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Complex seismo-acoustic and lithological study of the Lateglacial and postglacial sediments northern Gulf of Riga, eastern branch of the central Baltic Sea

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Department of Geology, Institute of Ecology and Earth Sciences, Faculty of Science and Technology, University of Tartu, Estonia.

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LIST OF ORIGINAL PUBLICATIONS

This thesis is based on the following published Papers, which are referred to in the text by their Roman numerals. The Papers are reprinted by kind permission of the publishers.

I Kalm, V., **Tsyrulnikov, A.**, Hang, T., Tuuling, I. and Flodén, T. 2006: Late Weichselian and Holocene sediments and their acoustic signatures in the northeastern part of the Gulf of Riga. Baltica 19, 51–57.

II **Tsyrulnikov, A.**, Tuuling, I., Kalm, V., Hang, T. and Flodén, T. 2012: Late Weichselian and Holocene seismostratigraphy and depositional history of the Gulf of Riga, NE Baltic Sea. Boreas 41, 673–689.

III **Tsyrulnikov, A.**, Tuuling, I. and Hang, T. 2008: Streamlined topographical features on and offshore the Gulf of Riga as evidence of Late Weichselian glacial dynamics. Geological Quarterly 52, 81–89.

Author's contribution

Paper I: As a person who worked out very first seismo-acoustic correlation scheme for the Gulf of Riga (based on 1995 profiling), the author was one of the key persons in planning/suggesting the sites for additional seismic profiling and sediment core samplings. He took part in the marine geological expedition on the R/V Fyrbyggaren 2004 to the Gulf of Riga, was responsible for the macroscopic description and digital photographing the cores, as well as interpretation of the seismic data and correlation of the seismo-acoustic data with the lithostratigraphic descriptions. He took actively part in writing the paper and designing/drawing the figures and preparing manuscript for printing.

Paper II: As this paper is based largely on the same material as the Paper I, the description given above is relevant also for the Paper II. Author described furthermore all additional cores and based on received new information he also worked out a new (advanced) lithostratigraphic and seismo-acoustic schemes for the northern Gulf of Riga. He was one of the key persons in writing of this paper and all the figures presented in it are designed, prepared and drawn by him. He also prepared this paper for printing.

Paper III: The author took actively part in planning of this paper, as well as in compiling, collecting and analysing of various cartographical (geological, bathymetrical and topographical maps) material and seismic data. He took actively part in discussing the subject of this paper, wrote preliminary manuscript and prepared all the figures presented in it. He also prepared this paper for printing.

1. INTRODUCTION

The Gulf of Riga (GR), shared by Estonia and Latvia, is part of a large epicontinental basin, the Baltic Sea, which separates Scandinavia from Central and Eastern Europe (Fig. 1). As an easterly branch of the central Baltic Sea (northern Baltic Proper), the GR represents a NW–SE elongated, up to 170 km long and 130 km wide semi-closed embayment-depression between the West Estonian Archipelago and the Latvian mainland. It has a surface area of about 16 300 km^2 and an average water depth of 26 m.

The Kurzeme Peninsula and West Estonian Archipelago separate the GR from the Baltic Sea proper. The gulf is connected to the sea via a system of shallow and narrow straits in the north and the Irbe Strait in the west (Fig. 1). A submerged ridge-like continuation of the Sõrve Peninsula forms its natural western boundary. In the northeast the gulf is joined by Pärnu Bay.

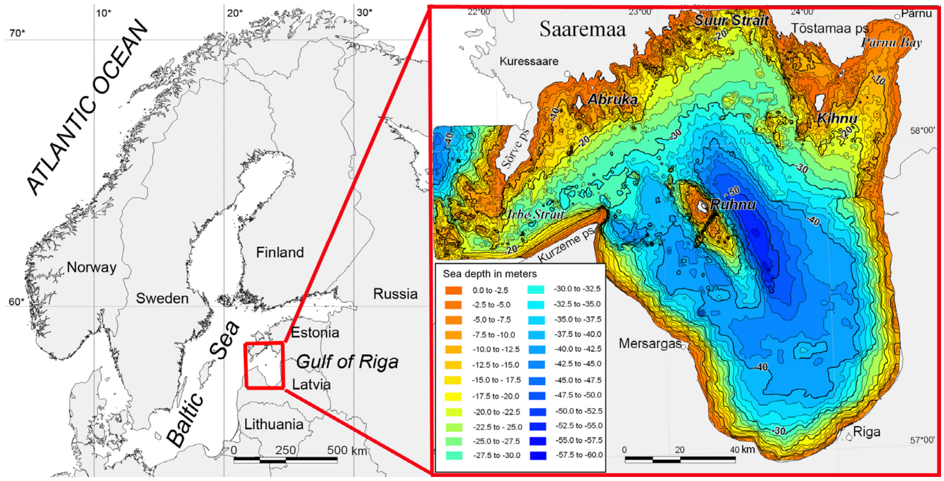

Figure 1. Location of the study area with the bathymetric map of the Gulf of Riga.

The Baltic Sea depression is an outcome of combined geological processes – tectonic, glacio-isostatic and erosional (Harff et al. 2011; Tuuling et al. 2011). Besides extensive pre-glacial river erosion in the Cenozoic, which is best expressed in a NE–SW oriented cuesta relief in the central Baltic Sea, features of the Pleistocene glacial erosion are evident in many areas below (e.g. Tuuling and Flodén 2001, 2011; Noormets and Flodén 2002a, b; Tuuling et al. 2011) as well as around the Baltic Sea (e.g. Tavast and Raukas 1982; Isachenkov 1988; Karukäpp 1997a, b; Boulton et al. 2001; Zelčs et al. 2003). The bathymetry of the GR (Fig. 1) clearly reflects a complex pattern of glacial relief features (Tsyrulnikov et al. 2008), evidencing that the GR has largely been shaped by the erosion of the ice streams.

The outlines of the recent topography east of the central Baltic Sea were formed during the Late Weichselian event of the European glaciation by the Baltic, Riga and Peipsi (Lake Peipsi) ice streams (Miidel et al. 2001; Zelčs and Markots 2004; Kalm 2012). The GR was covered, and thus the formation of its depression and bottom topography with various erosional and accumulative glacial relief features was generally controlled by the Riga ice stream. As a result, the evidences of the last active stage of this ice stream are largely imprinted into the time-transgressive deglaciation pattern of the GR. Due to the central position of the Riga ice stream, the GR furthermore serves as a key area in connecting and generalizing abundant mainland deglaciation data available for the Peipsi and Baltic ice streams, respectively east and west of the gulf.

Concomitantly with the melting and recession of the glaciers, a large ice lake as an embryo of the Baltic Sea, which started to evolve in front of the receding Scandinavian ice sheet, inundated gradually also the GR area. Since then, gouged by glacial erosion, the depression of the GR has been a depositional area where, unlike in the areas surrounding the gulf, a nearly continuous sequence of Lateglacial and postglacial sediments has settled simultaneously with the glacio-isostatic gradual rise of the area (Juškevičs and Talpas 1997; Kalm et al. 2006; Tsyrulnikov et al. 2012). Thus, a steady transition from the Lateglacial to postglacial periods with an almost continuous sedimentation in the depression of the GR offers also a good opportunity for restoring the post-deglaciation history, i.e. the development of the Baltic Sea in this region.

The concepts of this study have branched from a cooperative Swedish–Estonian marine geological project launched in the early 1990s, to explore and correlate the Palaeozoic sequence across the central Baltic Sea between Estonia and Sweden by means of extensive continuous seismic reflection profiling (see Tuuling and Flodén 2009). A few preliminary seismic lines to study the Palaeozoic bedrock layers in the GR were shot with a low frequency transmitter (air gun) already in 1991. Alongside with the air gun, a mud-penetrator sounder for more detailed recording of the Quaternary layers was introduced in 1995 when the northern (Estonian) part of the GR was covered with a regular set of seismic lines. On the basis of these data, an additional expedition for shooting auxiliary seismic lines and sampling of the sea bottom sediments was planned in 2004 to improve the preliminary seismostratigraphic scheme (Tsyrulnikov et al. 2004) and to link it to a lithological section generalized based on the coring data from the northern GR.

The interpretation of seismic data together with seafloor morphology provoked a need for a more detailed bathymetric study of the GR to discover and map glacier-derived streamlined relief features within the gulf. In combination with analogous data from the adjoining mainland areas, a far more detailed and complete data set than before became available for estimating the possible glacial dynamics in and around the GR.

Considering the subject of our study, the methods used and available data, the aims of this thesis can be formulated as follows:

1. By combining the seismic and coring data, to work out generalized lithological column and corresponding correlative lithostratigraphic and seismostratigraphic schemes for the Late Weichselian and Holocene (Lateglacial and postglacial) sediments of the northern GR.
2. On the basis of these schemes, to reconstruct the Lateglacial and postglacial depositional history of the GR as a part of the Baltic Sea.
3. To study the distribution and orientation of the streamlined topographical features expressed in the seafloor bathymetry (by means of the compiled 3D elevation model and bathymetric map) and buried under younger sediments (based on seismic profiling data) of the GR.
4. To investigate all available glacial dynamics revealing geomorphological/ geological features around the GR (by analysing already published data, as well as recently obtained detailed cartographic material).
5. By combining the mainland and offshore data, to reconstruct the ice flow dynamics of the Late Weichselian glaciation for the GR and adjoining land areas.

2. HISTORICAL BACKGROUND

Compared to the surrounding mainland areas, where versatile geological studies on the Palaeozoic bedrock as well as on the Quaternary sequence have been performed already since the first half of the 19th century (e.g. Engelhardt and Ulprecht 1830; Eichwald 1840), the period of marine geological studies within the GR is rather short. Preliminary data on the bedrock surface and Quaternary deposits within the GR were obtained during regional mapping in the 1960s. However, apart from one exception from the southern part of the gulf (Ulst et al. 1963), these data are still unpublished (Seredenko et al. 1997). The first sporadic data on the distribution of Lateglacial and Holocene deposits in the northern GR are based on the samplings performed along its coastline, both nearest onshore and offshore areas (Kessel 1976, 1980; Lutt 1987).

A more comprehensive and systematic marine geological study of the GR was commenced in connection with the geological mapping in the late 1980s and early 1990s. On the Latvian side, in addition to a regular set of seismo-acoustic profiles of different frequency ranges (75–125 Hz, 250–400 Hz, 400–600 Hz, 600–800 Hz and 10 kHz) the Quaternary sequence was sampled by vibrocoring and drilling in several places. The results of these studies were summarized in a series of joint maps (scale 1:200 000) of the GR (Bedrock geology, Quaternary sediments, Bottom sediments and Landscape-ecological) with explanatory notes, released in 1996 and 1997 (Juškevičs et al. 1996; Stiebrinš and Väling 1996; Baraškovs et al. 1997; Zaicevs et al. 1997). On the basis of the performed corings, the first lithostratigraphical sections of the GR were published, describing the Lateglacial and postglacial sequences in the central and southern parts of the gulf (Kalnina et al. 1999; Kalnina 2001).

At the same time, a large amount of seismic data was collected by a Swedish–Estonian team from the northern part of the GR in 1995. Although these profiles were used by the Estonian–Latvian mapping team in compiling the aforementioned geological maps (Juškevičs et al. 1996; Zaicevs et al. 1997), their more detailed interpretation and analysis along with new complementary coring and seismo-acoustic data from 2004 constitute the pivotal part of the current thesis.

3. TECTONIC SETTING

The GR rests in the northwestern part of the East European Craton, a bit south from the outstanding structural boundary of erosional heritage that separates East European Platform and Fennoscandian (Baltic) Shield areas, lying respectively south and north of this boundary. Consolidation of the continental crust, i.e. formation of the crystalline basement in this region, occurred largely during the Svecofennian Orogeny 1.93–1.80 Ga ago (Bogdanova et al. 2008; Kirs et al. 2009). The crystalline basement directly below and around the gulf consists of an extensive Estonian–Latvian Granulite Belt (1.84–1.78 Ga) that in the western half of the GR is intruded by a large Riga Rapakivi Pluton (1.59–1.54 Ga) (Kirs et al. 2009).

The platform sedimentary cover in Estonia and Latvia is made up of Early Palaeozoic rocks, whereas the erosional boundary between the Silurian calcareous and Devonian terrigenous rocks, outcropping respectively in the northern and the southern half of the GR, traverses the gulf (Zaicevs et al. 1997). The sedimentary bedrock layers on the southern slope of the Baltic Shield (including also the GR area) are concomitant with the upper surface of the Precambrian crystalline basement sloping about 10–15 minutes towards the south, forming thus a widespread homocline.

Although the Baltic region with a very old and rigid continental crust represents a tectonically rather stable and slightly deformed area, deep crustal-derived structures may also have played an important role in the formation of the GR depression. According to various regional geological and tectonic maps and descriptions (e.g. Grigelis et al. 1979; Koistinen 1996; Puura and Vaher 1997; Seredenko et al. 1997), several differently oriented deep crustal faulting zones that are also expressed in the platform sedimentary cover criss-cross distinctly the GR area. In addition, the boundary between the Estonian–Latvian Granulite Belt and Riga Rapakivi Pluton (Ruhnu–Ragaciems fault in Fig. 2), bending from NW–SE to NE–SW and continuing as the Jelgava deep fault zone on the mainland of Latvia, the GR is traversed also by the regional NE–SW oriented Talsi–Pärnu–Tapa fault zone (Puura and Vaher 1997; Seredenko et al. 1997). A NW–SE oriented fault (Hilleste) enters the gulf area from the north, a little northeast of Saaremaa (Fig. 2).

It is obvious that the fracturing/deformation of the sedimentary rocks diminished their resistance to erosion and determined thus pathways and movement of glacier lobes. The deepest erosion occurred along the fracture zones oriented in the prevailing (N–S to NW–SE) directions of the advancing glaciers on the southern slope of the Baltic Shield. Some of the older tectonic faults may have been reactivated under the pressure of thick and massive ice cover, which furthermore boosted glacial erosion (Juškevičs and Talpas 1997; Seredenko et al. 1997).

