PROGLACIAL LAKE SHORELINES OF ESTONIA AND ADJOINING AREAS

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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 A_1 in Estonia is synchronous with the Bgl_I level in Latvia and with one level in NW Russia of undefined index. Proglacial lake A_1 was formed concurrently with the Pandivere-Neva ice-margin about 13,300 cal. yrs BP. Proglacial lake A_2 level formed probably about 12,800 cal. yrs BP and correlates with the level of Bgl_{II} in Latvia and G_{III} in NW Russia. Simulated isobases of proglacial lake water-levels 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 towards the 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 the Peipsi and Baltic basins were connected via strait-like systems and had identical water levels. Our reconstructions also show that after the glacier halted at the Pandivere-Neva ice margin about 13,300 cal. yrs BP, there was a connection with the initial Baltic Ice Lake in the west of the Gulf of Riga.

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

INTRODUCTION

The Baltic Sea history is complicated and up to now there is no generally accepted opinion on the ages of the different stages (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 the eastern Baltic: stages A1 and A2 from Estonia (Lõokene, 1959; Pärna, 1960; Vassiljev *et al.*, 2005), stage GIII from NW Russia (Markov, 1931) and stages BglI and BglII from Latvia (Grinbergs, 1957). Correlation of the above-mentioned proglacial lake shorelines is complicated due to different ice recession schemes and a limited number of radiocarbon dates, which do not allow for precise determination of the ages of shorelines.

Correlations, based on geomorphological, bio- and chronostratigraphical data together with geostatistical analyses, can be the only solution to study the pattern and distribution of the Late Glacial shorelines. The authors of the current study earlier applied 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 geostatistical analyses and a GIS-based palaeogeographic reconstruction of spatial distribution and bathymetry of proglacial lakes.

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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; Lõokene, 1959; Pärna, 1960; Gudelis, 1979; Kessel, Raukas, 1979; Veinbergs *et al.*, 1999; Zelčs, Markots, 2004). In Estonia, proglacial lake A_1 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 and flat-topped glaciolacustrine and glaciofluvial landforms. This lake was followed by a proglacial lake A_2 at the 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 A_1 (Vassiljev *et al.*, 2005), however a most recent study indicates that it could be 500 years younger (Rosentau *et al.*, in press). Earlier Estonian researchers considered the shorelines of A_1 and A_2 to represent shores of local ice lakes (Lõokene, 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 A_2 stage.

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 basis 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} also seems to be complex as the height of these shorelines at 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 A_1 and A_2 shorelines in Estonia with Bgl_I proglacial lake in Latvia and with G_I–G_{II} in the Leningrad district and considered that the shoreline of Bgl_{II} started to form during the Allerød and completed in the Younger Dryas.

Investigating the shorelines in the Leningrad district, Markov (1931) 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 ^{14}C yr BP (*c.* 14,000 cal. yrs BP) and suggested that the initial Baltic Ice Lake emerged about 12,600 ^{14}C yr BP. Uścinowicz (1999) showed that after the retreat of the ice sheet from the Southern Middle Bank Phase (dated to 14,900–14,600 cal. yrs BP; Marks, 2004) the marginal lakes in the Gdańsk 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. yrs 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. First, the visual correlation between Estonian and neighbouring sites was done and the prospecting sites were identified. Secondly, point kriging interpolation with a linear trend approach was used to create interpolated water-level surfaces of the proglacial lakes. The grid size was 5×5 km. Then residuals (actual site elevation difference from the interpolated surface) were calculated and sites with residuals greater than 1.0 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). The 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 200×200 m (Rosentau *et al.*, 2007);
B. Shuttle Radar Topography Mission (SRTM-90) elevation data with resolution 3 arc seconds (approx. 90×90 m) for Latvia and NW Russia (CIAT, 2004);
C. Topography of the Baltic Sea (Seifert *et al.*, 2001).

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

RESULTS AND DISCUSSION

ISOBASES OF THE LATE GLACIAL PROGLACIAL LAKES ANALYSED

The isobases of proglacial lakes A_1 and A_2 and their correlation with the Latvian and NW Russian shorelines are presented (Figs. 1, 2). According to our reconstruction, the proglacial lake A_1 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 A_2 level with Bgl_{II} in Latvia and with G_{III} in Russia.

