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# Late Weichselian and Holocene sediments and their acoustic signatures in the northeastern part of the Gulf of Riga

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**Abstract** Five sediment cores, up to 5.3 m long, taken in 2004 from the north-eastern part of the Gulf of Riga, were studied in order to support interpretations of acoustic profiles. The acoustic profiles, altogether 1000 km long, were recorded using mud-penetrating ecosounder at 4 kHz. The sequence of Late Weichselian and Holocene deposits was subdivided into nine sediment layers, which correspond to six acoustically different zones in acoustic profiles. A transitional lithologic boundary on top of rhythmic couplets of the Baltic Ice Lake clay and silt, together with two sharp disconformities levels that occur below and above a homogeneous brownish grey clay, are the most distinct surfaces in acoustic profiles. The maximum thickness of nine sediment layers above the Late Weichselian till is 8,6 m.

***Keywords*** *Stratigraphy, sedimentology, acoustic profiling, Late Weichselian, Holocene, Gulf of Riga, Baltic Sea.*

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## INTRODUCTION

The Gulf of Riga is a northwest–southeast oriented, semi–closed part of the Baltic Sea, separated in part by the Saaremaa and Muhu Islands. The Gulf of Riga has a surface area of 19,000 km$^2$, is up to 67 m deep, and has a relatively uniform bathymetry. According to Berzinsh (1995), the average depth of the gulf is 26 m. The current bathymetry reflects glacial erosion by the Central Latvian glacier lobe (Karukäpp 2004) and reveals the central deepest part of the depression. With the exception of the area around the Irbe Strait, the seafloor deepens towards the Ruhnu Island. The Ruhnu Island and the surrounding, elevated seafloor area comprise a large drumlin-like landform (Fig. 1). According to seismo-acoustic data, the main sea-bed depression, its contours and the depth of glacial erosion around the Ruhnu Island are well expressed on the till surface from the Late Weichelian glaciation. The till surface is widely exposed in the near-shore, shallow water areas (Juškevičs & Talpas 1997), and becomes gradually covered by a layer of late glacial and Holocene sediments, thickening towards the centre of the depression. Change from glacial to glaciolacustrine sedimentation occurred after the glacier retreat from the Valdemarpils (Sakala in Estonian) marginal zone, ca 13,000 $^{14}$C years (Savvaitov & Veinbergs 1999) or ca 14,100 cal. $^{14}$C years ago (age of the Sakala zone, Kalm 2006).

Earlier information on sedimentology and lithostratigraphy of the late glacial and Holocene deposits of the Gulf of Riga is mainly focused on near-shore and on-shore sediments (Kessel 1976 1980; Lutt 1987) or the central and south-western parts of the gulf

(Kalnina et al. 1999; Kalnina 2001). However, extensive acoustic profiling was performed in 1995 in the northern part of the Gulf of Riga. With the exception of a small section along one profile offshore Saaremaa Island (Noormets & Flodén 2001a), the high quality seismo-acoustic data is largely unstudied. In order to support interpretation and correlation of the acoustic data, a series of sediment cores were taken from the northern and north-eastern parts of the gulf in the summer of 2004. We provide these new data on sediment structure, stratigraphy and deposition environments, obtained from analyzed sediment cores. Secondly we provide examples and discuss correlation between the distinguished sedimentary layers and echograms.

## MATERIAL AND METHODS

An analogue, single-channel, continuous seismic reflection technique was used for seismic profiling in the northern part of the Gulf of Riga in 1995 (Juškevičs & Talpas 1997). Altogether ca 1000 km of profiles were shot and the Estonian part of gulf was covered with a grid of regularly spaced, north-south oriented seismic/acoustic lines, located 5 km apart (Fig. 1). The pulse of the echo sounder working with 4 KHz easily penetrated the late glacial and postglacial lacustrine and marine sediments but was largely rebounded from the upper surface of the underlying glacial till. Till deposits above the bedrock surface were traceable using low frequency seismic recordings (250-500 Hz).

