

**DEVELOPMENT OF PROGLACIAL
LAKES IN ESTONIA**

ALAR ROSENTAU



TARTU UNIVERSITY
PRESS

The Faculty Council of Biology and Geography, University of Tartu, has on September 28, 2006 accepted this dissertation to be defended for the degree of Doctor of Philosophy (in Geology).

Supervisors: Prof. Volli Kalm, University of Tartu
PhD Tiit Hang, University of Tartu

Opponent: Dr. habil. Szymon Uścińowicz, Polish Geological Institute, Poland

This thesis will be defended at the University of Tartu, Estonia, on November 24, 2006, at 14.15 in Vanemuise 46, room 246

The publication of this dissertation has been funded by Institute of Geology, University of Tartu.

ISSN 1406–2658
ISBN 9949–11–470–5 (trükis)
ISBN 9949–11–471–3 (PDF)

Autoriõigus Alar Rosentau, 2006

Tartu Ülikooli Kirjastus
www.tyk.ee
Tellimus nr 582

CONTENTS

LIST OF PAPERS	6
ABSTRACT.....	7
INTRODUCTION	8
1. BACKGROUND AND EARLIER STUDIES	12
2. MATERIAL AND METHODS.....	18
2.1. Lake basin investigations.....	18
2.2. Shoreline investigations.....	18
2.3. Water-level reconstruction and analysis	19
2.4. Palaeogeographical methods.....	20
2.5. Time scale.....	22
3. RESULTS AND DISCUSSION.....	23
3.1. Reconstruction of water-level changes in proglacial lakes.....	23
3.1.1. Proglacial lakes during the Otepää Stade	23
3.1.2. Proglacial lakes during the Laeva–Piirissaar and Siimusti–Kaiu Stades	24
3.1.3. Proglacial lakes during the Pandivere–Neva and Palivere Stades.....	25
3.2. Tilting of proglacial lakes shorelines and glacioisostacy	28
3.3. Changes in shoreline tilting directions	30
3.4. Shore displacement curve for the Lake Peipsi basin	31
3.5. Palaeogeographical reconstructions	34
3.6. Development history of the proglacial lakes in Estonia and their connections with neighbouring water bodies	35
CONCLUSIONS	39
ACKNOWLEDGEMENTS.....	41
REFERENCES	42
SUMMARY IN ESTONIAN: Jääpaisjärvede areng Eestis.....	47
PAPERS I–IV	49

LIST OF PAPERS

This thesis is based on following published and unpublished papers, which are referred to by their Roman numeras:

- I. **Rosentau, A.**, Hang, T. and Miidel, A. 2004: Simulation of the shorelines of glacial Lake Peipsi in Eastern Estonia during the Late Weichselian. *Geological Quarterly* 4, 13–21.
- II. **Rosentau, A.**, Hang, T., Kalm, V. Water-level changes and palaeogeography of proglacial lakes in eastern Estonia: synthesis of data from Saadjärve Drumlin Field area. (manuscript).
- III. **Rosentau, A.**, Vassiljev, J., Saarse, L. and Miidel, A. 2007: Palaeogeographic reconstruction of proglacial lakes in Estonia. *Boreas* 36, 1–11 (in press, accepted 1st August 2006).
- IV. **Rosentau, A.**, Vassiljev, J., Saarse, L. and Miidel, A. Proglacial lake shorelines of Estonia and adjoining areas. *Polish Geological Institute Special Papers* (in press, accepted 6th April 2006).

The author of this thesis initiated the studies and performed all palaeogeographic analyses and 60–80% of manuscript preparation. The author carried out the fieldwork collecting the empirical data in Paper II and undertook the data analyses. Tiit Hang and Avo Miidel are responsible for shoreline data and correlations in Paper I and Jüri Vassiljev, Leili Saarse and Avo Miidel for shoreline data and correlations in Paper III. The author participated in the analyses of shoreline data in Paper IV.

ABSTRACT

This PhD thesis presents a GIS-based palaeogeographic reconstruction of the development of the proglacial lakes during the deglaciation of Estonia and examines their relationship with each other and with the neighbouring water bodies. Ice marginal positions, correlation and timing of late glacial shoreline data and modern digital terrain model were used. The study is based on investigations of the coastal landforms and proglacial lake sediments from the Saadjärve Drumlin Field and interpretation of previously studied shoreline data. The main results presented in four scientific papers are included in the thesis. The study reveals that the development of the large proglacial lakes in Estonia started about 14.7 cal. kyr BP when a deep water Glacial Lake Peipsi formed in south-eastern Estonia. This lake shared strait-like connections with Privalday Lake in the east and a proglacial lake in the Gauja basin in the west. Following the ice retreat, Glacial Lake Peipsi extended to the north, inundating the Emajõgi River valley and large areas of the Saadjärve Drumlin Field, and reaching the Lake Võrtsjärv basin. This is manifested in the Saadjärve Drumlin Field by the formation of the highest shoreline about 14.0–13.8 cal. kyr BP and by accumulation of glacial varved clay. About 13.3 cal. kyr BP a large proglacial lake in western Estonia (stage A₁) was formed, followed about 12.8 cal. kyr BP by proglacial lake stage A₂ at a lower height. Evidence demonstrates that proglacial lakes A₁ and A₂ formed within a north-easterly elongated bay of the Baltic Ice Lake (BIL), which developed in Estonia earlier than previously suggested. The BIL had the same water level as Glacial Lake Peipsi, because these water bodies were connected *via* straits from central and northern Estonia. The study concludes that shore displacement of proglacial lakes in Estonia between 14.7–12.8 cal. kyr BP was regressive, induced by glacioisostatic land uplift and existence of the connection routes with neighbouring water bodies. The compiled shore displacement curve shows that regressive shore displacement continued in central part of the Lake Peipsi basin until 12.1–11.7 cal. kyr BP and then transformed into transgression that still continues.

INTRODUCTION

The last deglaciation of the Scandinavian ice sheet produced a huge volume of meltwater that led to formation of large proglacial lakes, such as Baltic Ice Lake (BIL) and Privalday Lake (Kvasov, 1979; Björck, 1995; Mangerud *et al.*, 2004). Their development and drainage history was influenced by the intensity of the ice melting and retreat, location of the outlets and by glacioisostatic movements of the Earth's crust. The study of proglacial lakes provides insight into the development of ancient water bodies and landscapes and to glacioisostatic phenomena. The most prominent features of proglacial lakes are glacioisostatically raised and therefore tilted shorelines around the Baltic Sea coast (Agrell, 1976; Svensson, 1991). Empirical and theoretical models show strong relationships between glacioisostatic uplift and proglacial lake shoreline tilting pattern in heavily ice loaded areas (Mörner, 1978; Björck, 1995; Svensson, 1991; Lambeck *et al.*, 1998). There is much less agreement in the literature regarding the isostatic behaviour in the peripheral areas of the glacioisostatic uplift, where the thickness and load of ice was less. It has been demonstrated that in such areas the glacioisostatic process is highly affected by climatic, hydroisostatic and other factors (Lambeck *et al.*, 1998; Lampe, 2005). Several regional studies of Scandinavian and Laurentide glaciation identify the role of marginal displacement of the crust in peripheral areas involving an upward bulging effect (forebulge) during deglaciation and its later collapse (Bylinski, 1990; Fjeldskaar, 1994; Harff *et al.*, 2001; Dyke and Peltier, 2000; Hetherington *et al.*, 2004). Several large proglacial lakes developed in Estonia during the last deglaciation, traced in the relief by glacioisostatically raised shorelines, which were investigated in detail in earlier studies (Orviku, 1958; Lõokene, 1959; Pärna, 1960; Raukas and Rähni, 1969; Liblik, 1969; Raukas *et al.*, 1971). Due to the limited number of study regions, difficulties in the dating of late glacial shorelines and owing to the different intensity of glacioisostatic uplift, the reconstruction of the developmental history of proglacial lakes is complicated. During the past decade, the use of digital terrain models in GIS-based reconstructions of former water bodies has opened new perspectives for reconstruction of proglacial lakes and exploring their distribution, water depth and drainage history (Mann *et al.*, 1999; Leverington *et al.*, 2002; Mangerud *et al.*, 2004). In this PhD thesis, GIS-based reconstructions of spatial distribution and bathymetry of Estonian proglacial lakes are used to interpret their relations with each other and with the neighbouring water bodies. It also explores the proglacial lakes water level changes and provides new empirical shoreline data from the Saadjärve Drumlin Field area.

The current study is aimed at reconstruction of the development history of proglacial lakes in Estonia and sets the following tasks:

- (1) to reconstruct the water level change in proglacial lakes;
- (2) to describe the effect of glacioisostatic movements to changes in water level of proglacial lakes;
- (3) to reconstruct the distribution and water depths of proglacial lakes;
- (4) to examine the relationship of the Estonian proglacial lakes with neighbouring proglacial lakes.

This study comprises data from four scientific papers that address the development of proglacial lakes and water-level changes in Estonia and neighbouring areas, which are summarised in the following section.

PAPER I

Rosentau, A., Hang, T. and Miidel, A. 2004: Simulation of the shorelines of glacial Lake Peipsi in Eastern Estonia during the Late Weichselian. *Geological Quarterly* 4, 13–21.

The development of Glacial Lake Peipsi was studied using the two geomorphological correlation approaches following the Raukas and Rähni (1969) and Hang (2001) and GIS-based palaeogeographic reconstructions. The study introduces and discusses the potential and limitations of palaeogeographic reconstruction based on GIS analysis, by which interpolated water-level surfaces and average thickness of Holocene peat deposits were systematically subtracted from the modern digital terrain model. The configuration of shorelines, main outlets and water depths of Glacial Lake Peipsi, corresponding to Otepää, Piiressaar, Kaiu and Pandivere–Neva Stades during the deglaciation of the Lake Peipsi depression, have been reconstructed.

PAPER II

Rosentau, A., Hang, T., Kalm, V. Water-level changes and palaeogeography of proglacial lakes in eastern Estonia: synthesis of data from Saadjärve Drumlin Field area. (manuscript).

We studied the water-level changes and palaeogeography of proglacial lakes in eastern Estonia using the shoreline and sediment distribution proxies from Saadjärve Drumlin Field, geomorphological correlation and GIS-based palaeogeographic reconstructions. Our results show that about 14.0–13.8 cal. kyr BP the waters of Glacial Lake Peipsi inundated large areas of the Saadjärve Drumlin Field and Emajõgi River valley, and reached to the Lake Võrtsjärv basin. This is manifested in the Saadjärve Drumlin Field by accumulation of glacial varved clay in different interdumlin basins over a short period (up to

63 years) and by the formation of highest shoreline, which correlates well with the valley terraces in south-eastern Estonia and which reflects the water-levels in Glacial Lake Peipsi and the proglacial lake in the Võrtsjärv basin. Study suggests the suitable conditions for 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 separation of the lakes from proglacial lakes in the Peipsi and Võrtsjärv basins after the formation of the second highest shoreline. Our results show that about 14.0–13.8 cal. kyr BP the connection route between Glacial Lake Peipsi and proglacial lake in Gauja basin in Latvia shifted from Võhandu–Hargla valley to Väike–Emajõgi valley and the strait between Glacial Lake Peipsi and large Privalday Lake in NW Russia emerged initiating the inflow into Glacial Lake Peipsi.

PAPER III

Rosentau, A., Vassiljev, J., Saarse, L. and Miidel, A. 2007: Palaeogeographic reconstruction of proglacial lakes in Estonia. *Boreas* 36, 1–11 (in press, accepted 1st August 2006).

This paper presents a GIS-based palaeogeographic reconstruction of the development of proglacial lakes formed during deglaciation in Estonia and examines their common features and relations with the Baltic Ice Lake. Ice marginal positions, interpolated proglacial lake water-levels and a digital terrain model were used to reconstruct the spatial distribution and bathymetry of the proglacial lakes. Our results suggest that the proglacial lakes formed a bay of the Baltic Ice Lake since the halt at the Pandivere–Neva ice margin at about 13.3 cal. kyr BP. Shoreline reconstruction suggests that two major proglacial lake systems, one in eastern and the other in western Estonia, were connected *via* straits from central and northern Estonia and thus had identical water levels. The water budget calculations show that a strait from central Estonia was able to pass a water volume several times greater than the melting glacier could produce. As this strait compensated for the water level difference between the proglacial lakes in east and west, the subsequent further merging in north Estonia did not result in catastrophic drainage, as earlier proposed.

PAPER IV

Rosentau, A., Vassiljev, J., Saarse, L. and Miidel, A. Proglacial lake shorelines of Estonia and adjoining areas. Polish Geological Institute Special Papers (in press, accepted 6th April 2006).

A uniform database of coastal landforms of proglacial lakes in Estonia, Latvia and NW Russia was created and used to reconstruct the spatial distribution of the proglacial lakes using kriging point interpolation and GIS approaches. Correlation of the late glacial coastal landforms confirms that the proglacial lake stage A₁ in Estonia is synchronous with the Bgl_I level in Latvia and with one level in NW Russia, whose index was not defined. Proglacial lake A₁ was formed concurrently with the Pandivere-Neva ice-margin about 13,300 cal. yr BP. Proglacial lake A₂ formed probably about 12,800 cal. yr BP and its water level coincides with the level of Bgl_{II} in Latvia and G_{III} in NW Russia. Simulated isobases of proglacial lake water-levels suggest a relatively regular pattern of land uplift along the eastern coast of the Baltic and in the northern part of the Lake Peipsi basin, with a steeper tilt to the northwest. Isobases in the southern part of Lake Peipsi basin bend towards the southeast and are up to 14 m higher than the regional trend suggests. This phenomenon can reflect the forebulge effect during deglaciation and its later collapse. Shoreline reconstruction suggests that proglacial lakes in the Peipsi and Baltic basins were connected via strait systems and had identical water levels. Our reconstructions also show that after the glacier margin halt at the Pandivere–Neva ice margin about 13,300 cal. yr BP, there was a connection with the Baltic Ice Lake in the west of Gulf of Riga.

1. BACKGROUND AND EARLIER STUDIES

Development of the proglacial lakes in Estonia is closely associated with the deglaciation of the area, which took place between 15.7 and 12.7 cal. kyr BP (Kalm, 2006; Fig. 1A). Four morphologically expressed zones of ice-marginal formations (Haanja, Otepää, Pandivere and Palivere) have been identified in Estonia (Kalm, 2006), some of which have been correlated with ice-marginal formations in neighbouring areas in NW Russia (Haanja–Luga, Pandivere–Neva) and Latvia (Kalm, 2006; Fig. 1A). In addition, Piirissaar–Laeva and Kaiu–Siimusti ice marginal positions are recognized in eastern Estonia (Raukas *et al.*, 1971) and Sakala ice marginal position in western Estonia (Fig. 2; Raukas *et al.*, 1971; Rattas and Kalm, 2004).

Two major proglacial lake systems developed in Estonia during the last deglaciation, one in the Lake Peipsi basin (Glacial Lake Peipsi) in eastern Estonia (Raukas and Rähni, 1969; Hang, 2001) and the other in western Estonia (Lõokene, 1959; Pärna, 1960; Raukas *et al.*, 1971; Kessel and Raukas, 1979). Glacial Lake Peipsi formed in the southern part of the Lake Peipsi depression (Raukas and Rähni, 1969; Raukas *et al.*, 1971; Hang, 2001) when the continental ice retreated from the Haanja–Luga marginal formations to the Otepää line and enlarged to the north correspondingly with ice retreat (Fig. 2). It has been suggested that at the time of the Otepää Stade Glacial Lake Peipsi was a part of the marginal water bodies in front of the Scandinavian ice sheet extending to the North Sea (Fig 1B; Kvasov, 1979). Due to the ice retreat to the Laeva–Piirissaar line and deglaciation of the Emajõgi River valley (Fig. 2), Glacial Lake Peipsi joined with the proglacial lake in the Lake Võrtsjärv basin (Raukas *et al.*, 1971). The proglacial lake in western Estonia formed during the Pandivere–Neva Stade (Fig. 2), when western Estonia became ice-free (Lõokene, 1959; Pärna, 1960; Raukas *et al.*, 1971). This proglacial lake can be traced in relief by the two highest shorelines – proglacial lake stages A₁ (Voose Ice Lake) and A₂ (Kemba Ice Lake). In addition, the proglacial lake stage A₃ (Nõmme Ice Lake; Pärna, 1962; Raukas *et al.*, 1971) was proposed to have formed in western Estonia when ice retreated to Palivere ice margin position (Fig. 2) but this lake is very poorly defined (Vassiljev *et al.*, 2005) and its development is not addressed in this study.

Different hypotheses have been proposed to explain the relations between Glacial Lake Peipsi and the proglacial lake in western Estonia (stages A₁, A₂) and their connection with the Baltic Ice Lake (Björck, 1995). Pärna (1960) had proposed that Glacial Lake Peipsi had a higher water level than proglacial lake A₁, but later (Pärna, 1962) suggested that Glacial Lake Peipsi was part of the proglacial lake A₁. Most Estonian researchers have considered that shorelines of A₁ and A₂ in western Estonia correspond to shores of local and separate ice lakes (Lõokene, 1959; Pärna, 1960 Kessel and Raukas, 1979) and BIL formed

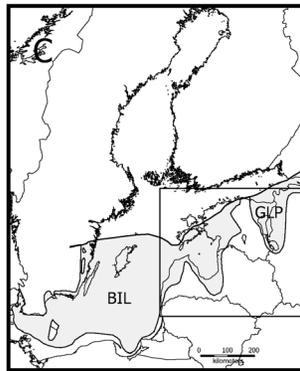
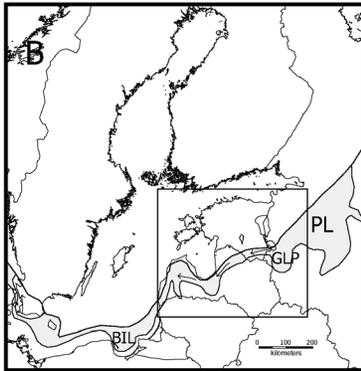
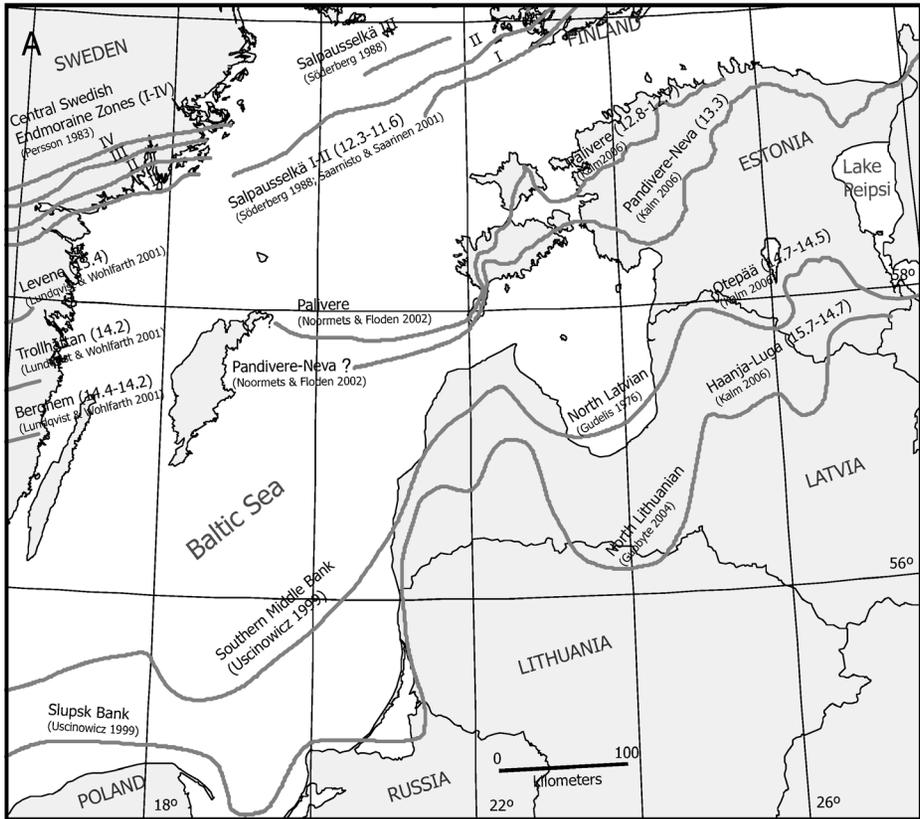


Fig. 1. A. Main late glacial ice marginal positions around the Baltic with ages (cal. kyr BP) according to Kalm (2006), Lundqvist and Wohlfarth (2001) and Saarnisto and Saarinen (2001). **B–C.** Overview maps showing the palaeogeography of Privalday Lake (B) about Otepää stade (PL; Kvasov, 1979) and early Baltic Ice Lake (C) about Pandivere-Neva Stade (BIL; Björck 1995) in relation to Glacial Lake Peipsi (GLP). The area of palaeogeographic reconstructions in Fig. 10 is marked by a rectangle.

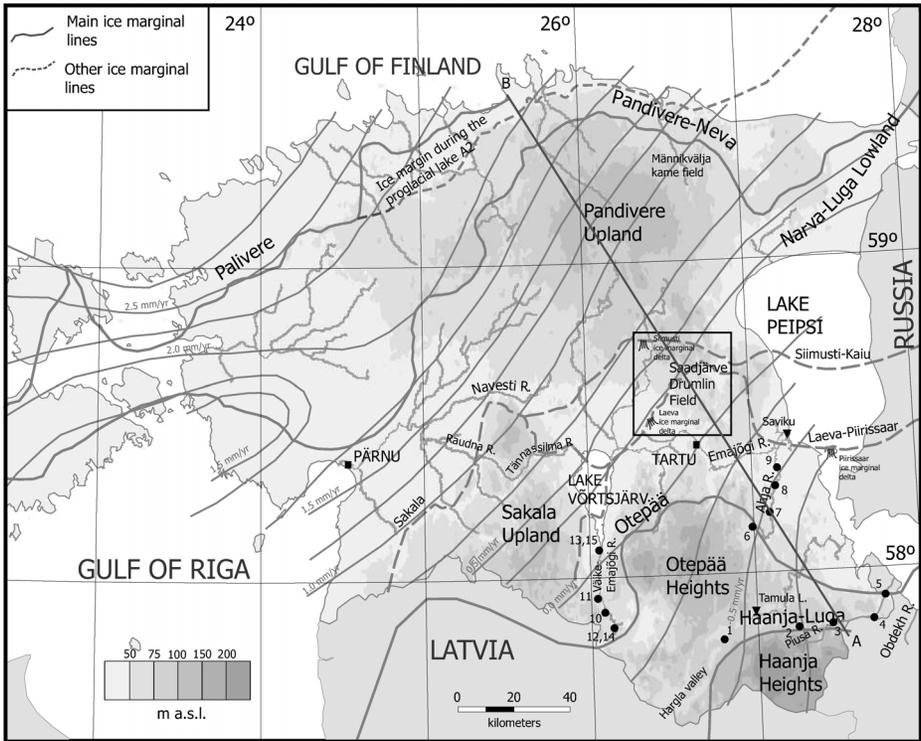


Fig. 2. Map of the Estonia showing the lateglacial ice-marginal positions, present-day vertical crustal movements (Torim, 1998) and site locations. Dots with numbers refer to the valley terraces reflecting the proglacial lake water-levels in southern part of Lake Peipsi (Hang *et al.*, 1995; Liblik, 1966) and Võrtsjärv basins (Palusalu, 1967): 1 Hargla valley (79–73 m a.s.l.), 2–5 Piusa valley (95–71.5; 62–60; 51–45; 41–33), 6–9 Ahja valley (62.5–61.5; 54–50; 44–41; 39–34), 10–15 Väike-Emajõgi valley (61; 61), 12–13 (41; 41), 14–15 (38; 38). The location of the cross-section in Fig. 5 (line A–B) is shown on map. The local study area at Saadjärve Drumlin Field is marked by a rectangle.

only when the ice had retreated to the Salpausselkä end-moraines as it was defined in Finland (Fig. 1A; Glückert, 1995). Kvasov and Krasnov (1967) and later Kvasov and Raukas (1970) suggested that the ice retreat at Männikvälja Kame Field (Fig. 2) at the end of the Pandivere–Neva Stade caused a catastrophic drainage of Glacial Lake Peipsi into the proglacial lake A₂ in western Estonia, which indicated the beginning of the BIL. They compared the impact of this event with the final drainage of BIL at Billingen in Sweden. However, this suggestion has been challenged by the lack of drainage varves in the Lake Peipsi basin (Hang, 2001). Furthermore, recent re-examination of available data on the late glacial coastal landforms of Estonia showed that the

water levels of proglacial lake stages A₁ and A₂ in western Estonia were same to the water level of Glacial Lake Peipsi (Vassiljev *et al.*, 2005). Björck (1995) indicated that about 14.0 cal. yr BP the eastern coast of the BIL extended to western Estonia (Fig. 1C). However, he agrees that the reconstruction of the eastern part of the BIL remains theoretical.

Altitudinal correlation of coastal landforms and valley terraces has been used to reconstruct the proglacial lakes water levels in Estonia (Raukas and Rähni, 1969; Raukas *et al.*, 1971; Hang, 2001). Such correlation depends on the glacioisostatic movements of the Earth's crust, which results in the tilting of the shorelines. Owing to the different intensity of glacioisostatic movements (Fig. 2), correlation of shoreline data within and between proglacial lakes is complicated. This has resulted in different opinions regarding changes in water levels of proglacial lakes, partly presented in Table 1. The shoreline tilting of proglacial lakes A₁ and A₂ in northern and north-western Estonia is estimated to be *ca.* 50 cm km⁻¹ and *ca.* 40 cm km⁻¹, respectively (Vassiljev *et al.*, 2005). Tilting of these shorelines decreases towards the southeast, being *ca.* 30–20 cm km⁻¹ in Saadjärve Drumlin Field area (Fig. 2) and less (*ca.* 5–10 cm km⁻¹) in the south-eastern areas (Vassiljev *et al.*, 2005). Study of valley terraces from south-eastern Estonia led Hang *et al.* (1995) to estimate a similar shoreline tilting gradient (5 cm km⁻¹) for Glacial Lake Peipsi. This estimate has been substantiated by a correlation of coastal landforms on the western coast of the Lake Peipsi basin (*ca.* 4–9 cm km⁻¹; Liblik, 1969) and by geological data from the over-deepened river mouths of the Emajõgi, Ahja and Obdekh rivers (Fig. 2 in Rosentau *et al.*, 2004 – Paper I).

Several attempts have been made to correlate the proglacial lake shorelines in Estonia with shorelines in neighbouring areas (Kessel and Raukas, 1979; Donner and Raukas, 1989). A wide spectrum of late glacial shorelines have been differentiated in Latvia and NW Russia, some of which are said to have formed synchronously with proglacial lakes in western Estonia (Table 2).

