Geological Quarterly, 2008, **52** (1): 81–89

Streamlined topographical features in and around the Gulf of Riga as evidence of Late Weichselian glacial dynamics

Arkady TSYRULNIKOV, Igor TUULING and Tiit HANG

Tsyrulnikov A., Tuuling I. and Hang T. (2008) — Streamlined topographical features in and around the Gulf of Riga as evidence of Late Weichselian glacial dynamics. Geol. Quart., **52** (1): 81–89. Warszawa.

Based on various cartographic sources, a digital terrain model and acoustic profiling data, linear relief features of glacial origin have been distinguished and analysed in the Gulf of Riga and adjacent mainland areas in order to reconstruct the dynamics and pathways of former ice streams. North-east–south-west oriented features in the till topography prevail in the central part of the gulf and along the southern coast of the island of Saaremaa, which corroborate the previously known south/south-east direction of the main Riga ice stream. North-east to south-west directed features dominate in the Pärnu Bay and around the Irbe Strait. Similar deviations from the Riga ice stream are most likely due to ice divide zones, namely the Sakala Upland in Southern Estonia and Kurzeme in northwestern Latvia, which locally changed the course of the main ice flow. The influence of the Kurzeme ice divide is traceable at the bottom of the gulf up to the southern coast of Saaremaa. There is no evidence of an ice-marginal zone crossing the central part of the Gulf of Riga as was supposed earlier. The Pandivere–Neva and Palivere ice-marginal zones, which merge on the Sõrve Peninsula, probably continue offshore into the Irbe Strait. As the age of the glacier relief features is poorly contained, the chronological reconstruction of the ice dynamics is tentative.

Arkady Tsyrulnikov, Igor Tuuling and Tiit Hang, Institute of Geology, University of Tartu, Vanemuise 46, 51014 Tartu, Estonia; arkadyts@ut.ee, igor.tuuling@ut.ee, tiit.hang@ut.ee (received: May 7, 2007; accepted: August 20, 2007).

Key words**:** Gulf of Riga, the Baltic Sea, Late Weichselian glaciation, glacial topography, Riga ice stream, bottom relief.

INTRODUCTION

The main features of recent topography in Estonia and Latvia were formed during the last Weichselian event of the European glaciation, when large areas east of the Baltic Sea were affected by the Baltic, Riga and Peipsi (Lake Peipsi) ice streams. The ice streams, which have left behind erosional troughs, terminated in lobes and were separated by ice divide or interlobate formations. The Gulf of Riga was covered, and its bottom topography influenced, by the Riga ice stream. Thus, the time-transgressive deglaciation pattern of the gulf reflects mostly the last active stage of this ice stream which displayed a complex lobate structure with a number of small glacier tongues.

The ice flow directions around the Gulf of Riga have been reconstructed previously, based on the distribution of erratic boulders, till fabric orientation and topographic lineations such as drumlins, flutings, striae, erosional troughs and other radial structures (Raukas, 1977, 1986; Raukas and Karukäpp, 1979; Karukäpp, 1996, 2004; Zelčs and Markots, 2004, *etc.*). Very little, however, was known about the lineations indicating the ice movement directions within the gulf. Large-scale marine charts enabled, a series of subparallel landforms to be reported from the central Gulf of Riga (Juškevičs and Talpas, 1997). According to Zelčs and Markots (2004), these features are most likely of subglacial origin, being formed during ice recession from the Valdemārpils marginal zone (Sakala in Estonian deglaciation scheme; *ca*. 14 100 ^{14}C yrs BP in Kalm, 2006) to the Pandivere–Neva marginal zone (*ca*. 13 550 ^{14}C yrs BP in Kalm, 2006).

The aim of this paper is to analyse all available topographical, geological and acoustic profiling data concerning the topography and distribution pattern of Quaternary deposits on the sea floor of the Gulf of Riga and the adjacent Estonian mainland (Fig. 1). The study was primarily concentrated on recognition of elongated glacial relief features, the orientation of which closely reflecting on the directions of ice movement in western Estonia during the Late Weichselian glaciation.

MATERIAL AND METHODS

The analysis made and conclusions drawn in this paper are largely based on the previously published maps or compiled by authors cartographical data (see below), which reflect the

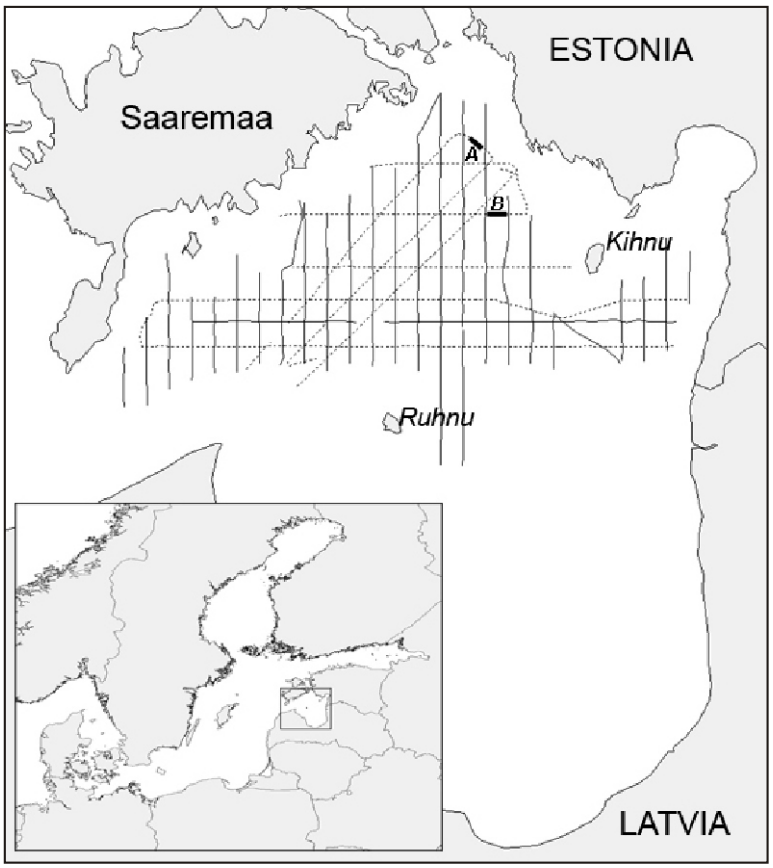


Fig. 1. Area of investigation with acoustic lines shot in 1995 (black) and in 2004 (dotted)

A–B sections of acoustic lines displayed in Figure 4

geology and topography of the sea floor of the Gulf of Riga and surrounding mainland areas. Additionally, some acoustic profiling data at 4 kHz from the Estonian part of the gulf (Fig. 1) were used to verify the glacial origin and lateral extension of different submarine relief forms under younger postglacial sediments.