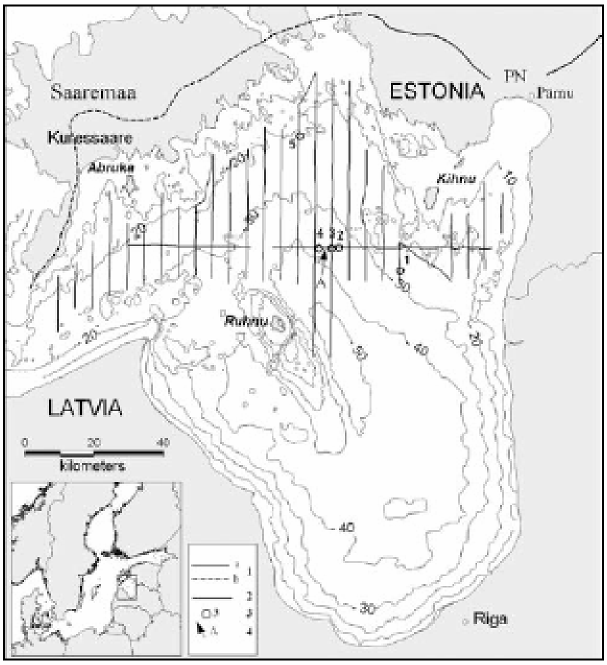


Fig. 1. Bathymetry of the Gulf of Riga, seismo-acoustic survey lines, coring sites and location of the seismic section displayed in Fig. 2. 1 – ice marginal formations of Pandivere age: (a) well-dated; (b) poorly-dated; 2 – seismo-acoustic profiles shot in 1995, 3 – sediment cores used in this study, 4 – location of the seismic section in Fig. 3.

A vertical resolution in the acoustic profiles, which were displayed on an EPC precision graphic recorder with a time-sweep of 0.5 s, was about ten centimetres. A seismic wave velocity of 1500 m/s was applied in sediment thickness calculations (Flodén 1980; Winterhalter 2001; Noormets 2002a).

Based on the acoustic signature variations, six units were earlier distinguished in the Quaternary sediments of the area (Tsyrulnikov *et al.* 2004). Relying on that information the coring locations were selected so that: 1) all acoustically different sediment layers were represented in the cores, and 2) boundaries between these layers were penetrable using 6 m long piston corer. In the summer 2004, from the *R/V Fyrbyggaren* 15, sediment cores were taken from the study area, out of which five (Fig. 1, Table 1) were subjected to detailed macroscopic description of textures, lamination, character of lamination boundaries and colour (Munsell), and lithostratigraphic interpretation. With the aid of geological-palaeogeographical data from Estonian and Latvian onshore areas (Kiipli *et al.* 1993; Juškevičs & Talpas 1997; Kalm & Kadastik 1998; Veski *et al.* 2005; Kalm 2006) and from central Baltic Sea (Björck 1999; Noormets & Flodén 2002a, 2002b) an event stratigraphic interpretation of sediment layers was performed.

## RESULTS AND INTERPRETATION

### Lithology of sediment layers

In the north-eastern part of the Gulf of Riga the sequence of late glacial and Holocene deposits can be divided into nine major sediment layers, which are displayed in a generalized section (Table 2). None of the studied cores contain all of the described sediment layers. From the bottom up the sediment layers are as follows:

Layer A (maximum thickness 91 cm). Massive, matrix supported plastic, grey clayey diamicton, with a few pebbles and pieces of gravel. Upper half of the diamicton becomes gradually sandy and a gravely zone occurs (Fig. 2A). Upper surface of the sandy diamicton is sharply erosional. The clayey diamicton is interpreted to represent deposition from the last grounded glacier, corresponding to the Valdemarpils/Sakala or the following Pandivere oscillation. The sandy-gravely till represents the beginning of deglaciation and some melt water drainage at the bottom of the glacier.

