Geological Quarterly, 2004, **48** (4): 299–307

Simulation of the shorelines of glacial Lake Peipsi in Eastern Estonia during the Late Weichselian

Alar ROSENTAU, Tiit HANG and Avo MIIDEL

Rosentau A., Hang T. and Miidel A. (2004) — Simulation of the shorelines of glacial Lake Peipsi in Eastern Estonia during the Late Weichselian. Geol. Quart., **48** (4): 299–307. Warszawa.

Digital reconstruction of the evolution of glacial Lake Peipsi, Eastern Estonia, was based on a geographic information system (GIS) method that removed isostatically deformed palaeowater planes from the current digital terrain model. A reconstruction of the proglacial water levels was performed with respect to geomorphological correlation of river terraces, raised shorelines and eroded surfaces of various aqueoglacial landforms. The configuration of shorelines, main outlets and water depths of glacial Lake Peipsi, corresponding to the Otepää, Piirissaar, Kaiu and Pandivere–Neva stades during the deglaciation of the Lake Peipsi depression, was simulated. The two approaches used, reflecting the geomorphological correlation of Raukas and Rähni (1969) and Hang (2001), are discussed.

Alar Rosentau, Tiit Hang, Institute of Geology, Tartu University, Vanemuise 46, 51014 Tartu, Estonia; e-mail: alar.rosentau@ut.ee; tiit.hang@ut.ee; Avo Miidel, Institute of Geology, Tallinn Technical University, Estonia 7, 10143 Tallinn, Estonia; e-mail: miidel@gi.ee
(received: March 10, 2004; accepted: July 26, 2004).

Key words: Late Weichselian, glacial Lake Peipsi, proglacial environment, GIS, water level changes, glacial rebound.

INTRODUCTION

The Lake Peipsi depression in Eastern Estonia (Fig. 1), located south-east of the Younger Dryas (Salpausselkä) ice-marginal deposits, was free of continental ice in the Gotiglacial during the Weichselian Glaciation. The glacially-eroded depression was occupied by the Peipsi ice stream, which was situated between the Baltic and Ladoga ice streams (Aseev, 1974; Karukäpp, 1997). Broken chains of end moraines and glaciofluvial deposits define the margin of the ice sheet in the current topography. These moraines and deposits are believed to represent temporary stagnations of the ice front when the glacier regime was close to equilibrium (Karukäpp and Raukas, 1997; Boulton *et al*., 2001). Glacial Lake Peipsi was formed when the continental ice retreated from the Haanja–Luga marginal deposits in the southern part of the lake depression (Fig. 1). The level of this proglacial lake gradually lowered owing to the expansion of the basin and the opening of new thresholds. Reconstruction of water level changes is difficult because of the lack of an open connection between the proglacial lake and the Baltic Ice Lake and due to uneven glacial rebound, which has been faster in the northern part of the lake depression.

The aim of this study was to simulate the spatial distribution, water depth and possible drainage of glacial Lake Peipsi with respect to water level changes based on two scenarios of shoreline tilting. Alar Rosentau was responsible for data processing and analysis, and Tiit Hang and Avo Miidel for the geological and geomorphological data and correlations. All authors contributed to interpretation of the results, discussion and conclusions.

GEOLOGICAL SETTINGS AND EARLIER INVESTIGATIONS

Lake Peipsi, which drains into the Gulf of Finland (Fig. 1), is the fourth largest lake in Europe, measuring about 150 km in length and 23–42 km in width. The lake is shallow, with a mean water depth of about 8 m (max. 15 m). Lake Peipsi is surrounded by a flat lowland area 30–45 m a.s.l. with rare landforms higher than 80 m a.s.l. The most prominent elevations bordering the lake depression are the Pandivere, Otepää and Haanja Heights in the west and the Luga Heights in the east (Fig. 1). These elevated hummocky areas lie 100–300 m a.s.l. Elongated depressions between these areas join the lake depression with the adjoining lowlands.

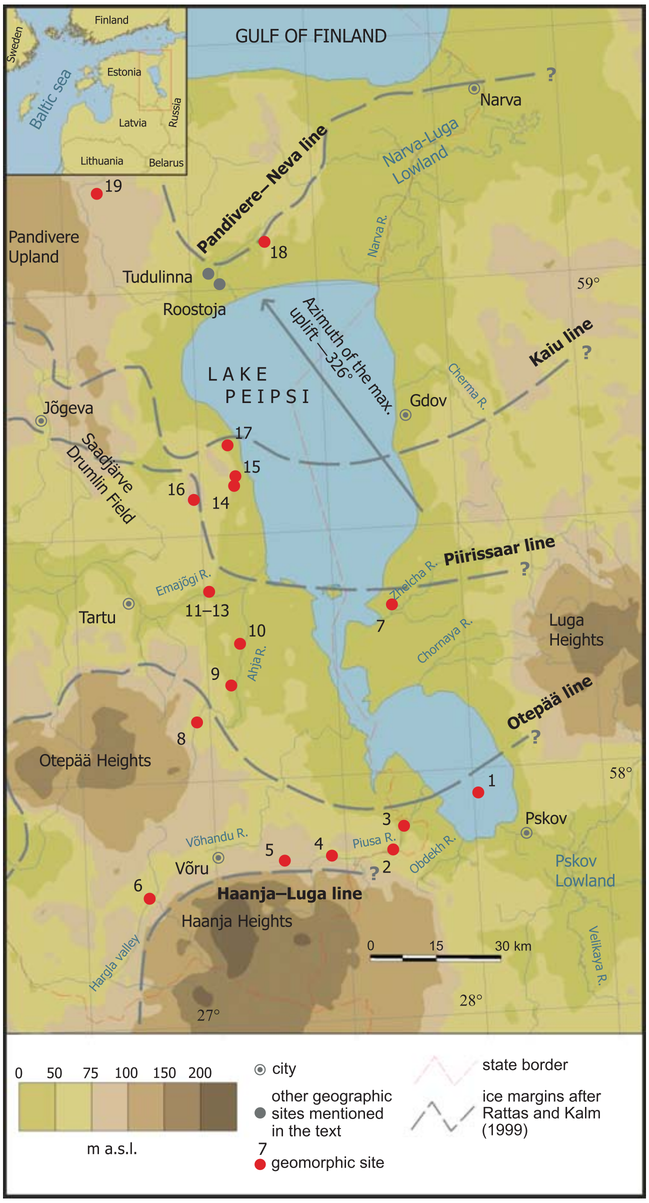

Fig.1. Study area around Lake Peipsi

Red dots with the numbers refer to the Late Weichselian geomorphic sites displayed in Table 1 and used for reconstruction of the water level during the different stages in the development of glacial Lake Peipsi

The elongated depression that presently contains Lake Peipsi was formed in Ordovician and Devonian sedimentary bedrock. The boundaries of the depression in the bedrock range between 40 and 50 m a.s.l. The altitude of the bedrock surface tends to decrease from 70–100 m in the surrounding heights to –30 m a.s.l. in the central part of the lake (Miidel *et al*., 2001). The lowland (20–30 m a.s.l.) north-east of the Lake Peipsi depression connects the lake with the depression of the Gulf of Finland.

