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Simulation of proglacial lake shore displacement in Estonia

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The Late Glacial shoreline database compiled for Estonia covers 149 sites on the proglacial lakes A_1 (Voose) and A_2 (Kemba). Eighty-two sites were used in further simulations. Point kriging interpolation with a linear trend approach was applied to create interpolated surfaces of water levels for checking the spatial correctness of data. The sites with altitudes visually not matching with sites nearby were discarded, as well as those with residuals of more than 1 m and 0.7 m respectively. The final surfaces were analysed geostatistically by simulating isobases, direction of tilting, and shoreline gradient. The simulated isobases suggest that both proglacial lakes A_1 and A_2 were connected with the glacial lake in the Lake Peipsi basin. The interpolated surface aspect shows that the direction of tilting varies between 320° and 340°. The surface gradient of lake A_1 is highest in the NW and SE parts of the study area (50 and 25 cm km^{-1}, respectively), and that of lake A_2 is highest in the NW and SE parts (40 and 20 cm km^{-1}, respectively). Using the modelling data, the shoreline correlation between the two proglacial lakes has been revised.

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INTRODUCTION

During glacial recession many short-lived lakes, known as proglacial lakes, were formed in front of the ice margin. Their extent and water level changed following the retreat of the ice margin. Glaciofluvial deltas, flat-topped kames, coastal scarps, belts of erratic boulders, terraces, glaciolacustrine deposits and beach-ridges have been traced in order to reconstruct the ancient shorelines of these proglacial lakes.

Several proglacial lakes have been reported and studied in Estonia (Hausen, 1913; Tammekann, 1926; Ramsay, 1929; Parts, 1933; Lõokene, 1959; Pärna, 1960; Raukas and Rähni, 1969; Raukas *et al*., 1971; Hang, 2001). As a result, many different maps of shoreline isobases and equidistant shoreline diagrams have been compiled (Ramsay, 1929; Pärna, 1960; Kessel, 1961; Kessel and Raukas, 1979; *etc*.). However, shore displacement charts have been revised several times, an consequently it is hard to decide subsequently when certain glaciolacustrine landforms appeared, which makes their correlation very uncertain. Correlation problems also arise because different indices of glacial lakes were used (see Appendix), and the study region was commonly limited to a small area, for example, the basin of lakes Peipsi or Võrtsjärv or the West Estonian Lowland only.

A large proglacial lake was formed during the ice lobe retreat from the southern part of the Pihkva depression. Following ice recession, the area of the Pihkva proglacial lake enlarged to join the Lake Peipsi basin (Raukas and Rähni, 1969). The proglacial lake histories of Pihkva and Peipsi, their shorelines and the deglaciation model of this area are fully discussed in the literature (Liblik, 1969; Raukas and Rähni, 1969; Raukas *et al*., 1971; Orviku, 1973; Hang, 1997, 2001; Karukäpp and Raukas, 1999; Rosentau *et al*., 2004) and, therefore, not repeated here. We focus on the proglacial lakes A_1 (Voose) and A_2 (Kemba), which were more closely studied by Ramsay (1929), Lõokene (1959), and Pärna (1960, 1962). Pärna (1960) gave them the following names and indices: A_0 (small local ice lakes), A_1 (Voose), A_2 (Kemba), and A_3 (Nõmme) proglacial lakes, which differ from the indices used by Kessel (1961), Kessel and Raukas (1979) and Raukas (1986) (G_0, G_1, G_2, G_3 or G_I, G_{II}).

When the Pandivere ice-marginal deposits accumulated at about 12 330 varve years BP (Hang, 1997, 2001), 13 300 calendar years BP (Saarnisto and Saarinen, 2001) or 12 480–12 230 ^{14}C BP (Raukas *et al*., 2004), a large proglacial lake A_1 (Voose) was formed between the ice margin and the northwestern slope of the Pandivere and Sakala uplands. Its coastal deposits on the distal part and glaciofluvial landforms on the proximal part, indicating the lake level, have been de-

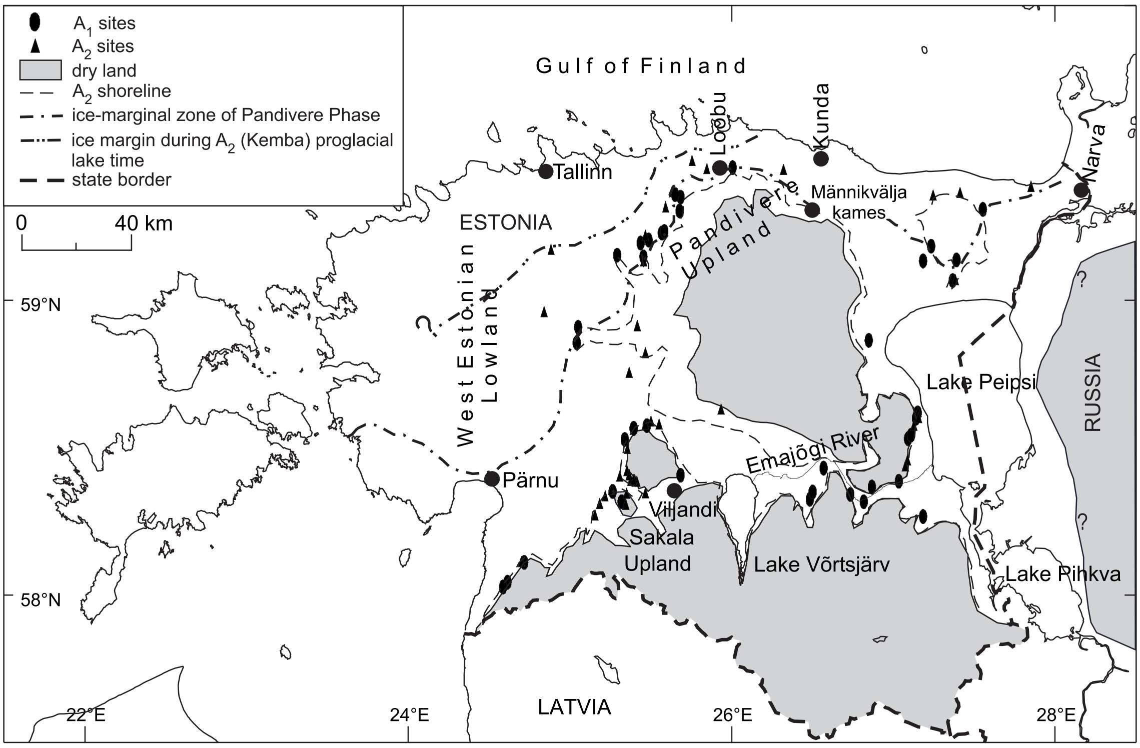

Fig. 1. Location of the study area and sites indicating shoreline displacement of the proglacial lakes A_1 (Voose) and A_2 (Kemba)

scribed in 83 sites at altitudes of 41–93 m a.s.l. (Appendix). The northern part of the A_1 (Voose) proglacial lake was rather narrow, stretching between upland slopes and ice margin, wider in the southwestern part, where it submerged the Võrtsjärv Lowland and the lower parts of SW Estonia (Fig. 1).

