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Stratigraphy of sediments from the Baltic Sea and Kattegat by foraminifers and paleoceanology

Nadezhda Lukashina

Abstract

Foraminiferal analysis of sediments of Holocene in the Baltic and Kattegat Seas has been carried out . It was found that these deposits contain euryhaline benthic foraminifera along with stenohaline planktonic species typical for the North Atlantic. Growth of concentrations of the first and appearance of the second unambiguously indicate a more intensive penetration of saline water from the North Sea into the Baltic Sea. This allows to use foraminifera for stratigraphic analysis of deposits of the Baltic Sea. More rich and various fauna of benthic foraminifera in the Kattegat Sea allows also to reconstruct the characteristics and dynamics of bottom and surface water masses, circulated between the Baltic and North Seas.

☐ *Baltic Sea, Kattegat, benthic and planktonic foraminifera, water masses, Subatlantic, Subboreal, Atlantic.*

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INTRODUCTION

The Baltic Sea is a saline-water basin, which periodically through Danish Straits the North Atlantic receives saline water favourable for living foraminifers. Northeastwards from the Danish Straits the temperature and salinity of water gradually falls, leading to a decrease in amount and variety of benthic foraminifers. In the modern Baltic Sea 12 to 38 species of benthic foraminifers are found (Saidova 1981; Brodniewicz 1965; Hermelin 1987; Lutze 1965). Most of them are represented by agglutinating species, shells of which are quickly destroyed when washing out a sample. From time to time the North Atlantic water transports into the Baltic Sea planktonic foraminifers inhabiting in the upper 200-m layer of the oceans. As far as we know, there are no references on planktonic foraminifers in the Baltic Sea sediments.

Brackish-marine conditions in the Baltic Sea area existed twice during the last 10 thousand years - in Preboreal and during Atlantic-Subatlantic. To distinguish these horizons it is normal to use palynology and diatom biostratigraphy methods. Marine conditions are also imprinted in the sediments as increase in concentrations of benthic foraminifers and, in some cases, as occurrence of planktonic species (Lukashina 1995). This work aims to show that benthic and planktonic

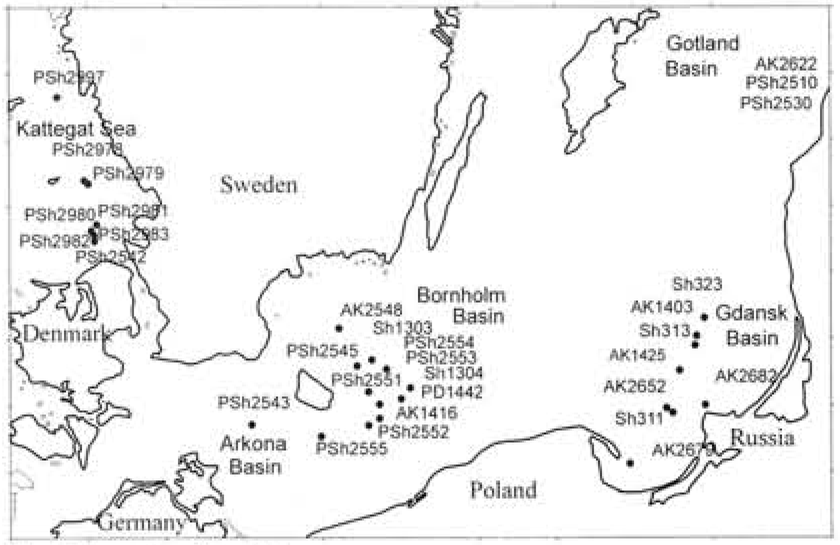


Fig. 1. Location of studied cores.

foraminifers in the Baltic Sea and Kattegat may be used for stratigraphic and paleooceanological purposes.

MATERIALS AND METHODS

The work is based on material collected by scientists of P.P.Shirshov Institute of Oceanology (Atlantic Branch, Laboratory of Geology of Atlantic Ocean) in 1980-1997 under the leadership of Prof. E.M. Emelyanov, including 3 cores of bottom sediments taken in Gotland Basin, 9 cores from Gdansk Basin, 11 cores and 59 surface samples from Bomholm Basin, 1 core from Arkona Basin and 8 cores from Kattegat (Fig. 1). In most cases 2 cm samples were taken at 5-cm intervals. All specimens of foraminifers with diameter larger than 0.1 mm were analyzed and counted per sample and per 1 g of sediment.

RESULTS

In the Gotland Basin foraminifers were found in pelitic mud overlying blue-grey clays (Fig. 2). In the cores PS-2510 and PS-2530 at sea depths of 239 and 238 m, correspondingly, benthic foraminifers are represented by species Elphidium - *E.excavatum, E.incertum, E.albiumbilicatum.* Their concentration in the sediments amounts to 1700 specimens per 1 g of sediment. These cores, as well as the core AK-2622 from a depth of 240 m are found to contain planktonic foraminifers belonging mainly to the Boreal group: *Globigerinita glutinata, Globigerina pachyderma* dex., *Globigerina bulloides, Globigerina quinqueloba*. Among them one may see the Arctic form – *Globigerina pachyderma* sin., subtropical species *Globorotalia inflata, Globorotalia scitula, Globigerina calida*, and even tropical *Globigerinoides ruber* (Lukashina 1995a; Emelyanov & Lukashina 1995). Concentration of these species in sediments reaches 200 individuals per 1 g. This is enough for an approximate evaluation of water temperature. The latter proved to be 10.5°C and compares well with the year average temperature in the North Sea (Atlas of Oceans 1977). Shells of planktonic foraminifers are small in size and often partly dissolved. Occurrence of large amount of planktonic foraminifers in surface samples proved to be a good ground for conclusion that these sediments were deposited, when invasion of the North Sea water into the Baltic Sea was the most intensive over the whole Holocene - in Subboreal. This conclusion is supported by carbon dating (Emelyanov, Bustrom et al. 1995): horizon 0-10 cm is dated back to 2400±100 yars B.P.

In the Gdańsk Basin (Fig. 3) foraminifers have been found in 5 bottom cores out of 9, and two of them include planktonic species *G. pachyderma* sin., *G.pachyderma* dex., *G. quinqueloba* and *G. inflata*. In the core AK-2679 at a sea depth of 76 m the concentration of benthic foraminifers, represented by elfidiums, is high - to 5000 specimens per 1 g of sediments. In the core AK-1425 at depth of 102 m amount of planktonic species comes up to 60 specimens per 1 g. Maximum concentrations of both species belong to deposits of Subboreal, becoming much lower in Subatlantic. Benthic species are more plentiful in coastal areas, while planktonic ones - in the open part of the Gdańsk Basin. Shells of foraminifers are small in size and partly dissolved. The core AK-1425 was earlier stratified with reference to diatoms (Kabailenė et al. 1978). Sediments of the Baltic Glacial Lake, Yoldia Sea, Ancylus Sea, Litorina and post-Litorina Seas were distinguished in this core. Spore and pollen analyses support the proposed distribution. At the same time, three samples taken from lacustrine deposits of Ancylus stage show the occurrence of planktonic foraminifers. Presently the author is not in a position how to explain this phenomenon, may be it is connected with redeposition.

In the Bornholm Basin benthic foraminifers have been found only in 17 out of 59 surface samples, while planktonic - in ten samples from sea depths of more than 70 m. Besides elphidiums, benthic species comprise also *Bulimina marginata* and Cibicides sp., while planktonic species are represented by *Globigerina pachyderma* sin., *Globigerina pachyderma* dex., *Globigerina quinqueloba, Globigerina bultoides, Globigerinita glutinata* and *Globorotalia inflata*. One may easily observe gradual decrease in concentration of benthic foraminifers from 150 specimens per g in the northwestern part of the basin to unique specimens in the southern and eastern parts. It is quite probable that the quantitative distribution of those species reflects inflow of saline North-Atlantic water through the Bornholm gat. In the Bornholm basin benthic foraminifers have been found in 10 out of 16 cores (Fig. 4), while planktonic ones - in 4 cores. The concentration of both species in the sediments is quite low and ranges from 0.5 to 50 specimens per 1 g for the case of planktonic foraminifers, and from 1 to 56 - for benthic. Deposits containing the above mentioned foraminifers are held to be of not dividing Subboreal and Atlantic. 3 cores from Bornholm Basin, which were used as reference points in our studies, have been studied and stratified by lithological analysis and by means of spore-pollen and diatom analyses (Emelyanov 1997).

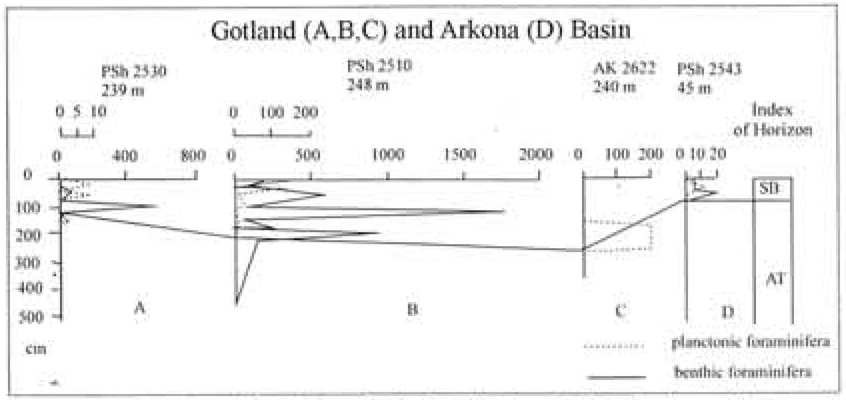


Fig. 2. Distribution of benthic and planktonic foraminifers in the sediments of the Gotland and Arkona Basins (specimens per 1 g of sediment).

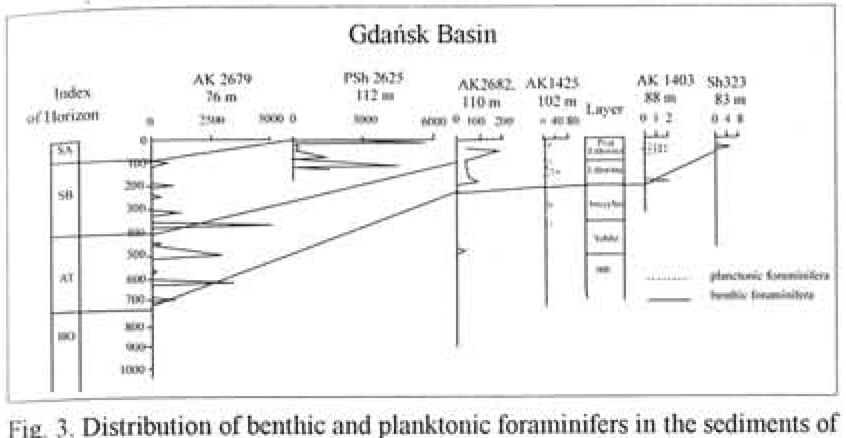


Fig. 3. Distribution of benthic and planktonic foraminifers in the sediments of the Gdańsk Basin (specimens per 1 g of sediment).

In the core from Arkona Basin (Fig. 2) planktonic (up to 20 specimens per 1 litre) and benthic (up to 15) foraminifers have been found in the sediments at 0-50 cm horizon.

Community of benthic foraminifers found in bottom samples of the Kattegat is much more richer and various than that in the Baltic Sea. In the northern part of the sea at the depths more than 80 m *Cassidulina reniforme* dominates. This species is related to *Cassidulina laevigata*, which is an indicator of the North-Atlantic surface water in the Atlantic ocean (Lukashina 1983). At the depths from 60 to 20 m predominant species are *Bulimina marginata, Ammonia beccarii*, while subdominant is *Nonion labradoricum*, frequently with a considerable share of agglutinated species. Elphidiums are rarely found species. *Bulimina marginata* is common for coastal shallow waters of Sweden and indicates water with low content of oxygen and high concentration of organic matter. It prefers salinity of about 33-35 per mill and a temperature range from 10 to 14°C (Streeter & Lavery 1982; Van Weering & Qvale 1983). It is commonly found on the shelf of the northern Great Britain, where its concentration reaches 55% (Lukashina 1983). *Ammonia beccarii* is found in coastal shallow waters of low salinity and moderate temperature along the coasts of Denmark and Sweden (Van Weering & Qvale 1983). *Nonion labradoricum* is characteristic of the shelf of Newfoundland, which is washed over by the cold Labrador current. Here concentration of this species comes up to 29% (Lukashina 1983).

It has been found that 5 cores from 21 to 29 m from the Kattegat contain 3 horizons each. In the lower horizon the concentration of foraminifers varies from 10 to 1500 specimens per 1 g of sediment. This horizon is characterised by predominance *of Elphidium albiumbilicatum* and by intermittent occurrence of planktonic foraminifers – *Globigerina quinqueloba, Globigerina pachyderma* dex., *Globigerina calida*, in concentrations up to 20 specimens per 1 g. It is probable that these sediments were deposited during the Atlantic period. The horizon second from below is notable for the increased content of foraminifers (up to 3000 specimens per 1 g), as well as by the increased amount of *Ammonia beccarii* and occurrence of *Hyalinea baltica*. Planktonic specimens are absent. Middle horizon is supposed to be of Subboreal period. In the upper horizon there are no elfidiums, but *Nonion labradoricum, Bulimina marginata* and agglutinating species appear, the concentration of benthic foraminifers does not exceed 500 specimens per 1 g. It was probably deposited during Subatlantic period.