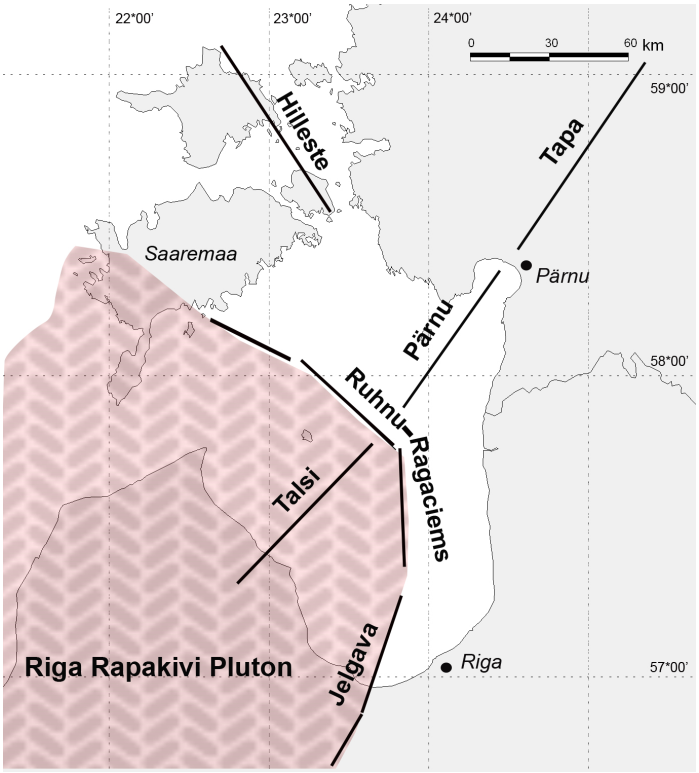

Figure 2. Main tectonic features predetermining the location and shape of the Gulf of Riga depression.

Thus, the NW–SE oriented central depression of the GR follows distinctly the Ruhnu–Ragaciems fault zone along the boundary of the Riga Rapakivi Pluton, being thus apparently largely gouged and shaped by the erosion of the Riga ice stream (Juškevičs and Talpas 1997; Tsyrulnikov et al. 2008). Pärnu Bay in the northeastern part of the gulf, intruding deeply into land, follows the NE–SW oriented Talsi–Pärnu–Tapa fracture zone. The fragments of buried valleys discovered within the gulf, which are deeply cut into the bedrock and largely also follow the aforementioned fracture zones, reflect evidently the preferred preglacial river courses in this area (Juškevičs and Talpas 1997).

4. MATERIAL AND METHODS

As mentioned before, this study was largely initiated, and thus based on the original seismo-acoustic and coring data of the Lateglacial and postglacial sediments collected during the Swedish–Estonian mutual expeditions to the northern GR in the summers of 1995 and 2004. For generalizing deglaciation pattern of the GR area, dynamics of the Riga ice stream in particular, glacier-derived streamlined topographical features were studied in and around the depression of the GR by compiling, interpreting, combining and analyzing topographical, geological and novel seismo-acoustic data.

4.1. Continuous seismo-acoustic profiling

In 1995, a continuous seismic reflection profiling equipment (air-gun transmitter with an eel-like 50 element hydrophone receiver) was run onboard R/V Strombus simultaneously with a low-frequency echo sounder (mud-penetrator) to investigate the geology of the Palaeozoic bedrock and Quaternary sequences of the Estonian part of the GR. In all, about 1000 km of profiles were shot to perform a regular set, mainly of N–S seismic/acoustic lines 5 km apart (Fig. 3).

Based on the acoustic signature variations in the 4 KHz echo sounder profiles, six preliminary units were distinguished in the Quaternary sediments of this area (Tsyrulnikov et al. 2004). For further seismo-acoustic subdivision and correlation of the Lateglacial and postglacial sediments this initial set was complemented with eight additional, E–W and NW–SE oriented profiles (over 600 km) onboard R/V Fyrbyggaren in 2004 (Fig. 3).

The pulse of a low-frequency echo sounder at 4 KHz easily penetrated the Lateglacial and postglacial lacustrine and marine sediments but was largely reflected from the upper surface of the underlying glacial till. The presence of a ubiquitous till layer between the bedrock surface and Lateglacial sediments was followed in the seismic recordings at the frequency range of 250–500 Hz. A vertical resolution in the 4 kHz profiles, which with a time-sweep of 0.5 s were displayed either on an EPC precision graphic recorder (profiles from 1995) or on the PC display using the MeriData software SVIEW (profiles from 2004), was about 5 cm. In sediment thickness calculations, commonly used seismic wave velocity for the Lateglacial and postglacial sediments in the Baltic Sea of 1 500 m/s (Flodén 1980; Noormets and Flodén 2002a) was applied.

Occasionally, seismo-acoustic profiles were used to follow extension of partially and entirely buried relief features along the till surface in the northern part of the GR and thus verify their glacial origin.

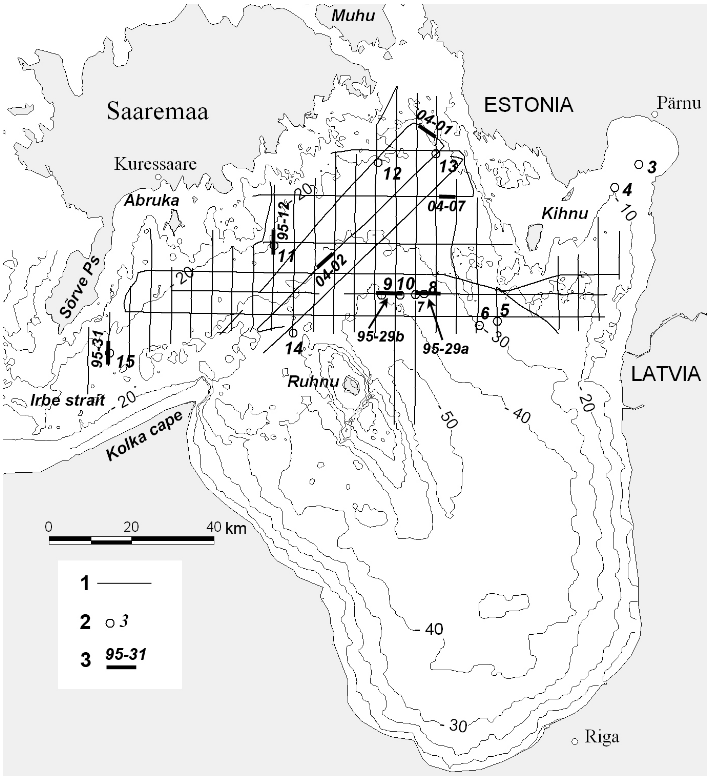

Figure 3. Map of marine geological data from 1995 and 2004 expeditions used in this study: (1) seismo-acoustic profiles, (2) sampling cores and (3) sections of profiles displayed in Figs 6–11 and 13.

4.2. Sampling of Lateglacial and postglacial sediments

To support the correlation between the seismic data and Lateglacial/postglacial sediments, thirteen cores were taken by means of a piston (Kullenberg) corer (Fig. 3, Table 1). The coring sites were preliminarily located and finally selected based respectively on the profiles shot in 1995 and 2004, according to the following criteria: i) all acoustically different sedimentary units discussed in Tsyrulnikov et al. (2004) were represented in the cores, and ii) boundaries between these units were penetrable using a 6 m long piston corer.

All the cores were subjected to detailed macroscopic description of textures, lamination, character of lamination boundaries, colour (Munsell scale), litho-stratigraphic interpretation and digital photography. On the basis of the description and comparison of all sedimentary cores, Lithostratigraphical column of Lateglacial and postglacial sediments was generalized for the northern GR.

Table 1. Coordinates, water depth and recovery of the sampling cores. (Paper II, Table 1; p. 675).

Core No	Latitude (WGS84)	Longitude (WGS84)	Water depth (m)	Recovery (m)
3	58°16.99'	24°25.08'	8	2.20
4	58°13.99'	24°19.07'	10	2.98
5	57°56.59'	23°50.24'	28	5.20
6	57°56.06'	23°45.80'	30	5.11
7	57°59.91'	23°21.75'	32	4.85
8	57°59.95'	23°26.31'	32	2.80
9	58°00.02'	23°30.07'	40	5.19
10	58°00.11'	23°32.19'	38	5.33
11	58°06.17'	22°55.14'	22	4.87
12	58°17.16'	23°20.54'	23	3.42
13	58°18.38'	23°34.92'	21	3.69
14	57°54.84'	23°00.20'	34	3.27
15	57°51.76'	22°15.34'	22	3.69

4.3. Correlation of the seismo-acoustic and coring data

The striking and widespread changes in the seismic signatures, caused by variations in the acoustic impedance, reveal foremost the lithological, and thus the sedimentary environment (influx of different terrigenous components, salinity, redox potential, content of organic matter etc.) changes throughout the Lateglacial and postglacial history of the GR. Hence, by juxtaposing and comparing the lithological descriptions with the nearby acoustic recordings and making use of geological-palaeogeographical data from the Estonian mainland (Kalm and Kadastik 2001; Veski et al. 2005; Kalm 2006), offshore GR (Kiipli et al. 1993; Juškevičs and Talpas 1997; Kalnina et al. 1999; Kalnina 2001) and the central Baltic Sea (Björck 1999; Winterhalter 2001; Noormets and Flodén 2002a, b), the seismo-lithostratigraphic subdivision of the Lateglacial and postglacial sediments of the GR was worked out. Based on that, the thickness values of distinguished lithostratigraphic units were corrected and estimated between the cores.

4.4. Allostratigraphic subdivision

Both, the lithological descriptions of different cores and the seismo-lithostratigrtaphic units between the cores reveal a lithologically variable complex of the Lateglacial and postglacial sediments in the northern GR, where number and thicknesses of the distinguished lithological/acoustic units laterally can change considerably. This kind of small-scale lithological variability characterizes the entire Baltic Sea and hampers considerably correlation of the coeval sediments and their units between its different regions.

To mitigate this problem ubiquitous discontinuity surfaces, that were distinctive both in the lithological sections and seismic recordings, were considered as allostratigraphical boundaries reflecting significant changes in the depositional environment of the Lateglacial and postglacial history of the GR and separating the first-order allounits traceable at the regional scale.

4.5. Bathymetric data

In order to study and analyze glacier derived streamlined relief features, a detailed bathymetric map (Fig. 1) and digital terrain model (DTM) were compiled for the GR. The original data set for the Estonian part of the gulf was assembled in digitizing the depth values of eight marine charts in scale 1:50 000 (Estonian... 2000, 2001a–c, 2002a–d) (Lumi 2007). 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 in every 2 km was used.

All assembled data were processed with the GIS software package Vertical Mapper within MapInfo Professional to interpolate a regular depth points grid (200 x 200 m) for the entire gulf. Based on that grid the bathymetric map (Fig. 1) and digital terrain model (DTM) of the GR were compiled using the same software. Both of them reveal bathymetry of the GR in the highest available details and were therefore used as the main sources for describing the general seafloor morphology and estimating the orientation of elongated glacial relief features in the offshore area.

4.6. Topographical data

The Estonian mainland relief around the GR (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 isobasis in 5 m interval. Additionally, the shoreline configuration, above all the orientation of alternating bays and capes was analysed to get further indications about the possible pathways of moving ice streams.

4.7. Data from geological maps

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

Similarly to the offshore area, the distribution and pattern geometry of the outcropping glacial and postglacial sediments were analysed around the GR onshore Estonia using the Quaternary and Geomorphological maps of Estonia in scales 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 onshore area around the gulf.

5. RESULTS AND DISCUSSION

This chapter recapitulates the results and discussions on the seismo-acoustic and lithological study of the Late Weichselian and Holocene sediments and streamlined glacial relief features performed in and around the GR for this thesis. All this data is in more detail handled in three published papers (Kalm et al. 2006; Tsyrulnikov et al. 2008, 2012).

5.1. Lithostratigraphy of the Lateglacial and postglacial sediments

Preliminary lithostratigraphical section that was based on five sediment cores from the northeastern GR is discussed in Paper I (Kalm et al. 2006). A more advanced column generalizing the whole lithological section of the Lateglacial to Holocene sediments for the entire Estonian (northern) part of the GR (Fig. 4) is based on all available 13 sediment cores and is presented in Paper II (Tsyrulnikov et al. 2012).

The vertical extent, i.e. the total thickness of the section (Fig. 4), was drawn by combining all available thickness data of every sediment layer in different cores. However, according to the low-frequency echo sounder recordings, the thickness values of the sediment layers between the cores can outnumber those given in the generalized section (Fig. 4).

In total, nine major sediment layers (layers A–I, Fig. 4) were distinguished in the Late Weichselian to Holocene sequence in the northern GR.

Layer A (thickness >91 cm) is the lowermost sediment layer, penetrated partially (91 cm) in core 8 (Fig. 3; layers A1 and A2, Fig. 5A). It consists of a massive, matrix supported, plastic, dark grey clayey diamicton with a few pebbles and pieces of gravel. In the upper half, the diamicton gets gradually sandier with a 5 cm thick gravelly zone. The lower, clayey part of the layer (Fig. 4; A1, Fig. 5A) is interpreted to represent deposition from the last grounded glacier, corresponding to the Valdemarpils/Sakala or the following Pandivere–Neva oscillation. The sandy-gravelly till in the upper part (Fig. 4; A2, Fig. 5A) reflects the beginning of deglaciation and drainage of some meltwater under the glacier.

Layer B (60 cm) was penetrated in core 8. It is made up of four distinctive sublayers, which upwards in the section appear as: (B1) gravelly diamicton (till) (18 cm); (B2) sandy diamicton (till) (11 cm); (B3) package of few thin (0.4–1.2 cm) laminas/layers of brownish massive clay and grey clayey-sandy diamicton (9 cm); (B4) brown massive clay (22 cm) (Fig. 4; B1–B4, Fig. 5A). The sandy and gravelly tills (B1 and B2) are interpreted to reflect the deglaciation period of the last ice cover. Alternating layers of clayey-sandy diamicton and massive clays (B3) reflect gradual transition to ice-free bottom sedimentation. Subaqueous clayey sediments (B4) reflect the end of the ice decoupling period.