Proglacial lake A_2 (Kemba) appeared after the retreat of the ice margin north of the Männikvälja kame field due to the merging of the local ice lakes east and west of the Pandivere Upland (Raukas and Rähni, 1969). According to Kvasov and Raukas (1970), this event corresponded to the beginning of the Baltic Ice Lake. The area of A_2 proglacial lake was considerably larger than that of A_1, as the ice margin had moved further northwestwards (Fig. 1). Landforms indicating the water level of the A_2 (Kemba) proglacial lake have been studied at 66 sites between altitudes of 37 and 78 m a.s.l. (Appendix). During emergence of proglacial lakes at the Männikvälja kame field, water level in the A_1 proglacial lake lowered abruptly from 85 to the 72 m near Kemba (Pärna, 1960) or even more considering records from the Reka and Reka–Koitjärve area (Appendix).

The Nõmme proglacial lake was formed during the re-advance of the ice sheet of the Palivere Phase, marked by large deltas west and east of Tallinn at an elevation of 40–45 m (Pärna, 1960). The age previously attributed to the Palivere Phase (11 200 ^{14}C BP; Raukas *et al.*, 1971) has been questioned (Donner, 1978, p. 31; Berglund, 1979, p. 112). Donner (1978) suggested that the Palivere Phase could have been older as the ice margin probably retreated from the southern coast of Finland between 11 600 and 11 800 ^{14}C BP, which was later accepted by Raukas *et al.* (2004). The shoreline of Nõmme proglacial lake is considered to be at 30–40 m a.s.l. in western Estonia, about 30 m lower than the succeeded Baltic Ice Lake level (Pärna, 1960). As the shorelines of the Nõmme proglacial lake are poorly known, its development is not treated here.

The aim of this study is to provide a uniform shoreline database for the proglacial lakes A_1 (Voose) and A_2 (Kemba), to revise critically the original data on shore displacement, to analyse the proxies obtained statistically and to simulate the shoreline isobases, their azimuth and their tilting. Shore displacement data for these proglacial lakes are given in the Appendix. Jüri Vassiljev was responsible for the modelling; Leili Saarse and Avo Miidel for the compilation of the database. All authors contributed to the interpretation of the results, discussion and conclusions.

METHODS

The initial database of the proglacial lakes A_1 (Voose) and A_2 (Kemba) includes sites recorded by various investigators. Therefore, some erroneous proxies might be expected. To check and remove incorrect records, the database was revised using a combination of different methods. First, sites with altitude visually not matching with those situated nearby were eliminated. Second, point kriging interpolation with a linear trend approach was used to create interpolated surfaces of water levels of the proglacial lakes A_1 and A_2. The grid was 5 × 5 km in size. The advantage of this method is that it interpolates accurate surfaces from irregularly spaced sites and it is easy to pick up mistaken data. Next, residuals (differences between the actual site elevation and the interpolated surface) were calculated and sites with residuals more than 1 m and 0.7 m respectively were discarded. Thereafter, residuals for the entire database were calculated to check whether there was any potential site which could match with proglacial lake shoreline characteristics under simulation. The final surfaces were designed and analysed geostatistically, by modelling the terrain slope and aspect, and the gradient operation. The terrain slope and aspect describe the steepest slope and the azimuth of the isobases of the grid, whereas the gradient operation helps to characterise the grid surface geometry.

MATERIAL

The Late Glacial shore displacement database created by the authors holds 149 sites in Estonia, 83 of which represent the proglacial lake A_1 and 66 the proglacial lake A_2 (Fig. 1), reported by different researchers (see Appendix). The location and altitude of the sites were tested using topographic and digital maps scaled to 1:25 000 and 1:50 000 (Digital…, 1996). Although deposits of the lake A_1 have been identified at 83 different sites, a spatial check shows that some are either too high or too low as compared to the elevation of the neighbouring sites. In total, 40 sites were used in the simulations of the shoreline characteristics. Among them, glaciofluvial deltas and flat-topped kames prevail (17 sites), while the rest of the sites are represented by coastal landforms (erosional scarps, beach-ridges, and so on). The large number of discarded sites (43) may be the result of several factors, such as inaccurate altitudes taken from the topographic map, incorrect correlation of shorelines, short-term water level fluctuations (e.g. due to heavy storms), which created shorelines at different levels and which were variously interpreted by different authors.

The database of proglacial lake A_2 includes 66 sites, 42 of which proved to be suitable for simulation purposes (Appendix). The lake's highest shoreline is represented by various coastal landforms (erosional scarps, beach-ridges, and so on). A total of 11 sites was not included into the initial database because of incomplete records, mostly due to the absence of coordinates. The coastal deposits of proglacial lakes A_1 and A_2 treated in the present paper represent the highest shorelines of these lakes. On the basis of the source material it was impossible to identify coastal deposits at certain lower levels, probably due to the short-lived duration of the proglacial lakes.

RESULTS

ISOBASES AND SHORELINE GRADIENTS

The isobases of the proglacial lakes A_1 and A_2 are displayed in Figure 2A and B. Pärna (1960) suggested that the water level had reached 85 m a.s.l. in lake A_1 and 72 m a.s.l. in A_2 in North Estonia. The simulation is consist with coastal deposits of A_1 at even higher altitudes, at 91–93 m (see Appendix, Fig. 2). Most of the isobases follow a northeast–southwest direction. While in the Peipsi basin isolines of proglacial lake A_1 are inclined to the east (Fig. 2A). This means that the uplift of the northern part of the Peipsi basin has been more pronounced than that of the southern part already by the Late Glacial. As proxies from the eastern part of the Peipsi basin are absent, this conclusion, though, should be treated with precaution.

The direction of tilting varies generally between 320° and 340° (Fig. 3A, B). Even though both proglacial lakes have a pretty scattered picture, the tilting direction seems to be declined more to the west in eastern Estonia and more to the north in western Estonia. The interpolated surface slope is slightly steeper for A_1, attaining in both cases between 0.01° and 0.03° (Fig. 4A, B). The values are higher in the northwestern direction than in the southeastern one. The shoreline gradient (gradient operators of the interpolated surfaces) is displayed in Figure 5A and B. The A_1 shoreline gradient value increases towards the north-west: from 25 cm km^{-1} in the south-east to 50 cm km^{-1} in the north-west. Lake A_2 has lower shoreline gradient values than A_1: 20 cm km^{-1} in the southeastern and 30–40 cm km^{-1} in the northwestern part of the study area. Pärna (1962) obtained similar results, suggesting that the shoreline gradient was 35 cm km^{-1} for A_1 and 26 cm km^{-1} for A_2.