SUBMARINE DATA

The bathymetric map and digital terrain model (henceforth DTM) of the Gulf of Riga (Figs. 2 and 3) compiled by us were the main sources for describing the general sea floor morphology and estimating the orientation of elongated glacial relief features in the offshore area. The original data set for the Estonian part of the gulf was assembled by digitizing the depth values of eight marine charts at the scale of 1:50 000 (Estonian..., 2000, 2001*a–c*, 2002*a–d*). The distance between the depth points on the charts varies from 200 m in near-shore areas up to 2 km further away from the shoreline. To cover the Latvian part, a public data set (www.io-warnemuende.de/iowtopo) (Seifert *et al.*, 2001) with regular sea depth values every 2 km was used. All assembled data were processed with the GIS software package *Vertical Mapper* (*MapInfo Professional*) to interpolate a regular depth points grid (200 × 200 m) for the entire gulf. Based on that grid, the DTM and bathymetric map of the Gulf of Riga were compiled using the same software.

The presence and orientation of possible linear relief features of glacier origin offshore were furthermore estimated based on the geometry of the outcropping late- and postglacial deposits on the Quaternary geology map of the Gulf of Riga (Juskevičs *et al.*, 1996). After the ice sheet recession, the sediments started to infill and thus level the irregularities of the relief left behind by the glaciers (Juskevičs and Talpas, 1997). The elongated concentric patterns of outcropping late- and postglacial sediments therefore indicate partially infilled glacial troughs, as the older deposits between them still define entirely unburied elevations of glacial origin.

Ample acoustic profiling data, shot in the course of Swedish–Estonian joint marine expeditions to the Estonian part of the Gulf of Riga in 1995 and 2004 (Fig. 1), were used. The 4 kHz frequency, penetrating all the Quaternary deposits except for the glacier till (Noormets and Flodén, 2002), enabled us to follow both partially and entirely buried relief features along the till surface and thus indicate their glacial origin (Fig. 4).

MAINLAND DATA

The Estonian mainland relief around the Gulf of Riga (the islands of Saaremaa, Muhu, Ruhnu, Abruka and Kihnu; the Tõstamaa Peninsula and Pärnu area) was studied in detail using the Estonian Base Map (Digital version for MapInfo 1:50 000, 1998) with 5 m contours. Additionally, the shoreline configuration, above all the orientation of alternating bays and capes was analyzed to obtain further indications concerning the possible pathways of moving ice streams.

As in the offshore area, the distribution and pattern of the outcropping glacial and postglacial deposits were analysed around the Gulf of Riga onshore Estonia using the Quaternary and geomorphological maps of Estonia at the scales of 1:400 000 (Kajak, 1999), 1:200 000 (Väärsi and Kajak 1969; Kajak and Kala, 1972, 1973) and 1:50 000 (Eltermann *et al.*, 1993). In Latvia, the map of the Late Weichselian directional ice-flow features (Zelčs *et al.*, 2003) and the Glaciotectonic Map of Latvia (Zelčs and Dzeltzītis, 2003) were used to distinguish linear relief forms and to measure their orientation in the onshore area around the gulf.

GENERAL SEA FLOOR MORPHOLOGY OF THE GULF OF RIGA

The semi-closed Gulf of Riga (16 300 km^2) is shared by Estonia and Latvia. The Kurzeme Peninsula and West-Estonian Archipelago separate it from the Baltic Sea proper. The

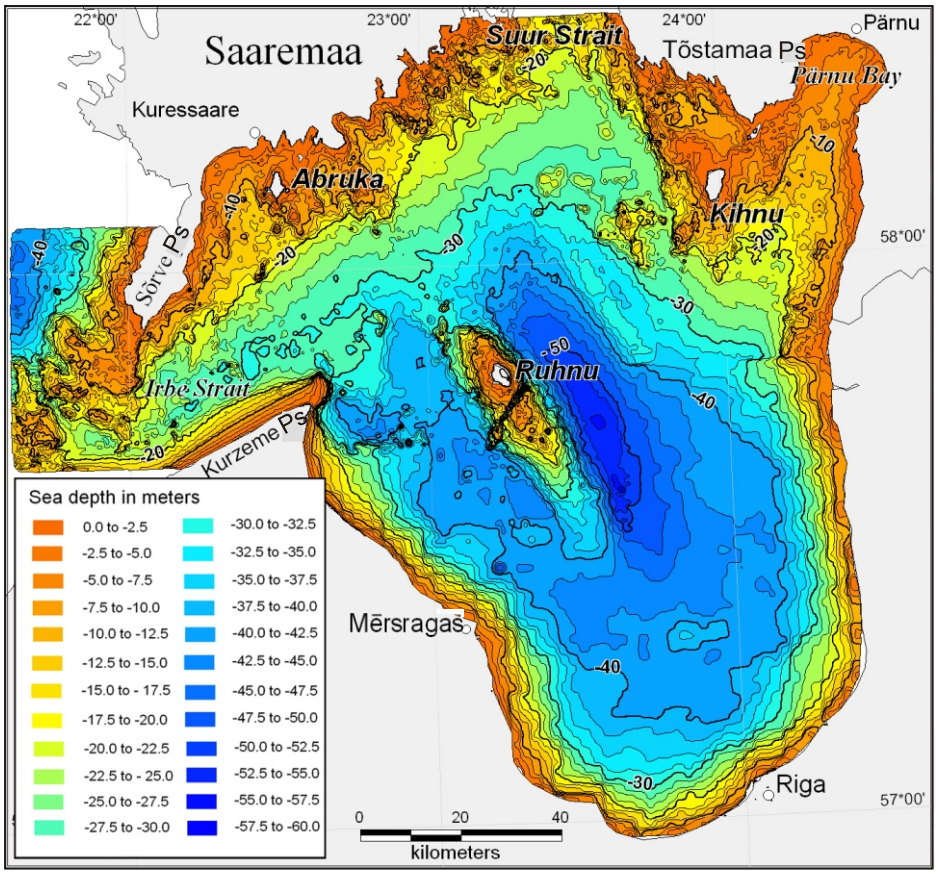


Fig. 2. Bathymetric map of the Gulf of Riga

gulf is connected to the sea *via* a system of shallow and narrow straits in the north (Suur Strait *etc.*) and the Irbe Strait in the west (Fig. 2). The submerged ridge-like continuation of the Sõrve Peninsula forms a natural western boundary to the gulf. The north-west–south-east elongated general shape of the gulf is joined by Pärnu Bay in the north-east and by the Irbe Strait in the west.