Layer B (121 cm) consists of two divisions. The lower portion (Layer $B_1$, ca 50 cm) is represented by vague layers of grey diamicton and brown massive silty clay. It is covered by greyish brown, silty clay with indistinct varve-like lamination (Layer $B_2$). Occurrence of clasts (balls) of clay and sand is characteristic of the silty clay sequence. These sediments are interpreted as a subaqueous, waterline glacial diamicton (lower por-

Table 1. Location of core sites, depth of water and core recovery in this study.

| Core No. | Latitude (WGS84) | Longitude (WGS84) | Water depth, m | Recovery, m |
|---|---|---|---|---|
| 1 | 57°56.59´ | 23°50.24´ | 28 | 5.35 |
| 2 | 58°00.11´ | 23°32.19´ | 32 | 5.33 |
| 3 | 58°00.02´ | 23°30.07´ | 32 | 5.19 |
| 4 | 57°59.91´ | 23°21.75´ | 38 | 3.60 |

tion), deposited mostly from floating ice through basal melt out and debris flow (Kalm & Kadastik 2001), which was followed by proglacial cyclic deposition at a later stage.

Layer C (50 cm). Very clearly laminated, greyish brown, silty clay with distinct finer (clay) and coarser (silt) sub-layers. The entire layer usually consists of 20-50 couplets, which are up to 5.5 cm thick (Fig. 2B). Both, lower and upper boundaries of the layer are transitional. Sediments in layer C are interpreted as annual varves deposited in proximal conditions in the Baltic Ice Lake.

Layer D (102 cm) includes medium to finely but distinctly laminated (1.5–0.2 cm), greyish brown, silty clay. Lamination in the sequence thins upwards and the sediments represent a transition from proximal to distal conditions of varve deposition in the Baltic Ice Lake.

Layer E (10 cm). Massive or occasionally micro-laminated, dark reddish brown, silty clay. This is a very distinct and easily traceable unit because of its reddish colour. These sediments are preliminary correlated with period of intensified erosion of land areas (Devonian "Old Red Sandstone" areas) in response to the drainage of the Baltic Ice Lake and the base level lowering, between 11,565 and 11,545 cal. $^{14}C$ years BP (Andrén *et al.* 2002). According to Talviste (1988) and Veski *et al.* (2005) the catastrophic regression lowered the water level in the Pärnu area, north-eastern part of the Gulf of Riga, by approximately 24-25 m.

Layer F (90 cm) comprises brown to greyish-brown, massive clay, with occasionally vague lamination and silty interlayers. The upper surface of the layer shows a sharp boundary and bioturbation. The latter may indicate a very low rate of deposition or even a discontinuity. The sediment layer is interpreted as the deposit of the freshwater Yoldia Stage, following the water level drop and drainage of the Baltic Ice Lake.

Layer G (440 cm) is the thickest sedimentary sequence and may be subdivided into five divisions. Layer G, which is present in three out of five studied cores, generally includes light grey to greyish-brown, massive clay and silty clay, with black dots, patches and lenses of Fe-monosulphide (FeS). The layer begins with a 5-20 cm thick, massive layer of dark grey to black clay, followed by grey clay with very few black dots. In the Estonian offshore the first FeS-rich layer, representing anoxic conditions and increased organic contents in the sediments, probably reflects the beginning of the Ancylus Lake phase (Kiipli *et al.* 1993). The middle part of layer G consists of clay, again rich in Fe-monosulphide black patches. The layer ends with grey massive silty clay with few black patches in its uppermost part. The upper boundary of the layer is very distinct and sharply erosional (Fig. 2C). The layer G is interpreted as the deposit of the Ancylus Lake phase when predominantly anoxic conditions prevailed in the sediments.