Table 1. Proglacial lake water levels (m a.s.l.) in Peipsi basin and in western Estonia according to different authors.

	Otepää	Laeva-Piirisaar	Siimusti-Kaiu	Pandivere-Neva		Palivere	
	L.Peipsi basin	L.Peipsi basin	L.Peipsi basin	L.Peipsi basin	W.Estonia	L.Peipsi basin	W.Estonia
Pärna, 1960					A ₁ (Voose Ice Lake), 85–41 and A ₂ (Kemba Ice Lake), 72–38		A ₃ (Nõmme Ice Lake), 40
Raukas and Rähini, 1969	Pihkva Ice Lake I, 95–70	Pihkva Ice Lake II, 90–45	Peipsi Ice Lake I, 86–40	Peipsi Ice Lake II and III, 80–38			
Raukas <i>et al.</i> , 1971	Pihkva Ice Lake I, 95–70	Pihkva Ice Lake II, 90–45	Peipsi Ice Lake I, 86–40	Peipsi Ice Lake II and III, 80–38	A ₁ (Voose Ice Lake), 85–41 and A ₂ (Kemba Ice Lake), 72–38	Peipsi Ice Lake IV	A ₃ (Nõmme Ice Lake), 30–40
Hang, 2001	Glacial Lake Peipsi, >75	Glacial Lake Peipsi, 62–60	Glacial Lake Peipsi, 54–45	Glacial Lake Peipsi, 44–32			
Vassiljev <i>et al.</i> , 2005				stages A ₁ , 90–42 and A ₂ , 75–40	stages A ₁ , 90–42 and A ₂ , 75–40		

Table 2. Relationships between Estonian (Kessel and Raukas, 1979), Latvian (Grinbergs, 1957) and NW Russian (Markov, 1931) proglacial lake stages according to Donner and Raukas (1989).

Estonia	Latvia	NW Russia
Voose Ice Lake	Bgl _I	G _I -G _{II}
Kemba Ice Lake		G _I -G _{II}
Nõmme Ice Lake	Bgl _{II}	G _I -G _{II}

2. MATERIAL AND METHODS

2.1. Lake basin investigations

Proglacial lake sediments from six successively isolated small lake basins from the Saadjärve Drumlin Field (Fig. 2), close to the supposed highest shoreline of Glacial Lake Peipsi (Raukas *et al.*, 1971) were investigated in order to detect the changes in water level of proglacial lakes and to estimate the duration of proglacial lake conditions. The lake sediments were cored from the lake ice and at the shores with a Russian type peat corer (chamber length 1m, inside diameters 5 and 2 cm). The distribution (altitude, thickness) of glaciolacustrine sediments in lake basins was mapped according to our and previously (Pirrus, 1983; Saarse and Kärson, 1982) compiled cross-sections. The previously compiled cross-sections were checked in the field at 3–10 locations along each profile to unify the descriptions of sediments with our lithostratigraphy. Master cores were taken from each lake for detailed lithostratigraphical description and varve counting at the locations providing the most complete late glacial stratigraphical record. Two parallel sediment sequences with 0.5 m overlap were used to collect the master cores. Six master cores and 39 compiled profiles were used for interpretation (Fig. 2 in Rosentau *et al.*, manuscript – Paper II).

2.2. Shoreline investigations

Shoreline study was carried out in the Saadjärve Drumlin Field to detect the late glacial water-level changes in the region. Special focus was directed to identifying the highest shoreline for the area. Altitude measurements and coring of coastal landforms were used for shoreline investigation. A GIS database of previously studied coastal landforms was completed prior to fieldwork and later complemented with new data. Previously investigated coastal landforms were confirmed in the field before being accepted as water-level indicators. Coastal scarps from the Raigastvere and Soitsjärv lake basins (Fig 2. in Rosentau *et al.*, manuscript – Paper II) were instrumentally measured. Other coastal landforms were observed in the field and their altitudes ascertained from topographic maps on a scale of 1:10,000. Coordinates for sites were obtained using the hand-GPS. Altogether 38 coastal landforms were used for interpretation.

The coastal landforms were divided into two groups according to altitude: sites above, and sites below the highest Holocene shoreline, which was determined according to previous data on sediment distribution, stratigraphy and radiocarbon datings (Saarse and Kärson, 1982; Pirrus, 1983; Pirrus and Rõuk, 1979). Coastal landforms were projected to the cross-section and shores

above the highest Holocene shoreline were first visually correlated. Thereafter, the linear regression 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 identified shores. Finally, 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 towards to an azimuth of 326° reflecting the azimuth of the fastest tilting of shorelines (Hang *et al.*, 1995).

2.3. Water-level reconstruction and analysis

Water-levels of proglacial lakes were reconstructed for different time periods on the basis of altitudes and estimated ages of shoreline data from Rosentau *et al.*, manuscript – Paper II and previously published papers. For Estonia the coastal landforms database of proglacial lake stages A_1 and A_2 , (Vassiljev *et al.*, 2005) and the data of the valley terraces from Lake Peipsi (Liblik, 1966; Hang, 2001) and Lake Võrtsjärv basins (Palusalu, 1967) and coastal landforms from Saadjärve Drumlin Field area (Rosentau *et al.*, manuscript – Paper II) was used. The Estonian shoreline database of proglacial lake stages A_1 and A_2 (Vassiljev *et al.*, 2005) was supplemented with the coastal landforms from Latvia (Grinbergs, 1957) and NW Russia (Markov, 1931). Altogether, 158 sites from Estonia, Latvia and NW Russia were used in different water-level reconstructions (Fig. 3).

Water levels were reconstructed by correlating altitudes of shoreline data and their interpolation into the water-level surfaces. Two approaches were used for water level surface interpolation. Correlation of shoreline data of proglacial lake stages A_1 and A_2 follows the methodology of Vassiljev *et al.* (2005) based on point kriging interpolation with a linear trend. The advantage of this method is that it interpolates accurate surfaces from irregularly spaced sites and helps to examine the irregularities of the surfaces. Due to the limited shoreline data the reconstruction of other water-level surfaces were based on linear solution of Natural Neighbour interpolation using the constant shoreline tilting direction towards to the azimuth of 326° (see Rosentau *et al.*, 2004 – Paper I for detailed description). The grid size of the interpolated surfaces was 5×5 km.

The geometry of the water level surfaces of the proglacial lakes were analysed using spatial statistics, such as surface profiling and terrain aspect. Terrain aspect was used to characterize the azimuth of the fastest uplift for A_1 and A_2 water-level surfaces. All the spatial statistic calculations were performed using Conformal Transverse Mercator projection: TM-Baltic (Estonian Land Board, 1996). The Surfer program was used for water-level surfaces reconstructions and MapInfo Vertical Mapper for surface profiling and terrain aspect calculations.

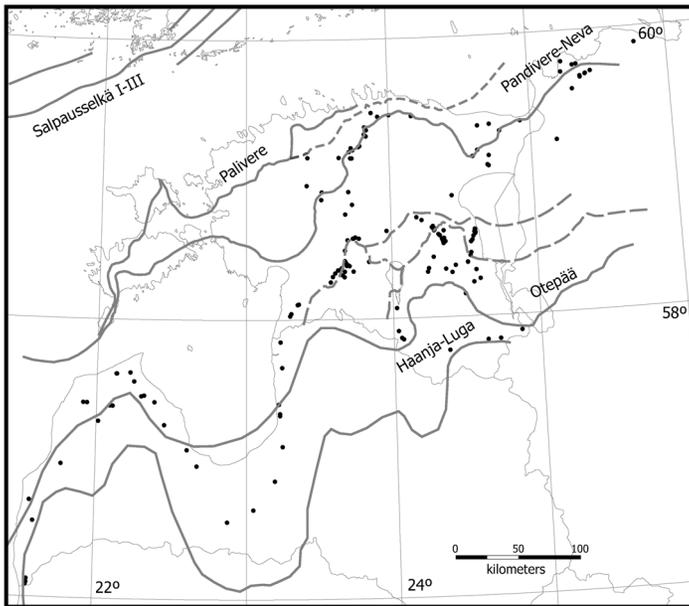


Fig. 3. Distribution of coastal landforms and valley terraces in Estonia, Latvia and NW Russia used in water-level reconstructions in relation to the late glacial ice marginal positions.

2.4. Palaeogeographical methods

Reconstruction of proglacial lake shorelines and bathymetry was based on GIS analysis, by which interpolated water-level surfaces and average thickness of Holocene peat deposits were systematically subtracted from the modern digital terrain model (DTM; Fig. 4; see Rosentau *et al.*, 2004 – Paper I for complete description).

The DTM with a grid size 200×200 m was generated from the Digital Base Map of Estonia in scale 1:50,000 (Estonian Land Board, 1996). For neighbouring areas the Shuttle Radar Topography Mission (CIAT, 2004) and Baltic Sea topography (Seifert *et al.*, 2001) data was used. The DTM was complemented with more detailed elevation data: Soviet topographic maps on a scale of 1:10,000 for the Emajõgi River valley and Lake Võrtsjärv bottom and topographic maps on a scale of 1:25,000 for the Saadjärve Drumlin Field, Navesti River valley and Männikvälja Kame Field (Fig. 2).

The Holocene peat deposits were subtracted from DTM in 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). The water depths and mapped thicknesses (Rosentau *et al.*,

manuscript – Paper II; Saarse and Kärson, 1982; Pirrus, 1983; Pirrus and Rõuk, 1979) of Holocene deposits (peat, gyttja and lake marl) of lake basins in the Saadjärve Drumlin Field study area (Fig. 2) were subtracted from the DTM. After the subtracting of the Holocene deposits, lake water depths and the interpolated water level surface from DTM, the shoreline and bathymetry were deduced for proglacial lakes. The MapInfo Vertical Mapper was used for palaeogeographical reconstructions.

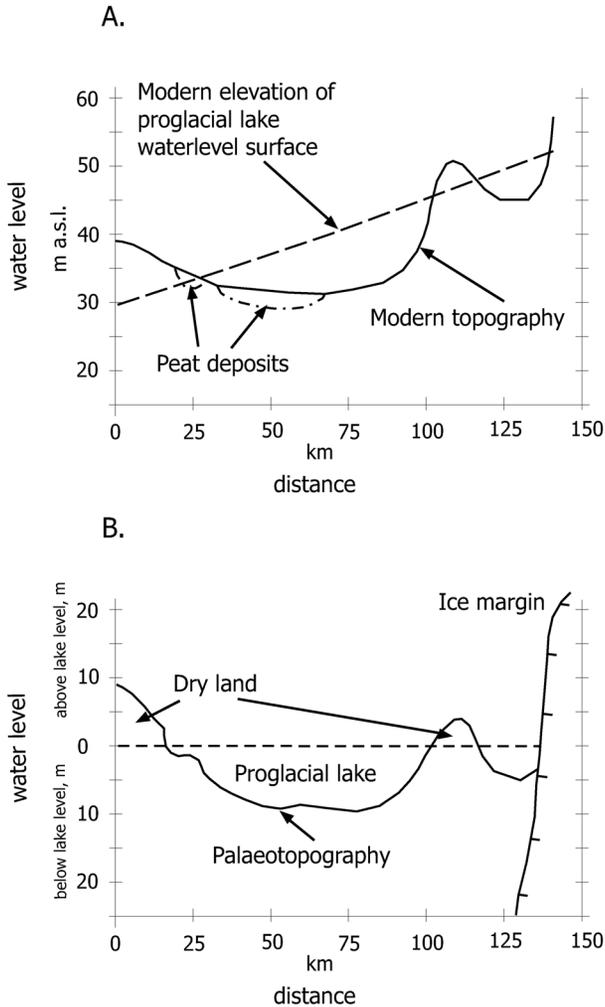


Fig. 4. Principle cross-sections showing the current topography in relation to isostatically deformed (uplifted) proglacial lake water level surface today (A) and during proglacial lake formation (B).

2.5. Time scale

The dating of proglacial lakes is based on calendar years time scale referred as cal. yr BP or cal. kyr BP (thousand years). Due to the difficulties in dating late glacial coastal landforms and valley terraces, the proglacial lake ages were mostly estimated on the basis of dating of ice-marginal formations (Kalm, 2006) and on the basis of varve chronological data (Sandgren *et al.*, 1997; Hang, 2001). Radiocarbon dates (Sarv and Ilves, 1975) was used to calculate the shore displacement for Lake Peipsi. Radiocarbon dates were calibrated using the OxCal v3.10 calibration programme (Bronk Ramsey, 2001) based on the atmospheric data for the Northern Hemisphere (Reimer *et al.*, 2004).

3. RESULTS AND DISCUSSION

3.1. Reconstruction of water-level changes in proglacial lakes

3.1.1. Proglacial lakes during the Otepää Stage

Reconstruction of water-levels in Glacial Lake Peipsi during the Otepää Stage (Rosentau *et al.*, 2004 – Paper I) is based on a series of horizontal terraces at glaciolacustrine deposits in the Piusa and Hargla valleys at altitudes of 95–71.5 m a.s.l. and 79–73 m a.s.l., respectively (Fig. 2; Liblik, 1966). Results show that these terraces were formed within the strait between Glacial Lake Peipsi and the proglacial lake in Gauja basin and therefore represent the lake water-levels (Rosentau *et al.*, 2004 – Paper I). Terraces in Piusa and Hargla valleys reflect a gradual lowering of the base level of Glacial Lake Peipsi during the Otepää Stage (Liblik, 1966; Hang *et al.*, 1995). The age of the beginning of the terrace formation in Piusa–Hargla valley was estimated according to the start of the varved clay accumulation in Lake Tamula (Fig. 2), dated at 14.7 cal. kyr BP

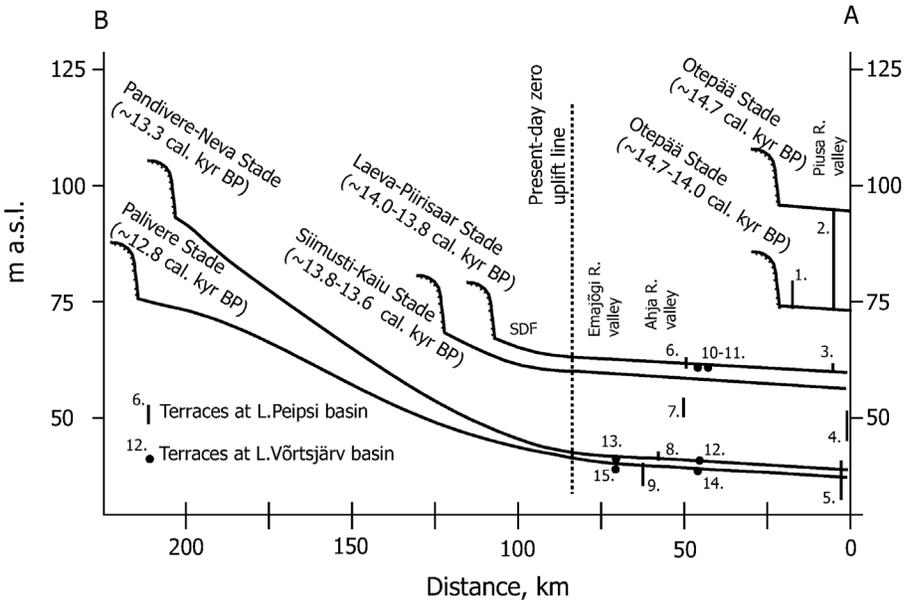


Fig. 5. Reconstruction of proglacial lake water-levels between 14.7–12.8 cal. kyr BP at different ice-margin positions. The locations of profile and valley terraces with numbers are shown in Fig. 2.

(corrected varve years in Kalm, 2006; after Sandgren *et al.*, 1997). This age reflects the deglaciation and start of glaciolacustrine conditions in Piusa–Hargla valley (Sandgren *et al.*, 1997) and therefore the approximate age of the beginning of the terrace formation at the highest level. Two water-levels (Fig. 5) were tentatively identified in Glacial Lake Peipsi during the Otepää Stade, representing the beginning of the terrace formation in the Piusa valley at an altitude of 95 m a.s.l. (Liblik, 1966), and secondly the emergence of the strait at Piusa–Hargla valley at an altitude of 73 m a.s.l. (Rosentau *et al.*, 2004 – Paper I). Reconstruction of the water-levels is based on an estimated shoreline tilting gradient of 5 cm km⁻¹ for Glacial Lake Peipsi in south-eastern Estonia (Hang *et al.*, 1995).

3.1.2. Proglacial lakes during the Laeva–Piirissaar and Siimusti–Kaiu Stades

Reconstruction of proglacial lake water-levels during Laeva–Piirissaar and Siimusti–Kaiu Stades (Fig. 2) is based on the identified shoreline altitudes from the Saadjärve Drumlin Field study area (Rosentau *et al.*, manuscript – Paper II) and their correlation with late glacial valley terraces in Lake Peipsi (Hang *et al.*, 1995) and Lake Võrtsjärv (Palusalu, 1967) basins.

Two late glacial shorelines were identified in the Saadjärve Drumlin Field using the correlation of investigated coastal landforms. The highest shoreline at an altitude of 68–64 m a.s.l. formed in front of the Laeva–Piirissaar ice margin about 14.0–13.8 cal. kyr BP and the second highest shoreline was formed 4 m lower in front of the Siimusti–Kaiu ice margin at about 150 years later (Rosentau *et al.*, manuscript – Paper II). The elevation of the highest shoreline was verified by comparison with the distribution of glacial varved clays. Systematic coring of lake sediments revealed a short period (up to 63 years) of formation of glacial varved clays in front of the Laeva–Piirissaar ice margin (Rosentau *et al.*, manuscript – Paper II). Results show the formation of glacial varved clays only in the deepest parts of the interdrumlin 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 is about 15–20 m (Pirrus, 1968; Hang, 2001). Therefore, the critical water-level during the varved clay accumulation in interdrumlin basins must have been about 75–70 m in central part and 65–60 m in southern part of the study area. These inferred critical water-levels are in good agreement with the altitude of the highest shoreline and supports the elevation of the highest shoreline determined from geomorphological data (Fig. 5 in Rosentau *et al.*, manuscript – Paper II).

According to altitudes of two highest shorelines and DTM the open connection between proglacial lakes in Saadjärve Drumlin Field area and proglacial lakes in Peipsi and Võrtsjärv basins must have existed in front of the Laeva–Piiressaar and Siimusti–Kaiu ice margins. The water-level correlation in Rosentau *et al.*, manuscript – Paper II shows that the highest shoreline in the Saadjärve Drumlin Field area correlates with the valley terraces of the Laeva–Piiressaar Stade, which represent the water-level in southern part of the Glacial Lake Peipsi (Hang, 2001), and also with the highest late glacial terraces 61 m a.s.l. at Väike–Emajõgi valley reflecting the water-level of proglacial lake in Võrtsjärv basin (Fig. 5; Palusalu, 1967). This correlation agrees with the relatively low (5 cm km^{-1}) estimate of shoreline tilting in south-eastern Estonia (Hang *et al.*, 1995), which increases towards to north being *ca.* 28 cm km^{-1} in the Saadjärve Drumlin Field area during the Laeva–Piiressaar Stade (Fig. 5; Rosentau *et al.*, manuscript – Paper II). The second highest shoreline displays a similar tilting gradient (*ca.* 24 cm km^{-1}) in the Saadjärve Drumlin Field area (Rosentau *et al.*, manuscript – Paper II). However, this shoreline shows *ca.* 5 m higher water-level than valley terraces of the Siimusti–Kaiu Stade (Fig. 6), which represent the water-level in the southern part of Glacial Lake Peipsi (Hang, 2001). Considering the calculated proglacial lakes regression rates in eastern Estonia of between 14.0–13.3 cal. kyr BP (*ca.* 2m/100 years; Rosentau *et al.*, manuscript – Paper II), it was concluded that most probably the second highest shoreline is a few hundred years older than the terraces of Kaiu Stade.

3.1.3. Proglacial lakes during the Pandivere–Neva and Palivere Stades

Reconstruction of proglacial lake water-levels during the Pandivere–Neva and Palivere Stades (Fig. 2) is based on correlation of coastal landforms of proglacial lake stages A₁ and A₂ (Vassiljev *et al.*, 2005) with late glacial coastal landforms in Latvia (Grinbergs, 1957) and NW Russia (Markov, 1931) and with late glacial valley terraces in the Peipsi (Hang, 2001) and Võrtsjärv basins (Palusalu, 1967; Miidel *et al.*, 2004).

Results show that the ice-proximal shoreline data of proglacial lake stage A₁ matches well with the Pandivere–Neva ice margin, dated by varve chronology at 13.3 cal. kyr BP (Hang, 2001; Kalm, 2006), representing the age of this shore (Rosentau *et al.*, 2007 – Paper III). The inferred position of the ice front during the proglacial lake A₂ near the Palivere ice marginal zone (Fig. 2; Pärna, 1960) and water-level comparisons with the BIL levels from Sweden (Svensson, 1991; Björck, 1995) suggests that the formation of proglacial lake A₂ took place prior to the first drainage of the BIL, most likely at about 12.8 cal. kyr BP (Rosentau *et al.*, 2007 – Paper III), which is equivalent with the age

of the Palivere stade (12.8–12.7 cal. kyr BP; Kalm, 2006). This age is about 400–300 years older than previously proposed (Vassiljev *et al.*, 2005).

Simulation of the water-level surface isobases (Rosentau *et al.*, in press – Paper IV; Fig. 6A–B) shows that proglacial lake A₁ water-level correlates well with the coastal landforms of the highest shoreline (stage Bgl_I) in Latvia (Grinbergs, 1957) and with coastal landforms 63 m a.s.l. in NW Russia (Markov, 1931), and the water-level of the proglacial lake A₂ correlates well with the second highest shoreline (stage Bgl_{II}) in Latvia (Grinbergs, 1957) and G_{III} in NW Russia (Markov, 1931). These correlations show that the isobases of the proglacial lakes A₁ and A₂ are distributed relatively regularly in a northeast-southwest direction along the eastern coast of the Baltic Sea and in the northern part of the lake Peipsi basin (Fig. 6A–B).

In the central part of the Lake Peipsi basin, the isobases of the proglacial lake A₁ and A₂ curve notably towards the southeast, being higher than expected from the regular northeast-southwest oriented isobase pattern (Fig. 6A–B). The cause of the curving is attributed to a lowering of the tilting gradient to *ca.* 10–5 cm km⁻¹. Similar low tilting gradients (5 cm km⁻¹) were suggested for the southern part of the Glacial Lake Peipsi on the basis of the correlation of terraces at Ahja and Piusa valleys formed during the Pandivere–Neva Stade (Hang, 2001). Moreover, the altitudes of these terraces are the same with proglacial lakes A₁ and A₂ water-levels (Rosentau *et al.*, manuscript – Paper II). Hang (2001) suggested that the terraces at an altitudes of 44–41 m a.s.l. in Ahja valley correspond to the Pandivere-Neva ice-margin position (Fig. 2) and the terraces at 39–34 m a.s.l. formed during the ice retreat from this position. Water-level surfaces of proglacial lakes A₁ and A₂ at Ahja valley show the same altitudes as these terraces: 41 m a.s.l and 39 m a.s.l., respectively (Fig. 2; Rosentau *et al.*, manuscript – Paper II). The terraces in the Väike-Emajõgi valley (40 m a.s.l and 38 m a.s.l; Fig. 2; Palusalu, 1967) also exhibit similar altitudes to lakes A₁ and A₂, reflecting probably the late glacial water-levels of proglacial lake in the Võrtsjärv basin (Miidel *et al.*, 2004). Therefore, it is likely that coastal landforms of proglacial lake A₁ and A₂ formed synchronously with the above-mentioned terraces and can be use to expand the A₁ and A₂ correlations to south-eastern Estonia (Fig. 6C–D). As expected, the water-level surface isobases in this simulation display a continuous curvature in south-eastern Estonia.

By eliminating the proxy data attributed to the curvature of proglacial lake isobases in south-eastern Estonia, a scenario of regularly distributed water-level surface isobases was simulated for A₁ and A₂ stages (Fig. 6E–F). This simulation displays higher magnitude of shoreline tilting in south-eastern Estonia and predicts the proglacial lakes A₁ and A₂ water-levels in southern end of the Lake Peipsi basin at altitudes of 0 and 10 m, respectively (Fig. 6E–F). According to the maximum incision of the Obdekh River valley (Fig. 2)

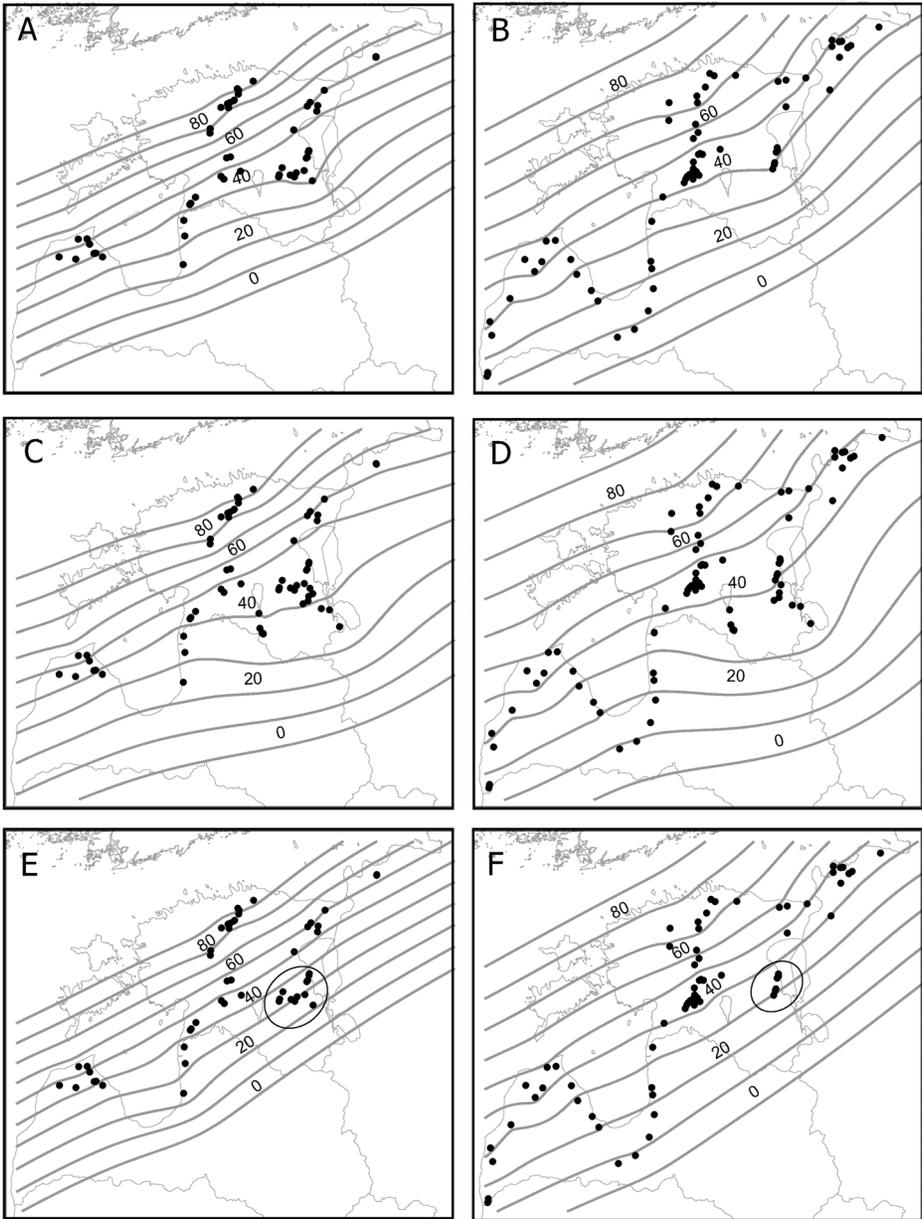


Fig. 6. Simulations of water-level surface isobasis during the proglacial lake stage A₁ about 13.3 cal. kyr BP (A,C,E) and stage A₂ about 12.8 cal. kyr BP (B,D,F). Simulation A–B considers only the coastal landforms proxies, C–D coastal landforms and valley terraces and E–F coastal landforms without proxies marked by circle.

the lowest water level in the Peipsi basin (Lake Small Peipsi stage) was reported for the southern end of the lake at an altitude of 20 m a.s.l. (Fig. 2; Miidel *et al.*, 1995; Hang *et al.*, 1995). Thus, the simulation in Fig. 6E–F clearly contradicts geological data by showing a 10–20 m lower water-level. Therefore, it is concluded that most likely the shoreline tilting in south-eastern Estonia (Fig. 6C–D) differs from the expected regional shoreline tilting pattern (Fig. 6E–F). Low tilting seems to be common to late glacial shorelines in south-eastern Estonia as the correlation of older coastal landforms and valley terraces formed during the Otepää, Laeva–Päärissaar and Siimusti–Kaiu Stades also suggest (Fig. 5).