The core PS-2542 (Fig. 5) was taken as reference for description of sediments from depths reaching 30 m. It has been studied by Konradsen (Christiansen et al. 1993), whose results compare quite well with ours. However, interpretation is different (content of ^{14}C in the shell of Cardium mollusk): below 40 cm they are Preboreal and Boreal, characterised by lagoon and fresh water conditions. The same stratification was found in the core 058-030 at a depth of 22 m (Klingberg 1996). The author (Lukashina, 1995) can't agree with that conclusion due to some reasons, e.g. occurrence of planktonic foraminifers under 100 cm from the core surface, and insists upon validity of biostratigraphical model, according to which the principal changes in

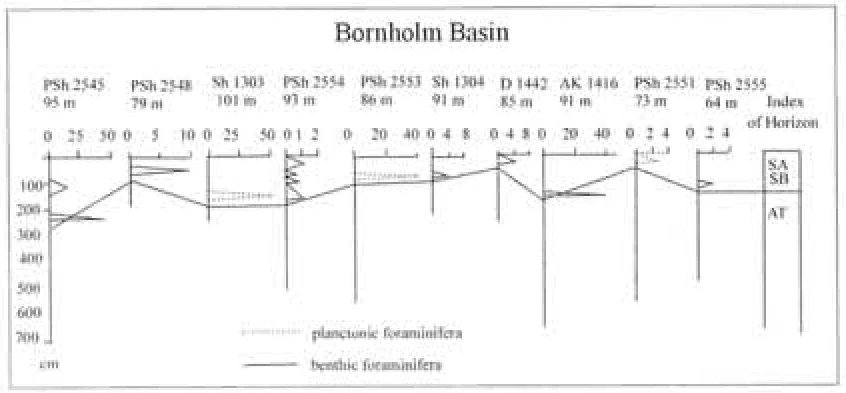
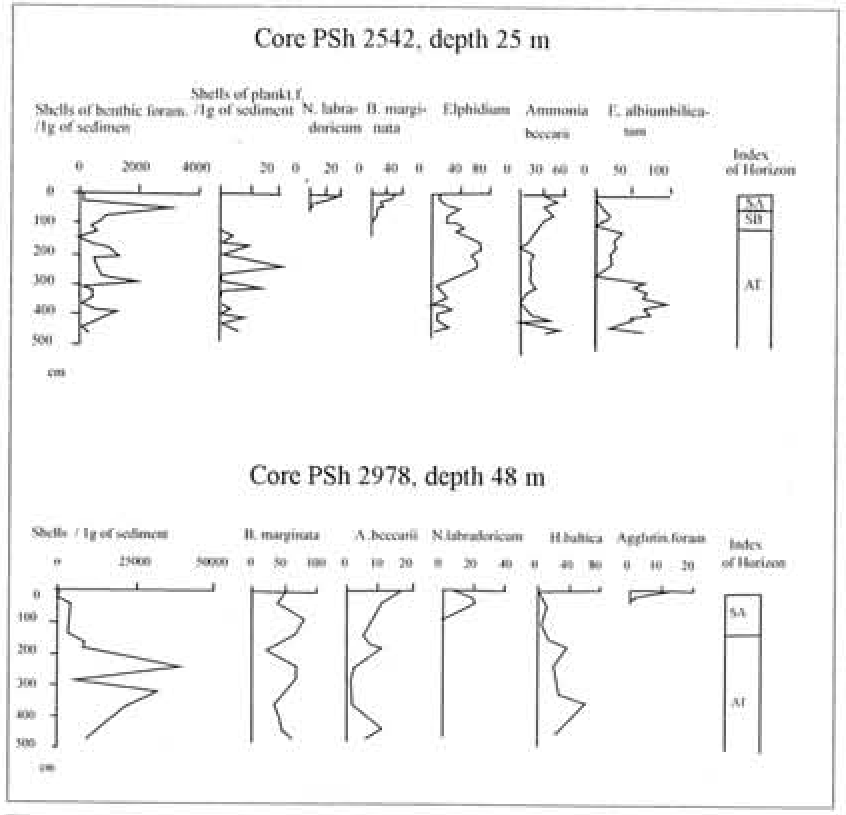


Fig. 4. Distribution of benthic and planktonic foraminifers in the sediments of the Bornholm Basin (specimens per 1 g of sediment).


Core PSh 2542, depth 25 m

Core PSh 2978, depth 48 m

Fig. 5. Distribution of benthic and planktonic foraminifers in the sediments of the Kattegat (specimens per 1 g of sediment).

communities of benthic foraminifers in Kattegat have been caused by hydrological changes 4000 and 2000 years B.P. (Nordberg 1991).

Three cores from Kattegat, situated at the depths from 50 to 60 m, show predominance of *Bulimina marginata*. Occurrence of other benthic species allow to distinguish two horizons in the cores. The lower horizon is characterised by high concentrations of foraminifers (up to 40000 specimens per 1 g) with large amount *of Bulimina marginata* and *Hyalinea baltica*, while the latter was found earlier in Skagerrak at the depths from 200 to 400 m (Van Weering & Qvale 1983). One core contains planktonic species *Globigerina pachyderma* dex. It is quite probably that deposits of the lower horizon were accumulated during Subboreal period. The upper horizon is distinguished by a sharp decrease in foraminifers concentration (up to 5000-1000 specimens per 1 g), by occurrence *of Nonion labradoricum*, which hasn't been found at the lower layer, and by growth *of Ammonia beccarii*. Bottom part of this layer was found to contain silicoflagellates, characteristic of marine conditions (as of A.G. Matul – senior scientist from Institute of Oceanology RAS, personal communication). In the surface layer of the upper horizon predominance of agglutinating foraminifers takes place. This horizon was deposited in Subatlantic period (see core PSh 2978, Fig .5).

DISCUSSION

Distribution of foraminifers in the cores taken from the Kattegat, as described above, allows the reconstruction of oceanographic conditions in Holocene. *Bulimina marginata*, indicator of the North Atlantic water, was a predominant species at the depths exceeding 30 m during the Subboreal and Subatlantic. During the last 5000 years elphidiums – shallow-water species and those adapted to brackish water conditions - inhabited the depths exceeding 30 m during the Atlantic period in high concentrations (Lukashina 1983; Feyling-Hanssen 1972; Van Weering 1983). The conclusion can be made that the period between 8000 and 5000 years ago has been characterised by intensive outflow of surface water of low salinity from the Baltic Sea into the North Sea. Predominance of *Ammonia beccarii* allows to conclude that during Subboreal—early Atlantic surface water probably was more saline then later. *Nonion labradoricum* was found to occur in large amounts in the middle part of Subatlantic at the depths between 30-50 m, it evidences penetration of cold and saline water from the North into the Kattegat. *Hyalinea baltica* has been found to be predominant in Subboreal at the depths of about 50 m and probably evidences about more intensive penetration of saline North-Atlantic water into the Baltic Sea.

The amount and species variation of foraminifers in the Baltic Sea is much less than that in the Kattegat. Large concentrations of benthic species and maximum concentrations of planktonic species were found in the Gotland Basin - the last deep basin along the flow of saline North Sea water. Two thirds of that water mass is distributed in the Baltic Sea at the depths between 90 to 50 m, and only one third - in near-bottom layer (Stigebrandt 1995). In the first case the North-Atlantic water passes over sills and reach the Gotland Basin preserving largely its properties. This water creates favourable conditions for life activity of benthic foraminifers and the transport of shells of dead planktonic foraminifers followed by their burial. Occurrence of planktonic foraminifers is possible also to the north of Gotland Basin. Maximum concentrations of benthic species in the Baltic Sea are characteristic of coastal water of Gdańsk Basin, while minimum - of Bornholm Basin.

CONCLUSION

Foraminifers were found to be suitable, along with diatoms, spores and pollen, for biostratigraphic analysis of deposits in the Baltic Sea area. Foraminifers are sensitive indicator by which one may judge the intensity of penetration of salt water into the Baltic Sea. Occurrence of planktonic foraminifers in the sediment indicates an intensification of the North-Atlantic water inflow into the Baltic Sea, that for the last time took place during Atlantic-Subatlantic, when the Dutch Sills were deeper than today.

More variable fauna of benthic foraminifers in the Kattegat made it possible not only to determine the stratigraphy of bottom sediments, but also to reconstruct a paleooceanographic conditions and to judge about properties and dynamics in the exchange of surface and bottom water masses between the North Sea and Baltic Sea during the Holocene.

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Interaction between the drifting dunes of the Curonian Barrier Spit and the Curonian Lagoon

Ramūnas Povilanskas, Boris V. Chubarenko

Abstract

The paper analyses the interaction between the Curonian drifting dunes and the lagoon. The advance of the dunes into the Curonian Lagoon in 1955-1995 has created a wide diversity of coastal processes at the leeward foot of dunes. Patterns of these processes are analysed and their characterisation is given, based on results of the comparative cartometric analysis and field survey. Formation of sand debris, slumps, suffosion gullies and gyttja exposures is analysed, as well as development of new capes in the lagoon. Impact of dune advance on the development of the lagoon coastline and the littoral is discussed.

☐ *Dunes, barrier spit, lagoon, coastline, littoral, gyttja, suffosion.*

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INTRODUCTION

The drift of sand dunes, first, parabolic dunes, then starting from the 17-18th centuries barkhane dunes is the most important morphodynamic agent shaping the coastal zone in the western part of the Curonian Lagoon (Kuršių Marios) (Povilanskas & Dučinskas, in press). The aim of this paper is to analyse, what is the impact of the drifting dunes on the lagoon coastline in the second half of the 20th century.

The Curonian barrier spit (Kuršių Nerija) (Fig. 1) is the largest accumulative coastal macro-form in the Baltic Sea region (Gudelis 1995). The length of the Curonian Spit is 94 km (*sensu stricto*), the width varies from ca. 4 km to ca. 370 m only (Gudelis 1998). It originated as a whole during the late Litorina and post-Litorina time (Kabailienė 1997a).

The present landscape of the Curonian Spit is the result of the dramatic changes that took place during 17-19th centuries. During that period, the climax of which was after the Seven-year war (1757-1763), the ancient parabolic dunes which covered the whole surface of the Curonian Spit since Litorina period (Paul 1944-1951; Gudelis 1989-1990) were completely destroyed by drifting sand and replaced by barkhane dunes. The main reasons for such a shift are considered to be the deforestation of the original mixed forests which covered the parabolic dunes, overgrazing of the open sand plains and extensive forest fires (Mager 1938; Kunskas 1997). However, the natural factors, related to the climate fluctuations should not be ignored either. Archaeologists have observed intensive accumulations of marine sand at other coastal strips of the south-east Baltic in 17-18th centuries as well (Žulkus 1989/1990).

This phenomenon might be related to a more intensive erosion of the morainic Sambian coast during that period and the longshore transport and discharge of sediments to the north of it along the accumulative Curonian Spit and continental coast of Lithuania and Latvia. Such a coastal development of the south-east Baltic might be compatible with the sharp changes in coastal dynamics observed at other European regions during the same historic period (Davies & Williams 1991). As a result of these changes, the chain of drifting barkhane dunes has evolved and rapidly advanced eastwards across the spit under the prevailing westerly winds.

It is not clear, why parabolic dunes were replaced by the barkhane dunes on the Curonian Spit in 18-19th centuries. E.g., on the Skaw Spit, Denmark, parabolic dunes were still very active sand drift agents in the same period (Lyng Anthonsen 1998).

By comparing different maps of the Curonian Spit from the 18-19th centuries, some general conclusions about the barkhane dune movement and morphologic development of the lagoon coast in that period can be made (cf. Mardosienė & Kirlys 1988). In the map from 1733 we see that already then the central part of the Curonian Spit was woodless and covered by drifting barkhane dunes. As a consequence, the lagoon coast became indented, with a lot of new, 100-300 m long and 2-3 km wide, sandy capes appearing on the formerly graded coastline. In the 19th century this process expanded over the entire lagoon coastline. Though the main crest of the barkhane dune ridge was half-way between the sea and the lagoon coast, the single sand masses from the blow-outs in the dune-ridge which were promoted by the stronger windstreams blowing through the blow-out valleys advanced faster towards the lagoon. In this way, a series of lagoon capes developed in front of the blow-out valleys. As the local tradition said, some dunes "fell into the lagoon" (Mager 1938).

During the turn of the 18th and 19th centuries the drifting sand has posed an ever growing threat to local villages, Berlin-St. Petersburg mail route, and Klaipėda (Memel) seaport navigation channel (Gudelis 1998). Therefore the effective program of sand stabilisation by forest planting was carried out since the beginning of the 19th century. Today there are four strips of the drifting barkhane dune ridge left intact on the Curonian Spit. The total length of these is 30.6 km, 20.9 km being on the Russian side and 9.7 km on the Lithuanian side of the Curonian Spit (Povilanskas & Chubarenko 1998).

METHODOLOGY

Quite a few comparative cartometric surveys have been carried out on the Curonian Spit since the pioneering surveys of Berendt (1869) and Heß von Wichdorf (1919). Michaliukaitė (1967) measured the barkhane dune drift rate and the changes in the coastline of the northern and central part of the Curonian Spit over the period of 1910-1955. Her survey was aimed to assess the impact of the drifting dunes on the development of the lagoon coastline after the extensive afforestation program of the 19th century. Mardosienė (1988), Mardosienė and Vainauskas (1984), Gudelis and Kazakevičius (1988) examined the advance of several highest drifting dunes of the Curonian Spit over the period of 1910-1984. Kazakevičius (1979 1985 1988 1989-1990) investigated the changes in the marine and lagoon coastline of the entire Curonian Spit over the same period.

In our survey we have made a comparative cartometric analysis of the morphologic changes in all four wandering dune areas existing today and along the entire lagoon coastline of the Curonian Spit over the period of 1955-1995. For the comparative analysis we used the cartographic materials from different periods. These materials included the bathymetric chart of the northern part of the Curonian lagoon from 1943 in scale 1:25,000, the topographic map of the Curonian Spit from 1955 in scale 1:25,000, the topographic map from 1993 (Lithuanian part, scale 1:10,000), and from 1994 (Russian part, scale 1:25,000). Also, the coastal zone maps produced from the results of the geodetic surveys carried out along the lagoon coast of the Curonian Spit by the Institute of Geography in 1987-1997 were used as well.

