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EDITORIAL ADDRESS * Prof. Dr.hab. Algimantas Grigelis, Lithuanian Academy of Sciences, 2600 VILNIUS, LITHUANIA * Phone +[370] 2 236504 * Fax +[370] 2 236408 * E-mail grigelis@geology.aiva.lt * PUBLISHER ACADEMIA PRESS, A. Goštauto 12, 2600 Vilnius, Lithuania.

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Litorina Maximum Transgression on the Southeast Coast of the Baltic Sea

Vytautas Gudelis

Gudelis, V. 1997: Litorina maximum transgression on the southeast coast of the Baltic Sea. *Baltica, Vol. 10*, pp. 5–8 Vilnius. ISSN 0067–3064

Vytautas Gudelis, Lithuanian Academy of Sciences, Gedimino Pr. 49a–21, 2001 Vilnius, Lithuania; *received 17th December, 1996, accepted 24th January, 1997.*

The article deals with the problem of maximal spread of the Litorina Sea transgression on the SE coast of the Baltic Sea (Lithuania). The shoreline of Litorina maximum lies at abs. height 5–6 m in the northern part of the coast and above 5–6 m below the modern MSL. The shoreline is inclined from N to S, the gradient of it is ca. 0.9 m / 10 km. The total range of post-Litorina crustal rise reaches approximately 5–6 m in the northern part of the coast. There are no evidences of Litorina shoreline deformation since Litorina maximum transgression.

Keywords: Baltic, SE coast, Litorina max., shoreline, morphometry.

INTRODUCTION

First schemes of isobases for different stages and phases of the Baltic Sea development during Late-Glacial and Post-Glacial times were published almost a century ago, and their compilation continued further up to the present days. The first schemes of isobases were constructed using direct geomorphological and stratigraphical data gathered mostly in Finland, Sweden and Denmark, whereas the corresponding isobases for East Baltic area (except for Estonian and Leningrad region territories) were extrapolated.

This article is devoted to the problem of the limit of the Litorina Sea maximum transgression (the so-called Litorina maximum or shortly Litorina limit). More information of the SE Baltic coast during the Late- and Post-Glacial times is available in earlier publications (Gudelis 1955, 1959, 1979, 1982; Kabailienė 1959, 1960; Rimantienė 1979).

Fig. 1. Cliff and accumulation terrace of Litorina maximum transgression about 3 km to the south from Palanga. The height of the cliff reaches here ca. 4–5 m. The upper part of the marine terrace is covered by eolian sands. Photo by V.Gudelis, 1953.

GEOMORPHOLOGICAL AND STRATIGRAPHICAL EVIDENCES

The Litorina maximum on the Lithuanian coast of the Baltic Sea is represented by an accumulative marine terrace bordered by a gently sloping cliffs (bluffs) cut into the glacial deposits, mainly boulder clay. The Litorina Sea terrace and cliffs are better expressed in the relief of the northern part of the Lithuanian coast (Šventoji-Palanga-Nemirseta). Southwards from Klaipėda seaport, the shore cliffs are represented in a form of small, low (0.5–1.0 m) and gentle land scarps. Spreading of Litorina maximum is shown in Fig. 2.

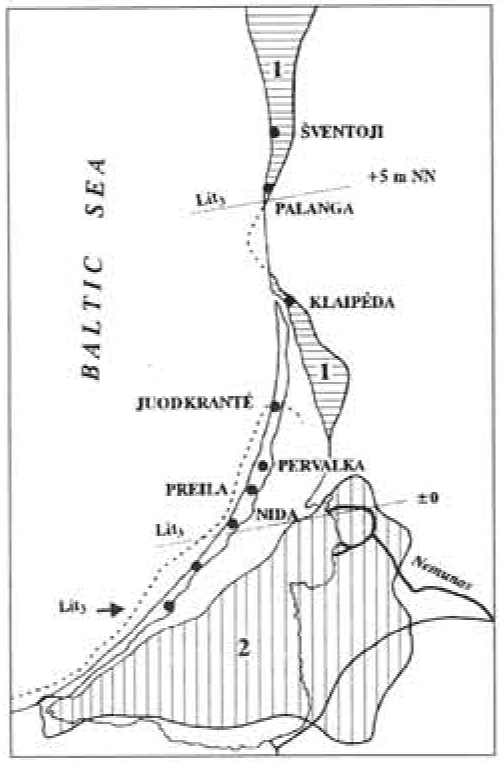

Fig. 2. A scheme showing the distribution of land and water during the Litorina transgression: *1* areas occupied by Litorina transgression, *2* territory of the Nemunas River delta and coastal lakes and lagoons. The situation of Litorina maximum ± 0 and + 5 m isobases is indicated too (Gudelis 1979).

Detailed stratigraphical investigations of the Litorina sediment series at the foot of the cliff about 0.5 km southwards from the so-called Birutė Hill in Palanga gave us a possibility to find and fix in many prospecting pits the absolute height of the Litorina marine sediment contact with underlying ground moraine. The altitude of the former Litorina waterline is passing about 5–6 m above the mean sea level (Fig. 3). The pollen and diatom investigations carried out in many places of the Litorina terrace with organogenic deposits stated the Late Atlantic and Early Subboreal age of it, i.e. ca. 5000 years B.P. (Kabailienė 1959). Thus, the age of the seashore cliff as well as the above-mentioned contact layer is most probably the same.

Some boreholes drilled in the southern part of the Nemunas River delta and the lagoon of Kuršių Marios (Šventlunka bay) revealed the presence of terrestrial wood-peat layers of Late Atlantic age situated now at ca. 5.5–6.0 m below the recent mean sea level. This fact speaks in favour of a 5–6 m submergence of this area during the last ca. 5000 years (Gudelis 1955).

As the Figs. 4, 5 show all old shorelines of the Baltic Sea on the Lithuanian coast are inclined from N to S. There is no doubt that this shoreline inclination is of a tectonic nature. The average rate of vertical displacement of Earth crust might reach about 1–1.5 mm per year. The "axis" of crustal tilting of the Litorina maximum shoreline or the so-called Zero-isobase was drawn by the author in the past across the Kuršių Nerija spit in the vicinity of the settlement of Nida (Gudelis 1981).

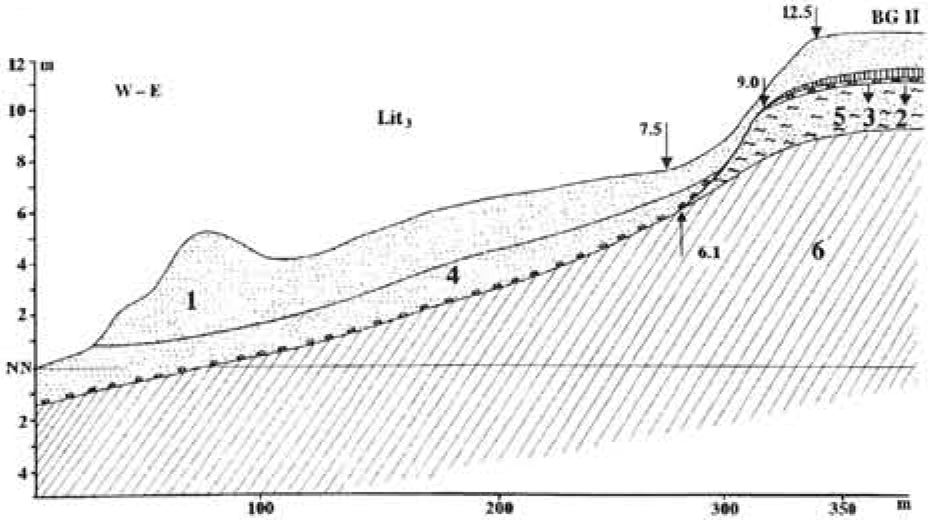

Fig. 3. Cross-section of the Litorina maximum accumulation terrace (Lit$_3$) in the neighbourhood of Palanga. *1* Eolian sands, *2* fen peat of Sub-Atlantic age, covered by eolian sand, *3* basal gravel with pebbles, *4* marine sands of various grain size of the transgressive phase (Lit$_3$), *5* clay at the basis of the BG II terrace, *6* boulder clay (till) of the last glaciation (Gudelis 1979).

Now the more precise estimation of a distance between the known absolute altitude of the contact level (terrestrial-lagoonal) in the borings made in SW corner of the Kuršių Marios Lagoon, as well as the marine contact layers in the vicinity of Palanga made it possible to draw the Zero-isobase of the Litorina maximum on the SE coast of the Baltic Sea more precisely.

Accepting the inclination ca. 0.9 m/km for the shoreline of the Litorina Sea maximum we are able to fix the absolute heights of isobases in the examined area as follows: Palanga +5.5 m; Klaipėda (Kopgalis) +3.7 m; Juodkrantė –1.0 m; Pervalka +0.6 m; Preila –0.3 m; Nida –1.0 m; Rasytė –3.7 m; Šventlunka bay –5.5 m. Thus, the Zero-isoline of the Litorina maximum on the Kuršių Nerija spit crosses the spit between the settlements of Preila and Pervalka.

The linear continuity of the Litorina maximum shoreline witnesses the absence of local vertical crustal dislocations (faults or flexures). The reacti-

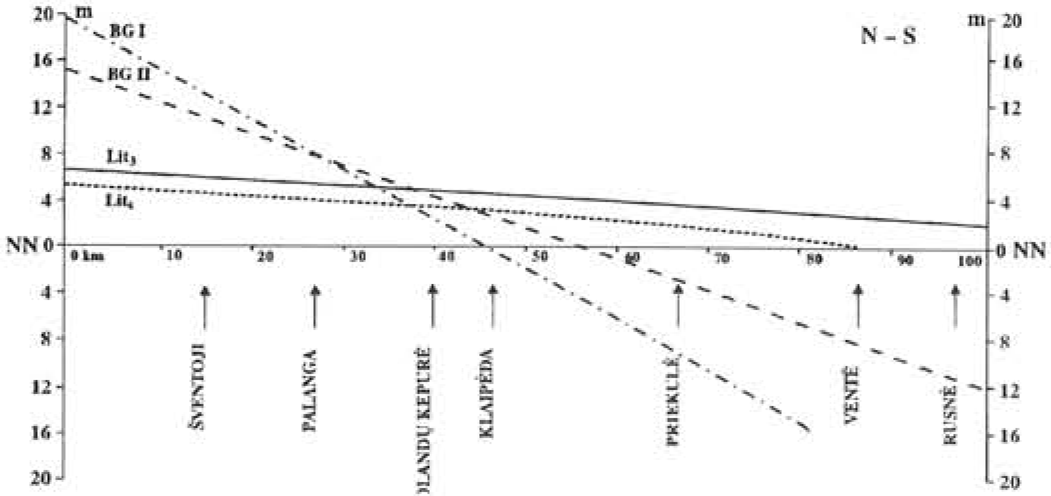

Fig. 4. Shoreline diagram of the Lithuanian coast. BG I and BG II – shorelines of the Baltic Ice Lake, L_3 and L_4 of the Litorina Sea (Gudelis 1955).

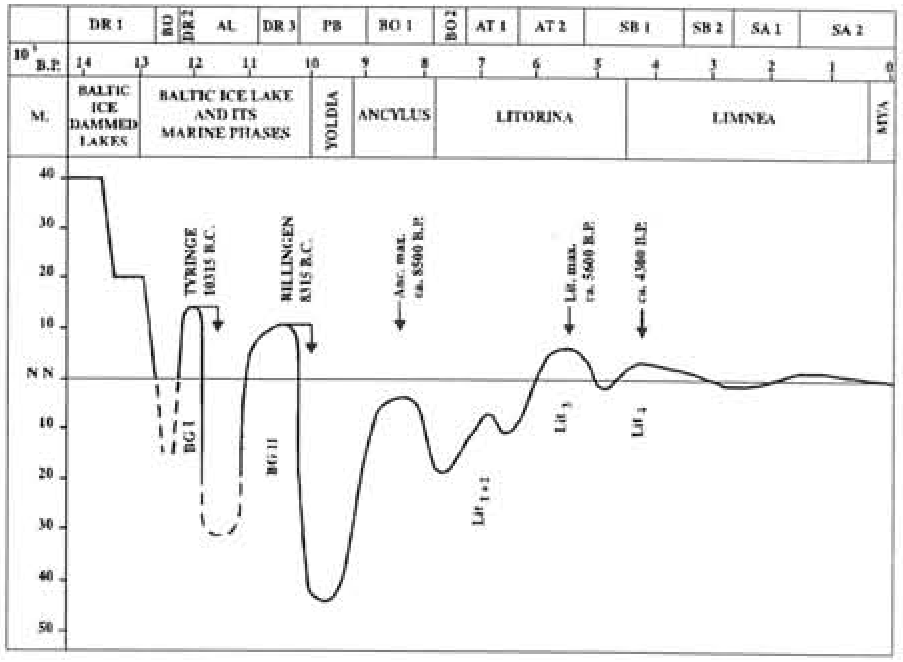

Fig. 5. Shoreline displacement curve for the northern part of the Lithuanian coast (Palanga) throughout the Late and Post-Glacial times. Since the beginning of Late Glacial, the crustal uplift at this site is estimated to be ca. 11–12 m (Gudelis 1979).

vation of old fault lines in some places of mentioned area in Late Glacial (Allerød) cannot be neglected. Certainly, the more accurate picture of neotectonic development could be achieved by special complex investigations of the Litorina maximum coastal features and corresponding sediment sequences in the key sites. Nevertheless, we must admire the mentality of pioneers of the Baltic Sea history – G. De Geer, H. Munthe, M. Sauramo – who were able on a relatively scarce data gathered in the Nordic countries to draw so accurate isobases of former stages of the Baltic Sea, including the Litorina maximum on the SE coast of the modern Baltic.

CONCLUSION

The Litorina maximum transgression is represented by an accumulative marine terrace and erosional cliffs. The Litorina maximum shoreline is tectonically inclined from north to south. The gradient of inclination (tilting) is ca. 0.9 m/10 km. The Zero-isobase of this shoreline is crossing the Kuršių Nerija spit between the settlements of Preila and Pervalka. The average rate of crustal tilting in this region equals to about 1–1.5 mm per year. A straight-line character of the shoreline excludes the presence of local disjunctive dislocations in the area examined.

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Lithostratigraphical Identification of Tills in the Southeastern Part of the Baltic Sea by the Method of the Rounded Hornblende Grains

Jadviga Majore, Renāte Riņķe,
Alexander Savvaitov
and **Ints Veinbergs**

University of Latvia, Institute of Geology

Majore, J., Riņķe, R., Savvaitov, A. & Veinbergs, I. 1996: Lithostratigraphical identification of tills in the southeastern part of the Baltic Sea by the method of the rounded hornblende grains. *Baltica, Vol. 10,* pp. 9–12. Vilnius. ISSN 0067–3064.

Jadviga Majore, Renāte Riņķe, Alexander Savvaitov, Ints Veinbergs, University of Latvia, Institute of Geology, 19, Raiņa Boulev., LV 1586 Rīga, Latvia;

received 19th September 1996, accepted 24th November 1996

Content of the rounded hornblende grains has been determined in glacial deposits afrom the boreholes situated at the southeastern offshore part of the Baltic sea with three tills – Upper, Middle and Lower – singled out. The data obtained by this method applied for glacial deposits onland of the Baltic coast showed that the investigated Upper till was formed during Weichselian, the Middle till – by Saalian and the Lower till – by Elsterian Glaciations. The subdivision of these tills in the investigated sections of the boreholes is given in the paper.

Keywords: the till, the contents of the rounded hornblende grains, Weichselian, Saalian, Elsterian Glaciations, sections of boreholes, southeastern part of the Baltic Sea.

INTRODUCTION

The article deals with the lithostratigraphical identification of the tills and their correlation with some Quaternary sections in the southeastern part of the Baltic Sea. The method of investigation of the rounded hornblende grains has been applied for this purpose (Ulsts & Majore 1964). The equivalent names of the stratigraphical nomenclature of western Europe have been used by authors of the present article for indexing the fixed tills. The well known nomenclature of the Alpine stratigraphy is used also.

The Quaternary cover in the southeastern part of the Baltic Sea is penetrated only by several boreholes. The basic information about the structure of the Quaternary cover in this part of the Baltic Sea is known from the results of the seismic reflection profiling. According to this data the three separate tills can be ascertained in the Quaternary deposits here. Stratified and unstratified interglacial sediments are spread between the tills (Bjerkéus et al. 1995).

The first lithostratigraphical subdivision of the tills was carried out by Gaigalas et al. (1987). Three different tills (two corresponding to Upper Pleistocene and one – to Middle Pleistocene) were identified by mentioned authors in the Nida section (D-6-2/1) according to the data of debris petrographical associations. The opinion about the different age of the tills inside the Quaternary cover in the southeastern part of the Baltic Sea appeared at that time as well (Emelyanov & Gaigalas 1987). Gelumbauskaitė (1987) and Repečka (1987) considered that the upper tills forming the modern bottom topography in the some areas of the southern and central parts of the Baltic Sea belong to Saalian and Weichselian Glaciations. That point of view was proposed by Repečka et al. (1991, 1992, 1993) as in the monograph "Geology and Geomorphology of the Baltic Sea" (ed. Grigelis 1991), as well as in the Geological Map of the Quaternary Deposits of the Baltic Sea Bottom and Adjacent Land Areas, scale 1 : 500 000 (ed. Grigelis 1993).

The well-known geological cross sections along the onshore of the Baltic Sea from Ovīši to Ziemupe (Konshin et al. 1970), between Labrags and Jūrkalne (Veinbergs & Savvaitov 1970) and from Rucava to Sokolniki (Vonsavičius 1987) give reason to suppose that the tills and interglacial deposits of different age known here probably can be spread also in the Quaternary cover of the adjacent part of the Baltic Sea.

MATERIALS AND METHOD

The till samples for the rounded hornblende grain analysis were collected in 1989. A majority of samples were obtained from the cores of the boreholes by geologist V.Shibanov at the time, when these were drilled by the r/v "Kimberlite". The preliminary description of the drilled sections also was carried out by geologist V.Shibanov. Totally the samples were collected from the 11 boreholes. Locations of the boreholes sampled are shown in the scheme (Fig. 1). The contents (in %) of the rounded hornblende grains corresponding to fraction 0.25–0.1 mm were determined in the collected samples. The main point of the laboratory practice of the method has been written in details by Ulsts and Majore (Ulsts & Majore 1964). According to the authors of this method the tills of different age – Elsterian (Mindelian), Saalian (Rissian) and Weichselian (Würmian) – can be distinguished by means of it clearly on the large area of Baltic, Belarus and Russia. Each till differs from other ones by the characteristic indices of the content of rounded hornblende grains. This fact seems to be most obvious in the sections where all tills occur together.

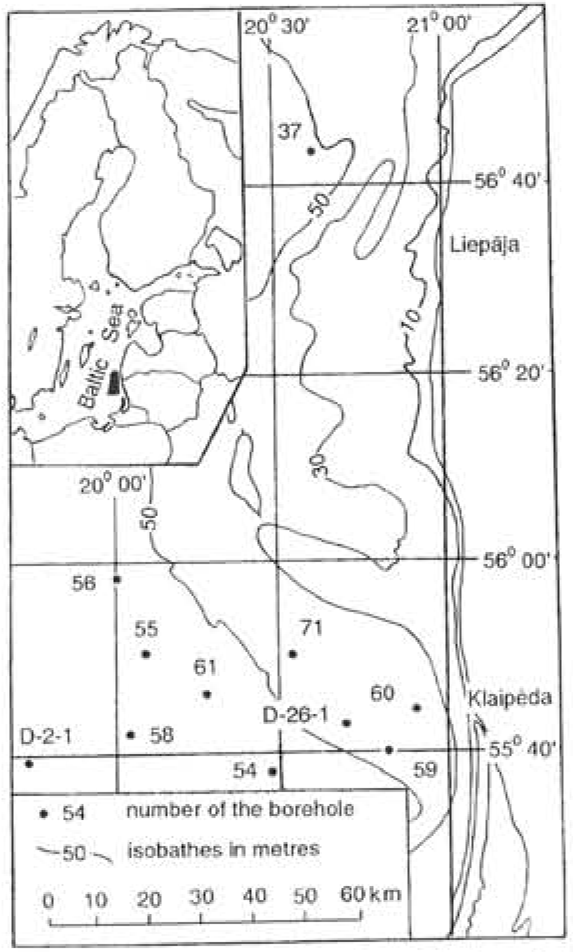

Fig. 1. A scheme showing the location of the investigated sections of the boreholes in the southeastern part of the Baltic Sea. Isobathes are used from Bathymetric Map by Bjerkéus et al. (1995). The area of borehole locations is marked by a black quadrangle.

RESULTS AND DISCUSSION

The analytical data obtained from the till samples as well as the structure of the investigated sections are shown in Fig. 2. According to these data, the Upper till is determined practically in all the investigated sections as under the thick of Late and Post Glacial sediments, as well as at the surface of the sea bottom. The Middle till under Late and Post Glacial sediments is observed from the top in borehole No. 59 only. The differences between tills are clearly expressed.

Three different tills can be distinguished in the Quaternary cover by means of the hornblende grains analysis of the cores from mentioned boreholes. The Upper till is represented by the brown, grayish-brown and gray loam with debris. The Middle till contains the gray, greenish-gray and grayish-brown loam with debris. The Lower till consists of gray, dark-gray and brown loam with debris. The content of the rounded hornblende grains in the Upper till varies from 16 to 25%, in the Middle till – from 21 to 42% and in the Lower till – from 6 to 17%. The concentration of the rounded hornblende grains often is maximal in the lower part of Upper till, whereas in the same part of the Middle till it is minimal. This can be explained by the glacial assimilation of the material from the deposits over which the ice-sheets advanced. It is necessary to consider marked indices of the glacial assimilation as the undoubted indications that the tills were formed by the ice-sheets.

The Middle till differs from other ones by the highest content of rounded hornblende grains. This feature enables to distinguished them from the Upper and the Lower tills. It gives a reason to consider the Middle till as a marker bed for subdivision and correlation of the local sections. The Upper and the Lower tills are distinguished one from another less clearly, nevertheless the content of rounded hornblende grains in the Upper till is higher than in the Lower till.

The above-mentioned differences between the tills are evident in the investigated borehole cores, especially where all three tills occur together.

Lithostratigraphical features of the investigated tills in the southeastern offshore part of the Baltic Sea is similar as in the tills spread in the adjacent land part of the Baltics.

According to Ulsts and Majore (1964), the content of rounded hornblende grains for Weichselian (Würmian) till varies from 6 to 22%, for Saalian (Rissian) till – from 28 to 37% and for Elsterian (Mindelian) till – from 11 to 18%. These data were obtained basing on the investigations of numerous samples from different tills, widespread in the Quaternary cover in the onland region. It should be noted that results obtained in the Baltic Sea offshore during the studies of rounded hornblende grains in the tills from investigated region of the Baltic Sea offshore are very similar to the onland ones. In both cases the correlated tills are characterized by the same contents of rounded hornblende grains and have the same position in general geological sections.

Similarities between tills in the southeastern part of the Baltic Sea offshore and Baltic land area, according to the contents of rounded hornblende grains, as well as by the position in geological sequence, gives a reason to compare them also by age. The Upper till in the investigated borehole sections from the southeastern part of the Baltic Sea is dated as belonging to the Weichselian, the Middle till – to the Saalian and the Lower till – to the Elsterian glaciations.

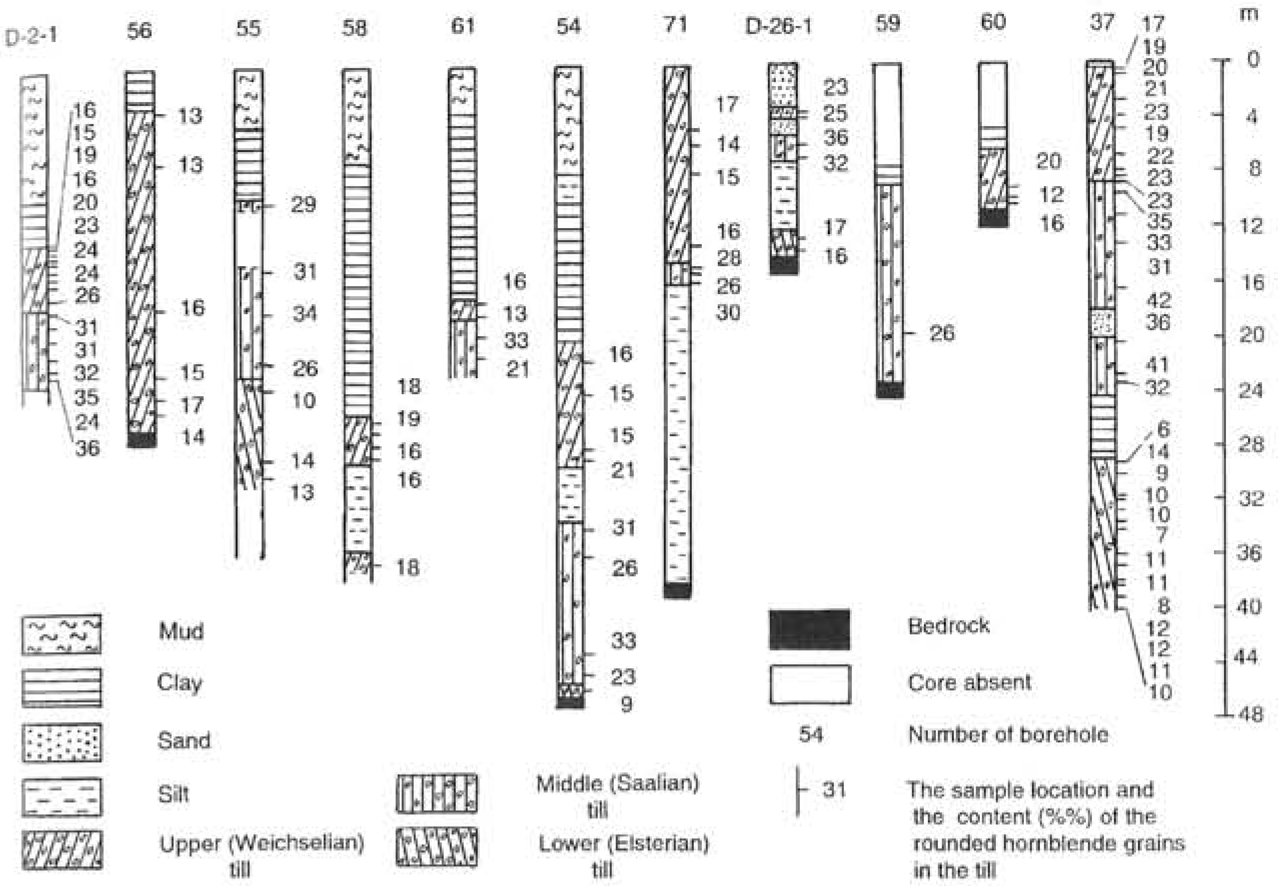

Fig. 2. Distribution of rounded hornblende grains in the tills and structure of the investigated borehole sections.

CONCLUSIONS

The applied method of rounded hornblende grains allowed to receive new lithostratigraphical information, which showed that the tills of the southeastern offshore part of the Baltic Sea were formed during Weichselian, Saalian and Elsterian glaciations. Probably the till deposits known from interpreting data of seismic reflection profiling (Bjerkéus et al. 1995), are of the same age as well. However more ancient glacial deposits can be ascertained also in the southeastern offshore part of the Baltic Sea by an analogy with adjacent land areas.

The method of rounded hornblende grains is recommended to be appliied for distinguishing tills in the borehole cores and for the samples from the bottom surface.

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Early Holocene Shore Displacement of the Baltic Sea East of Tallinn (N Estonia)

Leili Saarse, Atko Heinsalu, Anneli Poska, Siim Veski, Raivo Rajamäe, Sirje Hiie, Kersti Kihno and Tônu Martma

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Leili Saarse, Atko Heinsalu, Anneli Poska, Siim Veski & Tônu Martma, Institute of Geology, Estonia puistee 7, EE–0001 Tallinn, Estonia; Sirje Hiie and Kersti Kihno, Institute of History, Rüütli 6, EE–0001 Tallinn, Estonia; *received 19th November 1996, accepted 23d November 1996.*

In the environs of Tallinn (North Estonia), 5 sections have been studied, yielding records on the Yoldia Sea regression and the Ancylus Lake transgression. New results confirm that during the Yoldia Sea regression, which lasted until 9500 BP (conventional radiocarbon age), the sea level dropped relatively by 12 m (from 40 to 28 m). The transition to the Ancylus transgression occurred by 9500 BP. Its maximum is registered about 9300–9200 BP when the water level reached the elevation of 36 m east of Tallinn and 35 m at Maardu. At the beginning of the Holocene, the average land upheaval rate in the area surrounding Tallinn was about 1.4–1.5 cm/yr.