The water depth of the Gulf of Riga increases from the north towards the central deep (40–50 m) which occupies most of the gulf. The average water depth is 26 m, while the deepest (– 67 m) point is located north of Mērsrags close to the western coast (Fig. 2). According to the water depth and the depth gradient, which reflect the main features of the bottom topography, the Gulf of Riga can be morphologically divided into two parts: northern and southern. The northern/northwestern part of the gulf is shallower with a distinctly smaller depth gradient compared to that of the southern part (Fig. 2). The depth gradient around the Irbe Strait is 2–3 m/km and the width of the shallow-water area (provisionally up to the 30 m contour) is 10–15 km. Along the southern coast of the Saaremaa Island (henceforth Saaremaa) the same parameters are *ca.* 1 m/km and 30–35 km, around the Tõstamaa Peninsula *ca.* 1 m/km and 30 km and in the Pärnu Bay 0.2–0.5 m/km and 65 km. These parameters are clearly different from those of the rest of the gulf further south-east, where the depth gradient is *ca.* 3.5 m/km and the width of the shallow-water area is only 8–9 km. Due to the shallowness and rugged glacial topography (Juskevičs and Talpas, 1997), the occurrence of a number of small islets and shallows is another feature characteristic of the northern and northwestern region of the Gulf of Riga compared to the southern deep-water areas. Just at the transition of these two parts, approximately between the Kurzeme and Tõstamaa peninsulas, a conspicuous north-west to south-east elongated elevation emerges from the sea floor with its top forming Ruhnu Island (Figs. 2 and 3). This elevation divides the main depression of the Gulf of Riga into two separate, north-west–southeasterly elongated deeps, with the deepest area (>50 m) of the gulf east of Ruhnu Island (Fig. 2)

LINEAR RELIEF FEATURES

Distinguished and analyzed relief features are grouped based on the type of source map (*I–V*) and on their location in onshore (*a–d*) or offshore (*A–F*) areas (Fig. 5). In most cases the groups distinguished were made up of closely located linear relief features, indicating construction by the same ice stream or even by the same glacier lobe.

THE GULF OF RIGA

FEATURES BASED ON THE DTM (SOURCE TYPE *I*)

Because of the closely-spaced depth data available offshore Estonia, the detail in the DTM was greatest in the northern, shallow-water half of the Gulf of Riga (Fig. 3). The most striking relief features in this part of the gulf are elongated elevations of varying orientation close to the Estonian coast. Acoustic recordings suggest that, the cores of these elevations are made up of till (Fig. 4), i.e. they are certainly of glacial origin. Further away from the coast, where late- and postglacial deposits largely obscure the original glacial relief, only a few large linear relief features rise above the sea bottom. In total, six types of linear relief features with different orientations were distinguished based on the DTM (Figs. 3 and 5):

IA — north-east–south-west oriented features east and south of Kihnu Island;

IB — north-west–south-east directed features: a group of features along the southeastern coast of Saaremaa up to the Vätta Peninsula; a few solitary features south-west of the Sõrve Peninsula; two large features in the central part of the gulf. In the latter case, the largest, with Ruhnu Island on top, divides the main depression of the gulf; another occurs midway between the islands of Ruhnu and Kihnu;

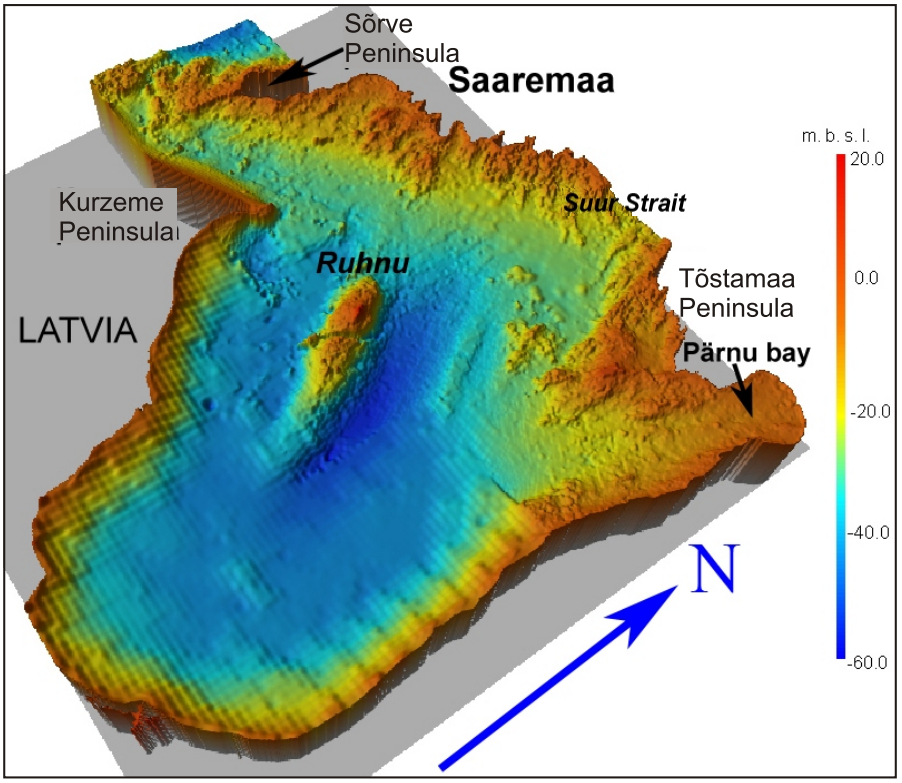


Fig 3. Digital terrain model (DTM) of the Gulf of Riga

For details on the original data set see text

IC — a group of south/south-east oriented forms south-west of the Tõstamaa Peninsula;

ID — scattered sub-longitudinal forms in the Irbe Strait, along the eastern coast of the Sõrve Peninsula, south-east of Abruka Island and at the northern end of the gulf: just offshore of the south-eastern coast of the Saaremaa and western coast of the Tõstamaa Peninsula;

IE — a slightly wavy, southwesterly oriented feature south of the Sõrve Peninsula;

IF — a sub-latitudinal single feature and about 18 km long about 20 km west of Kihnu Island. According to acoustic data this feature is made up of several closely-spaced till hummocks.

FEATURES BASED ON THE QUATERNARY DEPOSITS MAP (SOURCE TYPE *II*)

The concentric and elongated patterns of the outcropping late- and postglacial deposits visible on the Quaternary Deposits Map of the Gulf of Riga (Juskevičs *et al.*, 1996) obviously reflecting alternating troughs and elevations of original glacial relief. They appear mainly in the central and western part of the gulf. Three types of similar structures were distinguished (Fig. 5):

IIA — north-east–south-west oriented features: a group of features between the Sõrve and Kurzeme peninsulas; a few closely-spaced features east of the Kurzeme Peninsula, offshore Mērsrags;

IIB — several groups of north-west–south-east oriented features of different size around the Ruhnu Island.;

IIC — solitary submeridional features located in the southern part of the gulf.