Such a correlation differs from the earlier suggested system by Donner, Raukas (1989). Along the eastern Baltic coast 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 the southeast, being up to 14 m higher than expected from the regional pattern (Figs. 1B, 2B).
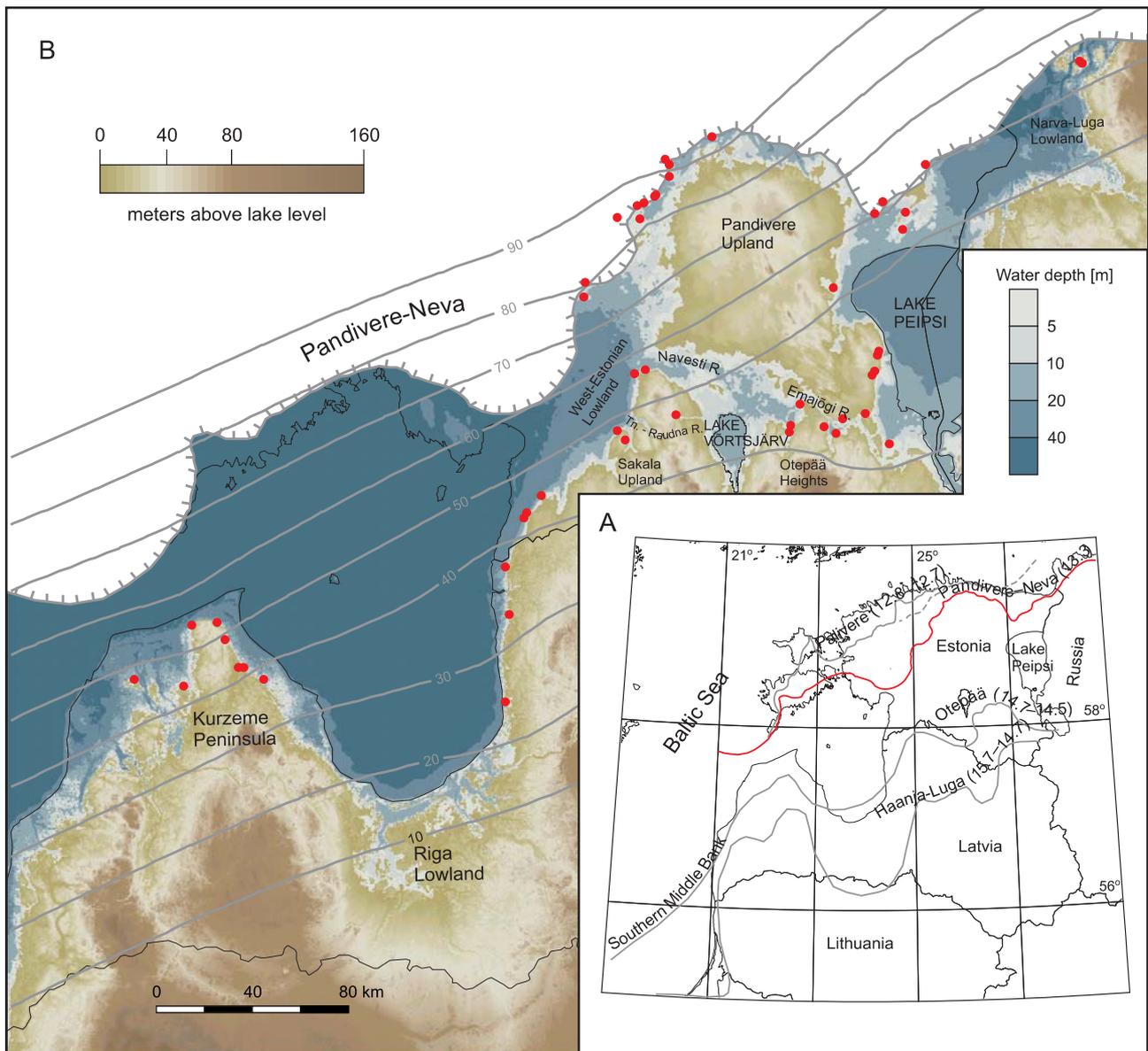
Fig. 1. A – **Overview map showing the main ice marginal positions in Estonia with ages (cal. kyr BP) according to Kalm (2006) in relation to the ice-margin position during the proglacial lake A_1 (red line).** B – **Palaeogeographic reconstruction of the proglacial lake at *c.* 13.3 kyr BP and correlation of proglacial lake coastal landforms in Estonia (stage A_1), Latvia (stage Bgl_I) and NW Russia (altitude of 63 m a.s.l.)**