Keywords: Yoldia regression, Ancylus transgression, pollen, diatoms, shore displacement, Estonia.

INTRODUCTION

Five new sections east of Tallinn have been studied bio-, litho- and chronostratigraphically for the retrieval of evidence of the early history of the Baltic Sea. Tondi, Sõjamäe, Rae (Kessel 1961; Kimmel et al. 1996) and Vandjala mire sequences store information on the Yoldia Sea history, lakes Maardu, Ülemiste and Saha mire sections complement this picture and add some evidence on the development of the Ancylus Lake. The Ancylus shore displacement, at an elevation of 35–36 m, is well developed morphologically with spits at Iru, Kroodi, Kallavere and beach ridges at Ülemiste (Kessel 1961; 1979; Kessel & Punning 1984; Raukas et al. 1965). The isolation contact has been determined mostly on the basis of sediment lithology, loss on ignition, diatoms, and *Pediastrum*. The lake threshold elevation is assumed to be the levelled water surface plus the estimated erosion of the outlet (Svensson 1991). The mires of Sõjamäe, Tondi, Rae and Vandjala are situated 1–2.5 m below the Yoldia maximum isobase, L. Ülemiste is near the Ancylus maximum isobase, and L. Maardu and the Saha mire is below it (Fig. 1).

Bottom deposits of the lakes Ülemiste, Maardu, and Sõjamäe, Tondi and Rae mires have been studied earlier (Kessel 1961, 1979; Künnapuu 1962; Saarse & Arbeiter 1979; Kessel et al. 1986; Saarse et al. 1990; Veski 1992). It was assumed that the bottommost peaty gyttja beds in L. Ülemiste were formed during the Early Boreal (Kessel et al. 1986). The new high-resolution palynological record, together with radiocarbon dates and ^{13}C analyses, indicated the presence of Pre-Boreal deposits.

The main objectives of the study is identification of sections yielding evidence on the Baltic Sea evolution in the environs of Tallinn, estimation of magnitude between the Yoldia minimum and Ancylus maximum limits, and refinement of the chronology of the Baltic Sea's Yoldia and Ancylus stages in North Estonia.

METHODS

Five cores were collected using a Russian peat sampler and were subsampled at 1 cm intervals for pollen and diatom analysis, 2 cm intervals for the bulk organic, inorganic and carbonate fractions, and 10 cm for the radiocarbon dates. For pollen analyses, standard chemical treatment was used and ca 500 AP (tree pollen) was counted at each level. The basis for the percentage calculations was the

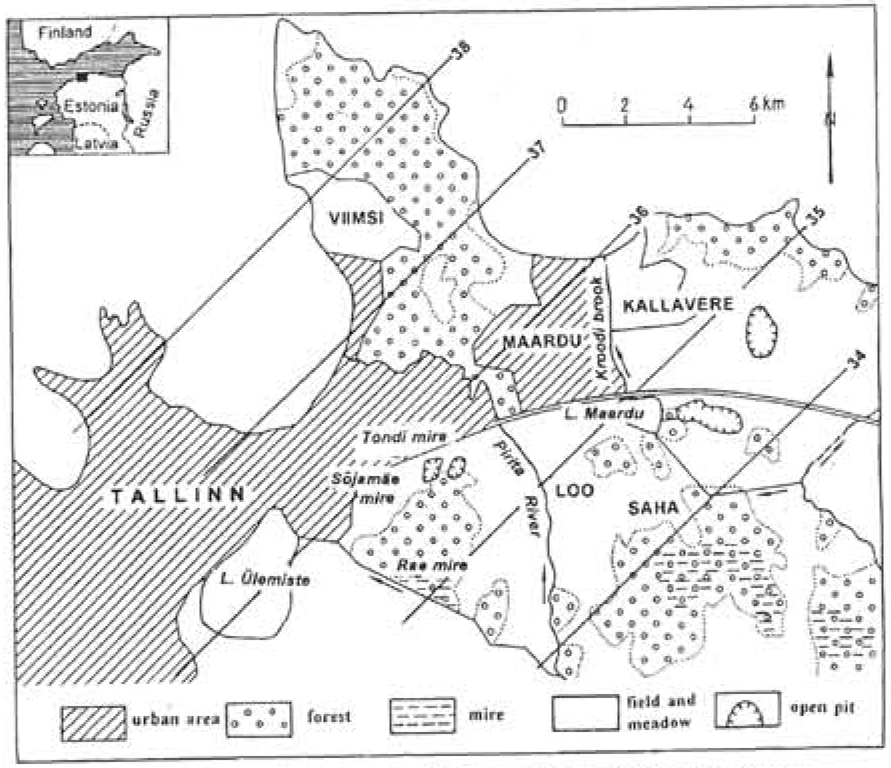

Fig. 1. Studied lakes and mires east of Tallinn with indication the isolines.

sum of pollen (AP+NAP, tree and herb pollen). For diatom analysis, 0.5–1 cm³ of wet sediment was digested using the hydrogen peroxide method (Battarbee 1986). The sediment residual was mounted in Naphrax. Whenever possible at least 500 diatom valves were counted from each sediment sample. The diatom floras of Hustedt (1930), Mölder & Tynni (1967–1973) and Tynni (1975–1980) were used for the indentification. The samples for the macrofossil analyses were dispersed in KOH for one day before washing under tap water through a 0.25 mm sieve. The macrofossils and seeds were picked out, stored and analysed. Organic, inorganic and carbonate fractions were determined by loss-on-ignition at 500° and 825° C. The results were plotted using Tilia and Tilia Graph programs (Grimm 1992). Six conventional radiocarbon dates were obtained from the basal peaty gyttja soluble and insoluble fractions from L. Ülemiste, one from gyttja of Vandjala mire, and one from gyttja of Saha mire.

BACKGROUND

The location of studied sites is shown in Figure 1. They are all in the area where the Quaternary cover is thin (Künnapuu et al. 1981).

The **Tondi** mire has a 5–6 m deep depression, filled with silt, silt with plant remains, gyttja, and peat (Fig. 2; Kessel 1961; Kimmel et al. 1995). The surface of mineral bottom lies at an elevation of 36–37 m a.s.l. Its threshold between two spits has an elevation of 38.5 m. The silt and the basal part of gyttja accumulated during the Pre-Boreal, the rest of the gyttja formed during the Boreal and Early Atlantic (Kessel 1961).

The **Sõjamäe** mire occupies a 4–5 m deep depression, with its threshold at an elevation of 38 m, and is orientated towards the Rae mire. The mineral bottom surface is at an altitude of 36–37 m a.s.l. The basin is filled with sand, sandy and peaty gyttja, and peat (Fig. 2). During the Pre-Boreal and Early Boreal period highly compressed sandy and peaty gyttja in the depth of 400–445 cm accumulated (Kessel 1961).

The **Rae** mire is about 2 km south of Sõjamäe. Its basin is at least 5 m deep and is filled with laminated clay, silt, lacustrine lime, gyttja, and peat. The threshold is in the east at an elevation of 37.5 m. Minerogenic deposits lie at an elevation of about 35 m. Silt is deposited in the Younger Dryas and Pre-Boreal, and lacustrine lime in the Boreal period (Kessel 1979).

The **Vandjala** mire occupies a small basin 2 km east of L. Maardu. The threshold lies at an elevation of 37.0 at its western side. The former lake basin is filled with sand, gravel, silt and gyttja overgrown by peat (Fig. 2). The Pre-Boreal portion of sediments is represented by sand, silt and silty gyttja (Fig. 3).

The **Saha** mire, about 1.5 km southwest from L. Maardu, is a shallow drained basin about 2.5 m deep, filled with silt, calcareous gyttja, silty gyttja, and fen peat (Fig. 2, core 1, 2) from the Pre-Boreal and Boreal age (Figs. 4, 5). The threshold is located at an elevation of 33 m and the basin's mineral bottom is at an elevation of 31–32.5 m.

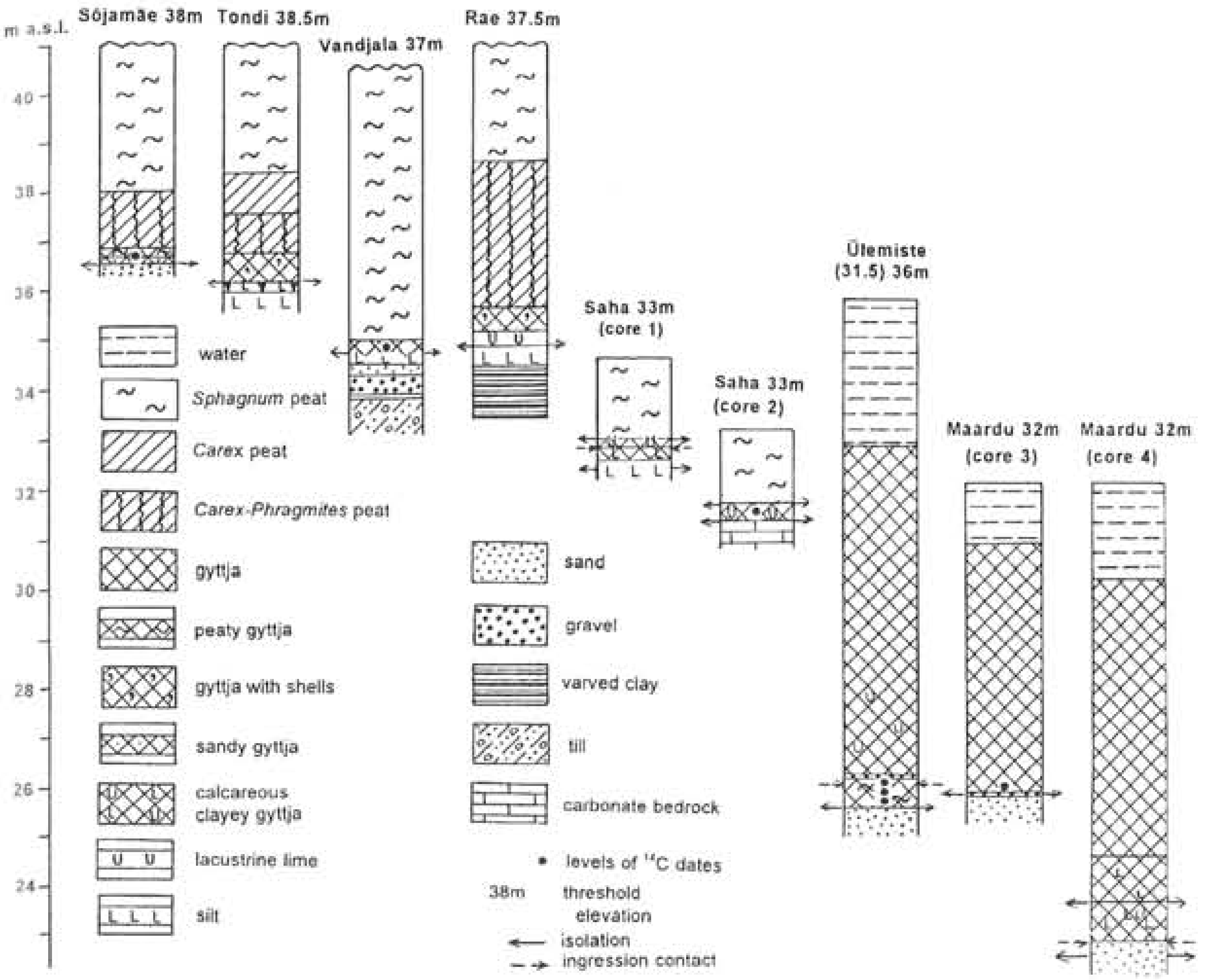

Fig. 2. Sediment lithostratigraphy with indication of isolation and ingression contacts.

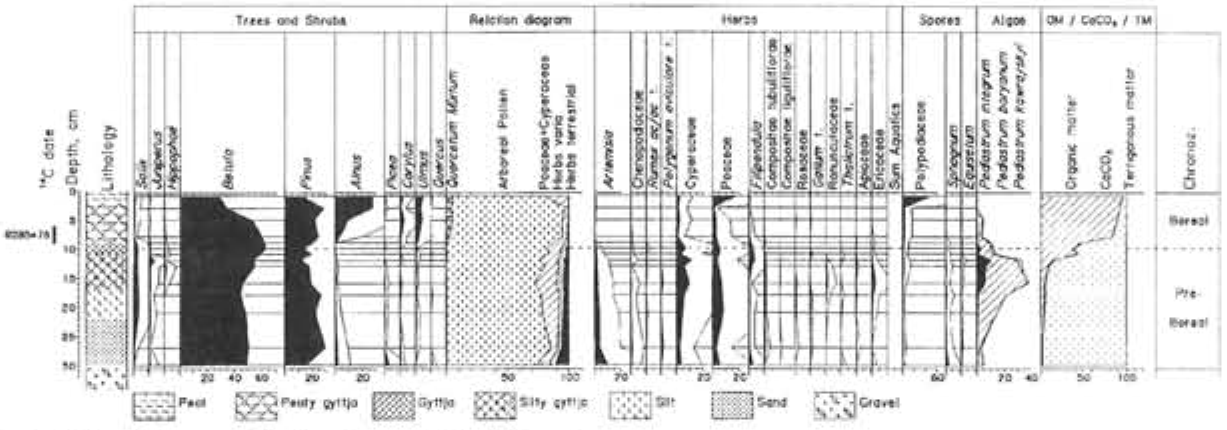

Fig. 3. Pollen diagram of the basal part of Vandjala mire.

L. Ülemiste in the southeastern part of Tallinn, has an up to 9.5 m deep basin filled with sand, peaty gyttja, calcareous gyttja, and fine detritus gyttja (Fig. 2). Its modern threshold at 36 m is located in the northern part of the lake at the site of the previous outlet of the Härjapea River which is now drained by pipes. At an elevation of 31.5 m, the L. Ülemiste's primary Pre-Boreal threshold is marked by an abraded esker ridge crest, which is buried under fine aeolian and medium grain marine sand, like in Maardu (Saarse et al. 1990). The elevation of the basin"s carbonate bedrock bottom

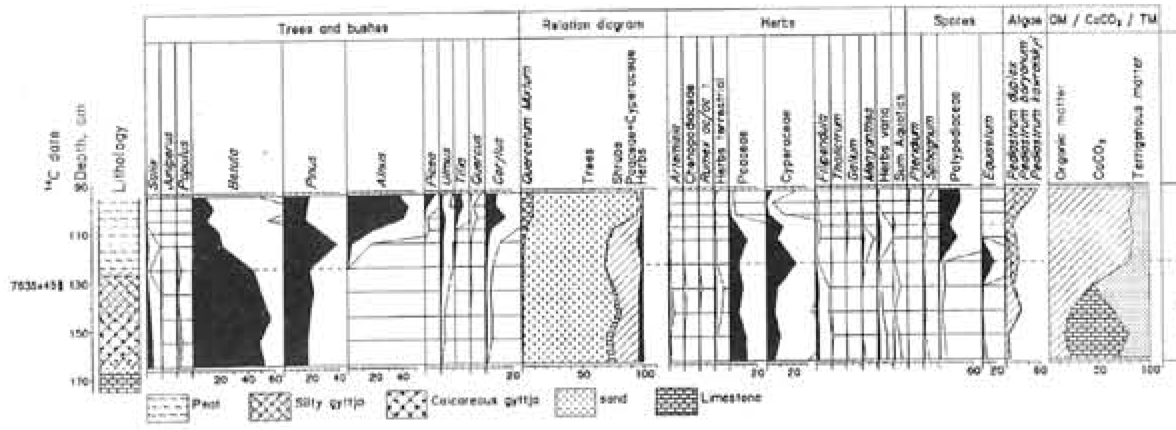

Fig. 4. Pollen diagram of Saha mire basal part (core 2).

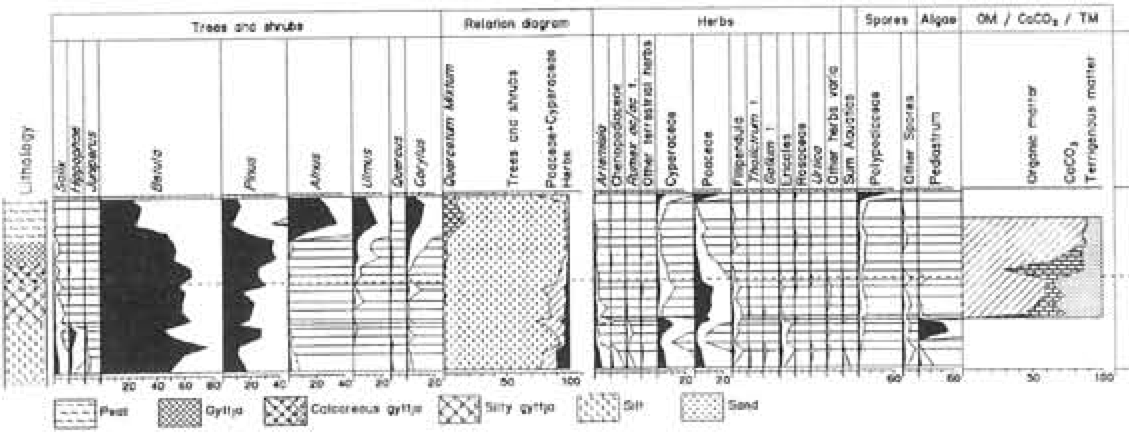

Fig. 5. Pollen diagram of Saha mire basal part (core 1).

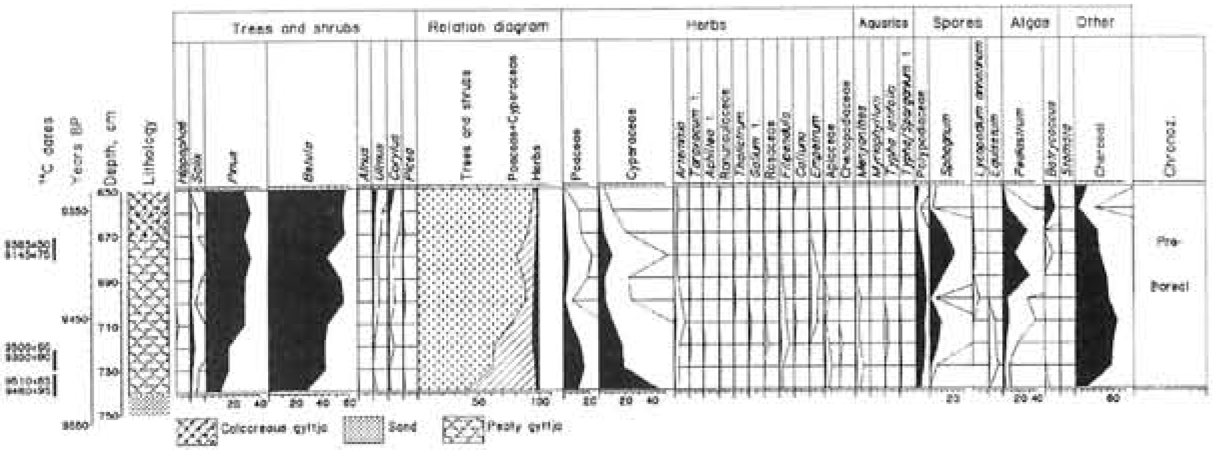

Fig. 6. Pollen diagram of the basal part of L. Ülemiste deposits.

differs with the parts of the lake, being at 32–34 m in the eastern part, less than 26 m in the western part. The mineral bottom was 25.6 m a.s.l. at the coring point. During the Pre-Boreal age sand, peaty gyttja and calcareous gyttja accumulated (Fig. 6).

L. Maardu is situated about 15 km east of Tallinn. It also has a rather deep (9.4 m) basin, filled with sand, silty gyttja, and gyttja (Fig. 2). The basin's mineral bottom lies at an elevation of 22.6–26 m, and the threshold at 32 m is marked by fluvioglacial deposits, destroyed and reworked during the highway construction. The Pre-Boreal part of the sequence is represented by sand and silty calcareous gyttja (Fig. 7).

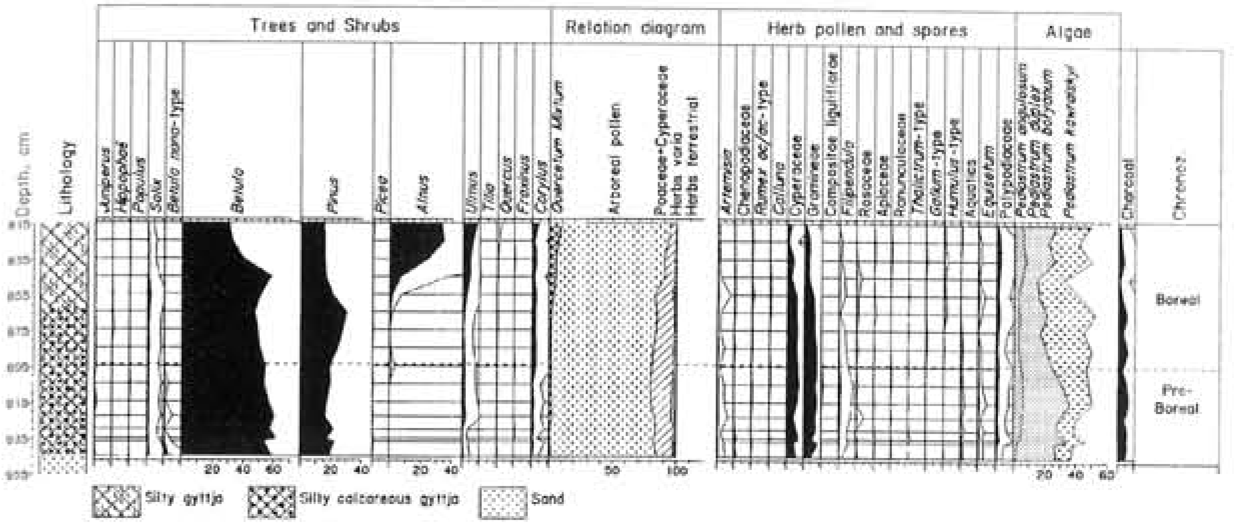

Fig. 7. Pollen diagram of the basal part of L. Maardu deposits, core 4.

RESULTS

Radiocarbon dates

A total of six radiocarbon dates on peaty gyttja have been obtained from the basal part of the L. Ülemiste sediments, both from the soluble and insoluble fraction and from testes using the $\delta^{13}C$ analyses (Table 1). They fully support the pollen analytical results. The $\delta^{13}C$ of the L. Ülemiste samples ranges between –27.8 – –29.4‰. All ^{14}C dates of the soluble fraction of L. Ülemiste are somewhat older than those of the insoluble fraction and their $\delta^{13}C$ have more negative values (Table 1), confirming the different source of carbon which could have been assimilated by macrophytes during the photosyntesis from the ground water or inherited from older sediments. The Table 1 presents also the earlier published ^{14}C dates from the lakes Ülemiste (Ilves 1980), Maardu (Saarse et al. 1990; Veski 1992) and Sõjamäe mires (Kessel 1979).

The ^{14}C date 8915±90 (Tln-135) from a thin gyttja bed at Sõjamäe is considerably younger than expected on the base of pollen record. Trying to determine the reason, we dated thin gyttja deposits from the Saha and Vandjala mires and got similar results (Table 1). All dates are almost 1000 years younger than expected. The reason for this seems to be the younger roots (mostly *Typha, Phragmites*) which penetreted into the thin gyttja bed during the paludification of these basins and contaminated the gyttja with the younger carbon.

Table 1. **Results of the ^{14}C (uncorrected) and $\delta^{13}C$ datings**

Depth, cm	Core no	Fraction	Lab. no	^{14}C- age	$\delta^{13}C$ ‰	Material
L. Ülemiste	4/94	Sol	Tln-1860	9385±50	–28.7	peaty gyttja
670–680		INS	Tln-1861	9145±75	–28.3	peaty gyttja
720–730	4/94	Sol	Tln-1857	9500±60	–29.3	peaty gyttja
		INS	Tln-1856	9300±80	–27.8	peaty gyttja
730–741	4/94	Sol	Tln-1858	9510±65	–29.4	peaty gyttja
		INS	Tln-1859	9480±95	–28.7	peaty gyttja
570–580	1/73	Bulk	TA-691	8300±90		limy gyttja
L. Maardu						
570–580	6	Bulk	Tln-1265	8625±85		gyttja
535	3	Bulk	Ua-2390	9490±110		wood
580–590	13	Bulk	Tln-1313	9655±70		gyttja
Sõjamäe						
430–450		Bulk	Tln-135	8915±90		gyttja
Vandjala						
88–93	2	INS	Tln-1884	8285±75		gyttja
Saha						
128–132		Bulk	Tln-1916	7635±45		gyttja

Pollen stratigraphy

Five new detailed pollen diagrams have been completed and their lowest parts, reflecting the pollen composition of sediments corresponding to the Yoldia and Ancylus stages are presented in Figures 3–7. Interpretation of the pollen records is given in the included discussion.

Diatoms

In L. Maardu, the diatom analysis covers the lower 100 cm in the core 4. The sand and the lowermost part of the calcareous gyttja are barren of diatoms. Further up the core, the diatoms can be divided into two zones (Fig. 8).

Zone MD1 (930–905 cm)

This assemblage is characterized by the peak of planktonic *Aulacoseira ambigua* and *A. granulata* while towards the top of the zone their frequency decreases. *Cyclotella comta* is common. Periphytic forms of *Fragilaria construens, F. construens* var. *venter* and *F. brevistriata* are also abundant.

Zone MD2 (885–840 cm)

This zone is dominated by *Fragilaria* – primarly *F. construens* and *F. inflata*, constituting up to 60% of the taxa. Also *Navicula schoenfeldii* and *N. scutelloides* are present at the relatively high percentage. *Aulacoseira* spp. has declined.

In L. Ülemiste, the diatom analysis covers the lower 90 cm of sequence. The lowest investigated sequence of the sediments consists of mainly corroded and fragmented frustules and at the depth of 670 cm, diatoms are lacking. There are not clear changes in the abundance of diatom species in the core despite the variable lithostratigraphy, and they haven't divided into zones. The sum of *Fragilaria* spp. is constantly between 25–40%, with *F. construens* var. *venter, F. construens, F. brevistriata* and *F. lapponica* the more frequent. In the lower part of the peaty gyttja *Cocconeis plancetula, Achnanthes exigua, Navicula cari* are present at relatively high percentages, and the amount of *Gyrosigma attenuatum, Navicula scutelloides* and *Amphora pediculus* increases in the calcareous gyttja. *Ellerbeckia arenaria* is found in low percentages through the whole investigated sequence (Fig. 9).

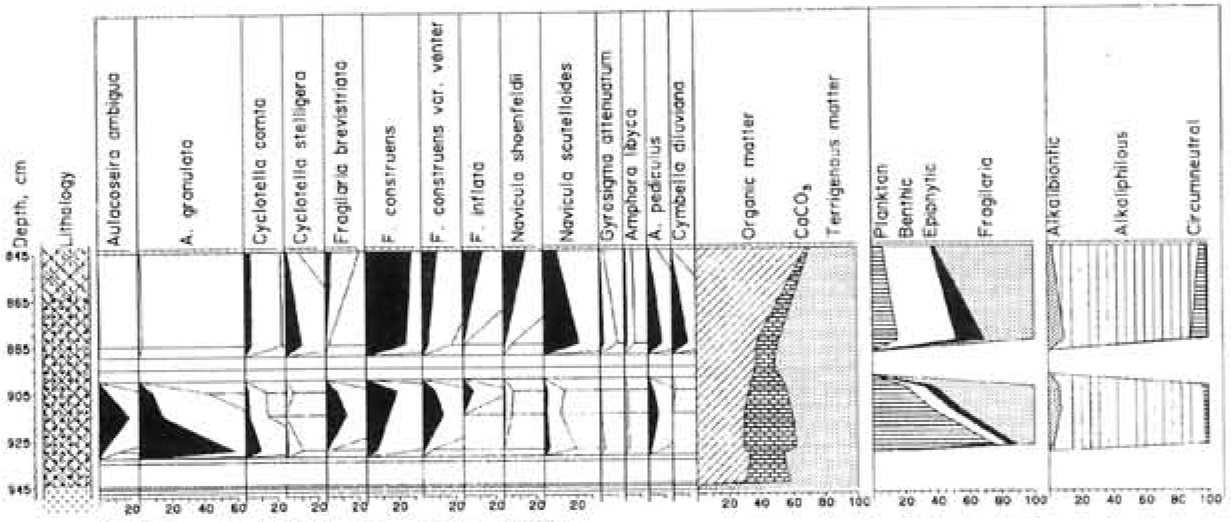

Fig. 8. The diatom diagram from L. Maardu (core 4).