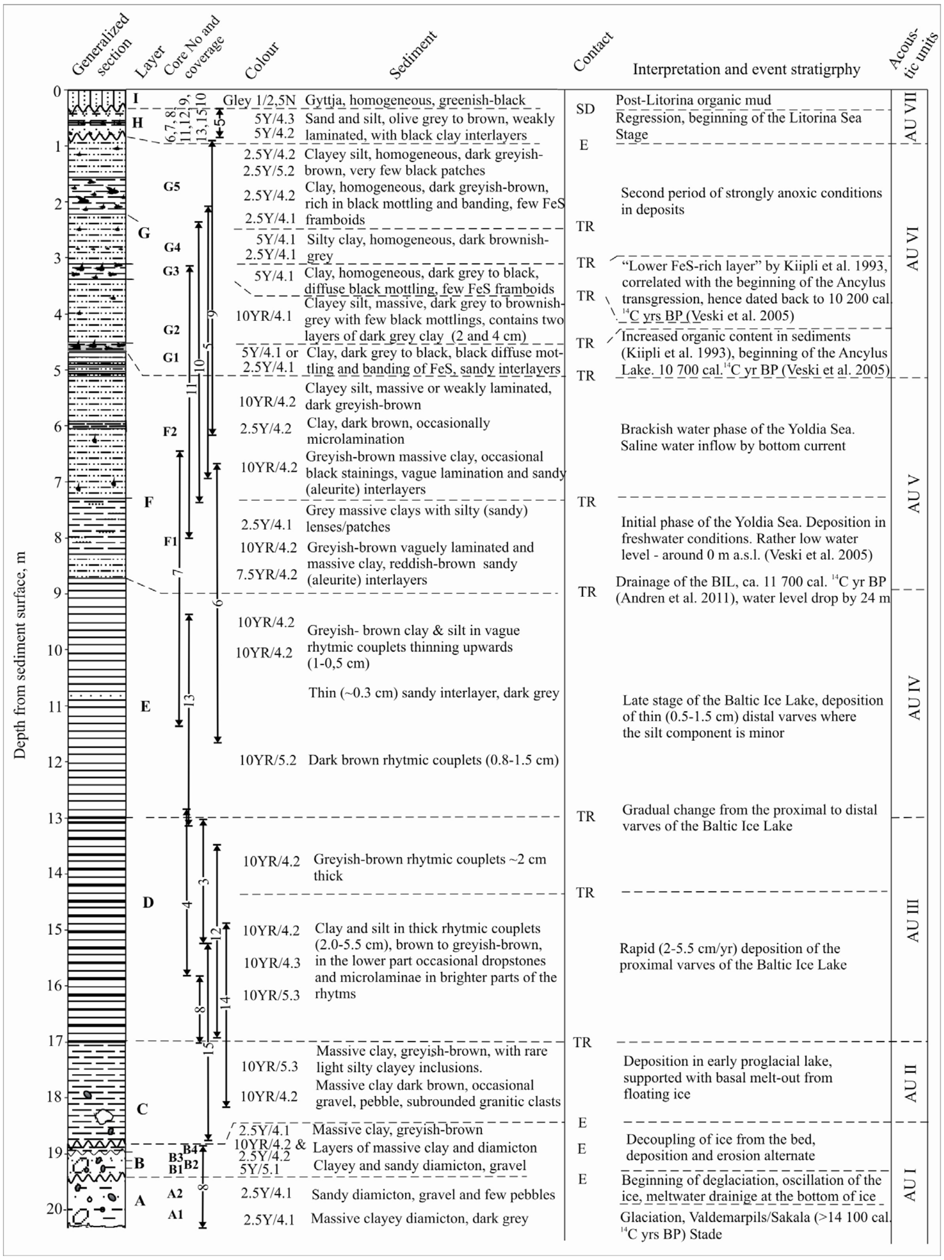

Figure 4. Generalized section of the Late Weichselian and Holocene deposits in the northern part of the Gulf of Riga. TR, E and SD = transitional, erosional and sharp discontinuity types of contact, respectively. For description of acoustic units see Table 2. (Paper II, Figure 2; p. 676).

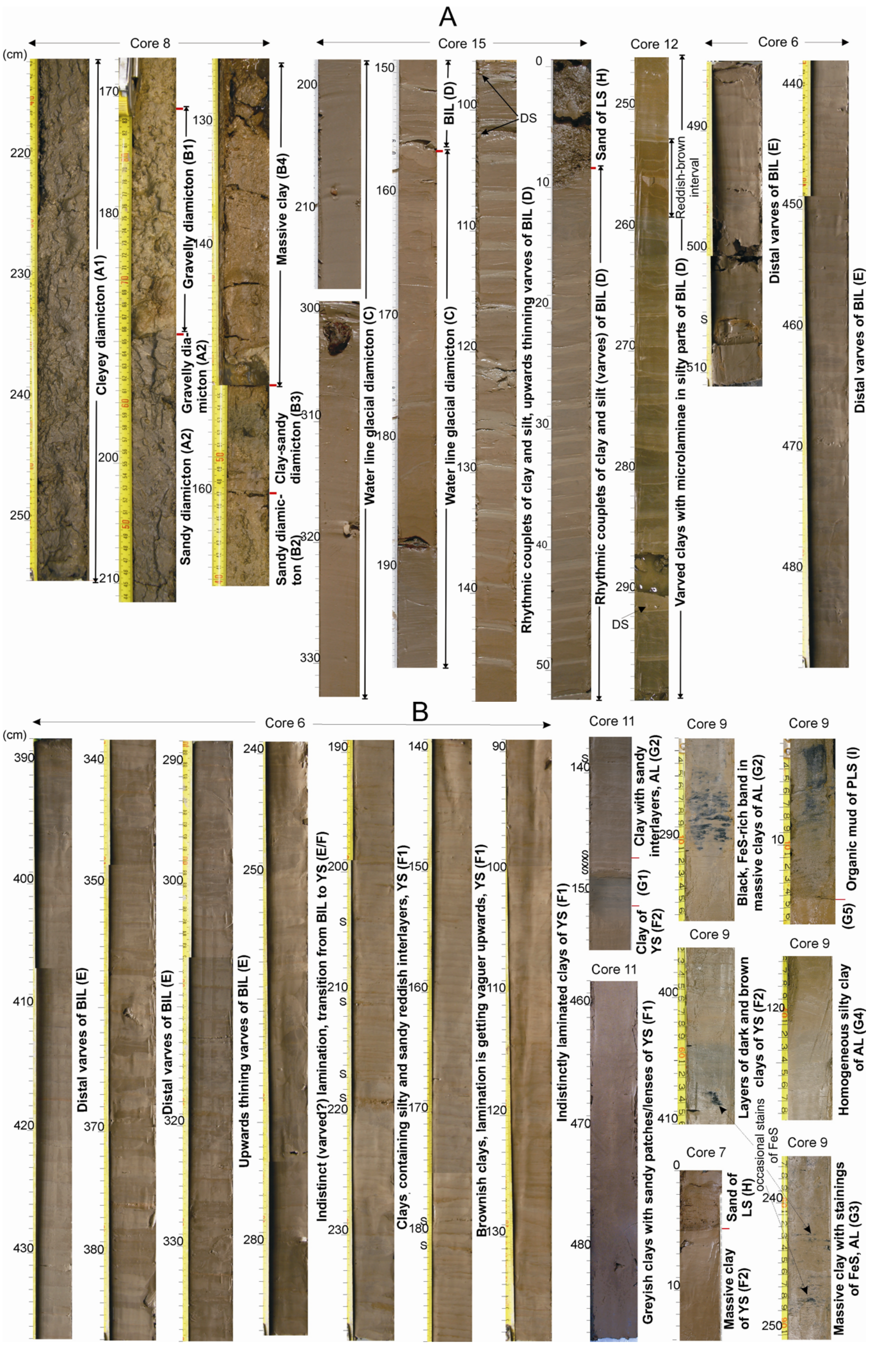

Figure 5A, B. Photographs of the most characteristic lithological units (layers A–I) and their stratigraphic interpretation (BIL = Baltic Ice Lake; YS = Yoldia Sea; AL = Ancylus Lake; LS = Litorina Sea; PLS = post-Litorina Sea) and some lithological features (S = sandy interlayer; DS = dropstone) described in various cores and discussed in the text. (Paper II, Figure 3; p. 677).

The clays in sublayer B4 (Fig. 5A) are rather similar to the clayey matrix described earlier onshore (Kalm and Kadastik 2001) in the waterlain glacial diamicton (WGD) but they contain no WGD-distinctive gravelly particles. Therefore we do not exclude that sublayer B4 might have been formed simultaneously with the overlying WGD layer (C), however at a far greater distance from the ice margin.

Layer C (>177 cm) was partially sampled only in two cores 14 (117 cm) and 15 (177 cm), in the western part of the gulf (Figs 3, 4). It is made up of brown, up to dark brown massive clay with dispersed silt (core 14) that may contain rare gravel grains and half-rounded granitic clasts (core 15, Fig. 5A). Very similar sediments were earlier distinguished as a WGD unit on and near-shore the nearby islands of Saaremaa and Hiiumaa (Kalm and Kadastik 2001). Thus, unit C is interpreted as the WGD, i.e. it consists of sediments deposited in subaqueous conditions, mostly through the active and continuous basal melt-out from the floating ice.

Layer D (>400 cm) was sampled in cores 3 (220 cm), 4 (298 cm), 8 (123 cm), 12 (330 cm), 14 (181 cm) and 15 (182 cm) (Figs 3, 4). It is made up of alternating couplets of silty and clayey layers forming annual varves. The colour of the sediments varies from grey to brown (Fig. 5A, B). Distinctive brownish intervals occasionally occur in some cores (e.g. core 12, Fig. 5A). Varves are gradually thinning upwards: from 5.5 cm thick rhythmic couplets of distinct clay (3–5 cm) and silt (0.5–2.5 cm) layers in the lower part to only 2 cm thick couplets in the upper part of layer D (Fig. 4; cores 12 and 15, Fig. 5A). Occasional microlaminae within silty part of the varves were described in the basal part of this layer (core 12, Fig. 5A). The coarse-grained material found sporadically in the lower part of layer D (core 15, Fig. 5A) was probably rafted by ice ('drop-stones'). Layer D represents a typical seasonal/rhythmic sequence of proximal varves of the BIL.

Layer E (>400 cm) was sampled in cores 6 (289 cm), 7 (250 cm) and 13 (369 cm). It is made up of grayish-brown clays including less than 2 cm thick vague varves with negligible silty layers (core 6, Fig. 5A, B). The entire layer E represents annual varves that were subsequently deposited in a more distal position, gradually continuing the rhythmic sequence of the BIL.

Layer F (>400 cm) was sampled in cores 5 (210 cm), 6 (222 cm), 7 (237 cm), 9 (136 cm), 10 (276 cm) and 11 (336 cm) (Figs 3, 4). It is made up of greyish-brown massive or vaguely laminated clay with reddish-brown silty and sandy interlayers (0.1–1 cm), which are particularly distinct and high in numbers in the lower part of layer (F1, Fig. 4). The upper, vaguely laminated part (F2) contains rare black stripes or stains of Fe-monosulphide (FeS) (core 9, Fig. 5B). Exceptionally, in core 11 (about 25 m b.s.l., Fig. 3) F1 appears as a massive layer of clay with sandy/silty lenses/patches (core 11, Fig. 5B).

The occurrence of a larger number of reddish-brown silty-sandy interlayers at the base of the layer F, i.e. at its contact with layer E (core 6, Fig. 5B), obviously marks the lowering of the water level associated with the basin drainage, indicating the end of the BIL stage (ca. 11 700 cal. ^{14}C a BP according to Andrén et al. 2011). Thus, the sandy-clayey lower and the vaguely laminated FeS-rich upper parts of layer F, i.e. the layers F1 and F2, probably indicate the freshwater and the brackish-water stages of the Yoldia Sea, respectively (Fig. 4).

Layer G (>370 cm) was penetrated in cores 5 (260 cm), 9 (369 cm), 10 (225 cm) and 11 (151 cm) (Figs 3, 4). It consists of grey to greyish-brown massive silty clays, often with distinct intervals of black, irregular bands and stains of FeS. On the basis of the latter intervals layer G can be occasionally, in the deeper part of the gulf, divided into five distinct sublayers G1–G5 (Fig. 4; core 9 in Fig. 5B). In most sediment cores, however, these intervals become unclear, as the dark bands and stains of FeS are less numerous and scattered irregularly all over layer G. Nevertheless, the striking interval of dark FeS-rich clay (G1 in core 11, Fig. 5B) at the base of layer G (Fig. 4) is distinguishable everywhere. The occasional intervals with bands and stains of FeS within postglacial lacustrine sediments are typical features indicating deposits of the Ancylus Lake stage (Kiipli et al. 1993; Winterhalter 2001; Andrén et al. 2011).

Layer H can reach over 50 cm in thickness. It occurs as the uppermost thin sediment unit in cores 6 (10 cm), 7 (5 cm), 8 (5 cm), 11 (3 cm), 12 (2 cm), 13 (2 cm) and 15 (10 cm) (Figs 3, 4). Exceptionally, in core 5, slightly south of Kihnu Island (Fig. 3), it is about 50 cm thick. Layer H is represented by olive grey to brown sand and silt with a black FeS-rich interlayer of clay (2–4 cm) in its middle part (Fig. 4). Sediment unit H overlies discordantly the older units; in our case the BIL in cores 8, 12 and 15 (Fig. 5A), the Yoldia Sea in cores 7 (Fig. 5B) and 13 or Ancylus Lake in cores 5 and 11. In the development of the Baltic Sea, the olive grey sandy silt is typical sediment of the Litorina Sea stage, which set in with an extensive regression and widespread erosion (Kiipli et al. 1993; Veski et al. 2005).

Layer I is 32 cm thick. It consists of massive, loose organic mud (gyttja), which is greenish-black in the lower half and becomes brownish, highly organic-rich at the top of the layer. The layer was discovered only in cores 9 (14 cm) and 10 (32 cm) from the deepest part of the gulf (Fig. 3), where it rests discordantly on the Ancylus Lake sediments (core 9, Fig. 5B). This layer represents the post-Litorina Sea mud of the Baltic Sea.

5.2. Seismo-acoustic subdivision of the Lateglacial and postglacial sediments

The preliminary seismo-acoustic subdivision scheme discussed and presented in Paper I (Kalm et al. 2006) was improved in the later stages of this study due to the interpretation of new seismo-acoustic and corring data obtained in 2004. Thus, the final seismo-acoustic subdivision of the Late Weichselian and Holocene sequence for the northern GR is presented and discussed in detail in Paper II (Tsyrulnikov et al. 2012).

Owing to varying geometry, intensity and density of the seismic reflectors, the low-frequency echo sounder recordings reveal a picture where homogeneous, uniformly colored lighter/darker stripes with rare internal reflectors alternate with slightly or intensively layered and reflected darker bands (Fig. 6). In all, seven acoustically contrasting units were distinguished, the characteristics of which are summarized in Table 2. The thicknesses of the solitary bands/stripes, and thus also of the distinguished acoustic units in postglacial sediments (units III–VIII), vary depending largely on the relief, i.e. on the minor depressions and elevations of the underlying till surface. Furthermore, together with the thickness change, the acoustic signature in these units may also vary to some extent (Table 2; Figs 6–10). Due to sparse sampling and the fact that most of the layers were sampled only partially, similar thickness changes were practically not identified in the sediment cores. Therefore, the acoustic data supplement considerably our knowledge about thickness variations in the sedimentary layers described above.