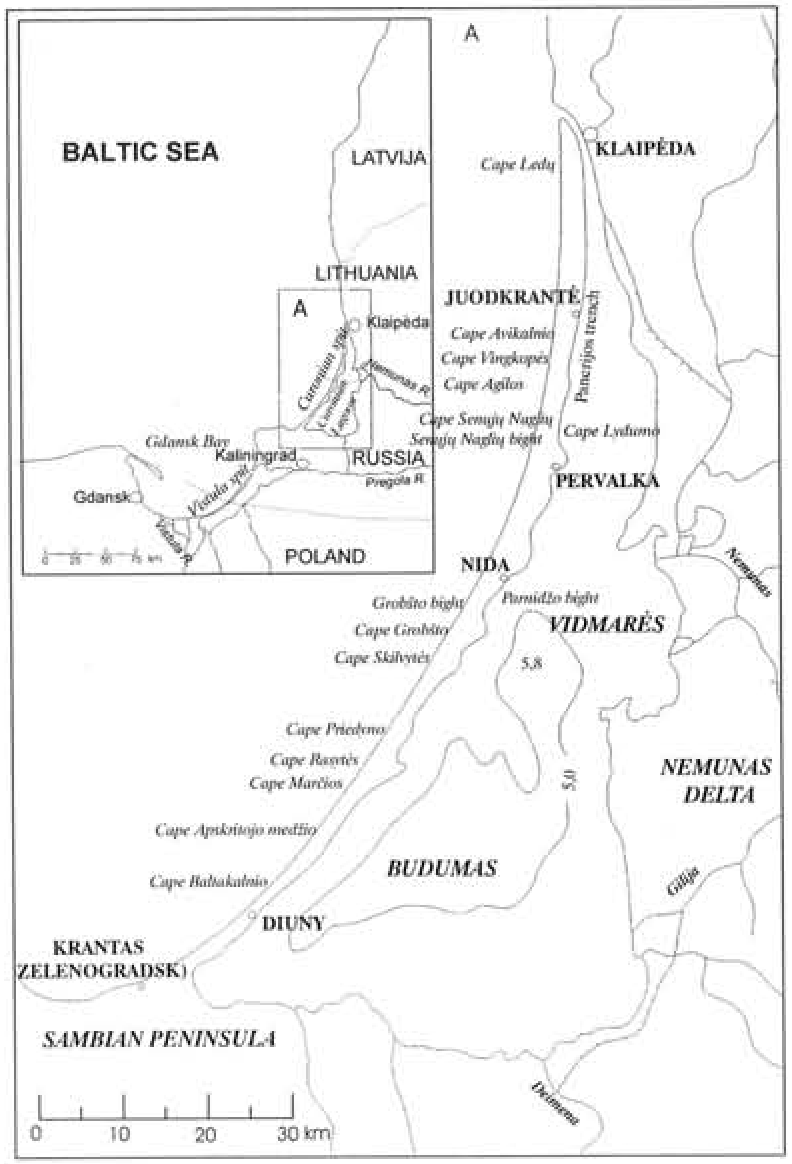

Fig. 1. The Curonian Lagoon and the South-East Baltic Region.

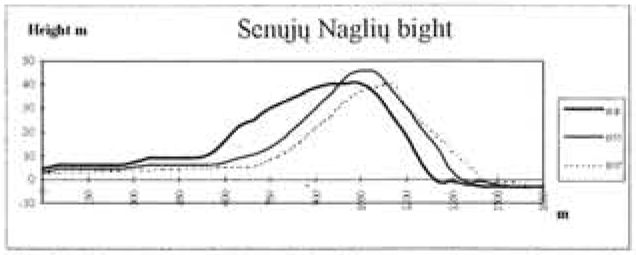

Fig. 2. Dynamics of migrating dunes on the northern strip of the Curonian Spit.

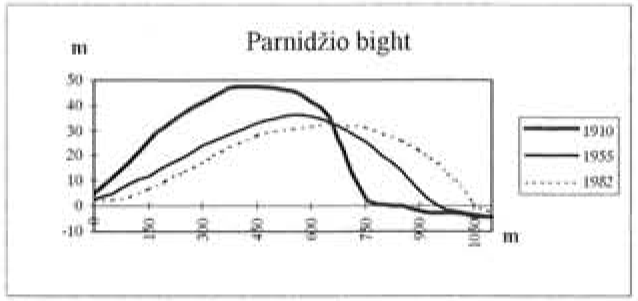

Fig. 3. Dynamics of migrating dunes on the central strip of the Curonian Spit.

Changes of the drifting dunes and coastal zone were assessed using 258 profiles with an average distance of 387.6 m between neighbouring profiles. The profiles covered the whole width of the dune ridge and the lagoon coastal zone of the Curonian Spit (down to 3 m depth). During the geodetic survey the position of the surface points was identified with a minimum accuracy of d(x) = ± 5 m. The accuracy of the depth and height measurements is d(y) = ± 0.2 m. The standard error of all metric and planimetric procedures is 0.4 mm, which means that the minimum accuracy of the cartometric survey using maps with a scale of 1:25,000 and larger is d(x) = ± 10 m. The estimation of the net dune volume changes between 1955 and 1994 for each cross-section was a three-step procedure.

First, we calculated the horizontal shifts of points with altitudes of 35 m, 30 m, 25 m, 20 m, 15 m, 10 m, 5 m (where available), 2.5 m, 0 m; or with depths of -0.5 m, -1 m, -1.5 m, -2 m, -2.5 m and 3 m. Then we estimated the aggregate area of profile changes between 1955 and 1994. Finally, the deposit volume change in the dunes and the foreshore was estimated by multiplying the average area of profile changes in the neighbouring cross-sections by the distance between these cross-sections.

The digitisation and computation procedures were carried out using software adapted at the Atlantic Department of the Shirshov Institute of Oceanography. The coastal processes resulting from the interaction between the drifting dunes and the lagoon were studied and mapped in site during field surveys carried out during various seasons in 1993-1998.

RESULTS

The results of our survey confirm the assumption that without a steady supply of sand from the seashore the annual migration rate of the dune ridge crest has slowed down from 11-13 m per year in 1837-1861, to 2-3 m per year in 1955-1997. The migration rate of the dune crest in the southernmost (Diuny—Marčios) strip of the drifting dunes was 3-4 m per year while in the northernmost (Pervalkos-Avikalnio) strip it was only 1-2 m per year (Figs. 2-5).

While the drifting dunes were advancing, the length of the contact interface between the dunes and the lagoon was rapidly increasing. In 19th century there was a palve* plain between the drifting dunes and the lagoon in many places. However, in the second half of 20th century drifting dunes were in the direct contact with the Curonian Lagoon at over 29 km of the 30.6 km total length of the dune ridge (Povilanskas & Chubarenko 1998). The interaction between the migrating dunes and the lagoon creates a wide diversity of coastal processes at the leeward foot of the Curonian dunes: formation of slumps and sand debris, suffosion gullies, and gyttja exposures.

The favourable conditions for the slump and debris formation occur all year round due to the steady supply of sand which rolls over the dune crest from the windward slope of the drifting dune to the leeward slope being driven by westerly winds. At the same time, the waves and drifting ice on the Curonian Lagoon constantly erode the dune foot. Both processes increase the steepness of the leeward part of the dune profile and promote slump and debris formation (Fig. 6).

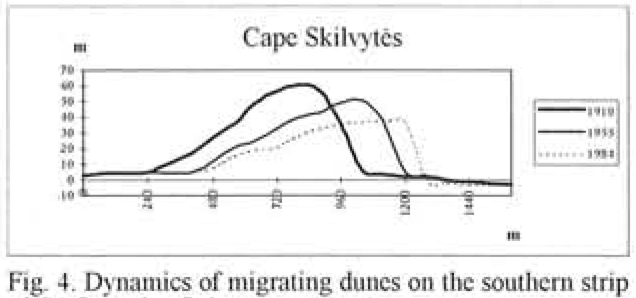

Fig. 4. Dynamics of migrating dunes on the southern strip of the Curonian Spit.

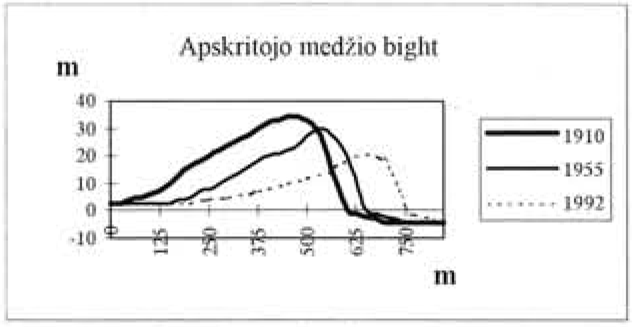

Fig. 5. Dynamics of migrating dunes on the southernmost strip of the Curonian Spit.

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* Here and further in the text the term "palve" means a plain on the barrier spits formed by the sand drifted from the beach or migrating dunes, overgrown with grass, bushes, forest (cf. Gudelis 1993).

Fig. 6. Formation of sand debris on the lagoon coast of the Curonian Spit. Cape Senųjų Naglių. Photo by R. Povilanskas, March 1998.

There exists a very distinct geographic variation of the morphodynamic processes. While debris formation occurs along the entire length of the contact zone between the drifting dunes and the lagoon, slumps occur only on the northernmost (Pervalka-Avikalnis) strip of the drifting dunes. Both slopes of these grey dunes are covered by grass vegetation, which makes deflation of sand and thus development of loose sand debris at the dune foot more difficult. The formation of slumps is the prevailing morphodynamic process on the leeward dune slopes there. The slumps form mainly during spring due to large variations in humidity and temperature on the dune surface (Povilanskas 1998). Unfortunately, no instrumental measurements of the slump and debris development have been ever taken on the Curonian Spit.

Development of suffosion gullies on the lagoon coast of the Curonian Spit is also directly related to the dune advance. The ground water discharges at the leeward foot of the drifting dune and carries out sand particles to the coast. This process makes the leeward dune slope steeper, which promotes the creation of suffosion gullies. Suffosion is spread along the entire northern strip of the lagoon coast, however all traces of suffosion are rapidly erased by the dune advance combined with the impact from drifting ice and waves. The only fully developed suffosion gully on the lagoon coast of the Curonian Spit is in front of the island Kiaulės Nugara. The continuity of suffosion processes at this site is witnessed by the steepening slopes and permanence of the shape of the gully since 1913 (Fig. 7).

Another geomorphologic process, which is directly triggered by the dune advance, is the development of the lagoon gyttja exposures. Gyttja is composed of the fine organic material: fine detritus - about 50%, pelitic (clayey) particles - 30%, sometimes up to 60%, and carbonates - 15-20% or less (Kabailienė 1997b). Due to its plasticity, gyttja is pressed out of the underlying layer by the huge mass of the advancing dune. However, the reason, why these exposures occur only on the central and northern part of the Curonian Spit coast is unclear.

According to the results of our field survey carried out in 1996-1998, there were three such exposures, existing on the lagoon coast: at the Vingopės cape (Fig. 8), at the Parnidžio bight and in the Grobšto bight (Fig. 9 and Fig. 10). The stability of gyttja exposures depends on the activity of coastal agents at these strips. Thus, the Parnidžio exposure is declared a natural heritage site, which presumes its long-term existence. Meanwhile, the gyttja exposure to the north of the Agilos cape, which was found in 1985 by Kazakevičius and Klimašauskas (Kabailienė 1997b), was already eroded away by waves and drifting ice in 1998.

The dune advance is the prevailing agent of long-term changes of the lagoon coastline of the Curonian Spit. This prevalence is still very apparent, in spite of slowing down of the dune drift rate. At the foot of the drifting dune the average annual advance of the lagoon coastline eastwards is 4 m, which is more than 2 times faster than at other accumulative strips of the Curonian Lagoon coastline. The coastline changes

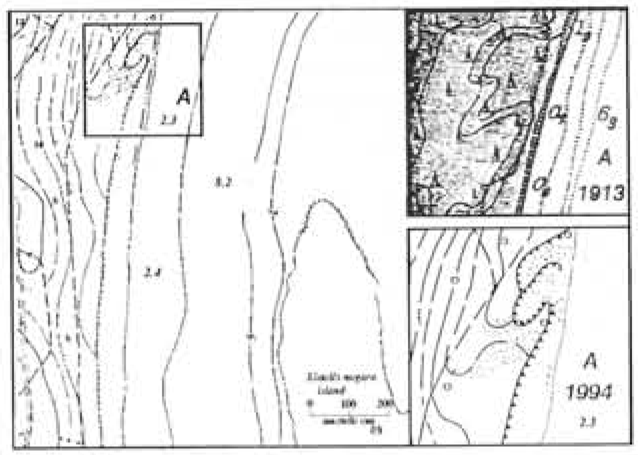

Fig. 7. Development of suffosion gully. Cape Ledų. 1913-1994. (By comparing the situation of 1913 with the situation of 1994 we can see how the slopes of the gully have developed into the steep eroded scarps forming the valley of a short brooklet).

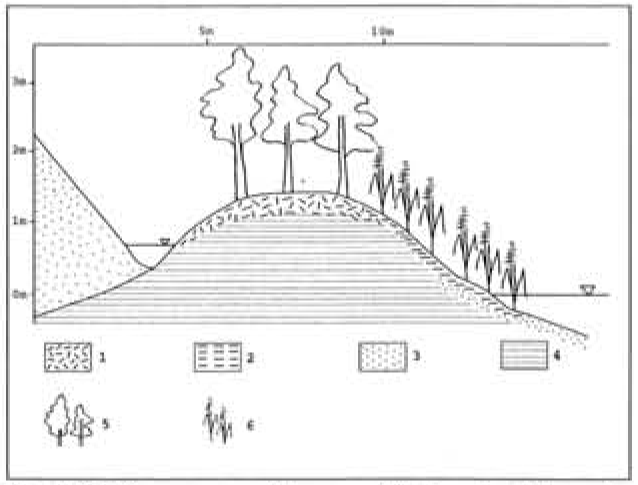

Fig. 8. Gyttja exposure of the cape Vingkopės with vegetation belts. 1 Soil; 2-Ooze; 3-Sand; 4-Gyttja; 5-Black alder; 6-Reed.