Layer H (45 cm) has olive grey to brown sand and silt with a black FeS-rich clay interlayer (2-4 cm) in the middle. The lower portion of the sand has normal grading and a sharp distinct lower boundary. This sandy layer is present in most of the cores, often discordantly overlying the Baltic Ice Lake, Yoldia Sea or Ancylus Lake deposits. In agreement with Kiipli *et al.* (1993)

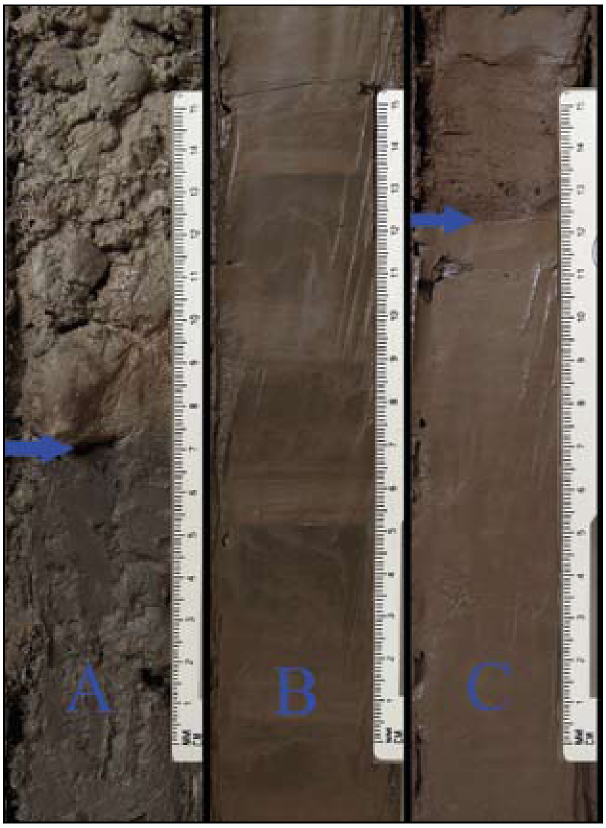


Fig. 2. Photos of the most characteristic sediment layers. A – dark grey clayey diamicton below with overlying sandy diamicton with gravel and pebbles; the arrow indicates a pebbly–gravelly zone between two diamicton types. B – clay and silt in 4–5 cm thick rhythmic couplets, interpreted as proximal varves of the Baltic Ice Lake. C – homogeneous clay below, with overlying laminated sand; the arrow points at the sharp contact between clay and sand, which is interpreted as the Ancylus Lake–Litorina Sea boundary.

Table 2. Generalized section of Late Weichselian and Holocene deposits in the north-eastern part of the Gulf of Riga.