ESTONIAN ONSHORE AREAS

The elongated relief forms of glacial origin on the Estonian mainland have been discussed earlier (Laasi, 1937; Raukas, 1992; Kadastik and Kalm, 1998; Raukas *et al.*, 2004; Rattas and Kalm, 2004; Karukäpp, 2004, *etc.*). In contrast to the offshore examples the internal structure and composition of these features onshore have often been investigated in detail, and thus their genesis and orientation with respect to the moving ice stream are better established.

BASED ON QUATERNARY AND GEOMORPHOLOGICAL MAPS (SOURCE TYPE *III*)

In Estonia, the following linear glacial relief features were distinguished onshore around the Gulf of Riga (Fig. 5):

IIIa — ice-marginal: structures in western Saaremaa and along the Sõrve Peninsula; two sections north-west and north-east of Pärnu Bay;

IIIb — drumlins: north-west–south-east oriented 10–18 km long linear forms on the Tõstamaa Peninsula; a few northeast–south-west oriented 1–3 km long forms south-east of Pärnu Bay close to the Estonian–Latvian border;

IIIc — eskers: a north-south directed, linear form about 13 km long, in northern Saaremaa; north-west–south-east oriented, about 2 km long forms in the central part of the Tõstamaa Peninsula; a north–south oriented form north of Pärnu Bay; east-west oriented, 2–3 km long forms in southern Saaremaa, north-east of the Vätta Peninsula;

IIId — elongate outcrops of glaciofluvial deposits: mainly north-east–south-west oriented 2–3 km long features in eastern Saaremaa; north/north-west–south/south-east oriented forms on the Tõstamaa Peninsula.

BASED ON ESTONIAN BASE MAP (SOURCE TYPE *IV*)

In addition to those features previously known (Raukas, 1977, 1992; Eltermann *et al.*, 1993; Kajak, 1999; Karukäpp *et al.*, 2002; Rattas and Kalm, 2004) several new linear relief forms have been distinguished on the Estonian Base Map 1:50 000 (1998) along the Estonian coast of the Gulf of Riga (Fig. 5):

IVa — north-south oriented features: a group of elevations about 1.5–4 km in length and 0.2–1.5 km in width in northeastern Saaremaa; an about 3 m high, 3 km long and 0.4 km wide swell-like form on the Abruka Island;

IVb — north-west–south-east oriented features: elevations in the central and western part of Muhu Island; a linear array of small (*ca.* 5 m in height) hummocks in the eastern part of the same island; a group of north-west–south-east oriented

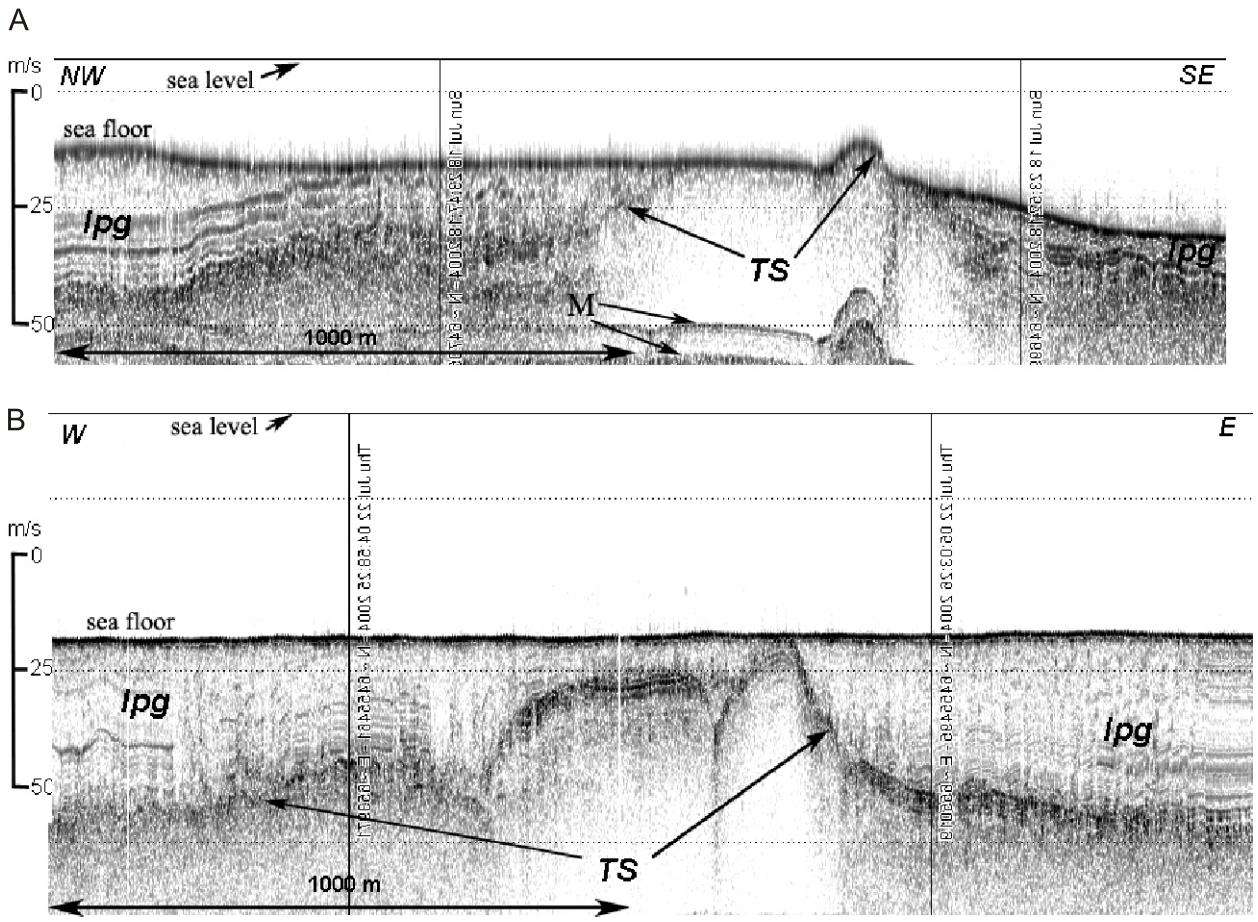


Fig. 4. Sections of the acoustic profiles (for location see Fig. 1) demonstrating the glacial relief features along the till surface (TS) impenetrable for the 4 kHz acoustic pulse

A — visible on sea floor, B — buried under the late- and postglacial deposits (lpg), M — multiple reflectors

ridge-like forms 5–10 m, 3 km and 0.1 km in height, in length and in width, respectively, on the Tõstamaa Peninsula;

IVc — north-east–south-west oriented features: about 2 km long and 0.2–0.4 km wide ridge-like forms east of the Suur Strait; a linear elevation, an emerged part of which forms Kihnu Island.