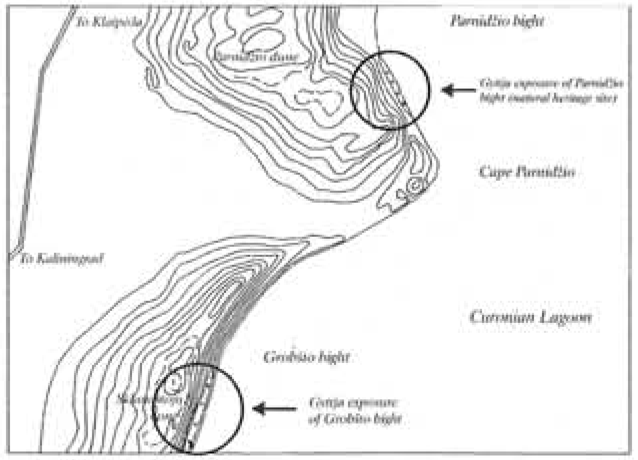

Fig. 9. Gyttja exposures to the south from Nida.

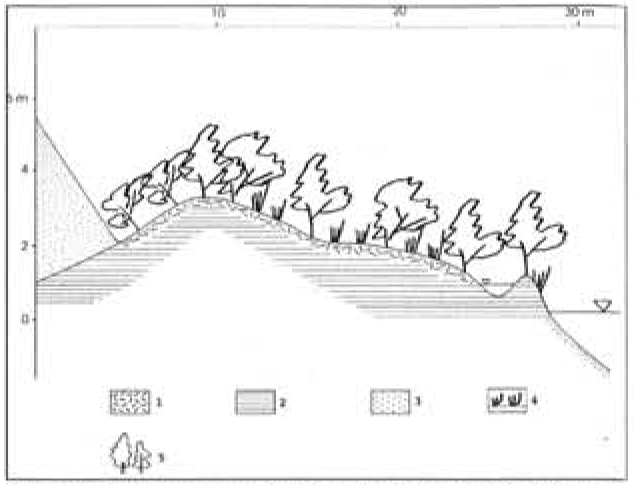

Fig. 10. Gyttja exposure in Grobšto bight. 1-Soil; 2-Gyttja; 3-Sand; 4-Forbs; 5-Shrub.

depend on the ratio between the amount of sand, which is blown out from the windward slope of the dune and the amount of sand reaching the lagoon on the leeward side. In the white dune strip between Diuny and cape Marčios this ratio is 81.7%, while in the grey dune area between Pervalka and cape Avikalnio this ratio is only 34.2% (Table 1).

The advance of the dunes into the Curonian Lagoon in 1955-1995 has also led to the formation of new capes in the lagoon in front of the blow-out valleys of the dune ridge as in former periods. These newly developed capes are cape Vingkopės and cape Senųjų Naglių in the northernmost coastal dune strip and cape Lotmiškio in the southernmost strip.

Waves and currents spread the sand from dunes over the foreshore. The prevailing sediment transport direction in the Curonian Lagoon is northwards under the impact of strong southern and south-west winds during the autumn and winter storm seasons (Kirlys & Stauskaitė 1982). In the long term the littoral of the lagoon in front of the dunes becomes steeper due to faster advance of dunes compared to the distribution of sediments by waves and currents. In the coastal areas immediately north of the drifting dune strips the littoral becomes flatter and more shallow due to the deposition of sand sediments brought by the longshore drift from dune areas.

Table 1. Net sediment input from different strips of migrating dunes to the lagoon shore-zone of the Curonian Spit from 1955-1994

Migrating dune strip	Dune strip length* m	V_A km³	V_B km³	V_C km³	V_D km³	V_E km³
Agilos – Avikalnio	2730	3.5±0.2	2.4±0.2	1.1±0.2	0.2±0.1	0.9±0.1
Lydumo – Agilos	4410	7.5±0.4	4.8±0.4	2.7±0.3	0.8±0.2	1.9±0.2
Parnidžio – Nidos	638	1.7±0.1	0.8±0.1	0.9±0.1	0.6±0.1	0.3±0.1
Grobšto bight	788	2.1±0.09	1.8±0.04	0.3±0.04	0.1±0.1	0.2±0.1
Cape Grobšto	1880	1.2±0.1	0.1±0.05	1.1±0.1	0.1±0.05	1.0±0.1
Priedyno – Skilvytės	5888	14.1±0.4	7.5±0.3	6.6±0.3	4.1±0.3	2.5±0.2
Cape Apvaliojo Medžio - Cape Marčios	8555	39.8±0.6	7.1±0.4	32.7±0.6	14.2±0.4	18.5±0.5
Baltakalnių - Cape Apvaliojo Medžio	4525	8.9±0.4	1.8±0.2	7.1±0.4	2.4±0.2	4.7±0.3
TOTAL:	29414	78.8±1.0	26.3±0.6	52.5±0.8	22.5±0.7	30.0±0.7

V_A - volume of blown out sand in the dune strip; V_B - volume of accumulated aeolian sediments before the shoreline of 1955; V_C - net volume of aeolian sediments deposited in the shore-zone; V_D - volume of aeolian sediments deposited between the 1955 and 1994 shoreline; V_E - volume of aeolian sediments deposited in the littoral.

The distribution of sediments from the drifting dunes along the lagoon coast of the Curonian Spit forms the distinct system of littoral cells. Whether these cells are relatively permanent or not depends upon the long-term permanence of the sand input from the drifting dunes.

DISCUSSION

According to Mader (1995), the Curonian Lagoon creates a natural boundary which prevents the drifting dunes from further advance eastwards due to coastal erosion and water infiltration into the lower part of the dune body. Such assumption partially corresponds to the statement of Kunskas (1997) concerning the early development stages of the Curonian Spit. However, neither the cartometric analysis of the dune migration and the lagoon coast development in 19th century, nor our cartometric survey results confirm the assumption of Mader. The prevailing morphodynamic trends on the Curonian Spit after the afforestation are the flattening of the dune profile and the steady advance of its leeward foot into the lagoon.

The interest in the interaction between the drifting dunes and the lagoon is not only theoretical. Whether or not such interaction is taken into account might have tremendous practical effect for the effective development and implementation of the truly integrated shoreline management program for the Curonian Spit.

ACKNOWLEDGEMENTS

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SANTRAUKA

Kuršių nerijos pustomų kopų sąveika su Kuršių mariomis

Kuršių nerijos pustomų kopų slinkimas aktyviai transformuoja marių krantą. 1955-1995 m. laikotarpiu iš 30.6 km bendro Kuršių nerijos slenkančiųjų kopų gūbrio ilgio net 29.4 km ilgyje kopos buvo betarpiškame sąlytyje su Kuršių mariomis. Ties pustomomis kopomis stebimas sparčiausias kranto linijos persistūmimas į marias (vidutiniškai 2,2 karto spartesnis, negu priekrantinės pernašos nešmenų suklostymo vietose). Šio proceso sparta priklauso nuo to,- kokia dalis priešvėjiniame pustomų kopų šlaite išpustyto smėlio patenka į marias pavėjiniame šlaite. Didžiausias priešvėjiniame kopų šlaite išpustytas smėlio kiekis patenka į marių kranto zoną ties Budumo krantais esančiame Baltakalnių-Marčios rago pustomų kopų ruože (81,7%) o ties Vidmarių ir Panerijos duburio kranto zona esančiuose pustomų kopų ruožuose šis santykis žymiai mažesnis (atitinkamai 49,7% ir 34,2%). 19 a. viduryje, t.y., intensyviausio Kuršių nerijos pustomų kopų slinkimo laikotarpiu nustatytas dėsningumas, kad kranto linija sparčiausiai stūmėsi į marias raguose, susidariusiuose ties defliacinėmis pralaužomis kopagūbryje, tinka ir dabartiniam kopų sąveikos su mariomis etapui. Ties defliacinėmis pralaužomis formuojasi nauji Kuršių nerijos ragai (Senųjų Naglių, Vingkopės, Lotmiškio).

Svarbiausias pustomų kopų poveikis kranto zonos dinamikai pasireiškia atabrado morfodinaminės tendencijos pokyčiais. Patenkantis į Kuršių marias pustomų kopų smėlis priekrantės srovių poveikyje pasklinda platesniame atabrado ruože. Todėl ties pustomomis kopomis sutinkamas sparčiai gilejantis atabradas, nes spartaus kranto linijos stūmimosi į marias nespėja kompensuoti priekrantės seklėjimas. Tiems priekrantės ruožams, kurie yra pustomų kopų kaimynystėje ir intensyvios priekrantės nešmenų pernašos poveikio zonoje, būdingas lėkštas atabradas.

Dėl Kuršių nerijos slenkančiųjų kopų sąveikos su Kuršių mariomis ir po eolinėmis nuogulomis slūgsančiu substratu, marių pakrantėje vyksta aktyvūs šlaitiniai procesai: gravitaciniai (nuogriuvos, nuobiros, nuoslankos), sufozija ir marių mergelio atodangų susidarymas. Nuogriuvos ir nuobiros būdingos visiems Kuršių nerijos slenkančiųjų kopų ruožams, tuo tarpu nuoslankos daugiausia susidaro šiauriniame Kuršių nerijos slenkančiųjų kopų ruože, kur kopų pavėjinis šlaitas apaugęs žoline augalija, stabdančia nuogriuvų ir nuobirų formavimąsi. Sufozija bei marių mergelio atodangų formavimasis taip pat vyksta tik centrinėje ir šiaurinėje Kuršių nerijos marių pakrantėje.

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Holocene shoreline displacement and palaeogeography of the Kõpu Peninsula, Hiiumaa Island, Estonia

Leili Saarse, Atko Heinsalu, Juha Karhu, Jüri Vassiljev, Siim Veski

Abstract

A sediment profile from the Kõivasoo Bog, Hiiumaa Island, Estonia was examined for the lithology, pollen, diatoms and isotopic composition of carbon and oxygen in gastropod shells to record relative sea level changes during the Holocene. The Kõivasoo basin was first isolated from the Baltic Sea basin in the Late Boreal, about 8300 BP, forming a small coastal lake. It reconnected to the Baltic Sea basin about 8000 BP at the beginning of the Litorina Sea stage. The Kõivasoo basin finally isolated from the sea about 7800 BP and formed a shallow alkaline lake. At the beginning of the Subboreal the lake was overgrown. A new shore displacement curve was reconstructed for the Kõpu Peninsula, and compared with that for Saaremaa Island and West Estonia. Culmination of the Litorina Sea transgression was diachronous depending on the character of land uplift.

☐ *Pollen, diatoms, ^{14}C dates, isotopic composition, shore displacement curve, Kõpu Peninsula, Hiiumaa Island, Estonia.*

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INTRODUCTION

In the history of the Baltic Sea four main stages have been distinguished (the Baltic Ice Lake, the Yoldia Sea, the Ancylus Lake and the Litorina Sea) governed by the recession of the last ice sheet and consequent land uplift, and connections with the ocean. The coastal formations of the Baltic Ice Lake (12,600–10,300 BP) have been identified in two main levels, the B I and the B III (Donner 1995). Owing to the retreat of ice in south-central Sweden and opening up of the connection with the Atlantic Ocean, the Baltic Ice Lake level dropped about 25–28 m and the Yoldia Sea stage began (Svensson 1989; Björck 1995; Donner 1995). The Yoldia Sea (10,300–9500 BP) has been divided into three sub-stages, with brackish-water conditions in the middle (Svensson 1989; Wastegård et al. 1995; Heinsalu 2000). Due to land uplift the straits closed and the Ancylus Lake (9500–8000 BP) was formed, with transgression that culminated between 9200–9000 BP (Björck 1987, 1995). Establishment of a new outlet and reaching of the equilibrium between the Baltic Sea basin and the ocean level marks the end of the Ancylus Lake. A relatively rapid eustatic sea level rise and decreased land uplift caused the ingression of marine waters into the Baltic Sea basin and the onset of the Litorina Sea stage.

Besides these four main stages, the Mastogloia Sea has been recognised as a transitional diatom-stratigraphic unit, preceded by the freshwater Ancylus Lake and succeeded by the Litorina Sea (Kessel & Pork 1974; Hyvärinen et al. 1988; Åker et al. 1988). The Mastogloia Sea strata are distinguished by sparse presence of weakly brackish-water diatoms *Rhoicosphenia curvata, Nitzschia tryblionella, Campylodiscus echeneis* and *Mastogloia* spp. among the prevailing freshwater taxa, particularly in profiles of the littoral areas (Hyvärinen 1984), while in the offshore sequences such a transitional unit is commonly absent (Ignatius et al. 1981). The slightly brackish-water diatoms appeared around 8500 BP in sequences of southern Sweden (Berglund 1964, 1971), around 8000 BP in Finland (Alhonen 1971; Eronen 1974; Hyvärinen 1982) and about 7800–8000 BP in western Estonia (Kessel & Pork 1974). They mark a gradual penetration of salt water into the Baltic Sea basin, after the opening up of the Danish Straits due to the eustatic rise of the ocean level. Due to insufficient biostratigraphic records, the Mastogloia Sea sediments in Estonia (e.g. Lumiste on Muhu Island) have been related to the Litorina Sea (Kessel & Pork 1974).

The beginning of the Litorina Sea stage in a strict sense is usually placed at between 7500 and 7000 BP, a time when a more pronounced increase in salinity can be traced in the Baltic Sea sediments (Hyvärinen 1980; Eronen 1983). In the off-shore sediments this event is marked by a well-defined lithostratigraphic boundary (Ignatius et al. 1981). According to mollusc faunas the maximum salinity of the Litorina Sea ranged between 15–20 ‰ (Hyvärinen et al. 1988). In Estonia and Finland only one major transgression of the Litorina Sea has been distinguished, although this transgression culminated at different times between 7000 and 6000 BP, depending on the local land uplift (Eronen 1974, Hyvärinen 1980). The salinity of the Baltic Sea basin gradually decreased since 4000 BP during the following Limnea Sea stage (Hyvärinen et al. 1988).