| Layer | Colour | Sediment | Contact | Interpretation and event stratigrphy |
|---|---|---|---|---|
| I | Gley 1/2,5N | Gyttja, homogeneous, greenish black | Discontinuity | Post-Litorina organic mud |
| H | 5Y/4.3<br>5Y/4.2 | Sand and silt, olive grey to brown, weakly laminated, with black clay interlayers | Sharp erosional | Regression, beginning of the Litorina Sea Stage ca 9000 yrs BP (Veski et al. 2005) |
| G, $G_5$ | 2.5Y/4.2<br>2.5Y/5.2<br>2.5Y/4.2<br>2.5Y/4.1 | Clayey silt, homogeneous, dark greyish brown, very few black patches;<br>Clay, homogeneous, dark greyish brown, rich in black mottling and banding, few FeS framboids | Transitional | Second period of strongly anoxic conditions in deposits |
| G, $G_4$ | 5Y/4.1<br>2.5Y/4.1 | Silty clay, homogeneous, dark brownish grey | Transitional | "Lower FeS-rich layer" by Kiipli et al. 1993, beginning of the Ancylus transgression, dated to 10,200 cal. $^{14}C$ yrs BP (Veski et al. 2005) |
| G, $G_3$ | 5Y/4.1 | Clay, homogeneous, dark grey to black, diffuse black mottling, few FeS framboids | Transitional | |
| G, $G_2$ | 10YR/4.1 | Clayey silt, massive, dark grey to brownish grey with some black mottling, contains two, 2-4 cm dark grey clay layers | | |
| G, $G_1$ | 5Y/4.1 | Clay, finely laminated, dark grey to black with black diffuse mottling and banding of FeS | Sharp, disconti-nuity with bioturbation | First clear anoxic conditions, beginning of the Ancylus Lake Stage at 10,700 cal. $^{14}C$ yrs BP (Veski et al. 2005) |
| F | 10YR/4.2 | Clayey silt, massive or weakly laminated, dark greyish brown | Transitional | Deposition in the Yoldia Sea freshwater conditions |
| E | 2.5Y/4.2 | Clay, dark brown, occasionally microlamination | Transitional | Drainage of the BIL at 11565 cal. $^{14}C$ yrs BP (Andren et al. 2002), water level drop by 24 m |
| D | 10YR/4.2<br>10YR/4.2 | Clay & silt in rhytmic couplets thinning upwards (1,5-0,2 cm), greyish brown | | Gradual change from proximal to distal varves of the Baltic Ice Lake |
| C | 10YR/4.2<br>10YR/4.3 | Clay & silt in rhytmic couplets, brown to greyish brown, microlaminae in brighter parts of rhytmites | Transitional<br>Transitional | Short (50 varves) and rapid (4-5 cm/yr) deposition of proximal varves of the Baltic Ice L. |
| B, $B_2$ | 2.5Y/4.3<br>2.5Y/4.2 | Clay, greyish brown, rhytmic lamination, microlaminae within brighter parts of rhytmites | | Rhytmic deposition, supported with basal melt-out from floating ice |
| B, $B_1$ | 5Y/5.1 &<br>10YR/4.2 | Layers of grey diamicton and grayish brown massive clay | Sharp erosional boundaries | Decoupling of ice from the bed, deposition and erosion alternate |
| A | 2.5Y/4.1 | Sandy diamicton, dark grey<br>Sandy diamicton with gravel and few pebbles | | Beginning of deglaciation, oscillation of the ice, meltwater drainige at the bottom of ice |
| | 2.5Y/4.1 | Clayey diamicton, massive, dark grey | Sharp erosional | Glaciation, Valdemarpils/Sakala (>14100 cal. $^{14}C$ yrs BP) Stade |

and Veski *et al.* (2005), the olive grey sandy silt is interpreted to represent the Litorina Sea sediments, preceded by the regression at the beginning of the Litorina Sea Stage.

Layer I (36 cm). Massive, loose organic mud (gyttja), black in its lower half and becoming a brown, highly organic rich mud at the top of the layer. This thin gyttja layer was present in only one core.

## Acoustic signatures of sediment layers

Distinct and widespread seismic reflector surfaces enabled distinction of six acoustically contrasting layers in the Quaternary sediments of the study area. Acoustic signature pattern/configuration and the darkness in particular, vary also within these layers. Distinguished acoustically contrasting layers, the acoustic signature and hue variations inside the units and the correlation between acoustic layers and sediment layers are shown on Fig. 3. A selected section along an east-westerly acoustic profile (see location in Fig. 1) crosses a depression on the till surface and demonstrates variations in sediment thickness. As a rule the thickness of the late glacial and Holocene sediments increases gradually towards the centres of depressions on the till surface (Fig. 3), whereas on bathymetric highs the lowermost seismic units often wedge out.

Acoustic layer I is clearly visible in profiles as the lowermost zone and includes sediments which are largely impenetrable for a 4 kHz sediment sounder. In sediment cores this unit corresponds to massive, clayey or sandy diamicton that is sediment layer A (till) in the lithology diagram (Table 2). At this frequency interval we were not able to determine the thickness and location of the lower boundary of the till layer on the seismic recordings.