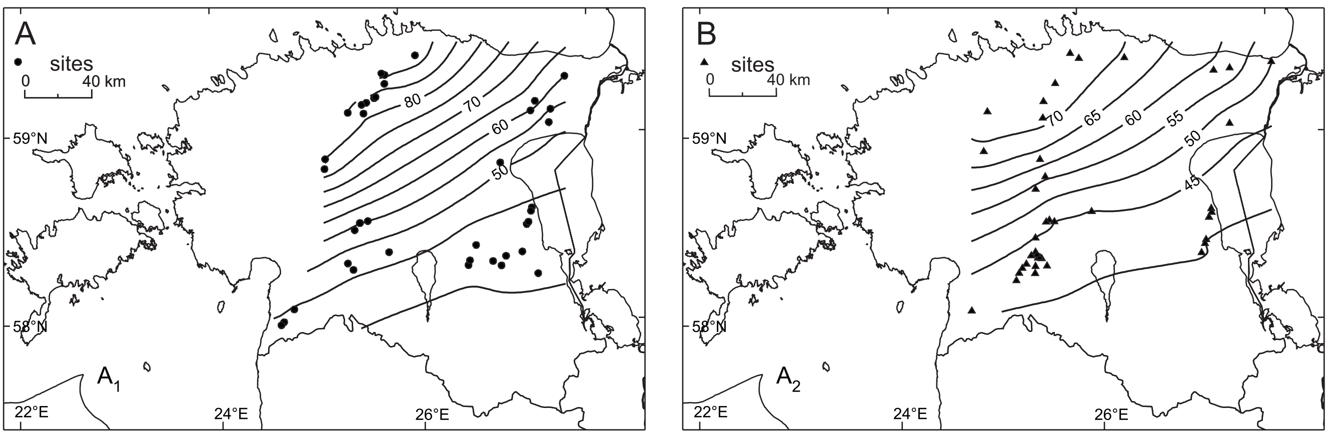

Fig. 2. Isobases of proglacial lakes A_1 (A) and isobases of proglacial lakes A_2 (B) with indication of sites used in the point kriging analysis

A shows disturbances west of Lake Peipsi, probably caused by differences in tectonic uplift north and south of the Lake Peipsi basin

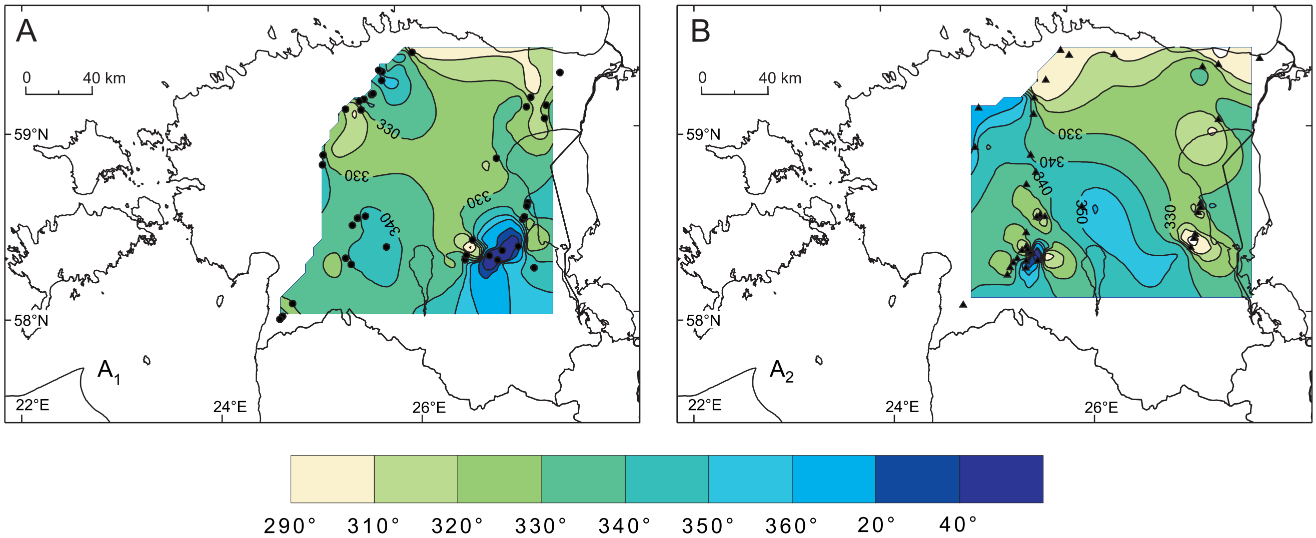

Fig. 3. Changes in fastest uplift direction during the proglacial lake A_1 (Voose) and A_2 (Kemba)

A — the situation during proglacial lake A_1 (Voose) time, B — during A_2 (Kemba) time; other explanations as on Figure 2

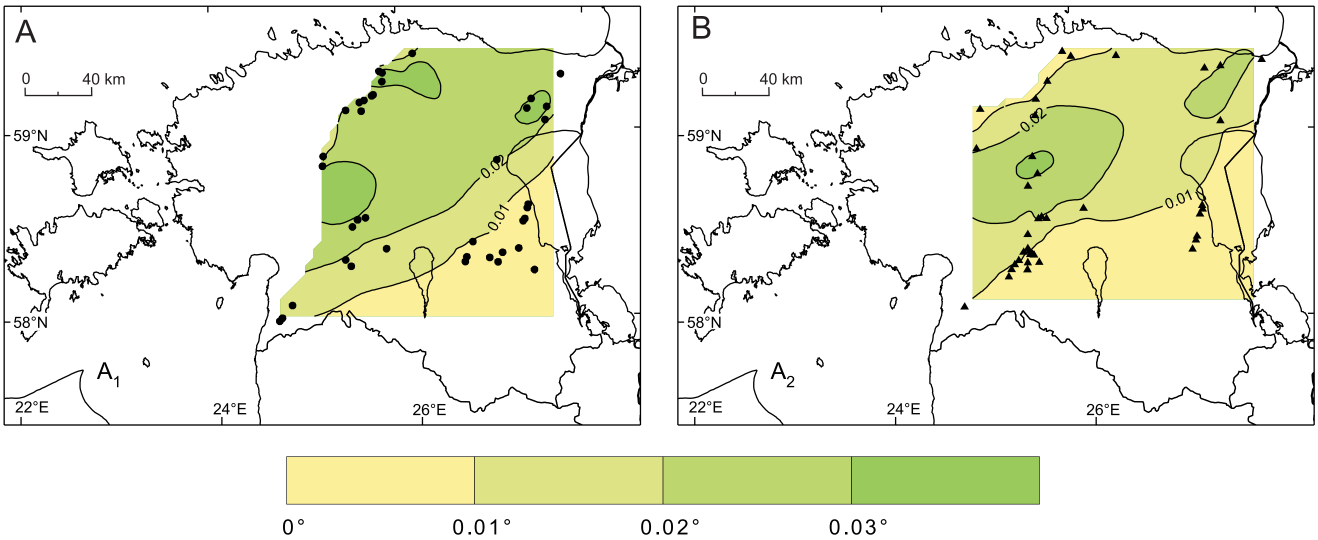

Fig. 4. Changes in tilting during proglacial lakes A_1 (A) and A_2 (B) times

The NE–SW orientated zone may be connected with the Pärnu–Narva fault zone; other explanations as on Figure 2