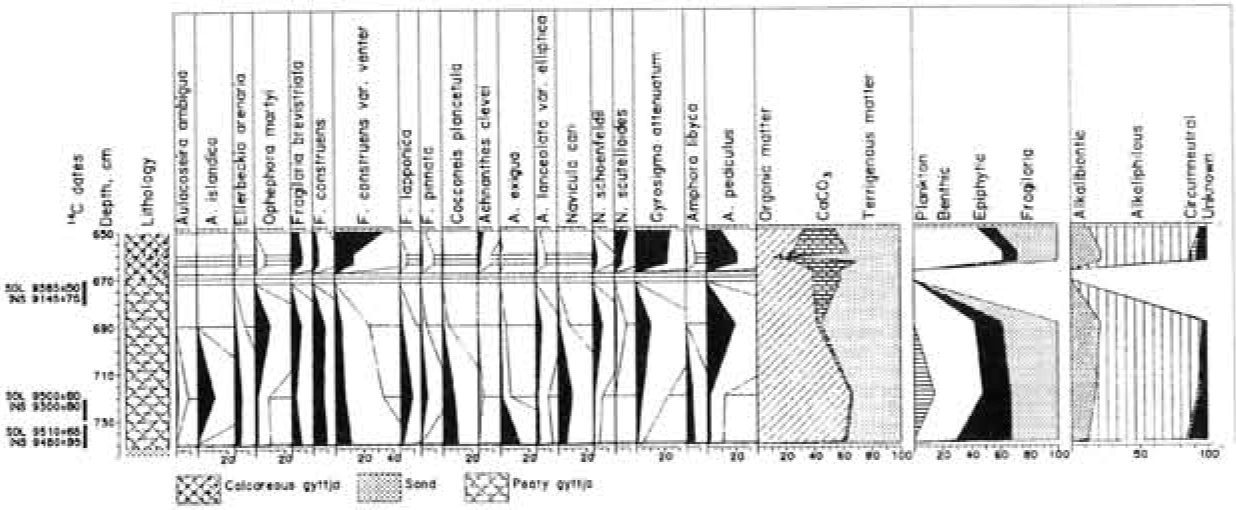

Fig. 9. The diatom diagram from L. Ülemiste.

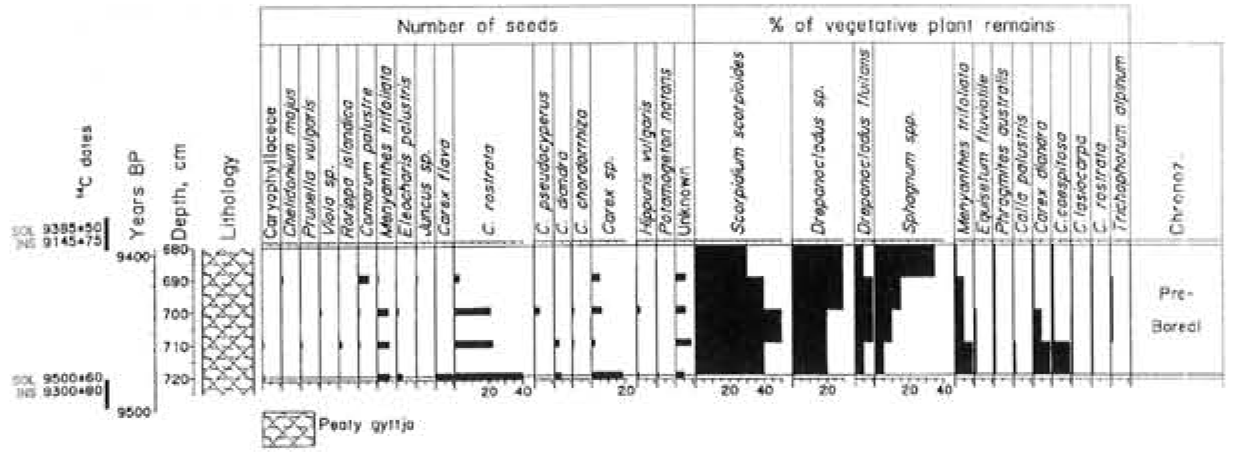

Fig. 10. Macrofossil remains from L. Ülemiste.

Macroremains

The lowest interval studied in L. Ülemiste is 710–720 cm, and it is characterized by the greatest number of *Carex*, especially *Carex rostrata* seeds, which decrease upwards in number (Fig. 10). The remains of aquatic moss *Scorpidium scorpioides* are abundant, and the share of *Drepanocladus* and *Sphagnum* is remarkable. The number of aquatic plants, including *Potamogeton, Hippuris vulgaris*, is low. In the next interval 700–710 cm, *Scorpidium scorpiodes* is most abundant. *Drepanocladus* increases in the interval of 690–700 cm and *Sphagnum* remains dominance in the topmost part (680–690 cm). Terrestrial herbs, *Prunella vulgaris*, Carophyllaceae are constantly present with low variable values. These results correlate well with pollen record (Fig. 6).

DISCUSSION

Correlation of sequences

Regional pollen stratigraphy is based on the radiocarbon dated L. Maardu pollen diagram (Veski 1996). Of special importance are two radiocarbon dates (8625±85, Tln-1265, and 9500±60, Tln-1857, Table 1). The former marks the end of *Betula* and *Pinus* pollen decrease and sharp increase (rational limit) in *Alnus* while the latter records the empirical limit of *Corylus* and *Ulmus*. Both postulated pollen-stratigraphic events are easily determined on the pollen diagrams (Figs. 3–7).

Yoldia stage

The isolation contact of the Tondi basin is recorded in the silt/gyttja transition (Fig. 2) by the indifferent to slightly brackish water diatoms and the macroremains in the silt (Kessel 1961; Kimmel et al. 1996). The interpolated age for this contact is 9900 BP (Kimmel et al. 1996; Fig. 11).

The lithology, pollen, and diatom record from Sõjamäe show the fall of isolation contact between sand and sandy gyttja (Fig. 2). But the age of the isolation of the Sõjamäe lagoon from the Yoldia Sea is disputable (Kessel & Punning 1984). In the earlier studies, the radiocarbon date 8915±90 (Tln-135, Table 1) was taken for the time "when the level of the Baltic Sea dropped below the absolute height of 40 m and the lagoon itself became isolated from the sea" (Kessel & Punning 1984). However, this was inconsistent with the pollen record showing the Pre-Boreal age of the dated gyttja deposits (Kessel 1961; Fig. 2). According to the pollen stratigraphy, the threshold elevation, and isobases of the Yoldia Sea, the Sõjamäe lagoon isolated from the sea about 9850 BP (Fig. 11). This age does not contradict the statement that the short-term brackish phase of the Yoldia

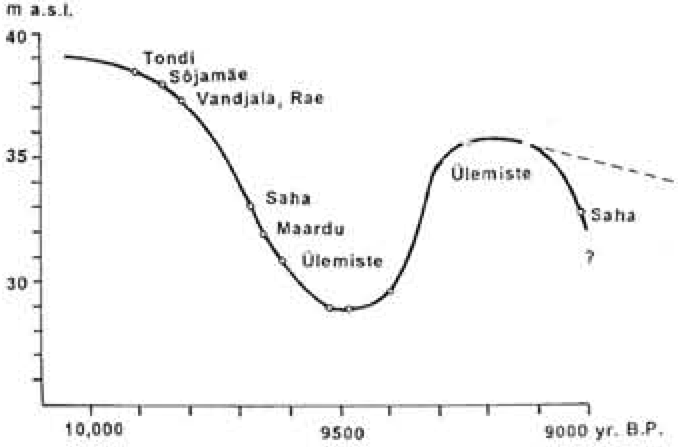

Fig. 11. Shore displacement curve east of Tallinn.

occurred about 10000–9900 (9800) yr. BP (Björck 1995). Some brackish water diatoms identified in gyttja just above the isolation contact are obviously residual and further more, they have not been found in the newly studied section (Kimmel et al. 1996).

The Rae basin isolated about 9800 BP. The isolation contact at 662 cm is identified by changes in lithology (silt/lacustrine lime; Fig. 2; Kessel 1961, 1979). The isolation of the Vandjala basin took place at about the same time as Rae. The silt/gyttja transition marks the isolation contact with a *Pediastrum* curve increase (Figs. 2, 3).

Isolation contact in the Saha core 1 (Figs. 2, 5) at the depth of 205–207 cm is registered in silt containing macroremains. In the pollen diagram, *Pediastrum* spores show a sharp increase, *Betula* pollen decreases, and *Pinus* has a peak. In core 2, the isolation contact at the depth of 165 cm is registered in the sand/gyttja transition in which *Pediastrum* rises, *Betula* pollen decreases, and the NAP and carbonate fraction increases (Figs. 2, 4). Saha isolated about 9700–9600 BP (Fig. 11).

L. Maardu isolated about 9600 BP (Saarse et al. 1990; Fig. 11). Unfortunately, this event is not reflected on the new pollen diagram from core 4 (Fig. 7), and could be hidden lower than the analysed part of the section. The date 9655±70 (Tln-1313), the increase in organic fraction, the decrease in terrigenous fraction, and the increase in *Pinus* on the account of *Betula* pollen in core 13 (Saarse et al. 1990) could be interpreted as the isolation contact (Fig. 11).

The isolation of L. Ülemiste occured about 9600 BP at the transition between sand and peaty gyttja, and is mainly indicated by the sharp changes in lithology. The contact could have been eroded, as the uppermost portion of sand consists of frustules of the brackish-water diatom species *Nitzschia navicularis* and *Campylodiscus echeneis* (Kessel et al. 1986). Due to the erroneous interpretation of the pollen record, sand accumulation in the Early Boreal period was proposed and the mentioned diatom taxa were regarded as redeposited from the sediments of the Yoldia Sea (Kessel et al. 1986). Now it appears that basal sands accumulated during the Pre-Boreal time, most probably during the Yoldia phase of the Baltic.

During the Yoldia regression the sea level dropped to an elevation of 28–29 m or lower (Figs. 11–13). During this low stage, the L. Ülemiste basin was overgrown by marcophytes and mosses and peaty gyttja started to accumulate at 9510± ±65 BP (Tln-1858, Table 1). Macroremains studies (Fig. 10) suggest the peaty gyttja formed in a shallow pond with a water depth about 0.5 m. But the high *Aulacoseira ambigua* content (up to 70%) in the peaty gyttja, identified earlier (Kessel et al. 1986), contradicts our conception of a very low water-level in L. Ülemiste during the formation of peaty gyttja. The new sediment section contains only about 10% of *Aulacoseira islandica* at a depth of 720 cm (Fig. 9). Most of these frustules are broken. The diatom assemblage here is dominated by epiphytes, with some quantity of benthic species of alkaliphilous character, and planktonic forms are almost absent (Fig. 9), which supports the idea of a very shallow waterbody overgrown by macrophytes.

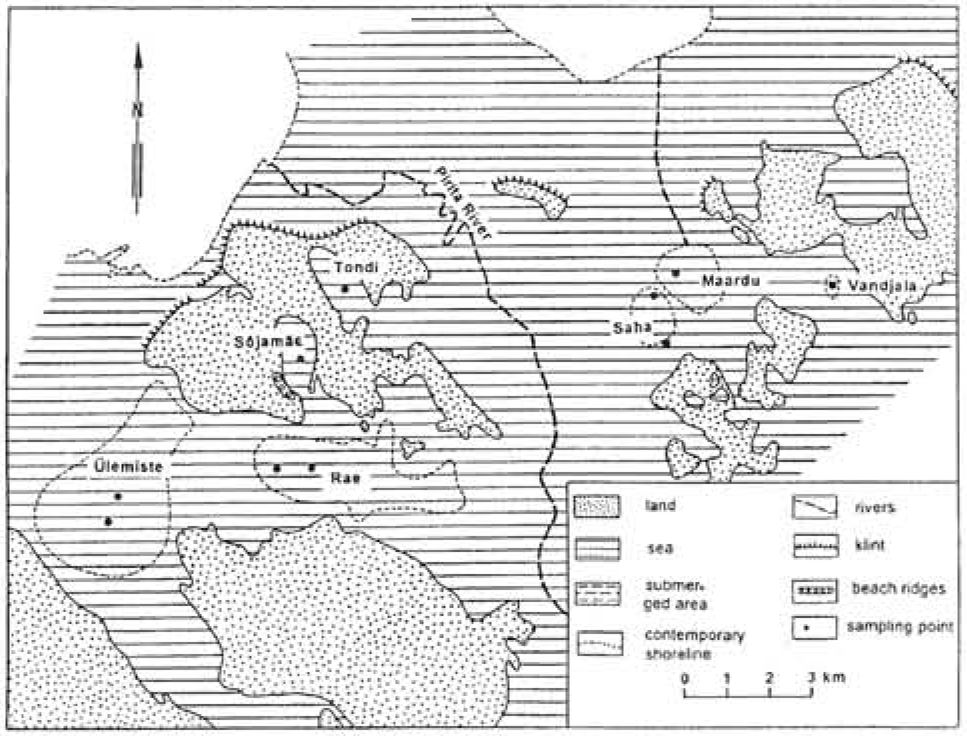

Fig. 12. Palaeogeography about 10,000 BP east of Tallinn.

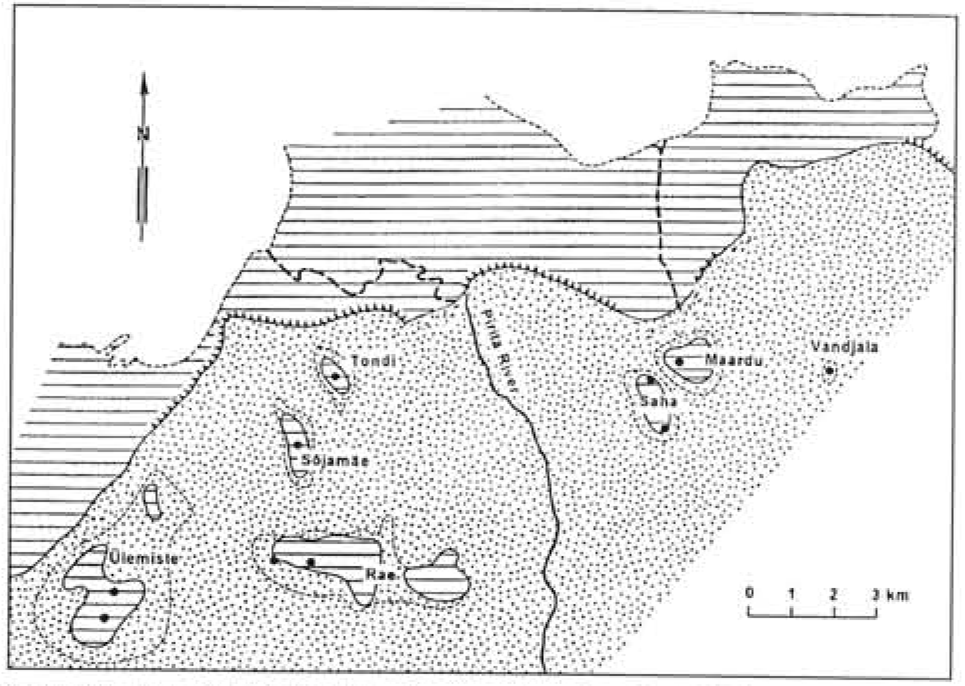

Fig. 13. Palaeogeography at the end of the Yoldia Sea regression about 9500 BP. For a legend see Fig. 12.

The early Holocene changes in sea level in the area of Tallinn are presented in Figure 11. On this two different threshold elevations are indicated for L. Ülemiste because it was considerably smaller than modern lake before the Ancylus transgression and its threshold, marked by esker ridge, now buried by sands was located at 31.5 m a.s.l. The Ancylus beach ridge northwest of lake (Fig. 14), dammed it up to the modern level with a threshold of about 36 m. The sea-level curve itself is reconstructed according to the Scandinavian method, which relies on isolation of lake basins (Berglund 1966; Björck 1979). To determine the isobases Kessel's equidistant shoreline diagram was used.

According to the radiocarbon dates from Ülemiste, the transition between Yoldia regression and the Ancylus transgression occurred around 9500 BP (Fig. 11). It is supported by ^{14}C dates from the peat under the Ancylus transgressional deposits at Lemmeoja, southwestern Estonia (9440±100, Hel-2208A and 9430±100, Hel-2208B; Haila & Raukas 1992) and by evidence obtained from southeastern Finland (Eronen 1976; Eronen & Haila 1982; Ristaniemi & Glückert 1987) and southern Sweden (Berglund 1964; Björck & Digerfeldt 1986; Björck 1987, 1995; Svensson 1989). The calcareous gyttja at a depth of 570–580 cm (L. Ülemiste, core I by L. Saarse from 1973) and its radiocabon date 8300±90 (TA-691) are not connected with the Ancylus transgression, as it was interpreted earlier (Kessel 1979; Haila & Raukas 1992, Fig. 118).

The amplitude of the Yoldia Sea shore displacement regression in the study area was 11–12 m (Fig. 11). It reached the minimum level about 9500 BP (Fig. 13). As a result of the land upheaval, the sea level dropped from 40–39 to at least 29–28 m, with the average regression rate being about 1.4–1.5 cm/yr. All the basins treated here isolated during the Yoldia regression in the following order: Tondi, Sõjamäe, Rae, Vandjala, Saha, Maardu and Ülemiste (Figs. 11, 13).

Ancylus stage

The Ancylus beach formations range up to 37.5 m north at Maardu (Kroodi spit) and 37 m near Iru (Iru spits; Fig. 14), which confirms the Ancylus Lake maximum limit at an elevation of 35–36 m (Tammekann 1936). As the thresholds of Maardu and Saha are lower than the Ancylus transgressional limit, the Ancylus Lake water should have ingressed into these basins. According to the palaeogeographical reconstruction, a shallow lagoon formed behind the above-mentioned spits (Fig. 14). The spit itself soon closed the connection with the Ancylus Lake, and a shallow water body, with threshold of 35 m, was formed behind it (Fig. 14). This means that for a short time Maardu and Saha were also dammed up.

The traces of Ancylus transgression are variable and differ with sediment cores. In L. Maardu (Fig. 8) it is recorded in the diatom diagram. The peak of planktonic diatom taxa at a depth of 930–900 cm are indicative of the Ancylus transgression (Fig. 8). In the Saha sequence, transgression is registred by increased terrigeneous fraction at a depth of 130–140 cm and by the accumulation of silty gyttja

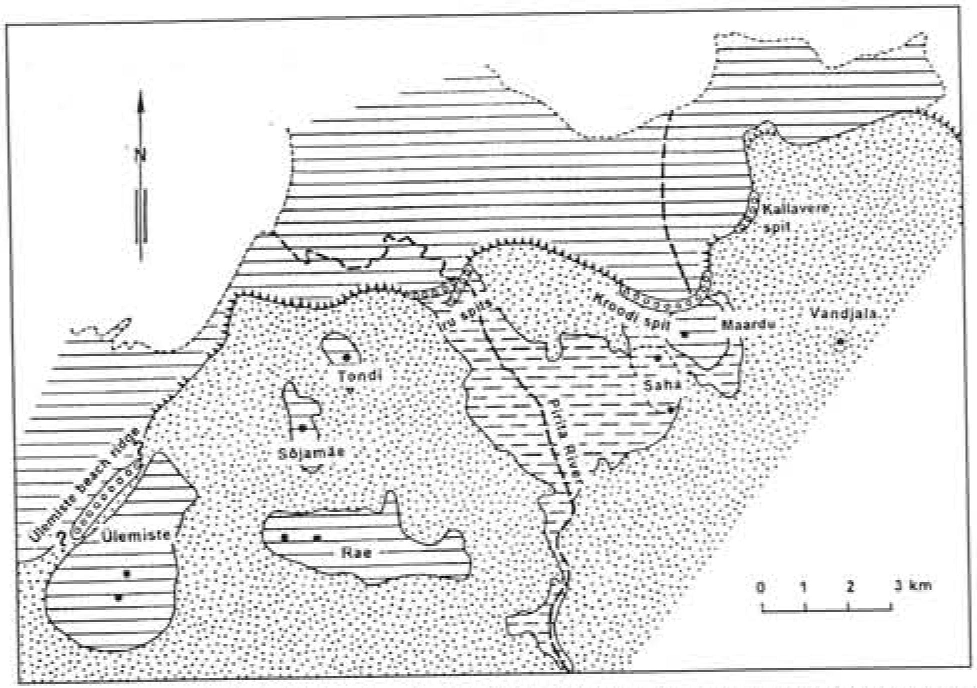

Fig. 14. Palaeogeography east of Tallinn during the Ancylus Lake transgressional limit, about 9300 BP. Legend see Fig. 12.

(Fig. 4). The uppermost part of the peaty gyttja of L. Ülemiste contains some diatom taxa *e.g. Ellerbeckia arenaria*, *Epithemia hyndmanni* reported as being typical for the Ancylus Lake (Eronen & Haila 1982; Risberg 1991; Fig. 9). The peak of terrigenous fraction could be indicative of the ingresson of water to L. Ülemiste during the heavy storms. Long distance transport of diatoms by wind, drifted wavesurf drops, and/or transport by waterfowls provides an alternative mechanism for dispersal of the Ancylus Lake diatom taxa to coastal L. Ülemiste of that time. For this reason the connection of L. Ülemiste with the sea is questioned (Fig. 14).

The Ancylus transgression, reaching the level 36 m near L. Ülemiste and 35 m near L. Maardu, started about 9500 BP and culminated about 9200–9300 BP in the study area. By the beginning of the Boreal period the transgression was over and the water level should have dropped to the level of 33 m or lower, because in the Saha mire fen peat started to accumulate (Figs. 4, 5, 11).

Palaeogeography

Fig. 12 illustrates landscape development about 10,000 BP. East of Tallinn there was an archipelago with several smaller and larger islands, the northermost of them fringed by klint escarpments. Sõjamäe and Tondi were lagoons backed by beach formations and straits opened towards the southeast. In principle, this reconstruction is similar to the previous ones (Kessel et al. 1986). At the end of the Yoldia regression about 9500 BP (Fig. 13), the sea retreated below the edge of the klint escarpment and the area south of it was dry land with several residual lakes. Lakes Rae and Ülemiste split up into two basins (Saarse & Arbeiter 1979). During the Ancylus transgression, about 9300–9200 BP (Fig. 14) the shore displacement followed the klint escarpment. Spits in Kallavere, Kroodi and Iru and the beach ridge west of L. Ülemiste were formed. The water level rose and a large area in the upper course of the Pirita River mouth submerged and turned into a shallow lagoon. We do not have evidence supporting the continuous connection of L. Ülemiste with the Ancylus Lake, but the temporary connection (during heavy storms) is quite obvious.

CONCLUSIONS

On the basis of the obtained evidences we can draw the following conclusions on the Yoldia Sea regression and Ancylus Lake transgression east of Tallinn:

1. Yoldia Sea deposits have been identified in Sõjamäe, Tondi (Kessel 1961; Kessel & Punning 1969; Lepland et al. 1995), Maardu (Saarse et al. 1990) and Ülemiste basins. They are represented by sand, clayey or peaty gyttja. We have one radiocarbon date from the Yoldia deposits in L. Maardu – 9655±70 (Tln-1313; Saarse et al, 1990) and two dates from L. Ülemiste (9510±65, Tln-1858; 9500±60, Tln-1857). The latter define the transition between the Yoldia and the Ancylus stages, as the uppermost peaty gyttja contains planktonic diatoms,with a clear peak in *Pediastrum*, and increased percentages of terrigenous compounds. The radiocarbon dates from Sõjamäe, Vandjala and Saha deposits are about 1000 years younger than expected, due to the contamination of gyttja with younger *Typha* and *Phragmites* roots.

2. The new results from L. Ülemiste show that the Yoldia Sea level was at its lowest (28–29 m) about 9500 BP. As the regression of the Yoldia Sea amounts to at least 11–12 m due to the land upheaval, the water level in the studied basins dropped. Deposits on the Yoldia/Ancylus contact have been dated twice. Both dates are quite similar: 9500±60 (Tln-1857, ^{14}C) and 9490±110 (Ua-2390, AMS). The first marks the age of peaty gyttja in L. Ülemiste; the second shows the age of a piece of wood between sand and gyttja in L. Maardu (core 3).

3. Ancylus Lake's maximum shore displacement east of Tallinn was levelled at an elevation of about 35–36 m (Tammekann 1936; Künnapuu 1959; Kessel 1961). Transgressional deposits were registered in the Maardu section at a depth of 900–930 cm in the silty calcareous gyttja (Figs. 2, 8) and in the Saha mire at a depth of 130–140 cm (Fig. 4). The Ancylus Lake transgression culminated about 9300–9200 BP.

4. The formation of peat in the Saha mire at the beginning of the Boreal confirms that the Ancylus Lake started to regress and, by the time the Saha basin isolated, its water level had decreased by 2–3 metres.

ACKNOWLEDGEMENTS

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Composition of Bottom Surface Sediments in the South East Baltic Sea

Marijonas Repečka, Petras Šimkevičius and Rolandas Radzevičius

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Marijonas Repečka, Petras Šimkevičius and Rolandas Radzevičius, Institute of Geology, Department of Baltic Marine Geology, T. Ševčenkos 13, LT 2600 Vilnius, Lithuania; *received 15th July 1996, accepted 27th January, 1997.*

Pelitic sediments in the South-Eastern Baltic Sea progressively change to coarser sediments on its slopes and sand in the shallow zone. Lag sediments are found on the surface of Pleistocene deposits (tills). Mineral composition of pelitic fraction, dependence of changes in amount of clay minerals on their source-rocks, relief of bottom surface and lithological composition of bottom sediments are studied and discussed. Also, there are concentrations of minor elements, such as As, Hg, Cd, Pb, Zn, Ni, Cu, Co and Cr in sediments of Gdansk and Gotland depressions given. Sediment accumulation and distribution, depending on lithology of sediments and amount of organic matter, are described.

Keywords: South-East Baltic Sea, bottom sediments, clay minerals, content of metals.

INTRODUCTION

The bottom of the Baltic Sea is treated as a final sink, where sedimentary material produced by abrasion processes, as well as its organogenous component formed in the sea are accumulated. The bottom sediments have been studied in an area of about 110000 km^2 in the southeastern part of the Baltic Proper. The major part of sediments entering the SE Baltic Sea is attributed to the Nemunas River catchment with its area making up 98102 km^2 (Geology of the Baltic Sea, 1976).

Glacial exaration and accumulation as the main Pleistocene processes influenced the evolution of the sea bottom relief. During Holocene sedimentation was most intensive in depressions, meanwhile on slopes and tops of elevations the Pleistocene and even pre-Quaternary deposits remained uncovered by Holocene sediments. The intensity of the sedimentation varied greatly: during the Yoldia Sea stage sediments were accumulating by 120 mm per 1000 years in average, during Lake Ancylus time this rate was about 60 mm and only 12 mm during the Littorina and Limnea Sea periods (Repečka et al. 1991). Type of sediment distribution on the sea floor surface points to a further evolution of bottom relief and widening of stabilization zones.

The recent bottom relief of the Baltic Sea depression has been formed during the Pleistocene, and it has been modified locally by abrasion and accumulation. The area studied includes the following orographic units: the Kurish–Sambian and Klaipėda–Ventspils submarine plateaus, the Gotland depression and the northern part of the Gdansk depression with its flat levelled slope (Fig. 1).

METHODS AND MATERIAL

During Lithuanian–Swedish expeditions in 1993–1995, bottom sediments were sampled at 212 sites by grab (Van Veen), Niemisto and gravity corers (Fig. 1). The grain size of bottom sediments was determined by washing out particles of less than 0.01 mm. The sand and coarse aleurite samples (100–300 g) were dried and sorted by a sieving shaker "Analizette 3". The percentages of the fractions from <0.01 mm to >10 mm were determined in 25 fractions. The sediments with a higher amount of particles with a diameter less than 0.01 mm were analyzed by the pipette method (Petelin 1967). The fractions <0.001 mm, 0.001–0.005, 0.005–0.01 and 0.01–0.05 mm have been measured. Sieving has been apllied for sediments containing more than 10% of particles with grain size exceeding 0.05 mm.