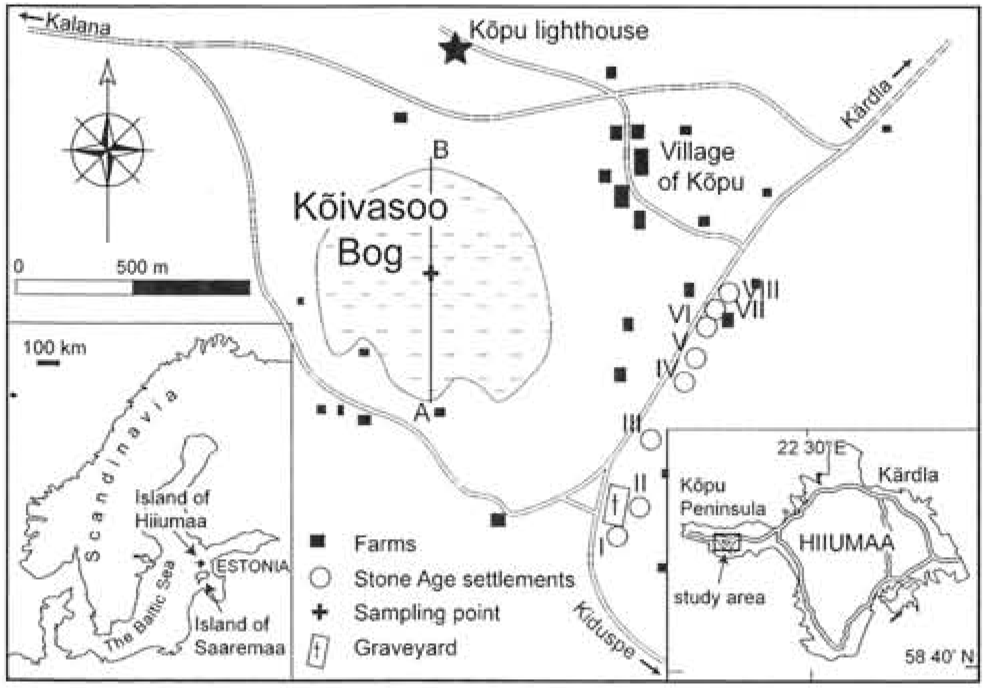

Fig. 1. Location of the study area and Kõivasoo Bog.

The main objective of the present paper is to revise the evolution of the Kõpu Peninsula on the basis of new pollen, diatom and isotopic data, and radiocarbon dates and to highlight the environmental conditions at the beginning of the Litorina Sea stage. New radiocarbon dated shore displacement diagram for the Kõpu Peninsula was reconstructed and compared with those of Saaremaa Island and West Estonia. A regional synthesis of the sea level changes at the beginning of the Holocene in the region is presented. The pollen record and radiocarbon dates of the Kõivasoo Bog sediments have been recently published by Königsson et al. (1998).

THE STUDY AREA

The Kõpu Peninsula on the Hiiumaa Island with its broken topography, wide spectrum of scarps and rather rapid land uplift is one of the best regions in Estonia for mapping of ancient coastal formations (Fig. 1). However, the possibilities to date these formations are rather restricted due to the limited extent of organic deposits. The first reports on the Ancylus Lake and the Litorina Sea deposits and shorelines of the Kõpu Peninsula were published seventy years ago (Ramsay 1929), and numerous studies have followed since that time (Kents 1939; Kessel & Raukas 1967, 1979; Ratas 1976; Haila & Raukas 1992; Lõugas et al. 1995; Raukas 1994, 1995; Raukas & Ratas 1995; Königsson et al. 1998; Hang & Kokovkin 1999). The shortage of biostratigraphic proxies and reliable radiocarbon dates has often led to misinterpretation of ancient coastal formations and their chronology. The highest shoreline on the Kõpu Peninsula is located at an elevation of 60–61 m (Kessel & Raukas 1967) and probably belongs to the Yoldia Sea stage. Morphologically, the well-developed scarps and beach ridges at an elevation of 44–45 m have been correlated with the Ancylus Lake (Kents 1939). On the basis of measured terraces, scarps and beach ridges, Kents (1939) distinguished five different levels in the development of the Litorina Sea, later supported by Kessel's investigations (Kessel & Raukas 1967, 1979). The highest Litorina Sea beach formations are found at 27.6 m (Kents 1939) or 26 m (Kessel & Raukas 1967).

Kõivasoo is a small raised bog between two series of scarps at 27.6 and 23.8 m a.s.l. with a narrow threshold in the south at an elevation of 26.5 m. The present overflow threshold lies at ca 25 m a.s.l., and it was deepened in connection with the drainage of the bog. The Kõivasoo Bog was selected as key site for investigations because it lies near the Litorina Sea limit and holds limnic, lagoonal and terrestrial deposits of Boreal to Subatlantic age.

MATERIAL AND METHODS

The morphology and sediment stratigraphy of the Kõivasoo Bog was examined along two transects using a Russian peat sampler. A total thickness of 351 cm of sediment was continuously sampled. Samples for diatom and isotope analyses were taken from the lower part of the main core (Fig. 1). Diatom samples were treated with 30% H_2O_2 according to Battarbee (1986). Diatom taxonomy follows Hustedt (1930), Mölder and Tynni (1967–1973), Tynni (1975–1980), Krammer and Lange-Bertalot (1986–1991). The organic and total carbonate content was estimated by loss-on-ignition at 550° C and at 825° C respectively.

Isotope ratios of carbon and oxygen in mollusc shells were determined at the Laboratory for Isotope Geology of the Geological Survey of Finland. Shells and shell fragments were separated from the sediment by sieving and hand picking. From each sample one to three gastropod shells, weighing 1–3 mg in total, were selected for analysis. Powdered shells were treated with 30% H_2O_2 overnight in order to remove organic material (Boiseau & Juillet-Leclerc 1997) and then reacted with >100% H_3PO_4 for more than 16 hours. The product CO_2 was purified cryogenically and analysed for its carbon and oxygen isotope composition using a Finnigan MAT 251 mass spectrometer. The $\delta^{13}C$ and $\delta^{18}O$ values are reproducible to better than ±0.1‰.

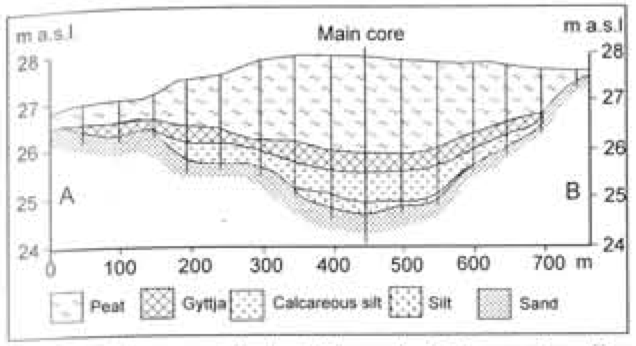

Fig. 2. Sediment profile A—B from the Kõivasoo Bog. For location see Fig. 1.

Table 1. Stratigraphy of the Kõivasoo Bog profile

Depth, cm	Sediment description
0–197	*Sphagnum* peat with *Eriophorum* and wood fragments
197–240	Gyttja, upper part contains abundant plant detritus
240–318	Calcareous silt with plant fragments and mollusc shells. The upper contact is sharp and with thin sand lamina indicative of aeolian activities and/or water-level changes
318–325	Silt with mollusc shells
325–351	Sand, fine grained, with mollusc shell fragments

Table. 2. Results of radiocarbon dates from the Kõivasoo Bog

Depth, cm	Adjusted depth, cm	^{14}C age, BP	Laboratory No.	Material
Investigated core				
36		2775 ± 65	Ua-12 073	Wood
140		4615 ± 70	Ua-12 072	Wood
245.5		6825 ± 85	Ua-12 071	Plant fragments
289.5		8495 ± 85	Ua-12 070	Plant fragments
Sarv, 1981				
0–10	0–10	1060 ± 60	TA-5223	Bulk organic
50–60	65–75	2440 ± 60	TA-524	Bulk organic
100–110	110–120	4360 ± 60	TA-525	Bulk organic
180–190	185–195	4860 ± 70	TA-526	Bulk organic
200–210	215–225	6580 ± 60	TA-527	Bulk organic
220–230	245–255	7440 ± 60	TA-528	Carbonate fraction
230–240	260–270	7850 ± 70	TA-529	Carbonate fraction
270–280	315–325	8190 ± 90	TA-530	Carbonate fraction

RESULTS

Lithostratigraphy and chronology

Five main lithostratigraphic units (sand, silt, calcareous silt, gyttja and peat) have been distinguished and examined in the sediment of the Kõivasoo Bog (Fig. 2). The lithostratigraphy of the studied profile is as follows:

The content of matter carbon in the lowermost sand and silt units is less than 1% and that of carbonate is around 8–10%. In the calcareous silt the organic fraction forms 5–7%, carbonate fraction increases rapidly to about 60–70%. The most pronounced change in the sediment lithology occurs at the depth of 240 cm, where the carbonate fraction decreases to less than 1%, the terrigenous fraction shortly increases to 60% and the organic fraction starts to rise.

Sarv (1981) and Sarv et al. (1982) have published conventional radiocarbon dates on the total organic and carbonate fraction, and AMS dates from wood and plant fragments have been reported by Königsson et al. (1998). All ages are given as uncalibrated and uncorrected radiocarbon years before present (Table 2). The AMS dates are preferred to conventional ones. However, the date 8495±85 from a plant fragment washed out from the calcareous silt at 289.5 cm is problematic and does not match with the pollen stratigraphy. The conventional radiocarbon dates of calcareous silt are probably too old due to the hard-water effect.

POLLEN ANALYSIS

A 351-cm profile from the central part of the Kõivasoo Bog was divided into five pollen assemblage zones (Fig. 3; Königsson et al. 1998). The lowermost part of the profile shows a high *Pinus* pollen frequency with low *Ulmus* and sporadic *Tilia*. This is not in harmony with other Early Atlantic pollen spectra in Estonia, according to which *Tilia* reached into the area at the Boreal/Atlantic transition and *Ulmus* having its maximum occurrence in the Early Atlantic. Such peculiar spectra with over-represented *Pinus* pollen are common to transgression/regression areas (Thomson 1929). The lowermost silt unit contains a high number of *Pediastrum* spores and redeposited *Picea* pollen. The uppermost calcareous unit is rich in *Botryococcus* colonies, and the values of *Pediastrum* are low. Two radiocarbon dates from this unit confirm its deposition during the Early Atlantic. Typical Atlantic spectra occur in gyttja, which started to accumulate at about 6825±85 BP. About 2000 years later, the coastal lake was filled in with peat and abundant pollen of dwarf shrubs and *Calluna* is characteristic of the upper part of the pollen profile (Fig. 3).

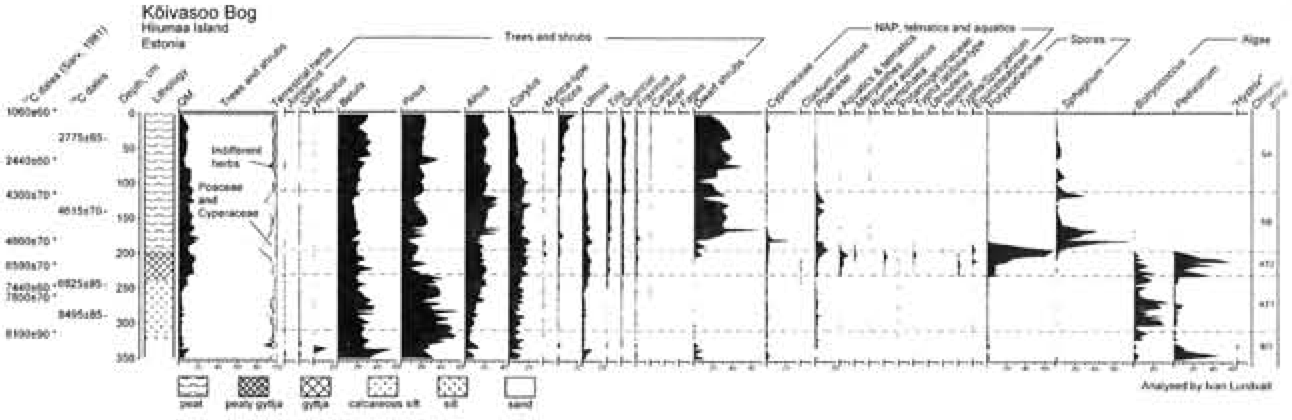

Fig. 3. Simplified pollen diagram from the Kõivasoo Bog.

DIATOM ANALYSIS

The sediment section of the Kõivasoo Bog was analysed for diatoms from 230 cm downwards. The diatom diagram displays freshwater floras throughout the analysed section, with pronounced changes at 325 and 265 cm. The diagram is subdivided into three diatom assemblage zones (Fig. 4).

DZ 1, 350–325 cm. The zone is characterised by a dominance of periphytic diatoms *Amphora pediculus* (Kützing) Grunow, *Opephora martyi* Héribaud, *Achnanthes clevei* Grunow and *Epithemia frickei* Krammer. *Amphora pediculus*, *Opephora martyi*, *Achnanthes clevei*, *Cocconeis thumensis* Mayer are epipsammic i.e. diatoms attached to sand and silt grains. They mostly inhabit littoral areas of eutrophic alkaline lakes in Estonia. *Epithemia frickei* is epiphytic. Planktonic and large-lake taxa are absent.