Acoustic unit I (AU I) appears in the 4 KHz echo sounder profiles always as the lowermost, greyish-black and non-layered zone with no penetration of the acoustic impulse (Figs 6–11, 13). In high-frequency (250–500 Hz) seismic profiles, this unit has a scattered and chaotic internal seismic pattern with rare reflectors above the bedrock surface (Fig. 6C). The top of this ubiquitous unit forms one of the strongest seismic reflectors in the Quaternary sequence (TS in Fig. 6C) and is clearly visible in all low-frequency echo sounder recordings as the upper limit of AU I (Figs 6–11, 13). Its undulating character reveals minor, variably shaped and successively placed elevations and depressions along this surface. Often these depressions/elevations occur as elongated (channel- or ridge-like) features (see Paper III for details), reaching over 20 km in length, 0.5 km in width and about 30 m in depth or height.

According to the seismic data, the thickness of AU I may reach more than 30 m in channel-like depressions of the bedrock surface (Fig. 6C). The uppermost part of this unit was sampled in core 8 (Figs 5A, 7) and interpreted as Weichselian till (Fig. 4; layers A and B, Fig. 5A).

Acoustic unit II (AU II) was distinguished and followed only in the northwestern part of the gulf between Kurzeme Peninsula and Saaremaa (see in Fig. 14). In the acoustic recordings, this unit always rests between AU I (glacial till) and the overlying AU III as a rather homogeneous, grey, acoustic interval, occasionally with some internal darker and blurred reflector-like features (Fig. 8A, B). Normally, its contact with the underlying till surface is rather even. However, because of the undulating upper boundary the thickness of this unit is very variable, reaching a maximum of 9 m. The AU II unit was recovered in cores 14 and 15 (Fig. 8) and described as the WGD layer (Fig. 4; layer C in core 15, Fig. 5A). Mainly grey, homogeneous hue of this unit (Fig. 8) is obviously due to the sporadically occurring coarse-grained material (gravel, granite clasts) (Fig. 4; layer C in core 15, Fig. 5A) that normally scatters the acoustic signal.

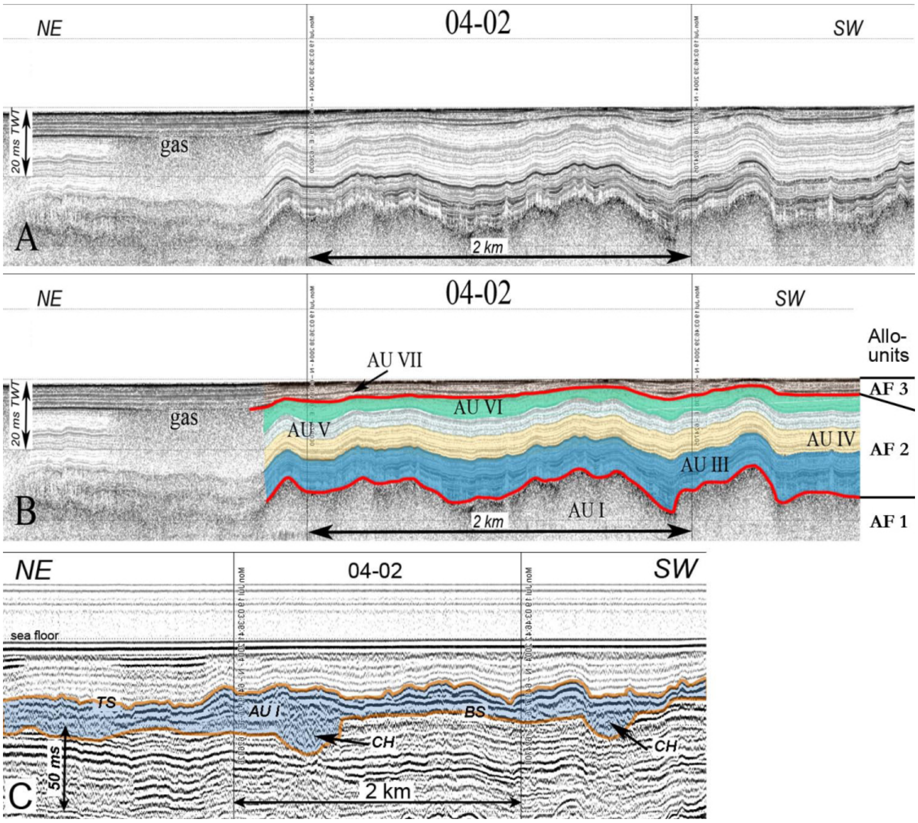

Figure 6. Section of acoustic profile 04–02 (A) and its interpretation (B), showing the succession and internal reflector configuration of most of the acoustic units (AU) discussed in the text; red lines mark regional disconformities on the boundaries of the distinguished allounits (AF). C. The same section on the seismic profile: AU I = layer of Late Weichselian till, TS = its undulating uppermost surface, CH = occasional channel-/valley-like structure in the bedrock surface (BS). For location of the section see Fig. 3. (Paper II, Figure 4; p. 680)

Acoustic unit III (AU III) is resting either on the acoustically impenetrable AU I (Figs 6, 7, 9, 10) or homogeneous AU II (Fig. 8) and appears as the lowermost clearly layered interval in the acoustic recordings. Its acoustic signature consists of alternating dark bands of numerous, very closely spaced strong acoustic reflectors and lighter homogeneous stripes without or rare internal reflectors (e.g. Fig. 7). Commonly, this unit might be divided into the darker lower and the lighter upper part (Figs 6, 7, 9, 10). Except the near-shore areas, where usually glacial till (AU I) outcrops on the sea floor, AU III is spread everywhere and its thickness varies normally from 6 to 9 m, reaching up to 20 m in the centre of the deepest depressions. AU III was sampled in cores 3, 4, 8 (Fig. 7), 12, 14, 15 (Fig. 8) and interpreted as the distinctly varved lowermost part of the BIL deposits (Fig. 4; layer D in cores 12 and 15, Fig. 5A).

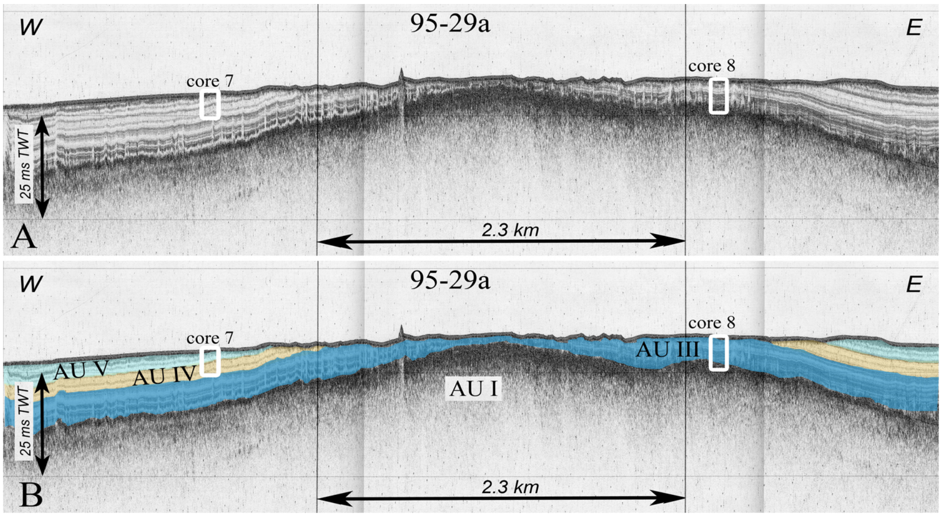

Figure 7. Section of acoustic profile 95–29a (A) and its interpretation (B), showing a minor elevation along the till surface and the acoustic units sampled in cores 7 and 8. For location of the section see Fig. 3. (Paper II, Figure 5; p. 682)

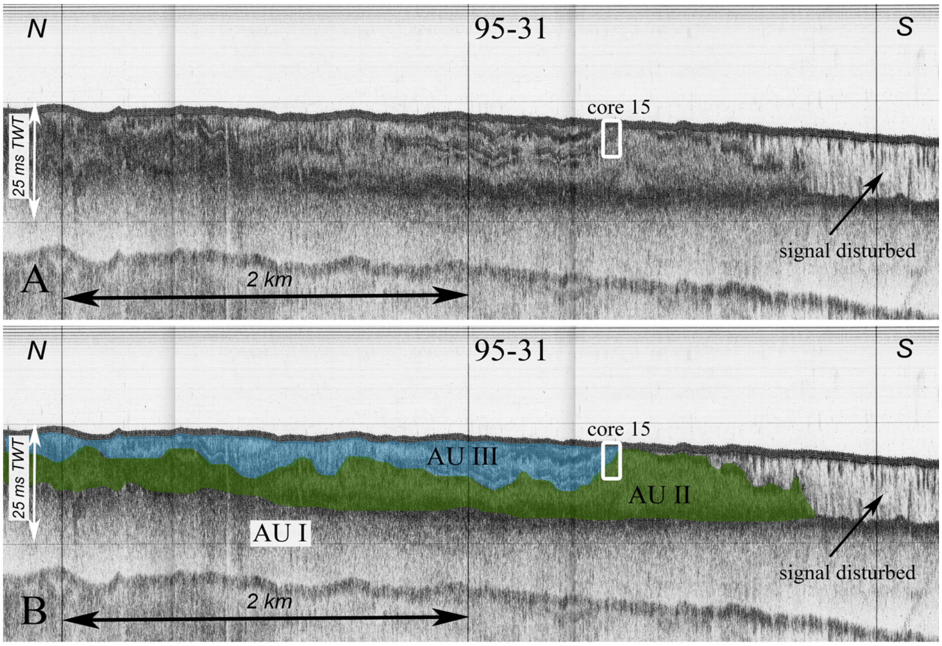

Figure 8. Section of acoustic profile 95–31 (A) and its interpretation (B), showing the structure and the homogeneous, grey acoustic signature of the WGD layer (AU II) sampled in core 15. For location of the section see Fig. 3. (Paper II, Figure 6; p. 682)

Table 2. Distinguished acoustic units and their characteristic features. (Paper II, Table 2; p. 681).

<table>
<tr><th>Acoustic unit</th><th colspan="2">Seismic/acoustic signature</th><th>Bedding, distribution and position of the unit</th><th colspan="2">Thickness</th></tr>
<tr><td>AU VII</td><td colspan="2">Dark greyish interval with subhorizontal, closely spaced parallel reflectors that are onlapping the undulating reflectors of the underlying units.</td><td>Uppermost unit with parallel bedding; overlies disconformably underlying units around minor depressions along the till surface in the deeper parts of the gulf.</td><td colspan="2">Absent on minor elevations along the till surface; up to 9 m, exceptionally 27 m thick in the deepest depressions.</td></tr>
<tr><td>AU VI</td><td rowspan="4">Uniformly coloured lighter and darker bands with rare internal reflectors alternating with slightly or intensively layered darker bands with numerous reflectors.</td><td>Light interval mostly void of reflectors; a few darker stripes may appear close to its bottom and top.</td><td rowspan="4">Bedded sequence resting conformably on the undulating top surface of AU I or AU II, widely distributed in and around the central depression of the gulf; lateral distributions of the units shrink upwards the succession.</td><td rowspan="4">Usually, does not exceed 25 m, however, up to 40 m in deepest depressions.</td><td>Normally 4–6 m, reaches 15 m.</td></tr>
<tr><td>AU V</td><td>Greyish interval divided by a strong stripe in the minor depressions along the till surface; additional reflectors appear towards minor elevations where this unit wedges gradually out.</td><td>Normally 3.5–5 m, reaches 10 m.</td></tr>
<tr><td>AU IV</td><td>Light homogeneous interval with a few thin and weak inner bands of closely spaced reflectors.</td><td>Normally 3.5–5 m, reaches 7 m.</td></tr>
<tr><td>AU III</td><td>Dark bands of closely spaced reflectors alternating with lighter stripes without or with rare reflectors.</td><td>Normally 6–9 m, reaches up to 20 m.</td></tr>
<tr><td>AU II</td><td colspan="2">Homogeneous grey acoustic interval with some occasional darker and blurred reflector-like features.</td><td>Non-layered unit on top of the AU I; occurs locally only in the western part of the gulf.</td><td colspan="2">Varying, reaches up 9 m.</td></tr>
<tr><td>AU I</td><td colspan="2">Impenetrable for 4 KHz acoustic impulse unit with heavily undulating upper surface; a scattered and chaotic seismic signature in the 250–500 Hz seismic profiles.</td><td>Ubiquitous non-bedded lowermost unit on top of the bedrock or on the Emian Sea deposits.</td><td colspan="2">Normally 1–10 m, locally more than 30 m.</td></tr>
</table>

Acoustic unit IV (AU IV) rests everywhere conformably on AU III and is separated from it by one of the strongest and darkest acoustic signature bands in the whole of the postglacial sedimentary succession (Figs 6, 7, 9, 10). Compared to the underlying, reflector-rich AU III unit, the AU IV appears on the profiles as a much lighter, rather homogeneous interval with a few thin and weak inner bands of closely spaced reflectors (Figs 6, 7, 9, 10). The thickness of this unit normally varies from 3.5 to 5 m, reaching in the centres of minor depressions up to 10 m. It is widely distributed around the gulf, missing only in the shallow near-shore areas where AU I, AU II or AU III are outcropping on the sea floor (Figs 7, 8). AU IV was sampled in cores 6, 7 (Fig. 7) and 13 and is interpreted as distally varved clays of the BIL (Fig. 4; layer E in core 6, Fig. 5A, B).