Samples from a thin layer (up to 1 cm thick) of superficial bottom sediments (lithologically from pelitic mud to fine aleurite) have been taken for XRD-analysis of their pelitic fraction (less than 1 μm). The following clay minerals have been found:

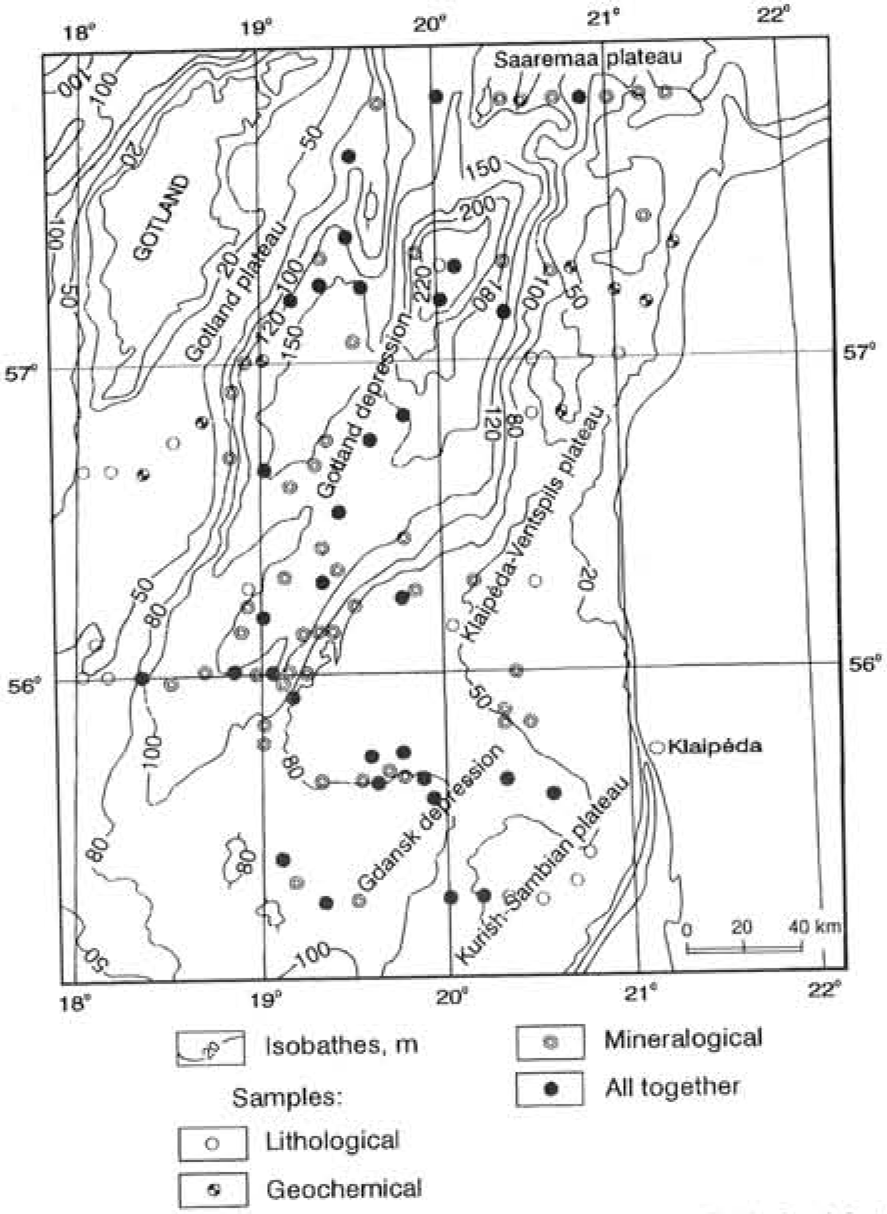

Fig. 1. Sampling sites and orographic subdivision of the South-Eastern part of the Baltic Sea (after Ž. Gelumbauskaitė and V. Litvin, 1991).

kaolinite, montmorillonite, chlorite and illite, with kaolinite and montmorillonite content ranging from from traces up to 20%, chlorite – from traces up to 15% and illite – from 60 up to 90% (Repečka & Šimkevičius 1994).

Metals have been analyzed in 45 samples. Sediments were put into plastic boxes, dried at a temperature of 20–25°C and ground into powder. The metals have been determined in the "Acme Analytical" laboratory (Vancouver, Canada). Samples for metal analyses have been dissolved in solution of $HCLO_4$-HF acids by adding a mixture of HCL-HNO_3. "Total" concentrations of As, Cd, Pb, Zn, Ni, Cu, Co, and Cr have been determined by ICP method, and AAS analysis has been applied for Hg. The error of analyses is estimated to be about 10–15 per cent.

Total organic carbon (TOC) was determined after burning samples to CO_2 at 900°C and applying automatic coulonometric titration method (device AH-7529, Russia) in the Institute of Geography (Vilnius, Lithuania).

DISCUSSION

Bottom Sediments

The classification used in many monographs, papers and maps for division of bottom sediments is based on grain size distribution and genesis of sediments (Sjoberg 1992, Emelyanov 1988, 1995; Emelyanov et al. 1994). Some authors classify bottom sediments according to their physical characteristics (Ignatius et al. 1981).

The information available has been generalized and a lithological map of the south-eastern Baltic Sea bottom surface, reflecting the distribution of sediments in the bottom surface layer (0–3 cm), has been compiled (Fig. 2). Bottom sediments are classified according to P.Bezrukov's and P.Lisitsin's classification (1960). The correlation of different sediment classifications is shown in Table 1.

Pre-Quaternary rocks at the sea bottom surface are found only in a shallow zone near Liepaja and on the steep western slope of Gotland plateau. There are outcrops of pre-Quaternary rocks on the eastern slope of the Gotland depression (they are not shown on the map).

Pleistocene glacial deposits (tills) are widespread in the south-western part of Klaipėda–Ventspils plateau, southwards from Gotland and in the western part of the Kurish–Sambian plateau. They consist of morainic loams, brown-grey, sometimes grey, hard, containing an admixture of gravel and pebbles. Locally glacial deposits overlie clay of the Baltic Ice Lake and Holocene sediments. Next to Pleistocene morainic loams, there is clay of the Baltic Ice Lake covered here and there by a thin (2–5 cm) lamina of inequigranular sand containing an admixture of gravel and pebbles found. This thin bed of coarse sediments represents residual deposits formed by abrasional processes. There are sediments of mixed granulometry, including gravel, pebbles, inequigranular sand and even aleuritic particles. Poor degree of sorting is a characteristic feature of these sediments. They are spread at depths greater than the sediments of usual granulometric composition occur at. Sediments of mixed composition – so-called mixtites, corresponding to coarse sand, are observed down to 125 m. Going deeper, the amount of aleuritic and pelitic particles increases and the uniformity coefficient

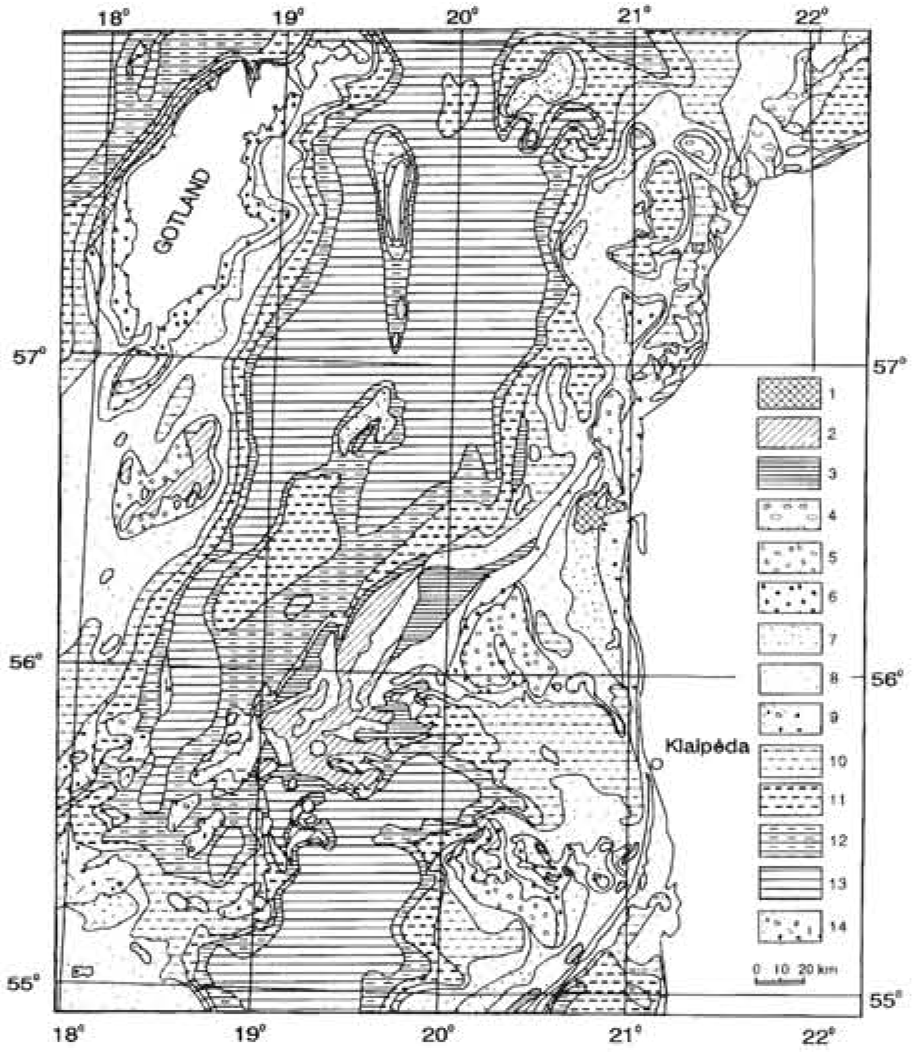

Fig. 2. The Baltic Sea bottom sediments

Types of sediments: 1 – pre-Quaternary deposits, 2 – glacigenous deposits (tills), 3 – clay of the Baltic Ice Lake, 4 – pebble (100–10 mm), 5 – gravel (10–1.0 mm), 6 – coarse sand (1.0–0.5 mm), 7 – medium sand (0.5–0.25 mm), 8 – fine sand (0.25–0.1 mm), 9 – different sand (1–0.1 mm), 10 – coarse aleurite (0.1–0.05 mm), 11 – fine aleuritic mud (0.05–0.01 mm), 12 – aleuritic-pelitic mud (50–70% <0.01 mm), 13 – pelitic mud (>70% <0.01 mm), 14 – mixed sediments.

Table 1. **Correlation table of sediment classifications**

Sediment size				Bezrukov, Lisitzin 1960		Classification of soil, USA (From F. Shepard, 1969)		Wentworth, 1922 (From F. Shepard, 1969)		Swedish Standard, 1981		
mm	mm	µk	$\varphi=$ -log$_2$ mm									
	255		-8	Boulders		Boulders		Boulders			Stone	Coarse
100	128		-7					Cobble				Medium
50	64		-6	Pebble	Coarse	Gravel	Coarse	Pebble		60	Gravel	Coarse
25	32		-5		Medium							
	16		-4		Fine							Medium
10	8 10		-3	Gravel	Coarse		Medium					
5	4		-2		Medium			Gravel				Fine
2,5	2	-2000	-1		Fine		Fine	Sand	Very coarse	2	Sand	Coarse
1,0	1	1000	0	Sand	Coarse	Sand	Coarse		Coarse			
0,5	1/2	500	+1		Medium		Medium		Medium			Medium
0,25	1/4	250	+2		Fine		Fine		Fine			
0,10	1/8	125	+3	Aleurite	Coarse		Very fine		Very fine			Fine
0,05	1/16	62,5	+4		Fine aleuritic mud	Aleurite		Aleurite	Coarse	0,06	Silt	Coarse
	1/32	31,5	+5						Medium			
0,01	1/64	15,6	+6	Pelite	Aleuritic-pelitic mud				Fine			Medium
0,007	1/128	7,8	+7						Very fine			
	1/255	3,9	+8		Pelitic mud	Clay		Clay	Coarse			Fine
	1/512	1,95	+9						Medium	0,002	Clay	
0,001	1/1024	0,98	+10						Fine			
	1/2048	0,49	+11						Very fine			
	1/4096	0,24	+12					Colloid				

grows worse. Sediments of mixed composition are more widespread south-westwards from the Klaipėda–Ventspils plateau, between Gotland and Gdansk depressions. Here abrasion processes have manifested themselves more intensively, and products of Pleistocene moraine desintegration form sediments of mixed composition – the mixtites.

Pebbles, gravel, glacial erratic boulders and inequigranular sand deposits are abundant in the zone of intensive abrasion. In the shallow zone, there are only local occurrences of inequigranular sand, gravel and pebbles. Farther apart from the dynamic shore line, particles of sediments become smaller. Nevertheless, fine sand of the same composition (Md – 0.166) is spread at the depths of the sea of 4.0; 30.5; 62 and 84 m. These levels with sediments of the same lithological composition could be related to fluctuations of the sea level during different stages of the Baltic Sea evolution. Coarse sediments are widespread in the region of the Kurish–Sambian and Klaipėda–Ventspils plateaus having no direct hydrodynamic relationship with the dynamic shore line. These sediments occur locally in the shallow zone, too.

With depth increasing, fine sand is substituted by coarse aleurite. Its distribution is analogous to that of coarser sediments. Coarse aleurites are widespread westwards from Klaipėda. Here already at a depth of 10 m sand grades into coarse aleurite which is substituted by fine aleuritic mud at depths of 60–70 m. On top of the Baltic Ice Lake sediments coarse aleuritic deposits of mixed granulometric composition are found at a depth of 107 m.

Fine aleuritic mud is observed on depression slopes and feet of separate hills at the depths of 65–140 m. With water depth increasing, these sediments are substituted by aleuritic-pelitic mud. Poor sorted sediments of mixed granulometry, found in the zone of morainic loam, make an exception.

Aleuritic-pelitic mud is spread at the margins of the Gotland and Gdansk depressions and at the feet of large elevations between 80 m and 160 m of depth. Poor sorted aleuritic-pelitic mud is observed near the margins of areas with Pleistocene moraines and sediments of mixed composition.

Pelitic mud is widespread in the Gotland and Gdansk depressions at depths more than 120 m. It is well sorted, thus showing a high degree of sediment differentiation. The pelitic mud is worse sorted at the sites where sedimentation is slow, or on the steep slopes of the bottom. Here (like in other cases) sediments of mixed composition overlie Pleistocene till deposits. The sorting coefficient is better, as size of sediment particles decreases. It indicates that the process of sediment differentiation reaches its highest degree in the depressions of the Baltic Sea. In the shallow parts of the basin poorly sorted muds and sediments of mixed composition – the mixtites – adjoining relictic sedimentation zones and outcrops of Pleistocene deposits, are observed.

Clay Minerals

Pelitic fraction of fine bottom sediments (pelitic, aleuritic-pelitic, aleuritic mud) has been studied in order to find out origin of sediments and dependence of sedimentation on physical conditions of the sea bottom. The distribution of clay minerals in the studied area may be analysed according to the following aspects:

(a) relief,
(b) water depth,
(c) lithology of bottom sediments.

Most complete studies on the pelitic fraction of sediments have been done for samples of sediments from the Klaipėda–Ventspils plateau and the Gotland depression (Figs. 1, 3–6). Other orographic regions are characterized only by few analyses.

The clay minerals in the fraction less than 1 µm (of sediments) are distributed in the studied area as follows and described below (Figs. 3–6).

At the Kurish–Sambian plateau (its northern and north-western parts) the amounts of kaolinite and montmorillonite are rather constant (10–15%) and there is everywhere less than 5% of chlorite with the exception for the area located near the Klaipėda inlet, where a sudden decrease of kaolinite and montmorillonite amounts to less than 5% and an increase of chlorite to 5–10% are observed. Content of illite decreases westwards from 85–90% to 70–75%. It shows the differentiation of clay minerals in the area.

At the Klaipėda–Ventspils plateau (its southern part) kaolinite amounts to 10–15%. There are small areas where this amount increases or decreases by 5%. The highest amounts of montmorillonite (10–15% and locally 15–20%) are observed in the north-eastern part of the studied area. Westwards and northwards they decrease gradually to 5–10% and less than 5%. Everywhere the chlorite amounts are less than 5%, only in the very northern and southern parts of the plateau areas with amounts of

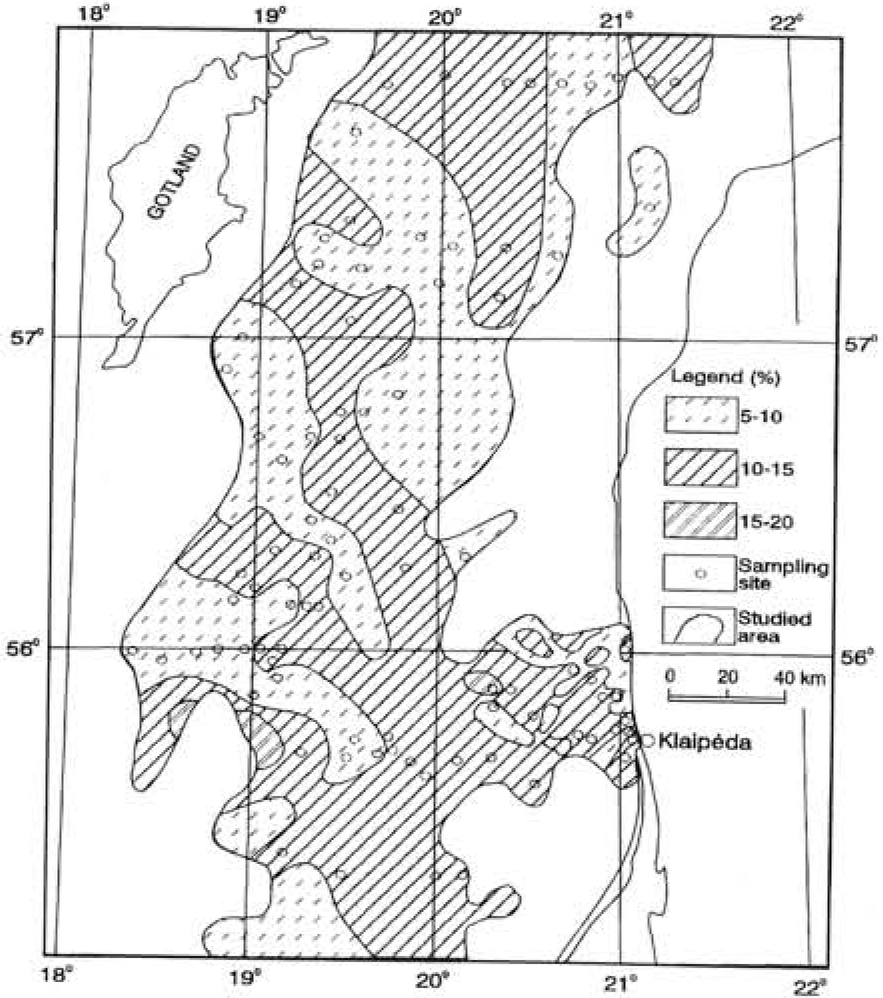

Fig. 3. Distribution of kaolinite in clay fraction of bottom sediments.

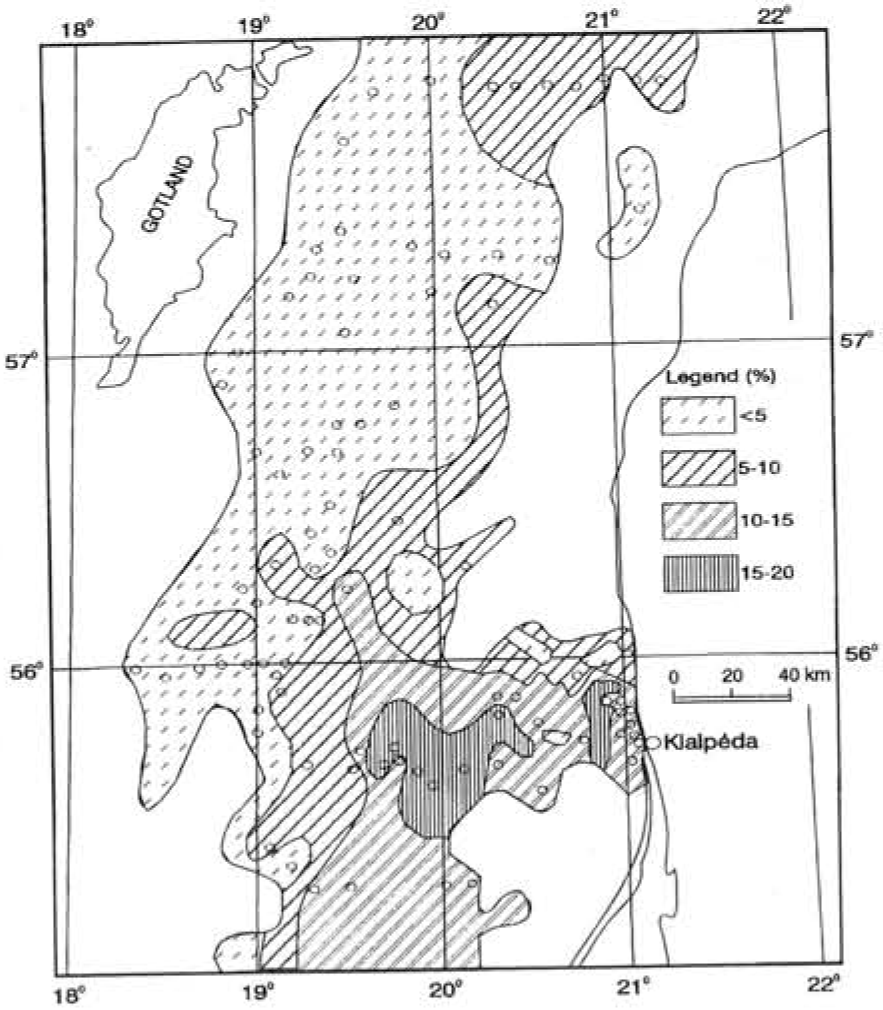

Fig. 4. Distribution of montmorillonite in clay fraction of bottom sediments.

5–10% and even up to 15% are found. The amounts of illite increase westwards and northwards from 60–65% to 75–80% (in some places up to 85%).

The Gotland plateau is characterized only by the analysis of sediments from 2 stations, where kaolinite ranges in 5–10%, montmorillonite is lower than 5%, chlorite – 10–15% and illite – 75–80%.

Only the very southern part of the Saaremaa plateau is covered by analyses of the clay composition. Here 5–15% of kaolinite, 5–10% of montmorillonite, 3–10% of chlorite and 70–80% of illite were found.

Most completely the distribution of clay minerals has been studied in the Gotland depression. In sediments of its western and middle-eastern parts kaolinite amounts to 5–10%, elsewhere to – 10–15%. The content of montmorillonite does not exceed 5% in the whole area of the depression, except for its easternmost part, where the montmorillonite content is 5–10%. Chlorite amounts to 5–10% in a major part of the studied area, only in the middle-eastern and northernmost parts it makes up less than 5% and in small areas on western slopes of the depression – more than 10%. Most of the sediments of the Gotland depression contain 75–80% of illite.

The northern part of the Gdansk depression has been studied. In this area two parts could be identified by the distribution of kaolinite: a north-eastern with 10–15% of kaolinite and a south-western one with – 5–10%. Montmorillonite behaves like kaolinite, only its amounts are higher by 5%. The content of chlorite is lower than 5% everywhere. The amount of illite slightly increases from 65–70 to 70–75% going from north to south, because pelitic fraction in the northern part is more highly enriched by montmorillonite and kaolinite.

In the uppermost sediment layer, some relationship between the montmorillonite distribution and the water depth is observed in the area studied. The highest amounts of montmorillonite (10–15%, in local small areas – 15–20%) are found down to the depth of 80–90 m and only in the deeper southern part of the aquatory they gradually decrease. Amounts of 5–10% are related to water depth of 120–140 m in the eastern part of the entire region studied. Westwards from these depths the content of montmorillonite decreases to less than 5% or it is absolutely absent, independently on the water depth.

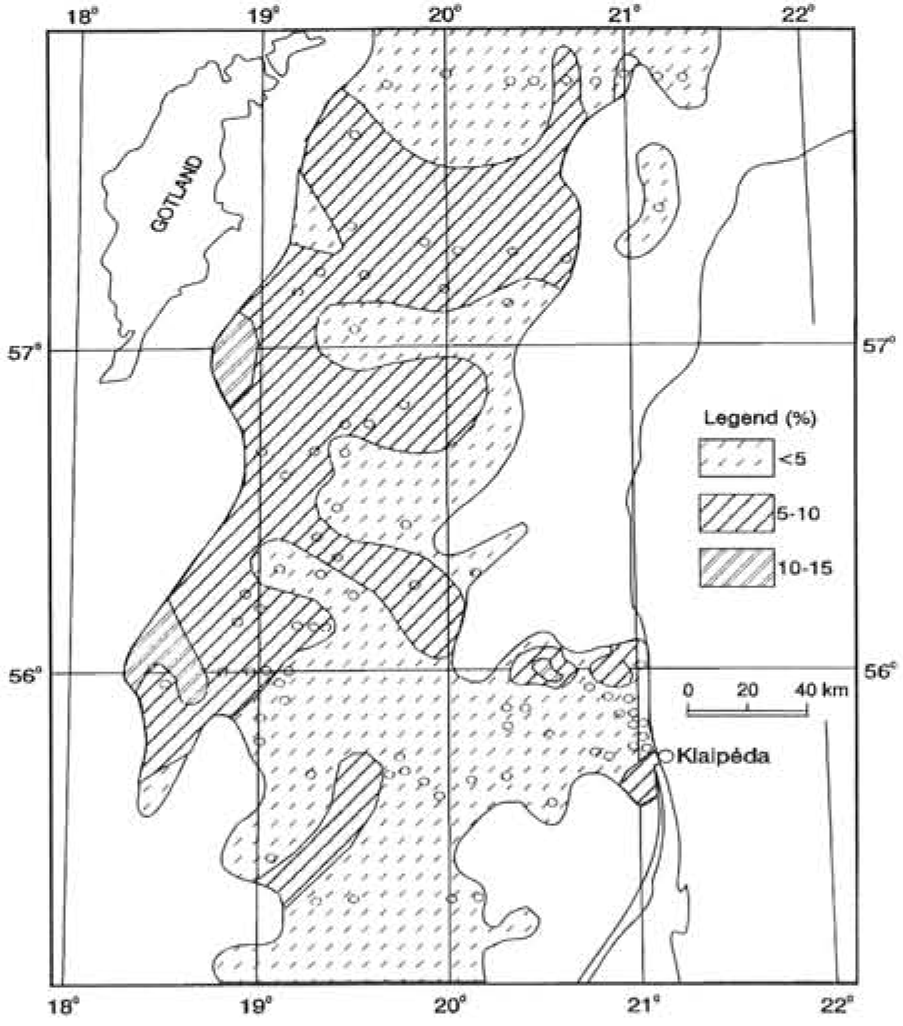

Fig. 5. Distribution of chlorite in clay fraction of bottom sediments.

There are two large areas where the amount of chlorite increases up to 5–10% and locally even to 15%. These areas are located mainly at depths of more than 60 m in the northern and western parts of the studied area. Elsewhere chlorites less than 5% are observed, without any dependence on water depth.

The distribution of kaolinite and illite does not depend on the water depth.

The clay fraction of the pelitic mud in the Gotland depression contains very small amounts of montmorillonite (less than 5%). An increase of its amounts (up to 10 and even 15%) is related here to an increase of grain size (aleuritic-pelitic and fine aleuritic mud) (Figs. 1, 2, 4). On the other hand, pelitic mud in the Gdansk depression is characterized by a high content of montmorillonite (10–20%). The same amounts are found in lithologically different bottom sediments of the Kurish–Sambian plateau. It shows, that the higher amount of montmorillonite is carried out from Klaipėda channel to the Baltic Sea.

Almost the entire area studied of the Klaipėda–Ventspils plateau and the southern part of the Saaremaa plateau is characterized by an amount of montmorillonite in the clay fraction of 5 to 10%. It does not depend on the lithological composition of the bottom sediments, that is rather diverse in these orographic regions.

Comparatively high amounts of chlorite (5–10%) are observed mainly in the pelitic mud of the Gotland depression and Gotland plateau (up to 15%), while pelitic sediments of the Gdansk depression are characterized by small amounts of chlorite (less than 5%). The clay fraction of coarser sediments contains small amounts of chlorite in the entire studied area (Figs. 1, 2, 5). The amount of kaolinite and illite is not related to lithological composition of sediments.