3.2. Tilting of proglacial lakes shorelines and glacioisostasy

Comparison of water-level profiles of proglacial lakes (Fig. 5) suggests the highest magnitude of shoreline tilting in north-western Estonia and relatively low shoreline tilting in south-eastern Estonia. In northern Estonia shoreline tilting decreases from 60–50 cm km⁻¹ (stage A₁) to 30 cm km⁻¹ (stage A₂) between 13.3–12.8 cal. kyr BP (Fig 5.; Rosentau *et al.*, 2007 – Paper III). Shoreline tilting gradients in northern Estonia decrease further during the Holocene, *ca.* 25 cm km⁻¹ for the Ancylus Lake stage and *ca.* 13 cm km⁻¹ for Littorina Sea stage (Saarse *et al.*, 2003). This trend reflects the ongoing (Fig. 2) and regular glacioisostatic land uplift process in northern Estonia with the decreasing magnitude of land uplift with time.

At the Saadjärve Drumlin Field in the east-central part of Estonia, the shoreline tilting gradients are lower, being *ca.* 28–25 cm km⁻¹ at 14.0–13.3 cal. kyr BP and decreasing slightly between 13.3–12.8 cal. kyr BP, which results in a tilting gradient of *ca.* 19 cm km⁻¹ during the proglacial lake A₂ (Rosentau *et al.*, manuscript – Paper II). Southeast of the Saadjärve Drumlin Field the shoreline tilting decreases rapidly to *ca.* 10–5 cm km⁻¹ at 13.3 cal. kyr BP and 12.8 cal. kyr BP (Rosentau *et al.*, 2007 – Paper III). Comparison of the proglacial lakes A₁ and A₂ isobases (Fig. 6C–D) with recent vertical movement of the Earth’s crust reveals that the distinct lowering in shoreline tilting (from 28–19 cm km⁻¹ to 10–5 cm km⁻¹) is related to the current zero land uplift isobase (Figs. 7; Rosentau *et al.*, 2007 – Paper III). Recent regional vertical movements indicate that the southern margin of the Baltic Shield is enclosed by a belt of subsidence, which could be associated with a collapsed structure of a circum-Fennoscandian ring bulge of the upper mantle after melting of the Weichselian ice sheet (Fig. 7; Bylinski, 1990; Fjeldskaar, 1994; Harff *et al.*, 2001). Measurements of the recent vertical movements place the subsidence belt in south-eastern Estonia with the lowest values in the southern part of the

Lake Peipsi basin ($-0,7$ mm/yr by Torim, 1996 or -1.6 by Randjärv, 1993 or $-2-3$ by Harff *et al.*, 2001), whereas regular uplift occurs to the north (Figs. 2, 7). This pattern of crustal tilting coincides well with the Late Weichselian shoreline tilting pattern (Figs. 6C–D and 8) and could reflect the ongoing forebulge collapse in south-eastern Estonia (Rosentau *et al.*, 2007 – Paper III).

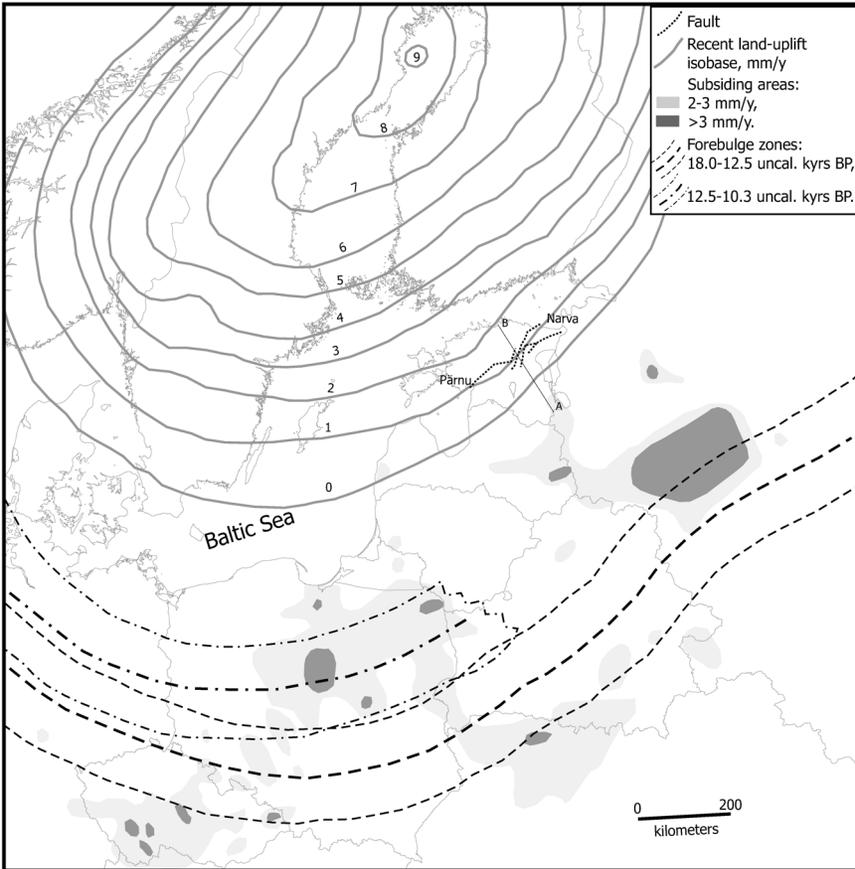


Fig. 7. Map of the Fennoscandian land-uplift (Ekman, 1996) and peripheral subsiding region associated with collapsing forebulge (Harff *et al.*, 2001). This subsiding area coincides approximately with two possible forebulge zones identified according to the increased incision and high sedimentation rates of rivers by Bylinski (1990). The location of the cross-section (A–B) in Fig. 5 is shown on the map.

Development of the rivers and lakes support the forebulge hypothesis in south-eastern Estonia and the neighbouring areas in Russia (Grachev and Dolukhanov, 1970; Bylinski, 1990). The forebulge in NW Russia and Eastern Europe was studied in detail by Bylinski (1990). He identified two major forebulge zones (Fig. 7) formed about 18.0–12.5 and 12.5–10.3 uncal. kyr BP and argued that the forebulge caused the increased incision and high sedimentation rates of rivers in these areas. It is probable that the great depth of the late glacial valleys (up to 70 m) in south-eastern Estonia and in the northern Pskov region (Russia), discharging water into the Peipsi basin, is related to the Bylinski's forebulge (Rosentau *et al.*, 2007 – Paper III). This uplift might also have produced a regression and formation of several isolated waterbodies in the southern part of the Lake Peipsi basin and the adjoining areas (Hang and Miidel, 1999). At the end of the Late Weichselian the rapid land-uplift included the northern part of the Lake Peipsi basin and subsidence became prevalent in the south (Rosentau *et al.*, 2007 – Paper III; see also chapter 3.4).

In addition to the effect of the forebulge, the tectonic fault zone between Pärnu and Narva (Fig. 7) could have affected the uplift of shorelines (Orviku, 1960; Pärna, 1960, 1962; Vallner *et al.*, 1988). Seismic events have also occurred in the Pärnu–Narva fault zone (Sildvee and Vaher, 1995). Evidence of the reactivation of old fault zones related with glacial unloading and accompanied by strong earthquakes in the Late Weichselian and Holocene has been found in many parts of Fennoscandia (Lundqvist and Lagerbäck, 1976; Mörner, 1978; Ojala *et al.*, 2004). However, the Pärnu–Narva fault zone is located north of the position where distinct lowering in shoreline tilting has been found (Figs. 5, 7). Proglacial lakes shoreline tilting and recent vertical movements support the forebulge hypothesis in southeast Estonia but no conclusive data has been obtained yet to substantiate this hypothesis.

3.3. Changes in shoreline tilting directions

The direction of the fastest shoreline tilting for proglacial lake stages A₁ and A₂ in Estonia was estimated (Rosentau *et al.*, 2007 – Paper III) and compared to the well-developed BIL stage B₃ (Saarse *et al.*, 2003) formed about 11.6 cal. kyr BP (Björck, 1995). The mean directions of the fastest tilting (Table 3 in Rosentau *et al.*, 2007 – Paper III) agree with those previously reported: for proglacial lakes A₁ and A₂ 335° and for B₃ 326° (Pärna, 1962). The direction of the fastest tilting is not a fixed value but varies, as their standard deviations indicate (Table 3 in Rosentau *et al.*, 2007 – Paper III). Higher variability in directions of the fastest tilting is reflected in the curvature of proglacial lake A₁ and A₂ isobases.

The results indicate that the direction of the fastest tilting was rather similar during the proglacial lakes A₁ and A₂, but migrated westward during B₃

(Fig. 8). This westerly trend continued in Estonia from the late Holocene and reached *ca.* 320° for the post-Littorina (Kessel and Raukas, 1979) being currently *ca.* 310° (derived from the isobase map of recent vertical crustal movements in Fig. 2). This trend in the change of the fastest tilting direction probably reflects the changes in glacioisostatic land uplift patterns related to deglaciation of the Scandinavian ice sheet and corresponding to the migration of glaciation centre to the west (Rosentau *et al.*, 2007 – Paper III).

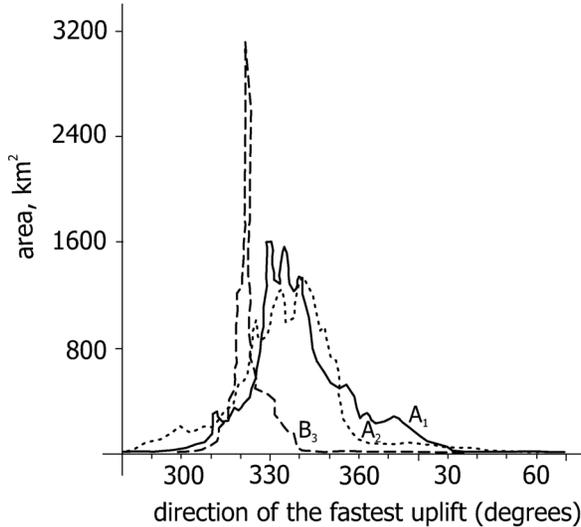


Fig. 8. Direction of the fastest uplift for A₁, A₂ and B₃ water level surfaces given as a frequency distribution diagram, where y-axis represents the sum of grid cells area (in km²) for an appropriate fastest uplift direction given in x-axis in degrees (Rosentau *et al.*, 2007 – Paper III). Calculations for A₁, A₂ and B₃ water level surfaces were performed within the same area showed by a square on Fig. 3 in Rosentau *et al.*, 2007 – Paper III.

3.4. Shore displacement curve for the lake Peipsi basin

Shore displacement curve (Fig. 9) was compiled for the central part of the Lake Peipsi basin using the altitudes of identified water-levels (Fig. 5) and radio-carbon dates from fen peat at Saviku section (Fig. 2; Sarv and Ilves, 1975). The shore displacement curve in Fig. 9 suggests the continuation of regression of the water body in Lake Peipsi basin after formation of the proglacial lake A₂ (Fig. 5), which agrees well with the previous shore displacement data for Lake Peipsi basin (Hang *et al.*, 1995). The minimum water level (23 m a.s.l.; 7 m below the current level) occurred 12.1–11.7 cal. kyr BP (Table 4; Fig. 9), 500–

100 years before the last drainage event of the BIL at 11.6 cal. kyr BP (Björck, 1995). The lowest water level at the end of the Late Weichselian (Lake Small Peipsi stage) was reported at similar altitude (*ca.* 10 m below the present Lake Peipsi level; Hang *et al.*, 2001) from the northern part of the Lake Peipsi basin. After this low level (23 m a.s.l.) relatively intense regression transformed into transgression with continuous water level rise up to the present (Fig. 9).

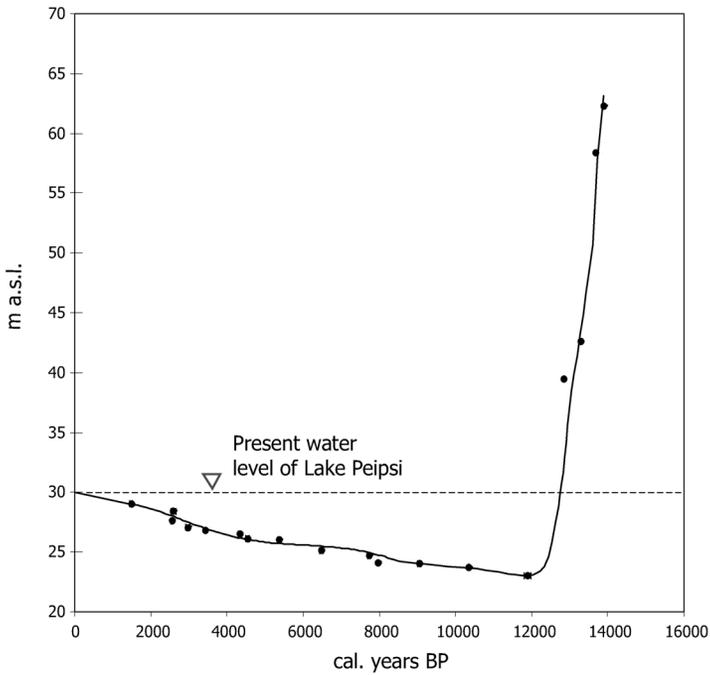


Fig. 9. Shore displacement curve for the central part of Lake Peipsi basin. The compiled shore displacement curve is based on altitudes of identified water-level surfaces shown in Fig. 5 and radiocarbon dates (Sarv and Ilves, 1975), improved by palynological data of fen peat at Saviku section (Fig. 2; Table 3). The use of the radiocarbon data from fen peat for shore displacement curve is based on assumption that the water-level rise and the growth of fen peat was in equilibrium (Hang *et al.*, 1995). All data was referenced to the Saviku section, located on the mouth of the Emajõgi River (Fig. 2).

Table 3. Data used to compile the shore displacement curve for Lake Peipsi basin in Fig. 9. All data were referenced to the Saviku section, located at the mouth of the Emajõgi River (Fig. 2).

Site	Altitude, m a.s.l.	¹⁴ C-years, BP ^a	Calibrated years, BP ^b
Laeva-Piirissaar	62.3		~14000–13800
Siimusti-Kaiu	58.4		~13800–13600
stage A ₁	42.6		~13300
stage A ₂	39.5		~12800
Saviku	23.1–23.0	10200±90	12080–11710
Saviku	23.8–23.7	9090±70	10380–10320
Saviku	24.1–24.0	8090±70	9140–8970
Saviku	24.2–24.1	7110±70	8010–7920
Saviku	24.8–24.7	6900±70	7800–7660
Saviku	25.2–25.1	5690±70	6570–6400
Saviku	26.1–26.0	4620±60	5470–5290
Saviku	26.2–26.1	4060±70	4630–4430
Saviku	26.6–26.5	3880±60	4420–4240
Saviku	26.9–26.8	3130±60	3450–3420
Saviku	27.2–27.1	2850±70	3070–2870
Saviku	27.7–27.6	2570±70	2760–2690
Saviku	28.5–28.4	2490±60	2720–2470
Saviku	29.1–29.0	1620±50	1560–1410

^a Radiocarbon years according to Sarv and Ilves (1975)

^b Radiocarbon dates were calibrated using the OxCal v3.10 calibration programme (Bronk Ramsey, 1995) based on the atmospheric data for for the Northern Hemisphere (Reimer *et al.*, 2004). The uncertainties of ¹⁴C dates are reported as 1 sigma.

General shape of the shore displacement curve in Fig. 9 differs from relative sea level (RSL) curves from the Estonian coastal areas, which show more or less continuous emergence (Kessel and Raukas, 1979). A comparison of Fig. 9 with the RSL curves is possible only indirectly due to the absent connection with the Baltic Sea during the Holocene. Nevertheless, some conclusions can be made about the glacio-isostatic movement of the area. The postglacial RSL curves in previously glaciated areas are of three general forms: sites that were heavily ice-loaded exhibit continuous emergence, peripheral sites exhibit initial emergence followed by submergence, a “J-shaped” curve” and more distal sites exhibit continuous submergence (Dyke and Peltier, 2000). Fig. 9 clearly depicts the “J-shaped” form characteristic of curves in peripheral areas of the glacioisostatic uplift region (Fig. 7) and is interpreted to have formed as a result of glacioisostatic uplift during the Late Weichselian, which turned probably into land subsidence during the Holocene. The land subsidence still continues in central and southern part of the Lake Peipsi basin, as show by measurements

of the recent vertical movements (Figs. 2 and 7) and archaeological finds below the modern lake level (Hang and Miidel, 1999).

3.5. Palaeogeographical reconstructions

The distribution of proglacial lakes and their water depths at six times between 14.7–12.8 cal. kyr BP were reconstructed (Fig. 10A–G) based on DTM and reconstruction of water-level changes discussed in Chapter 3.1 and summarized in Fig. 5.

The reliability of the reconstructions depends on the abundance and distribution of the shoreline proxy data. The data used to reconstruct the proglacial lakes during the Pandivere–Neva (56 sites) and Palivere stades (79 sites) provides good data coverage along the reconstructed shoreline and are therefore most representative (Fig. 10F–G). Due to the scarcity and uneven distribution of shoreline data for proglacial lakes during the Otepää (1 site and 2 sites), Laeva–Piiressaar (10 sites) and for Siimusti–Kaiu Stades (10 sites), the reconstructions are less reliable. There is no late glacial shoreline data available from the southern and eastern coast of Glacial Lake Peipsi and therefore extrapolation was used in order to examine the extension of Glacial Lake Peipsi into these areas (Fig. 10B–F).

Reconstructed proglacial lake shorelines coincide relatively well with the positions of shoreline proxy data, indicating that the DTM and digital reconstruction technique is suitable for proglacial lake studies (Fig. 10B–F). The addition of detailed elevation data from topographic maps (1:25,000 and 1:10,000 scale) for the Emajõgi and Navesti River valleys, Männikvälja Kame Field and Saadjärve Drumlin Field improved the model and made it possible to examine the narrow connection routes between proglacial lakes in eastern and western Estonia (Fig. 10A; Rosentau *et al.*, 2007 – Paper III) and the shallow water archipelago at the Saadjärve Drumlin Field (Fig. 10A; Rosentau *et al.*, manuscript – Paper II).

This study marks the first attempt to reconstruct Estonian proglacial lake water-depth. Reconstructed lake water-depth is dependent on the subsequent deposition and erosion since the time being modelled (Leverington *et al.*, 2002; Rosentau *et al.*, 2004 – Paper I). Although the peat deposits of the Holocene age were removed from the DTM, other postglacial deposits and landforms influenced the reconstruction of lakes water depth, especially at the larger sediment deposition areas in western Estonia and Peipsi and Võrtsjärv basins. In the northern part of the Lake Peipsi basin and in Võrtsjärv basin the Holocene gyttja and lake marl deposits have been reported to be up to 6 m (Hang *et al.*, 2001) and up to 10 m thick (Pirrus and Raukas, 1984), respectively. In western Estonia at Pärnu area (Fig. 2) the postglacial Baltic Sea deposits and coastal landforms have been described as at least 10 m thick

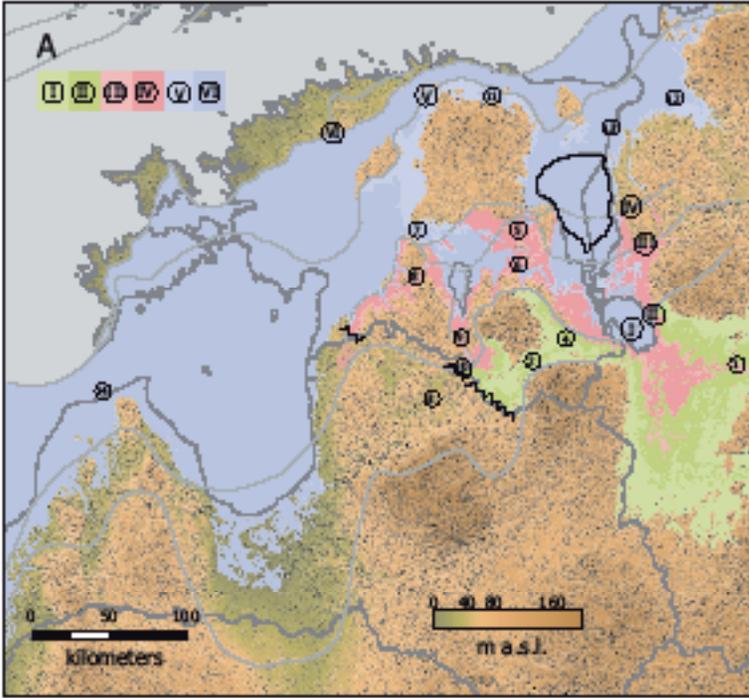


Fig 10. A. Palaeogeographic reconstruction of the proglacial lakes in Estonia and their relation with neighbouring water bodies. Lake stages are indicated by different colours and related to ice-margin positions: I,II Otepää Stade, III Laeva-Piirisaar Stade, IV Siimusti-Kaiu Stade, V Pandivere-Neva Stade and VI Palivere Stade. Dashed line marks the position of predicted shoreline of Lake Small Peipsi stage about 12.1–11.7 cal. kyr BP. Modern DTM (CIAT, 2004) and locations discussed in the text are shown on the map: 1. Porkhov strait, 2. Piusa-Hargla strait, 3. Proglacial lakes in Gauja basin, 4. Võhandu-Hargla strait, 5. Archipelago at Saadjärve Drumlin Field, 6. Emajõgi strait, 7. Navesti strait, 8. Tännassilma-Raudna strait, 10. Threshold at Valga, 11. Männikvälja strait, 12. Luga Bay, 13. Present threshold of Lake Peipsi at Narva River valley, 14. Connection with BIL. B–G. Shoreline and bathymetry of proglacial lakes for different ice margin positions and water-levels: B. Otepää stade, 95–90 m a.s.l., C. Otepää stade, 77–71 m a.s.l. D. Laeva-Piirisaar stade, 68–60 m a.s.l.; E. Siimusti-Kaiu stade, 67–56 m a.s.l.; F. Pandivere-Neva stade, 93–40 m a.s.l. and G. Palivere stade 76–38 m a.s.l. Thin grey lines on the map are lake water-level isobasis. Reconstruction of water-level changes in proglacial lakes is shown in Fig. 7. For background the modern DTM (CIAT, 2004) is shown on the maps.