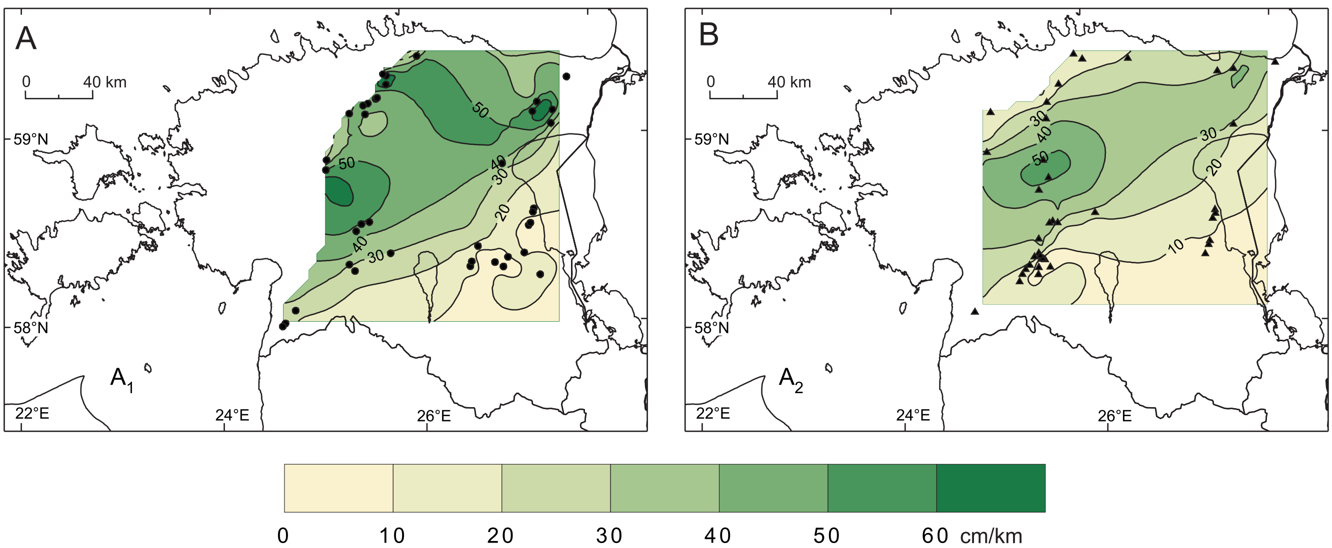

Fig. 5. Changes in the shoreline gradient during proglacial lakes A_1 (A) and A_2 (B) times

Other explanations as on Figure 2

THE AGE OF PROGLACIAL LAKES A_1 (VOOSE) AND A_2 (KEMBA)

As organic sediments are absent just below the coastal deposits studied, the age of the shorelines of proglacial lakes A_1 and A_2 was determined using indirect data. From two localities (Loobu near the Pandivere ice-marginal zone and Kunda to the north of it) organic debris has been dated by the radiocarbon method (at Loobu 13 970±115, TA-137; 14 725±260, TA-138; at Kunda 11 690±150, TA-194; Ilves *et al*., 1974). These dates have been considered too old, as they do not match with the biostratigraphic records (Pirrus, 1976; Pirrus and Raukas, 1996). In the present study, the timing of proglacial lakes A_1 and A_2 is based on the correlation of Peipsi proglacial lakes Pe_{III} and Pe_{IV}, respectively (Raukas and Rähni, 1969), whose age was dated using varvochronology (Hang, 2001).

At the beginning of the Pandivere Phase and formation of proglacial lakes Pe_{III} and A_1, the Peipsi basin was already free of ice. According to earlier estimations based on floating varve chronology, these ice-marginal deposits were formed at about 12 050 BP (Raukas *et al*., 1971, p. 200; Raukas, 1986). Later, Saarnisto and Saarinen (2001) suggested an age of *ca*.13 300 calendar years BP for the Pandivere–Neva ice-marginal zone, based on palaeomagnetic investigations and ^{14}C AMS dates from Lake Onega, which is consistent with the latest results from the Lake Peipsi basin (Hang, 2003). This means that proglacial lake A_1 was formed concurrently with or slightly earlier than the deposits of the Pandivere ice-marginal zone. How long lake A_1 existed is not known. Still, taking into account the age of the formation of the Pandivere Phase, the mean rate of ice recession (*ca*. 150 m yr^{-1}; Hang, 2001), and the distance between the coastal deposits of proglacial lakes A_1 and A_2 along an azimuth of 335°, we can calculate that A_2 was formed during the subsequent 120–150 years.

DISCUSSION

The creation of the final database for proglacial lakes A_1 and A_2 was a long and complicated task. The simulation shows that several deposits, which have previously been considered to belong to the Baltic Ice Lake (Lõokene, 1959), were obviously formed during proglacial lake A_2 stage (Appendix).

The isobases of the interpolated water-level surfaces for both proglacial lakes studied are in good agreement with previous results (Pärna, 1960; Kessel and Raukas, 1979), especially where the proglacial lake in the West Estonian Lowland is concerned. In the present research, shorelines in West Estonia and the Lake Peipsi basin were modelled together. The simulated isobases suggest that both proglacial lakes A_1 and A_2 were connected with the glacial lake in the Peipsi basin (Fig. 1), as previously suggested by Kessel (1980) and later repeated by Miidel *et al*. (2003). Raukas and Rähni (1969) also mentioned a connection between Pe_{III} and A_1. But later Raukas (1986, Fig. 4) did not show this connection, obviously because in the Emajõgi River valley the A_1 and A_2 shorelines lie quite close to each other and their distinction is rather uncertain. To examine more precisely the configuration of the proglacial lakes treated here, their outlets and connection with the other proglacial lakes, additional study will be carried out in the future.

The shorelines of the proglacial lakes A_1 and A_2, indicated on the shoreline diagram of the Võrtsjärv basin (Miidel *et al*., 2003), are considerably higher than those shown by our simulation. The threshold between the Peipsi–Võrtsjärv and West Estonian proglacial lakes lies today near the town of Viljandi (Fig. 1) at about 40.8 m a.s.l., that is, *ca*. 7–8 m below the A_1 water level and *ca*. 2–3 m lower than the A_2 water level. As this threshold is located in the peatland, which did not exist at that time, its actual height is even lower, which supports our conclusions on the connection of A_1 and A_2 with the proglacial lake in the Peipsi basin.

The isobases of the proglacial lakes A_1 and A_2 are arranged more tightly in the northwestern than in the southeastern part of the area studied and show a slight divergence to the east (Fig. 2A, B). The close spacing of the isobases could be explained by location on the Gotiglacial hinge-line, described by Sauramo (1939). Pärna in his manuscripts mentioned the shoreline gradients of the local ice-dammed lakes and the Baltic Ice Lake decrease on this hinge-line zone. Later, it was established that the hinge-line coincides with a wide dislocated zone in the basement and bedrock, in general along the Narva–Pärnu line (Orviku, 1960). Crustal movements were likely activated in this zone during the Late Pleistocene. Our data on isobases (Fig. 2), tilting (Fig. 4) and shoreline gradients (Fig. 5) support this opinion. Analysis of the isolines using a Laplacian operator (Fig. 6A, B) shows that negative values (discharge areas) occur just north-west, and positive values (recharge areas) south-east of the Pärnu–Narva line during both the A_1 and A_2 lake histories. The reason for such a distribution of values is not clear.