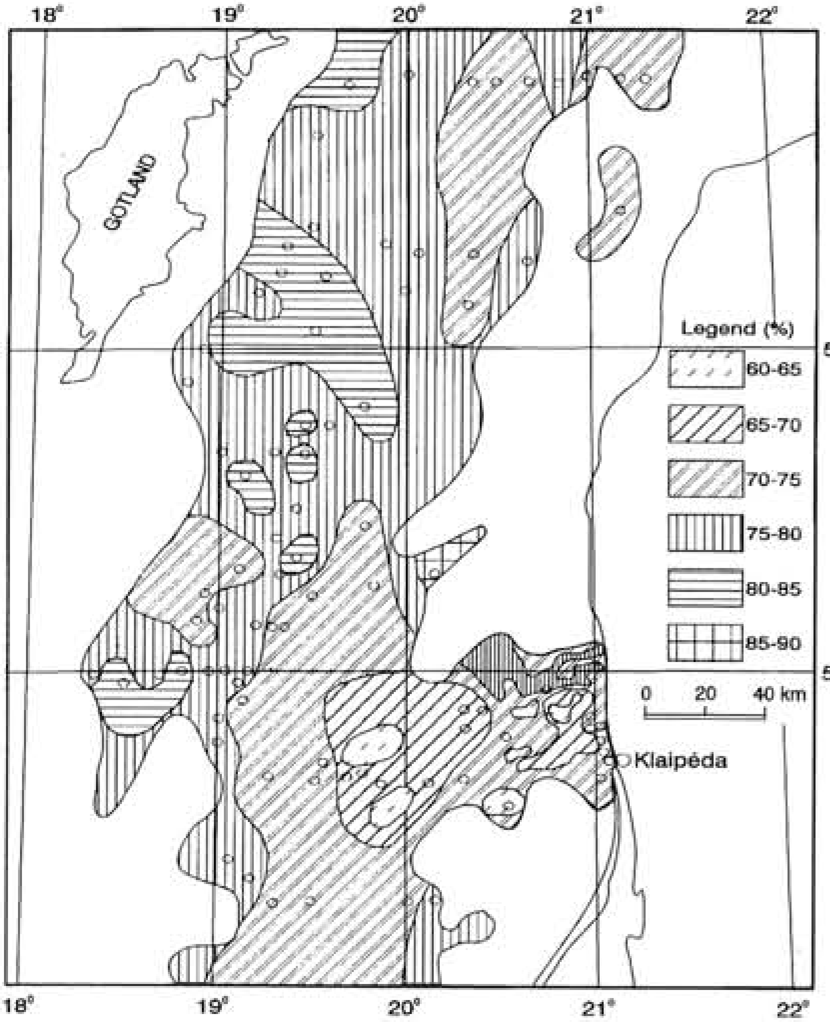

Fig. 6. Distribution of illite in clay fraction of bottom sediments.

Content of Metals

Table 2 shows data on metals and total organic carbon (TOC) in different types of surface bottom sediments. The changing average concentrations of elements depending on the lithological type of sediments are shown in Figs. 7, 8. The values obtained are less than those given in the literature (Blazhchishin, Emelyanov 1977; Jokšas 1994). Apparently they can be related to an incomplete dissolution of Al, Zr, Mn oxides, some sulfides and other minerals.

The distribution of metals and their accumulation in bottom sediments depends mainly on the following factors. Sedimentation in a basin is predetermined by distribution of terrigenous particles on the bottom surface. With increasing water depth, the hydrodynamic activity decreases and accumulation of organic matter increases together with an increase of the amount of pelitic particles (Fig 7). It is accompanied by an increase of the metals content in the bottom sediments (Blazhchishin, Emelyanov 1977; Jokšas 1994).

According to our results, the metals can be subdivided into two groups. As and Hg form one group, and the rest of the analyzed metals (Cd, Pb, Zn, Ni, Cu, Co) – the second. The concentration of As and Hg decreases in aleuritic-pelitic mud compared to their portions in fine aleuritic mud. As decreases from 14.5 to 13.7 ppm and Hg – from 184 to 138 ppb. Such a decrease of Hg and As concentrations is, apparently, related to a change of physical and chemical (Eh) conditions. This change of the Eh potential is connected with the lithological boundary between fine aleuritic mud and aleuritic-pelitic mud (Blazhchishin Emelyanov 1977). As and Hg are mobile in an oxic environment and under reductional conditions they precipitate (Perelman 1989). The concentration of metals (Zn, Cu, Cr, Pb) increases evenly with bottom sediments getting finer and increasing amount of TOC. Obviously, the amount of pelitic particles and organic matter affects the distribution of those metals most of all.

The distribution of Hg, Zn, Pb and Ni in superficial bottom sediments is shown in Figs. 9–12.

Table 2. **Concentration of metals in different sediment types**

Element	Type of sediments				
	Fine sand	Coarse aleurite	Fine aleuritic mud	Aleuritic pelitic mud	Pelitic mud
Hg	4.9–110 38 (10)	40 40 (1)	95–305 184 (11)	65–330 138 (16)	275–295 285 (2)
Zn	10–59 24 (13)	26 26 (1)	80–192 126 (12)	104–356 173 (17)	190–209 200 (2)
Pb	4.9–32 14 (13)	14 14 (1)	27–66 47 (12)	16–78 59 (17)	52–60 56 (2)
Cd	0.39–0.6 0.41 (13)	0.39 0.39 (1)	0.39–1.1 0.57 (12)	0.39–3.5 0.82 (17)	1.3–1.8 1.6 (2)
As	<5 <5 (13)	<5 <5 (1)	7–23 14.5 (12)	6–25 14 (17)	13–18 16 (2)
Co	1.9–6 3 (13)	3 3 (1)	5–25 14 (12)	12–21 16 (17)	20–24 22 (2)
Cr	1.9–27 12 (13)	7 7 (1)	52–99 77 (12)	49–99 82 (17)	76–90 83 (2)
Cu	1.9–14 5 (13)	4 4 (1)	15–49 33 (12)	25–56 42 (17)	46–49 48 (2)
Ni	1.9–16 6 (13)	8 8 (1)	19–58 40 (12)	33–59 45 (17)	54–58 56 (2)
TOC	0.06–1.7 0.49 (14)	0.2–2.26 1.2 (4)	1.01–4.0 2.6 (14)	1.2–3.8 3.1 (14)	2.8–3.1 2.9 (3)

Note: Hg and As in ppb; TOC in %; other elements in ppm
content limits (minimum value – maximum value)
mean content (number of samples obtained)

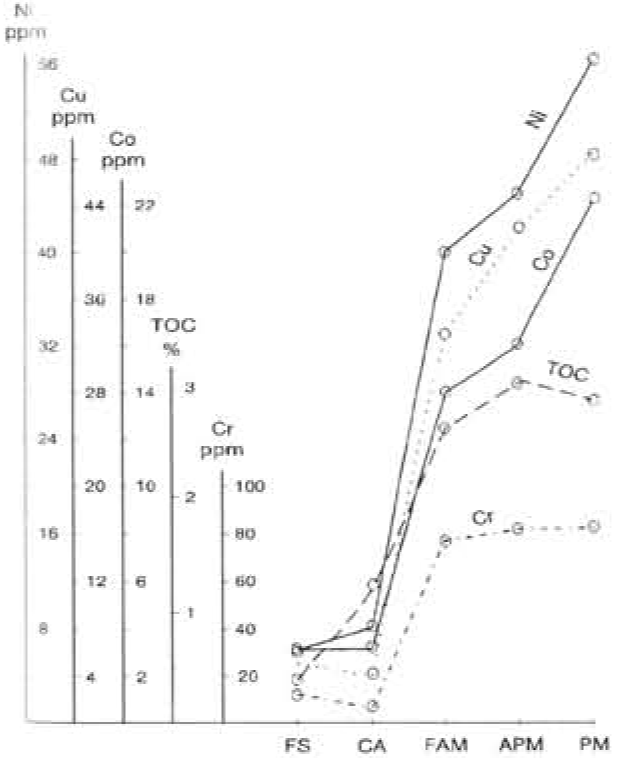

Fig. 7. Distribution of Ni, Cu, Co, Cr in different types of bottom sediments. Types of sediments: FS – fine sand, CA – coarse aleurite, FAM – fine aleuritic mud, APM – aleuritic-pelitic mud, PM – pelitic mud.

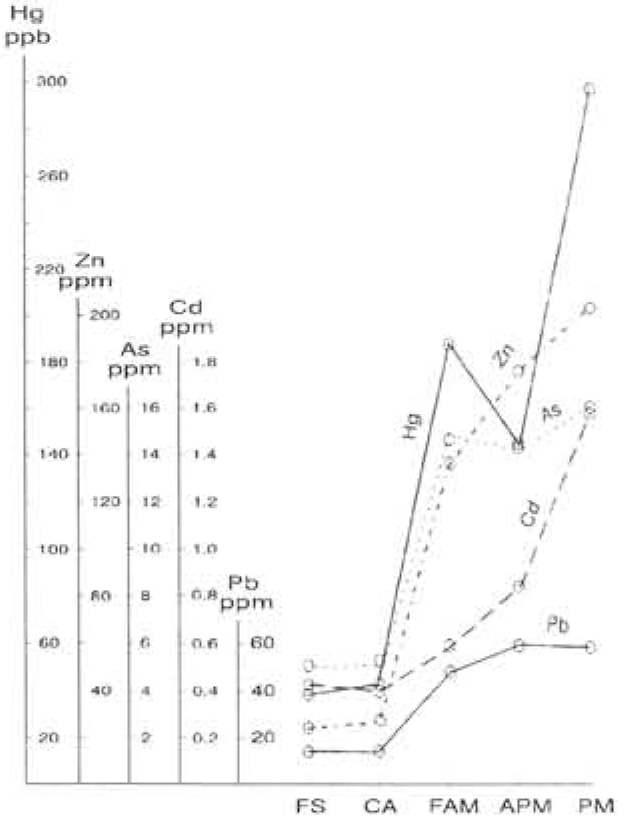

Fig. 8. Distribution of Hg, Zn, As, Cd, Pb in different types of bottom sediments.

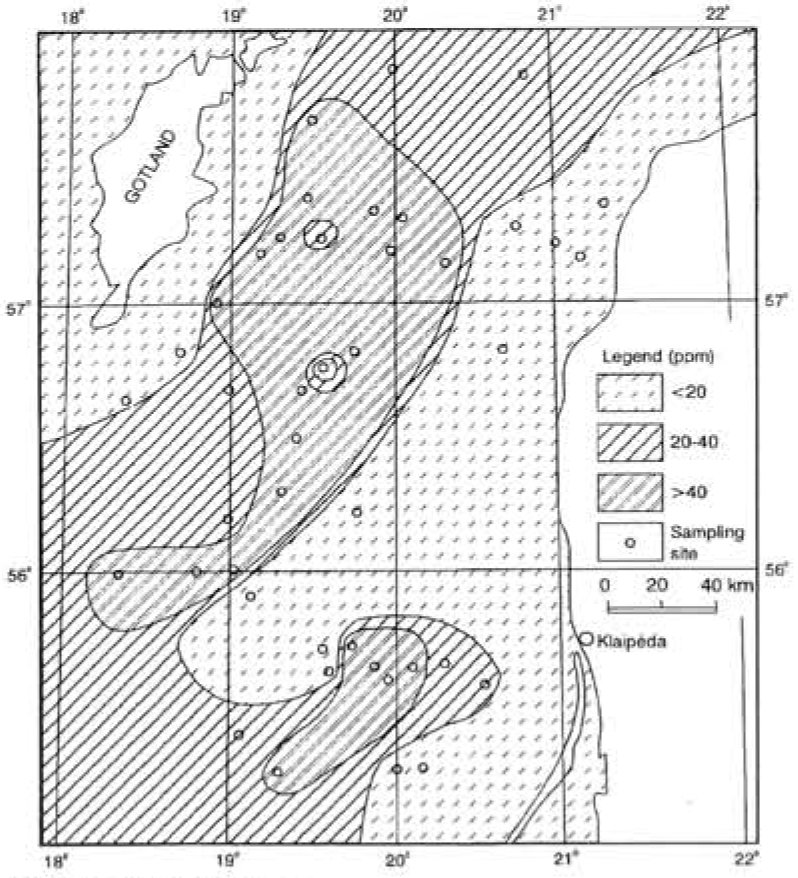

Fig. 9. Distribution of Ni in the bottom sediments

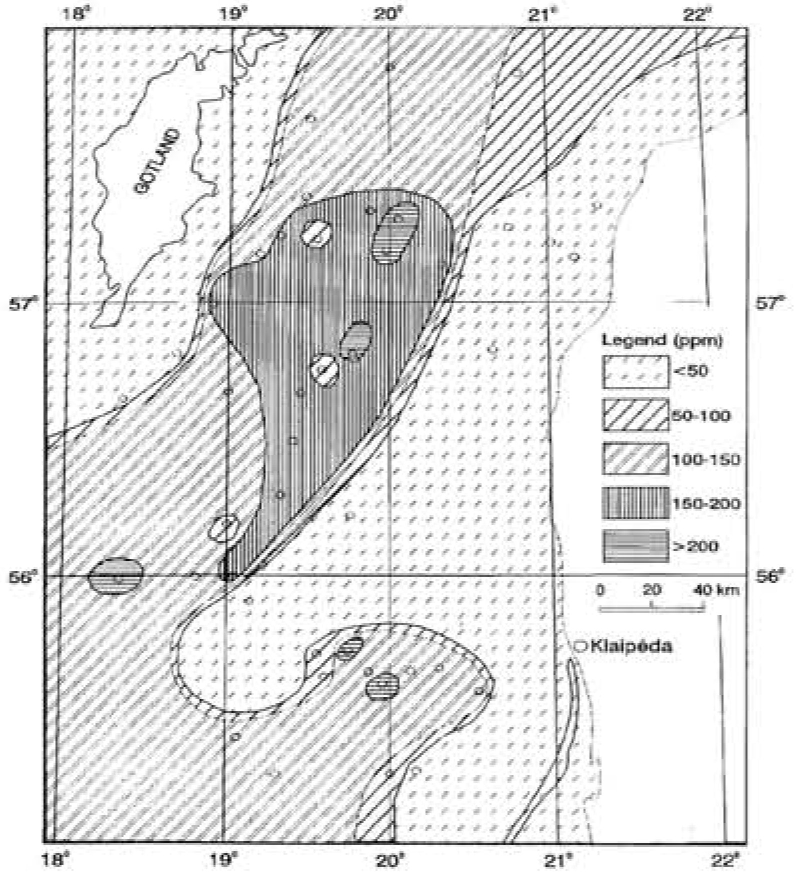

Fig.10. Distribution of Zn in the bottom sediments

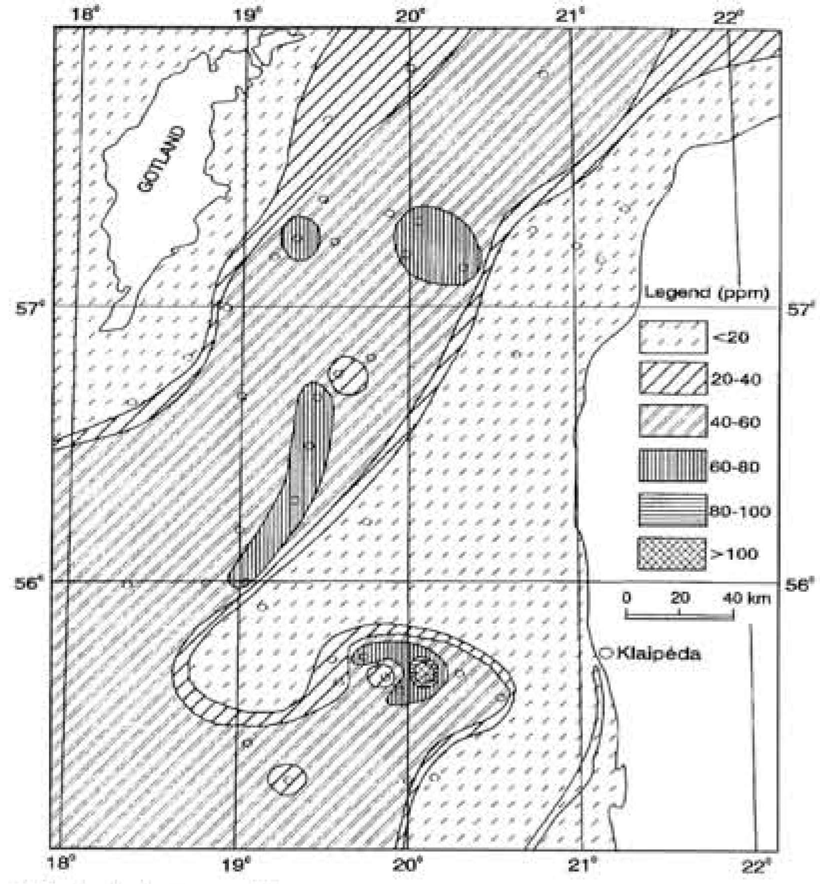

Fig. 11. Distribution of Pb in the bottom sediments

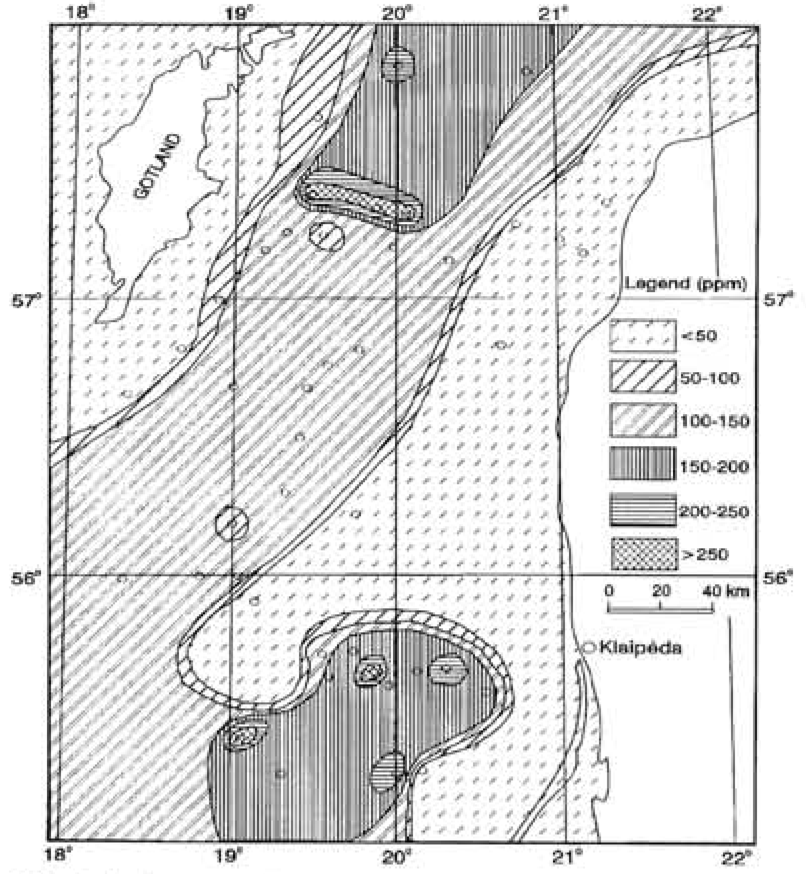

Fig. 12. Distribution of Hg in the bottom sediments

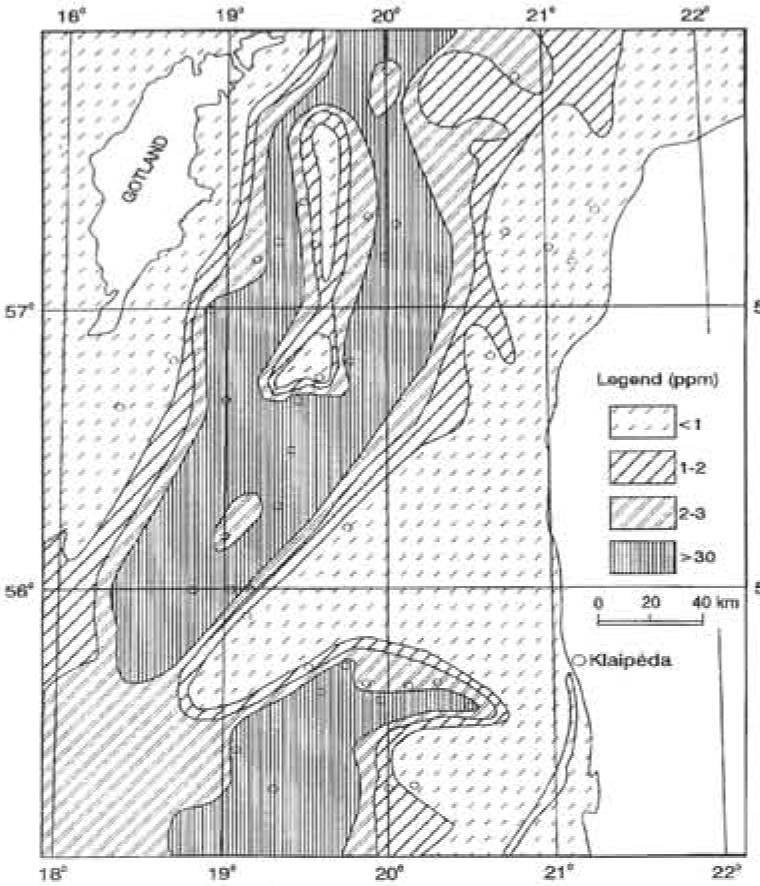

Fig. 13. Distribution of total organic carbon (TOC) in the bottom sediments.

Maximum concentrations of metals are related to the depressions. As the maps (Figs. 9–12) show, the distribution of metals and their anomalies differ for the Gotland and Gdansk depressions. Boundaries between different concentrations of elements have been drawn according to the lithological composition and the average amount of the different sediment types.

Anomalies of Zn and Ni (Cu, Cd, Pb, Cr) are observed in the same places in the Gotland depression. Maximum amounts of these elements are found around the Gotland Deep and near the eastern margin of the Gotland depression. Increased Pb amounts are found in the eastern part of the Gotland depression, and maximum Hg amounts – in the Gotland deep and its northern part. An anomaly of Hg, Pb, Ni, (As, Cu, Cr, Cd) was determined in the Gdansk depression. Distribution of metals is similar to TOC in the bottom sediments of the Gdansk depression (Fig. 13).

Most likely, two main factors have caused such different multielemental anomalies: namely, diverse metal supply and special geochemical conditions. The Gdansk depression has accumalated metals supplied by Vistula and Nemunas rivers, whereas the Gotland depression is not supplied by rivers. There are three geochemical zones in the Gotland depression and two ones in the Gdansk depression established (Blazhchishin, Emelyanov, 1977). They seem to influence the different distribution and accumulation of metals in bottom sediments.

CONCLUSIONS

The sedimentation of pelitic sediments in the south-eastern part of the Baltic Sea depression progressively changes to that of coarse sediments on its slopes. Sand is deposited in the shallow zone (up to 10–30 m of water depth). Lag sediments are found at the sites where clay of the Baltic Ice Lake, Pleistocene glacigenous deposits (tills), containing boulders, pebbles, gravel, sand and mixed sediments crop out at the sea bottom.

A decrease in amount of montmorillonite and an increase in chlorite going offshore seem to be related to their Paleozoic source rocks. An increase in montmorillonites in the southern part of the studied area may be related to Mesozoic rocks outcropping on the sea bottom here and containing high amounts of this clay mineral. Also, changes in composition of clay fraction depend on Pleistocene tills as source-rocks of clay minerals found on the sea bottom. The distribution of clay minerals depends on sea bottom relief, water depth, lithology of bottom sediments and hydrodynamic conditions.

The concentration of As and Hg depends on the lithological type of sediments and on changes in Eh potentials. Concentration of other elements increases with the increase of finer sediment particles.

An anomalous distribution of Hg, Pb, Ni (As, Cu, Cr, Cd) has been observed in the Gdansk depression. These elements are more intensively differentiated in the Gotland depression. It is due not only to different geochemical conditions of the environment but also to the influence of river-brought alluvial material that has enriched bottom sediments in the Gdansk depression by these elements, too.

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Geothermal Field of the Vydmantai-1 Borehole within the Baltic Heat Flow Anomaly

Povilas Suveizdis, Vita Rastenienė and Vladimir Zui

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Povilas Suveizdis, Vita Rastenienė, Institute of Geology, 13 Ševčenkos, Vilnius, Lithuania 2600; Vladimir Zui, Institute of Geological Sciences, Academy of Sciences of Belarus, 7 Zhodinskaya, Minsk, Belarus 220141; *received 16th July; 1996, accepted 16th December 1996.*

Consideration of geothermal data on the onshore boreholes and temperature readings confirm that the geothermal anomaly existing within western Lithuania and Kaliningrad area is stretching into the adjacent territories of the Baltic Sea. Detailed research of geothermal parameters for the reference borehole of Vydmantai-1 drilled nearby the seashore in the western part of Lithuania is conducted. Temperature measurements are made in the depth interval from 0 to 2240 m (+16,59–2423,4 m NN), and thermophysical properties for 100 hardrock samples and 12 bedrock samples are determined. This enables to calculate heat flow density for several depth intervals. The interval heat flow values range from 52 to 55 mW/m². The results show the vertical variation of heat flow density within sedimary sequence and the crystalline basement.

Keywords: geothermal anomaly, East Baltic area, reference borehole

INTRODUCTION

Temperature measurements within the area have been fulfilled during deep drillings in the Baltic Syneclise. The first published results show that the Baltic artesian basin belongs to areas of high geothermal activity (Erofeev 1986). Temperature values at the basement surface in some cases exceed 80°C. The geothermal field, as well as heat flow data beneath the Baltic Sea floor were not studied before. Heat flow measurements were absent for the adjacent Baltic Sea area. Only a single borehole Viki 532 located in the Saaremaa Island, Estonia, was studied in geothermal respect. Heat flow density is 42 mW/m² there (Urban, Tsybulya 1988). Heat flow in the sea was not studied until now as the traditional marine geothermal probes did not permit to receive reliable geothermal gradient values for shallow seas. Temperature variations at the sea surface reach the marine floor without sufficient attenuation, especially during storms. The temperature fluctuations propagate into bottom deposits and perturb the geothermal gradient in the uppermost part of the sediments. Under such conditions it is necessary to deploy the Oceanographic Bottom Stations (OBS) to register the temperature history at the sea floor or to use available boreholes drilled in the sea bottom or along the seashore.

The borehole Vydmantai-1 can be considered, in this respect, as giving an opportunity to investigate geothermal field parameters in the onshore part of the anomaly and in its offshore continuation in the adjacent area of the Baltic Sea too. The Vydmantai-1 hole is a single borehole in Lithuania, drilled into the Precambrian crystalline basement for 442 metres. More than 100 hardrock samples were studied for thermophysical properties, and the thermogram of the hole is available as well. At the same time there are some offshore holes drilled within the adjoining part of the Baltic Sea, for which 4 single temperature readings are available. Joint analysis both for onshore and offshore boreholes have permitted to draw the course of heat flow isolines for the geothermal anomaly (Fig. 1).

GEOLOGY

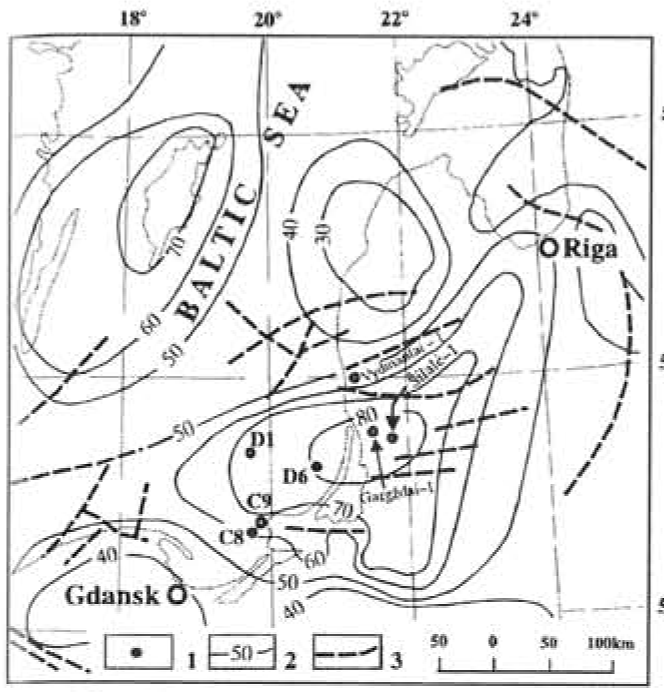

Fig. 1. Heat flow anomaly in west Lithuania and the Baltic Sea. 1 – marine boreholes: C8, C9, D1, D6; 2 – heat flow density isoline, mW/m²; 3 – platformic tectonic fault.