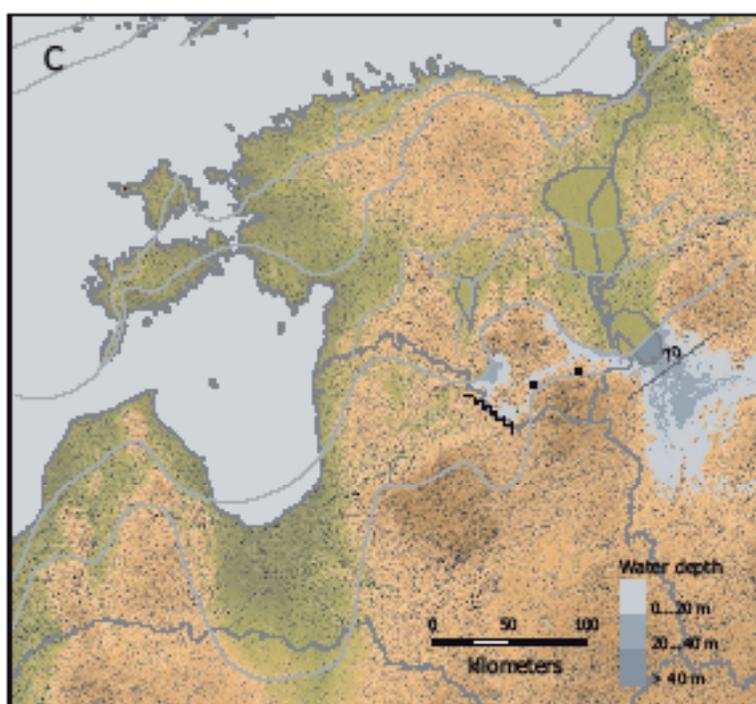
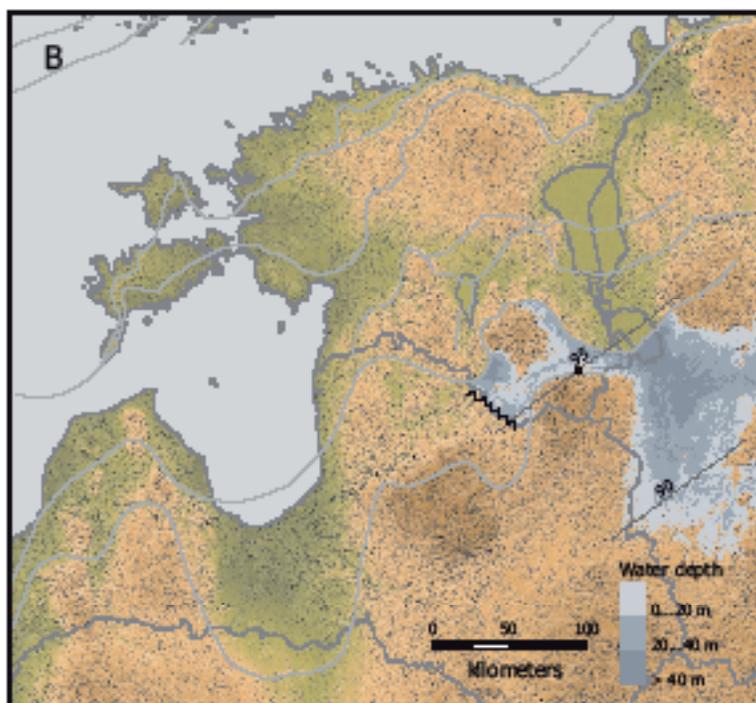


Fig 10. Continuation

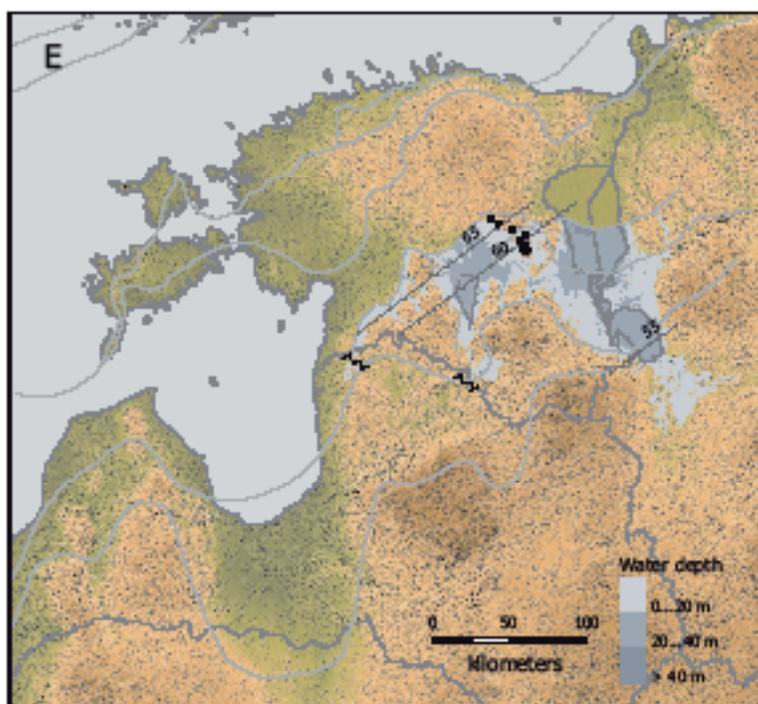
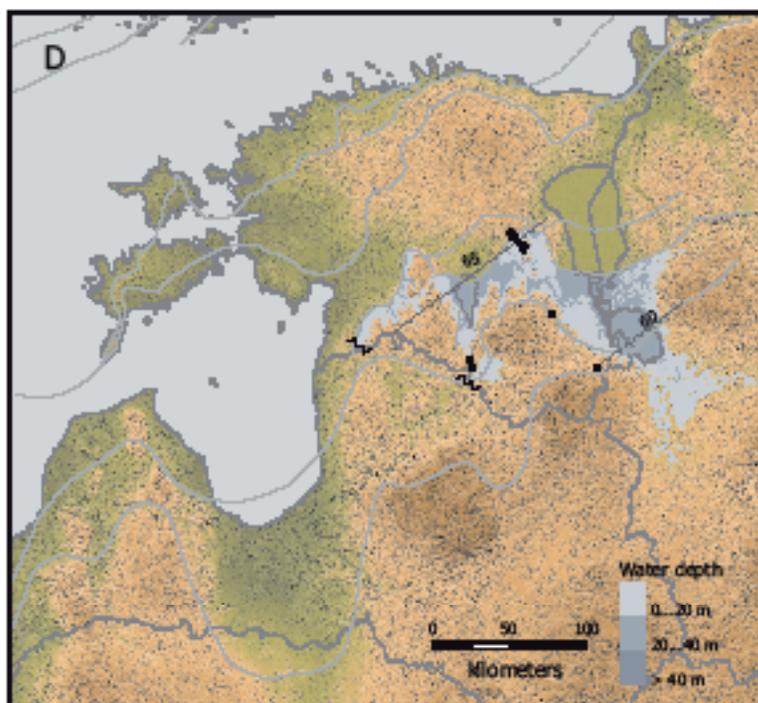


Fig 10. Continuation

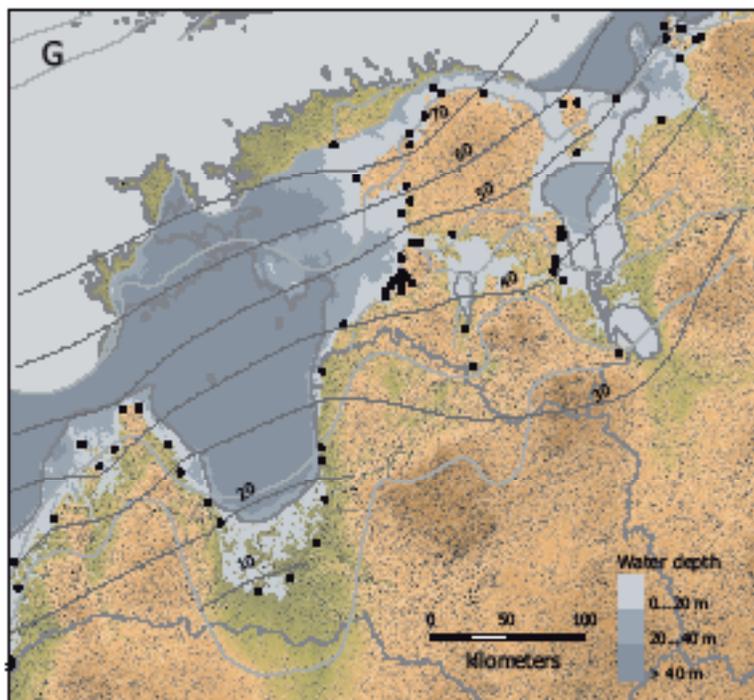
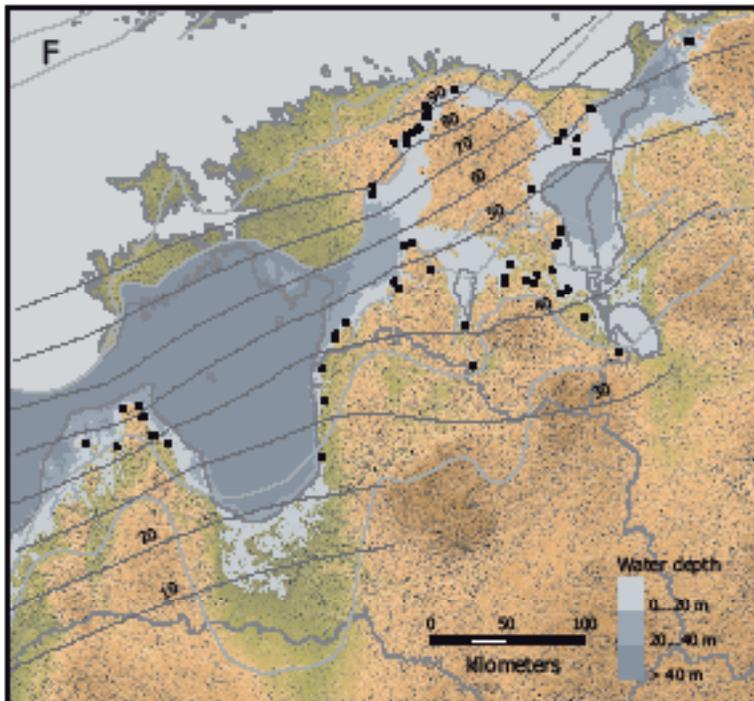


Fig 10. Continuation

(Veski *et al.*, 2005). Thus, the water-depth should be greater than the reconstructions show. Unfortunately, geological information on the spatial distribution of sediment thicknesses is insufficient to subtract the lacustrine sediments from the DTM.

3.6. Development history of the proglacial lakes in Estonia and their connections with neighbouring water bodies

Development of the proglacial lakes was studied using the palaeogeographic reconstructions of the lake shorelines and water depth presented in Fig. 10A–G. Timing of the proglacial lakes and the main palaeogeographic events in their development was discussed in Papers I–IV and summarized in Fig. 11.

Reconstruction of proglacial lakes between 14.7–12.8 cal. kyr BP shows regressive shore displacement induced by glacioisostatic land uplift and existence of various connection routes with neighbouring water bodies (Fig. 10A). Due to gradual deglaciation of new thresholds at lower altitudes, the proglacial lakes connection routes continuously shifted resulting in withdrawal of shorelines to lower altitudes (Fig. 5;10A). Proglacial lakes were ice-contact lakes centred in the modern lake depressions and lowlands showing the greatest water depths in these areas. The bathymetrical configuration of the lakes suggests the most suitable conditions for glacial varved clays accumulation (water depth > 20 m) in the Gulf of Riga, Peipsi and Võrtsjärv basins and in West Estonian, Narva–Luga and Pskov lowlands (Fig. 10B–G). The studies of varved clays from the Gulf of Riga (Kalm *et al.*, 2006), northern part of the Lake Peipsi basin (Hang, 2001), in western Estonian (Hang and Sandgren, 1996) and Narva–Luga lowlands (Rähni, 1963) support this suggestion.

Development of large proglacial lakes in Estonia started at about 14.7 cal. kyr BP when a deep-water (water depth dominantly >20 m) Glacial Lake Peipsi formed in south-eastern Estonia (Fig. 10A–B). This lake had relatively wide straits towards the east via Porkhov strait to Privalday Lake and to west via Piusa–Hargla strait to the proglacial lake in Gauja basin. Reconstruction of the straits supports the earlier assumption (Kvasov, 1979) of connection routes between these proglacial lakes (Fig. 1B). However, whereas Kvasov (1979) proposed a marginal drainage spillway towards the Gauja basin (Fig. 1B), current reconstructions together with horizontal glaciolacustrine terraces suggest a strait-like connection between Glacial Lake Peipsi and the proglacial lake in the Gauja basin (Rosentau *et al.*, 2004 – Paper I). Raukas and Rähni (1969) showed that the water level lowering to 75 m altitude during the Otepää Stade disrupted the strait between Glacial Lake Peipsi and the proglacial lake in the Gauja basin at Piusa and Hargla valleys. Shoreline reconstruction in

Rosentau *et al.*, 2004 – Paper I suggests that after the demise of the Piusa-Hargla strait the connection to Gauja basin could have persisted through the Võhandu and Hargla valleys at slightly lower altitude (73 m a.s.l.; Fig. 10C; Rosentau *et al.*, 2004 – Paper I).

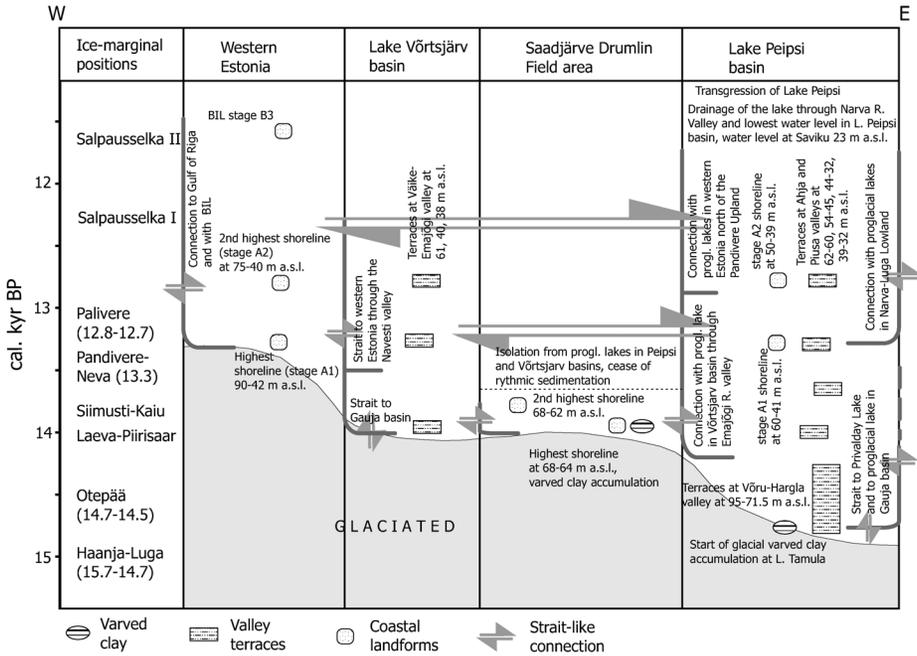


Fig 11. Event stratigraphic model for proglacial lake development in Estonia synchronizing the main events in lake history.

Following the ice retreat 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.10D). This is recorded in Saadjärve Drumlin Field area by a short period (up to 63 years) of accumulation of glacial varved clay in interdrumlin basins and formation of highest shoreline about 14.0–13.8 cal. kyr BP, which shows same water level as in Glacial Lake Peipsi and in the proglacial lake in the Võrtsjärv basin (Fig.10D). The shallow water archipelago of Glacial Lake Peipsi (with water depth dominantly < 10–15 m; Rosentau *et al.*, manuscript – Paper II) was formed in Saadjärve Drumlin Field area about 14.0–13.8 cal. kyr BP with suitable conditions for settling of glacial varved clay only in the deepest interdrumlin basins at the critical (minimal) water depths of about 15–20 m (Fig. 5 in Rosentau *et al.*, manuscript – Paper II). This shallow water archipelago expanded when ice retreated from the Laeva–Piirissaar ice margin position to the Siimusti–Kaiu line (Fig. 10E) and emerged thereafter as dry

land with small isolated lakes in the inter-drumlin basins (Rosentau *et al.*, manuscript – Paper II). Separation of the lakes in the Saadjärve Drumlin Field is marked by end of laminated proglacial sediments and estimates the duration of proglacial lake conditions to have been about 150 years in this area (Rosentau *et al.*, manuscript – Paper II).

Due to the land uplift and extension of the lake to the Laeva–Piiressaar line, the connection between the proglacial lake in Gauja basin and Glacial Lake Peipsi was shifted most probably from the Vöhandu–Hargla valley (isolation level at 73–70 m a.s.l.; Rosentau *et al.*, 2004 – Paper I) to the Väike-Emajõgi valley about 14.0–13.8 cal. kyr BP (Fig. 10C–D; Rosentau *et al.*, manuscript – Paper II). At the same time the Porkhov strait emerged (Fig. 10A) initiating the inflow at Porkhov valley into Glacial Lake Peipsi as suggested by Kvasov (1979). According to reconstructions in Fig. 10D, 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 (Löökene, 1959). However, this connection depends on the ice retreat pattern in Sakala Upland, whose palaeogeography and timing are unclear (Kalm, 2006).

When the ice front retreated to the Pandivere–Neva ice margin position about 13.3 cal. kyr BP (Hang, 2001), a large proglacial lake in western Estonia (stage A₁) formed (Fig. 10F). Palaeogeographic reconstruction shows that the proglacial lake A₁ in western Estonia was connected with the Glacial Lake Peipsi through the proglacial lake in Võrtsjärv basin and through straits in the Emajõgi and Navesti river valleys, and thus had identical water levels (Fig. 10F; Rosentau *et al.*, 2007 – Paper III). The water balance calculations (Rosentau *et al.*, 2007 – Paper III) confirm that this strait system was large enough to transfer the meltwater between the Lake Peipsi basin and western Estonia. Therefore there is no reason to expect that the water level in the Lake Peipsi basin was higher than in western Estonia, as was suggested earlier by Kvasov and Raukas (1970). The reconstruction shows also that a narrow and shallow strait between Glacial Lake Peipsi and proglacial lake in western Estonia may have existed just in front of the Pandivere–Neva ice margin at the northern slope of the Pandivere Upland, but is dependent on the exact position of the ice margin (Fig. 10F). This strait became the main connection route between Glacial Lake Peipsi and the proglacial lake in western Estonia during proglacial lake stage A₂ about 12.8 cal. kyr BP, when the ice margin retreated to the Gulf of Finland (Fig. 10G; Rosentau *et al.*, 2007 – Paper III). The north-eastern part of Glacial Lake Peipsi extended over the Narva–Luga Lowland forming a bay in the middle reaches of the modern Luga River (Fig. 10F–G). Correlations of water levels of the proglacial lakes A₁ and A₂ with coastal landforms in Latvia (see also Chapter 3.1) and corresponding palaeogeographic reconstructions (Fig. 10F–G) indicate that since 13.3 cal. kyr BP the Estonian proglacial lakes had an open connection with BIL (Rosentau *et al.*, in press – Paper IV), which existed in the southern part of the Baltic basin (Björck, 1995).

Thus the reconstructions do not support the earlier opinion (Kvasov and Krasnov, 1967; Kvasov and Raukas, 1970) that the BIL stage started in Estonia by catastrophic drainage of Glacial Lake Peipsi at the northern slope of the Pandivere Upland into the proglacial lake A₂ in western Estonia.

An unresolved issue in the palaeogeography of the region is the separation of Glacial Lake Peipsi from the BIL and the lake water-level fall to its minimum level (Hang, 2001; Rosentau *et al.*, 2004 – Paper I). The simulation with the proglacial lake stage A₂ palaeogeographic model (Fig. 10G) shows that the final strait-like connection between the BIL and Glacial Lake Peipsi ended from the Narva River valley if the proglacial lake A₂ water level surface (Fig. 5) were lowered to the altitude 35–32 m a.s.l. in the Narva River valley (Fig. 10A). Simulation of the lake water-level to the present threshold altitude in Narva River valley (28–26 m a.s.l.; Hang and Miidel, 1999) predicts a small water body within the northern part of modern Lake Peipsi (Fig. 10A) over a slightly larger area than established according to the mapped lake sediments of Lake Small Peipsi (Hang *et al.*, 2001). This simulation also shows the water level at the mouth of the Emajõgi valley (Saviku) at its minimum level, i.e. 23 m a.s.l. (Fig. 9), which occurred about 12.1–11.7 cal. kyr BP (see also Chapter 3.4). A possible interpretation is that the Narva River valley had eroded to the present threshold altitude due to the water level lowering to its minimum level about 12.1–11.7 cal. kyr BP. Moreover, if this assumption is correct, the lake lowering to its minimum level can be explained by lake drainage through Narva River valley concurrently or slightly before the final drainage of BIL at 11.6 cal. kyr BP (Björck, 1995).

CONCLUSIONS

The reconstructed developmental history of the proglacial lakes formed during the deglaciation of Estonia can be concluded as following.

- Development of the large proglacial lakes in Estonia started about 14.7 cal. kyr BP when a deep-water Glacial Lake Peipsi formed in south-eastern Estonia. This lake shared strait-like connections with Privalday Lake in the east and the proglacial lake in Gauja basin in the west.
- Following the ice retreat Glacial Lake Peipsi extended north inundating the Emajõgi River valley and large areas of the Saadjärve Drumlin Field, and reaching the Lake Võrtsjärv basin. This is recorded in the Saadjärve Drumlin Field area by formation of the highest shoreline about 14.0–13.8 cal. kyr BP and by accumulation of glacial varved clay. Study suggests the suitable conditions for settling of glacial varved clay in the deepest interdumlin 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 lakes in the Peipsi and Võrtsjärv basins after the formation of the second highest shoreline.
- About 14.0–13.8 cal. kyr BP the connection route between Glacial Lake Peipsi and proglacial lake in Gauja basin in Latvia shifted from Võhandu-Hargla valley to Väike-Emajõgi valley and the strait between Glacial Lake Peipsi and large Privalday Lake in NW Russia emerged initiating the inflow into Glacial Lake Peipsi.
- About 13.3 cal. kyr BP a large proglacial lake in western Estonia (stage A₁) formed followed about 12.8 cal. kyr BP by proglacial lake A₂ at a lower level. Palaeogeographical reconstructions and water level correlations with proglacial lakes in coastal areas of Latvia suggest that Estonian proglacial lakes A₁ and A₂ formed within a north-easterly elongated bay of the Baltic Ice Lake. The Baltic Ice Lake had the same water level as Glacial Lake Peipsi, because these water bodies were connected *via* straits from central and northern Estonia. Therefore, the results do not support the earlier opinion that the BIL stage started in Estonia by the catastrophic drainage of Glacial Lake Peipsi at the northern slope of the Pandivere Upland into the proglacial lake A₂ in western Estonia.
- The shore displacement of proglacial lakes, induced by glacioisostatic land uplift and existence of the connection routes with neighbouring water bodies, was regressive between 14.7–12.8 cal. kyr BP. The compiled shore displacement curve shows that regressive shore displacement continued in the central part of the Lake Peipsi basin until 12.1–11.7 cal. kyr BP and then turned into transgression, which still continues in this area. The minimum water-level in Lake Peipsi basin occurred 12.1–11.7 cal. kyr BP and can be

explained by lake drainage through the Narva River valley concurrently or slightly before the final drainage of BIL 11.6 cal. kyr BP.

- The analysis of proglacial lake water-level surfaces shows that shoreline tilting decreases rapidly south from the current zero land uplift line and therefore showing higher water-levels than expected. This may reflect the influence of forebulge in south-eastern Estonia during the deglaciation and its later collapse. Comparison of water level tilting directions of proglacial lakes reveals a westward drift in mean tilting directions between 12.8 and 11.6 cal. kyr BP. This reflects changes in glacioisostatic land uplift pattern related with deglaciation of the Scandinavian ice sheet and corresponding to the migration of the glaciation centre to the west.

ACKNOWLEDGEMENTS

I am most thankful to my family for support during my studies. I would like to express my gratitude to my supervisors Prof. Volli Kalm and Dr. Tiit Hang for all the advice and help I received. I am grateful to my co-authors of papers: Leili Saarse, Avo Miidel and Jüri Vassiljev. Many thanks to Dr Robert Szava-Kovats and Dr Ivar Puura checking the language. Special thanks go to Prof. Urve Miller and Dr. Jan Risberg (Stockholm University, Department of Physical Geography and Quaternary Geology), Dr. Aivar Kriiska (University of Tartu, Department of History) and to my colleagues from Institute of Geology, University of Tartu for their help and valuable advice during my studies. Financial support of the Estonian Science Foundation (grant No. 5370), Estonian State Target Foundation (project No. 0182530s03) and Swedish Institute through the Visby Program are gratefully acknowledged.

REFERENCES

- Agrell, H. 1976: The highest coastline in south-eastern Sweden. *Boreas* 5, 143–154.
- Bronk Ramsey, C. 2001: Development of the radiocarbon program OxCal. *Radio-carbon* 43, 355–363.
- Björck, S. 1995: A review of the history of the Baltic Sea, 13.0–8.0 ka BP. *Quaternary International* 27, 19–40. (calibrated ages from <http://www.geol.lu.se/personal/seb/>)
- Bylinski, E. N. 1990: Swell-like lithospheric uplifts due to glacio-isostasy and their probable influence on oil and gas deposits location in the north of Europe. *Geomorphology* 4, 3–13 (in Russian with English summary).
- CIAT – INTERNATIONAL CENTRE FOR TROPICAL AGRICULTURE. 2004: Hole-filled seamless SRTM data V1. Data available from the CGIAR-CSI SRTM 90m Database http://gisweb.ciat.cgiar.org/sig/90m_data_tropics.htm
<http://srtm.usgs.gov/>
- Donner, J. and Raukas, A. 1989: On the geological history of the Baltic Ice Lake. *Proc. Estonian Acad. Sci., Geol.*, 38, 3: 128–137.
- Dyke, A.S. and Peltier, W.R. 2000: Forms, response times and variability of relative sea-level curves, glaciated North America. *Geomorphology* 32, 315–333.
- Ekman, M. 1996: A consistent map of the postglacial uplift of Fennoscandia. *Terra Nova* 8, 158–165.
- Estonian Land Board 1996: *Digital Base Map of Estonia in scale 1:50000*.
- Fjeldskaar, W. 1994: The amplitude and decay of glacial forebulge in Fennoscandia. *Norsk Geologisk Tidsskrift* 74, 2–8.
- Glückert, G. 1995: The Baltic Ice Lake in south Finland and its outlets. *Quaternary International* 27, 57–51.
- Grachev, A.F. and Dolukhanov, P.M., 1970: Postglacial crustal movements of Canada and Fennoscandia. *Baltica* 4, 297–312 (in Russian with English summary).
- Grinbergs E.F. 1957: Late and postglacial history of coasts of Latvian SSR. Acad. Sci. Latvia, Institute of Geology and Mineral Resources. Riga (in Russian).
- Gudelis, V. 1976: History of the Baltic Sea. In Gudelis, V. & Emelyanov, E. (eds.): *Geology of the Baltic Sea*, 95–116. Vilnius (in Russian with English summary).
- Guobyte, R. 2004: A brief outline of the Quaternary of Lithuania and the history of its investigation. In Ehlers, J., Gibbard, P.L. (eds.): *Quaternary Glaciations – Extent and Chronology, Part I: Europe*, 245–250. Elsevier, Amsterdam.
- Hang, T. 2001: Proglacial sedimentary environment, varve chronology and Late Weichselian development of Lake Peipsi, eastern Estonia. *Quaternaria* 111, 44 pp. + 5 app.
- Hang, T., Miidel, A., Kalm, V. and Kimmel, K. 2001: New data on the distribution and stratigraphy of the bottom deposits of Lake Peipsi, eastern Estonia. *Proceedings of the Estonian Academy of Sciences, Geology* 50, 233–253.
- Hang, T., Miidel, A. and Pirrus, R. 1995: Late Weichselian and Holocene water-level changes of Lake Peipsi, eastern Estonia. *PACT* 50, 121–131.
- Hang, T. and Miidel, A. 1999: Main features of the morphology and formation of the river valleys. In Miidel, A. & Raukas, A. (eds): *Lake Peipsi. Geology*, 110–119, Sulemees Publishers, Tallinn.
- Hang, T. and Sandgren, P., 1996: Magnetostratigraphy of varved clays. In Meidla, T., Puura, I., Nemliher, J., Raukas, A., Saarse, L. (eds.): *The Third Baltic Stratigraphical Conference*. Abstracts and Field Guide, Tartu, pp. 152–153.