DZ 2, 325–265 cm. This zone is characterised by a new diatom assemblage. The dominating species of the previous zone disappear or decline at the zone border. Planktonic, large-lake *Aulacoseira islandica* (O. Müller) Simonsen and *Stephanodiscus neoastraea* Håkansson & Kling characterise the zone, even though their abundance is only moderate. In the upper part of the zone their amount decreases. *Mastogloia elliptica* (Agardh) Cleve, *M. smithii* Thwaites and *M. smithii* var. *lacustris* Grunow, *Cymbella leptoceros* (Ehrenberg) Kützing and *Gomphonema angustum* Agardh are common.

DZ 3, 265–230 cm. Large-lake diatoms have disappeared. The share of *Mastogloia smithii* and *M. elliptica* decreases, except at the depth of 240–235 cm. Other subdominant species of the previous zone either disappear or their values decrease and they are replaced by a small-lake flora with periphytic diatoms *Cymbella ehrenbergii* Kützing, *C. laevis* Naegeli, *Navicula radiosa* Kützing and planktonic *Cyclotella comta* Kützing and *C. krammeri* Håkansson. The last sample consists only of corroded valves of *Cymbella ehrenbergii*. Diatoms are not preserved above 230 cm.

ISOTOPIC COMPOSITION

The dynamic picture of diatom flora is supplemented by oxygen and carbon isotope records obtained from gastropod shells (Table 3). The isotope ratios of two *Cerastoderma glaucum* samples from the Litorina Sea deposits (Punning et al. 1988) are given for comparison. The $\delta^{18}O$ values vary from −6.0 to −3.4‰ and $\delta^{13}C$ displays values between 1.7–7.0‰ having an opposite trend of change. Oxygen isotope values are low in the bottommost part of the profile corresponding to the transition of the Boreal to the Atlantic, followed by an increase up to −3.4‰ at 250 cm. The $\delta^{13}C$ values show a distinct minimum in the middle of the calcareous silt. A rapid decrease in $\delta^{13}C$ by about 4‰ at the depth of 320–300 cm marks the start of the transgression.

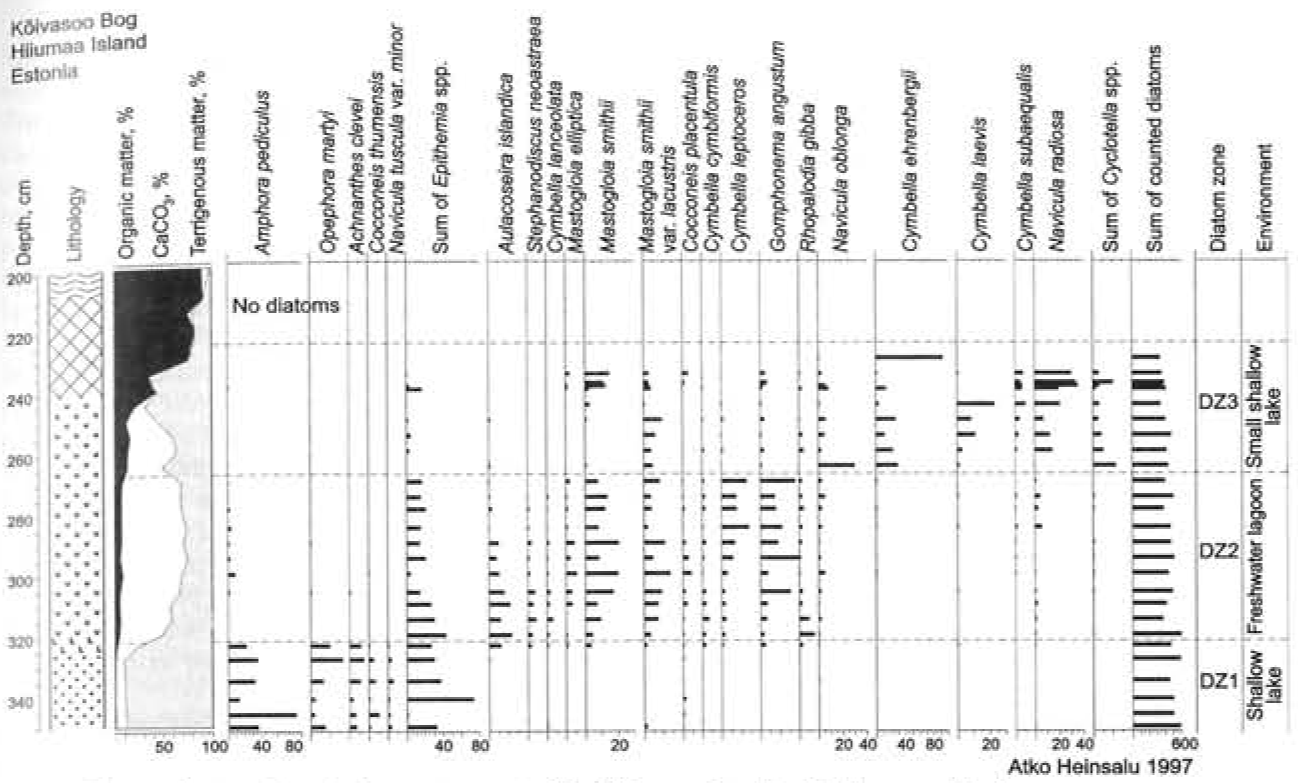

Fig. 4. Diatom diagram from the lowermost part of the Kõivasoo Bog. For lithology see Fig. 3.

Table 3. $\delta^{18}O$ and $\delta^{13}C$ values of mollusc shells from Hiiumaa Island

Site	Mollusc species	Depth, cm	Environment	$d^{18}O$,‰	$d^{13}C$,‰
Kõivasoo	*Lymnaea* spp.?	243	Closed lake	−4.50	6.99
Kõivasoo	*Lymnaea* spp.?	250	Closed lake	−3.39	4.99
Kõivasoo	*Lymnaea* spp.?	270–280	Lagoon	−5.05	1.70
Kõivasoo	*Lymnaea* spp.?	280–290	Lagoon	−5.96	2.50
Kõivasoo	*Lymnaea* spp.?	290–300	Lagoon	−5.02	1.21
Kõivasoo	*Lymnaea* spp.?	320–325	Closed lake	−5.01	5.32
Vanajõe[1]	Cerastoderma glaucum		Litorina Sea	−5.0	1.3
Suurepsi[1]	Cerastoderma glaucum		Litorina Sea	−5.5	1.9

[1] Values according to Punning et al. 1988

The mollusc shells collected from 315–320 cm and 250–243 cm of the core have $\delta^{13}C$ values varying from 5.0 to 7.0‰. These values are distinctively higher than those recorded for shells from deposits representing the Ancylus Lake, the Litorina Sea or the Limnea Sea stages of the Baltic Sea by Punning et al. (1988). Their study included 46 *Cerastoderma glaucum* and *Lymnaea balthica* shells from various stages of the Baltic Sea with $\delta^{13}C$ values of carbonate ranging from −6.8 to +2.3‰. These data suggest that the gastropods with $\delta^{13}C$-enriched carbonate shells represent a distinct environment, possibly not open to the Baltic Sea basin. In a restricted, closed lake environment the isotopic composition of dissolved inorganic carbon may evolve to higher $\delta^{13}C$ values due to high productivity (McKenzie 1985; Rozanski et al. 1988). Because molluscs are considered to secrete shell in near isotopic equilibrium with the environmental water (Fritz & Poplawski 1974), a shift in the $\delta^{13}C$ values of dissolved inorganic carbon would be reflected as a similar shift in the isotope ratios of shells.

DISCUSSION

Fig. 5 summarises the development of the Kõpu Peninsula between the transgressions of the Ancylus Lake and the Litorina Sea. During the culmination of the Ancylus Lake transgression at about 9200 BP Kõpu Peninsula was a small elongated island (Fig. 5a) which increased in size continuously due to land uplift. At about 8400 BP, the Kõivasoo basin emerged and probably formed a small lagoon where sand deposited (Fig. 5c). About 100 years later, it was isolated from the

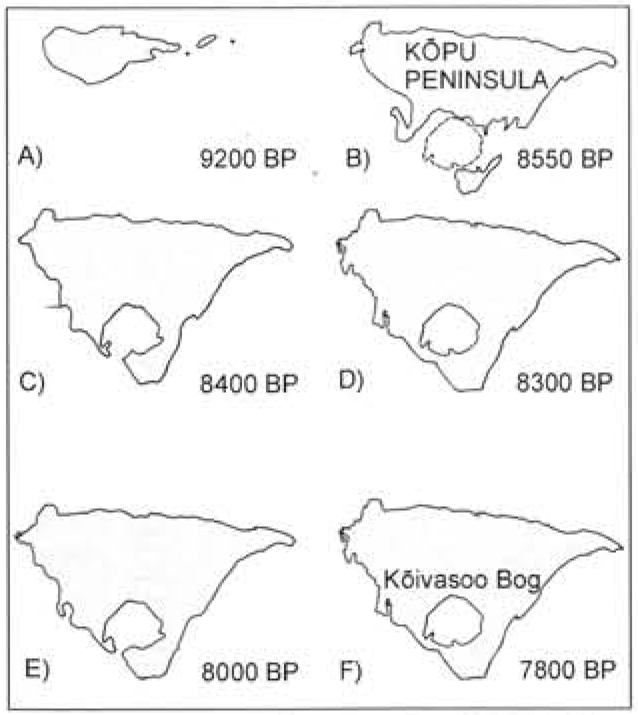

Fig. 5. Early Holocene palaeogeography of the Kõpu Peninsula.

Baltic Sea basin for the first time and turned into a coastal lake (Fig. 5d). The Ancylus Lake level decreased below the Kõivasoo basin threshold (26.5 m), most probably to about 24 m. If it would have dropped more, the Kõivasoo basin would have dried up due to a highly permeable Ancylus Lake beach ridge of sand and gravel, which borders Kõivasoo basin from the south. According to the authors' observations the Ancylus Lake regression had an amplitude of about 20 m on the Kõpu Peninsula (Fig. 6). Raukas et al (1996) suggest a deeper regression, down to 20 m a.s.l., in that case the coastal lake of Kõivasoo should have disappeared. Diatom assemblage (Fig. 4, DZ 1) indicates alkaline freshwater conditions in this very shallow coastal lake, which remained on the sandy coast of the retreating Ancylus Lake (Fig. 7). The high amount of *Pediastrum* coenobia and the $\delta^{13}C$ values of shells also refer to post-isolational conditions (Fig. 3, Table 3). The presence of *Alnus*, *Ulmus* and *Quercus* pollen with increasing *Pinus* pollen confirms the Late Boreal age of the isolation.

Changes in lithology (Table 1), a sharp decrease in *Pediastrum* (Fig. 3), appearance of large-lake diatom taxa (Fig. 4) indicate consistent changes in the environmental conditions at 318–325 cm. Large-lake planktonic diatoms *Aulacoseira islandica* and *Stephanodiscus neoastrae* and periphytic *Cymbella lanceolata* (Ehrenberg) Kirchner (Fig. 4, DZ 2) suggest the inundation of the Kõivasoo basin and the establishment of a connection with the Baltic Sea basin. The relatively high abundance of small-lake species reveals that this connection was weak. The described rise in the water level of the Baltic Sea basin, after the Ancylus Lake regression, could have happened due to establishment of the connection with the ocean. Eustatic rise of the ocean level led to intermittent inflows of saline water over the sills of the Danish Straits into the Baltic Sea basin. Soon after at 8800–8900 BP the first indications of saline water penetration into the Baltic Sea basin appeared in the areas close to the entrance along the coast of Blekinge, southern Sweden (Berglund & Sandgren 1996) and in the Bornholm basin (Andrén et al. 2000). However, in southern Finland the coastal waters became brackish at about 8000 BP (Hyvärinen 1984). This slow spread of brackish water across the Baltic Sea basin can be explained by the limited water exchange between the Kattegat and the landlocked Baltic Sea basin. The density differences of the marine and fresh water forced the saline water to flow as a bottom-current, vertical mixing of the water column was prevented by a permanent halocline and the sills separating the various sub-basins were obstacles for the spread of saline water towards the northern basins.

According to the diatom assemblage we can suggest the formation of a sheltered freshwater lagoon at about 8100–8000 BP (Fig. 5e) in the Kõivasoo basin. Brackish littoral diatom species are absent and it is highly speculative to state about the salinity of the Kõivasoo basin relying only on the salinity indifferent *Mastogloia* spp. The diatom data suggests that saline water had not yet reached the coastal area of Hiiumaa Island by that time. The environment of that shallow freshwater lagoon was highly eutrophic and alkaline. Epiphytic *Cymbella leptoceros*, *Gomphonema angustum* and *Epithemia* spp. refer to abundant benthic macrophyte vegetation, consistent with more frequent aquatic pollen appearance (Fig. 3).

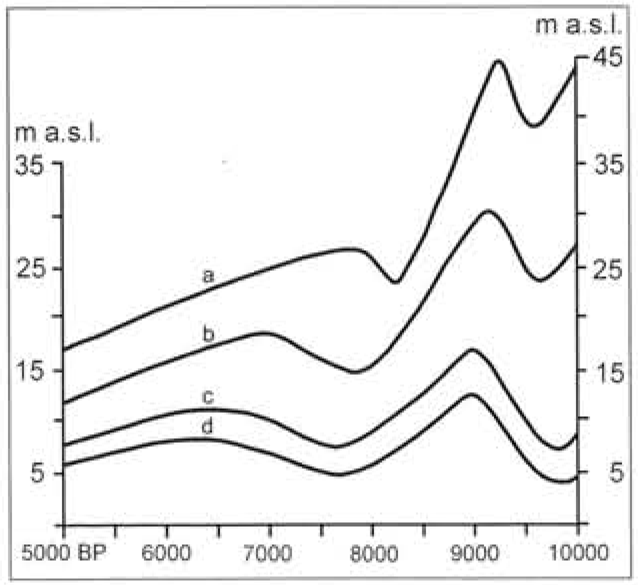

Fig. 6. Early Holocene shore displacement curves for the (a) Kõpu Peninsula, (b) Saaremaa Island, (c, d) West Estonia.