The thickness of Quaternary deposits varies in accordance with the bedrock topography. The thickness increases from 5–10 m on the higher bedrock elevations to a maximum of 45 m in the central part of the lake (Noormets *et al*., 1998). The greatest thicknesses outside the lake are associated with the glacial accumulative landforms and buried valleys (Kajak, 1964). The sediment cover in the northern part of the lake basin consists of till and glaciolacustrine clay overlain by Holocene lake deposits (Noormets *et al*., 1998; Hang *et al*., 2001).

Despite almost a century of research, much of the history of deglaciation and of the development of the lake remain unresolved, notably the location of glacier margins in the depression (for summary Raukas *et al*., 1971; Karukäpp and Raukas, 1997; Karukäpp and Raukas, 1999). In most interpretations, five zones of ice-marginal deposits (Haanja–Luga, Otepää, Piirissaar, Kaiu and Pandivere–Neva), identified in Eastern Estonia and NW Russia (Rattas and Kalm, 1999), have been interpreted to represent stadials during the deglaciation (Fig. 1).

Geomorphological evidence of river terraces (Hang *et al*., 1964; Liblik, 1966; Miidel and Tavast, 1981), raised shorelines (Liblik, 1969; Hang *et al*., 1995) and abraded peaks of kames and eskers (Raukas and Rähni, 1969) have been used to reconstruct the Late Weichselian water level changes. Studies of peat bogs surrounding the recent lake (Thomson, 1929; Orviku, 1960; Sarv and Ilves, 1975; Miidel *et al*., 1995) and of lake deposits (Hang *et al*., 2001) suggest that the lowest water level occurred at the end of the Late Weichselian. Due to difficulties in the dating of river terraces, ancient shorelines and glaciolacustrine deposits and owing to the different intensity of glacioisostatic uplift, correlation of these features between the northern and the southern part of the lake depression are problematic. Hang *et al*. (1964) suggest that the river terraces located in different valleys at the same altitude are contemporary. Raukas and Rähni (1969) adopted this idea for the southern part of the depression and complement this correlation with the elevations of eroded eskers and kames in the northern part. This correlation yielded an estimate of tilting up to 60 cm km^{-1}.

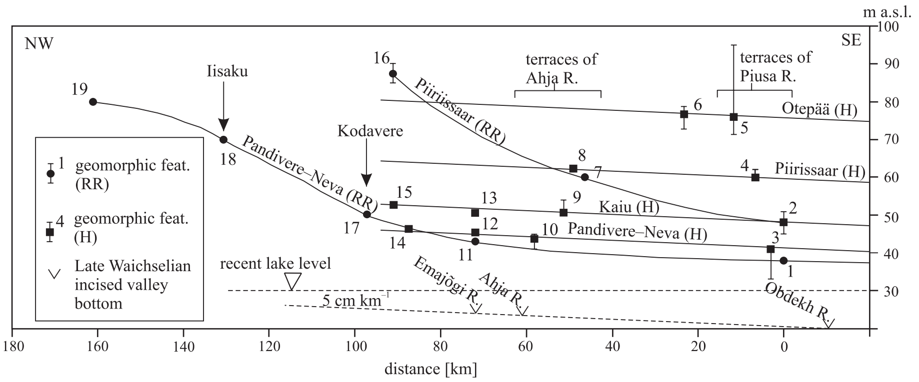

Fig. 2. Height-distance diagram of the geomorphic features reflecting the glacial Lake Peipsi water levels

The correlation lines used for reconstructing the palaeowater planes are according to H — Hang (2001) and RR — Raukas and Rähni (1969); data is projected to the azimuth of 326°; the Late Weichselian incised valley bottoms support the idea of a lower gradient for shoreline tilting; for description and geographical location of the sites and data see Figure 1 and Table 1

They also divided the lateglacial development of the Lake Peipsi into nine different stages (Raukas and Rähni, 1969).

Studies of abrasional scarps and terraces on the west coast of the recent Lake Peipsi led Liblik (1969) to estimate a shoreline tilting gradient of 4–9 cm km^{-1} (Fig. 2). This estimate was supported by geological data from the over-deepened river mouths of the Emajõgi, Ahja and Obdekh rivers (Fig. 2) (Miidel, 1981; Miidel *et al.*, 1995). The altitude of the bottom of these valleys reflects the incision of rivers during the period of low base-level (Lake Small Peipsi, *ca*. 20 m a.s.l.) at the end of the Late Weichselian (Hang *et al.*, 2001). The current difference in altitude of these valley floors (Fig. 2) also suggests a tilting gradient of *ca*. 5 cm km^{-1}. Hang *et al.* (1995) proposed a geomorphological correlation of shorelines and river terraces based on the lower tilting gradient. This correlation scheme (Fig. 2) considers only geomorphological data directly dependent on water level changes in glacial Lake Peipsi without considering eskers and kames, because the evolution of the kames and eskers could have been controlled by other factors. Thus, the final form of the kames and eskers could have been formed peri- or even subglacially prior to the glacial Lake Peipsi waters reaching the area. However, the low tilting gradient, suggested by Hang *et al.* (1995), is inconsistent with the shoreline data of the earlier stages of the Baltic Ice Lake in Western Estonia (Pärna 1962; Svensson, 1989), which suggests a tilting gradient of 34–45 cm km^{-1}.

MATERIAL AND METHODS

Digital reconstruction of the evolution of glacial Lake Peipsi was based on GIS method (McMartin, 2000; Leverington *et al.*, 2002) that removes the simulated, isostatically deformed palaeowater planes (i.e. interpolated elevations of palaeowater level data) from the current digital terrain model (DTM).