Acoustic unit V (AU V) is composed of a set of vague and closely spaced reflectors. It obtains a distinctly darker greyish shade compared to the acoustic units below and above it (Fig. 9). Unit AU V overlies everywhere conformably AU IV. It is widely distributed around Ruhnu Island in the central part of the gulf but occurs also in the deepest nearshore depressions along the till surface (Figs 6, 7, 9, 10). In general, the seismic signature and greyish hue of AU V are highly varying, being clearly dependent on undulations in the till surface. In the central part of deeper depressions, a dark and striking stripe divides this unit into two distinct parts (Fig. 9). The lower, lighter part is practically void of internal reflectors, the upper one, however, has clearly a darker hue due to the numerous internal reflectors. Towards the tops of elevations, the upper part wedges gradually out and becomes darker, as the reflectors inside it are getting stronger and more accentuated (Fig. 9). In places, in the near-shore depressions, AU V may arise as a light acoustic interval practically void of continuous reflectors (Fig. 10). The thickness of this unit normally varies between 3.5 and 5 m, reaching up to 10 m in the deepest depressions. AU V was covered by cores 5–7 (Fig. 7), 9 (Fig. 9), 10, 11 (Fig. 10) and is interpreted as the clayey sequence of the Yoldia Sea (Fig. 4; layer F in cores 6, 7, 9, 11, Fig. 5A, B).

Acoustic unit VI (AU VI) is widely distributed in the central part of the gulf, but occasionally occurs also in the deepest near-shore depressions. It rests everywhere conformably on the darker greyish AU V, being separated from it by a distinct band of closely spaced parallel reflectors (Fig. 9). The latter boundary gets normally darker and thus more accentuated above the slopes of the minor depressions. AU VI is largely void of reflectors, however, a few darker bands of reflectors occur close to the bottom and top of this unit (Fig. 9). The thickness of AU VI is normally between 4 and 6 m, though, it increases gradually towards the minor depressions in the till surface. Thus, similarly to AU III, AU IV and AU V, the thickest portions of this unit (up to 15 m) occur in the middle of these depressions. Furthermore, the seismic signature and general hue of AU VI are distinctly dependent on its thickness, that is, on its position above the minor depressions–elevations transects (Fig. 9). Therefore, in some profiles AU VI may arise as a greyish-white interval without any clear internal reflectors (Fig. 10). This unit was sampled in cores 5, 9 (Fig. 9), 10, 11 (Fig. 10) and it is correlated with the homogeneous FeS-mottled clay sequence of Ancylus Lake (Fig. 4; layer G in core 9, Fig. 5B).

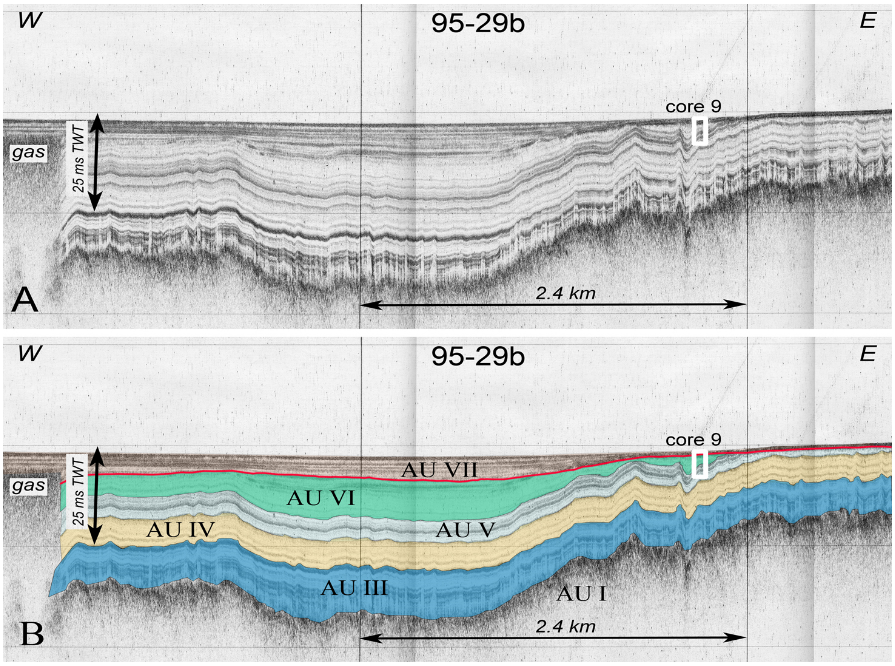

Figure 9. Section of acoustic profile 95–29b (A) and its interpretation (B), showing the thickness and acoustic signature changes in AU III–AU VII along the undulating till surface along a minor elevation–depression transect and the acoustic interval sampled in core 9. Red line marks the disconformity between AU VI and AU VII. For location of the section see Fig. 3. (Paper II, Figure 7; p. 683).

<u>Acoustic unit VII (AU VII)</u> is the uppermost acoustic unit. It was distinguished in and around the minor depressions in the central part of the gulf, where it may discordantly overlie all six underlying acoustic units. In the acoustic profiles it appears as a unit with a dark greyish colour that is obviously caused by the abundance of very closely spaced, sub-horizontal and parallel reflectors (Figs 6, 9). If AU VII reaches more than 6.5 m in thickness, normally gas-rich sediments impenetrable for the acoustic pulse appear at its bottom (Figs 6, 9). Therefore, the maximum thickness of AU VII (up to 9 m, exceptionally 27 m in the deepest depressions) was measured in the (250–500 Hz) seismic recordings. AU VII was penetrated by cores 5, 9 (Fig. 9) and 10 and correlated to the acoustically indivisible sediments of the Litorina and post-Litorina Sea (layers H and I, Fig. 4; layer I in core 9, Fig. 5B). Continuous disconformity between the AU VI and AU VII (core 9, Fig. 5B, Fig. 9) corresponds to the regional erosional surface that formed in this region during the regression at the beginning of the Litorina Sea stage. Numerous closely spaced, parallel reflectors in this unit (Figs 6, 9)

are obviously produced by intercalating sandy, clayey and muddy layers that are typical of the Litorina and post-Litorina sequence (layers H and I, Fig. 4).

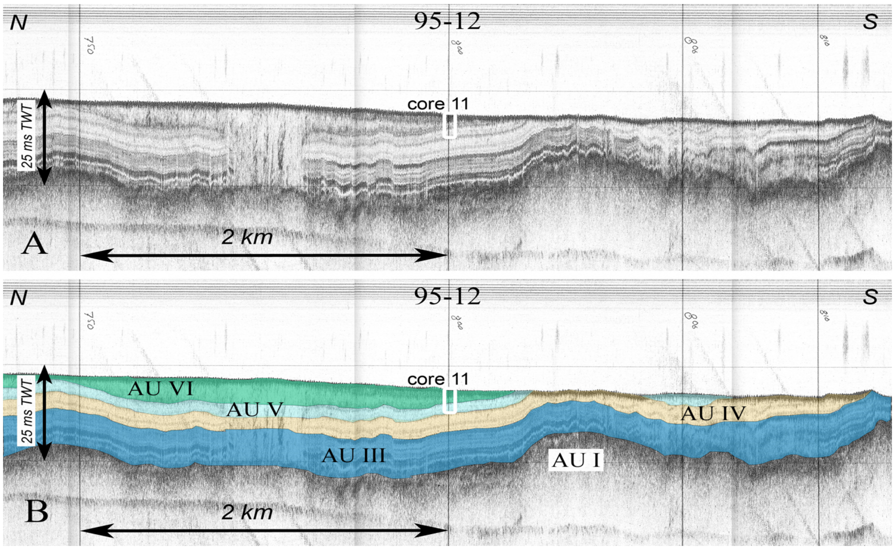

Figure 10. Section of acoustic profile 95–12 (A) and its interpretation (B), showing the acoustic signatures of AU III–AU VI in the near-shore area and the acoustic interval penetrated by core 11. For location of the section see Fig. 3. (Paper II, Figure 8; p. 783).

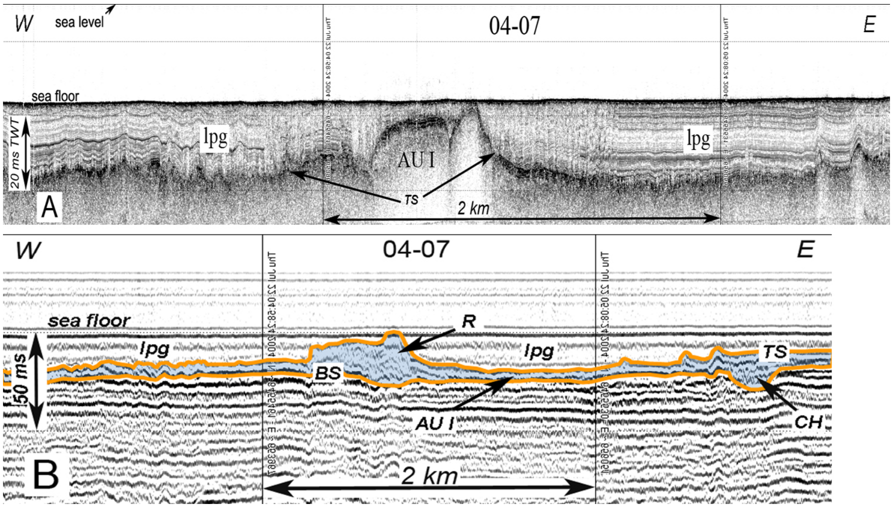

Figure 11. Section of acoustic (A) and seismic (B) recordings of profile 04–07 demonstrating a ridge-like glacial relief feature (R) along the undulating till surface (TS) buried under the Lateglacial and postglacial deposits (lpg), and a channel-like (CH) feature in the bedrock surface (BS) filled in with glacial deposits (AU I). For location of the section see Fig. 3. (Paper II, Figure 9; p. 684)

5.3. Allostratigraphic subdivision and correlation with Archipelago Sea SW of Finland

Allostratigraphic subdivision of the Quaternary sediments of the GR and its correlation with the Archipelago Sea southeast of Finland is presented and discussed in detail in Paper II (Tsyrulnikov et al. 2012).

Two regional discontinuity surfaces can be followed both in seismo-acoustic recordings (Fig. 6) and sedimentary cores (Fig. 4). These enabled three allounits to be distinguished in the northern part of the GR (Table 3). The lower discontinuity between lithological layers B and C (AU I and AU II) separates the Late Weichselian glacial diamicton (Allounit 1) from the sequence of WGD, glaciolacustrine and postglacial lake/marine deposits (Allounit 2). The regional discontinuity between lithological layers G and H (AU VI and AU VII) marks the onset of the Litorina Sea and separates the Litorina Sea to present Baltic Sea brackish water deposits (Allounit 3) (Table 3).

Table 3. Allostratigraphic units. (Paper II, Table 3; p. 685).

Baltic sea development stage	Lithostratigraphic layer in Table 2	Acoustic unit	Allostratigraphic unit
Post-Litorina	I	AU VII	Allounit 3
Litorina Sea	H		
Ancylus Lake	G	AU VI	Allounit 2
Yoldia Sea	F	AU V	
Baltic Ice Lake	E	AU IV	
	D	AU III	
Ice recession	C	AU II	
Late Weichselian Glaciation	B	AU I	Allounit 1
	A		

Comparison of allostratigraphical boundaries and units in the Lateglacial and postglacial sediments of the northern GR with these of the Archipelago Sea, SW of Finland (Virtasalo et al. 2007, 2010a), reveals a great similarity. Both regional discontinuity surfaces followed in the northern GR divide the alloformations also in the Archipelago Sea. There the boundaries between the lithological layers B/C and G/H coincide with the lower boundary of the Dragsfjärd Alloformation and separates the Korppoo and Nauvo alloformations. Unlike in the Archipelago Sea, in the northern GR we could not find any evidence of a discontinuity surface from the ice recession to the drainage of Ancylus Lake, which separates the Dragsfjärd and Korppoo alloformations in the Archipelago Sea. The latter boundary obviously marks some local episodic event (Virtasalo et al. 2010a) and therefore probably has rather restricted extension.

5.4. Late Weichselian to Holocene depositional history of the Gulf of Riga

Depositional history of the Late Weichselian to Holocene sediments of the GR, based on the interpretation and synthesis of our seismo-acoustic and coring studies, as well as on the earlier published data all around the Baltic Sea, is discussed in detail in Paper II (Tsyrulnikov et al. 2012).

On the basis of the distinctive and widespread discontinuity surfaces the entire section can be first divided into three portions, allounits, which besides the GR are followed also in the other areas inside and outside the Baltic Sea. Thus, the allostratigraphic approach allows us to consider the basal till or diamicton (layers A–B, AU I), the intermediate ice-proximal WGD, glaciolacustrine and postglacial lake/marine deposits (layers C–G, AU II–AU VI) and the uppermost brackish-water marine deposits (layers H–I, AU VII) as the first-order units representing the main stages in the development of the Baltic Sea region, traceable at the regional scale. The varying lithology, as well as the rapidly changing thicknesses and the wedging out of the lithological units inside the distinguished allounits, reflect the complex Lateglacial and postglacial history of the GR in accordance with the melting of the Scandinavian ice-sheet with the corresponding glacioisostatic rebound and evolving of the Baltic Sea in front of the retreating ice margin.

5.4.1. Diamicton of the Late Weichselian glaciation

On the basis of the shape, bathymetry and orientation of the GR, as well as the bedrock elevation dividing its central part, it was concluded that the main depression of the gulf has been largely eroded by NW–SE advancing Pleistocene ice streams. The retreating Late Weichselian glaciers left behind a till layer (layers A and B, Fig. 4), which corresponds to AU I and covers an erosional, slightly undulating bedrock surface all over the study area (Figs 6C, 11B). Sediment layers A and B reflect a gradual ice retreat, i.e. enable us to follow transition between the deposits of the grounded glaciers and ice-free bottom sediments. Oscillation and meltwater drainage at the bottom of the ice has shaped the upper, irregular surface and thus caused the undulating thickness (1–10 m) of AU I (Figs 6C, 11B). However, more than 30 m thick channel- and ridge-like features of different size and shape appear locally along this layer (Figs 6C, 11B). They obviously represent various elongated glacial or glaciofluvial relief forms (valleys, eskers, drumlins, etc.), well known on the mainland.

5.4.2. WGD, glaciolacustrine and postglacial lake/marine deposits

Ice recession and WGD deposition. – Continuous subaqueous basal meltout from floating ice, debris flows, dumping and grounding caused deposition of the WGD that in the lithological section (Fig. 4; layer C in core 15, Fig. 5A), as well as in the acoustic recordings (AU II, Fig. 8) is distinguished only in the northwestern part of the gulf (see in Fig. 14). Limited distribution of the WGD sediments obviously reflects its relation to the Pandivere and Palivere ice-marginal zones, located nearby on the Sõrve Peninsula (see in Fig. 14). Similarly, the WGD layer was earlier described in the Pandivere and Palivere end-moraine zones on the Saaremaa and Hiiuma islands (Kalm and Kadastik 2001). Thus, we suggest that continuous deposition of the WGD occurred during the stagnation of the position of the ice margin. A smooth transition from the WGD unit to the overlying glaciolacustrine clays (core 15, Fig. 5A) reflects a gradual change towards cyclic sedimentation in the proglacial lake.