The first deep geothermal borehole Vydmantai-1 is located at the settlement Vydmantai of near to Palanga town. The coordinates of the Vydmantai-1 borehole are 55°53'42"N : 21°08'09"E, the elevation is 16.59 m. The hole passed through the entire sedimentary cover and entered the Precambrian crystalline basement at the depth of 2122.2 (2104.3 m NN). Borehole's bottom is at the depth of 2564 (2545.6 m NN). The main purpose of drilling was to carry out detailed geothermal investigations both within the platform cover and in the upper part of the crystalline basement.

A wide range of observations was undertaken in the borehole both under field conditions during its drilling, as well as after its completion, and during laboratory measurements. The following logs took place in the hole: standard logging, caliper, gamma-ray, neutron, spontaneous potential, apparent resistivity, screened contact log, acoustic, resistivity, deepmeter and temperature. All hydrothermal complexes, as well as petro-geothermal intervals were drilled with coring. Rock samples were studied by different methods: chemical analysis of rock composition, rare elements concentration within the crystalline basement, microprobe analysis of minerals (for the basement), grain size and mineralogical analysis of sedimentary rocks, as well as the filtration coefficient determination for Devonian strata, analysis of cracks, chemistry of groundwater, content of microelements in groundwater and thermophysical properties of crystalline rocks.

During the hole drilling the stem tests has been used to receive data on productivity of Lower Devonian and Cambrian rocks. After the hole was cased, the Cambrian hydrogeothermal complex was tested to estimate its planned productivity of 100 m³/hour.

The borehole revealed rocks of the Precambrian crystalline basement in the depth interval of 2112.2–2564 (2104.3–2545.6 m NN) (Table 1). Three different complexes are distinguished within this parts of the basement by K. Kepežinskas (1993), composed from below of:

(a) Crystalline schists and gneisses of the ooid texture formed under conditions of progressive metamorphism and belonging to low and moderate temperature facies.

(b) Charnockite-hyperstene rocks of an intrusive type with imprints of high-temperature regional metamorphism under conditions of moderate pressure.

(c) Tuffs and tuff breccia are not deformed and not subjected to the regional metamorphism (Fig. 2).

These complexes were formed in different geologic time. The crystalline schists and gneisses forming the volcanogenic-sedimentary complex belong stratigraphically to the Vydmantai Complex of the Lower Proterozoic. Charnockites belong to the Šiupariai Complex of the Lower Proterozoic, and tuffs and tuff breccia correspond to the Volynian Group of the Vendian.

Rocks of the Vydmantai Complex are observed within the interval of 2483.8–2526.6 and 2531.3–2564 (2465.5–2508.3 and 2513.0–2545.6 m NN). They represent dark-grey and black quartz-biotite

Table 1. **Geological section of the Vydmantai-1 borehole**

Stratigraphy	Depth*, m	Lithology	Temperature, °C
Quaternary	50.4	Morainic clay, sand	14
Triassic	180.4	Clay, marl	17.2
Permian	210.4	Dolomite	17.4
Upper Devonian	593.4	Clay, dolomite, marl, sand, silt	24.7
Middle Devonian	822.4	Sand, siltstone, dolomite, marl,limestone	31.4
Lower Devonian	1121.9	Differently grained sandstone, siltstone, clay, dolomitized siltstone and clay	38.7
Silurian	1825.3	Claystone, marl, limestone	67.8
Ordovician	1954.2	Organogenous limestone, marl	72.6
Cambrian	2104.3	Differently grained sandstone and siltstone, claystone	75.7
Proterozoic	2545.6	Tuff, charnockite, schist, gneiss, granite-gneiss	83.6 (at 2423.4 m)

* Depth references below sea level

potassic-spar and quartz-muscovite-biotite-feldsparooid crystalline schists. The bedding of rocks of low-temperature metamorphism is below the rocks of high-temperature metamorphism. It witnesses the existence of an overthrust here.

The Šiupariai Complex rocks are observed within the interval of 2122.8–2154.1; 2155.3–2483.8 and 2526.6–2531.3 (2104.5–2135.8; 2137.0–2465.5 and 2508.3–2513.0 m NN). Charnockites, both light- and dark-coloured, of intrusive type prevail in the section. They differ in their mineral composition, structure and texture. Series of fine- and coarse-grained, massive and shaly, leucocratic and melanocratic, similar grained and porphyroblast differences of charnockites are found. Despite of these features charnockites have a permanent paragenesis of minerals: Hy + Cr + Bi + Sp + Mt + Ilm + Pl + Kfeldsp + + Q + Ap + Zr, with percentages ranging rather widely. Vein injections of granitoid composition are rather widely developed within both described complexes.

Tuffs in the borehole of Vydmantai-1 and tuff breccia without signs of regional metamorphism are found in the borehole of Vydmantai within the interval of 2122.2–2122.8 and 2154.1–2155.3 (2104.3–2104.5 and 2135.8–2137.0 m NN). They belong to the Vendian age. The existence of Vendian rocks among more old charnockites can be explained by a thrust tectonics. The petrogeothermal massif is formed by rocks of the crystalline basement.

Terrigenous rocks of the Cambrian form the interval of 1972–2122.2 (1954.2–2104.3 m NN). The Lower Cambrian is represented by interlayering of mudstones and siltstones of the typical texture „kräksten“. The lower part of the Cambrian is represented by gentle sloped basal sandstone composed of different grains, quartziferous (97.8–98.2%), micaceous (0.2–0.4%), glauconitic (0.4–0.6%). The Middle Cambrian is mainly composed of sandy rocks (90%). The sandstones are light and light-grey, differently grained (fine-grained, quartziferous (99.3%), irregularly silty, micaceous (0.2–0.4%) with irregularly distributed glaukonite grains (0.4–0.6%). Sandstones contain regeneration-quarziferous cement, irregularly distributed, which causes their transition into quartzites. All sediments here are subjected to cracking. The cracks are differently oriented from horizontal to vertical ones. Cambrian sequence form a hydrothermal complex.

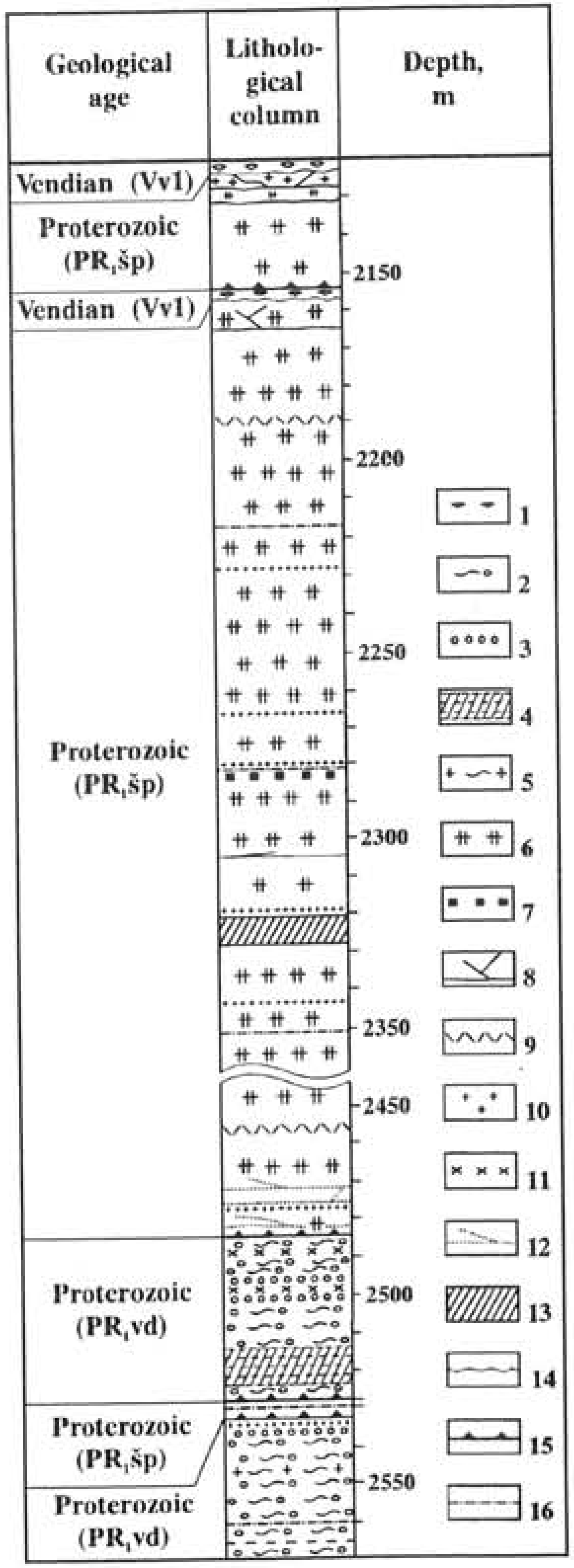

Fig. 2. Simplified geological column of the crystalline basement of the borehole Vydmantai-1. 1 – Volynian Group (Vv_1) tuff and breccia; 2–5 metavolcanic Vydmantai Complex (PR_1vd): 2 – augen biotite and muscovite schist, 3 – melanocratic schistous biotite rocks with amphibolite and pyroxene, 4 – thrusted crystalline schist and gneiss, 5 – granite-gneiss; 6–7 – Šiupariai Complex ($PR_1šp$): 6 – charnockite, 7 – pyroxenite, 8–12 – intrusive rock: 8 – basic lava filling up fracture, 9 – vein of felsic intrusive, 10 – fine- and coarse-grained granite, 11 – vein of gabbro-syenite, 12 – melanocratic biotite-clinopyroxene dike and veinlet; 13 – zone of granitization and K-feldspar; 14 – stratigraphical unconformity; 15 – tectonic unconformity (thrust); 16 – milonitic zone.

Hydrogeological properties within the Cambrian hydrogeothermal complex are determined by differently and coarse grained siltstones of Deimena Group of the Middle Cambrian and sandy coarse grained siltstones of the Lower Cambrian. Sandstones are quartziferous (99.8%) with irregular distribution of mica (0.1–0.2%) and glauconite (0.6%). Sandstones have an irregular cementation, firmly cemented differences prevail. As it was mentioned above all rocks have cracks. Laboratory measurements show a low porosity and permeability (1.2–13.1% and 0.1–329.8 millidarcy, respectively). According to the interpretation of logging diagrams it is found 42 metres of an effective thickness with the porosity ranging from 4.6 to 12.8%. The cased interval of 1972–2030 (1954.2–2013.4 m NN) was tested within the Cambrian complex, where the effective thickness reaches 32.4 m and the calculated coefficient of permeability ranges from 131.9 to 140.6 millidarcy. A geothermal water flow was obtained. The bulk coefficient of productivity is 32.4 m³/day. The temperature at the roof of the Cambrian hydrothermal complex at the depth of 1972 (1954.2 m NN) is 72.6 °C, and it reached 75.7 °C at its base at the depth of 2123 (2104.3 m NN). The aquifer water has the mineralization up to 163.9 g/cm³ and the density is 1.22 g/cm³.

Ordovician overlies the Cambrian ones with stratigraphic unconformity within the interval of 1843–1972 (1825.3–1954.2 m NN). The geologic section is composed of clayey-carbonaceous rocks, represented by claystones, clayey limestones, clayey dolomites, quartziferous-glauconite sandstones.

Silurian [1139–1843 (1121.9–1825.3 m NN)] is represented by monotonous mudstone-claystone layering with a thickness of 704 m. The Ordovician and Silurian form together the extended regional water-tight layer for the Cambrian hydrothermal complex.

Devonian overlies conformly the Silurian in the interval of 227–1139 (210.4–1121.9 m NN) it is represented by terrigenous and carbonate-terrigenous section with a thickness of 912 m. Deposits of all three series are observed in the section.

Lower Devonian, 300 m thick is represented by the Dittonian and Breconian Stages, between which there is a regional and structural unconformity separating the Caledonian structural complex from the Hercynian one. Rocks of the Gargždai Group correspond to the Dittonian Stage. Lithologically the section is represented by interlayering of dark-coloured, mainly red-coloured clayed siltstones, mudstones, micaceous clays and more seldom of dolomites. The thickness of individual packets reaches of 8–11 m. Sandstones and coarse grained siltstones are bedded among them with the thickness of packets of 2–4 m. They comprise 15–20% of the total thickness. Sandstones quartziferous, differently grained, irregularly cemented are distributed non-uniformly mainly within the lower part of the section.

The Kemeri Group corresponds to the Breconian Stage. The section is represented lithologically by interlayering of sandy and clayed strata. The former strata prevail and reach up to 70%. Their thickness ranges from 2 to 5 and sometimes from 10 to 18 m. Sandstones (sands) or siltstones (silts) are grey and light grey, differently grained, potassium-spar (3.2–16.4%), quartziferous (69–95%), irregularly micaceous (0.4–9.4%), sometimes with an admixture of glauconite. Sandstones are mainly cemented with clayed or dolomitic cement. Strata separating them represent the interlayering of clays with clayed fine-grained siltstones.

The sediments of the lower part are saturated with water, and together with the Pärnu Regional Stage of the Middle Devonian form the Lower-Middle-Devonian they hydrothermal complex.

Hydrogeological properties of this hydrogeothermal complex are much better than those in the Cambrian one. Differently grained with prevailing coarse grained sandstones are the main porous rocks there. A high permeability (207.3–6294.9 millidarcy) and porosity (20.1–31.2%) is determined by laboratory tests. The interpretation of geophysical logs also confirms their high hydrogeological properties. As a result, the effective thickness was revealed to be 115.5 m. An intensive flow of an aquifer water is observed during the tests. The estimated permeability ranges from 24 to 232 millidarcy. The water mineralization is 27.6 –45.7 g/l with the density of 1.02 g/cm³.

The temperature values at the complex roof at the depth of 839 (822.4 m NN) and at the complex base at the depth of 1139 (1121.9 m NN) are 31.4 and 38.7 °C, respectively.

Pärnu Regional Stage with a thickness of 30 m is bedded in the lower part of the Middle Devonian. Their lithology is rather changeable and consists of dolomitic claystones, sometimes clays with interlayers of sandstones and siltstones, cemented by clayed cement. Breccia of claystones, dolomites and sandstones occur at the base of Pärnu Stage.

The terrigenous-carbonate Narva Regional Stage with a thickness of 96 m overlays it. These deposits are water-tight, they form an aquitard for the underlied hydrothermal complex.

The Middle Devonian is ended by of the Upninkai Formation, represented by interlayering of sands, silts and clays. The sands and silts are differently grained, potassium-spar (9.4–26.4%), quartziferous (60–90%), non-uniformly micaceous (0.6–3.8%) with an admixture of glauconite (0.2–2%). Sometimes the sands and silts are cemented with clayed, clayed-dolomitic or dolomitic cement and form sandstones and siltstones. Clays are irregularly silty, micaceous and dolomitic.

The Šventoji Formation begins the Upper Devonian. It is represented by regularly interlayering sandstones or sands, siltstones or silts, and clays with seldom interlayers of sandy dolomites, claystones and dolomites. Differently grained, nonuniformly silty and clayed, potassium-spar (6.2–33%), quartziferous (65–93%), irregularly micaceous (0.2–0.6%) sands prevail in the section. Sandstones are cemented with clayed or dolomitic cement. Irregularly sandy siltstones and silts are of an analogous composition. Clays are ununiformly micaceous, dolomitic, sometimes substituted by clayed dolomitic claystone. The Upninkai and Šventoji Formations form the Middle-Upper Devonian hydrothermal complex.

Within the Middle-Upper Devonian hydrothermal complex the hydrogeologic properties are formed by differently grained with prevailing fine-grained sands (sandstones) and coarse sandy silts (siltstones). A high porosity ranged from 32.97 to 36.33%, and low filtration rate of 0.065 m/day was observed during the laboratory tests. The coefficient of permeability ranged from 4 to 70 millidarcy. An interpretation of geophysical log diagrams confirmed the results of laboratory investigations. The derived bulk effective thickness reache 49.8 m with the porosity of 15–21.3%

The main part of the Upper Devonian is composed of carbonate-terrigenous deposits, it is represented lithologically by a complex interlayering of claystones and dolomites with irregularly gypseous, cavernous and cracked dolomites, massif dolomites, interlayering of siltstones, clays, dolomites. This part of the Upper Devonian deposits represents an aquitard for the underlaid Middle-Upper Devonian hydrothermal complex.

The Permian occupies the interval from 197 (180.4) to 227 (210.4 m NN) Lithologically it is represented by cracked and cavernous irregularly clayed dolomites with interlayers of clays.

The Triassic is observed in the interval from 67 (50.4) to 197 (180.4 m NN). It is are lithologically composed of red-coloured clays and clayed claystones.

The Quaternary occupies the interval of 0–67 (+16.59–50.4 m NN). It is represented by till deposits with pebble and gravel.

TEMPERATURE DIAGRAM AND GEOTHERMAL GRADIENT

The following data on the borehole Vydmantai-1 are received in during the geothermal investigations: temperature versus depth diagram, data on the coefficients of heat conductivity, thermal diffusivity and volumetric heat capacity. Heat flow density values are calculated for a number of depth intervals.

Temperature diagram is registered in a process of drilling and testing. It is well known that in a process of drilling the natural temperature distribution along the borehole axis is distorted due to convection caused by circulating drilling mud. Usually the upper part of the section is warmed up and the lower one is cooled. The time since the drilling was finished and temperature measurements were undertaken, was not enough to reach the complete temperature equilibrium for the borehole Vydmantai-1 (Fig. 3). The so-called „neutral layer", or the depth where annual temperature oscillations are attenuated to such a degree that they are not visible in the diagram, or the depth where a negative geothermal gradient (for the case of summer measurements) changes for a positive one, is at a depth around 30 m with a corresponding temperature of 13.8 °C. For other boreholes Gargždai-8 and Šilale-1, situated in western Lithuania, this temperature is approach 8.2 and 8.3 °C, respectively (this corresponds approximately to the annual mean ground surface temperature within this area) observed at depths around 20 and 30 metres, respectively. It means that the „neutral layer" is still warmed up for around 5.5 °C for the moment of measurements. During the drilling mud circulation was longer for the upper part of the hole and shorter for the lower part, the latter one has no visible evidences of such distortions and is closer to the equilibrium state.

The temperature diagram has five main parts, where geothermal gradient sufficiently differs: intervals 0–227 (+16.59–210.4)(Permian, Triassic and Quaternary deposits), 227–1139 (210.4–1121.9) (Devonian sediments), 1139–1972 (1121.9–1954.2)(Silurian and Ordovician deposits), 1972–2122.2 (1954.2–2104.3) (Cambrian rocks) and 2122.2–2564 (2104.3–2545.6) m (crystalline basement). The geothermal gradient within the upper one is 21.6 mK/m, but as it was mentioned it represents only an approximate value because of terrestrial temperature field distortion in the rocks around the hole during the process of drilling. The actual value is around 27–29 mK/m but less than in the borehole Gargždai-8, where the gradient for the same interval reaches 30.2 mK/m. For the next interval of Devonian section it corresponds to 23.6 mK/m and is still subjected to distortions especially within its upper part. It should be also more close to the value 28.2 mK/m, typical for analogous interval for the reference hole Gargždai-8. Where the Ordovician and Silurian [1139–1972 (1121.9–1954.2 m NN)] underlies the Devonian, the geothermal gradient is again higher and reaches 40.7 mK/m. The next two – complexes the Cambrian and the Precambrian – are composed of rocks with higher heat conductivity, and they are characterized by rather low gradient dropping to 21.3 mK/m within the Cambrian interval and to 25 mK/m within the crystalline basement. A distinct thermal boundary exists between Caledonian and Hercynian tectonic complexes. This feature is typical of other boreholes of the Baltic Syneclise, where temperature diagrams were obtained under equilibrium conditions (Zui et al. 1985).

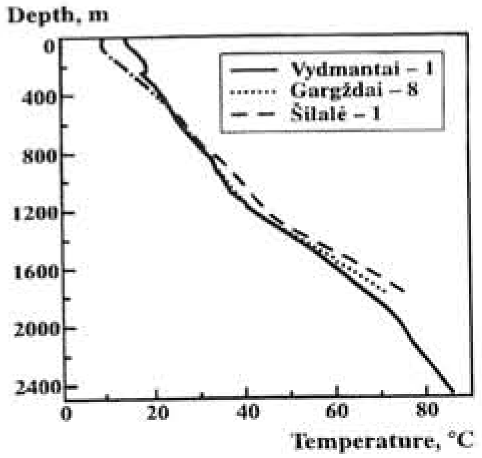

Fig. 3. Temperature versus depth diagram for boreholes Vydmantai-1, Gargždai-8 and Šilale-1.

Among three temperature-depth curves shown in Fig. 3, the highest temperature values for comparable depths are observed within the borehole Šilalė-1, the closest one to the center of the heat flow anomaly existing in west Lithuania and the Kaliningrad Enclave, Russia. At the same time its lowest values are found in the borehole Vydmantai-1 drilled at the north-western flank of the anomaly. Temperature decreases both eastward of the Vydmantai-1 borehole towards the Mazurian-Belarussian Anteclise and the Latvia Saddle, and northwards to the Kurzeme Massif.

For all three boreholes the upper part of the geological section is represented by loose sediments, with high permeability promoting rather intensive groundwater flow. Especially high filtration rates exist within a zone of active water exchange in the uppermost layer of 200–250 m where the concave form of the termogram could be explained by the influence of atmospheric precipitation (Van Dalfsen 1981) prevailing especially during a cold season of the year (March, April, October, November). Only when permeable sands are substituted by clays, mudstones, dolomites, like in borehole Gargždai-8, the termogram becomes less concave within corresponding depth intervals. For all studied holes the geothermal gradient within the zone of active water exchange is poorly controled by the lithology of permeable sediments due to groundwater movement.

Even within the crystalline basement where the groundwater movement is absent, or a stagnant regime exists, if the rocks are cracked, and the advective heat exchange is very attenuated, the temperature curve is not a direct line. Its shape is controled by rock thermophysical properties differing within individual layers in the upper part of the basement.

THERMOPHYSICAL PROPERTIES OF ROCKS

112 rock samples were taken from the drill core to determine their thermophysical properties in the laboratory (Fig. 4). Among them 100 samples (their position in the Fig. 4 is shown by closed circles) belong to the crystalline basement and the 12 samples (closed squares) are taken from the sedimentary cover. The general picture of their distribution versus the depth and the heat conductivity coefficient show that there is a gap (950–1950 metres), where samples have not been available. Therefore, only the uppermost and the lower part of the geological column could be characterized by

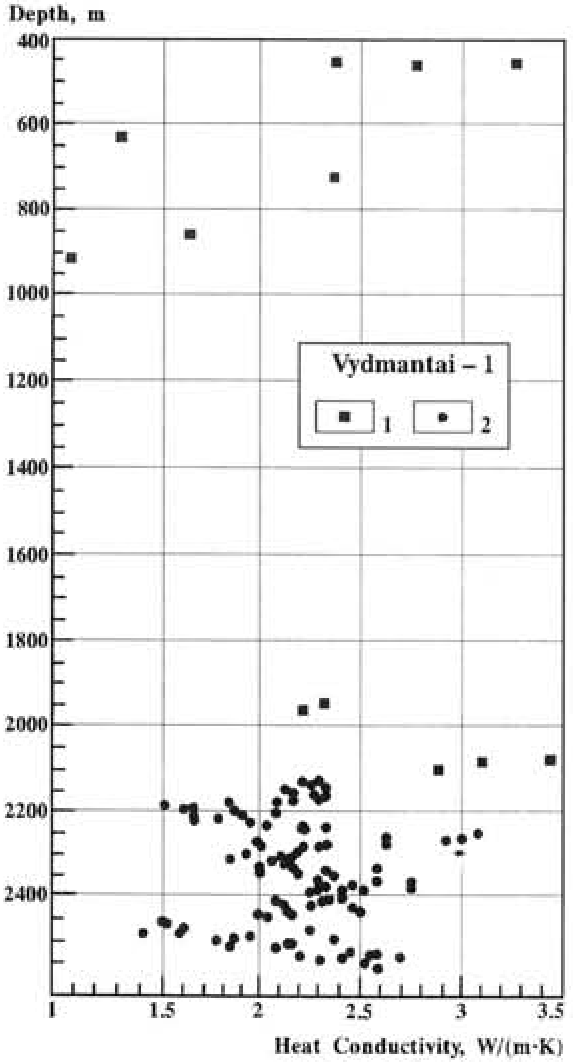

Fig. 4. Distribution of rock samples and their heat conductivity coefficients for the borehole Vydmantai-1. 1 – heat conductivity of the sedimentary cover; 2 – heat conductivity of the crystal line basement.

Table 2. **Results of measurements of heat conductivity coefficients for samples of sedimentary rocks**

No.	Depth*, m	Age	Rock type	Heat conductivity, W/(m · K)
1	458	D	Siltstone sandy	2.39 ± 0.05
2	462.5	D	Siltstone sandy	3.28 ± 0.2
3	467.5	D	Siltstone sandy	2.78 ± 0.2
4	631.5	D	Siltstone sandy	1.32 ± 0.03
5	726.3	D	Siltstone clayed	2.38 ± 0.07
6	861.2	D	Siltstone	1.66 ± 0.23
7	910	D	Siltstone clayed sandy	1.06 ± 0.03
8	1956	O	Siltstone sandy	2.30 ± 0.04
9	1965.8	O	Sandstone silty glauconitic	2.22 ± 0.25
10	2081.3	∈	Sandstone silty clayed	3.46 ± 0.07
11	2086.1	∈	Sandstone silty clayed	3.11 ± 0.11
12	2106.1	∈	Siltstone sandy clayed	2.89 ± 0.12

* Depth below ground level

thermophysical properties. Sedimentary rocks were studied in the Institute of Geological Sciences, Minsk, and the crystalline samples were investigated in the Physical Institute of Latvian University (Bormanis 1993). Samples of sedimentary rocks are used only to measure the heat conductivity coefficient. The coefficients of heat conductivity, thermal diffusivity and volumetric heat capacity were determined for the rest samples. All samples lost their natural water content. No artificial water saturation was applied for permeable samples before tests. All measurements were done under the room temperature and atmospheric pressure.

A transient probe method is applied to measure thermophysical properties of crystalline rocks, it is based on the observation of parameters of a heat wave propagation after the heat pulse was produced in the sample. The heat conductivity, thermal diffusivity and volumetric heat capacity coefficients are determined simultaneously. Two of them are measured and the third one is calculated. The heat conductivity of sedimentary rock samples (Fig. 4) exibit a wide range of its variation (1.06–3.46 W/(m · K)), that is sensitive to the amount of main rock-forming minerals (Horai and Simmons 1969), such as quartz particles having high heat conductivity. Their values are given in Table 2. Small amount of studied sedimentary samples and only two main types of studied rocks (siltstones and sandstones) do not permit to apply statistical analysis.

A detailed diagram of the heat conductivity distribution for 100 samples within the crystalline basement is shown in Fig. 5. A scatter of dots showing the individual values reflects separate layers of the basement, which in turn, differ lithologically. The trend at this background shows a general tendency for heat conductivity coefficient to increase with the depth within the interval of 2128–2563 m. This trend follows the relationship h.c. = 0.000291d + + 1.5068 W/(m · K), showed by a solid line in Fig. 5.

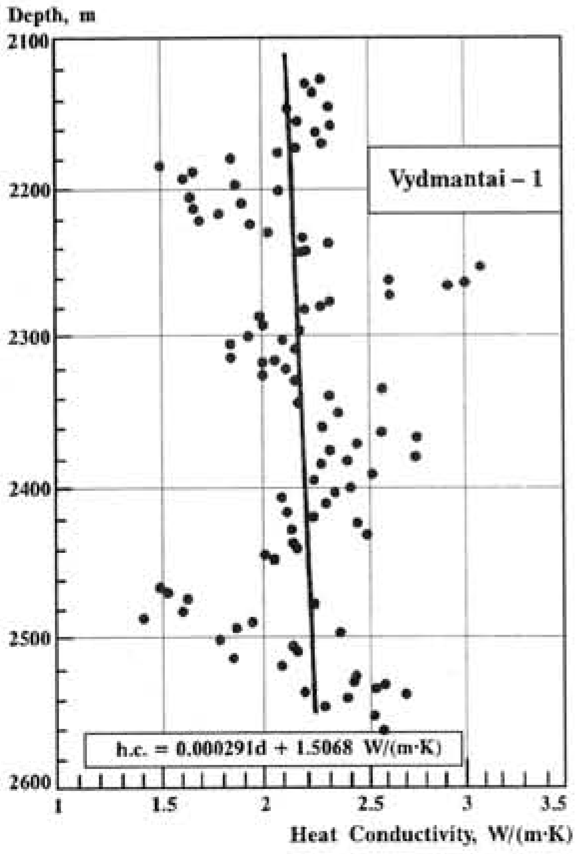

Fig. 5. Heat conductivity within crystalline basement for the borehole Vydmantai-1.