Different geomorphic features from earlier published sources were used to reconstruct past water levels. Site locations are shown in Figure 1 and the altitude, description and reference relief forms are presented in Table 1. Continuous raised shorelines represented by abrasional scarps and terraces have

Table 1

Late Weichselian geomorphic features, reflecting the glacial Lake Peipsi water level during the Otepää, Piirissaar, Kaiu and Pandivere–Neva stades according to the correlation of Hang (2001) and Raukas and Rähni (1969)

No. on Figure 1	Name	Altitude of geomorphic features [m a.s.l.]	Description	Reference
Otepää stade (Hang, 2001)				
5	Piusa valley	71.5–95	horizontal lake terraces (group A)	Liblik (1966)
6	Hargla valley	73–79	horizontal lake terraces (group A)	Liblik (1966)
Piirissaar stade (Hang, 2001)				
4	Piusa valley	60–62	river terraces (group B)	Liblik (1966)
8	Ahja valley	61.5–62.5	river terraces (group B)	Muru (1970)
Piirissaar stade (Raukas and Rähni, 1969)				
2	Piusa valley	45–51	river terraces (group C)	Liblik (1966)
7	Knyazhya Gora	60	flat-topped kame	Raukas and Rähni (1969)
16	Selgise	85–90	flat-topped kame	Raukas and Rähni (1969)
Kaiu stade (Hang, 2001)				
2	Piusa valley	45–51	river terraces (group C)	Liblik (1966)
9	Ahja valley	50–54	river terraces (group C)	Muru (1970)
13	Kavastu	50.5	coastal scarp	Liblik (1969)
15	Alasoo	51.5	coastal scarp	Liblik (1969)
Pandivere–Neva stade (Hang, 2001)				
3	Piusa valley	33–41	river terraces (group D)	Liblik (1966)
10	Ahja valley	41–44	river terraces (group D)	Muru (1970)
12	Kavastu	45.5	coastal scarp	Liblik (1969)
14	Alatskivi	47	coastal scarp	Liblik (1969)
Pandivere–Neva stade (Raukas and Rähni, 1969)				
1	Pskov Depression	38	inferred level	Raukas and Rähni (1969)
11	Kavastu	43	coastal scarp	Liblik (1969)
17	Kodavere	50	coastal scarp	Liblik (1969)
18	Iisaku	70	flat-topped esker	Raukas and Rähni (1969)
19	Saara	80	flat-topped kame	Raukas and Rähni (1969)

for the geographical locations of the enumerated data see Figure 1 been investigated (Liblik, 1969) only along the western coast of Lake Peipsi between sites 11 and 17 (Fig. 1). These coastal formations distinguish a continuous shoreline that lies 1–1.5 m higher in the north, showing that crustal uplift has been faster in the north. Glacial Lake Peipsi — in front of the retreating ice margin — provided a base level for the developing rivers in Southern Estonia. In the course of the lowering of the base level, rivers cut deep into the sediments and terraces were formed on the slopes of the valleys. The terrace spectra open downstream indicating a stepwise downcutting of the rivers. The altitudes of the terraces at the downstream end (shown with the site numbers on Figure 1) are thought to indicate the approximate altitude of the base level during terrace formation. The altitudes of terraces were adopted from earlier investigations (Table 1). The eroded peaks of kames and crests of eskers have been indicated and altitudes determined from topographic maps (Raukas and Rähni, 1969). Raukas and Rähni (1969) suggested that abrasional processes in glacial Lake Peipsi levelled the kame and esker surfaces, which therefore reflect the approximate water level of the lake.

A small number and uneven distribution of these geomorphological features precluded an independent estimation of the azimuth of maximum crustal tilting in the study area. Interpolation of the Baltic Ice Lake (BIL) shoreline data from Estonia, Northern Latvia and NW Russia suggests an azimuth of 326° for mainland Estonia (Pärna, 1962; Liblik, 1969; Kessel and Raukas, 1979; Hang *et al*., 1995) which is in accordance with recent results of azimuth modelling (Saarse *et al*., 2003) and therefore accepted in current study.

Two gradients of shoreline tilting were considered: a constant 5 cm km^{-1} and a higher, irregular gradient (Fig. 2). The lower gradient was used to simulate the palaeowater planes corresponding to the Otepää, Piirissaar, Kaiu and Pandivere stades during the deglaciation of the lake depression, while the terraces from the Piusa valley were taken as initial points for the water planes reconstruction (Figs. 3, 4, 6 and 7). Due to uncertainties in the compilation of geomorphological data (unknown azimuth of tilting, rapid and irregular changes of gradient) in the study by Raukas and Rähni (1969), only two simulations (Figs. 5 and 8) based on their data and corresponding to the Piirissaar and Pandivere stages are presented.

The palaeowater planes were generated using the linear solution of the Natural Neighbor interpolation of the Vertical Mapper GIS package. The grid size of the interpolated surfaces was 100 100 m. The calculated palaeowater plains were removed from the current digital terrain model (DTM) to simulate the extension and bathymetry of proglacial bodies of water. The DTM was generated using four elevation datasets:

— Estonian Base Map (1998, Digital version for MapInfo 1:50 000) — isobasis with 10 m intervals and a density of the irregularly distributed elevation points of 0.45 points km^{-2};

— bottom topography of Lake Peipsi after Noormets *et al*. (1998) — isobasis with 2 m intervals;

— bottom topography of the Russian part of Lake Peipsi (Veeteede ja Sadamate Valitsus, 1943) — density of the irregularly distributed elevation points 0.2 points km^{-2};

— topography of NW Russia and Latvia (EDC DAAC, 1996) — 30 30 arcsec cells.