- Harff, J., Frischbutter, A., Lampe, R. & Meyer, M. 2001: Sea-Level Changes in the Baltic Sea: Interrelation of Climate and Geological Processes. In Gerhard L.C., Harrison, W.E. & Hanson, B.M. (eds.): *Geological perspectives of global climate change*: AAPG studies in Geology 47, 231–250. Tulsa, AAPG.
- Hetherington, R., Barrie, J.V., Reid, R.G.B., MacLeod, R. and Smith, D.J. 2004: Paleogeography, glacially induced crustal displacement, and Late Quaternary coastlines on the continental shelf of British Columbia, Canada. *Quaternary Science Reviews* 23. 295–318.
- Kalm, V. 2006: Pleistocene chronostratigraphy in Estonia, southeastern sector of the Scandinavian glaciation. *Quaternary Science Reviews* 8. 960–975.
- Kalm, V., Hang, T., Tuuling, I., Tsyruльников, A. and Floden, T. 2006: Litostratigraphy of late glacial and Holocene deposits in the northeastern part of the Gulf of Riga. In *The Baltic Sea Geology: The Ninth Marine Geological Conference. Extended Abstracts*, 47–50
- Kessel, H. and Raukas, A. 1979: The Quaternary history of the Baltic. Estonia. In Gudelis, V. & Königsson, L.-K. (eds.): *The Quaternary history of the Baltic*, 127–146. Acta Universitatis Upsaliensis, Uppsala.
- Kvasov, D. D. 1979: The Late-Quaternary History of Large Lakes and Inland Seas of Eastern Europe. *Annales Academiæ Scientiarum Fennicæ, Ser. A III, Geologica-Geographica* 127, 1–71.
- Kvasov, D. D. and Krasnov, I. I. 1967: Main problems in the history of proglacial lakes in northeast. In Kvasov D. D. (ed.), *Northwest lakes history*. Leningrad, 7–17 (in Russian).
- Kvasov, D. D. and Raukas, A. 1970: Postglacial history of the Gulf of Finland. *Proceedings of the Geographical Society of the Soviet Union* 102, 432–438 (in Russian).
- Lambeck, K., Smither, C. and Ekman, M. 1998: Tests of glacial rebound models for Fennoscandia based on instrumented sea- and lake-level records. *Geophysical Journal International* 135, 375–387.
- Lampe, R. 2005: Lateglacial and Holocene water-level variations along the German Baltic Sea coast: review and new results. *Quaternary International* 133–134, 121–136.
- Leverington, D. W., Teller, J. T. and Mann, J. D. 2002: A GIS method for reconstruction of late Quaternary landscapes from isobase data and modern topography. *Computers & Geosciences* 28, 631–639.
- Liblik, T. 1966: Jooni Piusa oru geomorfoloogiast. Eesti Geograafia Seltsi aastaraamat 1964/1965: 34–55.
- Liblik, T. 1969: Ancient coastal formations on the west coast of Lake Peipsi (in Russian). *Transactions of the Tartu State University*, 237, Publications on geography, VI: 3–16.
- Lundqvist, J. and Lagerbäck, R. 1976: The Pärve Fault: A late-glacial fault in Precambrian of Swedish Lapland. *Geologiska Föreningens i Stockholm Förhandlingar* 98, 45–51.
- Lundqvist, J. and Wohlfarth, B. 2001: Timing and east-west correlation of south Swedish ice marginal lines during the Late Weichselian. *Quaternary Science Reviews* 20, 1127–1148.
- Löökene, E. 1959: Geomorphologie des nördlichen Teils des Höhengbiets von Sakala. *Transactions of the Tartu State University* 75. *Publications on Geology I*, 119–154 (in Russian with German summary).

- Mangerud, J., Jakobsson, M., Alexanderson, H., Astakhov, V., Clarke, G. K. C., Henriksen, M., Hjort, C., Krinner, G., Lunkka, J. P., Möller, P., Murray, A., Nikolskaya, O., Saarnisto, M. and Svendsen, J. I. 2004: Ice-dammed lakes and rerouting of the drainage of northern Eurasia during the Last Glaciation. *Quaternary Science Reviews* 23, 1313–1332.
- Mann, J.D., Leverington, D.W., Rayburn, J. and Teller, J.T. 1998: The volume and paleobathymetry of glacial Lake Agassiz. *Journal of Paleolimnology* 22, 71–80.
- Markov, K. 1931: Development of the relief in the north-western part of the Leningrad district. *Transact. Geological and Prospecting Service U.S.S.R.*, 117: 1–256 (in Russian with English summary).
- Miidel, A., Hang, T., Pirrus, R. and Liiva, A. 1995: On the development of the southern part of Lake Peipsi in the Holocene. *Proceedings of the Estonian Academy of Sciences, Geology* 44, 33–44.
- Miidel, A., Raukas, A. and Vaher, R. 2004: Geology of the lake basin. In Haberman, J., Pihu, E. & Raukas, A. (eds.): *Lake Võrtsjärv*, 33–46. Estonian Encyclopaedia Publishers, Tallinn.
- Mörner, N.-A. 1978: Faulting, fracturing, and seismicity as functions of glacio-isostasy in Fennoscandia. *Geology* 6, 41–45.
- Noormets, R. and Floden, T. 2002: Glacial deposits and ice-sheet dynamics in the north-central Baltic Sea during the last glaciation. *Boreas* 31, 4, 362–377.
- Ojala, V. J., Kuivamäki, A. and Vuorela, P. 2004: Postglacial deformation of bedrock in Finland. Geological Survey of Finland. *Nuclear Waste Disposal Research. Report YST-120*, 23 pp., Espoo.
- Orru, M. 1995: *Handbook. Estonian mires*. 240 pp. Geological Survey of Estonia, Tallinn (in Estonian with English summary).
- Orviku, K. 1960: On the neotectonic movements in Estonian SSR on the base of geological data. In Želnin G. A. (ed.): *Materials on the meeting of the neotectonic movements in Peribaltic*, 120–143. Tartu (in Russian with English summary).
- Orviku, L. 1958: Neue Angaben über die Geologie des Sees Võrtsjärw. *Eesti NSV Teaduste Akadeemia Geoloogia Instituudi uurimused III*, 269–293 (in Russian with German summary).
- Palusalu, H. 1967: Väike-Emajõe alamjooksu oru geomorfoloogiast. Diploma Work. 45pp.
- Persson, Ch. 1983: Glacial deposits and the Central Swedish end moraine zone in eastern Sweden. In Ehlers, J. (ed.): *Glacial deposits in north-west Europe*, 131–139, Balkema, Rotterdam.
- Pirrus, E. 1968: *Estonian varved clays*. 144pp. Valgus, Tallinn (in Estonian with English summary).
- Pirrus, R. 1983: Vooremaa maastikukaitseala järvesetete geoloogia ja järvede areng. Manuscript in the Institute of Geology at Tallinn University of Technology. 122pp.
- Pirrus, R. and Raukas, A. 1984: Uusi andmeid Võrtsjärve geoloogiast. In Haberman, J. (ed.): *Võrtsjärve ökosüsteemi seisund*, 15–20, Tartu.
- Pirrus, R. and Rõuk, A.-M. 1979: New data on the geology of the Soitsjärw Lake. In Raukas, A. (ed.): *Eesti NSV Saarkõrgustike ja järvenõgude kujunemine*, 118–144. Valgus, Tallinn (in Estonian with English summary).
- Pärna, K. 1960: Zur Geologie des Baltischen Eisstausees sowie der lokalen grossen Eisstauseen auf dem Territorium der Estnischen SSR. *Eesti NSV Teaduste*

- Akadeemia Geoloogia Instituudi uurimused V*, 269–278 (in Russian with German summary).
- Pärna, K. 1962: *On the geology of the Baltic Ice Lake and large local proglacial lakes on the territory of Estonia*. Ph.D. Dissertation. Academy of Sciences of ESSR, Institute of Geology. 163 pp. Tallinn.
- Randjärv, J. 1993: Vertical movements of the earth's crust in the Baltic region. Finnish Geodetic Institute, Helsinki, 33 p.
- Rattas, M. and Kalm, V. 2004: Glaciotectonic deformation patterns in Estonia. *Geological Quarterly* 48, 1, 15–22.
- Raukas, A. and Rähni, E. 1969: On the Geological Development of the Peipsi-Pihkva Depression and the Basins Distributed in that Region. *Proceedings of the Estonian Academy of Sciences. Chemistry, Geology* 18, 2, 113–125 (in Russian with English summary).
- Raukas, A., Rähni, E. and Miidel, A. 1971: *Marginal glacial formations in North Estonia*. 226 pp. Valgus, Tallinn (in Russian with English summary).
- Reimer, P.J., Baillie, M.G.L., Bard, E., Bayliss, A., Beck, J.W., Bertrand, C.J.H., Blackwell, P.G., Buck, C.E., Burr, G.S., Cutler, K.B., Damon, P.E., Edwards, R.L., Fairbanks, R.G., Friedrich, M., Guilderson, T.P., Hogg, A.G., Hughen, K.A., Kromer, B., McCormac, 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. and Weyhenmeyer, C.E. 2004: IntCal04 Terrestrial Radiocarbon Age Calibration, 0–26 Cal Kyr BP. *Radiocarbon* 46, 1029–1058.
- Rähni, E. 1963: On the geochronology of north-east Estonian varved clays. *Eesti NSV Geoloogia Instituudi Uurimused*, 12, 81–94 (In Russian).
- Saarnisto, M. and Saarinen, T. 2001: Deglaciation chronology of the Scandinavian ice sheet from east of Lake Onega basin to the Salpausselkä end moraines. *Global and Planetary Change* 31, 387–405.
- Saarse, L., Vassiljev, J. and Miidel, A. 2003: Simulation of the Baltic Sea Shorelines in Estonia and Neighbouring Areas. *Journal of Coastal Research* 19, 261–268.
- Saarse, L. and Kärson, J. 1982: Sedimentational peculiarities of the lakes Elistvere, Prossa and Pikkjärv. *Proceedings of the Estonian Academy of Sciences. Chemistry, Geology* 18, 2, 113–125 (in Russian with English summary).
- Sandgren, P., Hang, T. and Snowball, I. F. 1997: A Late Weichselian geomagnetic record from Lake Tamula, SE Estonia. *GFF* 119, 279–284.
- Sarv, A., and Ilves, E. 1975: Über das Alter der holozänen Ablagerungen im Mündungsgebiet des Flusses Emajõgi (Saviku). *Proceedings of the Estonian Academy of Sciences. Chemistry, Geology*, 24, 64–69 (In Russian with German summary)
- Seifert, T., Tauber, F. and Kayser B. 2001: A high resolution spherical grid topography of the Baltic Sea – revised edition. Baltic Sea Science Congress, November 25–29, 2001, Stockholm, Sweden, Poster 147.
- Svensson, N. O. 1991: Late Weichselian and Early Holocene shore displacement in the central Baltic Sea. *Quaternary International* 9, 7–26.
- Sildvee, H. and Vaher, R. 1995: Geologic structure and seismicity of Estonia. *Proceedings of the Estonian Academy of Sciences, Geology* 44, 1, 15–25.
- Söderberg, P. 1988: Notes on continuation of the Salpausselkä ice marginal zone in the northern Baltic Proper. *Geological Survey of Finland. Special Paper* 6, 69–72.
- Torim, A. 1998: *Renovation of the Estonian Levelling Network*. Manuscript in Estonian Land Board Development Centre. Tartu, 55 pp.

- Vallner, L., Sildvee, H. and Torim, A. 1988: Recent crustal movements in Estonia. *Journal of Geodynamics* 9, 215–233.
- Vassiljev, J., Saarse, L. and Miidel, A. 2005: Simulation of the proglacial lake shore displacement in Estonia. *Geological Quarterly* 49, 3, 253–262.
- Veski, S., Heinsalu, A., Klassen, V., Kriiska, A., Lõugas, L., Poska, A. and Saluäär, U. 2005: Early Holocene coastal settlement and palaeoenvironment on the shore of the Baltic Sea at Pärnu, southwestern Estonia. *Quaternary International* 130, 75–85
- Uścińowicz, S., 1999: Southern Baltic area during the last deglaciation. *Geological Quarterly* 43, 2, 137–148.

SUMMARY IN ESTONIAN

Jääpaisjärvede areng Eestis

Käesolev väitekiri esitab Eesti alal eksisteerinud hilisjäaaegsete jääpaisjärvede arengumudeli, mis põhineb neljal uurimisel, kus käsitleti jääpaisjärvede veetaseme muutuseid, paleogeograafiat ning seoseid Loode–Venemaa ning Läti rannikualadel paiknenud jääpaisjärvedega. Jääpaisjärvede arengut uuriti nende leviku ja veesügavuste modelleerimise abil mis põhineb glatsioisostaatilisel deformeeritud paleo-veetasemete lahutamisel tänapäevasest kõrgusmudelitest. Paleo-veetasemete rekonstrueerimisel kasutati varasemalt ning käesoleva uurimuse käigus mõõdistatud rannamoodustiste ja oruterrasside kõrgused ning nende korrellatsiooni.

Uuringu tulemused näitavad, et suuremate jääpaisjärvede kujunemine Eesti alal algas ligikaudu 14 700 aastat tagasi sügavaveelise (valdavalt 20 m ja enam) Peipsi jääpaisjärve moodustumisega (joonis 10B). Otepää jääserva ees laiunud Peipsi jääpaisjärv oli Porhovi väina kaudu ühenduses ulatusliku Privalday jääpaisjärvega Loode–Venemaal ja Piusa–Hargla ning hiljem Võhandu–Hargla väinade kaudu ühenduses jääpaisjärvega Gauja jõe orundis (Rosentau *et al.*, 2004 – Paper I, Rosentau *et al.*, manuscript – Paper II). Jääserva taandudes Laeva–Piiressaar jooneni (~14 000–13 800 aastat tagasi) kujunes Emajõe orundi ja Saadjärve voorestiku kaudu ühendus Peipsi ning Võrtsjärve jääpaisjärvede vahel (joonis 10D). Paleoveekogude rekonstruktsioonid näitavad, et sellel ajal isoleerusid Võhandu–Hargla ja Porhovi väinad ning algas sissevool Peipsi jääpaisjärve üle Porhovi orundi (joonis 10C–D, Rosentau *et al.*, manuscript – Paper II). Ühendus Peipsi ja Gauja jääpaisjärvede vahel siiski säilus, kuid oli nihkunud Võhandu–Hargla orundi kohalt Väike–Emajõe orundi kohale (joonis 10 C–D). Jääserva taandudes Laeva– Piiressaar ja edasi Siimusti–Kaiu jooneni (joonis 10D–E) ujutasid Peipsi ja Võrsjärve jääpaisjärved üle Saadjärve voorestiku madalamad osad, kujundades piirkonna kaks kõrgemat rannavööndit. Kõrgeimast veetasemest madalamal kujunesid suhteliselt lühikese perioodi vältel (kuni 63 a) viirsavid. Nende levik on piiratud voortevaheliste nõgudega andes kriitiliseks (minimaalseks) viirsavide settimissügavuseks 15–20 meetrit (Rosentau *et al.*, manuscript – Paper II). Jääjärvelised settimistingimused keetsid Saadjärve voorestiku järvenõgudes ligikaudu 150 aastat ning katkesid arvatavasti seoses järvede isoleerumisega Peipsi ja Võrtsjärve nõgudes eksisteerinud jääpaisjärvedest.

Ligikaudu 13 300 aastat tagasi, kui mandrijää oli taandunud Pandivere–Neva servamoodustiste vööndini, moodustus Lääne-Eestis ulatuslik jääpaisjärv ning kujunesid sealsed kõrgeima – A₁ taseme (Voose) rannamoodustised (joonis 10F). Paleogeograafilised rekonstruktsioonid näitavad, et Lääne-Eesti jääpaisjärv A₁ oli väinalises ühenduses Peipsi jääpaisjärvega

Navesti ja Emajõe orundite kaudu, mistõttu olid nende veetasemed 13 300 aastat tagasi võrdsed (Rosentau *et al.*, 2007 – Paper III). Liustikuserva edasisel taandumisel avanes Peipsi ja Lääne–Eesti jääpaisjärvede vahel uus väinaline ühendus üle Pandivere kõrgustiku põhjanõlva (joonis 10G) ning kujunesid A₂ taseme (Kemba) rannamoodustised, mille vanuseks on hinnatud ligikaudu 12 800 aastat (Rosentau *et al.*, 2007 – Paper III). Jääpaisjärvede ühendusteade rekonstruktsioonid lubavad väita, et varasemalt arvatud Peipsi jääpaisjärve mahajooks Pandivere kõrgustiku põhjanõlvalt A₂ jääpaisjärve, mida on peetud Balti Jääpaisjärve (Baltic Ice Lake) alguseks Eesti alal (Kvasov and Krasnov, 1967; Kvasov and Raukas, 1970), ei olnud katastroofiline sündmus, kuna väinad Navesti ja Emajõe orundite kohal tegid võimatuks Peipsi jääpaisjärve ülespaisutamise (Rosentau *et al.*, 2007 – Paper III). Uuringu tulemused näitavad (Rosentau *et al.*, in press – Paper IV), et A₁ ja A₂ jääpaisjärvede veetasemed korreleeruvad hästi kahe kõrgeima jääpaisjärve tasemega Läti rannikualadel (Bgl_I ja Bgl_{II}; Grinbergs, 1957) ning rannamoodustistega kõrgusel 63 m ü.m.p. ja tasemega G_{III} Loode–Venemaal (Markov, 1931). Paleogeograafiliste rekonstruktsioonidega tõestati (Rosentau *et al.*, in press – Paper IV), et A₁ ja A₂ jääpaisjärved olid avatud ühenduses Balti Jääpaisjärvega mis eksisteeris Läänemere lõunaosas (Björck, 1995), paigutades seega Balti Jääpaisjärve staadiumi Eesti alal varasemasse perioodi, kui seda on näidanud eelnevad uuringud (Pärna, 1960; Kvasov and Krasnov, 1967; Kvasov and Raukas, 1970).

Käesoleva uurimuse alusel võib väita, et Eesti jääpaisjärvede rannajoone muutused olid 14700–12 800 aastat tagasi regressiivse iseloomuga, mis oli tingitud glatsioisostaatilisest maakerkest ning jääpaisjärvede ühendusteedest naaberaladel paiknevate jääpaisjärvedega. Koostatud Peipsi järve veetasememuutuste kõver näitab, et Peipsi nõo kesk- ja lõunaosas jätkus regressioon kuni hilisjäaaaja lõpuni (12100–11700 aastat tagasi) ning asendus seejärel veetaseme tõusuga, mis kestab tänaseni. Esmakordselt on käesolevas töös esitatud jääpaisjärvede veesügavuste rekonstruktsioonid, mis näitavad, et viirsavide settimiseks sobilikud veesügavused (20 m ja enam) langevad hästi kokku teadaolevate suuremate viirsavi levikualadega Peipsi nõo põhjaosas (Hang, 2001), Riia lahes (Kalm *et al.*, 2006) ning Lääne–Eesti (Hang and Sandgren, 1996) ja Narva–Luga madalikul (Rähni, 1963).

PAPERS I-IV

Rosentau, A., Hang, T. and Miidel, A. 2004: Simulation of the shorelines of glacial Lake Peipsi in Eastern Estonia during the Late Weichselian. *Geological Quarterly* 4, 13–21.

Reprinted for this thesis with permission by the Polish Geological Institute

Rosentau, A., Hang, T., Kalm, V. Water-level changes and palaeogeography of proglacial lakes in eastern Estonia: synthesis of data from Saadjärve Drumlin Field area. (manuscript).

Rosentau, A., Vassiljev, J., Saarse, L. and Miidel, A. 2007: Palaeogeographic reconstruction of proglacial lakes in Estonia. *Boreas* 36, 1–11 (in press, accepted 1st August 2006).

Reprinted for this thesis with permission by the Taylor & Francis AS.

Rosentau, A., Vassiljev, J., Saarse, L. and Miidel, A. Proglacial lake shorelines of Estonia and adjoining areas. *Polish Geological Institute Special Papers* (in press, accepted 6th April 2006).

Reprinted for this thesis with permission by the Polish Geological Institute.

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

Alar ROSENTAU, Tiit HANG and Volli KALM

Institute of Geology, University of Tartu, Vanemuise 46, 51014 Tartu, Estonia;
alar.rosentau@ut.ee; tiit.hang@ut.ee; volli.kalm@ut.ee

ABSTRACT

We studied the water-level changes and palaeogeography of proglacial lakes in eastern Estonia using the shoreline and sediment distribution proxies from Saadjärve Drumlin Field area, geomorphological correlation and GIS-based palaeogeographic reconstructions. Our results show that about 14.0–13.8 cal. kyr BP the 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 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 proglacial lake in Võrtsjärv basin. Study suggests the suitable conditions for 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 lakes 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. Results show that about 14.0–13.8 cal. kyr BP the connection route between Glacial Lake Peipsi and the proglacial lake in Gauja basin, northern Latvia, shifted from Võhandu–Hargla valley to the Väike–Emajõgi valley and the strait between Glacial Lake Peipsi and large Privalday Lake in northwest Russia emerged initiating the inflow into Glacial Lake Peipsi.

INTRODUCTION

Two large proglacial lakes developed in eastern Estonia in course of the last deglaciation, the Glacial Lake Peipsi (Raukas and Rähni, 1969; Raukas *et al.*, 1971; Hang, 2001) and proglacial lake in the Lake Võrtsjärv basin (Orviku, 1958; Raukas *et al.*, 1971; Moora *et al.*, 2002). The Glacial Lake Peipsi came into being together with ice retreat from the Haanja–Luga to the Otepää line of ice-marginal position (Fig. 1A; Hang, 2001) and expanded north following the ice recession. At the initial stage, the Glacial Lake Peipsi was connected with the large Privalday Lake in northwest Russia and with the proglacial lake in Gauja basin in Latvia (Kvasov, 1979). Proglacial lake in the Lake Võrtsjärv basin did form later when glacier retreated from the Otepää ice-margin position to the Laeva–Piirisaar line (Fig. 1B; Raukas *et al.*, 1971; Moora *et al.*, 2002). Proglacial lake in Võrtsjärv basin was connected with the Glacial Lake Peipsi through the Emajõgi River valley while the water-level was so high that 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 an indicators of the distribution and water-level of the proglacial lake, have so far been poorly investigated (Pirrus and 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. Reconstruction of configuration and bathymetry of proglacial lakes was performed using the correlation of shorelines, a digital terrain model (DTM) and GIS analysis in order to understand how proglacial lakes are distributed and related in eastern Estonia.

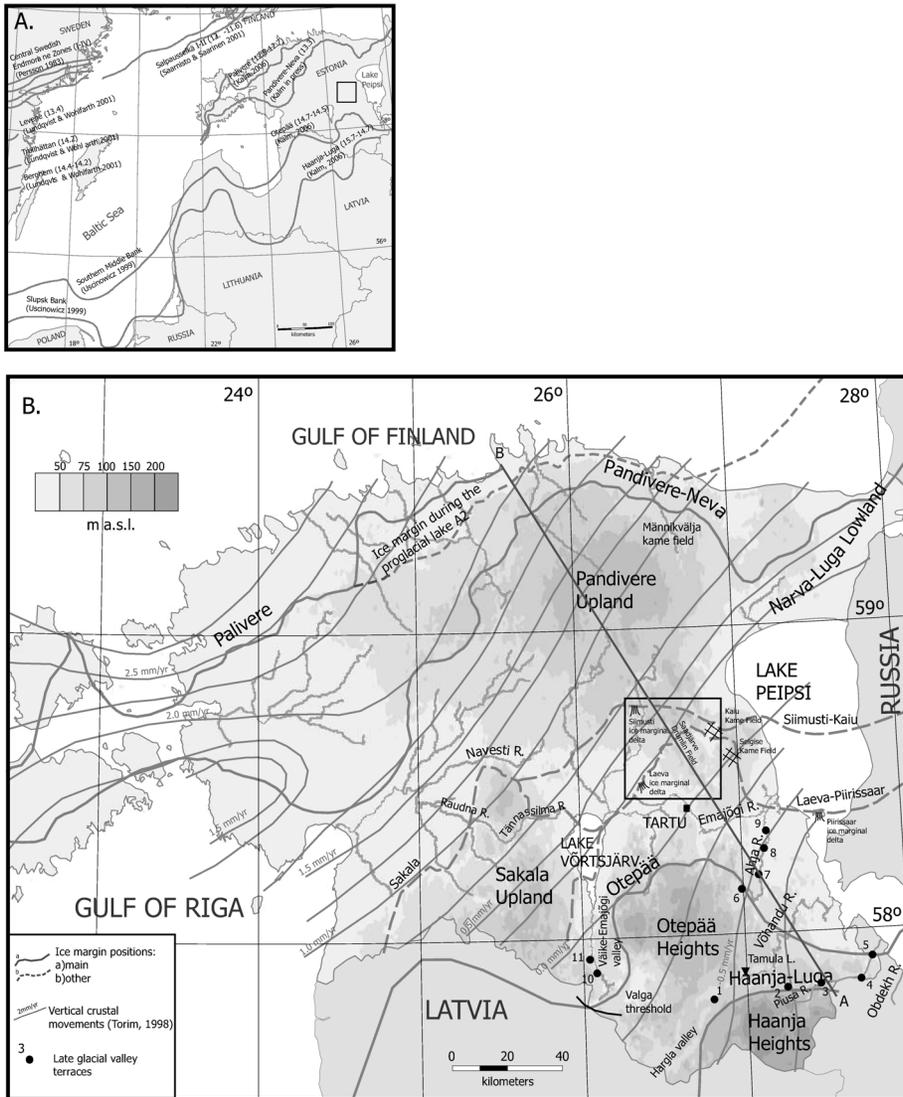


Fig. 1. (A) Index map with main late Wechselian ice margin positions around the Baltic with ages (cal. kyr BP) according to Kalm (2006), Lundqvist and Wohlfarth (2001) and Saarnisto and Saarinen (2001). (B) Location of the study area (rectangle) in Estonia in relation to the ice marginal positions and 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 (Hang *et al.*, 1995; Liblik, 1966) and Lake Võrtsjärv basins (Palusalu, 1967): 1 Hargla valley (79–73 m a.s.l.), 2–5 Piusa valley (95–71.5; 62–60; 51–45; 41–33 m a.s.l.), 6–9 Ahja valley (62.5–61.5; 54–50; 44–41; 39–34 m a.s.l.), 10–11 Väike-Emajõgi valley (61; 61 m a.s.l.). The location of the cross-section in Fig. 6 (line A–B) is shown on map.

GEOLOGICAL SETTING AND REGIONAL BACKGROUND

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 Weichelian glacial deposits, forming NW–SE oriented and morphologically clearly expressed drumlins and drumlinoid ridges (Fig. 2; Rattas, 2004). Inter-drumlin basins contain glacio-lacustrine 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).