Acoustic layer II is characterized in the profiles as a lighter part of the succession overlying the till, largely void of internal seismic reflections (Fig. 3). The layer has very distinct upper boundary, expressed as the first dark band, made up of number of very closely spaced seismic reflectors. Thickness of the layer in the acoustic profiles varies from 0 to 2.5 m. In sediment cores this acoustic layer corresponds to a massive or vaguely laminated diamicton and clay with proglacial laminated clay (sediment layer B in Table 2).

Acoustic layer III is distinguished in most of the profiles as a dark band of numerous, very closely spaced seismic reflectors, which are occasionally intercalated by thin lighter stripes. However, in the depressions where the unit is thicker, two distinct dark stripes, with a lighter zone between them denote the lower and the upper boundary of the unit (Fig. 3). Sediments of this acoustic layer were described in the cores 4 and 5 and they include varved clay (sediment

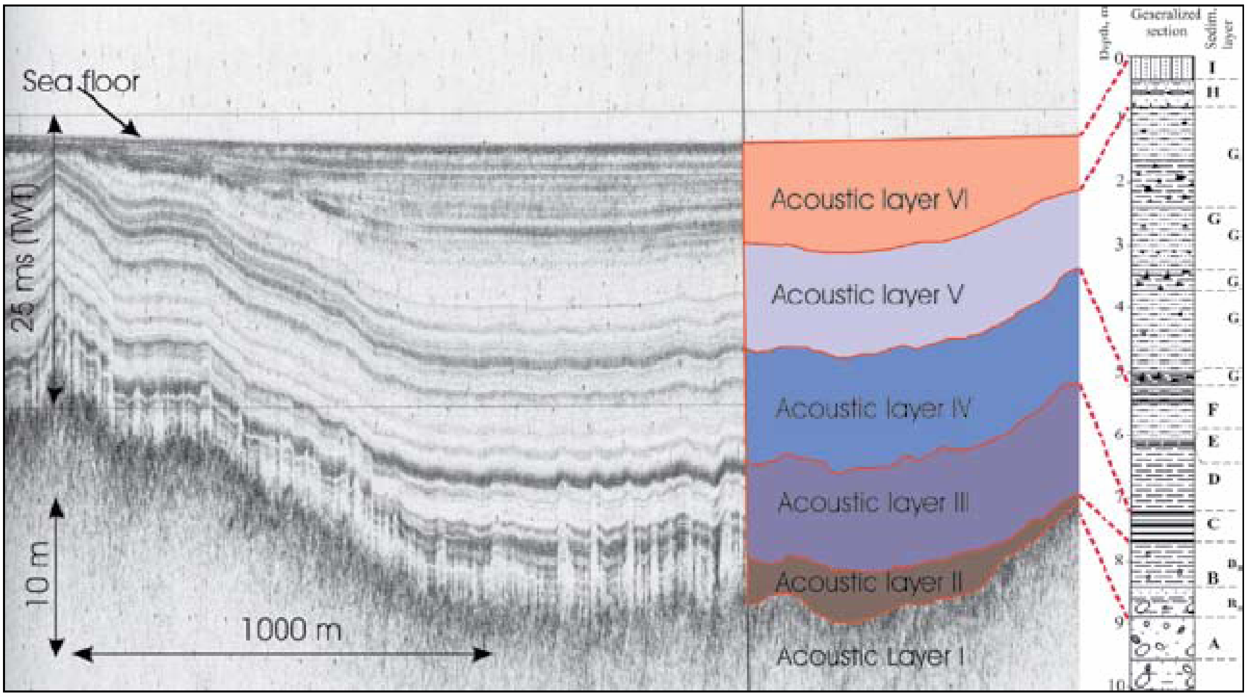


Fig. 3. A selected section of acoustic profile (location see Fig. 1) presenting acoustic subdivision of the Late Glacial and Holocene sequence and their correlation with the sediment layers.

layer C) deposited in proximal conditions in the Baltic Ice Lake. According to the acoustic data, the thickness of the layer usually varies from 4 to 6 m.