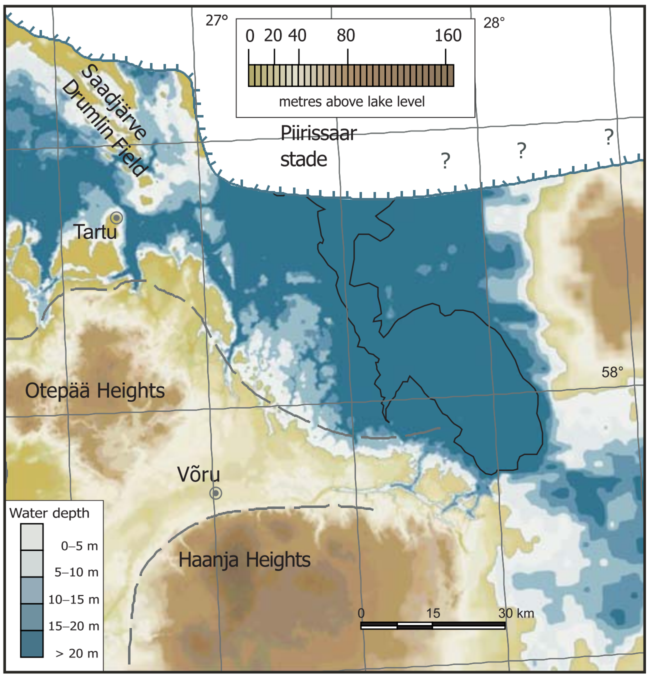

Fig. 4. Glacial Lake Peipsi during the Piirissaar stade

The simulation reflects the lower gradient of shoreline tilting (Hang, 2001; Fig. 2) with a lake elevation from 66–57 m a.s.l.; other explanations as on Figure 1

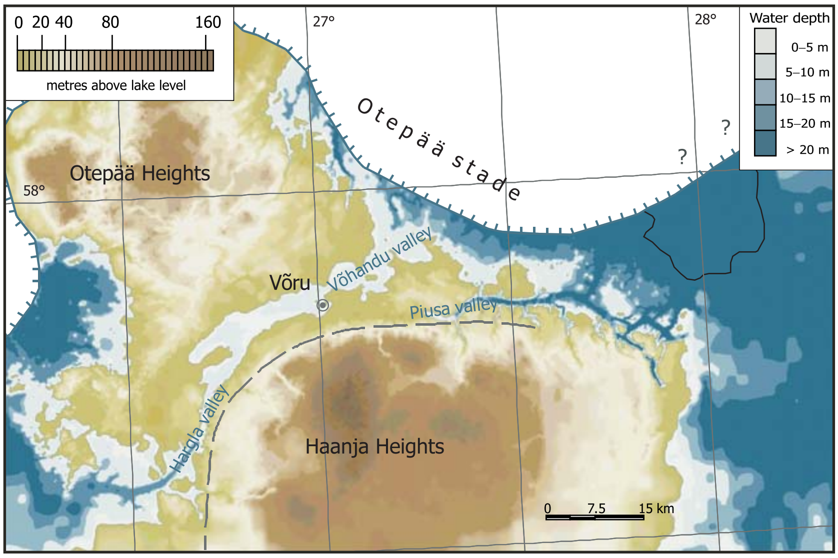

Fig. 3. Glacial Lake Peipsi during the Otepää stade after the main watershed at 75 m a.s.l. in the Piusa valley had emerged

A short period of westward connection could remain via Võhandu–Võru–Hargla valley; formation of the river terraces started in the Piusa valley; the simulation reflects the lower magnitude gradient of shoreline tilting (Fig. 2) with the lake elevation from 77–72 m a.s.l.; other explanations as on Figure 1

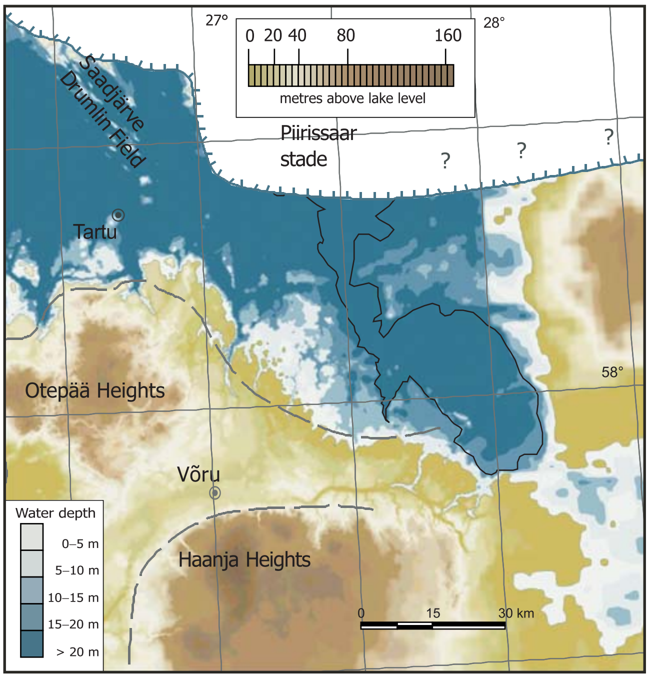

Fig. 5. Glacial Lake Peipsi during the Piirissaar stade

The simulation reflects the higher magnitude gradient of shoreline tilting (Raukas and Rähni, 1969; Fig. 2) with a lake elevation from 88–48 m a.s.l.; other explanations as on Figure 1

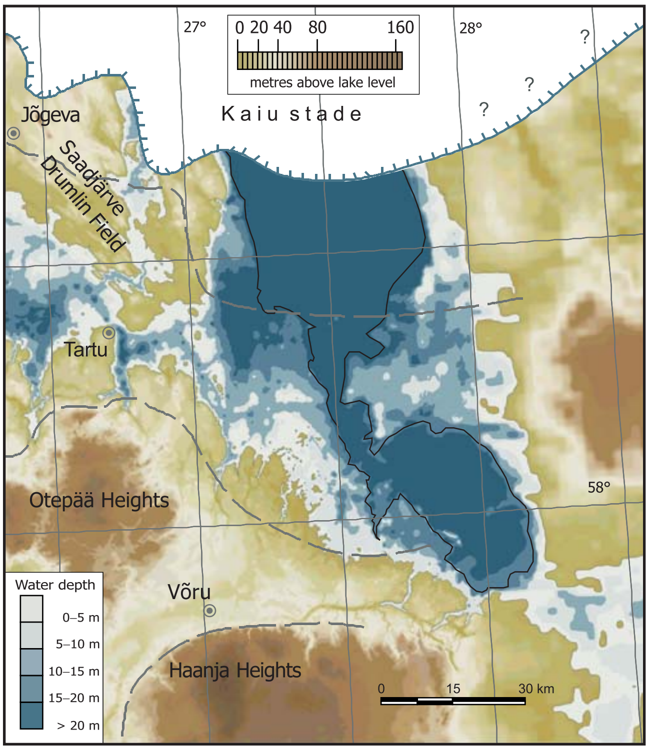

Fig. 6. Glacial Lake Peipsi during the Kaiu stade

The simulation reflects the lower gradient of shoreline tilting (Hang, 2001; Fig. 2) with a lake elevation from 54–45 m a.s.l.; other explanations as on Figure 1

Limitations in the application of the recent DTM as a base for reconstruction arise due to complications in the extraction of younger sediments and landforms. Holocene peat deposits were removed from the DTM. The thickness of peat was considered constant for three types of mires: 4 m for raised bogs, 2 m for transitional mires and 1 m for mires (Orru, 1995).