Stratigraphy of sediments and morphology of inter-drumlin basins have been studied for many years. Special emphasis has been paid to the Holocene vegetation history and water level change (Pirrus, 1983; Pirrus and Rõuk, 1979; Saarse and Kärson, 1982). History of late Weichselian water-level changes is much less known, occasionally discussed in connection with the development of the Glacial Lake Peipsi (Raukas and Rähni, 1969; Raukas *et al.*, 1971) or in stratigraphical interpretations (Pirrus, 1983; Pirrus and Raukas, 1996). On the basis of the flat-topped kames in Selgise Kame Field (Fig. 1B) position of the highest shoreline was inferred for Saadjärve Drumlin Field at an altitude *ca.* 85–90 m a.s.l. (Raukas and 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 positioned at Laeva-Piirisaar line. Later local studies (Pirrus and Rõuk, 1979; Pirrus, 1983) report that the highest shoreline locates at 75 m a.s.l. which is 10–15 m lower compared to the earlier suggestions. However, the estimation of this 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 Saadjärve Drumlin Field area the modest land uplift which ranges between 0.75–0 mm/yr (Fig. 1B). Correlation of coastal landforms formed during the Pandivere–Neva (proglacial lake at stage A₁) and Palivere Stades (proglacial lake at stage A₂) in western Estonia and in the Lake Peipsi and Lake Võrtsjärv basin in eastern Estonia (Vassiljev *et al.*, 2005; Rosentau *et al.*, 2007) suggests that the NW-SE oriented shoreline tilting in Saadjärve Drumlin Field area has a gradient *ca.* 20–30 cm km⁻¹. South from the present-day zero uplift line (Fig. 1B) the late glacial shoreline tilting decreases rapidly to tilting gradient *ca.* 5–10 cm km⁻¹ (Vassiljev *et al.*, 2005). Similar low tilting gradient was reported (5 cm km⁻¹) from the studies into late glacial river terraces in the Lake Peipsi basin, southeastern Estonia (Hang *et al.*, 1995; Hang, 2001). Nearly horizontal terraces from the same period were also observed from the Väike-Emajõgi River valley (Fig. 1B), reflecting there the proglacial lake level in the Võrtsjärv

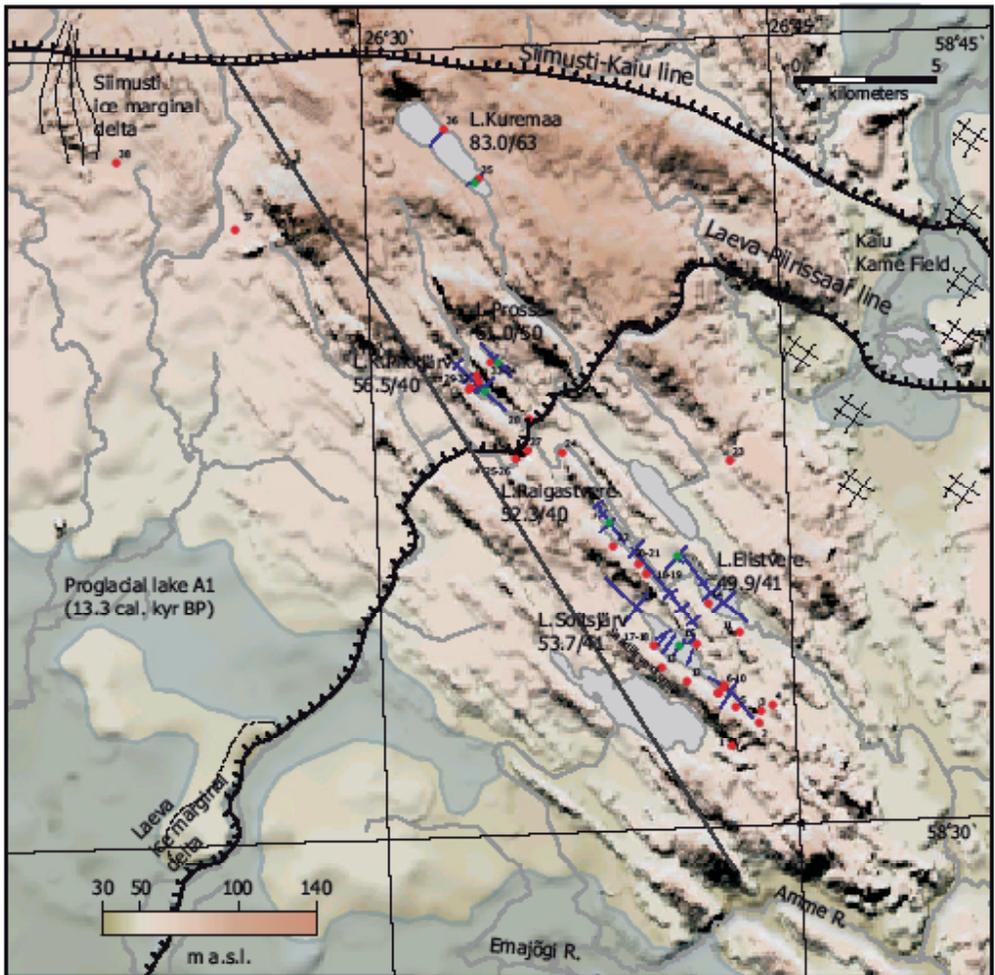


Fig 2. Recent digital terrain model (DTM) of the Saadjärve Drumlin Field with indication of ice margin positions (Raukas et al., 1971) and glacial landforms mentioned in the text. Geological profiles (blue lines) used for mapping of glaciolacustrine deposits and location of master cores (green dots) are shown on the map. Red dots with the 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 map. Numbers below the lake name indicate the lake-level altitude and the lowest recorded altitude of the till surface in the basin. The distribution of proglacial lake at stage A1 about 13.3 cal. kyr BP (derived from Rosentau et al., 2007) is shown on the map.

Table 1. Estimates of Glacial lake Peipsi water levels (m a.s.l.) during the deglaciation of the lake basin at different ice margin positions. Water levels are given for study area at Saadjärve Drumlin Field (SDF) and for terrace groups at R. Ahja and R. Piusa valleys. Location of ice-margin position, study area and valley terraces shown in Fig. 1B.

	Otepää Stade		Laeva-Piirisaar Stade		Siimusti-Kaiu Stade		Pandivere- Neva Stade		
	R.Piusa	R.Piusa	R. Ahja	SDF	R.Piusa	R. Ahja	SDF	R.Piusa	R. Ahja
Raukas <i>et al.</i> , 1971	70–95	45–51	~60	~85–90	~40	~86	~38	~40	
Pirrus and Rõuk, 1979				~75					
Hang <i>et al.</i> , 1995	>75	60–62	62.5–61.5		45–51	50–54		33–41	41–44
Vassiljev <i>et al.</i> , 2005									41

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 resulted on different views summarized in Table 1.

MATERIAL AND METHODS

LAKE BASIN AND SHORELINE INVESTIGATIONS

Late glacial 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 Russian type peat corer (chamber length 1m, 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 and Rõuk, 1979; Saarse and Kärson, 1982; Pirrus, 1983) compiled cross-sections (Fig. 2). The previously compiled cross-sections 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 lithostratigraphical 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 fieldworks and later complemented with new original data. Previously investigated coastal landforms were checked in the field before they accepted as water-level indicators. Altitude of coastal scarps from the Lake Raigastvere and Lake Soitsjärv basins were instrumentally measured. Other geomorphological evidences of water-level were observed on the field and their altitudes derived from Soviet topographic maps on a scale of 1:10,000 (0.5 m/1 m contour intervals). Positioning of sites was performed by GPS.

CORRELATION OF COASTAL LANDFORMS

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 and Rõuk, 1979; Saarse and Kärson, 1982; Pirrus, 1983). Coastal landforms were projected to the cross-section on the graph and sites above the highest Holocene shoreline were first visually correlated. Thereafter, the linear regression 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 identified 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 towards 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 proglacial lakes shorelines and bathymetry 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 Lake Peipsi (Hang *et al.*, 1995) and Lake Võrtsjärv (Palusalu, 1967) basins. Reconstruction of water-level surfaces is based on linear solution of natural neighbour interpolation using the constant shoreline tilting direction towards to the azimuth of 326° (Rosentau *et al.*, 2004). The grid was 5×5 km in size.

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

- A. Digital terrain model for Estonia, with grid size 200×200 m (Rosentau *et al.*, 2007) based on elevation data from Digital Base Map of Estonia on a scale of 1:50,000 (Estonian Land Board, 1996);

- B. Shuttle Radar Topography Mission (SRTM-90) elevation data with resolution 3 arc seconds (approx. 90×90 m) for neighbouring areas in Latvia and NW Russia (CIAT, 2004);
- C. 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).

The Holocene peat deposits were subtracted from DTM in 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 study area (Fig. 2) the lake water depths and mapped thicknesses of the Holocene deposits (peat, gyttja and lake marl) were subtracted from the DTM according to our and previously published data (Pirrus and Rõuk, 1979; Saarse and Kärson, 1982; Pirrus, 1983). After the subtracting of the Holocene deposits, lake water depths and the interpolated water level surface from 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 (Estonian Land Board, 1996).

RESULTS

CORRELATION OF COASTAL LANDFORMS

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 at an altitude 68–64 m a.s.l. is represented by 6 sites (*Shore 1*) and is traceable in the central and southern part of the drumlin field area. *Shore 1* is marked 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⁻¹. The position of this, highest, shoreline in the region shows *ca.* 20 m lower water-level than suggested earlier by Raukas *et al.* (1971) and *ca.* 10 m lower water-level than suggested by Pirrus and Rõuk (1979). The second highest shoreline (*Shore 2*) is traceable in the northern part of the study area and represented by 10 sites at an altitude between 68 m and 60 m. This ancient shore is marked in the central and southern part of the drumlin field by coastal terraces and scarps and by some small outwash plains (Table 2). In the northern part of the study area, south from the Siimusti ice marginal delta, *Shore 2* is marked by two large (*ca.* 1×1 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⁻¹) display a similar gradient to *Shore 1*. Comparison of *Shore 1* and *Shore 2* tilting gradients with following stages (A₁ and A₂, Vassiljev *et al.*, 2005) in the

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

<i>No. on Fig.2</i>	<i>Site</i>	<i>Coordinates (degrees)</i>		<i>Elevation, m a.s.l.</i>	<i>Type of landform</i>	<i>Type of measurement</i>	<i>Level</i>	<i>References</i>
		<i>Longitude</i>	<i>Latitude</i>					
1	Saadjärv	26.711	58.525	60	outwash plain	topogr.map	Shore 2	Pirrus, 1983
2	Soitsjärv	26.727	58.533	58	coastal scarp	instr. measure	below HHS	Pirrus, 1983
3	Toolamaa	26.729	58.536	60	coastal scarp	n.a.	Shore 2	Pirrus and Rõuk, 1979
4	Toolamaa	26.737	58.538	60	coastal scarp	n.a.	Shore 2	Pirrus and Rõuk, 1979
5	Soitsjärv	26.714	58.538	57	outwash plain	topogr.map	below HHS	this study
6	Soitsjärv	26.704	58.542	63.9	coastal scarp	instr. measure	Shore 1	this study
7	Soitsjärv	26.704	58.542	61.1	coastal scarp	instr. measure	Shore 2	this study
8	Soitsjärv	26.704	58.542	57.3	coastal scarp	instr. measure	below HHS	this study
9	Soitsjärv	26.708	58.544	49	coastal terrace	instr. measure	below HHS	Pirrus, 1983
10	Soitsjärv	26.708	58.544	55	coastal scarp	instr. measure	below HHS	Pirrus, 1983
11	Elistvere	26.720	58.561	60	outwash plain	topogr.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	instr. measure	Shore 2	this study
14	Elistvere	26.714	58.565	55	coastal scarp	instr. measure	below HHS	Pirrus and Rõuk, 1979
15	Soitsjärv	26.665	58.558	56.9	coastal scarp	instr. measure	below HHS	this study
16	Soitsjärv	26.666	58.558	54.7	coastal scarp	instr. measure	below HHS	this study
17	Elistvere	26.700	58.571	49	coastal terrace	instr. measure	below HHS	Saarse and Kärson, 1982
18	Raigastvere	26.664	58.581	59.6	coastal scarp	instr. measure	above HHS	this study
19	Raigastvere	26.664	58.581	54.3	coastal scarp	instr. measure	below HHS	this study

Table 2. Continuation

<i>No. on Fig.2</i>	<i>Site</i>	<i>Coordinates (degrees)</i>		<i>Elevation, m a.s.l.</i>	<i>Type of landform</i>	<i>Type of measurement</i>	<i>Level</i>	<i>References</i>
		<i>Longitude</i>	<i>Latitude</i>					
20	Raigastvere	26.659	58.584	57.3	coastal scarp	instr. measure	below HHS	this study
21	Raigastvere	26.659	58.585	54.1	coastal scarp	instr. measure	below HHS	this study
22	Raigastvere	26.644	58.590	65	coastal scarp	instr. measure	Shore 1	Pirrus, 1983
23	Kõrenduse	26.717	58.616	62	outwash plain	topogr.map	Shore 2	this study
24	Nava	26.615	58.621	60.3	coastal terrace	topogr.map	below HHS	this study
25	Ilmjärv	26.586	58.617	59	coastal terrace	instr. measure	below HHS	Pirrus, 1983
26	Ilmjärv	26.587	58.619	67	coastal terrace	topogr.map	Shore 1	this study
27	Ilmjärv	26.594	58.622	66	coastal terrace	topogr.map	Shore 1	this study
28	Nava	26.595	58.632	66.5	coastal terrace	topogr.map	Shore 1	this study
29	Pikkjärv	26.560	58.642	68	coastal terrace	instr. measure	Shore 1	Saarse and Kärson, 1982
30	Pikkjärv	26.565	58.644	55	coastal terrace	instr. measure	below HHS	Saarse and Kärson, 1982
31	Pikkjärv	26.560	58.642	58	coastal terrace	instr. measure	below HHS	Saarse and Kärson, 1982
32	Pikkjärv	26.564	58.646	57.5	coastal terrace	instr. measure	below HHS	Saarse and Kärson, 1982
33	Prossa	26.575	58.649	61.5(62–61)	coastal terrace	instr. measure	below HHS	Saarse and Kärson, 1982
34	Prossa	26.573	58.650	63.5 (64–63)	coastal terrace	instr. measure	Shore 2	Saarse and Kärson, 1982
35	Kuremaa	26.570	58.709	79	coastal terrace	topogr.map	below HHS	this study
36	Kuremaa	26.550	58.724	70	coastal terrace	topogr.map	below HHS	this study
37	Pakaste	26.421	58.695	65 (64–66)	coastal plain	topogr.map	Shore 2	this study
38	Siimusti	26.349	58.717	67.5(67–68)	coastal plain	topogr.map	Shore 2	this study

HHS – highest Holocene shoreline; n.a. – not available

development of proglacial lakes in Estonia, display a similar tilting during the stage A₁ (28 cm km⁻¹) and decrease in tilting during the stage A₂ (19 cm km⁻¹).

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 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 was in these lakes even lower than today (Fig. 2).

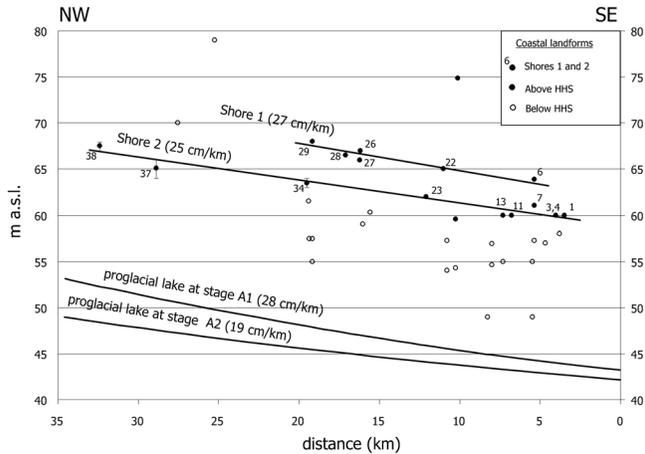


Fig 3. Height-distance diagram showing the distribution of the studied coastal landforms and identified shorelines above the highest Holocene shoreline (HHS). For comparison the proglacial lakes A₁ (~13.3 cal. ka BP) and A₂ (~12.8 cal. ka BP) water level surfaces (Vassiljev *et al.*, 2005; Rosentau *et al.*, 2007) are shown on the diagram. Location of cross-section is shown on Fig. 2 and description of coastal landforms in Table 1.

DISTRIBUTION OF GLACIOLACUSTRINE SEDIMENTS

Glaciolacustrine sediments are distributed in inter-drumlin basins and represented with clay, silt and fine sand deposits. Fine sand is common in shallow parts of these basins, both few meters above and below the modern lake level. Glaciolacustrine sand is not 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 in changing sedimentary environment. In order to describe the changes in sedimentary environment we identified different lithostratigraphic units for studied glaciolacustrine sediments designated upwards from unit A to unit D (Fig. 4).

The lowermost unit A consists of brownish-gray proglacial varved clay which lays on top of late Weichselian till. Varved clay comprises mostly of 2–4

cm thick couplets of silt and clay layers considered as annual varves (Fig. 4). Relatively short period of varved clay accumulation (maximum 63 varves) is characteristic to all studied sequences. The upper surface of the varved clay spreads up to the altitude of 55 m in the central part (lakes Pikkjärv and Prossa) being about 10 m lower in the southern part of the study area (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 (B₁–B₃) (Fig. 4). Subunits B₁ and B₃ are comprised of 0.1–0.3 cm thick couplets of brownish-gray silt and clay layers. In Lake Pikkjärv basin we counted as a total 81 couplets in these subunits (B₁ and B₃). However, the annual-layered character of subunits B₁ and B₃ is not clear as the distinct summer-winter layers are often not clearly visible. The subunit B₃ is rich in profundal ostracods in Lake Pikkjärv sequence (Sohar, 2004). The subunit B₂ contains gray massive clay of variegating thickness (mainly 2–5 cm) with clear discontinuity at its lower and upper boundaries. The upper surface of unit B spreads up to the altitude of 56 m in the central part (lakes Pikkjärv and Prossa) being ca 10 m lower in the southern part of the study area (lakes Soitsjärv, Raigastvere and Elistvere). In the northernmost of studied lake basins, Lake Kuremaa, (Fig. 2) the sequence of glaciolacustrine deposits starts with the subunit B₃, which lies there directly on the till and its upper surface is recorded at an altitude of 80 m.

Units	Principal section	Description	L. Soitsjärv PAZ (Pirrus, 1983)	Chronozones (Pirrus and Rauka, 1986)	Definition of lower boundary*	Shore displacement and event stratigraphy
		Gyttja/lake marl. Gytja, dark brown to greenish brown, in deeper part of lake basins. Lake marl, light gray, with detritus, in shallower parts.	Betula-Pinus	Preboreal	10.0 (-12.0-11.2)	
D		Silt (50-80 cm), greyish brown, massive, with abundance of littoral water mosses.	Artemisia-Betula nana	Younger Dryas	13.8 (-13.0-12.6)	Lowest water-level during the late glacial. Water-level at L. Soitsjärv and L. Elistvere below the modern lake level.
C		Silt (20-50 cm), gray, massive with black coloured sulphide rich interlayers. Contains littoral ostracods.	Pinus and Pinus-Betula	Allered	13.8 (-13.0-13.4)	Ice margin at line Pandivere-Neva (13.3 cal. ka BP). Lowering of water table and isolation of the lakes from Glacial Lake Peipsi and proglacial lake in the L. Võrtsjärv basin.
B ₃		Same as subunit B1 (10-20 cm). Contains 31 couplets at L. Pikkjärv core. Abundance of sublittoral and profundal ostracods.				Ice margin at line Siimusti-Kalu. Lowering of water table ca. 4 m and formation of Shore 2 at -13.8-13.6 cal. ka BP, start of sedimentation in L. Kuremaa
B ₂		Clay (mainly 3-5 cm), gray, massive.				
B ₁		Silt and clay rhythmites with 0.1-0.3 cm laminaes (15-30 cm), beige. Contains 51 couplets in L. Pikkjärv core.				Ice retreat and accumulation of finely laminated silt-clay rhythmites
A		Varved clay (up to 150 cm), brownish gray, with 2-4 cm thick couplets, summer layers consist of coarse silt or fine sand and winter layers consist of clay. Contains up to 63 varves (mainly 40-50)	Artemisia-Chenopodiaceae	Older Dryas	12.2 (-14.6-13.8)	Deglaciation of the southern and central part of the study area at ~14.0-13.8 cal. ka BP and formation of Shore 1. Ice margin at line Laeva-Piirissaar. Accumulation of glacial varved clay only in the deepest inter-drumlin basins at critical (minimal) water depths of about 15-20 m. An archipelago of proglacial lake was formed at Saadjärve Drumlin Field area.

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

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

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

The overlying unit D consists of gray homogeneous silt with abundance of different littoral water mosses (Pirrus and Rõuk, 1979). The upper surface of the unit D in lakes Soitsjärvi and Raigastvere is located *ca.* 1 m above the current lake-level, while in lakes Pikkjärvi, Prossa, Elistvere and Kuremaa the unit D remains few meters below of it. The unit D is covered by Holocene gyttja deposited in the deeper parts of the lake basins, or by lake marl/calcareous gyttja at nearshore part of the lakes (Fig. 4).

DISCUSSION

WATER-LEVEL CHANGES IN SAADJÄRVE DRUMLIN FIELD AREA

The late Weichselian lake-level changes in the study area, deduced from geomorphic and lithological data are summarized on Figs. 4 and 5. Following the ice retreat from the central and southern part of the study area in the Saadjärve Drumlin Field the deposition of glacial varved clays took place over the 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 the altitude of 55 m a.s.l. in the central part and being at *ca.* 10 m lower altitude 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 central part and 65–60 m in 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 may have been synchronous with the period of the accumulation of varved clays in the study area. Moreover, as the coastal landforms of the *Shore 1* and varved clays in the lake basins are distributed only in the central and southern part of the study area approximately in front of the ice margin position at Laeva-Piirisaar 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-Piirisaar position. The timing of this event could only tentatively be estimated to be 14.0–13.8 cal. kyr BP. This is derived from the modeled age of the deglaciation of the southern and central part of the Saadjärve Drumlin Field (about 14.0 cal. kyr BP; Kalm, 2006) as well as from the ages of the Piirisaar (about 14.0–13.8

Our results show the cease of rhythmic sedimentation in 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 the *Shore 2* (Fig. 5). As derived from 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 the *Shore 2*. We resume that most probably the lowering of the water-level below the *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). The assumption is based on the discovery of buried coastal terraces in the bottom of the Lake Soitsjärv and Lake Elistvere. These, buried under younger Holocene lake deposits, terraces (49 m a.s.l.) consist of littoral sediments, which contain abundance of water mosses characteristic for the 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). Younger Dryas low water-level have been estimated in many Estonian small lakes (Saarse and Harrison, 1992) as well as in Lake Peipsi (Hang *et al.*, 2001) and in Lake Võrtsjärv (Müdel *et al.*, 2004), which is in good agreement with our results.

CORRELATION OF *SHORE 1 AND SHORE 2* TO THE PEIPSI AND VÕRTSJÄRV BASINS

According to altitudes of *Shores 1 and 2* and compiled DTM the open connection between proglacial lakes in our study area and proglacial lakes in 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 water-levels of *Shores 1 and 2* with proglacial lake water-levels in Peipsi (Hang, 2001) and Võrtsjärv (Palusalu, 1967) basins identified according to correlation of terraces at Ahja, Piusa and Väike-Emajõgi valleys (Fig.1B).

Correlation of *Shores 1 and 2* with aforementioned terraces in south-eastern Estonia depends on the shoreline tilting pattern. Our results show that the tilting of *Shores 1 and 2* is rather similar to the shoreline tilting of younger, proglacial lake stage A₁ (13.3 cal. kyr BP), shoreline (Fig. 3). This suggests the comparable pattern also in the adjoining areas further to the south. This to be true, an exploiting (assuming) of similar to the A₁ low tilting gradient (Fig. 6) south of the study area displays a good correlation of *Shore 1* with the altitude of terraces at the Ahja R. and Piusa R. valleys earlier connected with the Glacial Lake Peipsi water-level during the Laeva–Piirissaar Stade (Hang, 2001). Also

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

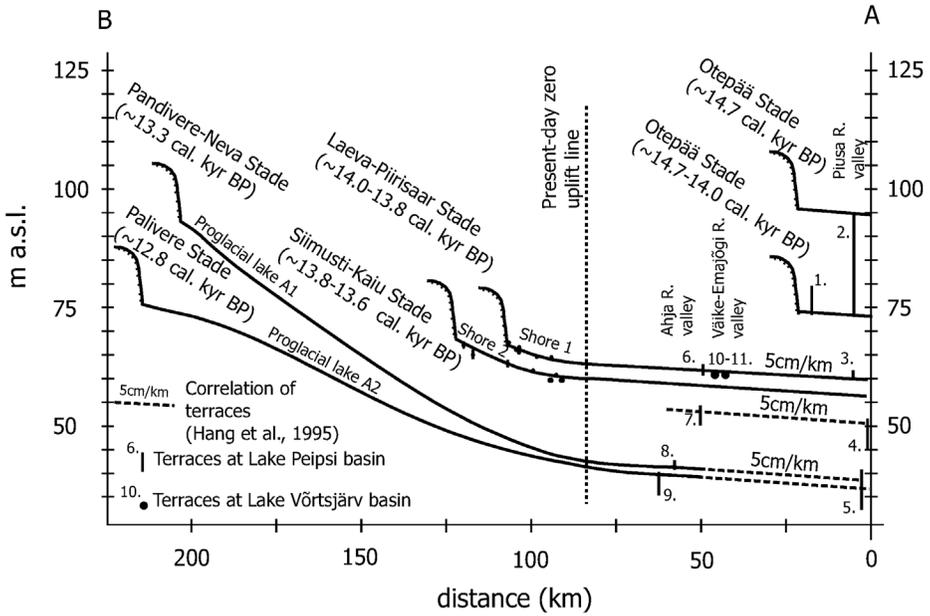


Fig 6. Correlation of *Shore 1* and *Shore 2* with the late Weichselian valley terraces reflecting the water-levels in the Glacial Lake Peipsi (Hang *et al.*, 1995) and in the Lake Võrtsjärv basin (Palusalu, 1967). For the comparison, main proglacial lake stages are given according to Hang *et al.* (1995)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

Following the same approach for the *Shore 2* no correlation with the river terraces south of the study area was achieved (Fig. 6). The terraces at the Ahja R. valley, earlier connected with Glacial Lake Peipsi water-level during the Siimusti–Kaiu ice margin position (Fig. 6), remain *ca.* 5 m below the extension of *Shore 2* level. This suggests that the valley terraces of the Siimusti–Kaiu Stade and the *Shore 2* are slightly metachronous. Considering the proglacial lake regression rates between *Shore 1* and proglacial lake A₁ (*ca.* 2 m/100 yrs; Fig. 6), the *Shore 2* might have formed few hundred years before 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 lake distribution and water-depth were performed (Fig. 7B,C), based on water levels 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 displayed (Figs. 6; 7A).