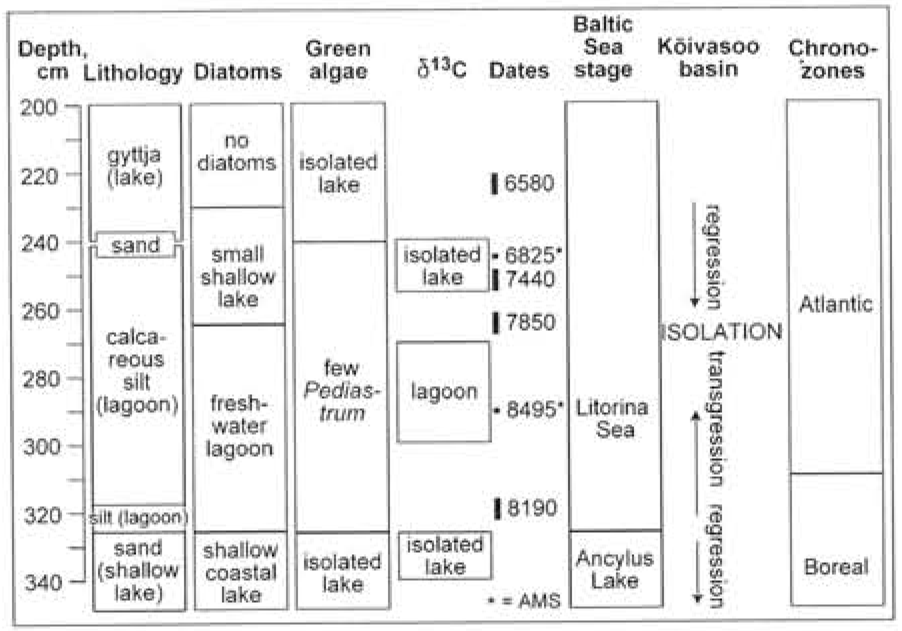

Fig. 7. Summary diagram for the environmental development of the Kõivasoo basin.

This connection of the Kõivasoo lagoon with the Baltic Sea basin lasted for a rather short time, approximately up to ca 7800 BP (Fig. 5f). Evidence of low *Ulmus*, sporadic *Tilia* and high *Pinus* pollen (Fig. 3) supports the Early Atlantic isolation. The upper limit of the isolation defined by lithology and *Pediastrum* frequencies, lies at the depth of 235–240 cm and occurred with some delay in comparison with the changes in the diatom flora and the isotopic $\delta^{13}C$ record. Diatoms, characteristic to small lakes occur since 265 cm and the $\delta^{13}C$ value of the shell at 250 cm indicates closed lake conditions. A similar discrepancy between the lithological and diatom records, defining the isolation contact, has also been described in a sediment sequence near Virolahti (Miettinen & Hyvärinen 1997).

The saline Litorina Sea never flooded Kõivasoo basin. Aeolian activities and dune formation, which activated in Kõpu Peninsula, can explain the increased terrigenous fraction in the sediment composition and associated change in the composition of diatoms (Fig. 4). After the final isolation, the Kõivasoo basin became a shallow eutrophic coastal lake where gyttja deposited and from 4900 BP onwards it was filled in with peat. Kõpu Peninsula itself joined with the main island at about 4000 BP.

A model of the 27-m Litorina Sea isobase for the Kõpu Peninsula is presented in Figure 6a. It covers a time span between 10 000 and 5000 BP and it is compared with the shore displacement curves from Saaremaa Island (Fig. 6b) and West Estonia (Fig. 6c, d). The latter are based on biostratigraphical, geomorphological and ^{14}C data by Veski (1998) with input from previous data. The shore displacement curves (Fig. 6) support the opinion, that the culmination Litorina Sea transgression peak was diachronous, depending on the rate of the isostatic uplift. The transgression occurred later in areas with a lower rate of land uplift (Eronen 1974; Hyvärinen et al. 1992; Miettinen & Hyvärinen 1997).

CONCLUSIONS

A continuous limnic profile and new biostratigraphic records indicate the Ancylus Lake regressional limit down to 24 m a.s.l. on the Kõpu Peninsula, which contradict the suggestion of a much deeper regression of Raukas et al (1996).

The Kõivasoo basin isolated twice, first at the end of the Ancylus Lake regression at about 8300 BP and the second time after the Litorina Sea transgression 7800 BP. Freshwater conditions still occurred during the culmination of the Litorina Sea transgression on Kõpu Peninsula. The saline Litorina Sea never inundated the Kõivasoo basin (Fig. 7).

Reconstructed shore displacement curves for Kõpu Peninsula, Saaremaa Island and West Estonia support the opinion that the peak of the Litorina Sea transgression was diachronous, depending on the rate of isostatic uplift. The peak occurred later in areas with a lower rate of land uplift.

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Sulfide geochemistry and mineralogy from two different Baltic Sea environments: Bothnian Sea and Gotland Deep

Matti Mälkki

Abstract

The purpose of this study is to compare sedimentary sulfide formation of the Bothnian Sea (EB-1) with that of the Gotland Deep (BY-15). Only monosulfides are present at site EB-1, attributed to the lack of elemental sulfur that prevents pyrite formation. At site BY-15, sulfides occur mostly in the pyrite form. Organic matter is interpreted to be the main limiting factor for sulfide formation due to almost constant excess of elemental/organic sulfur at site BY-15. Because of intermittent anoxia most iron remains as dissolved Fe^{2+} form which prevents general iron-limitation. The limiting factor for sulfide formation is obscure at EB-1 site. For trace metals, only molybdenum appears to be assosiated with sulfur. Pyrite formation is closely linked with that of carbonate formation at BY-15 site. Synsedimentary and diagenetic crystals for both phases were observed.

☐ *Baltic Sea, geochemistry, petrography, sediments, sulfides.*

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INTRODUCTION

Ferrous sulfides, especially pyrite, are common authigenic minerals in sea sediments. Dissolved sulfate is reduced by anaerobic bacteria either in near-bottom or interstitial waters, and Fe-sulfides are formed by the reaction of hydrogen sulfide and ferrous ion. The subject has been studied both in present marine sediments (Berner, 1970, Jørgensen 1977, Filipek & Owen 1980, Sweeney & Kaplan 1980, Leventhal 1983, Howarth & Jørgensen 1984, King et al. 1985, Canfield 1989, Jørgensen 1989, Canfield et al. 1992, Luther et al. 1992, Thamdrup et al. 1994) and older sediments of Phanerozoic time (Berner & Raiswell 1983, Gibson 1985, Raiswell et al. 1988, Raiswell et al. 1993, Reynolds et al. 1994, Coleman & Raiswell 1995). Some previous studies about the sulfide formation in Baltic sediments have been made (e.g., Ignatius et al. 1968, Papunen 1968, Suess 1979, Lein 1983, Boesen & Postma 1988, Salonen et al. 1995). Especially Neumann et al. (1997), Sternbeck & Sohlenius (1997) and Lepland & Stevens (1998) have investigated sulfide formation with respect to carbonate formation in a given environment. The relationship between sulfides and authigenic phosphate minerals has also been exhibited in a freshwater/brackish environment (Postma 1982).

The Baltic region is characterized by different hydrographic conditions and sedimentation rates, which make the sediments of this relatively small area heterogeneous. Due to a small vertical salinity difference in water masses the surface sediments of the Bothnian Sea area are permanently oxic. This allows water mixing and oxygen penetration to surface sediments. A permanent salinity stratification exists in the Baltic Proper area which prevents the mixing of oxygen-rich surface water and oxygen deficient bottom waters. After oxygen depletion by organic matter degradation anoxic conditions prevail in near-bottom conditions until the next oxygenated saline water inflow event occurs from the Danish straits.

Different environmental conditions have an impact on the formation of authigenic minerals. The deep water salinity varies from 5-8 ‰ in the Bothnian Sea to 10-13‰ in the Baltic Proper (Kullenberg 1981, Wulff et al. 1994). A total carbon in the Bothnian Sea uppermost sediments (2.5-3.5%) has been measured by Brügmann & Lange (1990) and Leivuori & Niemistö (1995). The "background" carbon value is typically 2.5% and occurs > 80% as organic form in EB-1 sediments (Brügmann & Lange 1990). By contrast, total organic carbon (TOC) may reach 9-10% values in the Gotland Deep (Emelyanov 1988, Neumann et al. 1997). Pyrite formation is a function of a non-reactive (buried) organic matter and salinity (Berner 1984).

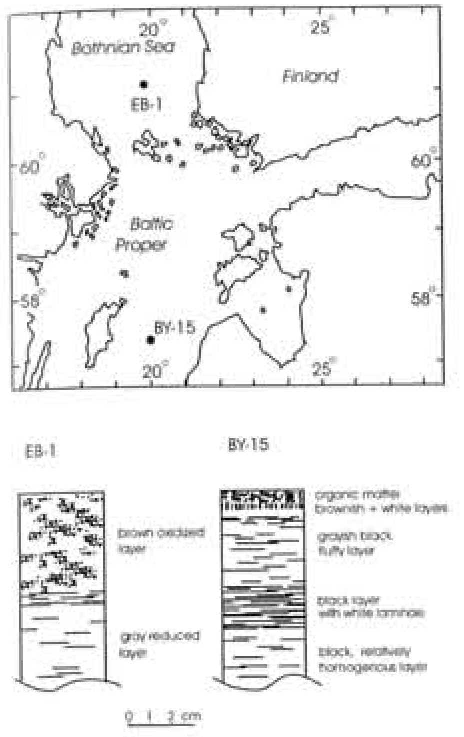

Fig. 1. Sampling sites and *in situ*-descriptions of the uppermost cores (c.f. Salonen et al. 1995).

The purpose of this study is to compare sulfide formation in the Gotland Deep (the Baltic Proper) and the Bothnian Sea sediments. The site EB-1 (61°04.00'N, 19°44.00'E; Fig. 1) is in the deepest part of the Bothnian Sea (water depth 130 m). The uppermost four meters of the sediment in the area are of postglacial clay material (Winterhalter 1972). The average sedimentation rate in the consolidated part of sediments is ca. 0.27 mm/y and in upper unconsolidated part ca. 2.4 mm/y, respectively (Niemistö 1982). The thickness of the oxidized surface sediments is ca. 5 cm. No visible structures are present, possibly because of bioturbation (Niemistö 1983). The site BY-15 (57°19.21'N, 20°03.00'E) is in the deepest part of the Gotland Deep (water depth 236 m). The thickness of postglacial clay layer is 5-7 m (Niemistö & Voipio 1974, Ignatius et al. 1981). The sedimentation rate has been estimated as 1.0-1.6 mm/y (Salonen et al. 1995) and the rate may vary even within a single area in the basin (Niemistö & Voipio 1974). The bioturbation is completely absent at the uppermost core of BY-15 (Fig. 1) suggesting generally an insufficient oxygen content for benthic fauna. Descriptions of the uppermost part of cores were made in field *in situ* (Fig. 1).

Table 1. A sequential extraction analysis (SEA) -procedure for K, Na; Ca, Mg; SO_4; Fe, Mn; Co,Cu, Mo, Ni, Pb, Zn. HXL = hydroxylamine hydrochloride

	step method	*expected target*	*measured elements*	*original reference*
I	ion exchanged water	pore water	K, Na; Ca, Mg; SO_4	(see text)
II	1 M NH_4Ac pH 7 2 d	"exchangeable"	K, Na; Ca, Mg; SO_4	Tessier et al. (1979)
III	NH_4Ac - HAc pH 4.8 15 min ultrasonic bath	"carbonates"	Ca, Mg; Fe, Mn	Tessier et al. (1979)
IV	1 M HXL - 2 M HAc 15 min wortex stirrer	"poorly ordered oxides and hydroxides"	Fe, Mn	Chester and Hughes (1967), Filipek and Theobald Jr. (1981)
V	0.3 M Na-citrate - 1 M $NaHCO_3$ - Na-dithionite 15 min heated at 80°C water bath	"crystalline Fe-oxides", "FeS -Fe"	Fe	Mehra and Jackson (1960), Thamdrup et al. (1994)
VI	4 M HCl with $KClO_3$ (*)	"sheet silicate -Fe", "FeS_2 -Fe", "elemental sulfur" (S^0) and "organic sulfur" (S_{org})	Fe; SO_4; Co, Cu, Mo, Ni, Pb, Zn	Olade and Fletcher (1974)

(*) HCl was added before oxidant in order to eliminate possible remnant monosulfide fraction after Step V, cf. "total" (HCl - $KClO_3$) dissolution.

All SEA element values were corrected using "total" HCl-$KClO_3$ leachable Fe (Fe_{ad}) and total SEA Fe value (Fe_{seq}), see Figs. 2C, 5C.

MATERIALS AND METHODS

During the r/v Aranda's cruise in September 1995 two sediment cores were taken in the Bothnian Sea (EB-1) and the Gotland Deep (BY-15) (Fig. 1). The Niemistö gravity corer (Niemistö 1974) was used to retrieve sediment samples. Both cores were sliced into 2 cm pieces which were placed in Petri-dishes, sealed immediately and stored frozen until analyzed.

The sediment samples were subjected to a sequential extraction analysis (SEA; Steps I-VI, see Table 1). During laboratory work the outermost part of samples was peeled out to maintain the originality. 10 g of frozen sample were transferred into a tube without any other pretreatments. After thawing of a sample, pore water was extracted by centrifugation. The SEA leachings were performed using 25-ml reagent. An inert gas (argon) was used in order to avoid contamination during laboratory storage.

A total "reactive iron" was extracted from separate samples using hot, concentrated (25%) HCl for 2 min. A dried, homogenized 0.5 g sample with 15-ml reagent was used. The method provides dissolving Fe almost completely from Fe-bearing sheet silicates, carbonates, monosulfides and oxides. Pyrite, even fine grained, is insoluble by this treatment (see Berner 1970, Postma 1982, Raiswell et al. 1988, Jørgensen 1989, Canfield et al. 1992, Raiswell et al. 1993). The HCl-soluble Fe reflects a maximum Fe-reactivity towards pyrite formation.