The shoreline gradient values (Fig. 5A, B) are in the same range as previously reported (Pärna, 1962), but A_1, at least, seems to have slightly higher gradients in northwestern Estonia than recorded before. Shoreline gradient values are much higher in the northwestern than in the southeastern part. The same tendency is observed in the modern uplift pattern, which shows the greatest uplift in northwestern Estonia (up to 2.8 mm yr^{-1}; Vallner *et al*., 1988; Punning and Miidel, 2004). Comparison of the uplift gradients obtained now and earlier for the different stages of the Baltic Sea (Saarse *et al*., 2003; *ca*. 32 cm km^{-1} for the Baltic Ice Lake, 25 cm km^{-1} for the Ancylus Lake, and 13 cm km^{-1} for the Littorina Sea) shows that water bodies at higher elevations have higher gradients, as many authors have shown earlier (Ramsay, 1929; Sauramo, 1939). This also indicates that, during the Late Glacial, land uplift was faster than in Holocene.

The direction of tilting, previously given for proglacial lakes A_1 and A_2 is 335° (Pärna, 1962) and for Peipsi is 326°. The simulation results suggest that the direction of tilting is not the same and its value varies between 320° and 340° (Fig. 3A, B). As the direction of tilting is supposed to be generally in the direction of the ice sheet centre, we should expect it to change in Estonia from the west to the east, from a more northerly to a more westerly direction, respectively. The simulation results support this assumption.

Comparison of the geometry of the simulated shoreline characteristics shows a quite clear north-east south-west orientation (Figs. 2, 4–6). A similar tendency was recorded earlier by

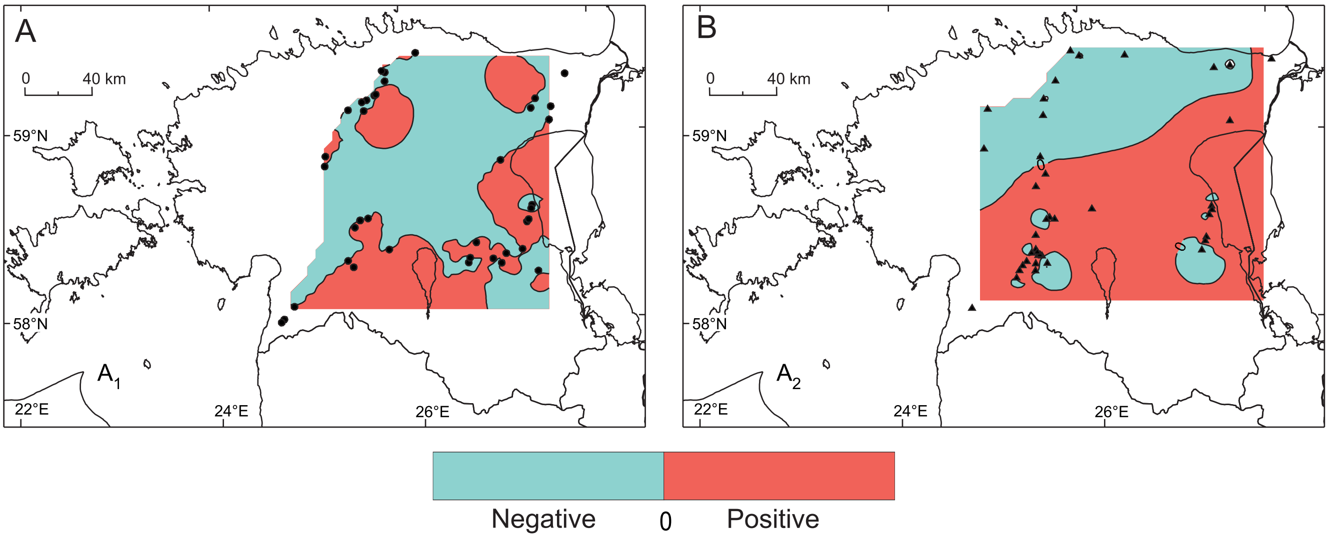

Fig. 6. Location of the discharge (negative) and recharge (positive) areas

A — proglacial lake A_1 (Voose), B — proglacial lake A_2 (Kemba); other explanations as on Figure 2

simulating the shorelines of the Baltic Ice Lake and the Baltic Sea (Saarse *et al*., 2003), which may be explained by the tectonic fault orientation in the bedrock and basement (Sildvee and Vaher, 1995; Puura and Vaher, 1997). However, tectonics does not account for variations in the tilting direction (Fig. 3).

CONCLUSIONS

A shoreline database has been created for proglacial lakes A_1 (Voose) and A_2 (Kemba). It includes 149 sites, from which only 82 have records meeting the demands of the simulation of shoreline characteristics.

Proglacial lake A_1 (Voose) was probably formed at the beginning of the Pandivere Phase at about 13 300 calendar years BP and A_2 (Kemba) about 120–150 years later.

Proglacial lake A_1 was predominantly defined on plateau-like surfaces of eskers and kames, A_2 mostly by erosional coastal features. In the southwestern part of the examined area, and especially in the Emajõgi River valley, the distinction between A_1 and A_2 shorelines is complicated as they lie at similar altitudes.

Water level in the studied proglacial lakes decreased continuously. The highest water level in the proximal part of A_1 was about 90–93 m a.s.l., determined on the altitude of delta-like surfaces; the highest water level of A_2 was at least 13–15 m lower.

The modelling results confirm that both proglacial lakes A_1 and A_2 were connected with the glacial lakes in the Peipsi and Võrtsjärv basins.

The simulated shoreline isobases are located unevenly, being more closely spaced in the northern parts of the Võrtsjärv and Peipsi basins. This was explained by the location of the basins above an activated fault zone, determined approximately along Pärnu–Narva line.

The direction of tilting for A_1 and A_2 varies between 320° and 340°.

The shoreline gradient values were highest during proglacial lake A_1 times, being about 50 cm km^{-1} in the northwestern and 25 cm km^{-1} in the southeastern part of the area investigated; during A_2 the gradient decreased to 40 cm km^{-1} in the north-west and to 20 cm km^{-1} in the south-east.