Start of the terrace formation (Fig. 6) and varved clay accumulation in 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 straits towards the east via Porkhov strait to Privalday Lake and to west via Piusa–Hargla strait and later via Võhandu–Hargla strait (Fig. 7A) to the proglacial lake in Gauja basin (Hang, 2001; Rosentau *et al.*, 2004). At the time when ice retreated from the Otepää ice margin position to the Laeva–Piirissaar line, the 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 Saadjärve Drumlin Field area by the formation of the shallow water archipelago (with water depth dominantly < 10–15 m) about 14.0–13.8 cal. kyr BP and formation of highest shoreline (*Shore 1*), which shows same water level as in Glacial Lake Peipsi and in the proglacial lake in the Lake Võrtsjärv basin (Fig. 7B). This shallow water archipelago expanded when ice retreated from the Laeva–Piirissaar ice margin position to the Siimusti-Kaiu line (Fig. 7C) and emerged thereafter as dry land with small isolated lakes in the inter-drumlin depressions. Separation of the lakes in the Saadjärve Drumlin Field is marked by end of laminated proglacial sediments and estimates the duration of proglacial lake conditions to have been about 150 years in this area

Due to the extension of the lake to the Laeva–Piirissaar line and corresponding lowering of the water-level, the earlier connection between the proglacial lake in the Gauja basin and the Glacial Lake Peipsi was shifted from the Võhandu–Hargla valley (Fig. 7A) to the Väike–Emajõgi valley (Fig. 7B). The shift of connection is supported by the location of 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) This differs from the proposal of Moora *et al.* (2002) who suggested the existence of the 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 retreat pattern in Sakala Upland, whose palaeogeography and timing are unclear (Kalm, 2006).

Our reconstructions show that during the ice retreat from Otepää ice margin position to the Laeva–Piiirissaar line, the Porkhov strait between Glacial Lake Peipsi and large Privalday Lake in NW Russia emerged (Fig. 7A–B) initiating the inflow into Glacial Lake Peipsi as suggested by Kvasov (1979). This isolation was considered as important palaeogeographic event, which marks the end of Privalday Lake 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 in front of the Laeva–Piiirissaar ice margin position about 14.0–13.8 cal. kyr BP and the second highest shoreline was formed at 4 m lower level when the ice margin was at Siimusti–Kaiu line. The reported here position of the highest shoreline is 10 m to 20 m lower than suggested in earlier studies.

The linear tilting gradients for two highest shorelines were calculated to be 27 and 25 cm km⁻¹ respectively. Comparison of our results with the shoreline tilting gradient data on proglacial lake stages A₁ (*ca.* 28 cm km⁻¹ about 13.3 cal. kyr BP) and A₂ (*ca.* 19 cm km⁻¹ about 12.8 cal. kyr BP) suggest that shoreline tilting in Saadjärve Drumlin Field area was rather similar between 14.0–13.3 cal. kyr BP and decreases between 13.3–12.8 cal. kyr BP.

The highest shoreline in our study area correlates with the valley terraces reflecting the water-level of Glacial Lake Peipsi during the Laeva–Piiirissaar Stade and with the highest late glacial terraces at an altitude 61 m a.s.l. at Väike–Emajõgi valley reflecting the proglacial lake-level in the Lake Võrtsjärv basin.

Palaeogeographical reconstruction suggests that during the ice stagnation at the Laeva–Piiirissaar line about 14.0–13.8 cal. kyr BP, the Glacial Lake Peipsi inundated the large areas of the Saadjärve Drumlin Field and the Emajõgi River valley and also reached the Lake Võrtsjärv basin. In Saadjärve Drumlin Field area this event is reflected in the formation of the highest shoreline and in the short period (up to 63 years) varved clay accumulation. Study suggests the suitable conditions for settling of glacial varved clay only in the deepest inter-drumlin basins at 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 lakes 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.

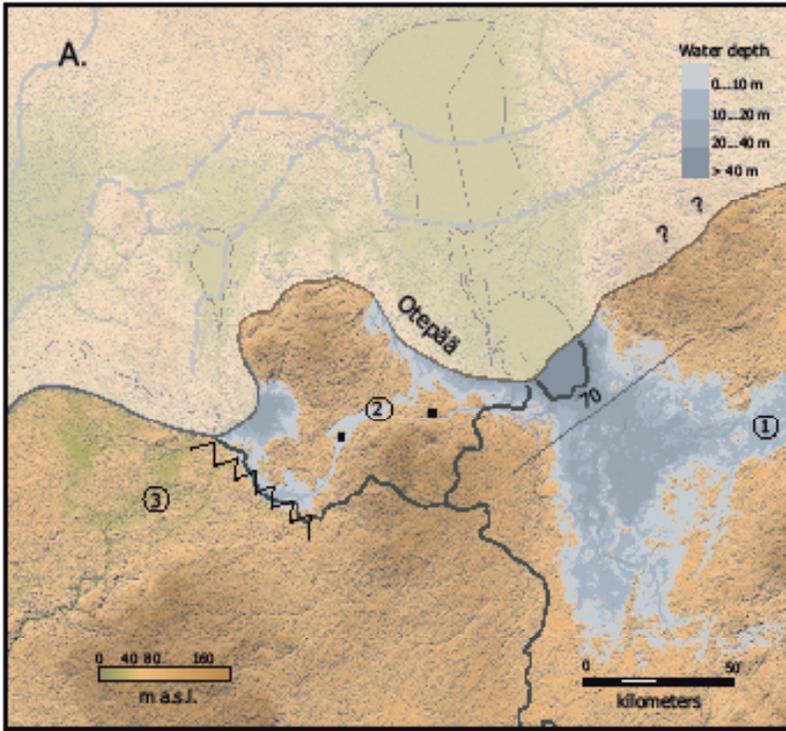


Fig 7. Palaeogeographic reconstruction of shoreline and bathymetry of proglacial lakes in eastern Estonia during the (A) Otepää Stadi (derived from Rosentau et al., 2004), (B) Laeva-Piirissaar Stadi and (C) Siimusti-Kaiu Stadi with indication of water-level surface isobases. Modern DTM (CIAT, 2004) and locations discussed in the text are shown on the map: 1. Porkhov strait, 2. Võhandu-Hargla strait, 3. Proglacial lake depression of the Gauja basin, 4. Connection route towards the Gauja basin. Coastal landforms (circles) and valley terraces (squares) used for reconstruction are shown on the maps.

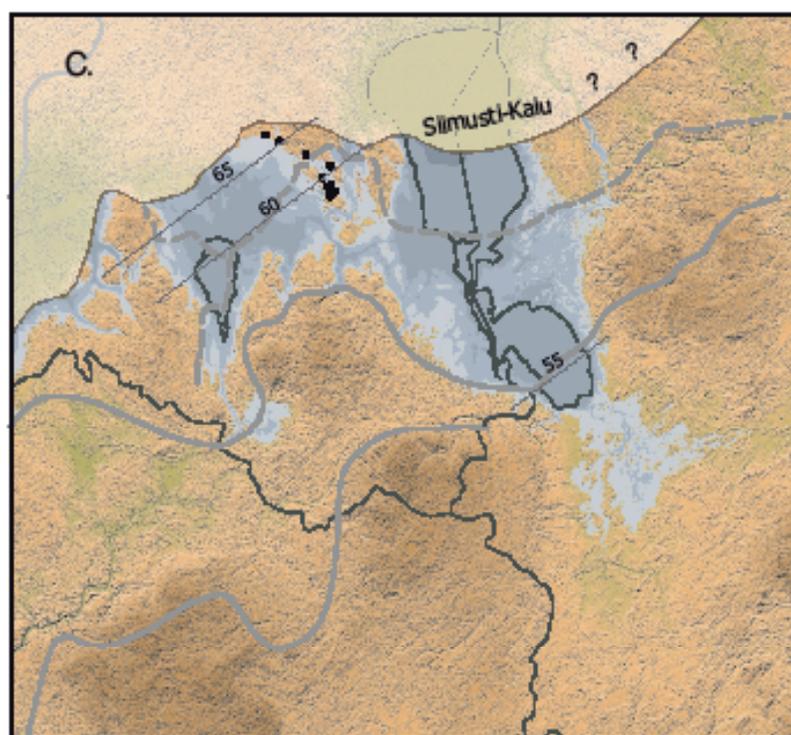
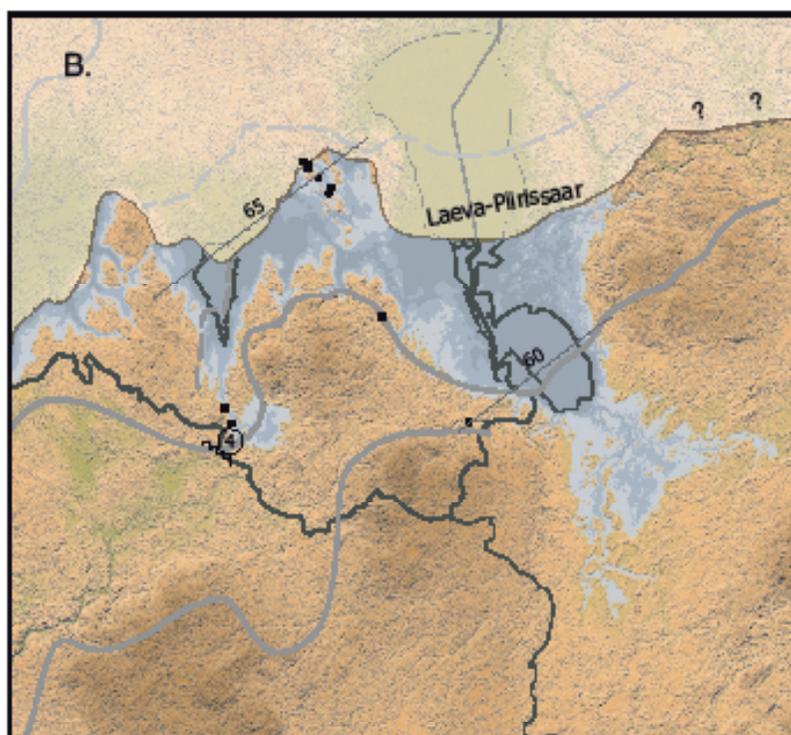


Fig 7. Continuation

About 14.0–13.8 cal. kyr BP the connection route between Glacial Lake Peipsi and proglacial lake in the Gauja basin in Latvia shifted from Võhandu–Hargla valley to the Väike–Emajõgi valley and the strait between Glacial Lake Peipsi and large Privalday Lake in NW Russia closed and was replaced by the inflow into the Glacial Lake Peipsi.

Acknowledgements. – We thank Dr. Robert Szava-Kovats improving the language. This study was funded by Swedish Institute through the Visby Program and Estonian Science Foundation Grant no. 5370.

REFERENCES

- Bronk Ramsey, C., 2001: Development of the radiocarbon program OxCal. *Radiocarbon* 43, 355–363.
- CIAT – INTERNATIONAL CENTRE FOR TROPICAL AGRICULTURE. 2004: Hole-filled seamless SRTM data V1. Data available from the CGIAR-CSI SRTM 90m Database http://gisweb.ciat.cgiar.org/sig/90m_data_tropics.htm <http://srtm.usgs.gov/>
- Estonian Land Board 1996: *Digital Base Map of Estonia in scale 1:50000*.
- Hang, T. 2001: Proglacial sedimentary environment, varve chronology and Late Weichselian development of Lake Peipsi, eastern Estonia. *Quaternaria* 111, 44 pp. + 5 app.
- Hang, T., Miidel, A., Kalm, V. and Kimmel, K. 2001: New data on the distribution and stratigraphy of the bottom deposits of Lake Peipsi, eastern Estonia. *Proceedings of the Estonian Academy of Sciences, Geology* 50, 233–253.
- Hang, T., Miidel, A. and Pirrus, R. 1995: Late Weichselian and Holocene water-level changes of Lake Peipsi, eastern Estonia. *PACT* 50, 121–131.
- Kajak, K. 1959: Die Geologie des Väike-Emajõgi-Tales. *Transactions of the Tartu State University* 75. *Publications on Geology* 1, 155–184 (in Russian with German summary).
- Kalm, V. 2006: Pleistocene chronostratigraphy in Estonia, southeastern sector of the Scandinavian glaciation. *Quaternary Science Reviews* 8. 960–975.
- Kvasov, D. D. 1979: The Late-Quaternary History of Large Lakes and Inland Seas of Eastern Europe. *Annales Academiæ Scientiarum Fennicæ, Ser. A III, Geologica-Geographica* 127, 1–71.
- Liblik, T. 1966: Jooni Piusa oru geomorfoloogiast. *Eesti Geograafia Seltsi aastaraamat* 1964/1965: 34–55.
- Ludqvist, J. and Wohlfarth, B. 2001: Timing and east-west correlation of south Swedish ice marginal lines during the Late Weichselian. *Quaternary Science Reviews* 20, 1127–1148.
- Lõokene, E. 1959: Geomorphologie des nördlichen Teils des Höhegebiets von Sakala. *Transactions of the Tartu State University* 75. *Publications on Geology* 1, 119–154 (in Russian with German summary).
- Mangerud, J., Jakobsson, M., Alexanderson, H., Astakhov, V., Clarke, G. K. C., Henriksen, M., Hjort, C., Krinner, G., Lunkka, J. P., Möller, P., Murray, A., Nikolskaya, O., Saarnisto, M. and Svendsen, J. I. 2004: Ice-dammed lakes and rerouting of the

- drainage of northern Eurasia during the Last Glaciation. *Quaternary Science Reviews* 23, 1313–1332.
- Miidel, A., Raukas, A. and Vaher, R. 2004: Geology of the lake basin. In Haberman, J., Pihu, E. & Raukas, A. (eds.): *Lake Võrtsjärv*, 33–46. Estonian Encyclopaedia Publishers, Tallinn.
- Moora, T., Raukas, A. and Tavast, E. 2002: Geological history of Lake Võrtsjärv. *Proceedings of the Estonian Academy of Sciences, Geology* 51, 157–179.
- Orru, M. 1995: *Handbook. Estonian mires*. 240 pp. Geological Survey of Estonia, Tallinn (in Estonian with English summary).
- Orviku, L. 1958: Neue Angaben über die Geologie des Sees Võrtsjärv. *Eesti NSV Teaduste Akadeemia Geoloogia Instituudi uurimused III*, 269–293 (in Russian with German summary).
- Palusalu, H. 1967: Väike-Emajõe alamjooksu oru geomorfoloogias. Diploma Work. 45pp.
- Persson, Ch. 1983: Glacial deposits and the Central Swedish end moraine zone in eastern Sweden. In Ehlers, J. (ed.): *Glacial deposits in north-west Europe*, 131–139, Balkema, Rotterdam.
- Pirrus, E. 1968: *Estonian varved clays*. 144pp. Valgus, Tallinn (in Estonian with English summary).
- Pirrus, R. 1983: Vooremaa maastikukaitseala järvesetete geoloogia ja järvede areng. Manuscript in the Institute of Geology at Tallinn University of Technology. 122pp.
- Pirrus, R. and Raukas, A. 1996: Late-Glacial stratigraphy in Estonia. *Proceedings of the Estonian Academy of Sciences, Geology* 45, 34–45.
- Pirrus and Rõuk, 1979: New data on the geology of the Soitsjärv Lake. In Raukas, A. (ed.): *Eesti NSV Saarkõrgustike ja järvenõgude kujunemine*, 118–144. Valgus, Tallinn (in Estonian with English summary).
- Rattas, M. 2004. Subglacial environments in the formation of drumlins – The case of the Saadjärve Drumlin Field, Estonia. *Dissertationes Geologicae Universitatis Tartuenssis, 14*, Tartu University Press, 117pp.
- Raukas, A. 2004: Application of OSL and ¹⁰Be techniques to the establishment of deglaciation chronology in Estonia. *Proceedings of the Estonian Academy of Sciences. Geology* 53, 2, 267–287.
- Raukas, A. and Rähni, E. 1969: On the Geological Development of the Peipsi-Pihkva Depression and the Basins Distributed in that Region. *Proceedings of the Estonian Academy of Sciences. Chemistry, Geology* 18, 2, 113–125 (in Russian with English summary).
- Raukas, A., Rähni, E. and Miidel, A. 1971: *Marginal glacial formations in North Estonia*. 226 pp. Valgus, Tallinn (in Russian with English summary).
- Reimer, P.J., Baillie, M.G.L., Bard, E., Bayliss, A., Beck, J.W., Bertrand, C.J.H., Blackwell, P.G., Buck, C.E., Burr, G.S., Cutler, K.B., Damon, P.E., Edwards, R.L., Fairbanks, R.G., Friedrich, M., Guilderson, T.P., Hogg, A.G., Hughen, K.A., Kromer, B., McCormac, 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., Hang, T. and Miidel, A. 2004: Simulation of the shorelines of glacial Lake Peipsi in Eastern Estonia during the Late Weichselian. *Geological Quarterly*, 4, 13–21.

- Rosentau, A., Vassiljev, J., Saarse, L. and Miidel, A. 2007 (in press): Palaeogeographic reconstruction of proglacial lakes in Estonia. *Boreas*, 36
- Saarnisto, M. and Saarinen, T. 2001: Deglaciation chronology of the Scandinavian ice sheet from east of Lake Onega basin to the Salpausselkä end moraines. *Global and Planetary Change* 31, 387–405.
- Saarse, L. and Harrisson, S.P. 1992: Holocene lake-level changes in the eastern Baltic region. *In Estonia. Man and Nature. Estonian Geographical Society*, 6–20. Tallinn.
- Saarse, L. and Kärson, J. 1982: Sedimentational peculiarities of the lakes Elistvere, Prossa and Pikkjärv. *Proceedings of the Estonian Academy of Sciences. Chemistry, Geology* 18, 2, 113–125 (in Russian with English summary).
- Sohar, K. 2004: Ida-Eesti järvede areng pleistotseenis ja Vara-Holotseenis ostrakoodi- and mestiku põhjal. MSc Thesis. 55pp.
- Sandgren, P., Hang, T. and Snowball, I. F. 1997: A Late Weichselian geomagnetic record from Lake Tamula, SE Estonia. *GFF* 119, 279–284.
- Torim, A. 1998: *Renovation of the Estonian Levelling Network*. Manuscript in Estonian Land Board Development Centre. Tartu, 55 pp.
- Vassiljev, J., Saarse, L. and Miidel, A. 2005: Simulation of the proglacial lake shore displacement in Estonia. *Geological Quarterly* 49, 3, 253–262.
- Uścińowicz, S., 1999: Southern Baltic area during the last deglaciation. *Geological Quarterly* 43, 2, 137–148.

Proglacial lake shorelines of Estonia and adjoining areas

ALAR ROSENTAU¹, JÜRI VASSILJEV², LEILI SAARSE² AND
AVO MIIDEL²

¹ Institute of Geology, University of Tartu, Vanemuise 46, 51014 Tartu, Estonia. Phone +372 375 896, fax +372 375 836, e-mail: alar.rosentau@ut.ee

² Institute of Geology at Tallinn University of Technology, Ehitajate tee 5, 19086 Tallinn, Estonia. Phone +372 6 203 010, fax +372 6 203 011
e-mail: vassilje@gi.ee, saarse@gi.ee, miidel@gi.ee

ABSTRACT

A uniform database of the proglacial lake coastal landforms of Estonia, Latvia and NW Russia was created and used to reconstruct the spatial distribution of proglacial lakes using the kriging point interpolation and GIS approaches. Correlation of the Late Glacial coastal landforms confirms that the proglacial lake stage A₁ in Estonia is synchronous with the Bgl_I level in Latvia and with one level in NW Russia, which index was not defined. Proglacial lake A₁ was formed concurrently with the Pandivere-Neva ice-margin about 13,300 cal. yr BP. Proglacial lake A₂ level formed probably about 12,800 cal. yr BP and correlates with the level of Bgl_{II} in Latvia and G_{III} in NW Russia. Simulated proglacial lakes water-level isobases show a relatively regular pattern of the land uplift along the eastern coast of the Baltic and in the northern part of the Lake Peipsi basin, with a steeper tilt to northwest. Isobases in the southern part of the Lake Peipsi basin are curving towards SE and are up to 14 m higher than expected from the regional trend. This phenomenon can reflect the forebulge effect during the deglaciation and its later collapse. Shoreline reconstruction suggests that proglacial lakes in Peipsi basin and in Baltic basin were connected via strait-like systems and had identical water levels. Our reconstructions also show that after the glacier halt at the Pandivere-Neva ice margin about 13,300 cal. yr BP, there was a connection with the initial Baltic Ice Lake in the west of Gulf of Riga.

Key word: proglacial lakes, Baltic Ice Lake, water level simulation, Estonia, Latvia, NW Russia

INTRODUCTION

The Baltic Sea history is complicated and up to now a generally accepted opinion on the ages of the different stages is absent (Hyvärinen, 1988). There is even no widely acknowledged understanding on the beginning of the Baltic Ice Lake (BIL) proposed almost 100 years ago by Munthe (1910). This problem is important in the context of the present paper dealing with the correlation and spatial distribution of the highest shorelines of proglacial lakes formed in coastal areas of eastern Baltic: stages A₁ and A₂ from Estonia (Lõökene, 1959; Pärna 1960; Vassiljev *et al.*, 2005), stage G_{III} from NW Russia (Markov, 1931) and stages Bgl_I and Bgl_{II} from Latvia (Grinbergs, 1957). Correlation of the above-mentioned proglacial lake shorelines is complicated due to different ice recession schemes and limited number of radiocarbon dates, which do not allow to determine the ages of shorelines precisely.

Correlations, based on geomorphological, bio- and chronostratigraphical data together with geostatistical analyses, can be one solution to study the pattern and distribution of the Late Glacial shorelines. The authors of the current study applied earlier the trend surface analyses (Miidel, 1995) and a point kriging interpolation (Saarse *et al.*, 2003) for the Baltic Ice Lake (stage B₃) and proglacial lakes A₁ and A₂ in Estonia to simulate the water-level surfaces (Vassiljev *et al.*, 2005). The present investigation correlates the water levels of the proglacial lakes A₁ and A₂ in Estonia with proglacial lakes in Latvia and NW Russia, using a geostatistical analyses and GIS-based palaeogeographic reconstruction of spatial distribution and bathymetry of proglacial lakes.

Age of the proglacial lakes and their relation with the Baltic Ice Lake

During the first stages of the proglacial lakes a series of raised shorelines were formed in front of the retreating ice (Ramsay, 1929; Grinbergs, 1957; Lõökene, 1959; Pärna, 1960; Gudelis, 1979; Kessel & Raukas, 1979; Veinbergs *et al.*, 1999; Zelčs & Markots, 2004). In Estonia, proglacial lake A₁ developed in front of the Pandivere-Neva ice margin (dated to 13,300 cal. yrs BP; Hang, 2001), which formed the ice-proximal coast of the lake, marked by several ice-contact slopes, flat-topped glaciolacustrine and glaciofluvial landforms. This lake was followed by a proglacial lake A₂ at lower level due to the isostatic land uplift. Its age has been considered, according to earlier studies, about 150-200 years younger than proglacial lake A₁ (Vassiljev *et al.*, 2005), however most recent study indicates that it could be 500 years younger (Rosentau *et al.*, in press.). Earlier Estonian researchers have considered the shorelines of A₁ and A₂ to represent shores of local ice lakes (Lõökene, 1959; Pärna, 1960). According to Kvasov and Raukas (1970), the ice withdrawal from the northern slope of the Pandivere Upland gave rise to the Baltic Ice Lake since the proglacial lake A₂.

On the Latvian coast a wide spectrum of the Late Glacial shorelines has been differentiated (Bgl_I, Bgl_{II}, Bgl_{III} with stages a, b, c) and regarded to have formed during the Baltic Ice Lake (Grinbergs, 1957). The two highest shorelines (Bgl_I and Bgl_{II}) were dated on the base of pollen records to the Older Dryas and Allerød, respectively (Veinbergs, 1979). Later Veinbergs *et al.* (1995) reassessed the age of the highest shoreline (Bgl_I) to the Allerød according to the similarities with the pollen spectra from the Gulf of Riga.

In the NW Russia Markov (1931) described the Late Glacial highest shorelines of stages G_{III} and G_{IV}. According to Sauramo (1958), G_{III} corresponds to the Baltic Ice Lake stage B_I and G_{IV} gives a complex spectrum which represents the stages B_{III-VI}. However, Markov's stage G_{III} seems also to be complex as the height of these shorelines in the same location varies in the range of 6–11 m. Actually, Markov (1931) described also proglacial lakes G_I and G_{II}, but these existed in the Neva-Ladoga basin, which was not connected with the proglacial lakes under discussion.

Donner and Raukas (1989) correlated A₁ and A₂ shorelines in Estonia with Bgl_I proglacial lake in Latvia, G_I–G_{II} in the Leningrad district and considered that the shoreline of Bgl_{II} started to form in the Allerød and completed in the Younger Dryas.

Markov (1931), investigating the shorelines in the Leningrad district, mentioned that the Baltic Ice Lake (first stage) emerged in the Older Dryas. Gudelis (1976) correlated the beginning of the Baltic Ice Lake with the release of the waters from the South-Baltic proglacial lake at Tyringe (South Sweden), which occurred also in the Older Dryas. Björck (1995) gave a profound overview on the Baltic Sea history. He indicated that large areas of the Southern Baltic became ice free at least 12,000 ¹⁴C yr BP (*c.* 14,000 cal. yr BP) and suggested that the initial Baltic Ice Lake emerged about 12,600 ¹⁴C yr BP. Uścińowicz (1999) showed that after the retreat of the ice sheet from the Southern Middle Bank Phase (dated to 14,900–14,600 cal. yr BP; Marks, 2004) the marginal lakes in the Gdansk and Bornholm Basin became connected initiating the development of the Baltic Ice Lake. This phase correlates with the Otepää ice-marginal formations in Estonia, which were dated to 14,700–14,500 cal. yr BP (Kalm, 2006).

MATERIAL AND METHODS

The coastal landforms database of the Estonian proglacial lakes, completed earlier (Vassiljev *et al.*, 2005), was supplemented in the current study with 33 sites from Latvia (Bgl_I and Bgl_{II}) and 14 sites from NW Russia. Altogether 127 sites were used in the simulation. In the first order the visual correlation between Estonian and neighbouring sites was done and the prospecting sites were identified. Secondly, point kriging interpolation with linear trend approach was used to create interpolated water-level surfaces of the proglacial lakes. The

grid size was 5 x 5 km. Then residuals (actual site elevation difference from the interpolated surface) were calculated and sites with residuals more than 1 m and 0.7 m were omitted.