The Baltic Ice Lake (glaciolacustrine deposition). – The Baltic Ice Lake (BIL) phase with clearly laminated varved clays is distinguished in the lithological section in layers D and E (Fig. 4; cores 6, 12 and 15, Fig. 5A, B). Distinct gradation from thicker and coarse-grained proximal varves to thinner and fine-grained distal varves upwards in these units reflects normal sedimentation in a proglacial lake with a gradually retreating glacier, where at each point studied proximal conditions gradually change to more distal conditions.

In the acoustic recordings the BIL stage is clearly visible in the two lowermost, clearly laminated units AU III and AU IV (Table 2; Figs 6, 7, 9, 10). The gradual retreat, possibly with shorter advancing pulsations, of the ice margin and replacement of the proximal varves by distal varves upwards in the section is revealed by the changes and variations in the hue (darkness) of these units. This could be due to the fact that the proximal varves are more liable to evoke reflectors because of their distinct lithological and thus acoustic heterogeneity caused by rather thick silty (summer) layers.

Thus, due to the numerous dense strong reflectors, the interval with proximal varves (layer D) (Figs 4, 5A) acquires in the acoustic recordings a distinctly darker hue with rare alternating thin and lighter stripes (AU III, Figs 6, 7, 9, 10). The distal varves, on the contrary, appear upwards in the section (layer E in Fig. 4 and in Fig. 5A, B) as a lighter interval with a few weak inner reflectors (AU IV, Figs 6, 7, 9, 10). This reflects unambiguously a higher lithological homogeneity, i.e. a lesser amount of the sandy-silty component in the distal varves.

The interval with strong reflectors that in places occur between AU III and AU IV (Figs 6, 7, 9, 10) was probably not penetrated by any of the sampling cores. However, we suggest that it might be associated either with the increase in the coarse component in the varves, due to the short re-advance of the glacier or with the interlayers of massive clay containing dispersed grains of coarser material. Such clays, lithologically distinctly differing from the rest of the BIL deposits (varved clays), and thus with greater potential for creating seismic reflectors, were sometimes described within the BIL sequence in the nearby Pärnu Bay area (Hang et al. 2010). A similar distinctively strong reflector within the BIL sequence was earlier described in the North Central Baltic Sea and supposedly correlated with a re-advance or a surge of the ice margin (Winterhalter 2001).

The origin of the distinct reddish-brown intervals occurring in varved clays (core 12, Fig. 5A) is not clear. However, they may indicate either occasional surges, which carried the reddish material that the glaciers washed out from Devonian bedrocks into the BIL or/and periods of the oxidation of bottom sediments due to the mixing of the water mass. The gradual increase in the thickness of the BIL sequence (AU III and AU IV) towards the centres of the minor depressions, followed along most of the acoustic lines (e.g. Figs 9, 10), shows that the accumulation rate and amount of sediments at that stage were clearly dependent on the bottom topography of the lake.

Yoldia Sea (postglacial brackish-/freshwater deposition). – A slightly darker band of closely spaced, weak reflectors in the lowermost part of AU V (Figs 6, 7, 9, 10) is obviously evoked by occasional sandy-silty interlayers close to the bottom of sediment layer F (Fig. 4; core 6, Fig. 5B). The presence of coarse-grained material just above the distal varves of the BIL (AU IV; layer E, Fig. 4) points to significant changes in the sedimentary environment: a rapid lowering of the water level, i.e. a much shallower sedimentary environment; and an abruptly increased influx of terrigenous material into the basin. Both of these facts can be linked to the catastrophic drainage of the BIL ca. 11 700 BP (Andrén et al. 2011), when a rapid sea level drop opened large areas to intensive land erosion. According to Talviste (1988) and Veski et al. (2005), the cataclysmic regression lowered the water level in the Pärnu area, northeastern part of the GR, by approximately 24–25 m. This remarkable drainage event, triggered by the opening up of the connection with the world ocean due to the ice margin retreat in south-central Sweden (Svensson 1991), is associated with the onset of the Yoldia Sea (ca. 11 700 BP in Andrén et al. 2011).

The greyish-brown massive or vaguely laminated clay of the Yoldia Sea stage (Fig. 4; layer F in cores 6, 7, 9, 11, Fig. 5A, B) has a distinctly different appearance on the acoustic records, with respect to its position and deposition depth in the minor depressions-elevations transects along the till surface (AU V in Figs 6, 7, 9, 10). In deeper water in the centres of depressions, a dark band clearly divides the clay into the lower and upper portions (Figs 8, 10). The lower part, practically void of internal reflectors, corresponds to massive or vaguely laminated clays of the initial, freshwater phase of the Yoldia Sea (Fig. 4; layer F1 in cores 6, 11, Fig. 5B). The upper, clearly darker part includes numerous internal acoustic reflectors, which are probably evoked by intervals with interlayers of coarse material (sand or silt) that occurred in the upper part of the Yoldia Sea succession (Fig. 4; layer F2 in cores 7, 9, 11, Fig. 5B). The growing number and strength of these reflectors towards the elevations (Fig. 9) reflects a probably rapid increase in the quantity and thickness of the sandy interlayers in the sequence (Fig. 4). Thus, the increasing content of coarse terrigenous material towards decreasing sedimentation depth on the elevations is obvious in the Yoldia Sea sequence. The FeS-rich dark (up to black) bands and stains of Fe monosulphide, sporadically occurring in the upper part of the Yoldia Sea sequence (Fig. 4; layer F2 in core 9, Fig. 5B) point to the presence of saline bottom water, and thus to the period of brackish water sedimentation. According to the position of core 9 on the acoustic profile, this sediment interval correlates to the upper part of AU V (Fig. 9). Thus, a dark band of reflectors in the middle of AU V (Figs 6, 7, 9), distinguished between the more sandy lower and clayish-silty upper portions, may also separate the initial freshwater and following brackish-water phases (11 550 and 11 300 cal. ^{14}C a BP, respectively, in Heinsalu and Veski 2007) of the Yoldia Sea stage.

Occasionally, near the shore of Saaremaa, AU V occurs as a light acoustic interval practically void of continuous reflectors (Fig. 10). In sediment core 11 this unit (layer F1 in core 11, Fig. 5B) is represented by a sequence of grey massive clay rich in sandy lenses/patches. This kind of Yoldia Sea sequence was probably formed close to the former shoreline, where shallow water and the activity of waves caused non-stratified deposition of inequigranular terrigenous material.

Ancylus Lake (postglacial lake deposition). – In Estonian offshore sections, the Ancylus Lake phase is characterized by FeS-rich layers, representing the increased organic content in sediments (Kiipli et al. 1993). These layers are probably caused by occasional inflow of saline bottom water into the postglacial lake (Virtasalo et al. 2010b) and downward diffusion of H2S from the overlying organic-rich sediments (Sohlenius et al. 2001). Similar features appear clearly in the greyish-brown silty to massive clay unit (layer G, Fig. 4) that contains several intervals rich in FeS black mottles (core 9, Fig. 5B). According to the core positions on the acoustic profiles (core 9 in Fig. 9 and core 11 in Fig. 10), layer G correlates with AU VI (Fig. 4). Thus, a darker band of reflectors at the base of AU VI (Figs 6, 9, 10) corresponds to the lowermost distinct interval of black clays with diffuse mottling of FeS and sandy interlayers (Fig. 4; layer G1 in core 11, Fig. 5B), traced all over the northern and central parts of the gulf (cores 5, 9–11, Figs 3, 4). Lack of the internal reflectors in the rest of AU VI is probably caused by homogeneity of the FeS stuffed clays of the Ancylus Lake sequence, which discriminates this unit clearly from the underlying proglacial laminated sequence (AU III–V) (Figs 6, 10).

On the basis of the FeS content, in places in the deepest part of the gulf (core 9, Figs 3 and 5B) the entire Ancylus sequence can be divided into five subunits (G1–G5, Fig. 4). Such a randomly stratified lithology of the Ancylus Lake deposits also affects slightly its acoustic appearance, likely evoking rare vague reflectors that appear within some minor depressions north of Ruhnu Island (in AU VI, Fig. 9).

5.4.3. Brackish-water Litorina Sea and present Baltic Sea deposits

Brackish-water sandy Litorina Sea deposits and present gyttja, respectively in layers H and I (Figs 4, 5B), clearly correlate with AU VII (Figs 6, 9). First, the erosional surface between the Litorina Sea and underlying Ancylus Lake sediments coincides well with a disconformity between acoustic units VI and VII, reflecting thus the regressional event associated with the establishment of the connection between the Baltic Sea and the ocean. However, the exact timing of this event is still highly controversial (e.g. 9 800–8 500 cal. a BP according to Andrén et al. 2011; ca. 7 200 cal. a BP according to Rößler et al. 2011). Secondly, the acoustic signature of AU VII is clearly distinguished from the rest of the underlying postglacial sediments, revealing thus a distinct change in the character of sedimentation during the last stage in the evolution of the Baltic Sea. Hence, a complex of discordantly overlaying and subhorizontal (bedding) surfaces of non-cohesive sand and silt or gyttja is revealed above the uneven, erosional top surface of AU VI, while undulating beds of the underlying postglacial sequence follow the minor elevations and depressions of the uneven till surface (Figs 6, 9). Limited extension of AU VII, only in the central part of the GR, corroborates the earlier suggestions that Litorina Sea sediments tend to accumulate in isolated depressions where bottom currents are negligible (Winterhalter 2001). Intervals of black, FeS-rich clay, occasionally described in the Litorina Sea sequence (core 5), obviously reflect the sedimentation anoxia, associated with the saline bottom water inflow and therefore obstruction of the vertical water circulation in the deepest parts of the basin due to the stratification of the water mass (Sohlenius et al. 2001).

5.5. General bathymetric/topographic and geological features in the Gulf of Riga area as evidences of pathways and dynamics of the Pleistocene glaciers

Based on the bathymetric and geological maps, digital terrain model and seismic data inside the gulf and complex mainland topographical/geological data around it, streamlined glacial relief forms are analyzed in Peper III (Tsyrulnikov et al. 2008) in order to restore possible pathways and dynamics of Pleistocene glaciers in the GR area.

5.5.1. General description of the bottom relief of the Gulf of Riga based on compiled bathymetric map and digital terrain model

The water depth of the GR is increasing from north towards the central deep (40–50 m) which occupies most of the gulf (Figs 1, 12). The average water depth is 26 m, while the deepest (– 67 m) point of the gulf is located north of Mērsrags close to the western coast (Fig. 1). According to the water depth and the depth gradient, which reflect the main features of the bottom topography, the GR can be morphologically divided into two parts: northern and southern.

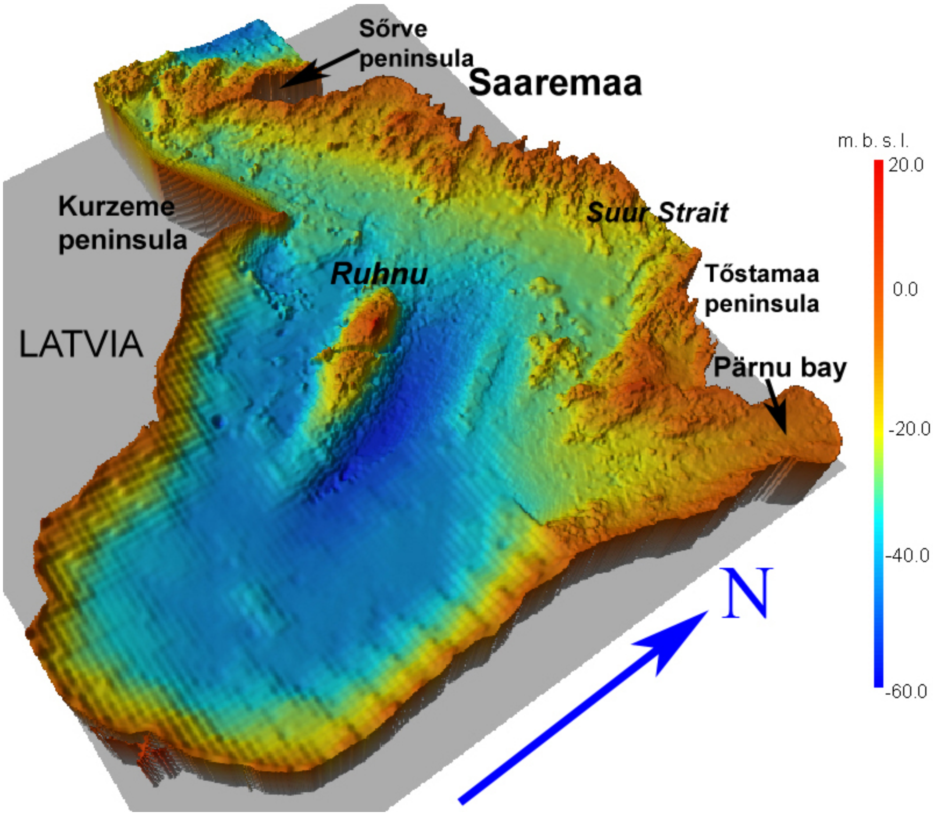

Figure 12. Digital terrain model (DTM) of the Gulf of Riga. (Paper III, Figure 3; p. 84).

The northern/northwestern part of the gulf is shallower with distinctly smaller depth gradient compared to that of the southern part (Figs 1, 12). The depth gradient around the Irbe Strait is 2–3 m/km and the width of the shallow-water area (provisionally up to 30 m isobasis) is 10–15 km. Along the southern coast of the Saaremaa Island the same characteristics 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 characteristics are clearly different from that of the rest of the gulf further southeast 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 shallowness and rugged glacial topography (Juškevičs and Talpas 1997) the occurrence of a number of small islets and shallows is another characteristic feature for the northern and northwestern region of the GR compared to the southern deep-water areas. Just at the transition of these two parts, approximately between the Kurzeme and Tõstamaa Peninsulas, a conspicuous northwest to southeast elongated elevation emerges from the seafloor with its top forming the Ruhnu Island (Figs 1, 12). This elevation divides the main depression of the GR into two separate, NW–SE elongated deeps, with the deepest area (> 50 m) of the gulf east of the Ruhnu Island (Fig. 1).