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APPENDIX

Coastal formation database of proglacial lakes A_1 (Voose) and A_2 (Kemba)

Site	Coordinates		Altitude [m a.s.l.]		Type of landforms	Index	References	Residuals [m]	
	latitude	longitude	given in references	used in simulation				A_1	A_2
1	2	3	4	5	6	7	8	9	10
Used in simulations for proglacial lake A_1 (Voose)									
Alasoo	58°37’5’’	27°9’0’’	44.4	44.4	beach-ridge	–	Liblik, 1969	0.0	2.7
Alatskivi	58°36’0’’	27°8’22’’	44.1	44.1	terrace	–	Liblik, 1969	–0.1	2.7
Armeiski	59°8’12’’	27°23’25’’	55	55	glaciolacust. plateau	P_{IV}	Raukas and Rähni, 1969	–0.1	5.2
Haaslava	58°19’0’’	26°49’0’’	42–43	42	dunes	A_1	Pärna, 1962	0.4	1.7
Junsi	58°21’5’’	25°15’50’’	47	47	scarp	A_3	Lõokene, 1959	–0.2	4.4
Kabina	58°22’0’’	26°52’0’’	41	41	beach sand	A_1	Pärna, 1962	–0.2	0.2

1	2	3	4	5	6	7	8	9	10
Kastna Hiiemägi	58°51’20’’	25°2’30’’	78	78	glaciofluvial plateau	A_1	Pärna, 1962	0.2	14.7
Kavastu	58°23’10’’	27°2’0’’	43	43	terrace	P_{III}	Raukas and Rähni, 1969	0.2	2.7
Keeri	58°19’30’’	26°29’0’’	41	41	beach-ridge	A_1	Pärna, 1962	–0.2	0.0
Kehklase	58°24’25’’	25°41’0’’	47–52	47	boulder field	A_2/A_3	Lõokene, 1959	–0.1	4.9
Koosa	58°31’50’’	27°5’25’’	43.7	43.7	abrasional slope		Liblik, 1969	0.1	2.7
Kullamäe (Vaikla)	59°4’0’’	27°22’0’’	52	52	glaciolacust. plateau	P_{IV}	Raukas and Rähni, 1969	–0.3	4.5
Kõpu	58°19’0’’	25°19’10’’	46	46	scarp	A_3	Lõokene, 1959	0.0	4.0
Kädva (Paluküla)	58°54’30’’	25°3’0’’	80	80	glaciofluvial plateau	A_1	Pärna, 1962	0.2	14.7
Labida	58°31’40’’	25°20’20’’	54	54	dunes	A_2	Lõokene, 1959	0.0	7.6
Lõuniku	59°18’10’’	25°40’40’’	86	86	glaciofluvial plateau	A_1	Pärna, 1962	–0.7	13.6
Lääniste	58°16’0’’	27°11’ 0’’	41	41	beach formations	A_1	Pärna, 1962	0.0	2.7
Merinäki	58°2’38’’	24°36’49’’	44.2	44.2	terrace, beach-ridge	A_2	Pärna, 1962	0.3	3.3
Metsakivi	58°32’33’’	27°6’32’’	43.5	43.5	scarp	–	Liblik, 1969	–0.1	2.5
Metsküla (Mäetaguse)	59°11’0’’	27°14’0’’	62	62	glaciofluvial plateau	P_{IV}	Raukas and Rähni, 1969	0.4	8.5
Possa	58°6’40’’	24°43’0’’	44.5	44.5	dunes	A_1	Pärna, 1962	–0.1	3.9
Punamäe (Jaagu)	59°13’40’’	25°34’5’’	84	84	glaciofluvial plateau	A_1	Pärna, 1962	0.0	11.2
Punamäe (Mäele)	59°14’0’’	25°35’0’’	84	84	glaciofluvial plateau	A_1	Pärna, 1962	–0.1	11.4
Põhjaka	58°33’55’’	25°23’35’’	55–60	55	sand field	A_1/A_2	Lõokene, 1959	–0.1	7.8
Põhjaka	58°33’55’’	25°23’40’’	55–60	55	sand field	A_1/A_2	Lõokene, 1959	–0.1	7.8
Reka-Koitjärve esker	59°21’0’’	25°41’0’’	91	91	glaciofluvial plateau	–	Ramsay, 1929	0.4	17.8
Reka-Koitjärve esker	59°21’30’’	25°39’0’’	92	92	glaciofluvial plateau	–	Ramsay, 1929	0.5	18.2
Rõhu	58°21’0’’	26°30’0’’	42–43	42	sand field	A_1	Pärna, 1962	0.3	0.6
Rõõsamäe (Paunküla)	59°9’10’’	25°17’30’’	85	85	glaciofluvial plateau	A_1	Pärna, 1962	0.2	12.4
Rääkjärve	59°18’30’’	27°33’10’’	60–63	60	glaciofluvial plateau	–	Ramsay, 1929	0.1	6.5
Saarevälja	59°8’0’’	27°11’0’’	60	60	glaciolacust. plateau	P_{IV}	Raukas and Rähni, 1969	0.0	7.5
Taevere	58°34’30’’	25°28’30’’	55	55	terrace	III	Ramsay, 1929	0.0	8.5
Tartu	58°20’30’’	26°44’0’’	41–42	41	beach-ridge	A_1	Pärna, 1962	0.0	0.1
Urisaare	58°1’40’’	24°35’50’’	43	43	beach-ridge	Gy	Kessel, 1961	–0.4	2.0
Vetla-Taganurga	59°12’15’’	25°29’10’’	84	84	glaciofluvial plateau	A_1	Pärna, 1962	0.2	10.2
Viitna esker	59°27’0’’	26°0’20’’	93	93	glaciofluvial plateau	–	Ramsay, 1929	0.4	21.4
Voose (Taaramäe)	59°11’38’’	25°26’12’’	83	83	glaciofluvial plateau	A_1	Pärna, 1962	–0.3	9.0
Voose-Kautla	59°8’50’’	25°27’15’’	81–83	81	glaciofluvial plateau	A_1	Pärna, 1962	–0.1	8.4
Vorbuse-Kärevere	58°25’50’’	26°34’5’’	41.5	41.5	scarp	A_1	Pärna, 1962	–0.3	–1.1
Võtikvere	58°51’50’’	26°50’51’’	51	51	boulder field	A_1	Pärna, 1962	–0.2	1.5
Proglacial lake A_2 (Kemba)									
Alasoo	58°37’0’’	27°9’10’’	41.7	41.7	abrasional slope	–	Liblik, 1969	–2.7	0.1
Hageri	59°10’0’’	24°41’0’’	73	73	beach-ridge	–	Ramsay, 1929	–11.8	0.0
Idavere	59°26’15’’	26°19’15’’	69.4–69.6	69.4	scarp	G_2	Kessel unpubl.	–13.6	0.1
Junsi	58°21’10’’	25°15’30’’	42.5	42.5	scarp	B_1	Lõokene, 1959	–4.9	–0.2
Jõhvi	59°21’35’’	27°24’45’’	58–59	58	terrace	A	Tammekann, 1926	–4.9	0.2
Kaerepere	58°57’20’’	24°50’25’’	69	69	beach formations	A_2	Pärna, 1962	–10.0	0.2
Kautla	59°7’40’’	25°27’20’’	72–72.5	72	dunes	A_1/A_2	Pärna, 1962	–8.4	0.1
Kavastu	58°23’5’’	27°2’5’’	40.4	40.4	abrasional slope	–	Liblik, 1969	–2.4	0.1
Keldripõllu	59°26’25’’	25°50’45’’	73	73	scarp	A_2	Pärna, 1962	–19.8	0.0
Kemba	59°28’5’’	25°45’20’’	74	74	glaciofluvial delta	A_2	Pärna, 1962	–20.1	0.0
Kohtla	59°21’5’’	27°14’40’’	59	59	beach-ridge	A	Tammekann, 1926	–6.3	0.1