Acoustic layer IV appears on the profiles as a light greyish interval with a few, slightly darker, thin internal bands of very closely spaced reflectors (Fig. 3). Its upper boundary is very distinct as it is the strongest/darkest stripe above the base of acoustic layer IV (Fig. 3). Sediments of this unit were studied in three different sediment cores (2, 3 and 5). The lower part of this acoustic layer is represented by silt and silty clay of distal varves of the Baltic Ice Lake (sediment layers D & E in Table 2) while its upper part consists of massive clayey silt of the Yoldia Sea (sediment layer F). The few closely spaced strong reflectors in the uppermost part of this acoustic layer presumably reflect the silty layers within the Yoldia Sea clay (Fig. 3). The striking upper seismic boundary of the acoustic layer coincides with the sharp discontinuity level between the sediment layers F and G, that is, between the Yoldia Sea and the Ancylus Lake sediments (Table 2). According to the echograms the thickness of the acoustic layer varies between 7.5 and 8.5 m.

Acoustic layer V is characterized by a signature and transparency very similar to the underlying acoustic layer IV (Fig. 3). Compared to layer IV, layer V has a slightly darker greyish tone in its lower part, which also includes few thin dark internal stripes. The upper, homogeneous and light half of the acoustic layer suggests to a homogeneous layer of sediments. This unit has a distinct upper seismic boundary, overlaid by a contrasting, dark greyish acoustic layer VI (Fig. 3). The acoustic layer V corresponds to the homogeneous clayey silt and silt of the Ancylus Lake (sediment layer G). Strong and dark thin stripe just above the lover boundary of the acoustic layer V is obviously due to a finely laminated dark clay layer with abundant black bands and staining of FeS. Based on the acoustic data, the thickness of the layer V is about 4-5 m.

Acoustic layer VI appears on profiles as a dark greyish unit made up of numerous, very closely spaced, sub-horizontal and parallel reflectors (Fig. 3). According to sediment core data this boundary corresponds to the erosional contact between the homogeneous clay (Ancylus Lake clay, sediment layer G) and the sand and silt of sediment layer H (Litorina Sea sand and silt). Spatial distribution of the acoustic layer VI is limited as it occurs only in restricted depressions, where its thickness reaches up to 5-6.5 m.

## DISCUSSION

The till layer at the bottom of the studied sediment succession is clearly visible in all acoustic profiles and makes the base for overlaid sediment layers that were deposited in subaquatic conditions. Similar beds, impenetrable for acoustic soundings and underlying late/postglacial sediments, are well known all over the Baltic Sea (e.g. Flodén 1981; Endler 1998; Winterhalter 2001). According to Juskevičs *et al.* (1997) the thickness of the till layer in the Gulf of Riga rarely exceeds 5-8 m, while Noormets and Floden (2002a) reported a 2-10 m (in ridges 20 m) thick till layer in the north-central Baltic Sea.

A sharply erosional contact which separates the till below from the waterlain glacial diamicton above is not distinct in acoustic profiles. The waterlain glacial diamicton, including debris flow and basal melt-out deposits, is widely spread over western Estonian islands (Kalm & Kadastik 2001) and near-shore areas around the islands (Eltermann 1993; Kiipli *et al.* 1993). Clearly laminated rhythmic couplets of varves (sediment layer C, proximal varves of the Baltic Ice Lake) are easily recognizable on acoustic profiles, although the layer has transitional boundaries at the base and top. The base level of varved clays in the Gulf of Riga area can easily be correlated with the reflector at the base of the late- to postglacial sediments, well known in many seismo-acoustic profiles from the other regions of the Baltic Sea (Mörner *et al.* 1977; Kiipli *et al.* 1993; Winterhalter 2001; Noormets & Floden 2002a, 2002b). The distinct seismic, as well as sediment boundary at the base of rhythmic couplets (acoustic layer III) is, however, diachronous and reflects the glacial retreat and onset of proglacial conditions in the Baltic Sea area.