5.5.2. Streamlined glacial relief features in and around the Gulf of Riga and reconstruction of the ice flow dynamics of the Late Weichselian glaciation

Elongated ridge- and trough-like glacial relief features are often distinguishable in the recent bathymetry of the shallow near-shore part of the GR (Fig. 12) and topography of adjoining land. In the deepest central part of the gulf, the glacial relief is buried under younger Lateglacial and postglacial sediments. However, its features can still be followed using seismo-acoustic data (Fig. 13). Furthermore concentric and elongated patterns of the outcropping Lateglacial and postglacial sediments shown on available maps of the Qaternary deposits in scales 1 : 400 000 (Kajak 1999), 1 : 200 000 (Väärsi and Kajak 1969; Kajak and Kala 1972, 1973; Juškevičs et al. 1996) and 1 : 50 000 (Eltermann et al. 1993) are obviously reflecting alternating troughs and elevations of original glacial relief.

In order to discuss possible directions and age relationships of moving ice streams, all studied on- and offshore linear relief features (see fig. 5 in Tsyrulnikov et al. 2008, paper III) were classified into six groups according to their orientation (numbers 1–6 in Fig. 14). Depending on the location and genesis of these features all groups were further divided into several subgroups (a–f in Fig. 14). In most cases the distinguished subgroups were made up of closely located linear relief features, pointing to the same ice stream or even the same glacier lobe.

Group 1. The curvilinear features around the northern coast of the GR:
1a – from northern Saaremaa across the Sõrve Peninsula into the Irbe Strait;
1b – two sections northwest and northeast of the Pärnu Bay.

These features represent the ice marginal formations, 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).

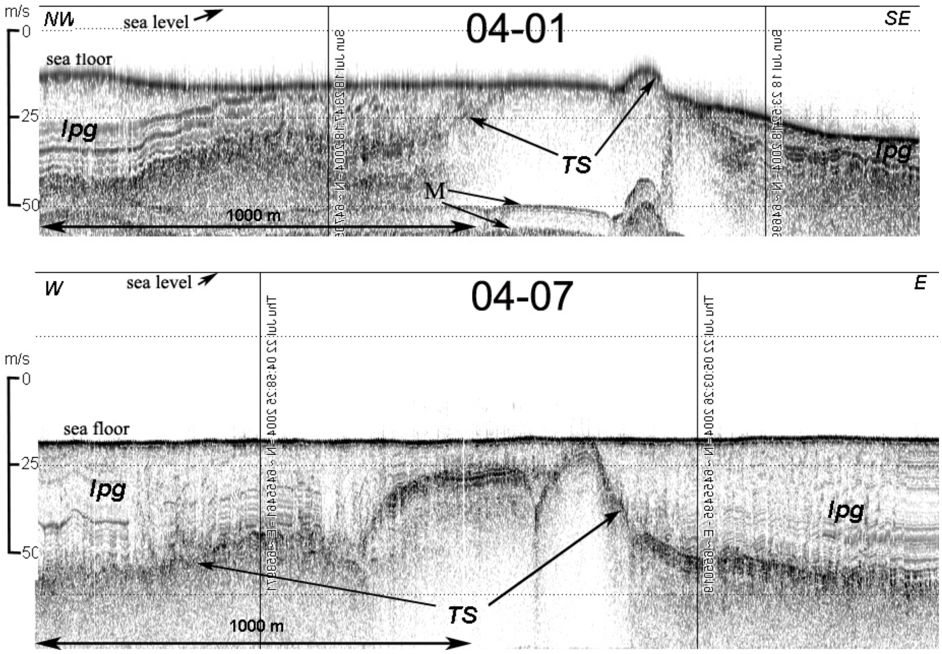

Figure 13. Sections of acoustic profiles demonstrating the glacial relief features along the till surface (TS) expressed in sea floor topography (04–01) and buried under Late-glacial and postglacial sediments (lpg) (04–07). M – multiple reflectors. For location of the sections see Fig. 3. (Paper III, Figure 4; p. 85).

Group 2. Northwest–southeast oriented features:
2a – in the middle of the gulf, around the Ruhnu Island;
2b – along the southern coast of Saaremaa:
2c – southwest of the Sõrve Peninsula;
2d – in northwestern Saaremaa;
2e – on the Muhu Island;
2f – in the central part of the Tõstamaa Peninsula.

This orientation is clearly dominating 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. 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 (Valdemarpils) phase of ice recession.

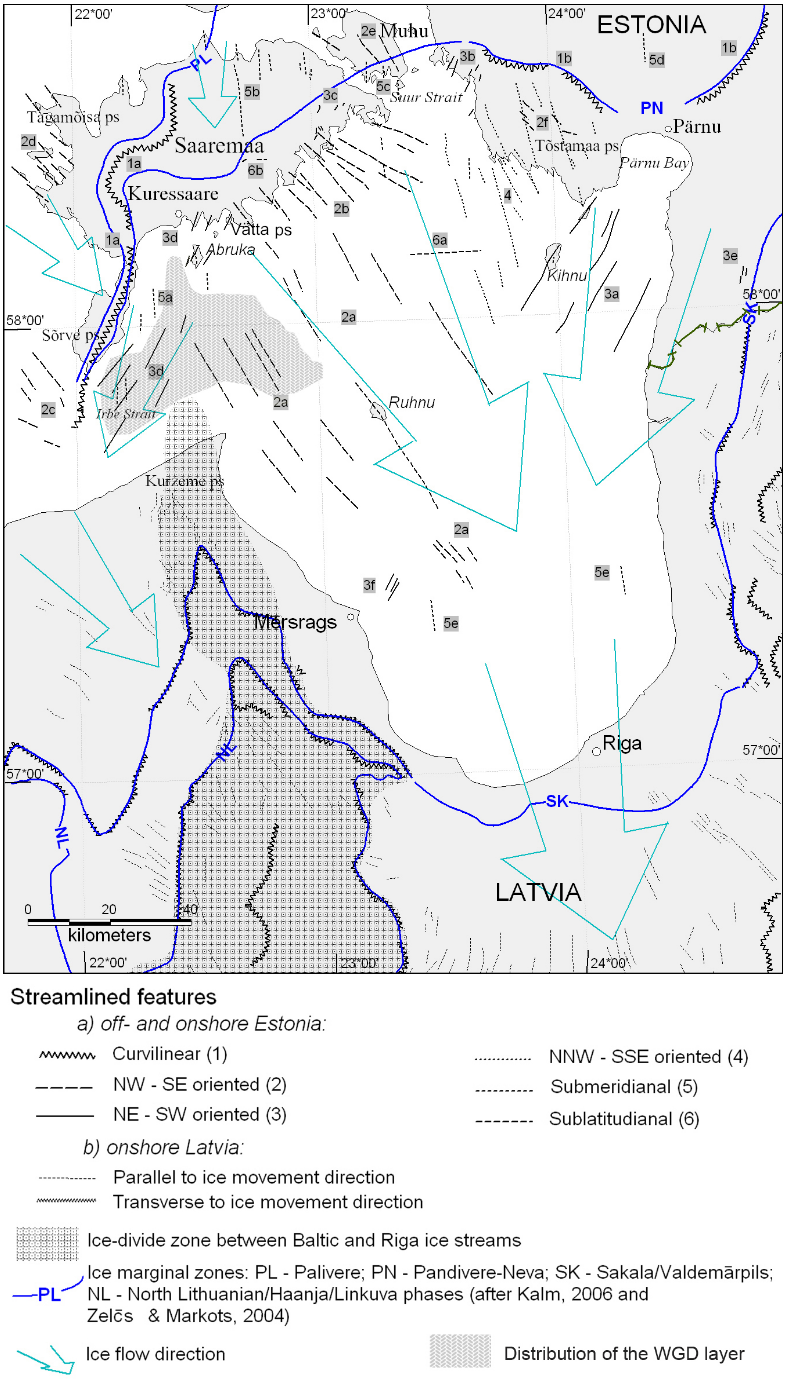

Figure 14. Ice flow reconstruction map of the Gulf of Riga and adjacent mainland areas based on the grouping (1–6 in text) of different kinds of linear relief features. (Modified from Figure 6 in Paper III, p. 87).

Similarly oriented forms on the Tõstamaa Peninsula (2f), made up of glaciofluvial material, represent the small-scale radial eskers, which obviously were formed at the end of the Sakala phase too. Similarly oriented topographic features on the Muhu Island (2e) point towards the same ice stream. However, considering their position in respect of the ice marginal zone (Fig. 14), these features may have been formed during the following Pandivere–Neva phase. The northwest–southeasterly oriented sea bottom and coastline features along the western and south–western 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. Northeast–southwest oriented features that occur:
3a – southwest of the Pärnu Bay;
3b – east of the Suur Strait;
3c – in the eastern part of Saaremaa;
3d – from the southern coast of Saaremaa across the Abruka Island along the eastern coast of the Sõrve Peninsula;
3e – southeast of the Pärnu Bay;
3f – east of the Kurzeme Peninsula offshore from Mērsrags.

The conspicuous features in the till topography southwest of the Pärnu Bay (3a) reveal 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 southwest deviating ice flow in the eastern flank of the Riga ice stream during the Sakala phase. The latter version 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 the Sakala Upland in southern Estonia, which was acting as an ice divide zone and pressed the eastern flank of the Riga ice stream westwards (see fig. 5 in Raukas and Karukäpp 1979).

The southwesterly oriented offshore features southeast 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 indentation northwest of the Tõstamaa Peninsula (3b) and in southeastern part of Saaremaa (3c) may reflect a surging glacier lobe during the Pandivere–Neva phase, as clear ice marginal formations in this section of relevant phase are missing (Fig. 14).

Group 4. North/northwest to south/southeast oriented features on and offshore from the Tõstamaa Peninsula (4).

The nature of these extensive linear forms in offshore till topography is unknown. As they display a similar orientation with the adjoining coastline indentations 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. As the younger linear glaciofluvial formations (2f) of the retreating Riga ice stream from the Sakala phase occur on top of them (Fig. 14), 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 southeast of the Sõrve Peninsula;
5b – in the central and northeastern part of Saaremaa;
5c – along the southern coast of the Muhu Island;
5d – north of the 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. 14) are known. These are radial glaciofluvial eskers, which probably have been formed in crevasses or subglacial tunnels during the Pandivere–Neva stage (Karukäpp 1997b). The submarine features of unknown genesis (5a) were formed either by Irbe ice tongue or are part of nearby placed and similarly oriented Pandivere–Neva and/or Palivere ice marginal zones (1a) onshore.

Group 6. Sublatitudinal features:

6a – a few closely spaced and E–W aligned hummocks in the till surface about 20 km west of the Kihnu Island;
6b – marginal glaciofluvial formations in the southern part of Saaremaa.

The latter have been considered as possible formations 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).

6. CONCLUSIONS

Complex seismo-acoustic and lithological study of the Lateglacial and postglacial sediments in the northern GR with analysis of the streamlined glacial relief features in and around the gulf revealed new knowledge about the formation and development of the GR as a part of the Baltic Sea Basin. It permits a correlation/comparison with similar sequences across the Baltic Sea and in other former glaciated basins and provides a substantial base for any further geological research and prospecting as well as for prognosis of the future development of the GR in changing environment. The following main conclussions are derived from this study:

1. During a complex lithological and seismo-acoustic study of Lateglacial and postglacial sediments in the northern GR nine distinctive layers were lithologically distinguished and correlated with seven seismic/acoustic units. A regular set of seismo-acoustic profiles enabled estimation of the distribution and thicknesses of sedimentary units and also of some depositional and environmental characteristics of sediments over a large area.

2. The location of the bedrock depression holding the GR is distinctly predetermined by deep tectonic structures that are criss-crossing the gulf area. Reactivation of these structures caused the faulting and fracturing of the platform sedimentary cover that favoured glacial erosion and determined thus pathways and directions of advancing glaciers.

3. The GR depression was largely gouged and levelled by the activity of Pleistocene glaciers. The omnipresent till layer is either exposed on the bottom in the shallow near-shore areas or covered by younger sediments in the deep parts of the gulf. It is 1–10 m thick, but can reach more than 30 m in bedrock valleys, channel- or ridge-like glacial relief forms.

4. An up to 9 m thick sediment unit, covering the till layer between the Sõrve Peninsula and Kurzeme Peninsula, is correlated with the waterline glacial diamicton (WGD) deposits earlier reported on the nearby islands.

5. The rest of the sediment sequence reflects well all stages in the development of the Baltic Sea, whereas the thicknesses and bedding configuration of AU III to AU VI (from the BIL to Ancylus Lake) clearly follow the undulations, that is, elevations and depressions on the surface of the Late Weichselian till. Therefore, the postglacial sediment layers are usually thicker and more complete in the centres of depressions and liable to thin and wedge out towards the elevations.

6. A distinct gradation from the proximal (layer D, AU III) to distal (layer E, AU IV) succession of glaciolacustrine varved clays, normally 10–15 m

thick, in channel-like depressions up to 30 m thick, reflects seasonal differences in sedimentation in the BIL and the gradual retreat of the ice margin. The postglacial Yoldia Sea stage (layer F, AU V), with the initial freshwater (F1) and the following brackish-water (F2) phase, is reflected in a 3.5–5 m thick sandy/silty clayey succession. The following lacustrine clay of the Ancylus Lake stage (layer G, AU VI) normally forms a 4–6 m thick layer. Exceptionally, in channel-like depressions the thickness of Yoldia Sea and Ancylus Lake layers may reach 15 m.

7. The sub-horizontally bedded, latest sediment interval, from the Litorina Sea to the present Baltic Sea (layers H and I, AU VII), overlies the older sediment units with an erosional disconformity that reflects a rapid regressional event related to the establishment of the connection between the Baltic Sea and the world ocean. The distribution of Litorina to post-Litorina sandy and muddy organic-rich sediments is strictly limited to deep bottom depressions, where their thickness may reach 9 m, exceptionally 27 m in the deepest depressions. If AU VII reaches more than 6.5 m in thickness, normally gas-rich sediments impenetrable for the acoustic pulse appear at its bottom (Figs 6, 9).

8. Differences between the generalized lithological sections based on the first 5 pilot cores (table 2 in Kalm et al. 2006) and all available 13 cores reveal distinctive variability, and thus complexity in correlating the Lateglacial and postglacial sediments in the Baltic Sea, even in this very restricted area.

9. An allostratigraphic approach (i.e. distinctive discontinuity surfaces between lithological layers B/C and G/H) enables distinction of Lateglacial till (layers A–B), pre-Litorina Baltic Sea (layers C–G) and Litorina to present Baltic Sea (layers H–I) allounits to be distinguished in the northern GR. Both of these allostratigraphic boundaries marking discontinuity surfaces can be followed, and thus correlated, outside the gulf in the northern Baltic.