BASED ON THE ANALYZE OF COASTLINE MORPHOLOGY (SOURCE TYPE *V*)

Advancing glaciers have influenced the shape of the Estonian coastline to a remarkable degree. This is reflected in the similar orientation of alternating bays and peninsulas/capes imprinted locally both into the bedrock and into the Quaternary cover (Tammekann, 1940; Orviku, 1974). Around the Gulf of Riga three striking orientations in the coastline indentation were distinguished that can be used as further indications in reconstructing the ice movement directions (Fig. 5):

Va — north-east–south-west orientated: along the southern coast of Saaremaa west of Vätta Peninsula and on Abruka Island; mainland coastline east of the Suur Strait;

Vb — north-west–south-east orientated: along the southern coast of Saaremaa east of the Vätta Peninsula; in north-western Saaremaa at and around the Tagamõisa Peninsula; southwestern coast of the Tõstamaa Peninsula;

Vc — sub-meridional orientation: the northern coast of Saaremaa east of the Tagamõisa peninsula; southern coast of Muhu Island.

DISCUSSION

GROUPING OF LINEAR RELIEF FEATURES AND THEIR POSSIBLE ORIGIN

In order to discuss the possible directions and age relationships of the former ice streams, all aforementioned on and offshore linear relief features were classified into six groups according to their orientation (numbers 1–6 in Fig. 6). Depending on the location and genesis of these features all groups were further divided into several subgroups (a–f in Fig. 6).

Group 1. The curvilinear features around the northern coast of the Gulf of Riga:

1a — from northern Saaremaa across the Sõrve Peninsula into the Irbe Strait;

1b — two sections north-west and north-east of Pärnu Bay.

These features represent ice-marginal structures, which were formed during the Pandivere–Neva and the Palivere phases of deglaciation in Estonia (Raukas, 1986, 1992, 1997; Raukas *et al.* 2004; Rinterknecht *et al.*, 2006).