After removal of the calculated palaeowater plane and Holocen peat deposits from the DTM, the configuration of the lake, the water depths and topography were derived for specific time periods. Shorelines not associated with the main body of the glacial lake were ignored.

THE WATER LEVEL AND CONFIGURATION OF THE GLACIAL LAKE PEIPSI

THE OTEPÄÄ STADE

Glacial Lake Peipsi was formed when the continental ice retreated from the line of the Haanja–Luga marginal deposits to the Otepää line (Fig. 1). Horizontal terraces in the depression between the Haanja and Otepää Heights (Figs. 1 and 2) in southeastern Estonia likely mark the water level during this initial stage of the glacial Lake Peipsi. On the basis of different water levels, Raukas and Rähni (1969) identified two stages (Pihkva Ice Lake Ia and Ib), which were probably a part of the large Privaldai Ice Lake (Kvasov, 1979). In this study, water levels higher than 75 m a.s.l. are attributed to the first stage in the development of glacial Lake Peipsi and more detailed subdivision is not considered. It has been reported that the strait-like connection of glacial Lake Peipsi to the west through the Piusa and Hargla valleys was interrupted when the water level sank to an altitude of 75 m, but, according to the present simulation, a connection could still remain through the Võhandu and Hargla valleys (Fig. 3). This connection was likely interrupted later at an altitude of 73–70 m. Prior to the termination of the connection, glacial Lake Peipsi extended to the Pskow Lowland (Fig. 1) and further to the east (Kvasov, 1979). The water depth in the lake generally exceeded 15 m (mean 19 m, max. 50 m) thus being suitable for the accumulation of fine-grained glaciolacustrine deposits including varved clays. According to the present position of the palaeoshorelines, the lake elevation was 77 m in the north to 72 m in the south (Fig. 3).

THE PIIRISSAAR STADE

The digital reconstruction of the lake configuration using the tilting gradient of 5 cm km^{-1} (Fig. 2), revealed a large proglacial body of water extending westwards to the Lake Võrtsjärv depression of central Estonia (Fig. 4). The correlation of terraces of group B at the Piusa and Ahja valleys (Table 1) was used to reconstruct the water level during the Piirissaar stade (Figs. 1 and 2). The simulation revealed a 17–18 km wide deep-water connection to the west over the recent Emajõgi valley. An archipelago was formed at the Saadjärve Drumlin Field with a water depth up to 15 m (Fig. 4) and a noteworthy emergence of land directly in front of the glacier margin on the southern slope of the Pandivere Heights. The mean depth of the

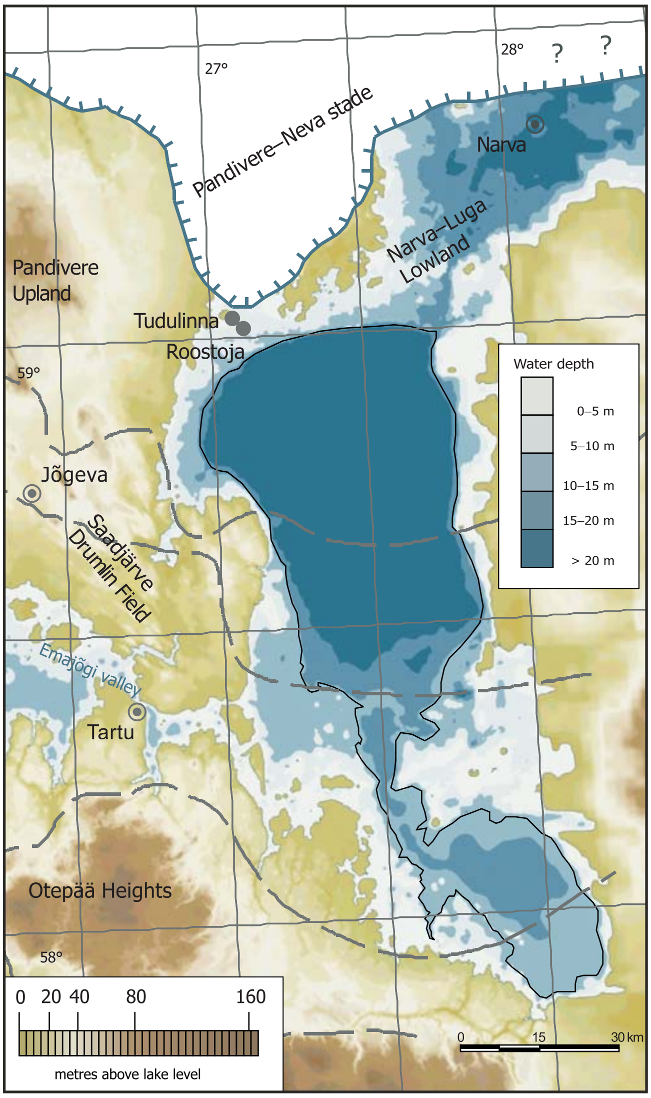

Fig. 7. Glacial Lake Peipsi during the Pandivere–Neva stade

The simulation reflects the lower gradient of shoreline tilting (Hang, 2001; Fig. 2) with a lake elevation from 48–40 m a.s.l.; other explanations as on Figure 1