1	2	3	4	5	6	7	8	9	10
Korvi	58°22'50''	25°24'50''	42–45	42	boulder field	A_3/B_1	Lõokene, 1959	–5.6	–0.2
Kure	58°34'30''	25°33'0''	45–46	45	scarp	B_1	Lõokene, 1959	–9.6	–0.2
Kuura	58°29'30''	25°21'15''	45	45	scarp	B_1	Lõokene, 1959	–7.2	–0.1
Kõpu-Osju	58°23'50''	25°18'30''	43.5	43.5	scarp	III	Ramsay, 1929	–5.2	0.1
Lahepera	58°35'17''	27°9'13''	40.8	40.8	scarp	–	Liblik, 1969	–4.2	–0.2
Laiksaare	58°6'30''	24°42'0''	40.5	40.5	beach-ridge	A_2	Pärna, 1962	–11.5	–0.1
Laupa	58°45'0''	25°22'0''	54	54	beach-ridge	B_1/B_2	Pärna, 1962	–3.2	0.3
Leevi	58°20'30''	25°28'0''	43	43	scarp	B_1	Lõokene, 1959	–4.6	0.0
Matsima	58°20'25''	25°21'0''	42–43	42	boulder field	B_1	Lõokene, 1959	–3.5	0.1
Meena	58°18'10''	25°20'40''	42–44	42	boulder field	A_3/B_1	Lõokene, 1959	–5.4	0.1
Nutru/Nuutru	58°23'0''	25°22'30''	42.5	42.5	scarp	B_1	Lõokene, 1959	–9.3	–0.2
Pakkasaare	58°35'5''	25°30'0''	46	46	scarp	B_1	Lõokene, 1959	–6.2	0.0
Poola	58°25'0''	25°21'10''	43	43	boulder field	B_1	Lõokene, 1959	–5.1	–0.3
Pootsiku (Nurme)	59°3'50''	27°23'0''	47	47	glaciofluvial plateau	–	Raukas and Rähni, 1969	–14.3	0.0
Reka	59°18'40''	25°39'10''	74	74	beach-ridge	IV	Ramsay, 1929	–2.6	0.1
Rupsi (Rehe)	58°34'12''	27°7'34''	41.2	41.2	scarp	–	Liblik, 1969	–4.8	0.0
Saare (Kõpu)	58°19'50''	25°13'0''	42.5	42.5	scarp	B_1	Lõokene, 1959	–5.8	–0.3
Saarepera	58°23'8''	25°24'0''	42	42	scarp	B_1	Lõokene, 1959	–9.5	0.2
Saunamäe	58°54'30''	25°25'0''	63–64	63	beach sand	A_2/B_1	Pärna, 1962	–5.4	0.2
Soolo/Solo	58°23'10''	25°23'30''	42.5	42.5	scarp	B_1	Lõáokene, 1959	–8.1	0.3
Taevere	58°34'30''	25°28'0''	47	47	scarp	III	Ramsay, 1929	–4.3	0.1
Taganõmme	58°16'0''	25°9'15''	42	42	dune	B_1	Lõokene, 1959	–3.1	–0.2
Toru	58°35'46''	27°9'20''	41	41	terrace	–	Liblik, 1969	–3.1	–0.1
Tähemaa	58°27'11''	27°5'10''	40	40	scarp	–	Liblik, 1969	–11.3	–0.1
Türi drumlin field	58°49'0''	25°28'0''	56–59	56	beach sand	B_1/B_2	Pärna, 1962	–5.0	–0.1
Vainristi	58°18'20''	25°11'0''	42	42	beach sand, dune	B_1	Lõokene, 1959	–9.5	–0.1
Vaivara Sinimäed	59°22'50''	27°51'0''	50	50	terrace	III	Ramsay, 1929	–9.7	0.2
Vetla	59°12'55''	25°28'0''	74.5	74.5	glaciofluvial plateau	A_2	Pärna, 1962	–6.6	–0.6
Viidu/Vidu	58°24'10''	25°22'0''	41–43	42	boulder field	B_1	Lõokene, 1959	–3.1	–0.1
Viira	58°25'55''	27°4'22''	40	40	abras. slope	–	Liblik, 1969	–9.7	–0.2
Võisiku	58°37'30''	25°56'0''	45–46	45	beach sand	A_2	Pärna, 1962	–3.2	–0.2
Sites not supported by A_1 simulations									
Alatskivi	58°36'0''	27°8'0''	45	45	beach-ridge	A_1	Pärna, 1962	0.8	3.5
Iisaku	59°7'0''	27°19'0''	70	70	terrace	P_{III}	Rähni, 1959	14.1	20.0
Junsi	58°21'5''	25° 15'45'	46	46	scarp	A_3	Lõokene, 1959	–1.3	3.4
Junsi	58°21'2''	25°15'56''	52	52	scarp	A_2	Lõokene, 1959	4.8	9.4
Junsi	58°21'2''	25°15'57''	53	53	scarp	A_2	Lõokene, 1959	5.8	10.4
Järavere	58°25'20''	25°21'10''	47–51	47	dune	A_3	Lõokene, 1959	–2.4	3.9
Keava	58°57'40''	24°57'0''	71–72	72	scarp	A_1/A_2	Pärna, 1962	–8.6	3.9
Kehtna	58°56'0''	25°52'0''	68	68	beach-ridge	IV	Ramsay, 1929	–0.7	10.5
Kobruvere	58°28'0''	25°25'30''	70.5–72.5	70.5	boulder field	A	Lõokene, 1959	19.8	26.6
Kodavere	58°41'50''	27°8'10''	49	49	beach-ridge	A_1	Pärna, 1962	3.0	5.7
Kure	58°34'20''	25°32'40''	58	58	terrace	G_I	Kessel and Raukas, 1979	3.5	12.8
Kure (Navesti)	58°34'10''	25°32'30''	72.5	72.5	scarp	A	Lõokene, 1959	18.1	27.4
Kure (Navesti)	58°34'13''	25°32'32''	64.5	64.5	scarp	A_1	Lõokene,1959	10.1	19.4
Kuremäe	59°11'30''	27°32'0''	62	62	glaciofluvial plateau	P_{IV}	Rähni unpubl.	5.6	11.5
Kõpu	58°19'0''	25°18'35''	61–62	61	terrace	A_2	Lõokene, 1959	15.0	19.0
Kõpu Asuküla	58°19'0''	25°19'15''	45	45	beach-ridge	A_1	Pärna, 1962	–1.0	3.0
Merinäki	58°2'37''	24°36'52''	49	49	scarp	A_1	Pärna, 1962	5.1	8.1
Metsküla	58°23'50''	25°24'20''	45–49	45	sand field, dune	A_3	Lõokene, 1959	–3.2	2.6
Nihatu-Välja-taguse	58°54'30''	25°25'40''	66–67	66	sand field	A_1	Pärna, 1962	–6.3	3.4
Nutru/Nuutru	58°22'30''	25°22'30''	50.5	50.5	scarp	A_2/A_3	Lõokene, 1959	2.9	8.1