The shorelines and bathymetry of the proglacial lakes were reconstructed using interpolated surfaces of water levels and a modern digital terrain model (DTM). Shoreline reconstruction was based on a GIS method that removed interpolated surfaces of water levels from DTM. DTM with a grid size 200×200 m was generated from the different digital elevation data sets:

- A. Digital terrain model for Estonia, with grid size 200 x 200 m (Rosentau *et al.*, in press.);
- B. Shuttle Radar Topography Mission (SRTM-90) elevation data with resolution 3 arc seconds (approx. 90 x 90 m) for Latvia and NW Russia (CIAT, 2004);
- C. Topography of the Baltic Sea (Seifert, 2001).

The results of the simulations were performed as palaeogeographic maps in Conformal Transverse Mercator projection (TM-Balti).

RESULTS AND DISCUSSION

Isobases of the studied Late Glacial proglacial lakes

The isobases of the A₁ and A₂ proglacial lakes and their correlation with the Latvian and NW Russian shorelines are presented (Figs. 1B, 2B). According to our reconstruction, the proglacial lake A₁ level correlates with Bgl_I in Latvia and with beach formations at 63 m a.s.l. in NW Russia (not indexed) and the proglacial lake A₂ level with Bgl_{II} in Latvia and with G_{III} in Russia.

Such correlation differs from the earlier suggested system by Donner & Raukas (1989). Along the eastern coast of the Baltic and in the northern part of the Lake Peipsi basin the isobases show a relatively regular pattern of the uplift, with a steeper tilt in NW. In the central part of the Lake Peipsi basin the isobases curve remarkably towards southeast, being up to 14 m higher than expected from the regional pattern (Figs. 1B, 2B). The reason of this curving is anomalous lowering of the tilting gradient reflected by continuous shorelines from the western coast of the Peipsi basin and shoreline data from the Emajõgi River valley (Fig. 1B). In the southern part of the Lake Peipsi basin, the low tilting gradients were noted also by correlation of over-deepened river mouths of the Emajõgi, Ahja and Obdekh rivers (Miidel *et al.*, 1995) and Late Glacial river terraces (Hang *et al.*, 1964; Hang *et al.*, 1995; Hang, 2001).

Geological reasons of the above-mentioned anomaly are not clear. In the regional scale recent vertical movements show that the southern margin of the Baltic Shield is enclosed by a belt of subsidence, which could be associated with a collapsed structure of a circum-Fennoscandian ring bulge of the upper

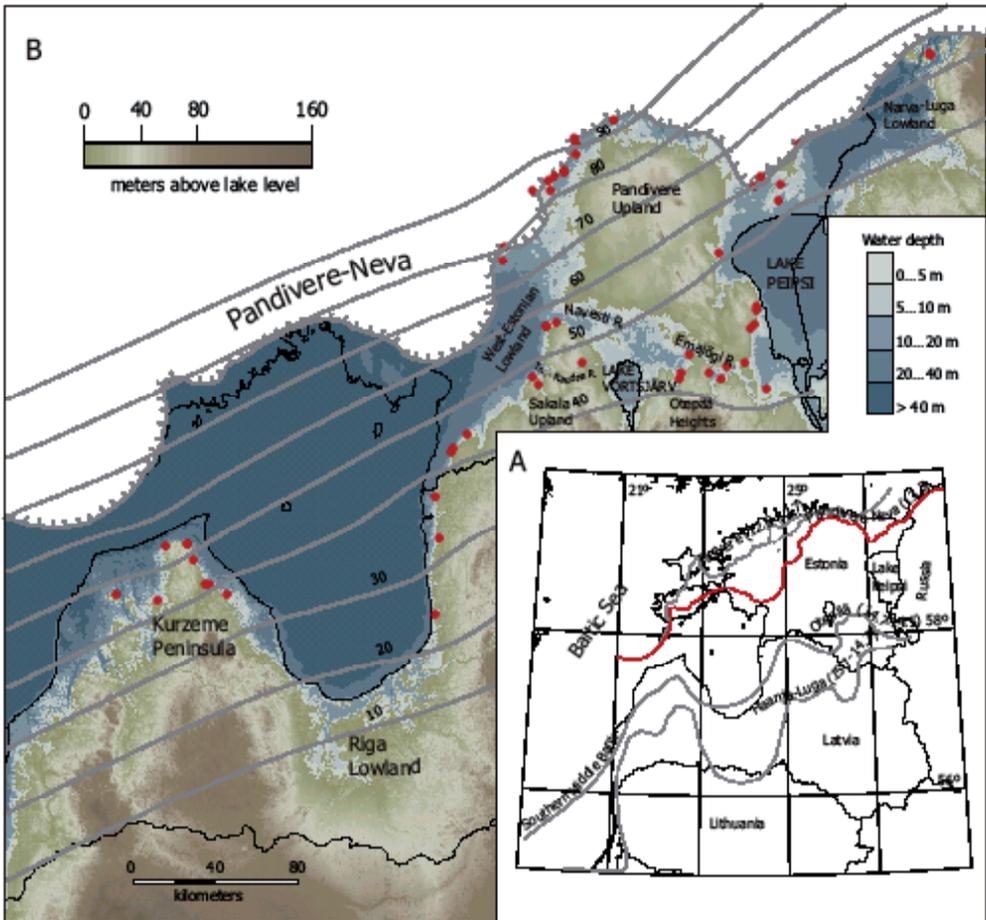


Fig. 1. A. Overview map showing the main ice marginal positions in Estonia with ages (cal. kyr BP) according to Kalm (2006) in relation with the ice-margin position during the proglacial lake A1 (red line). B. Palaeogeographic reconstruction of proglacial lake at c. 13.3 kyr BP and correlation of proglacial lake coastal landforms in Estonia (stage A1), Latvia (stage BgII) and NW Russia (an altitude of 63 m a.s.l.). Coastal landforms used in correlation and water-level surface simulation are shown by red dots.

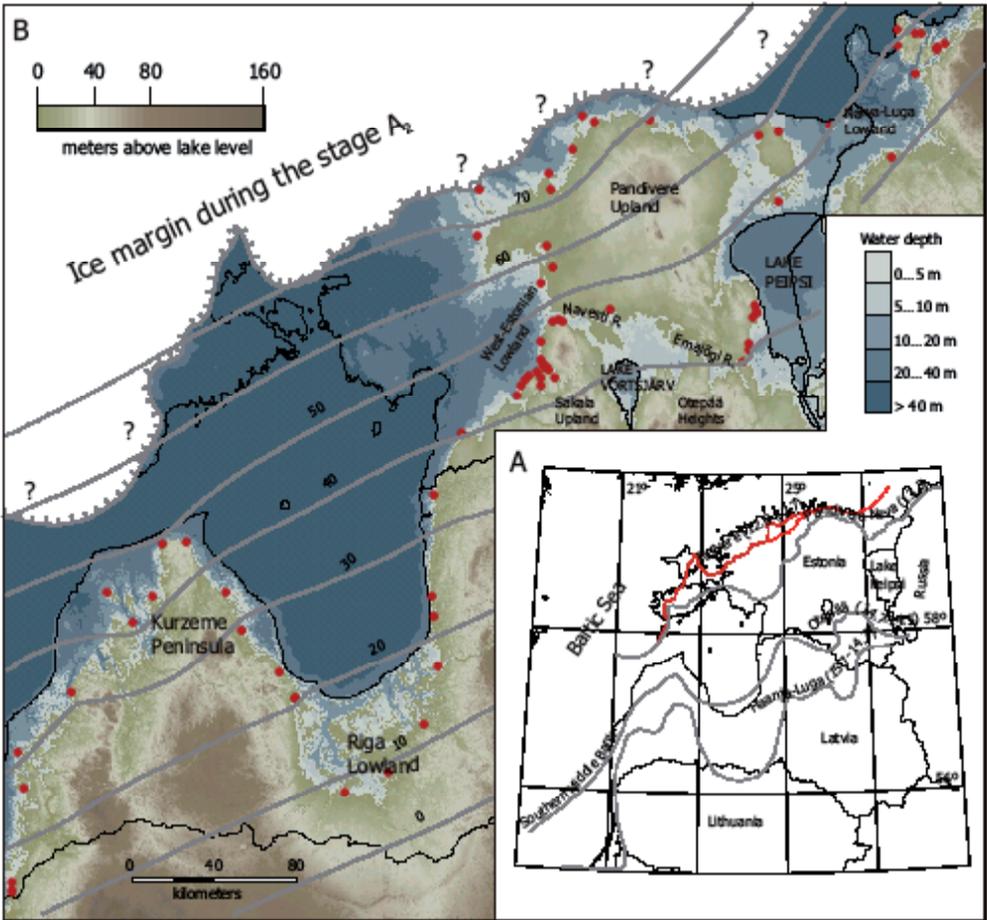


Fig. 2. A. Overview map showing the main ice marginal positions in Estonia with ages (cal. kyr BP) according to Kalm (2006) in relation with the ice-margin position during the proglacial lake A2 (red line). B. Palaeogeographic reconstruction of proglacial lake at c. 12.8 kyr BP and correlation of proglacial lake coastal landforms in Estonia (stage A₂), Latvia (stage BgIII) and NW Russia (stage GIII). Coastal landforms used in correlation and water-level surface simulation are shown by red dots.

mantle after melting of the Weichselian ice sheet (Fjeldskaar, 1994; Harff *et al.*, 2001). Vertical movement measurements place the subsidence belt to the southeast of Estonia with the highest values (-0.8 mm/yr by Vallner *et al.*, 1988 or -2–3 mm/yr by Harff *et al.*, 2001) in the southern part of the Lake Peipsi basin, whereas to the north from this belt a regular land uplift occurs. Such pattern of tilting of the crust fits well with the Late Glacial shoreline-tilting pattern (Figs.1B, 2B) and could reflect the ongoing forebulge collapse in southeastern Estonia.

It seems possible that some peculiarities of the development of rivers and lakes support the presence of a forebulge in southern Estonia and neighbouring areas of Russia. Above all, the large depth of the Late Glacial valleys (up to 70 m in Russia), discharging the water from south into the Peipsi basin indicates the high position of this area. The deep incision of rivers could be explained by the uplift of the forebulge. The more intense uplift of the southern part of the Peipsi depression and adjoining areas brought about a large-scale regression and formation of several isolated bodies of water. At the end of the Late Glacial, probably in the Younger Dryas, the rapid uplift embraced the northern part of the lake basin and in the south the relative subsidence became prevailing (Hang & Miidel, 1999).

However, the age of the Late Glacial shorelines in the Peipsi basin and neighbouring areas are estimated indirectly and therefore the evaluation of irregularities of the regional isostatic rebound needs more precise studies proved by direct datings.

Spatial distribution and discharge pathways of the proglacial lakes

Palaeogeographical maps with spatial distribution of the proglacial lakes in Estonia, Latvia and NW Russia are presented on Figures 1B and 2B. Reconstructed spatial distribution of the proglacial lake A₁ shows that it discharged southwest to the deglaciated Baltic Proper. In northeast this proglacial lake extended over the Luga Lowland forming in the middle reaches of the modern Luga River ca 40 km long Luga Bay (Kvasov, 1979; Spiridonov *et al.*, 1988; Fig.1B), which marks the outflow area of the ancient Luga River. The water body in the Narva-Luga Lowland and Peipsi basin was separated from the main part of the proglacial lake in the west, being connected only by strait-like systems. The existence of the reconstructed narrow proximal strait north of the Pandivere Upland is questionable because it highly depends on the precision of the ice terminus position (Fig 1B). Still, this outlet could have opened later, after the ice recession from the Pandivere-Neva line (Kvasov & Raukas, 1970; Rosentau *et al.*, in press.). Most probably, the water bodies in the east and west had a connection *via* Võrtsjärv Lowland through the straits in the Emajõgi, Navesti and Tännassilma-Raudna River valleys (Fig. 1B). According to the calculations (Rosentau *et al.*, in press.), this strait system was large enough to transfer the meltwater from the Peipsi and Narva-Luga basins and,

therefore, there is no reason to suggest that the water level in the Peipsi basin was considerably higher than west of the Pandivere Upland, in the Baltic Sea basin as it was suggested earlier by Kvasov & Raukas (1970).

Proglacial lake A₂ developed after the ice margin retreated northward from the Pandivere-Neva ice marginal position. The water level of lake A₂ was up to 15 m lower in the northern part of the study area, but only few meters in southern part compared to the proglacial lake A₁ shoreline, because in the landuplift differences (Fig. 2B). After the ice retreated to the Gulf of Finland, the proximal connection north of the Pandivere Upland opened and provided connection between the proglacial lakes in the Baltic, Lake Peipsi basin and Narva-Luga Lowland (Fig. 2B). At the same time the above described straits in the Emajõgi and Navesti river valleys narrowed and the proglacial lake in the Võrtsjärv basin started to isolate. The archipelago on the Riga Lowland was widened forming belts of elongated islets parallel to the present coastline. This could reflect an intensive accumulation of coastal deposits during the end of the Late Glacial and Holocene and, therefore, the distribution of archipelagos during A₂ and also during A₁ is not clear.

Reconstructions show that proglacial lakes A₁ and A₂ were not an isolated water bodies as supposed by earlier studies (Löökene, 1959; Pärna 1960; Kessel & Raukas 1979), but were connected in the west of Gulf of Riga with the initial Baltic Ice Lake, as defined by Björck (1995).

CONCLUSIONS

1. Simulation of water-level surfaces confirms that proglacial lake stage A₁ in Estonia (*c.* 13,300 cal.yr BP) correlates with the level Bgl_I in Latvia and with beach formations at 63 m a.s.l. in NW Russia, which was not indexed. The proglacial lake stage A₂ (probably *c.* 12,800 cal.yr BP) correlates well with the level Bgl_{II} in Latvia and G_{III} in NW Russia.
2. Isobases of simulated water-level surfaces show a relatively regular pattern of the land uplift along the eastern coast of the Baltic and in northern part of the Lake Peipsi depression, with a steeper tilt to northwest. Isobases in the central part of the Lake Peipsi depression are curving towards SE being up to 14 m higher from the regional trend. This phenomenon can reflect the forebulge effect during the deglaciation and its later collapse.
3. Shoreline reconstruction suggests that proglacial lakes in Peipsi basin and in Baltic basin were connected via strait-like systems and thus had identical water levels. Our reconstructions show that studied proglacial lakes were connected in the west of Gulf of Riga with the initial Baltic Ice Lake.

Acknowledgements. We thank Helle Kukk for improving the language. The study was funded by Estonian target funding projects 0182530s03 and 0332710s06, University of Tartu Grant PFLAJ 05909 and Estonian Science Foundation Grants no 5370, 5342 and 6736.

REFERENCES

- BJÖRCK S., 1995 – A review of the history of the Baltic Sea, 13.0–8.0 ka BP. *Quat. Internat.*, **27**: 19–40 (calibrated ages from <http://www.geol.lu.se/personal/seb/>).
- CIAT – INTERNATIONAL CENTRE FOR TROPICAL AGRICULTURE, 2004 –. Hole-filled seamless SRTM data V1. Data available from the CGIAR-CSI SRTM 90m Database http://gisweb.ciat.cgiar.org/sig/90m_data_tropics.htm
<http://srtm.usgs.gov/>
- DONNER J., RAUKAS A., 1989 – On the geological history of the Baltic Ice Lake. *Proc. Estonian Acad. Sci., Geol.*, **38**, 3: 128–137.
- FJELDSKAAR W., 1994 – The amplitude and decay of glacial forebulge in Fennoscandia. *Norsk Geologisk Tidsskrift*, **74**: 2–8.
- GRINBERGS E. F., 1957 – Late and postglacial history of coasts of Latvian SSR. Acad. Sci. Latvia, Institute of Geology and Mineral Resources. Riga [in Russian].
- GUDELIS V., 1976 – History of the Baltic Sea. In: *Geology of the Baltic Sea* (eds. V. Gudelis, E. Emelyanov). Vilnius: 95–116 [in Russian with English summary].
- GUDELIS V., 1979 – The Quaternary history of the Baltic. Lithuania. In: The Quaternary history of the Baltic (eds. V. Gudelis, L.-K. Königsson). *Acta Universitatis Upsaliensis*. Uppsala: 159–173.
- HANG T., 2001 – Proglacial sedimentary environment, varve chronology and Late Weichselian development of Lake Peipsi, eastern Estonia. *Quaternaria A11*. PhD Thesis.
- HANG E., LIBLIK T., LINKRUS E., 1964 – On the Relations between Estonian Valley Terraces and Lake and Sea Levels in the Late-Glacial and Holocene periods. *Transact. Tartu State Univ.*, **156**, Publications on geography IV: 29–42.
- HANG T., MIIDEL A., 1999 – Holocene history of the lake. In: *Lake Peipsi. Geology* (eds. A. Miidel, A. Raukas). Sulemees Publishers, Tallinn: 131–135.
- HANG T., MIIDEL A., PIRRUS R., 1995 – Late Weichselian and Holocene water-level changes of Lake Peipsi, eastern Estonia. *PACT*, **50**: 121–131.
- HARFF J., FRISCHBUTTER A., LAMPE R., MEYER M., 2001 – Sea-Level Changes in the Baltic Sea: Interrelation of Climate and Geological Processes. In: *Geological perspectives of global climate change* (eds. L. C. Gerhard et al.): 231–250.
- HYVÄRINEN H., 1988 – Definition of the Baltic stages. *Annal. Acad. Sci. Fennicae, ser. A III, Geol.-Geogr.*, **148**: 7–11.
- KALM V., 2006 – Pleistocene chronostratigraphy in Estonia, southeastern sector of the Scandinavian glaciation. *Quaternary Science Reviews*, **8**: 960–975.
- KESSEL H., RAUKAS A., 1979 – The Quaternary history of the Baltic. Estonia. In: The Quaternary history of the Baltic (eds. V. Gudelis, L.-K. Königsson). *Acta Universitatis Upsaliensis*. Uppsala: 127–146.
- KVASOV D. D., 1979 – The Late-Quaternary History of Large Lakes and Inland Seas of Eastern Europe. *Annal. Acad. Sci. Fennicae, ser. A III, Geol.-Geogr.*, **127**: 1–71.

- KVASOV D. D., RAUKAS A., 1970 – Postglacial history of the Gulf of Finland. *Proc. Geogr. Soc. Soviet Union*, **102**: 432–438 [in Russian with English summary].
- LÕOKENE E., 1959 – Geomorphologie des nördlichen Teils des Höhengbiets von Sakala. *Transact. Tartu State Univ.*, **75**, Publications on Geology I: 119–154 [in Russian with German summary].
- MARKS L., 2004 – Pleistocene glacial limits in Poland. In: *Quaternary Glaciations – Extent and Chronology, Part I: Europe* (eds. J. Ehlers, P.L. Gibbard). Elsevier, Amsterdam: 295–300.
- MARKOV K., 1931 – Development of the relief in the north-western part of the Leningrad district. *Transact. Geological and Prospecting Service U.S.S.R.*, **117**: 1–256 [in Russian with English summary].
- MIIDEL A., 1995 – An attempt to apply trend-surface analysis to the study of raised shorelines of the Baltic Sea in Estonia. *Proc. Estonian Acad. Sci., Geol.*, **44**, 2: 97–110.
- MIIDEL A., HANG T., PIRRUS R., LIIVA A., 1995 – On the development of the southern part of Lake Peipsi in the Holocene. *Proc. Estonian Acad. Sci., Geol.*, **44**, 1: 33–44.
- MUNTHE H., 1910 – Studies in the Late-Quaternary History of southern Sweden. *Geol. Fören. Stockh. Förh.*, **32**, 3:11–97.
- PÄRNA K., 1960 – Zur Geologie des Baltischen Eisstausees sowie der lokalen grossen Eisstauseen auf dem Territorium der Estnischen SSR. *Eesti NSV Teaduste Akadeemia Geoloogia Instituudi uurimused*, **V**: 269–278 [in Russian with German summary].
- RAMSAY W., 1929 – Niveauschiebungen, Eisgestaute Seen und Rezession des Inlandeises in Estland. *Fennia*, **52**: 2, 1–48.
- ROSENTAU A., VASSILJEV J., SAARSE L., MIIDEL A. – Palaeogeographic reconstruction of proglacial lakes in Estonia. *Boreas* (in press.).
- SAARSE L., VASSILJEV J., MIIDEL A., 2003 – Simulation of the Baltic Sea Shorelines in Estonia and Neighbouring Areas. *J. Coast. Res.*, **19**: 261–268.
- SAURAMO M., 1958 – Die geschichte der Ostsee. *Annal. Acad. Sci. Fennicae. Geol.-Geogr., ser. A III*, **51**: 1–522.
- SEIFERT T., TAUBER F., KAYSER B., 2001 – A high resolution spherical grid topography of the Baltic Sea – revised edition. Baltic Sea Science Congress, November 25–29, 2001, Stockholm, Sweden, Poster 147.
- SPIRIDONOV M. A., RYBALKO A. E., BUTYLIN V. P., SPIRIDONOVA E. A., ZHAMOIDA V. A., MOSKALENKO P. E., 1988 – Modern data and views on the geological evolution of the Gulf of Finland. In: *The Baltic Sea* (ed. B. Winterhalter). *Geological Survey of Finland, Special Paper*, **6**: 95–100.
- UŚCINOWICZ S., 1999 – Southern Baltic area during the last deglaciation. *Geol. Quart.*, **43**, 2: 137–148.
- VALLNER L., SILDVEE H., TORIM A., 1988 – Recent crustal movements in Estonia. *J. Geodyn.*, **9**: 215–233.
- VASSILJEV J., SAARSE L., MIIDEL A., 2005 – Simulation of the proglacial lake shore displacement in Estonia. *Geol. Quart.*, **49**, 3: 253–262.
- VEINBERGS I., 1979 – The Quaternary history of the Baltic. Latvia. In: *The Quaternary history of the Baltic* (eds. V. Gudelis, L.-K. Königsson). *Acta Universitatis Upsaliensis*. Uppsala: 147–157.

- VEINBERGS I., SAVVAITOV A., NULLE U., 1999 – The ancient shorelines of the Latvian Coast and their dynamic. *Baltica Special Publication*, **12**: 125–129.
- VEINBERGS I. G., SAVVAITOV A., STELLE V., 1995 – Deglaciation of the last ice sheet and development of the Late Glacial basins in the southeastern part of the Baltic Sea. *Baltica*, **9**: 51–56.
- ZELČS V., MARKOTS A., 2004 – Deglaciation history of Latvia. In: *Quaternary glaciations – Extent and Chronology* (eds. J. Ehlers and P. L. Gibbard). Elsevier, Amsterdam: 225–243.

CURRICULUM VITAE

Alar Rosentau

Date of birth, place: 22. January 1975, Võru, Estonia

Nationality: Estonian

Address: University of Tartu, Institute of Geology,
Vanemuise 46, 51014, Tartu

Phone: +372 737 5896

e-mail: alar.rosentau@ut.ee

Education

since 2001 University of Tartu, Institute of Geology, doctorate studies

1998–2001 University of Tartu, Institute of Geology, MSc study in applied
geology

1993–1998 University of Tartu, Institute of Geology, BSc study in geology

1990–1993 1th Secondary School, Võru, Estonia

Professional experience

since 2005 research scientist at University of Tartu, Department of History

2001–2005 senior engineer at University of Tartu, Institute of Geology

2000 engineer at University of Tartu, Institute of Geology

1999 senior lab assistant at University of Tartu, Institute of Geology

Publications

1. **Rosentau, A.**, Vassiljev, J., Saarse, L. and Miidel, A. Proglacial lake shorelines of Estonia and adjoining areas. *Polish Geological Institute Special Papers* (in press, accepted 6th April 2006).
2. **Rosentau, A.**, Vassiljev, J., Saarse, L. and Miidel, A. 2007: Palaeogeographic reconstruction of proglacial lakes in Estonia. *Boreas* 36, 1–11 (in press, accepted 1st August 2006).
3. Vassiljev, J., **Rosentau, A.**, Saarse, L. and Miidel, A. 2006: Proglacial lake shorelines of Estonia and adjoining areas *In The Baltic Sea Geology: The Ninth Marine Geological Conference. Extended Abstracts*, 117–119
4. Karro, E and **Rosentau, A.** 2005: Fluoride levels in the Silurian-Ordovician aquifer system of western Estonia. *Fluoride*, 38(4), 307–311.
5. Ainsaar, L. ja **Rosentau, A.** 2005: Setomaa paekivist. Rmt: Puura, I. Ja Pihu, S. (toim.) XXVIII Eesti Loodusuurijate Päev. Setomaa Loodus. Tartu, 11–18.

6. **Rosentau, A.**, Hang, T. and Miidel, A. 2004: Simulation of the shorelines of glacial Lake Peipsi in Eastern Estonia during the Late Weichselian. *Geological Quarterly* 4, 13–21.
7. Hang, T., **Rosentau, A.**, Rattas, M. ja Kalm, V. 2003. Kuremaa järve geoloogiast. Rmt: Puura, I. ja Reier, Ü. (toim.) XXV Eesti Loodusuurijate Päev. Vooremaa Loodus. Tartu, 17–26.
8. Hang, T.; **Rosentau, A.**, Talviste, P. ja Kalm, V. 2003. Maalihked – looduslikud või inimtegevuse tagajärg? *Eesti Loodus* 2/3.
9. Karro, E., Haamer, K. ja **Rosentau, A.** 2002. Fluor Siluri-Ordoviitsiumi veekompleksis Pärnu- ja Läänemaal. Rmt: Kukk, T. (toim.) XXV Eesti Loodusuurijate Päev. Pärnumaa Loodus. Tartu, 13–22.
10. **Rosentau, A.** 2001. Looduslikud ehitusmaterjalid Võrumaal. Rmt: Paal, T. (toim.) XXIV Eesti Loodusuurijate Päev. Lõuna- Eesti Loodus. Tartu, 51–56.

CURRICULUM VITAE

Alar Rosentau

Sünniaeg ja koht: 22.01.1975, Võru.

Rahvus.eestlane

Aadress: Tartu ülikooli Geoloogia instituut,
Vanemuise 46, 51014, Tartu

tel: +372 737 5896

e-post: alar.rosentau@ut.ee

Haridus

alates 2001 Tartu Ülikool, Geoloogia instituut, doktoriõpe

1998–2001 Tartu Ülikool, Geoloogia instituut, magistriõpe rakendusgeoloogias

1993–1998 Tartu Ülikool, Geoloogia instituut, bakalaureuseõpe geoloogias

1990–1993 Fr. R. Kreutzwaldi nimeline Võru I Keskkool

Teenistuskäik

alates 2005 erak. teadur Tartu Ülikooli ajaloo osakonnas

2001–2005 vaneminsener Tartu Ülikooli geoloogia instituudis

2000 insener Tartu Ülikooli geoloogia instituudis

1999 vanemlaborant Tartu Ülikooli geoloogia instituudis