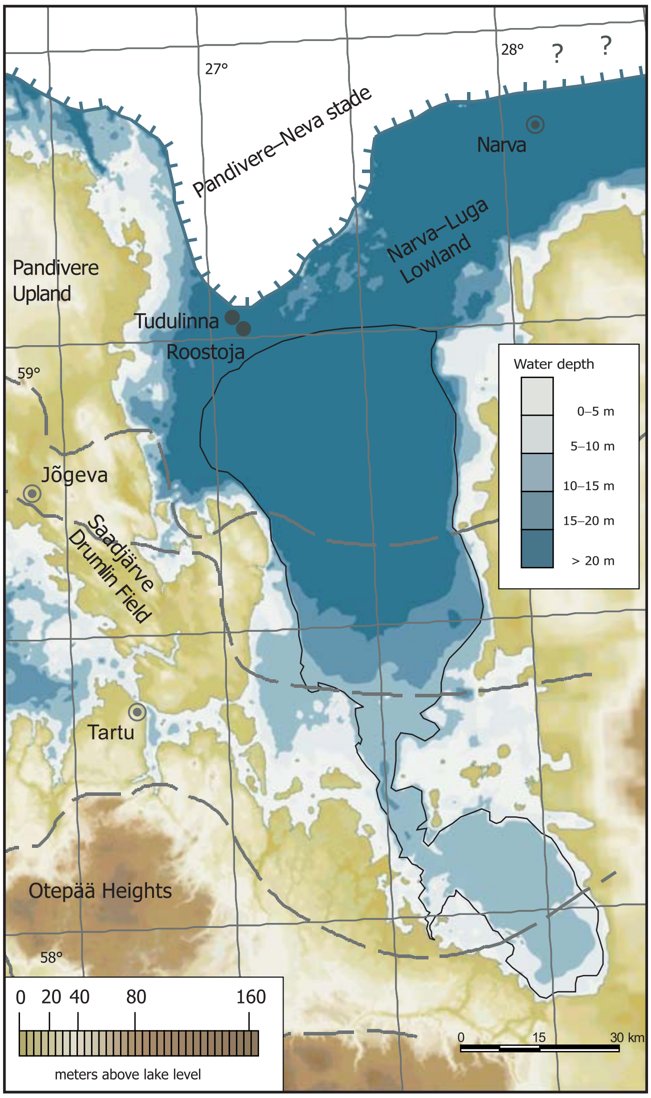

Fig. 8. Glacial Lake Peipsi during the Pandivere–Neva stade

The simulation reflects the higher magnitude gradient of shoreline tilting (Raukas and Rähni, 1969; Fig. 2) with a lake elevation from 80–38 m a.s.l.; other explanations as on Figure 1

lake was *ca.*18 m and the deepest part lay in the central part of the current lake, where the water depth reached 40 m. According to this simulation, the palaeolake shorelines in the current topography must have been up to 66 m in the north and 57 m in the south (Fig. 4).

Digital reconstruction with the higher uplift gradient (Fig. 2) revealed an open connection to the west with only a few drumlins emerging above the lake level (Fig. 5). The altitude of the palaeolake level was 88 m in the north to 48 m in the south. As expected, the mean (22 m) and the maximum water depth (55 m) as well as the area of the lake was greater than those simulated with the lower uplift gradient (Fig. 5). However, in general the configurations of the lake in both scenarios are similar.

THE KAIU STADE

The terraces of group C in the Piusa and Ahja valleys (Table 1) as well as the higher (51.5–50.5 m a.s.l.) continuous raised shoreline in the area between Alasoo (15) and Kavastu (13) were formed upon the stagnation of the ice margin on the Kaiu–Oudova line (Figs. 1 and 2). The simulated tortuous coastline (Fig. 6) was likely the result of shallow water in the littoral zone. The water depth in the central part of the Lake Peipsi depression reached 30 m and averaged *ca.* 17 m (Fig. 6). A connection to the west remained through the 3–12 km wide Emajõgi valley. Upon lowering of the water level, the Saadjärve Drumlin Field and the southern slope of the Pandivere Heights continued to emerge, forming most of the small isolated lakes within the drumlin field. The altitude of the shoreline of the simulated lake was 54 m in the north and 45 m in the southern part of the study area (Fig. 2).

THE PANDIVERE–NEVA STADE

Two tilting gradient scenarios were compared in simulating the configuration of glacial Lake Peipsi during the Pandivere–Neva stade (Figs. 7 and 8). According to the correlation of Hang (2001), the glacial Lake Peipsi shorelines during the Pandivere stade reached from 48 m a.s.l. in the north to 40 m a.s.l. in the south (Fig. 7). The terraces of group D in the Piusa and Ahja valleys (Table 1) were formed simultaneously with the continuous raised shoreline at 47–45.5 m a.s.l. in the area between Alatskivi (14) and Kavastu (12) (Figs. 1 and 2). The reconstruction of the lake configuration gives surprisingly similar contours to those of the current Lake Peipsi except for a *ca.* 20–25 km wide outlet towards the north-east and the strait-like connection westward through the Emajõgi valley (Fig. 7). According to the simulation, dry land lay directly in front of the glacier somewhat north of the current lake. The deepest parts of the lake lay in the middle of the Lake Peipsi depression and in the Narva–Luga Lowland where the water depth reached 20 m. The mean depth of the lake was 10 m.

Evidence from eskers and kames suggest a much higher (80–70 m a.s.l.) water level close to the ice margin during the same stade (Raukas and Rähni, 1969; Fig. 8). Correspondingly, this reconstruction results in a much deeper (mean 20, max. 60 m) and open connection towards NW Russia but also a connection to the west through the Emajõgi valley and at the northern slope of the Pandivere Upland (Fig. 8). The altitude of the palaeolake level was 80 m in the north to 38 m in the south. According to both reconstructions, the water depth in the southern part of glacial Lake Peipsi still remained at 10–15 m (Figs. 7 and 8).

DISCUSSION

DEVELOPMENT OF GLACIAL LAKE PEIPSI

The westward connection of glacial Lake Peipsi through the Võhandu and Hargla valleys during the Otepää stade was most likely strait-like rather than fluvial (Fig. 3), due to its relative shallowness and because of horizontal glaciolacustrine terraces in the Hargla valley at an altitude of 79–73 m (Liblik, 1966). This contradicts earlier views, which describe the system of marginal valleys in the area as westward drainage spillways of vast eastern proglacial lakes (Kvasov, 1979). According to our reconstruction, the strait-like connection through the Võhandu valley ceased once the water level in glacial Lake Peipsi lowered to an altitude of 73–70 m. However, the accuracy of the DTM used for reconstruction is inadequate and more detailed elevation data is needed to determine the exact end of the connection.

As expected, the two models display different parameters for glacial Lake Peipsi during the Piirissaar stade (Figs. 4 and 5). Simulation with the higher uplift gradient yields a typical water depth of at least 20 m, suitable for the simultaneous accumulation of glacial varved clays over vast areas (including the Võrtsjärv and Peipsi depressions). Unfortunately, geological mapping reveals only scattered distribution of varved clays in the deep valleys and in the central part of the Lake Peipsi depression. The lower gradient allows little opportunity for the accumulation of glacial varved clay in the depressions of small lakes, yet varved clay has been noted in several lakes in the Saadjärve Drumlin Field. If a water depth of at least 15–20 m is necessary for the varved clay accumulation, the lake level would need to be *ca.* 5–10 m higher than presented in Figure 4. This apparent contradiction may be due to a misinterpretation of the geomorphological data on the one hand, but could also simply reflect the short period of actual varve clay accumulation (60–70 years only) in the area, which is beyond the precision of the model. If the location of the ice margin during the Piirissaar stade is correct, the simulation with the low uplift gradient leaves emerged the southern slope of the Pandivere Heights emergent in front of the ice margin, which accounts for the lack of glaciolacustrine deposits in this area.