10. Reconstruction of the Late Weichselian and Holocene depositional history outlines distinctive characteristics of sedimentation in the GR through the different stages of development of the Baltic Sea Basin.

11. The linear glacial relief features described from the GR largely support earlier ice flow reconstructions in this region. A southeast direction in the northern and central part of the GR is dominant, as indicated by till topography (2a, 2b in Fig. 14) and the coastline indentation pattern of southern Saaremaa. Towards the southern part of the gulf the orientation of streamlined features turns slightly southwards, which is proved by rare features in the till topography offshore (5e in Fig. 14), but more explicitly by Latvian onshore features just south and southeast of the gulf.

12. Around Pärnu Bay and the Irbe Strait, unlike in the central part of the gulf, NE–SW oriented linear relief features dominate in the till topography (3a and 3d in Fig. 14). These deviations from the main direction of the Riga ice stream are in good accordance with the main land data around the gulf. They show that the ice divide zones in southern Estonia (Sakala Upland) and in the central part of the Kurzeme Peninsula locally changed the course of the ice flow.

13. The influence of the Kurzeme ice divide zone can be followed northwards, where it resulted in deviating linear bottom features (3d and 2a in Fig. 14) and coastline indentations at the southern coast of Saaremaa Island. The long radial esker in central Saaremaa (5b in Fig. 14), 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.

14. The only evidence of ice-marginal formations in the offshore GR occurs just south of the Sõrve Peninsula. A northeast–southwest 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 in Fig. 14). 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 GR, as has been shown earlier in some deglaciation reconstructions.

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

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SUMMARY IN ESTONIAN

Liivi lahe põhjaosa hilisjääaja ja jääaja järgsete setete kompleksne seismoakustiline ja litoloogiline uurimus

Võrreldes enam kui poolteist sajandit väldanud geoloogiliste uurimustöödega Eesti maismaal on Eestit ümbritseva mere geoloogiat süstemaatilisemalt uuritud veidi rohkem kui kolmkümmend aastat. Merealade otsene kättesaamatus, meregeoloogiliste uurimustööde spetsiifika nõuavad teistsugust lähenemist ja erinomaseid meetodeid, millede rakendamine ja läbiviimine on võrreldes maismaaga alati seotud suurte kulutustega. Seoses üha suureneva majandusliku survega rannikualadele on viimastel aastatel märgatavalt aktiviseerunud inimtegevus (maavarade otsing, tuuleenergia parkide rajamine jmt) ka rannalähedases meres, mis nõuab erinevate rakenduslike geoloogiliste uurimustööde teostamist. Mida põhjalikum ja detailsem on teaduslike baasuuringute taust, seda kindlamale alusele saavad toetuda ka erinevad rakendusuuringud.

Juba aastakümneid on olnud üheks põhiliseks meregeoloogiliseks uurimismeetodiks seismo-akustiline pidevsondeerimine (vt. Tuuling 2011), mille areng viimastel aastakümnetel on olnud otseselt seotud infotehnoloogilise ja digitaalse revolutsiooniga. See meetod on suuresti aluseks ka käesolevale tööle, mille eelduseks olid 1980 a lõpu ja 1990 a alguse põhjapanevad poliitilised muutused, mis avasid Läänemere idaranniku s.o. Baltimaade rannikualad rahvusvaheliseks koostööks.

Kuigi 1990 a alanud Rootsi–Eesti ühisprojekti teravik oli suunatud neid riike lahutava merealuse ala Paleosoilise settekompleksi uurimisele, kasutati suruõhukahuriga (100–500 Hz) kui seismiliste lainete allikaga paralleelselt Läänemere pudedate põhjasetete, s.o. hilisjääaja ja jääaja järgsete Läänemere setete uurimiseks ka madalsageduslikku kajaloodi (3–4 KHz). 1995 a suvel kaeti regulaarse (5 km vahemaa tagant) põhja lõunasuunalise seismiliste profiilide võrgustikuga Liivi lahe Eestile kuuluv põhjaosa (ligikaudu 1000 km profiile). Selle ekspeditsiooni madalsagedusliku kajaloodi andmetele tuginedes esitati esmane Riia lahe hilisjääaja ja jääaja järgsete Läänemere setete seismo-akustilise liigestuse skeem (Tsyrulnikov et al. 2004). Sellele tuginedes kavandati 2004 a suvel sellesse piirkonda täiendav ekspeditsioon lisaprofiilide tegemiseks (> 600 km) ning põhjasetetest puursüdamike võtmiseks (13 puursüdamikku) 6 m pikkuse Kullenbergi tüüpi settetoruga.

Saadud andmetest tulenes ka väitekirja põhieesmärk: Liivi lahe hilisjääaja ja pärast-jääaegsete setete seismo-akustilise – ja litoloogilise koondläbilõigete välja töötamine, nende omavaheline korreleerimine ning Liivi lahe jääaja järgse arengu rekonstrueerimine. Selle uurimustöö temaatikaga seotud aspekte ja saadud tulemusi on üksikasjalikult käsitletud väitekirjale lisatud teaduslikus artiklis Paper I (Kalm et al. 2006) ja Paper II (Tsyrulnikov et al. 2012). Kuna seismo-akustilised profiilid sisaldasid ka andmeid Liivi lahe hilisjääaja aegse reljeefi ja glatsiaalsete pinnavormide kohta, arenes sellest täiendav idee uurida nii lahe piires kui ka seda ümbritseval alal veel ka liustikulise päritoluga joonelisi pinnavorme, et saada informatsiooni Liivi lahe nõo kujunemisel olulist rolli mänginud Pleistotseeni liustike liikumisteedest, suundadest ja dünaamikast. Selle temaatikaga seotut käsitletakse üksikasjalikult väitekirjale lisatud teadusartiklis Paper III (Tsyrulnikov et al. 2008).

Eespool nimetatud teaduslikes artiklites esitatud tulemused näitavad uut informatsiooni Liivi lahe tekkimisest, kujunemisest ja arengust Läänemere osana. Saadud tulemuste detailne käsitlus võimaldab korrelatsiooni/võrdlemist sarnaste setete kompleksidega üle Läänemere ning moodustab põhjalikku baasi tulevastele geoloogilistele uuringutele, maavarade otsingutele, rajatiste ehitamisele ja arengu prognoosile. Olulisemad Liivi lahe hilisjääaja ja jääaja järgsete setete geoloogiat, Läänemere arengut, samuti selle piirkonna Pleistotseeni liustike liikumist ja dünaamikat käsitlevad teadustulemused on kokkuvõtvalt esitatud allpool:

1. Liivi lahe põhjaosa hilis- ja pärastjääaja setete kompleksne litoloogiline ja seismo-akustiline uurimine võimaldas eraldada üheksa litoloogiliselt selgelt eristuvat kihti, mis korreleeruvad seitsme seismo-akustilistel profiilidel eristuva kihiga. Selline korrelatsioon võimaldab regulaarsele seismo-akustiliste profiilide võrgule toetudes jälgida erinevate litoloogiliste üksuste levikut ja paksusi, aga samuti hinnata mõningaid sedimentoloogilisi ja settekeskkonna iseärasusi palju laiemal alal kui seda võimaldaksid üksikud puuraugud.
2. Liivi lahe nõo asukoht on seotud piirkonna süvastruktuuriga, kuna siin ristuvad erisuunalised süvamurrangute tsoonid on tektooniliste rikete ja kivimite purustusvööndítena jälgitavad ka platvormes settelises pealiskorras. Viimased on selgelt soodustanud liustiku erosiooni, määratledes sellega nende liikumisteid ja dünaamikat.
3. Liivi lahe nõgu on suuresti kujundatud Pleistotseeni liustike aktiivse kulutustegevuse tulemusena. Lahe põhjas kõikjal esinev moreeni kiht (kihid A ja B, AU I) on selle sügavamas keskosas maetud kõikjal nooremate setete alla, avanedes laialdaselt lahe madalamas, kaldalähedases osas. Selle paksus on 1–10 m, mis aga aluspõhjalistes orundites või liustikuliste kuhjevormides võib küündida kuni 30 m.
4. Kuni 9 m paksune moreenil lasuv settekiht (WGD), mis eristub üksnes Sõrve poolsaare ja Kolka neeme vahel (kiht C, AU II) korreleerub nn basseini moreeni kihiga, mis on varem kindlaks tehtud seda piirkonda ümbritsevatel saartel Saare- ja Hiiumaal.
5. Ülejäänud settekompleks korreleerub hästi erinevate Läänemere arengu staadiumitega, kusjuures Balti jääpaisjärve ja Antsülusjärve (kihid D – G, AU III – AU VI) komplekside paksus ja konfiguratsioon järgib selgelt viimase jäätumise moreenipinna reljeefi, s.t. selles esinevaid nõgusid. Need kihid on selgelt paksemad ja täiuslikuma läbilõikega nõgude keskosas, kaldudes õhenema ja välja kiilduma nõgude vahelistel kõrgematel aladel

6. Valdavalt 10–15 m paksuses viirsavide läbilõikes (kanalilaadsetes süvendites kuni 30 m) esinev selge üleminek liustiku serva lähedastelt (proksimaalsetelt) kihtidelt (kiht D, AU III) sellest eemale jäävate (distaalsete) kihtide suunas (kiht E, AU IV), peegeldab selgelt sesoonset settelist varieeruvust Balti jääpaisjärves ning liustikuserva pidevat taganemist. Pärastjääaegne Joldiamere staadium (kiht F, AU V) koos oma esialgse mageda (F1) ja soolase (F2) vee faasidega on esindatud 3.5–5 m paksuse, liivaka/aleuriidika savika kompleksiga. Järgnev Antülusjärve savikas kompleks (kiht G, AU VI) on tavaliselt 4–6 m paksune. Erandina võib nii Joldiamere kui ka Antsülusjärve settekompleksi paksus küündida kanali laadsetes süvendites kuni 15 m.
7. Noorim, horisontaalkihiline Litoriina ja Limneamere settekompleks (kihid H ja I, AU VII) lasub põikselt vanemaid kihte lõikaval erosioonipinnal. See peegeldab Läänemere taasühinemist ookeaniga, mis tõi kaasa basseini kiire ja ulatusliku regresseerumise. Litoriina- ja Limneamere levik on selgelt piiritletud lahe keskosa sügavamate nõgudega kus nende paksus küündib kuni 27 m.
8. Märkimisväärsed erinevused litoloogilistes koondläbilõigete mis tuginesid viie algselt uuritud (esitatud artiklis I – Kalm et al. 2006: Table 2) ja hiljem kogu kolmeteistkümne puursüdamiku (esitatud artiklis II – Tsyrulnikov et al. 2012) kirjeldamise vahel peegeldavad Läänemere hilisjääaja ja jääaja järgsete setete ja nende kihtide suurt varieeruvust ning nende korreleerimise keerukust juba väga piiratud alal.
9. Allostratigraafiline meetod (selged põiksuspinnad kihtide B/C and G/H vahel) võimaldab Liivi lahe põhjaosas kõikjal eristada selgelt hilisjääaja moreeni (kihid A–B), Litoriinamere eelset (kihid C–G) ja – järgset Läänemere settekomplekse. Mõlemad allostratigraafilised piirid on jälgitavad ka Liivi lahest väljaspool Läänemere põhjaosas.
10. Hilisjääaja ja jääaja järgse settimise ajaloo rekonstrueerimine annab ülevaate settimise iseärasustest Liivi lahes igal Läänemere arengu etapil.
11. Lineaarsed glatsiaalse päritoluga pinnavormid Liivi lahes ja selle ümbruses kinnitavaid suuresti selles regioonis tehtud varasemaid Pleistotseeni liustike liikumisteede ja dünaamika rekonstruktsioone. Loode kagusuunaline liustike liikumise suund domineerib selgelt Liivi lahe kesk- ja põhjaosas, millele viitavad selgelt moreenipinna reljeefi iseärasused lahe keskosas (2a, 2b Fig. 14) ja tugevasti Saaremaa lõunarannikut liigestavate lahtede orienteeritus (2b Fig. 14). Kaugemal lõunas muutub liustikutekkeliste pinnavormide orienteritus rohkem põhja lõunasuunaliseks, mida tõendavad harvad moreenipinnal jälgitavad reljeefivormid Läti ranniku lähedal (5e Fig. 14) aga veelgi enam lahest lõunase ja kagusse jäävatel aladel ja Läti maismaal (Fig. 14).
12. Erinevalt Liivi lahe keskosast domineerivad Pärnu lahe ja Irbeni väina ümbruse moreenipinna topograafias kirde edelasuunalised pinnavormid (3a ja 3d Fig. 14). Sellised kõrvalekalded Riia liustikukeele peamisest liikumissuunast on heas kooskõlas lahte ümbritsevate maismaa-andmestikuga, mis

näitavad et jäälahkme vööndid Lõuna Eestis (Sakala kõrgustik) ja Kuramaa poolsaare keskosas mõjutasid ja muutsid lokaalselt liustike liikumise suunda.

13. Kuramaa jäälahkme vööndi mõju ulatub ilmselt ka põhjapoole Liivi lahe alla, kus on jälgitav selgeid lahknevusi lahepõhja jooneliste pinnavormide (3d ja 2a Fig. 14) ja Lõuna Saaremaa rannajoone lahelise sopistumise (3d ja 2b Fig. 14) orienteerituses. Pikk radiaalne oos Kesk saaremaal (5b Fig. 14) formeerus ilmselt laias põhja-lõunasuunalises jäälõhes, mis arenes vahetult põhjapool Kuramaa jäälahkme alast mõjutatud piirkonnast.
14. Ainus liustiku servamoodustiste ala Liivi lahes esineb vahetult Sõrve säärest lõunasse, kus Irbeni väinas jälgitav kirde edelasuunaline jooneline merepõhja vallseljak on maismaal jälgitava Pandivere–Neeva või Palivere servamoodustise lõasuunaliseks jätkuks (1a Fig. 14). Meie uurimus ei kinnitanud mõningatel varasematel rekonstruktsioonidel kujutatud liustiku servamoodustiste vööndi olemasolu ja kulgemist üle Liivi lahe ida ja keskosa.
15. Liivi lahe ümbruse Pleistotseeni jäätumise liustike liikumiste ja dünaamika ning geoloogia detailsemateks aruteludeks oleks edaspidi hädavajalik täpsemalt määratleda siinsete liustikuliste pinnavormide ja setete vanust.

PUBLICATIONS

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