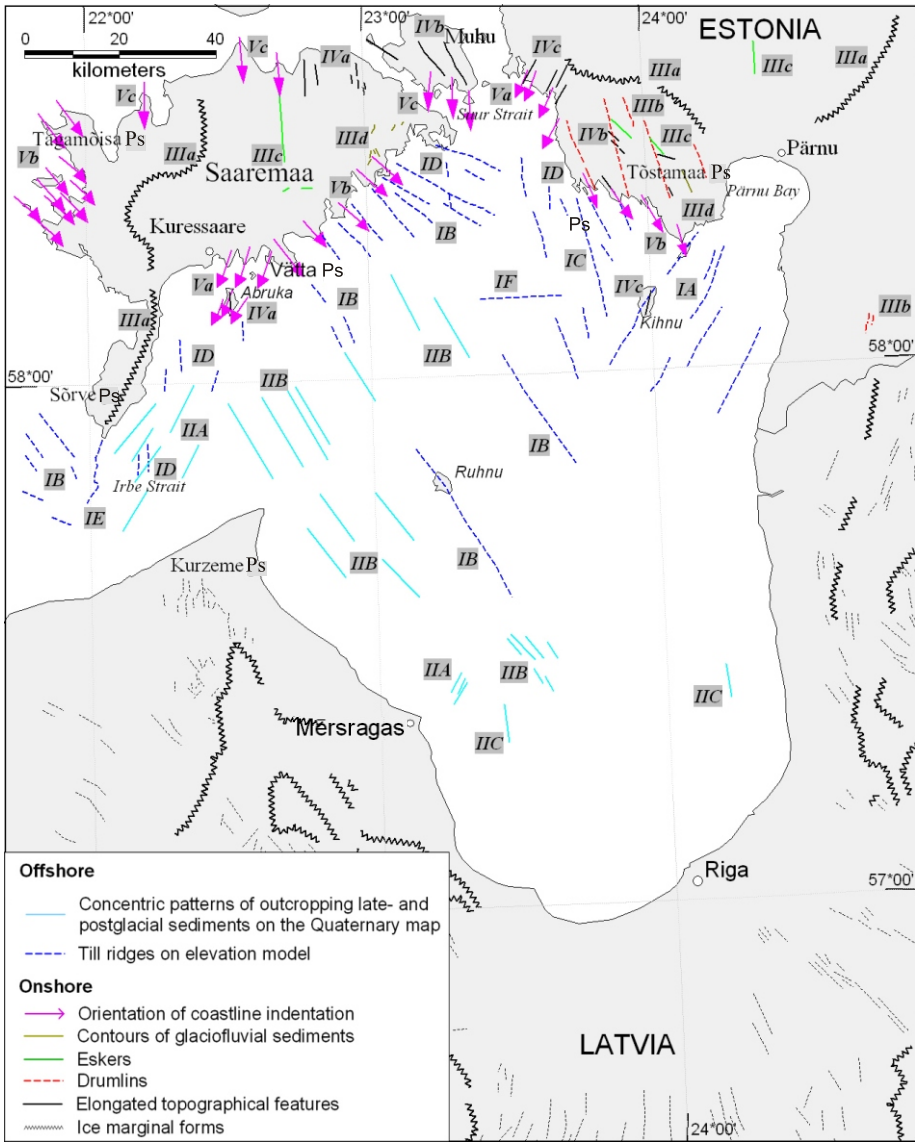


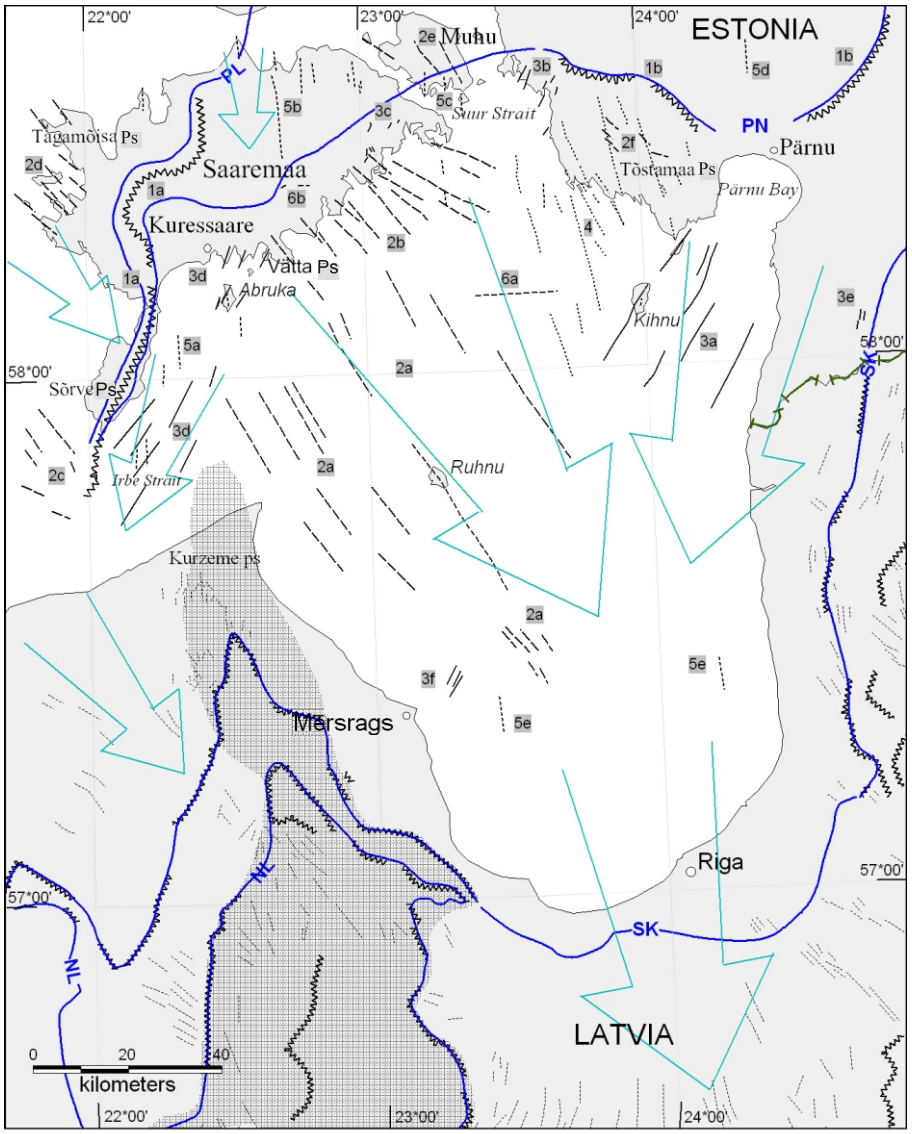
Fig. 5. Streamlined geological and topographical features of glacial origin based on different data sources (*I–V*) off shore (*A–F*) and onshore (*a–d*) Gulf of Riga, discussed in the text

Group 2. North-west–south-east oriented features:
2a — in the middle of the gulf, around Ruhnu Island;
2b — along the southern coast of Saaremaa;
2c — south-west of the Sõrve Peninsula;
2d — in northwestern Saaremaa;
2e — on Muhu Island;
2f — in the central part of the Tõstamaa Peninsula.

This orientation is clearly dominant in the central part of the gulf (2a) and along the southern coast of Saaremaa (2b) both in till topography and coastline indentation, and obviously reflects the main south/southeasterly direction of the main Riga ice stream. The two largest features of this orientation in the middle of the gulf are built up of bedrock and represent erosional forms of the advancing ice. The smaller features in the northern (2b) and western (2a) parts of the gulf, which are expressed in the till topography, may have been formed subglacially during the last active stage of the Sakala (Valdemārpils) Phase of ice recession.

Similarly oriented forms on the Tõstamaa Peninsula (2f), made up of glaciofluvial material, represent small-scale radial eskers, which obviously were also formed at the end of the Sakala Phase too. Similarly oriented topographic features on Muhu Island (2e) point towards the same ice stream. However, considering their position with respect to the ice-marginal zone (Fig. 6), these features may have been formed during the following Pandivere–Neva Phase. The north-west–southeasterly oriented sea bottom and coastline features along the western and southwestern coast of Saaremaa (2c, 2d) are younger. They were probably formed by the re-advancing ice prior to the formation of the Palivere ice-marginal zone.

Group 3. North-east to south-west oriented features that occur:
3a — south-west of Pärnu Bay;
3b — east of the Suur Strait;
3c — in the eastern part of Saaremaa;
3d — from the southern coast of Saaremaa across Abruka Is-



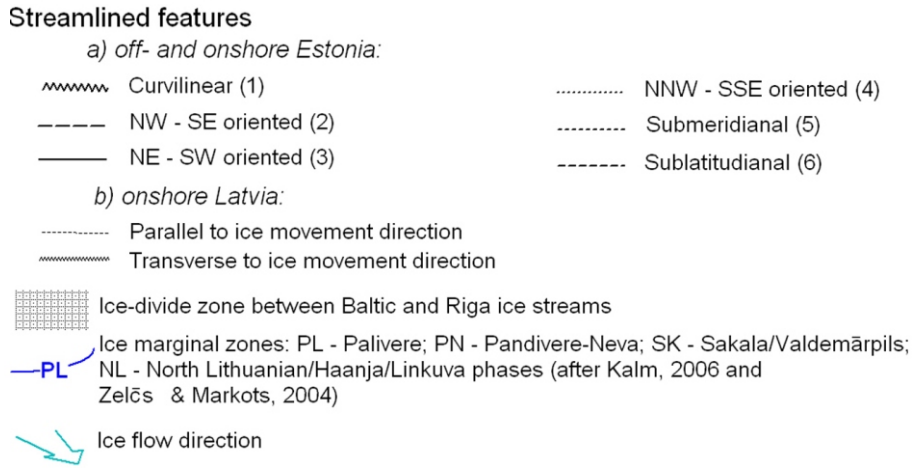


Fig. 6. Ice flow reconstruction map of the Gulf of Riga and adjacent mainland areas based on the grouping (1–6 in text) of different kinds of linear relief features

land and along the eastern coast of the Sõrve Peninsula;
3e — south-east of Pärnu Bay;
3f — east of the Kurzeme Peninsula offshore from Mērsrags.

The conspicuous features in the till topography south-west of Pärnu Bay (3a) reveal a different orientation compared to that of the main Riga ice stream in the central part of the gulf (2a, 2b). Thus, these features may reflect an ice flow direction prior to the last Weichselian glacial event. However, it is more likely that the features discussed indicate a locally south-west deviating ice flow in the eastern flank of the Riga ice stream during the Sakala Phase. The latter suggestion is supported by the similarly orientated scattered drumlins onshore along the eastern coast of the gulf in Estonia (3e), as well as in the northwestern section of the Burtnieki drumlin field in Latvia (see fig. 1 in Zelčs and Dreimanis, 1997). This kind of deviation from the main Riga ice stream direction may have been caused by Sakala Upland in Southern Estonia, which acted as an ice divide zone and caused the eastern flank of the Riga ice stream to flow westwards (see fig. 5 in Raukas and Karukäpp, 1979).