Expansion of this emergent area on the southern slope of the Pandivere Heights continued when the ice margin stagnated to the Kaiu line (Fig. 6). According to the simulation with the lower uplift gradient, most small lakes in the Saadjärve Drumlin Field were isolated from glacial Lake Peipsi at that time. Accumulation of varved clay likely continued in the central part of the recent Lake Peipsi depression, although verification would require further lithological and chronological research.

A comparison of two different scenarios with respect to the extension of glacial Lake Peipsi during the Pandivere stade is interesting. The simulation with the higher uplift gradient displays the traditional view of the ice-contact lake, whereas the lower gradient scenario shows glacial Lake Peipsi sharing a similar arrangement with the present lake. There is no NW continuation of the lake surrounding the Pandivere Upland, which had been considered a possible connection between the eastern and western proglacial lakes. A 25–30 m higher water level is needed to establish a connection across the northern slope of the Pandivere Heights. The emergent area in front of the ice margin north of the current lake could have been a field of dead ice, reflected in hummocky aqueoglacial topography in the current terrain. It is more difficult to explain the shallow water (0–10 m) proglacial conditions in front of the ice margin near Rannapungerja and Tudulinna where glacial varved clays, an indication of deeper water, have been noted. Sedimentological, chronological and palaeomagnetic investigations of the varved clays (Hang, 2001) demonstrate that these clays accumulated in the proglacial body of water before the ice retreated from the Pandivere–Luga line. Thus the water should have been deeper than simulated.

Another significant topic is the westward connection of glacial Lake Peipsi over the current Emajõgi valley. Both reconstructions reveal a narrow strait-like connection with the ice lake in the Võrtsjärv depression (Figs. 7 and 8) but are highly dependent on the correctness of the uncertain water level in the Lake Võrtsjärv depression.

An interesting issue in the palaeogeography of glacial Lake Peipsi is the drainage of the lake after the ice retreated to the Gulf of Finland. Our simulations show that NE drainage is the most probable (Figs. 7 and 8). The simulated water level with the lower uplift gradient (Fig. 7) is near the altitude of the present threshold (*ca.* 30–35 m)in the Narva valley, NE of the recent lake, and therefore a notable and long-lasting NE drainage is doubtful. At a higher water level (Fig. 8), NE drainage is reasonable initially, but we encounter complications as soon as the water level reaches an altitude of present treshold. According to Hang *et al*. (2001), the water level in glacial Lake Peipsi at the end of the Late Weichselian was 10 m lower than the current lake level (30 m a.s.l.). Our current knowledge of the ice recession and isostasy in the area fails to account for such a significant drop in the water level by lake drainage alone. We simply cannot see any outlets leading to the recorded low lake level.

METHODOLOGICAL ASPECTS OF DIGITAL RECONSTRUCTION

There are several limitations associated with the currently applied GIS method. Leverington *et al*. (2002) point out the role of the later deposition and erosion since the time being modelled. Although the widely distributed peaty deposits of the Holocene age (*ca*. 20% on mainland) were removed from the DTM, other postglacial deposits and relief forms influenced the reconstruction of palaeotopography. Aeolian deposits or redeposited glaciolacustrine deposits north of the recent lake certainly affected the results. This may have caused the simulation with the low uplift gradient to show emergent land in front of the ice during the Pandivere–Neva stade (Fig. 7). The erosional features displayed on our simulations and caused by the fluvial activity might also be younger than modelled. Unfortunately the geological information is insufficient to avoid these miscalculations.

Differences in the accuracy and the amount of geomorphological data need to be considered to evaluate these simulations. Both the levelling points and cartographically determined altitudes of the geomorphological features from earlier works lacked geographic coordinates. Currently the geomorphological data was inserted to GIS using the cartographically evaluated (1:25 000 topographic maps) descriptions of the authors and such a transformation of data might have influenced the simulation of palaeowater plains.

The limited number and scattered shoreline data might easily have resulted in an oversimplification of the palaeowater plains. For example, there is no clear evidence of late glacial shorelines from the eastern part of the lake depression. In addition, the simulated eastern shorelines of glacial Lake Peipsi are smoother due to less accurate elevation data from the area.

CONCLUSIONS

— Digital reconstructions of the configuration and bathymetry of glacial Lake Peipsi during its different stages are presented for two hypotheses on the magnitude of shoreline gradient.

— Removal of average thicknesses of Holocene peat deposits from DTM improved the model. Geological data is insufficient to consider other postglacial deposits and erosional forms that could affect the results of modelling as well.

— The simulations depend greatly on the amount, geographical distribution and quality of the input data. The simulation with the higher gradient of shoreline tilting display a classical view of an entirely ice-contact lake whereas the simulations with the lower gradient leave some unexpected emergent areas in front of the glacier margin.

— The emergent areas in front of the ice result from either subsequent deposition (dead ice, aeolian) or by miscalculated (inadequate) shoreline gradient due to a lack of morphological data from the northern part of the area investigated.

— As expected, the two scenarios display minor differences in the southern part of the investigated area due to similar source data and insignificant differences in geomorphological correlations.

— Reconstructed glacial Lake Peipsi outflows during the Otepää and Pandivere–Neva stade support current theories on the lake drainage but fail to resolve the drainage of the lake down to its minimum level of *ca*. 20 m a.s.l. (Hang *et al*., 2001) at the end of the Late Weichselian.

— The technique of digital simulation of the parameters of proglacial lake was shown to be suitable for glacial Lake Peipsi. Additional geological, biostratigraphical and geomorphological data are necessary to evaluate and improve the presented simulations.

Acknowledgements. We thank V. Kalm for valuable comments on an earlier version of the manuscript and R. Szava-Kovats for improving the language. Reviews by I. Pavlovskaya and an anonymous reviewer were much appreciated. The study was funded by Estonian target funding project 0182530s03 and Estonian Science Foundation Grants no 5370 and 5342.

REFERENCES

ASEEV A. (1974) — Drevnie matrikovye oledenenija Evropy. Nauka. Moscow.