The histogram in Fig. 6 reflects the wide range of heat conductivity variation (1.4–3.1 W/(m · K)) and reveals the range 2.0–2.4 W/(m · K) which includes 53% of measured samples. The highest number of samples (16%) satisfies to the value in a narrow range 2.1–2.2 W/(m · K).

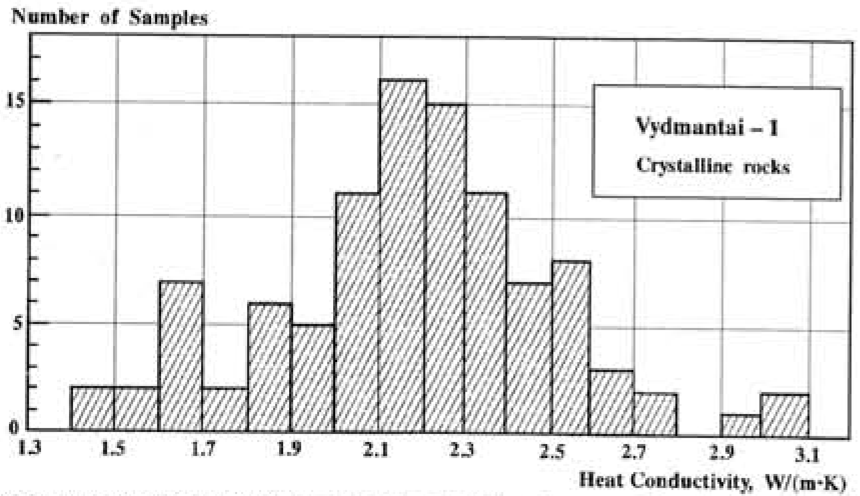

Fig. 6. Histogram of heat conductivity distribution within crystalline basement for the borehole Vydmantai-1.

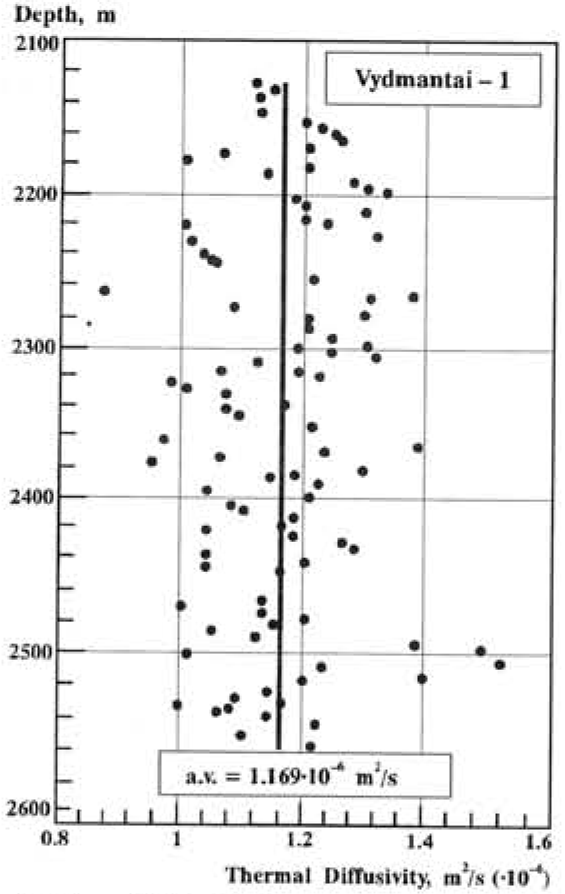

Fig. 7. Thermal diffusivity in crystalline basement for the borehole Vydmantai-1.

The thermal diffusion coefficient (Fig. 7) is analysed for 99 samples, as the lowest value 0.01 · 10^{-6} m²/s for the sample from the depth of 2234 m is not reliable one. The most of individual values are rather uniformly scattered in the range of (1–1.4) · 10^{-6} m²/s with the average value equal to 1.169 · 10^{-6} m²/s. A variation of the volumetric heat capacity coefficient for 100 samples of crystalline rocks are shown in Fig. 8. The character of the scatter of individual values is similar to the pattern shown in Fig. 5 for the heat conductivity coefficient with the average value of 1.897 · 10^6 J/m³K. Major part of the values is within the range of 1.5–2.5 · 10^6 J/m³K.

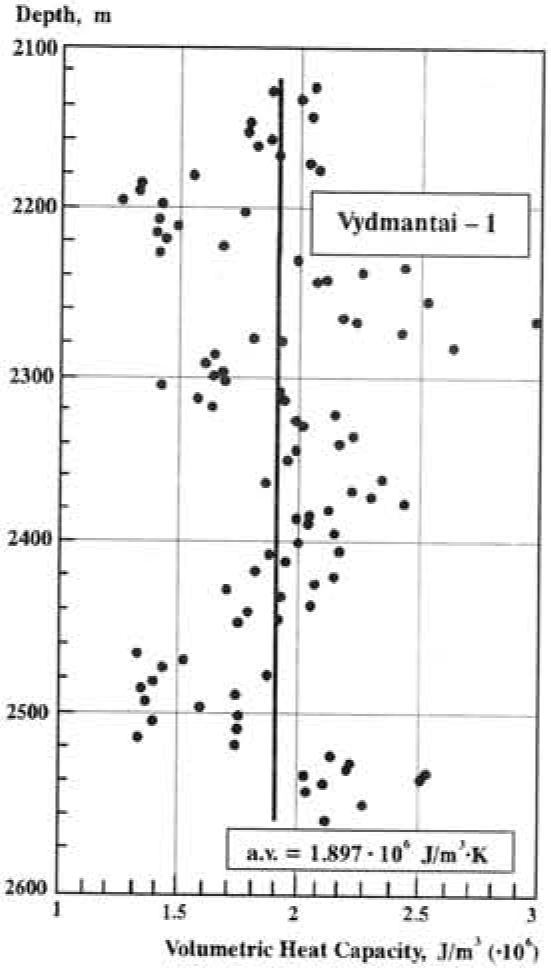

Fig. 8. Volumetric heat capacity within crystalline basement for the borehole Vydmantai-1.

HEAT FLOW DENSITY

In general, it was possible to calculate interval values of heat flow density only in the upper 900 m and the interval below 1950 m, where heat conductivity measurements are available. But taking into account that, firstly, only 7 rock samples

Table 3. **Heat flow density for the borehole Vydmantai-1**

Depth interval*, m	Age	Temp. gradient, mK/m	Heat conductivity, W/(m · K)	Heat flow density, mW/m²
2142–2200	PR	25.8	2.03	52
2270–2360	PR	24.1	2.17	52
2250–2440	PR	23.4	2.32	54
2400–2440	PR	24.1	2.28	55
Average weighed heat flow density accepted for the borehole				55

* Depth below ground level

were measured within the upper interval with sufficient scatter of the heat conductivity values and, secondly, the noticeable distortion of geothermal gradient was observed here both due to the fact that the temperature diagram was registered when the temperature equilibrium was not reached and the other near-the-surface factors (groundwater circulation, paleoclimatic variations of the ground surface temperature, etc.) are pronounced, it was decided to determine heat flow density only for the lower interval to minimize possible errors. Results of heat flow density calculations are shown in Table 3.

All four intervals are located within the crystalline basement section. Heat flow variation exists in the basement but the difference between the lowest and highest interval values is only 3 mW/m², that approximately corresponds to the error bar estimated to be ±5% or around ±2.5 mW/m². Vertical heat flow changeability is the feature of the Baltic Syneclise, it was observed in other boreholes also (Zui et al. 1985). Similar situation is observed within adjacent areas of the Mazurian Buried Salient, Poland. Geothermal investigations in the boreholes of Krzemianka and Udrynia (Majorowicz 1960) revealed a concave temperature diagram in the crystalline basement up to the depth of 2000 metres. The main reasons for the vertical heat flow density variations could be the influence of groundwater circulation in permeable sediments including the area around the Vydmantai-1 borehole and the subsoil propagation of long-period temperature cycles produced by ground surface temperature variations during Pleistocene. These effects are to be estimated in the course of future investigations.

CONCLUSIONS

A few temperature readings received during the stem tests for offshore boreholes D1, D6, C8 and C9 give us the ground to confirm that the positive geothermal anomaly, existing in west Lithuania and the Kaliningrad Enclave, is stretching into adjacent areas of the Baltic Sea. Its western margin is still unknown. Only several boreholes are drilled along the Polish seashore and studied in geothermal respect, they exhibit increased heat flow. This fact permits us to suppose that the marine area was also subjected to tectonic-thermal activation in the past. But the highest heat flow values above 80–90 mW/m² are observed as it was mentioned above for west Lithuania, the Kaliningrad Enclave and adjacent parts of the Baltic Sea.

Investigations conducted for a number of boreholes in the central part of the Baltic Syneclise show the vertical variations of interval heat flow values. Typically the observed heat flow is higher for deeper horizons of the sedimentary cover. Detailed geothermal data from the reference borehole Vydmantai-1 showed that the vertical heat flow variations were still detected in the uppermost part of the crystalline basement. Probably it is caused by groundwater circulation in cracked basement rocks, and the stagnant regime expected in the overlying sediments was not reached yet at the sediments-basement interface both in the onshore and offshore parts of the anomaly.

ACKNOWLEDGEMENTS

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Late Quaternary Rodents from the Southwestern Baltic Sea

Erik Otto Heiberg
and Ole Bennike

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Erik Otto Heiberg, Skibelundvej 29, 3. tv, DK-2720 Vanløse, Denmark; Ole Bennike, Geological Survey of Denmark and Greenland, Thoravej 8, DK-2400 Copenhagen NV, Denmark; *received 18th September 1996, accepted 27th January 1997.*

Four taxa of rodents have been recovered from submarine deposits from the southwestern Baltic Sea. A find of *Arvicola terrestris* represents the first record of Younger Dryas age from this region. A Late Boreal record of *Clethrionomys glareolus* from south of Bornholm indicates that this species was formerly a member of the Bornholm fauna. Finds of *Apodemus flavicollis* and *Microtus* sp. probably date from the Middle Holocene. The Late- and Postglacial history of these rodents in northwestern Europe is reviewed.

Keywords: Baltic Sea, macrofossils, rodents, Quaternary, biogeography, taphonomy, local extinction

INTRODUCTION

After the last deglaciation, the Baltic Sea has experienced a complex evolution involving large and rapid shore level changes (Björck 1995). In the south the net eustatic sea level rise has surpassed the isostatic rebound. Major areas now part of the Baltic Sea were dry land, mires or isolated lakes during parts of the Late Glacial and Early Holocene, and drowned tree stumps, notably of pine, are well known from some areas (Kolp 1967).

There are some reports of bones from large mammals recovered by sand-pump dredgers (Aaris-Sørensen 1988), but to our knowledge there have been no previous reports of rodent remains from the Baltic Sea. However, from Øresund remains of a vole (*Microtus* sp.) has been recorded from submarine deposits (Jessen 1923).

The Late Glacial and Early Holocene immigration of rodents to eastern Denmark, Sweden and Norway following deglaciation was dependent on land bridges. Such land bridges were extensive during periods when the Baltic Basin drained trough narrow outlets via central Sweden, Øresund or Storebælt, prior to the Atlantic transgression that transformed the eastern parts of Denmark into an archipelago (Björck 1995).

Most of the Quaternary rodent faunas from western and central Europe have been recovered from cave, rock shelter, fluvial and loess deposits (Toepfer 1963; Sutcliffe & Kowalski 1976; Sutcliffe 1985; Nadachowski 1989). Such deposits are rare in northern Europe and fossil remains must be sought in other contexts, such as tufa and lacustrine deposits. In general, little is known about Late Quaternary rodents in this part of Europe and the chronology of the finds is also poorly documented (Sutcliffe & Kowalski 1976; Heinrich 1990). It is now possible to directly radiocarbon date small mammal remains from the Late Quaternary by the AMS technique, as applied by Bennike et al. (1994) to Danish lemming remains.

During macrofossil analyses of submarine deposits from the southwestern part of the Baltic Sea (Fig. 1), remains of vertebrates were found to be fairly common. By far the majority are bones and scales of fishes, but a fragment of a tarsometatarsus

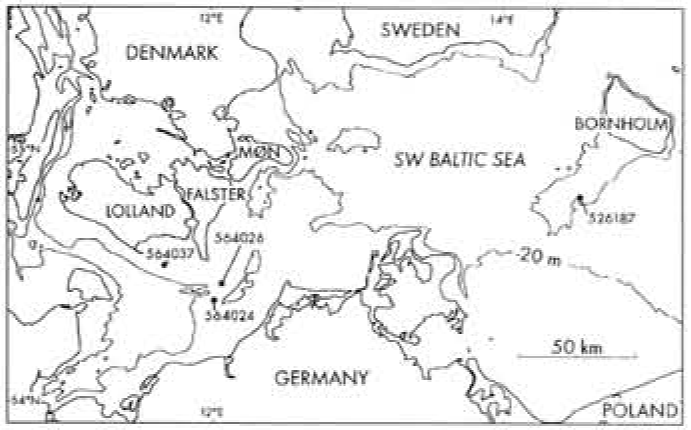

Fig. 1. Map of the southwestern part of the Baltic Sea showing the location of the rodent finds.

of an unidentified small passerine bird was also found (K. Rosenlund, pers. comm., 1994), in addition to four rodent remains, on which we report here.

MATERIAL AND METHODS

The samples were taken from up to 6 m long vibracores that were collected by the Geological Survey of Denmark and Greenland in connection with raw material mapping. Sample size was about 250 ml, and a total of about 4000 samples have been analyzed. Sediment samples were wet sieved using 0.4 and 0.2 mm sieves. The rodent remains were identified by comparison with extensive reference material. Details of the stratigraphy will be presented elsewhere. The nomenclature follows Sutcliffe & Kowalski (1976). The material is stored at the Geological Museum, Copenhagen (MGUH VP no 3353–3356).

ANNOTATED LIST OF TAXA

Family Cricetidae Rochebrune, 1883
Genus *Arvicola* Lacépede, 1799
***Arvicola terrestris* (Linnaeus, 1758) Water Vole.** One well preserved fragment of the distal end of a right mandible of an adult water vole was recovered (Fig. 2). The fragment is dark brown, the surface is hard and shiny, it is not worn apart from insignificant rounding of the fractures. The fragmentation was probably caused by a predator with weak gastric juice, such as an owl (Mayhew 1977; Dodson & Wexlar 1979; Kowalski 1990).

The bone fragment was recovered from core 564024, 230–240 cm below sea floor (b.s.f.). The coring site is located south of Falster, at 54°24.28'N, 12°00.50'E (Fig. 1). The bone was found together with a Late Glacial flora with abundant *Betula nana* remains and *Empetrum nigrum* endocarps. *Betula nana* leaves from 260–270 cm b.s.f. have yielded an AMS radiocarbon date of 10350±320 ^{14}C years BP (AAR-1918), which indicates that the bone is of late Younger Dryas age. The bone fragment itself is too small to be dated by the AMS technique. The sandy sediments were probably deposited near the shore of the Baltic Ice Lake.

There are no previous Younger Dryas records of *A. terrestris* from Denmark, but the species has been found in Allerød and Boreal-Subboreal deposits on Møn, where local extinction seems to have occurred in the Late Subboreal (Heiberg 1995), and in Allerød deposits from northern Jutland (Aaris-Sørensen 1995). It is interesting to note that *A. terrestris* no longer occurs on Møn, Lolland, Falster or Bornholm (Fig. 3). The local extinction of *A. terrestris* on Møn, Lolland, Falster and possibly also Bornholm must be ascribed to the rise of the relative sea level that turned the areas into islands, and the effects of the isolation that followed (Begon et al. 1990). The water vole has been recorded from Late Glacial deposits in Britain, Germany and Poland (Toepfer 1963; Sutcliffe & Kowalski 1976; Stuart 1982; Nadachowski 1989; Heinrich 1990). In Sweden and Norway the fossil record of the water vole goes back to the Atlantic chronozone (Fig. 3), and in Estonia and Latvia it goes back to the Subboreal (Lepiksaar 1986). The species has frequently been reported from Middle Holocene Danish sites (Winge 1904; Degerbøl 1926, 1928; Aaris-Sørensen 1980; Andersen & Johansen 1986; Bratlund 1993; Heiberg in Noe-Nygaard 1995; Heiberg 1995; Aaris-Sørensen & Andreasen 1995) and from a few Late Boreal sites (Degerbøl 1943, Richter 1982).

A. terrestris is at the present distributed over much of Europe and Asia. The species is amphibious and usually lives in dense vegetation near water (Macdonald & Barrett 1993).

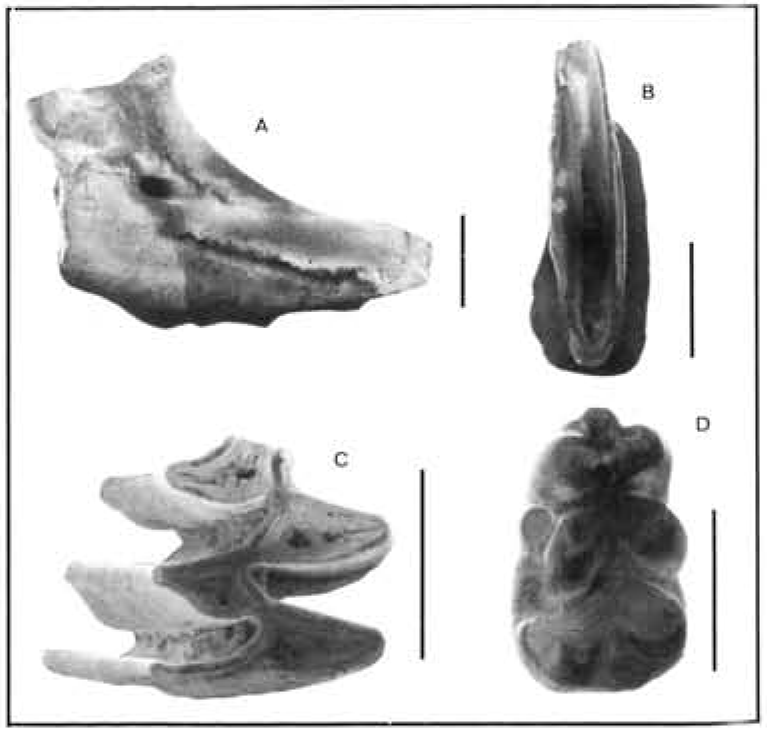

Fig. 2. SEM photographs of the finds. A. Lateral view of a fragment of a right mandible of *Arvicola terrestris*. B. Lateral view of a fragment of a molar of *Clethrionomys glareolus*. C. Oblique occlusal view of a fragment of a left lower second molar of *Microtus* sp. D. Occlusal view of a left lower first molar of *Apodemus flavicollis*. Scale bars: 1 mm.

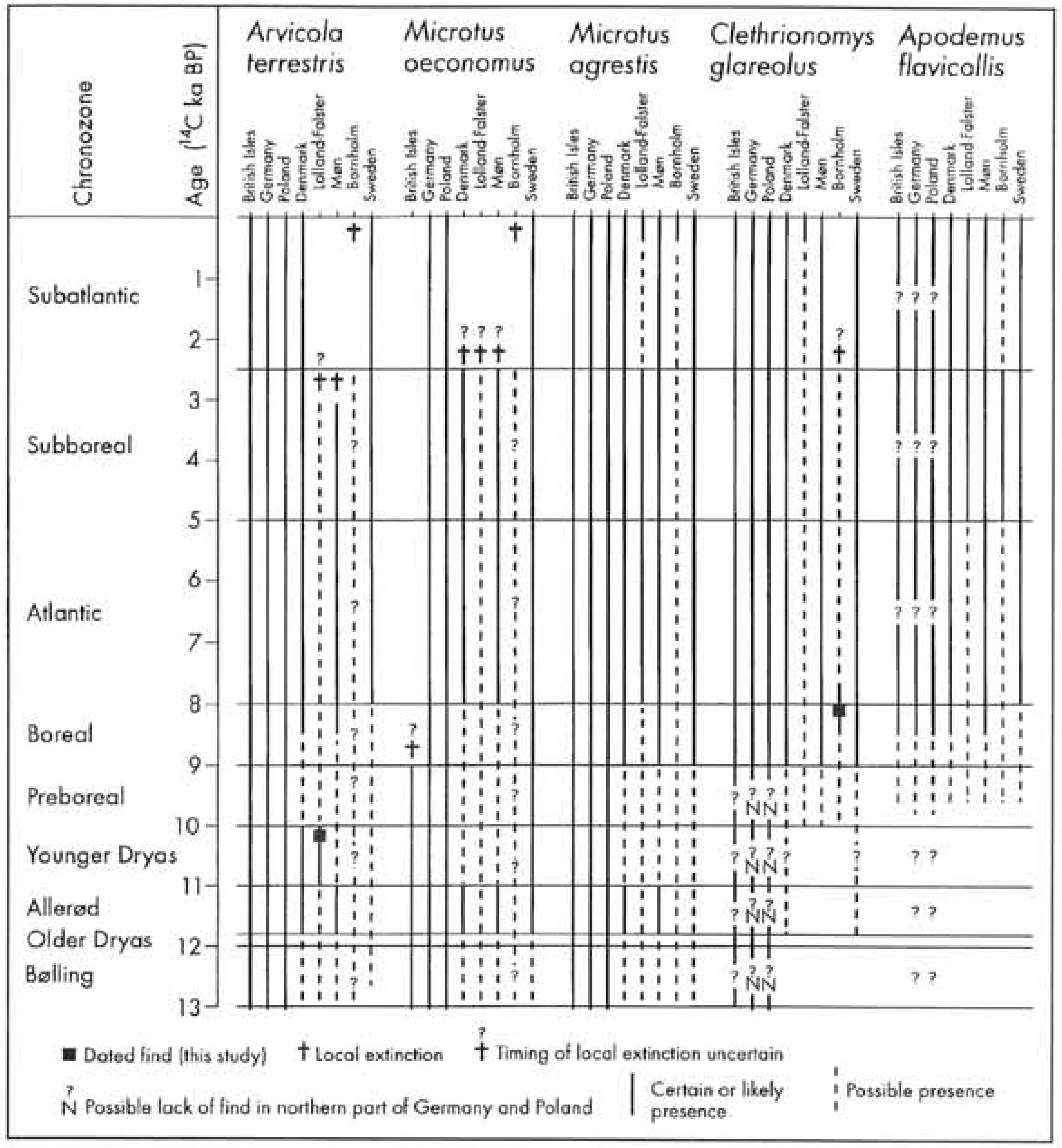

Fig. 3. Compilation of the Late Glacial and Holocene fossil record in northwesthern Europe of water vole, root vole, field vole, bank vole and yellow-necked mouse. The data are compiled from Winge (1904), Holst (1906), Lemche (1926), Degerbøl (1926, 1928, 1943), Toepfer (1963), Sutcliffe & Kowalski (1976), Petersen (1978), Richter (1982), Andersen & Johansen (1986), Lepiksaar (1986), Nadachowski (1989), Heinrich (1990), Heiberg in Richter (1991), Bratlund (1993), Heiberg in Noe-Nygaard (1995), Heiberg (1995), Aaris-Sørensen & Andreasen (1995), Aaris-Sørensen (1995) and this paper. Chronozone boundaries follow Mangerud et al. (1974), although the Older Dryas is now believed to be somewhat older (Björck 1984).

Genus *Clethrionomys* Tilesius, 1850
***Clethrionomys glareolus* (Schreber, 1780) Bank Vole.** A single well preserved enamel loop of a molar, most likely the left M_2 of an adult individual, was found (Fig. 2). The enamel is shining, bluish-black with some lighter bluish areas, especially along the rounded fractures. The specimen is of an ontogenetic age where the formation of enamel has stopped and the formation of the root is well advanced (Corbet 1964). Nearly all of the dentine, as well as the tartar between the enamel loops, is missing.

The fragmentation of the tooth can be ascribed to a predator (Mellett 1974; Mayhew 1977; Dodson & Wexlar 1979; Kowalski 1990) that may also be responsible for the missing dentine and cementum, as well as the rounding of the fractures, although the latter could perhaps also be ascribed to other taphonomic processes, such as diagenesis following deposition of the tooth.

The tooth fragment was recovered from core 526187, 365–380 cm b.s.f. The coring site is located on Adler Ground southwest of Bornholm, at 54°48.24'N, 14°31.77'E (Fig. 1). An AMS ^{14}C dating of terrestrial plant remains from the sample yielded an age of 8050±100 ^{14}C years BP (Ua-4859), corresponding to the Boreal chronozone. The sediments with the molar fragment are sandy and were probably deposited in an environment close to the shore of the Ancylus Lake.

The bank vole does not live on the island of Bornholm at present, nor is there any fossil record of this species from the island. However, the fossil find from Adler Ground indicates that *C. glareolus* was a member of the Early Holocene mammalian fauna of Bornholm. The time of local extinction of the bank vole on Bornholm is unknown (Fig. 3). The Early and Middle Holocene fauna of Bornholm also included a number of larger mammals that subsequently became extinct on the island (Aaris-Sørensen 1988).

The known fossil range of bank vole in Denmark and Sweden goes back only to the Early Holocene (Lepiksaar 1986; Heiberg 1995), although Lepiksaar (1986) and Aaris-Sørensen (1988) suggested a Late Glacial arrival. Bank vole remains are frequent in Middle Holocene Danish faunas (Winge 1904; Aaris-Sørensen 1980; Heiberg in Richter 1991; Bratlund 1993; Heiberg in Noe-Nygaard 1995; Heiberg 1995; Aaris-Sørensen & Andreasen 1995), and on the island of Møn where its record extends back to the Boreal, it is the most frequently found fossil rodent (Heiberg 1995). On the other hand, there have been no fossils of this species found on Lolland and Falster (Fig. 3). To our knowledge, there are no Late Glacial or Holocene finds from the northern parts of Germany or Poland, whereas there are records further south (Nadachowski 1989; Heinrich 1990). In Britain, the species probably disappeared during the Middle Weichselian, and it seems to reappear in the Boreal (Sutcliffe & Kowalski 1976).

C. glareolus is presently widely distributed in Europe, although it is absent from the southernmost and northernmost parts. It is also widespread in the northern and central parts of Asia. The species lives primarily in forest and scrub (Macdonald & Barrett 1993).

Genus *Microtus* Schrank, 1798

Microtus sp. **Unidentified Vole.** One well preserved fragment of a left molar (M_2) was recovered (Fig. 2). The breadth of the tooth is 1.20 mm. The enamel is black and shining and the dentine is dark brown. The cementum is missing, but there is no trace of abrasion. Depressions in the dentine of the occlusal surface and the missing cementum could indicate limited etching by the gastric juice of a predator (Mellett 1974; Mayhew 1979; Kowalski 1990).

The tooth fragment was recovered in core 564037, 410–420 cm b.s.f. The coring site is south of Lolland, at 54°32.67'N, 11°39.55'E. The sediments were deposited in a marine environment, and the sediments containing the tooth fragment are provisionally dated to the Middle Holocene.

The tooth fragment most likely comes from either *Microtus agrestis* (Linnaeus, 1761) (field vole), a species that is common in Denmark today, or from *M. oeconomus* (Pallas, 1776) (root vole), a species that no longer lives in Denmark, but probably became locally extinct during the Subatlantic chronozone (Fig. 3). In Denmark, the field vole is known from the Late Glacial and the Boreal chronozone (Heiberg 1995) and from the Middle and Late Holocene (Aaris-Sørensen 1980; Heiberg in Richter 1991; Bratlund 1993; Heiberg in Noe-Nygaard 1995; Heiberg 1995, Aaris-Sørensen & Andreasen 1995). A previous report of field vole from Allerød deposits in northern Jutland by Jessen & Nordmann (1915) has not been confirmed by recent studies (Aaris-Sørensen 1995). The root vole has been recovered from Late Glacial and Middle Holocene deposits on Møn (Heiberg 1995), and from Allerød deposits in northern Jutland (Aaris-Sørensen 1995). It is also known from the Late Glacial of southernmost Sweden (Holst 1906; Lepiksaar 1986). In Britain the root vole was formerly widely distributed, but it disappeared during the Early Holocene (Sutcliffe & Kowalski 1976).