Coastal landforms used in the correlation and water-level surface simulation are shown by red dots

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 by shoreline data from the Emajõgi River valley (Fig. 1B). In the southern part of the Lake Peipsi basin, the low tilting gradients were also indicated 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, 1995; Hang, 2001).

Geological reasons of the above-mentioned anomaly are not clear. On a regional scale, recent vertical movements show that the southern margin of the Baltic Shield was enclosed by a subsidence belt, which could be associated with a collapsed structure of a circum-Fennoscandian ring bulge of the upper mantle developed 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 of this belt a regular land uplift occurred. Such a pat-
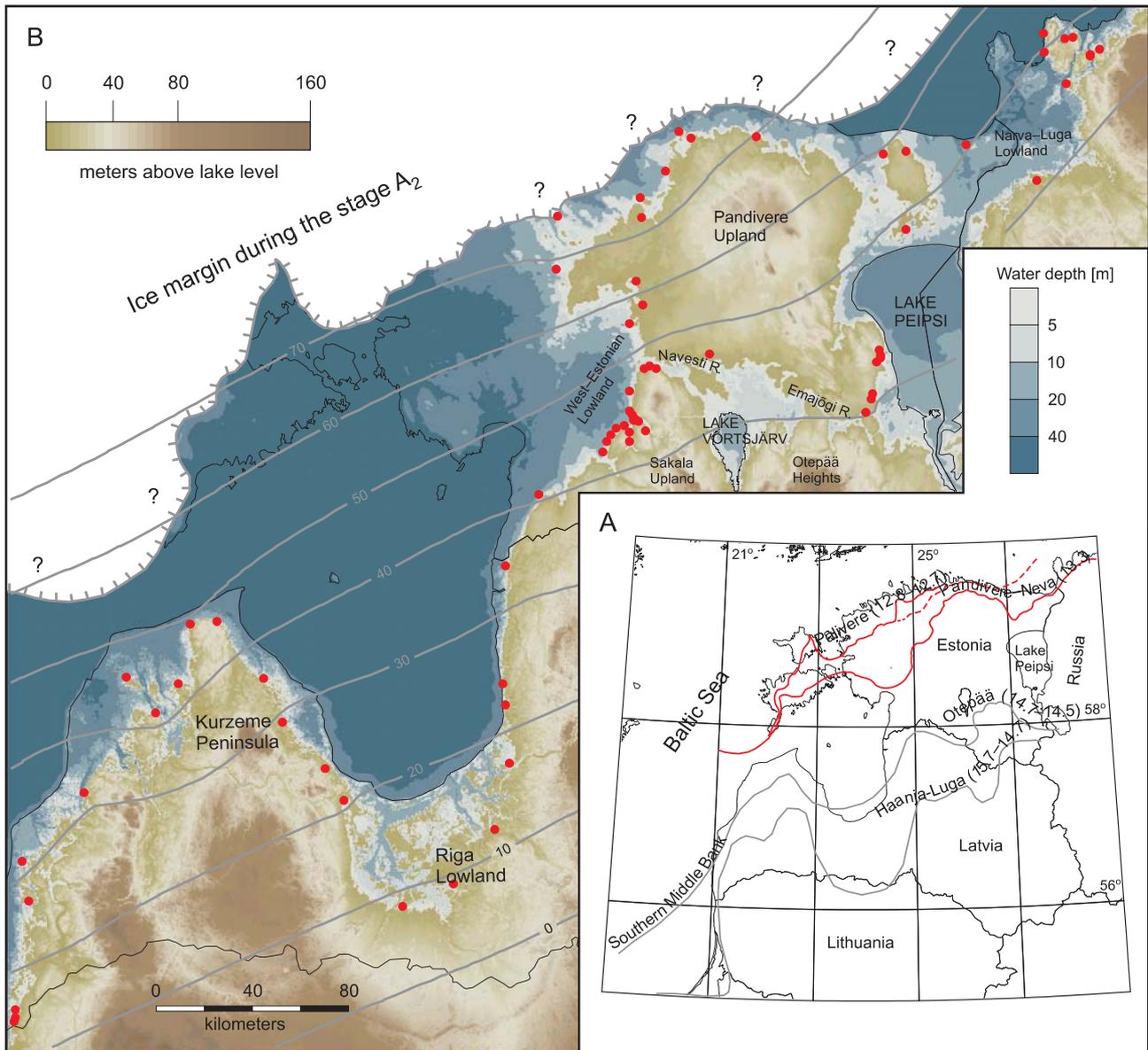
Fig. 2. A – **Overview map showing the main ice marginal positions in Estonia with ages (cal. kyr BP) according to Kalm (2006) in relation to the ice-margin position during the proglacial lake A$_2$ (red line).** B – **Palaeogeographic reconstruction of the proglacial lake at *c.* 12.8 kyr BP and correlation of proglacial lake coastal landforms in Estonia (stage A$_2$), Latvia (stage Bgl$_{II}$) and NW Russia (stage G$_{III}$)**

