Nimetatud ajaperioodil ujutas jääpaisjärve vesi Saadjärve voorestiku madalamad osad üle, kujundades piirkonna kõrgeima rannamoodustiste vööndi absoluutkõrgusel 68–64 m. Samal ajal, kuid suhteliselt lühikese perioodi (kuni 63 aastat) vältel, settisid voortevahelistes nõgudes vähemalt 15–20 m sügavuses vees viirsavid. Nimetatud kõrgeima rannavööndi rannamoodustised korreleeruvad hästi Kagu-Eesti hilisjääaegsete oruterrasside kõrgustega, mis kajastavad Peipsi ja Võrtsjärve jääpaisjärvede veetasemeid, lubades ühtlasi järeldada nimetatud paleoveekogude sarnast veetaset. Jääjärvelised settimistingimused Saadjärve voorestiku järvenõgudes kestsid ligikaudu 150 aastat ja katkesid arvatavasti seoses voortevaheliste järvede isoleerumisega suurest jääpaisjärvest pärast liustikuserva taandumist Siimusti-Kaiu joonelt põhja poole. Järvenõgude põhjasetetes markeerib isoleerumissündmust üleminek rütmiliselt kihitatud aleuriidilt homogeenseks aleuriidiks. Paleogeograafilised rekonstruktsioonid näitavad, et mandrijää taandudes Otepää servamoodustiste joonelt Laeva-Piirissaare vööndini toimus Peipsi jääpaisjärve ja Loode-Venemaal eksisteerinud ulatusliku Privaldai jääpaisjärve vahelise väina sulgumine, samuti muutus ühendustee Peipsi jääpaisjärve ja Põhja-Lätis eksisteerinud Strenči jääpaisjärve vahel.