The southwesterly oriented offshore features south-east of the Sõrve Peninsula (3d) are obviously due to Kurzeme ice divide zone which has locally changed the course of the western flank of the Riga ice stream. The same features east of Mērsrags (3f) are difficult to explain but may reflect the movement of the so-called Okste ice tongue, which branched off from the major lobe of the Riga ice stream (see fig. 2 in Zelčs and Markots, 2004). Similarly oriented topographic features and coastline indentations north-west of the Tõstamaa Peninsula (3b) and in the southeastern part of Saaremaa (3c) may reflect a surging glacier lobe during the Pandivere–Neva Phase, as clear ice-marginal structures in this section of that phase are missing (Fig. 6).

Group 4. North/north-west to south/south-east oriented features on the Tõstamaa Peninsula and offshore from it (4). The nature of these extensive linear forms in offshore till topography is unknown. As they display a similar orientation as do the adjoining coastline indentations (Vb in Fig. 5) on the Tõstamaa Peninsula, they most likely reflect the ice flow direction during the late Sakala Phase. Large-scale onshore features of similar direction have earlier been described as heavily eroded mega-drumlins (*IIIb* in Fig. 5). As the younger linear glaciofluvial deposits (2f) of the retreating Riga ice stream from the Sakala Phase occur on top of them (Fig. 6), these mega-forms are believed to reflect the ice-flow direction prior to the last Weichselian glacial event.

Group 5. Submeridionally oriented occasional features:
5a — east and south-east of the Sõrve Peninsula;
5b — in the central and northeastern part of Saaremaa;
5c — along the southern coast of Muhu Island;
5d — north of Pärnu Bay;
5e — in the southern part of the gulf.

Except for the coastline indentations (5c), only the genesis of the 5d and the most extensive of the 5b features (Fig. 6) are known. These are radial glaciofluvial eskers, which probably have been formed in crevasses or subglacial tunnels during the Pandivere–Neva stage (Karukäpp, 1997). The submarine features of unknown genesis (5a) were formed either by the Irbe ice tongue or are part of the nearby and similarly oriented Pandivere–Neva and/or Palivere ice-marginal zones (1a) onshore.

Group 6. Sublatitudinal features:
6a — a few closely spaced and east-westerly aligned hummocks in the till surface about 20 km west of Kihnu Island;
6b — marginal glaciofluvial deposits in the southern part of Saaremaa.

The latter have been considered as possible representatives of the Pandivere–Neva ice-marginal zone (Raukas *et al.*, 1971). Further investigations and mapping are needed to discuss the origin of the submarine hummocks (6a).

CONCLUSIONS

The linear glacial relief features described from the Gulf of Riga (Figs. 5 and 6) largely support earlier ice flow reconstructions in this region (Karukäpp, 1996, 2004; Boulton *et al.*, 2001; Zelčs and Markots, 2004). A south-east direction in the northern and central part of the Gulf of Riga is dominant, as indicated by till topography (2a, 2b) and the coastline indentation pattern of southern Saaremaa (2b) (Fig. 6). Towards the southern part of gulf the orientation of streamlined features turns slightly southwards, which is proved by rare features in the till topography offshore (5e), but more explicitly by Latvian onshore features just south and south-east of the gulf (Figs. 5 and 6).

Around Pärnu Bay and the Irbe Strait, unlike in the central part of the gulf, north-east–southwesterly oriented linear relief features dominate in the till topography (3a and 3d in Fig. 6). These deviations from the main direction of the Riga ice stream are in good accordance with the mainland data around the gulf (Raukas and Karukäpp, 1979; Karukäpp, 1996, 2004; Zelčs and Markots, 2004). They show that the ice divide zones in Southern Estonia (Sakala Upland) and in the central part of the Kurzeme Peninsula (Fig. 6) locally changed the course of the ice flow. The influence of the Kurzeme ice divide zone can be followed northwards, where it resulted in deviating linear bottom features (3d and 2a) and coastline indentations (3d and 2b) at the southern coast of the Saaremaa Island. The long radial esker in central Saaremaa (5b), however, was formed in a large north-south crevasse, which most likely developed due to an increased tension zone just north of deviating glacier flows (Eltermann, 1993).

The only evidence of ice-marginal formations in the offshore Gulf of Riga occurs just south of the Sõrve Peninsula. A north-east–south-west directed ridge-like form in the bottom topography of the Irbe Strait obviously represents an offshore continuation of the Pandivere–Neva or Palivere ice-marginal zone (1a) (Fig. 6). Our study did not show any evidence that could support the idea of ice-marginal zones located across the eastern or central parts of the Gulf of Riga, as has been shown earlier in some deglaciation reconstructions (e.g. Raukas *et al.*, 1971, 2004; Elterman, 1993; Karukäpp, 1996; Karukäpp *et al.*, 2002).

Age determinations of glacial relief features and/or late-glacial deposits are required for further discussion of glacial dynamics and for chronological reconstruction of the area.

Acknowledgements. This research was financed by Estonian Science Foundation Grants no 4446, 5681 and 6992. Scholarship provided to Arkady Tsyrulnikov by the World Federation of Scientists is gratefully acknowledged. We thank Tom Flodén for his cooperation in marine seismic work. We also appreciate the efforts of Mrs Evelin Lumi in digitizing the bottom topography, the advice of Alar Rosentau in compiling

the digital terrain model and the assistance of Vitaljis Zelčs, who provided us with the glacial maps of Latvia.

REFERENCES

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

ELTERMANN G. (1993) — Mandriliustiku hääbumine Lääne–Eesti saartel. Eesti Loodus, **5/6**: 218–219.

ELTERMANN G., PERENS R., PERENS H. and LEGLUS M. (1993) — Saaremaa kompleksse geoloogilise kaardistamise mõõtkavas 1:50 000 aruanne. Report and maps (in Estonian). Geoloogiakeskus. Tallinn.

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

ESTONIAN MARITIME ADMINISTRATION (2000) — Depth chart 1:50 000 (59°): Gulf of Riga. Island Ruhnu.

ESTONIAN MARITIME ADMINISTRATION (2001*a*) — Depth chart 1:50 000 (59°): Gulf of Riga. Sõrve peninsula to Allirahu Islet.

ESTONIAN MARITIME ADMINISTRATION (2001*b*) — Depth chart 1:50 000 (59°): Gulf of Riga. Ruhnu Island to Kihnu Shoal.

ESTONIAN MARITIME ADMINISTRATION (2001*c*) — Depth chart 1:50 000 (59°): Gulf of Riga. Kõiguste-Kübassaare-Sõmeri.

ESTONIAN MARITIME ADMINISTRATION (2002*a*) — Depth chart 1:50 000 (59°): Irbe Strait. Sõrve peninsula.

ESTONIAN MARITIME ADMINISTRATION (2002*b*) — Depth chart 1:50 000 (59°): Gulf of Riga. Kihnu Shoal to Heinaste (Ainaži).

ESTONIAN MARITIME ADMINISTRATION (2002*c*) — Depth chart 1:50 000 (59°): Gulf of Riga. Kaavi to Kolka cape.