Family Muridae Gray, 1821

Genus *Apodemus* Kaup, 1829

Apodemus flavicollis **(Linnaeus, 1758) Yellow-Necked Mouse.** One left molar (M_1) measuring 1.85 * 1.10 mm (length * breadth) with two roots preserved was found (Fig. 2). The enamel is black and shining and the dentine is dark brown. The tooth is unworn and well preserved.

The tooth was recovered from core 564026, 40–55 cm b.s.f., southeast of Falster, at 54°28.62'N, 12°03.83'E (Fig. 1). The sandy sediments were deposited in a shallow-water marine environment. Marine mollusc shells from 110–120 cm b.s.f. yielded a reservoir corrected radiocarbon date of 4940±90 years BP (AAR-2288). Thus the tooth is believed to be of Subboreal or Subatlantic age.

The European fossil record of the yellow-necked mouse is sparse, primarily due to difficulties in distinguishing remains of this species from the closely related wood mouse *(A. Sylvaticus)* (Sutcliffe & Kowalski 1976; Nadachowski 1989), but also due to the late acceptance of *A. flavicollis* as an independent species. The yellow-necked mouse was regarded a large form of the wood mouse into the beginning of this century (Degerbøl 1935). In Denmark, the record of the species extends back to the Boreal chronozone (Heiberg 1995), and it is frequently found in Middle Holocene deposits, notably on Møn, but there are fossil finds from all parts of Denmark, including Bornholm (Fig. 3) (Aaris-Sørensen 1988; Heiberg in Richter 1991; Bratlund 1993; Heiberg in Noe-Nygaard 1995; Heiberg 1995). In Sweden the record goes back to the Atlantic (Lepiksaar 1986), and in Britain there are a few finds, probably of Holocene age (Sutcliffe & Kowalski 1976). In Poland, *A. flavicollis* is thought to have arrived in the Holocene (Nadachowski 1989). We do not know of any Holocene finds of yellow-necked mouse from the northern parts of Germany and Poland.

The yellow-necked mouse is currently widespread in eastern and central Europe. It occurs as far west as southern Britain and north to southern Norway, Sweden and Finland (Corbet 1978). The species lives primarily in or near forest and scrub (Macdonald & Barrett 1993).

CONCLUSION

Our results show that it is possible to find and identify remains of rodents in submarine Late- and Postglacial deposits in the southwestern part of the Baltic Sea. However, it is necessary to sieve large amounts of sediment to obtain rodent remains, and an extensive reference collection is indispensable for the identification work.

Despite the limited number of finds, they are of importance for unravelling the history and arrival time of terrestrial microvertebrates to the region, particularly since the presently available information is scanty. In addition, they are useful in palaeoenvironmental reconstructions. The effect of isolation of islands that caused local extinction of small mammals is a topic for future analyses. Also, the finds can add to the understanding of the taphonomic processes that affect microvertebrates.

ACKNOWLEDGEMENT

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Morphometrical, Lithological and Mineralogical Traits of Eolian Formations in the Lithuanian Coastal Zone of the Baltic Sea

Algimantas Česnulevičius
and Regina Morkūnaitė

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Algimantas Česnulevičius, Institute of Geography, Department of Dynamical Geomorphology and Vilnius University, Department of General Geography; Academijos 2, Vilnius, 2600, Lithuania; Regina Morkūnaitė, Institute of Geography, Department of Dynamical Geomorphology; Akademijos 2, Vilnius, 2600, Lithuania; *received 15th November 1996, accepted 15th January 1997.*

Eolian formations cover a considerable part of Lithuanian area – 1.7%. All of them have been developed in Pleistocene and Holocene. The continental eolian formations are represented by dune ridges developed in the sites of periglacial basins and fluvioglacial terraces. Later on, when the climate became milder and plant cover developed, the eolian processes in the continental part of Lithuania almost stopped.

The Holocene eolian formations in Lithuania are spread on the Baltic Sea coast. Even today the conditions for eolian processes are favourable. By their morphometrical parameters of the surface the coastal eolian forms differ considerably from the continental dunes. Lithologically both segments of relief are uniform, whereas grain size distribution of continental dune sand is more diverse.

Keywords: Continental and coastal dunes, eolian forms, eolian form ages.

INTRODUCTION

Eolian formations in Lithuania cover about 1.7% of its territory (Fig. 1). Their development took place in the late phases of Pomeranian stage. During South Lithuanian phase, numerous shallow limnological basins situated in the south east part dried up. They were replaced by Dzūkija eolian relief. When the glacier paused in Central Lithuania several larger limnoglacial basins stretched at its external edges: i.e. at Kazlų Rūda, Kaišiadorys and Viešvilė. When the glacier moved northwards these basins dried up in a short time and eolian massive formations, somewhat smaller than the Dzūkija one, developed.

The next phase of eolian relief formation was related to the Baltic Sea development stages. In the Litorina stage fine sands predominated in the Nemunas delta. Some time later they were redeposited. The Baltic Sea

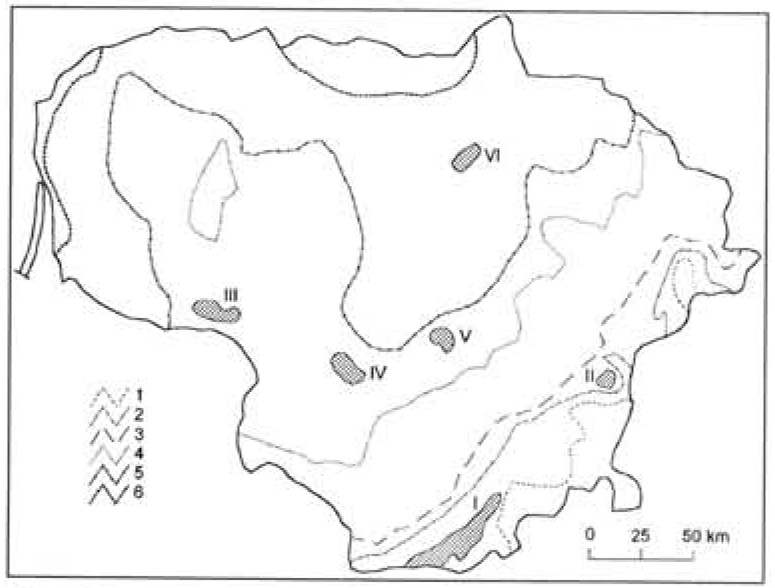

Fig. 1. Glacial edge formations and largest eolian massives in Lithuania. Glacial edge formations: 1 – Brandenburg Stage, 2 – Frankfurt Stage, 3 – Pomeranian Stage East Lithuanian Phase, 4 – Pomeranian Stage South Lithuanian Phase, 5 – Pomeranian Stage Middle Lithuanian Phase, 6 – Pomeranian Stage North Lithuanian Phase. Largest eolian massives: I – Dzūkija, II – Vilnia, III – Viduklė, IV – Kazlų Rūda, V – Kaišiadorys, VI – Žalioji Giria.

oscillations in Holocene predetermined that sand deposited on terraces was later redeposited by eolian processes. Eolian processes in the Lithuanian coastal zone take an active course today as well.

The coastal eolian Lithuanian relief is comprised of two segments (Fig. 2). The eolian formulation situated northwards from Klaipėda occupy a narrow strip of coast forming a beach and foredune ridge. Southwards from Klaipėda a sand spit has developed with by far more diverse eolian relief.

METHODS

The article analyses morphometrical, lithological and mineralogical peculiarities of the Lithuanian coastal eolian relief and compares it with the continental eolian relief. The studies on eolian relief forms were based on the morphometrical relief form classification compiled at the Institute of Geography (Česnulevičius 1995) (Table 1). The relief forms are classified according to three major parameters: height, length and inclination of slope.

For lithological analysis 5 intervals of grain size fractions were used: below 0.1, 1–0.25, 0.25–0.5, 0.5–1.0 and above 1.0 mm. Predominating fractions were determined for eolian formations of different age. Besides, for separate eolian complexes cumulative curves of grain size composition of deposits were drawn.

The mineral structure of deposits was determined by calculating the content of different minerals per volume unit and their percentage distribution given.

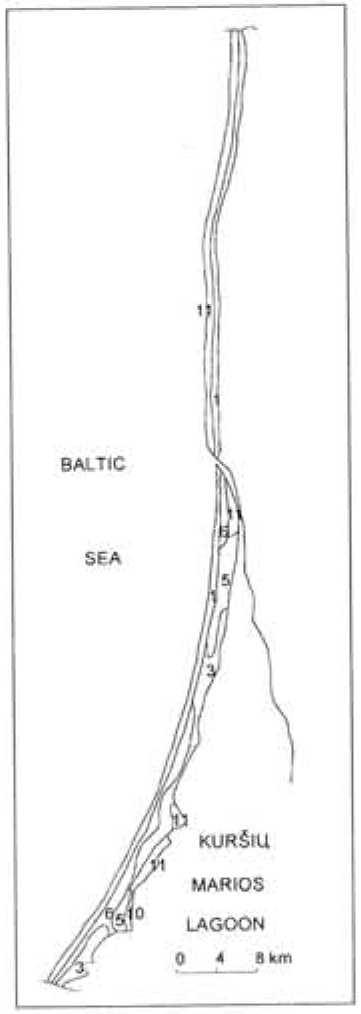

Fig. 2. Morphometrical types of Holocene eolian formations on Baltic Sea coast [A.Česnulevičius, 1995]: 1 – small, low, 2 – small, high, 3 – small, high, 5 – medium size, high, 6 – medium size, high, 10 – waves, 11–flat plain.

Table 1. **Morphometrical classification of relief forms** (Česnulevičius 1995).

Forms and their size	Height (depth) of forms	Low (shallow) 5–10 m	Medium 10–20 m	High (deep) over 20 m
Small (hillocks, ridges, hills, hillspurs, basins, pits, circusses, lobes, channels, gullies, ravines, valleys)	Slope length (m)	up to 50	50–100	over 100
		1 *	2 *	3 *
	Slope inclination (°)	over 7	over 7	over 7
	Areas (ha) 1	3	10	
Medium size (ridges, hills, hillspurs, kettles, channels, ravines, valleys)	Slope length (m)	50–100	100–200	over 200
		4 *	5 *	6 *
	Slope inclination (°)	3–7	3–7	3–7
	Areas (ha) 3	15	30	
Large (ridges, hills, hillspurs, kettles, valleys)	Slope length (m)	100–200	200–400	over 400
		7 *	8 *	9 *
	Slope inclination (°)	1–3	1–3	1–3
	Areas (ha) 15	50	100	
Waves	10 * Height (depth) of forms – up to 5 m, slope length – up to 50 m, slope inclination – up to 3°			
Plains	11 * Surface inclination below 1°			

* – Number of morphometrical types of relief.

MORPHOMETRY OF EOLIAN RELIEF

Three phases may be distinguished in the course of development of eolian relief. The first one – the pause of the glacier in the Middle Lithuanian phase of Pomeranian stage. The second one – the pause of the glacier in the North Lithuanian phase of the same stage. The third one – Holocene stage. The eolian relief developed in the place of shallow periglacial basins. The blowing winds, thickness of sand layer and its bedding conditions predetermined the diversity of eolian forms.

The eolian relief developed during the Middle Lithuanian phase includes two large segments: middle one is in a course of the Vilnia River and middle and lower courses of the Merkys River. Eolian forms are represented by small low and medium high dunes, parabolic dunes, barchans and dra. All forms are with steep slopes in many phases, the inclination reaches 0° and more. About 20% of eolian relief of this phase is represented by medium-size forms. Slope inclination reaches 5–6° and length is 50–100 and more meters. Eight percent of relief are represented by undulating plain. It is a slightly folded surface with 2–3 m high elevations and long slopes (50 m), their inclination values exceed 3°.

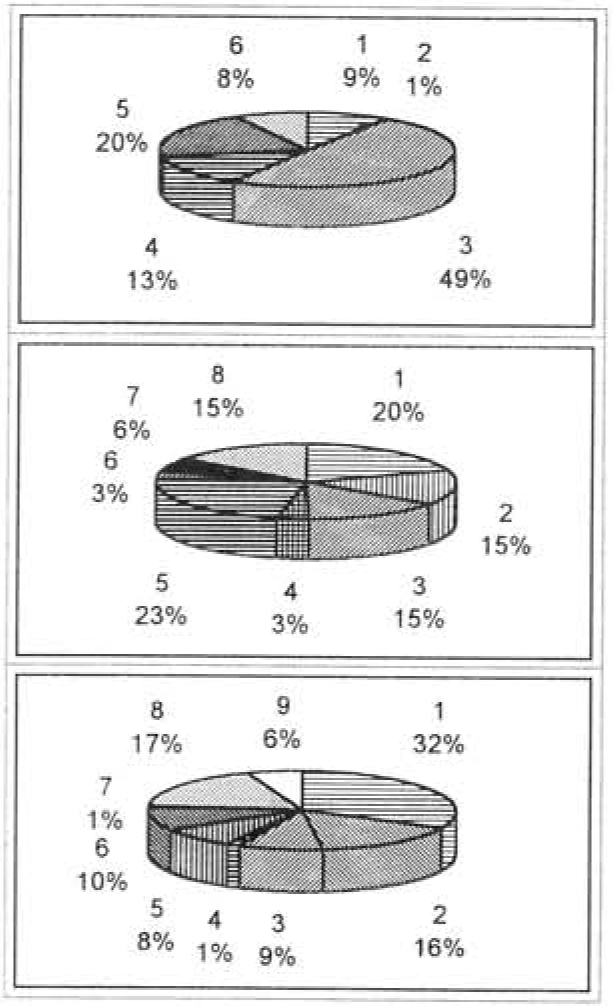

Fig. 3. Morphometrical structure of different age eolian formations: A – Middle Lithuanian Phase, 1 – small, low, 2 – small, high, 3 – small low and high, 4 – medium size, low, 5 – medium size, low and high, 6 – waves; B – North Lithuanian Phase, 1 – small, low, 2 – small, high, 3 – small, low and high, 4 – small, high and high, 5 – medium size, low, 6 – medium size, low and high, 7 – large, low, 8 – waves; C – Holocene, 1 – small, low, 2 – small, high, 3 – small, low and height, 4 – medium size, low, 5 – medium size, high, 6 – medium size, high, 7 – large, high, 8 – waves, 9 – flat plains.

In the North Lithuanian phase several complexes of eolian relief developed: Žalioji Giria, Kazlų Rūda, Viešvilė. Small eolian dunes prevail there including the whole spectrum: from small high to small low. Medium size and undulating forms occupy larger areas.

The shapes of Holocene eolian formations are more diverse. In the continental part predominate small low and small high forms of relief with a flat plain prevailing (in the beach). In the eolian relief of the Kuršių Nerija spit a few strips can be distinguished. A narrow sloping plain (beach) stretches along the shore. It is followed by a 100–200 m wide strip with small, low and medium size, high dunes. Further to the east a flat eolian plain is situated. These plains are about 0.5 km wide. Still further there is a belt (100–200 m wide) of small low dunes. In the east a belt of medium-size and large dunes can be found. They are 30–40 m high. Between Pervalka and Juodkrantė and southwards from Nida these dunes are abruptly sloping into the Kuršių Marios lagoon. The slope inclination reach of there 30°. Close to the Kuršių Marios lagoon a flat and wavy plains spread on the capes.

The morphometrical structure of various-aged eolian formations is given in Fig. 3, whereas the contours of eolian form of relief are shown in Fig. 4.

LITHOLOGICAL STRUCTURE

All eolian forms are composed of fine and medium-size sand. Its granulometric structure was predetermined by several factors:

1. Grain size of substratum developed by other geomorphological processes.
2. The distance which had to be covered by blown sand.
3. Duration of the process.
4. Wind regime.
5. Morphological structure (exposition and inclination of slopes).

Various-aged eolian formations differ in grain size. Fine sands prevail in eolian complexes developed during the Middle Lithuanian phase (Kristapavičius 1961a, 1961b). The eolian segment of Merkys lower course is typical of fine sands (0.1–0.25 mm) making 50–60% of the total sand

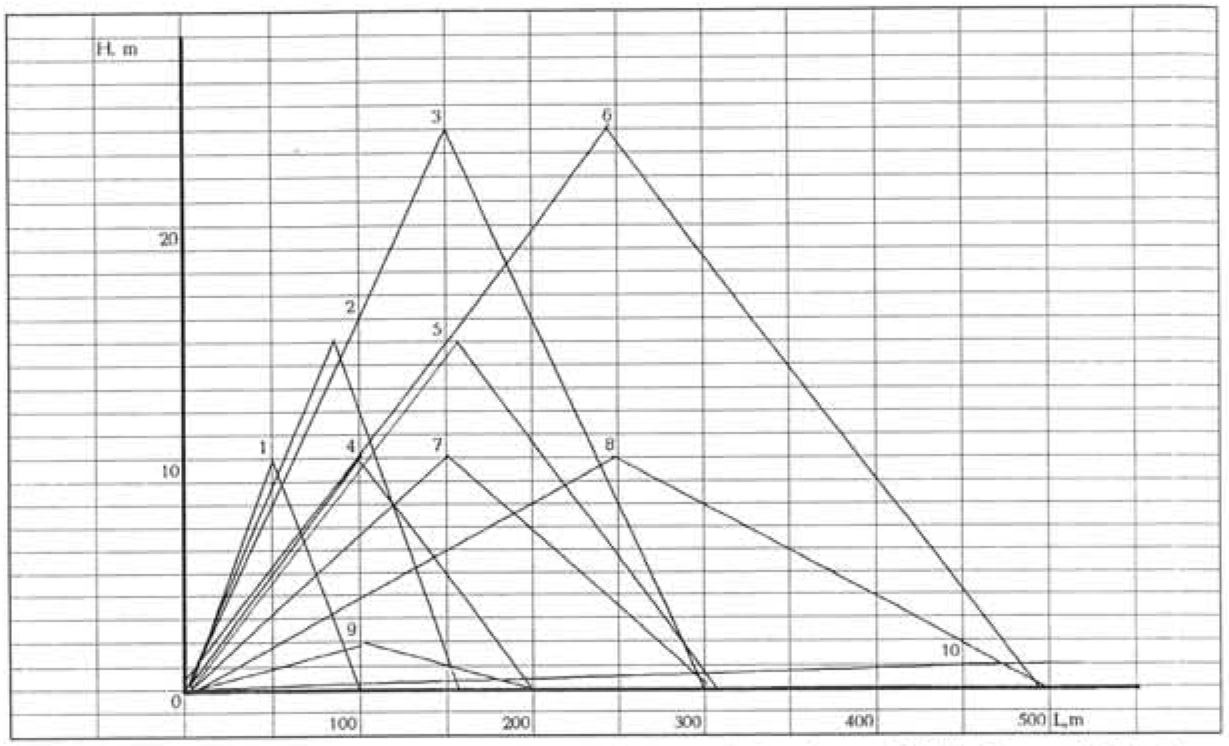

Fig. 4. Average morphometrical parameters of eolian relief: 1 – small, low, 2 – small, high, 3 – small, high, 4 – medium size, low, 5 – medium size, high, 6 – medium size, high, 7 – large, low, 8 – large, high, 9 – waves, 10 – flat plains.

Table 2. **Grain size in the eolian sands of Middle (M.L.Ph.) and North (N.L.Ph.) glacier phases and Holocene** (Gudelis, Stauskaitė 1959; Klimavičienė 1964, 1968, 1974).

Localisation	Grain size, mm					
	less 0.01	0.01–0.1	0.1–0.25	0.25–0.5	0.5–1.0	more 1.0
M.L.Ph.	0.32	7.74	60.79	29,39	1.70	0.06
N.L.Ph.	1.77	19.32	53.26	22.61	2.83	0.21
Holocene	–	2.70	45.20	47.80	3.40	0.80

Table 3. **Grain size of sea and beach parts of coastal zone** (Gudelis, Michaliukaitė 1959; Pustelnikov 1982).

Localisation	Grain size, mm					
	less 0.01	0.01–0.1	0.1–0.25	0.25–0.5	0.5–1.0	more 1.0
Seaside slope	31.6	32.1	–	36.3	–	–
Bar	5.3	39.2	–	55.5	–	–
Coastal zone	–	39.4	–	60.6	–	–
Beach	0.5	0.5	76.5	15.0	4.0	4.0

mass. The fraction of 0.1–0.25 mm in the middle course eolian segments makes up even 45% of sand mass. Identical data are given by R.Vaitonienė who thoroughly investigated the south-east Lithuanian relief (Vaitonienė 1976 a, 1976 b; Gudelis, Vaitonienė 1974 a, 1974 b).

The eolian formation developed in the North Lithuanian phase has also fine (0.1–0.25 mm) sands prevailing. However, a considerable part (10–30%) belongs to medium-size sand, as well (Table 2).

The eolian relief of Kuršių Marios lagoon is typical of medium size sand fraction (0.25–0.5 mm) prevailing. They make up to 50% of the total sand mass. Especially distinctively fine–grained fraction prevail in the belt of large dunes (Table 3).

After the grain size analysis of eolian formations in Lithuania a cumulative curve of deposits was drawn (Fig. 5). It shows the tendency of increase in the amount of coarser fractions when moving from east to west. It must be noted that in 1919 F.Salgeri determined that the grain-size of dune material in the old valleys of Polish rivers decreased moving from east to west. In 1958 his opinion was supported by B.Krygowski. However, further investigations of Polish researchers did not confirm this assumption and determined a close reciprocal dependence between the grain-size of dune material and substratum. The grain-size of dune material in old valleys vary moving from east to west and only in a short sector of the territory the mentioned regularity can be observed (Nowaczyk, 1986).

Similar environment of sediment formation is characteristic of eolian sands mentioned above – in this place ponds and deltas existed in the late glacial – the only difference is in the duration of eolian cover development. We make an assumption, which must be proved by additional investigations, that eolian processes in southeast Lithuania, presumably, took place for by far longer time, than in the coastal area.

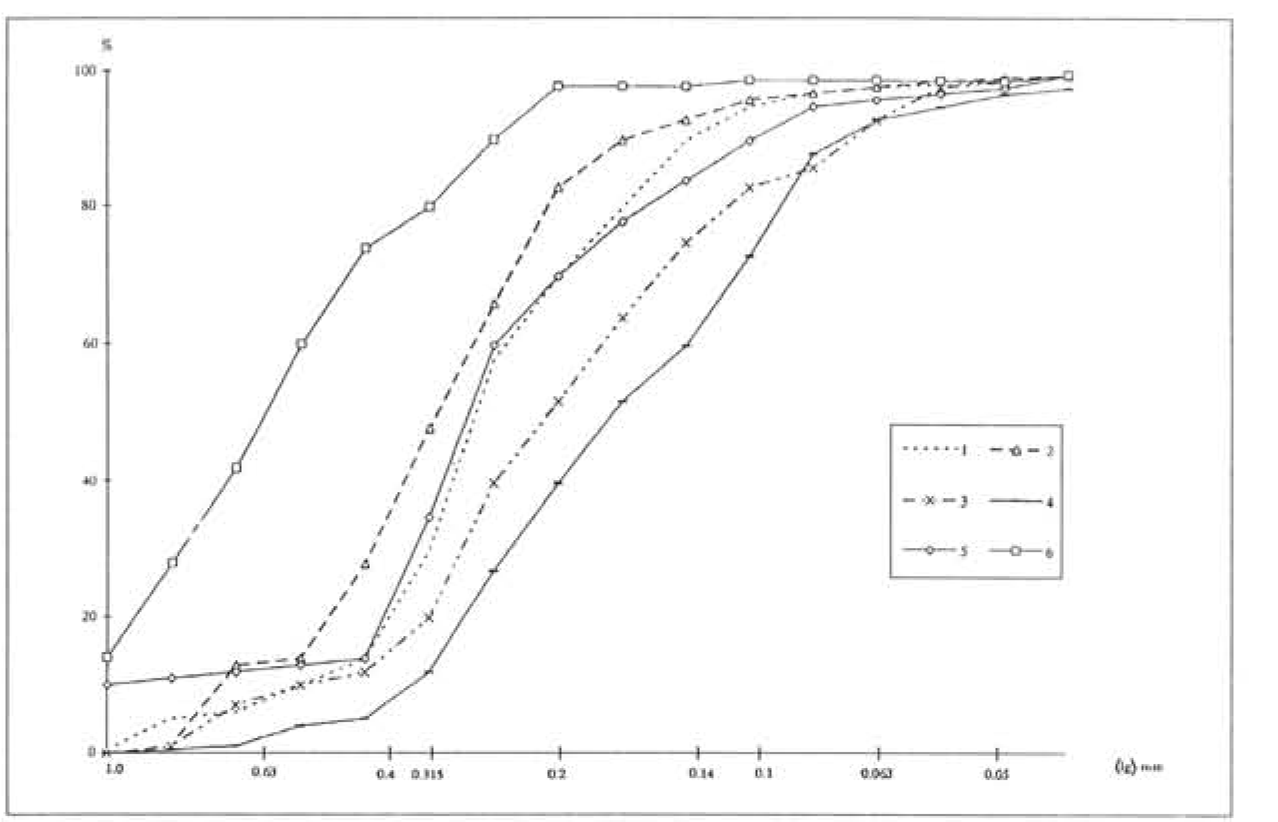

Fig. 5. Cumulative curves of grain size composition of eolian sand. Middle Lithuania Phase: 1 – area of Varėna (Mikalauskas 1974), 2 – area of Rūdninkai. North Lithuania Phase: 3 – area of Kazlų Rūda, 4 – area of Šimonys, 5 – area of Eičiai (Klimavičienė 1964). Holocene: 6 – area of Nida (Gudelis et al. 1959).

MINERAL COMPOSITION

Quartz should be regarded as one of the indicator minerals of eolian formations. It is resistant to decay and various mechanical impacts. For this reason the amount of quartz in eolian formations of east Lithuania is higher than in its western part: the content of quartz in eolian formations of the Middle Lithuanian phase reaches 89–91%, North Lithuanian – about 85%, Holocene – not more than 80%. The distribution of epidote, pyroxene and feldspars is different. These are easily decaying and mechanically abraded minerals. The distribution of feldspars is especially intensive. Their content in eolian formations of Curonian spit developed in Holocene reaches up to 20%, whereas, in south Lithuania – only 10–11%. The use of epidote and pyroxene for indication purposes is a problematic one. Their content in eolian formations is rather small – only several tenths of percent. The oscillations in their content may be most important for age interpretations of the deposits.

In this sense the eolian formations of Curonian spit are especially complicated. The amount of quartz reaches there up to 80%, whereas the amount of ilmenite and magnetite (10–18%) increases considerably. The content of feldspars is comparatively low. The increase in ilmenite and magnetite can be caused by the fact that blown sand had covered a short distance from the source till the sea beach.

V. Gudelis (Gudelis 1992) pointed out that the sand of coastal dunes contained a large amount of glauconite (2–4 %) which was carried by the nearshore sediment transport from the Sambian peninsula. This heavy metal was not found in the continental eolian sands (Klimavičienė 1968). The mentioned works state (Bakker et al. 1990) that on the Baltic coast there exist a close genetically relationship between the dune and marine sands.

The use of morphometrical, granulometrical, lithological and others supplementary parameters (e.g. polishing of grains) in the analysis of eolian formations would make it possible to determine the influence on these formations of substratum and duration of eolian processes. As was determined by some authors (Kabailienė, 1990) the absolute age of Lithuanian continental dunes is by 6–7 thousand years longer than that of coastal dunes. Futher investigations into this question would help to determine the relation age of these formations, i.e., the duration of eolian processes.

CONCLUSIONS

The eolian formations of Lithuania cover about 1.7% of its territory. Their development took place in the Middle Lithuanian, North Lithuanian phases of Pomeranian stage and in Holocene. The morphometrical, lithological and mineralogical peculiarities of Lithuanian coastal eolian relief are compared with the continental eolian relief.

The morphometrical parameters of Holocene eolian formations are more diverse than those of Pomeranian stages. Eolian forms and their inclinations increase moving from south-east to north-west Lithuania.

Grain size analysis of eolian formations shows the tendency of increase in amount of coarser fractions moving from east to west.

Mineralogical analysis of eolian sands reveals that the amount of indicator minerals is different in the Lithuanian territory. For example, the amount of quartz in eolian formations of east Lithuania is higher than in its western part. The distribution of epidote, pyroxene and feldspars is different too.

Morphometrical, lithological, mineralogical and others supplementary investigations (grain polishing, palynological analysis) will enable to evaluate the role in formation of coastal and continental eolian formations of the duration of eolian processes and composition of substratum. So far, according to the data of other authors it is assumed that the absolute age of coastal eolian sands is by 6–7 thousand years shorter than that of continental sands.

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