Coastal landforms used in the correlation and water-level surface simulation are shown by red dots

tern 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 south-eastern 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 the 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 the relative subsidence became prevailing in the south (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 A_1 shows that it discharged southwest to the deglaciated Baltic Proper. In the northeast, this proglacial lake extended over the Luga Lowland, forming the Luga Bay, ca 40 km long, in the middle reaches of the modern Luga River (Kvasov, 1979; Spiridonov et al., 1988; Fig. 1B). The bay was 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 may have opened later, after the ice recession from the Pandivere–Neva line (Kvasov, Raukas, 1970; Rosentau et al., 2007) 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., 2007), 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 in the area west of the Pandivere Upland, in the Baltic Sea basin as it was suggested earlier by Kvasov, Raukas (1970).

Proglacial lake A_2 developed after the ice margin retreated northward from the Pandivere-Neva ice marginal position. The water level of lake A_2 was up to 15 m lower in the northern part of the study area, but only a few metres lower in the southern part as compared to the proglacial lake A_1 shoreline, due to land uplift differences (Fig. 2B). After the ice retreated to the Gulf of Finland, the proximal connection, north of the Pandivere Upland, opened and provided a communication 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-day coastline. This could reflect an intense accumulation of coastal deposits during the end of the Late Glacial and Holocene and, therefore, the distribution of archipelagos during both A_2 and A_1 is not clear.

The reconstructions show that proglacial lakes A_1 and A_2 were not isolated water bodies as supposed by earlier studies (Lõokene, 1959; Pärna, 1960; Kessel, Raukas, 1979), but were connected in the west of the Gulf of Riga with the initial Baltic Ice Lake, as defined by Björck (1995).

CONCLUSIONS

1. Simulation of water-level surfaces confirms that the proglacial lake stage A_1 in Estonia (*c.* 13,300 cal. yrs 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 A_2 (probably *c.* 12,800 cal. yrs 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 Baltic coast and in the northern part of the Lake Peipsi depression, with a steeper tilt to the northwest. In the central part of the Lake Peipsi depression, isobases are curving towards SE, being up to 14 m higher than the regional trend. This phenom-

enon can reflect the forebulge effect during the deglaciation and its later collapse.

3. Shoreline reconstruction suggests that proglacial lakes in the Peipsi and Baltic basins were connected via strait-like systems, and thus had identical water levels. Our reconstructions show that the proglacial lakes under consideration were connected in the west of the Gulf of Riga with the initial Baltic Ice Lake.

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