BOULTON G. S., DONGELMANS P., PUNKARI M. and BRODGATE M. (2001) — Palaeoglaciology of an ice sheet through a glacial cycle: the European ice sheet through the Weichselian. Quater. Sc. Rev., **20**: 591–625.

ESTONIAN BASE MAP (1998) — Digital version for MapInfo in scale 1:50 000. Estonian Land Board.

EDC DAAC (1996) — GTOPO 30 Database. EROS Data Center Distributed Active Archive Center, US Geological Survey, EROS Data Center, Sioux Falls, South Dakota.

HANG T. (2001) — Proglacial sedimentary environment, varve chronology and Late Weichselian development of the Lake Peipsi, eastern Estonia. Quaternaria A, **11**.

HANG E., LIBLIK T. and LINKRUS E. (1964) — On the relations between Estonian valley terraces and lake and sea levels in the Late-Glacial and Holocene periods. Transactions of the Tartu State University, **156**, Publ. Geogr., 4: 29–42.

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., MIIDEL A., KALM V. and KIMMEL K. (2001) — New data on the distribution and stratigraphy of the bottom deposits of Lake Peipsi. Proc. Estonian Acad. Sc., Geol., **50** (4): 233–253.

KAJAK K. (1964) — Peipsi nõo geoloogiast ja geomorfoloogiast. Eesti Geograafia Seltsi Aastaraamat 1963: 20–33.

KARUKÄPP R. (1997) — Gotiglacial morphogenesis in the southeastern sector of the Scandinavian continental glacier. Dissertationes Geol. Univ. Tartuensis, **6**.

KARUKÄPP R. and RAUKAS A. (1997) — Deglaciation history. In: Geology and Mineral Resources of Estonia (eds. A. Raukas and A. Teedumäe): 263–267. Estonian Acad. Pub. Tallinn.

KARUKÄPP R. and RAUKAS A. (1999) — Deglaciation of the lake basin. In: Lake Peipsi. Geology (eds. A. Miidel and A. Raukas): 125–130. Sulemees Publishers. Tallinn.

KESSEL H. and RAUKAS A. (1979) — The Quaternary history of the Baltic, Estonia. In: The Quaternary History of the Baltic (eds. V. Gudelis and L.-K. Gönigsson). Acta Univ. Upsaliensis, Symp. Univ. Upsaliensis Ann. Quingentesimum Celebrantis **1**: 127–146.

KVASOV D. D. (1979) — The Late-Quaternary history of large lakes and inland seas of eastern Europe. Ann. Acad. Sc. Fennicae. Ser. A III. Geol.-Geogr., **127**: 1–71.

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 and 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 with English summary). Transactions of the Tartu State University, **237**, Publ. Geogr., **6**: 3–16.

MCMARTIN I. (2000) — Paleogeography of Lake Agassiz and regional post-glacial uplift history of the Flin Flon region, central Manitoba and Saskatchewan. J. Paleolimnol., **24**: 293–315.

MIIDEL A. (1981) — About the problems of the investigation of neotectonical movements in the Pihkva-Peipsi depression. In: Bottom Deposits of the Lake Pihkva-Peipsi (ed. A. Raukas): 116–126 (in Russian with English summary). Eesti NSV Teaduste Akadeemia. Tallinn.

MIIDEL A., HANG T., PIRRUS R. and LIIVA A. (1995) — On the development of the southern part of Lake Peipsi in the Holocene. Proc. Estonian Acad. Sc. Geol., **44**: 33–44.

MIIDEL A. and TAVAST E. (1981) — The development of rivers in the Pihkva-Peipsi depression (in Russian with English summary). In: Bottom Deposits of the Lake Pihkva-Peipsi (ed. A. Raukas): 127–133. Eesti NSV Teaduste Akadeemia. Tallinn.

MIIDEL A., NOORMETS R., HANG T., FLODÉN T. and BJERKÉUS M. (2001) — Bedrock geology and topography of the Lake Peipsi depression, eastern Estonia. GFF, **123**: 15–22.

MURU L. (1970) — Ahja jõe oru geomorfoloogiast. Unpubl. Diploma Thesis. Univ. Tartu.

NOORMETS R., HANG T., MIIDEL A., FLODÉN T. and BJERKÉUS M. (1998) — Seismic stratigraphy of Quaternary deposits in Lake Peipsi, eastern Estonia. GFF, **120**: 47–52.

ORRU M. (1995) — Estonian peat bogs. Handbook (in Estonian with English summary). Geol. Surv. Estonia. Tallinn.

ORVIKU K. (1960) — Geomorfologija. In: Geologija S.S.S.R., **28**: 209–230. Gosgeoltekhizdat. Moskva.

PÄRNA K. (1962) — On the geology of the Baltic Ice Lake and large local ice lakes in Estonia (in Russian). Unpublished cand. Thesis. Estonian Acad. Sc. Tallinn.

RATTAS M. and KALM V. (1999) — Classification and areal distribution of glaciotectonic features in Estonia. Geol. Quart., **43** (2): 177–182.

RAUKAS A., RÄHNI E. and MIIDEL A. (1971) — Marginal glacial formations in North Estonia (in Russian with English summary). Valgus. Tallinn.

RAUKAS A. and RÄHNI E. (1969) — On the geological development of the Peipsi-Pihkva depression and the basins distributed in that region (in Russian with English summary). Eesti NSV Teaduste Akadeemia Toimetised. Keemia, Geoloogia, **18** (2): 113–117.

SAARSE L., VASSILJEV J. and MIIDEL A. (2003) — Simulation of the Baltic Sea Shorelines in Estonia and neighbouring areas. J. Coastal Res., **19**: 261–268.

SARV A. and ILVES E. (1975) — Über das Alter der holozänen Ablagerungen im Mündungsgebiet des Flusses Emajtgi (Saviku) (in Russian with German summary). Eesti NSV Teaduste Akadeemia Toimetised. Keemia, Geoloogia, **24** (1): 64–69.

SVENSSON N.-O. (1989) — Late Weichselian and Early Holocene shore displacement in the central Baltic, based on stratigraphical and morphological records from eastern Småland and Gotland, Sweden. LUNDQUA Thesis, **25**.

THOMSON P. (1929) — Die regionale Entwicklungsgeschichte der Wälder Estlands. Acta et. Comm. Univ. Tartuensis. A, **17** (2): 1–88.

VEETEEDE JA SADAMATE VALITSUS (1943) — Map of the bottom topography of the Lake Peipsi in scale 1:100 000.