ESTONIAN MARITIME ADMINISTRATION (2002*d*) — Depth chart 1:50 000 (59°): Gulf of Riga. Pärnu-Kihnu-Sõmeri.

JUŠKEVIČS V. and TALPAS A. (1997) — Explanatory note to the map (scale 1:200 000). In: The Map of the Quaternary Deposits of the Gulf of Riga (eds. V. Seglinš and K. Kajak). Geol. Surv. Latvia and Estonia. Riga.

JUŠKEVIČS V., STIEBRINŠ O. and TALPAS A. (1996) — Map of the Quaternary deposits of the Gulf of Riga. Geol. Surv. Latvia Estonia. Riga.

KADASTIK E. and KALM V. (1998) — Lithostratigraphy of Late-Weichselian tills on West-Estonian Islands. Bull. Geol. Soc. Finland, **70** (1–2): 5–17.

KAJAK K. (1999) — Quaternary map of Estonia. Geol. Surv. Estonia. Tallinn.

KAJAK K. and KALA E. (1972) — Otchet o kompleksnoi geologo-gidrogeologicheskoi sjomke masshtaba 1:200 000 jugo-zapadnoi chasti Estonii (list O-34-XVIII). (Report and maps) (in Russian). Geoloogia Valitsus. Tallinn.

KAJAK K. and KALA E. (1973) — Otchet o kompleksnoi geologo-gidrogeologicheskoi sjomke masshtaba 1:200 000 o. Saaremaa (list O-34-XVI, XVII). (Report and maps) (in Russian). Geoloogia Valitsus. Tallinn.

KALM V. (2006) — Pleistocene chronostratigraphy in Estonia, southeastern sector of the Scandinavian glaciation. Quatern. Sc. Rev., **25**: 960–975.

KARUKÄPP R. (1996) — Baer-Babinet low in glacial dynamics. Proc. Estonian Acad. Sc. Geol., **45** (4): 216–224.

KARUKÄPP R. (1997) — Glacial topography. In: Geology and Mineral Resources of Estonia (eds. A. Raukas and A. Teedumäe): 385–387. Inst. Geol. Estonian Acad. Publ. Tallinn.

KARUKÄPP R. (2004) — Late-Glacial ice streams of the southeastern sector of the Scandinavian ice sheet and the asymmetry of its landforms. Baltica, **17** (1): 41–48.

KARUKÄPP R., ELTERMANN G. and RAUKAS A. (2002) — Liustikutekkelise pinnamoe kujunemine. In: Saaremaa (eds. H. Kään, H. Mardiste, L. Nelis and O. Pesti): 52–56. Estonian Encyclopedia Publishers. Tallinn.

LAASI A. (1937) — Põhja-Pärnumaa otsmoreenist. Eesti Loodus, **2**: 67–71.

NOORMETS R. and FLODÉN T. (2002) — Glacial deposits and ice-sheet dynamics in the north-central Baltic Sea during the last deglaciation. Boreas, **31**: 362–377.

ORVIKU K. (1974) — Estonian Seacoasts (in Russian with English summary). Acad. Sc. Estonian SSR. Tallinn.

RATTAS M. and KALM V. (2004) — Glaciotectonic deformation patterns in Estonia. Geol. Quart., **48** (1): 15–22.

RAUKAS A. (1977) — Ice-marginal formations and the main regularities of the deglaciation in Estonia. Z. Geomorph. N.F: 68–78.

RAUKAS A. (1986) — Deglaciation of the Gulf of Finland and adjoining areas. Bull. Geol. Soc. Finland, **58** (2): 21–33.

RAUKAS A. (1992) — Ice marginal formations of the Palivere zone in the eastern Baltic. Sveriges Geologiska Undersökning, **81**: 277–284.

RAUKAS A. (1997) — Evolution of the Baltic Sea. In: Geology and mineral resources of Estonia (eds. A. Raukas and A. Teedumäe): 263–268. Estonian Acad. Publ. Tallinn.

RAUKAS A. and KARUKÄPP R. (1979) — Structure and formation of accumulative insular heights in Estonia (in Estonian with English summary). In: Eesti NSV saarkõrgustike ja järvenõgude kujunemine (ed. A. Raukas): 9–28. Valgus. Tallinn.

RAUKAS A., KALM V., KARUKÄPP K. and RATTAS M. (2004) — Pleistocene glaciations in Estonia. In: Quaternary Glaciations — Extent and Chronology (eds. J. Ehlers and P. L. Gibbard): 83–91. New York. Elsevier.

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

RINTERKNECHT V. R., CLARK P. U., RAISBECK G. M., YIOU F., BITINAS A., BROOK E. J., MARKS L., ZELČS V., LUNKKA J.-P., PAVLOVSKAYA I. E., PIOTROWSKI J. A. and RAUKAS A. (2006) — The Last Deglaciation of the Southeastern Sector of the Scandinavian Ice Sheet. Science, **311**: 1449–1452.

SEIFERT T., TAUBER F. and KAYSER B. (2001) — A high resolution spherical grid topography of the Baltic Sea — 2nd edition. Baltic Sea Science Congress, Stockholm 25–29 November, 2001. Poster 147, www.io-warnemuende.de/iowtopo.

TAMMEKANN A. (1940) — The Baltic Glint. A Geomorphological Study. Part 1. Morphography of the Glint. Eesti Loodustead., **11** (3): 1–103.

VÄÄRSI A. and KAJAK K. (1969) — Otchet Juzhno-Estonskogo otrjada o kompleksnoi geologo-gidrogeologicheskoi sjomke masshtaba 1:200 000 jugo-zapadnoi Chasti Estonii (list O-35-XIII)(in Russian). (Report and maps).

ZELČS V. and DREIMANIS A. (1997) — Morphology, internal structure and genesis of the Burtnieks drumlin field, Northern Vidzeme, Latvia. Sediment. Geol., **111**: 73–90.

ZELČS V. and DZELTZĪTIS J. (2003) — Glaciotectonic map of Latvia. The XVI INQUA Congress, Reno, Nevada USA, July 23–30, 2003. Paper 39–4,http://www.lu.lv/fakultates/gzzf/geografija/geomorfologija/publikacijas-inqua16.html

ZELČS V. and MARKOTS A. (2004) — Deglaciation History of Latvia. In: Quaternary Glaciations — Extent and Chronology (eds. J. Ehlers and P. L. Gibbard): 226–243. Elsevier.

ZELČS V., MARKOTS A. and DZELTZĪTIS J. (2003) — Map of Late Weichselian directional ice-flow features of Latvia. The XVI INQUA Congress, Reno, Nevada USA, July 23–30, 2003. Paper 24–12, http://www.lu.lv/fakultates/gzzf/geografija/geomorfologija/publikacijas-inqua16.html