Two sharp discontinuity levels confining, below and above, the homogeneous clay (sediment layer G, Ancylus Lake clay) are rather distinct on acoustic profiles, as strong and dark thin stripes (Fig. 3). Transition from the homogeneous clay to olive grey laminated sand and silt is distinct and easily followed in the acoustic lines. The non-cohesive, Litorina Sea sand and silt show a discordant bedding on top of the uneven surface of the homogeneous Ancylus clays, similar to the "basin fill" type of a deposition described by Winterhalter (1992, 2001) in the north-central Baltic. The distinct, homogeneous clay/laminated sand boundary is also well demonstrated in sediment cores from the Gulf of Riga, and presumably reflects the regression event at the beginning of the Litorina Sea Stage. Although, as noted by Andren *et al.* (2000), the same transition level is gradational in the deepest parts of the Baltic Sea.

In the Pärnu onshore region, close to the study area (Fig. 1), the onset of the Litorina Stage with the regression occurred at about 9000 cal. $^{14}C$ years BP (Veski *et al.* 2005). From this we may conclude that the sediment layers from A to G, or acoustic layers from II to V (see Fig. 3), were deposited during ca 5000 years – from the beginning of deglaciation at 14.1 Ky BP until the regression at 9 Ky BP. The combined maximum thicknesses of the acoustic layers between the Late Weichselian till and the Litorina Sea sand (acoustic layer II – 2.5 m; layer III – 6 m; layer IV – 8.5 m; layer V – 5 m) is 22 m, while in the studied core sections the correlative sediments constitute only 8.1 m (Table 2). These approximate figures on sediment thicknesses exemplify how widely the information on deposition rates may vary when calculated from the data of few sediment cores (in our example 1.6 mm/yr) or from continuous acoustic profiles (4.4 mm/yr).

The acoustic layer VI also includes the post-Litorina gyttja (sediment layer I), but in our seismic recordings a clear gyttja layer is missing, most likely due to limitations of the seismic equipment and recording parameters (pulse frequency 4 kHz, and stylus sweep). In the north central Baltic Sea Basin the gyttja unit was traced with a 12 kHz DESO echo-sounder using a large vertical scale (Winterhalter 2001). The very loose and pure organic mud on top of the Litorina sand and silt was present only in one sediment core, thus supporting earlier conclusions about its deposition only in isolated depressions where bottom currents are negligible (Winterhalter 2001).

## CONCLUSIONS

Nine sediment layers, described in Late Weichselian and Holocene deposits of the Gulf of Riga, correspond to six subdivisions in acoustic profiles. The sharp erosional contact on top of the basal till layer under the waterlain glacial diamicton is not distinctive in acoustic profiles. Although the lithologic boundary at the top of the well developed rhythmic couplets (proximal varves of the Baltic Ice Lake) is gradational, it gives a very clear seismic reflection. There are two sharp disconformity levels confining the homogeneous grey clay (deposits of predominantly anoxic phase of the Ancylus Lake) and are rather distinct on acoustic profiles as strong and dark thin lines. The distinct discontinuity level on top of the homogeneous clay, under the laminated olive grey sand, is well demonstrated in sediment cores from the Gulf of Riga and presumably reflects the regression event at the beginning of the Litorina Sea Stage. Very loose and pure organic mud on top of the olive grey Litorina sand and silt was present only in one sediment core, supporting the earlier conclusions about its deposition only in isolated depressions. Deposition rates of post-glacial sediments vary widely when calculated from the data of few sediment cores (in our example 1.6 mm/yr) or from continuous acoustic profiles (4.4 mm/yr).


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