1	2	3	4	5	6	7	8	9	10
Nõmmeküla--Ravila	59°8’0’’	25°19’0’’	80.5	80.5	esker	III	Ramsay, 1929	–3.1	8.4
Nööripere	58°34’40’’	25°29’30’’	50	50	terrace	A_3	Lõokene, 1959	–5.0	3.8
Ooreküla	58°51’0’’	24°57’0’’	71	71	terrace	III	Ramsay, 1929	–5.7	7.0
Palivere (Türi)	58°55’40’’	25°30’40’’	66–67	66	boulder field	B_1/A_2	Pärna, 1962	–5.9	4.0
Punamäe	58°55’30’’	25°2’0’’	76	76	beach formation	A_1/A_2	Pärna, 1962	–4.3	9.9
Põhjaka	58°34’0’’	25°23’35’’	51	51	terrace	A_3	Lõokene, 1959	–4.2	3.8
Raikküla	58°55’0’’	24°43’0’’	61.1	61.1	beach formation	A_1	Pärna, 1962	–15.1	–5.5
Rasivere (Järvesoo)	59°10’0’’	26°44’0’’	80	80	beach-ridge, dunes	P_{III}	Raukas and Rähni, 1969	15.2	22.0
Reka-Koitjärve	59°19’0’’	25°43’0’’	85	85	glaciofluvial plateau	III	Ramsay, 1929	–2.7	12.9
Rõõsamäe	59°8’50’’	25°17’50’’	83	83	glaciofluvial plateau	A_1	Pärna, 1962	–1.5	10.5
Saara (Roela)	59°9’0’’	26°35’0’’	80	80	scarp	P_{III}	Raukas and Rähni, 1969	13.2	20.9
Sonni	58°19’30’’	25°21’0’’	50–51	50	boulder field	A_2	Lõokene, 1959	3.9	8.0
Suure-Nõmme	58°35’10’’	25°25’5’’	51	51	terrace/scarp	A_3	Lõokene, 1959	–4.9	3.4
Tõnissaare	58°27’10’’	25°45’0’’	59–61	59	boulder field	A_1/A_2	Lõokene, 1959	10.3	16.5
Urissaare	58°1’30’’	24°36’30’’	51	51	beach formation	IIb	Ramsay, 1929	7.6	10.3
Venisaare	58°19’10’’	25°12’20’’	53.5	53.5	dune	A_2	Lõokene, 1959	6.4	11.2
Villema	58°24’10’’	25°48’19’’	50–53	50	boulder field	A_2/A_3	Lõokene, 1959	3.0	8.3
Villevere	58°39’0’’	25°30’0’’	54	54	sand field	A_1	Pärna, 1962	–4.5	5.5
Voose-Kautla	59°11’0’’	25°26’0’’	85	85	glaciofluvial plateau	A_1	Pärna, 1962	2.2	11.3
Voose-Kautla	59°10’40’’	25°26’10’’	84	84	glaciofluvial plateau	A_1	Pärna, 1962	1.4	10.5
Vorbuse-Kä-revere	58°25’50’’	26°32’40’’	36	36	terrace	A_1	Pärna, 1962	–6.1	–6.6
Änni (NO)	59°17’45’’	25°40’40’’	85	85	glaciofluvial plateau	A_1	Pärna, 1962	–1.1	12.7
Änni (SW)	59°17’5’’	25°39’50’’	84	84	glaciofluvial plateau	A_1	Pärna, 1962	–1.6	11.7
Sites not supported by A2 simulations									
Alasoo	58°37’0’’	27°9’15’’	40	40	terrace	P_{IV}	Raukas and Rähni, 1969	–4.4	–1.6
Haljala	59°27’0’’	26°16’0’’	74–75	74	terrace	IV	Ramsay, 1929	–10.9	4.1
Jaaska	58°49’0’’	26°50’0’’	46	46	beach-ridge	P_{IV}	Raukas and Rähni, 1969	–4.0	–2.6
Kastna Hiiemägi	58°51’20’’	25°2’57’’	70–71	70	terrace	IV	Ramsay, 1929	–7.7	6.8
Koljaku-Oandu	59°33’20’’	26°0’0’’	46.2–46.5	46.2	glaciofluvial delta	G_{II}	Kessel unpubl.	–48.0	–27.1
Konju	59°24’25’’	27°37’20’’	44	44	beach-ridge	C	Tammekann, 1926	–17.8	–10.3
Koosa-Laane	58°31’47’’	27°7’5’’	39.6	39.6	abrasional slope	–	Liblik, 1969	–3.8	–1.1
Kukruse	59°23’0’’	27°22’0’’	60–61	60	terrace	A	Tammekann, 1926	–4.1	1.3
Kõnnu	58°48’30’’	24°50’40’’	60	60	glaciofluvial plateau	IV	Ramsay, 1929	–13.6	–3.0
Maidla-Aidunõmme	59°20’30’’	27°7’30’’	45–46	45	beach-ridge, dune	B	Tammekann, 1926	–21.5	–14.1
Merinäki	58°2’40’’	24°36’40’’	37.2	37.2	terrace, beach-ridge	A_2	Pärna, 1962	–6.7	–3.7
Merinäki-Nőőpste	58°3’10’’	24°37’25’’	38.5	38.5	terrace	A_2	Pärna, 1962	–5.6	–2.4
Muike	59°31’0’’	25°56’0’’	46–50	46	glaciofluvial delta	G_{II}	Kessel unpubl.	–48.4	–27.3
Nepste	58°3’30’’	24°38’0’’	38.5	38.5	beach-ridge	A_2	Pärna, 1962	–5.7	–2.3
Nööripere	58°35’0’’	25°30’0’’	48	48	terrace	A_2	Lõokene, 1959	–7.2	1.8
Paunküla	59°8’45’’	25°19’10’’	75	75	beach-ridge	IV	Ramsay, 1929	–9.0	2.5
Reka-Koitjärve	59°24’0’’	25°36’0’’	72–73	72	esker	IV	Ramsay, 1929	–20.7	–3.0
Ruunaraipe	58°24’30’’	25°22’0’’	39–40	39	dune	B_2/B_3	Lõokene, 1959	–9.8	–3.6
Taganõmme	58°16’0’’	25°9’20’’	43	43	beach-ridge	A_2	Pärna, 1962	–3.3	1.1
Tatruse	59°27’20’’	26°18’2’’	75	75	terrace	G_{II}	Kessel unpubl.	–9.1	5.2
Tatruse	59°27’20’’	26°18’5’’	73	73	terrace	G_2	Kessel unpubl.	–11.1	3.2
Varudi	59°25’0’’	26°38’0’’	64	64	terrace	A	Tammekann, 1926	–11.1	–0.8
Viitna	59°28’30’’	26°1’0’’	78	78	terrace, ridge	IV	Ramsay, 1929	–15.0	6.1
Voka	59°24’40’’	27°34’25’’	48.5	48.5	beach-ridge	B	Tammekann, 1926	–13.8	–6.9

Indexes (column 7) are given after the cited references. Residuals are given as actual site elevation minus simulated A_1 or A_2 surface elevation in metres