Table 2. Dry weight (dw-%) and PO_4^{3-} "inorganic phosphate" data (mg/g dw); EB-1

cm	dw	PO_4^{3-}
2	12	20
4	22.7	8.7
6	24.3	4.5
8	26.6	3.9
10	28.3	2.4
12	25.1	2.8
14	26.4	2.2
16	29.3	2.1
18	28.9	1.7
20	30.4	1.7
22	31.6	2
24	30.4	2.5
26	30.6	2.7
28	30.4	3.6
30	30.1	1.8
32	33.6	2.3
34	35	1.8

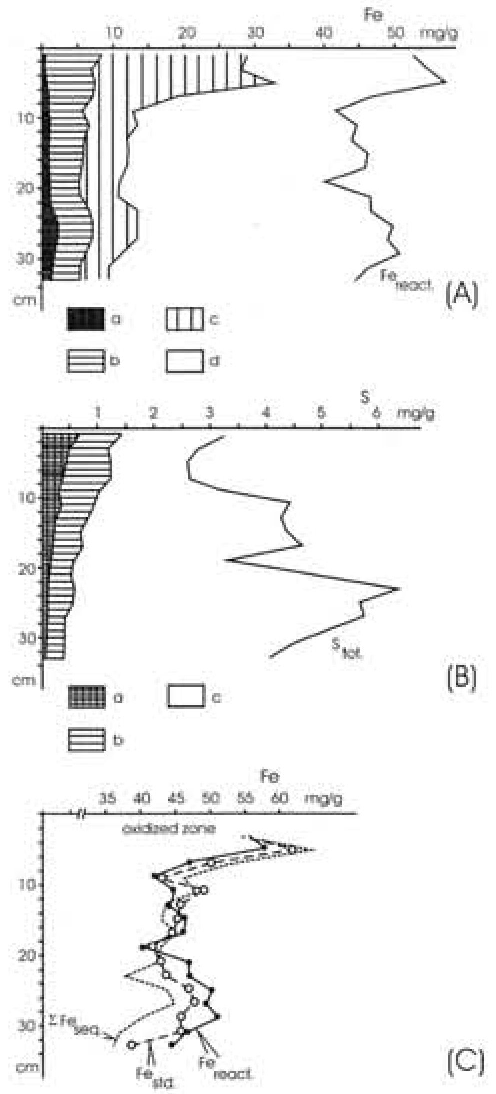

Fig. 2A. A "reactive iron" (EB-1). Symbols a, b and c denote Steps III, IV and V, respectively, see Table 1. Symbol d denotes HCl leachable "total reactive iron" subtracted by the Steps III, IV and V. Symbol d is attributed here as "sheet silicate -Fe".
Fig. 2B. Sulfur data (EB-1). Symbols a and b denote Steps I and VI, see Table 1. Symbol c denotes HCl-$KClO_3$-leachable "total S" subtracted by the steps I and VI. Symbol c is attributed here as "FeS -S".
Fig. 2C. A comparison of "total Fe" from SEA (S Fe_{seq}) after correction, "total Fe" from separate, reference HCl-$KClO_3$ leaching (Fe_{std}) and HCl-leachable Fe (Fe_{react}); (EB-1). Since (Fe_{react}) » (Fe_{std}), no pyrite exists in sediment samples, in agreement with the microscopical studies.

A "total" metal and sulphur content (HCl - $KClO_3$) was determined from separate, fresh samples. Iron was used to correct all element loss during SEA. An "inorganic" phosphorus (PO_4^{3-}) content was measured separately (see Carman & Jonsson 1991) in order to characterize possible authigenic phosphate phases (e.g. vivianite $Fe_3(PO4)_2 * 8 H_2O$).

The Na, K, Ca, Mg and Fe contents were measured by a flame-AAS (GBC903); phosphorus, sulfur, and trace metals possibly incorporated into sulfides (Co, Cu, Mo, Ni, Pb, Zn) were measured by an ICP-AES (Jobin Yvon 70+). During a dry weight (dw-%) determination (105°C for 22 h.) the role of mineral salt precipitates was ignored.

X-ray diffraction (XRD) analyses were made both in a total and a heavy liquid (D = 2.8 g/cm^3) fraction (Callahan 1987). The total samples were boiled in a 15% H_2O_2-solution (15 min.) in order to remove organic matter. The samples were ground on agate mortar before the heavy liquid separation. The positions of XRD-reflections were corrected using an internal silicon standard. A Philips PW3710 XRD unit with a graphite curved monochromator was used.

ICP, AAS and XRD analyses were carried out at the University of Helsinki, Department of Geology. Thin and polished sections were made in both cores and analysed visually by a polarizing microscope (PM) and a scanning electron microscope (SEM). Statistical analyses (correlation coefficients) were made for both cores separately.

RESULTS AND INTERPRETATIONS

Bothnian Sea (EB-1)

The salinity of pore water does not change significantly with sediment depth. The concentrations of Na^+ and K^+ correlate weakly with those of dw-% data (r = 0.76, r = 0.73; Tables 2, 3) which may be due to adsorption on dry matter. XRD examinations reveal a predominance of illite, chlorite, quartz, feldspars and amphibole, in agreement with previous studies (Papunen 1968, Boström et al. 1978). The concentrations of Ca^{2+} and Mg^{2+} do not vary with depth of the core and the correlations with the dw-% data are negative (r = -0.75, r = -0.76; Tables 2, 3). Also Ca^{2+} and Mg^{2+} exchangeable enrichments occur in the uppermost sediment relative to Na^+ and K^+ (Table 3). Except for surface sediment where bioturbation occurs (Niemistö 1983), pore water general stagnation may occur in EB-1 sediments.

Mn-oxides occur in uppermost 4 cm, in contrast with those of pore water and exchangeable Mn (Table 3). The Mn species reflect the redox conditions in sediments (Berner 1980); in addition, increasing contents of Fe-oxides occur in the lowermost part of the oxidized zone (Fig. 2A). It is possible that a suboxic zone exists at 4-6 cm depth interval. Sediments may have a positive redox potential throughout the surface oxide layer although the distribution of dissolved O_2 is limited only to the uppermost zone (Howarth & Jørgensen 1984, Jørgensen 1989, Thamdrup et al. 1994). The high Mn-oxide concentration (1.5 to 2 mg/g) relative to dissolved (3-5 mg/l; 8-13 mg/g) and exchangeable (200-400 mg/g) phases below oxic layer suggests a strong reoxidation tendency for Mn. Mn is involved redox reactions with O_2 in the upper part of the oxic sediment while Fe(III)/Fe(II) couple mainly controls the lower part of the oxic sediment (Bågander & Niemistö 1978).

Carbonates are absent (PM, XRD) in sediment samples which is also indicated by the near-zero HAc-NH_4Ac "carbonate" values (≈0.1 mg/g) (Table 3). The dissolution of Fe is more substantial (Fig. 3). The presence of H_2S may prevent siderite precipitation (Postma 1982). The maximum concentration of the HAc-NH_4Ac-leachable Fe occurs in a deep zone of the sediment, which is consistent with S deep maximum (Fig. 2B). This is a possible indication for a weak, *in situ* sulfide formation process between the "reactive" Fe and pore water S (Table 3).

Table 3. SEA for K, Na, Ca, Mg, Mn and SO_4 -ions mg/g dw (Step I mg/l); (EB-1). SEA for Fe, see Figure 2A. Symbol 0 denotes below detection limit values

	STEP I						**STEP II**					**STEP III**			**STEP IV**
cm	**Na^+**	**K^+**	**Ca^{2+}**	**Mg^{2+}**	**Mn^{2+}**	**SO_4^{2-}**	**Na**	**K**	**Ca**	**Mg**	**Mn**	**Ca**	**Mg**	**Mn**	**Mn**
2	1734	97	59	148	0	390	1.5	1	2	3.1	0	0.4	0.1	0.1	1.8
4	1876	109	57	143	0	428	1	0.7	1.3	2	0	0.3	0.1	0.1	1.3
6	1976	132	60	140	4	434	1.3	1	1.3	2	0.3	0.2	0.1	0.1	0.1
8	1920	147	56	131	3.9	400	1.2	1	0.9	1.6	0.4	0.1	0	0.1	0.1
10	1972	150	54	134	4.2	372	1.1	0.9	0.8	1.4	0.2	0.1	0	0	0
12	2160	168	57	136	2.5	385	1.1	1	0.9	1.6	0.2	0.1	0	0.1	0
14	2068	160	54	132	3.4	278	1	1	0.9	1.5	0.2	0.1	0	0	0
16	2155	162	56	136	2.3	279	1.2	1	0.9	1.6	0.2	0.1	0	0	0
18	2056	152	48	118	3.1	230	1	0.9	0.8	1.4	0.2	0.1	0	0	0
20	2141	153	50	126	3.1	210	1.1	0.9	0.8	1.4	0.2	0.1	0	0	0
22	2000	154	44	109	0.8	214	1.2	1	0.8	1.5	0.2	0.1	0	0	0.1
24	2257	150	49	119	2	177	1.3	1	0.9	1.6	0.3	0.1	0	0.1	0.1
26	2129	171	48	112	2.3	159	1.2	1	0.9	1.6	0.2	0.1	0.1	0.1	0
28	2111	144	46	116	1.9	156	1.1	1	0.8	1.5	0.3	0.1	0	0.1	0.1
30	1944	139	43	103	1.5	125	1.1	1	0.8	1.4	0.1	0.1	0	0.1	0
32	2299	167	48	125	1.2	113	0.8	0.8	0.7	1.1	0.2	0.1	0	0.1	0
34	2164	147	45	112	1.6	91	0.9	0.8	0.7	1.2	0.2	0.1	0	0.1	0

The HCl-leachable Fe in the sediment is characteristically bound by sheet silicates (Fig. 2A). According to Canfield et al. (1992) and Thamdrup et al. (1994), a sheet silicate-Fe is weakly reactive and forms Fe-sulfides during further burial in the time interval of thousands of years. Pyrite is virtually absent (PM, XRD, Figs. 2B,C). Most of S occur as at monosulfide stage (Fig. 2B). A calculated FeS -S content (2-4 mg/g, Fig. 2B) correlates stoichiometrically satisfactory with that of dithionite extractable iron (6-7 mg/g, Fig. 2A) in reducing sediments. FeS may occur even in oxidizing conditions due to reducing microenvironments (Jørgensen 1977, Seppänen, 1984).

No indication exists that any of measured trace elements (Co, Cu, Ni, Pb, Zn; Table 4) are incorporated into sulfides. The correlations with the "total S" fraction (r = -0.39 - +0.07) are absent. Authigenic PO_4^{3-} phases appear to be associated with surficial oxides as described by Carman & Jonsson (1991); (Tables 2, 3).

Gotland Deep (BY-15)

Negative correlations occur with dw-% and pore water cations (r = -0.67 for Na^+, r = 0.35 for K^+, r = -0.80 for Ca^{2+}, r = -0.82 for Mg^{2+}) which also applies to the relationship between dw-% and exchangeable Na, K, Ca and Mg (Tables 5, 6). The deviations are greatest in the surficial part of sediment suggesting the effect of the salt water inflow in 1993. The relationship between the surface fluffy layer and the increase of salinity is clear (Fig. 1, Table 6). The fluffy layer has been formed by the current activity (see Perttilä & Niemistö 1993).

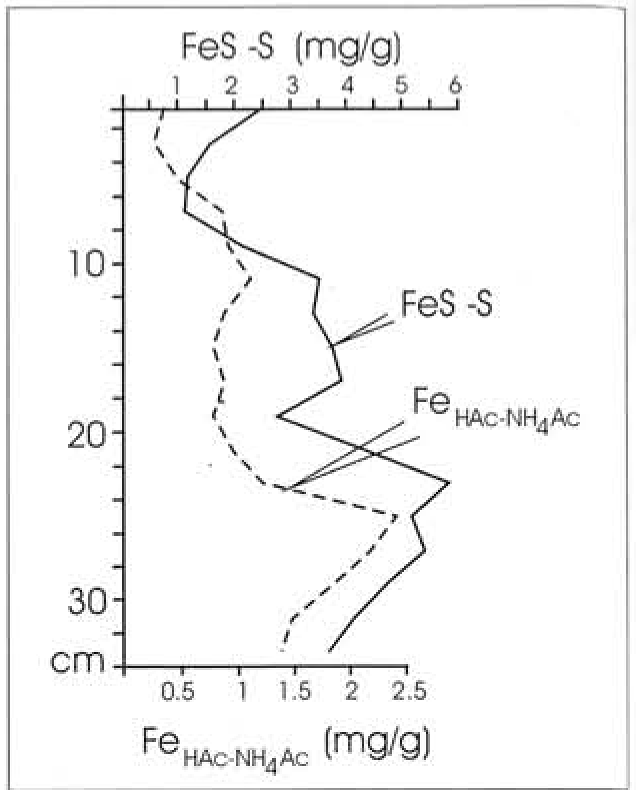

Fig. 3. FeS-S versus $Fe_{HAc\text{-}NH4Ac}$; (EB-1).

Table 4. Trace element data (mg/g dw); (EB-1). Step VI denotes "residual" (res.) fraction, e.g. pyrite, organic matter, silicate minerals. Steps I-VI denote "total" (tot.) fraction (HCl - $KClO_3$) which was done separately and assumed to represent the phases I-VI. ND = not detected

	VI	I - VI	VI	I - VI	I	I-VI	VI	I - VI	VI	I-VI	VI	I - VI
cm	**Co (res.)**	**Co (tot.)**	**Cu (res.)**	**Cu (tot.)**	**Mo (res.)**	**Mo (tot.)**	**Ni (res.)**	**Ni (tot.)**	**Pb (res.)**	**Pb (tot.)**	**Zn (res.)**	**Zn (tot.)**
2	28	28	39	60	ND	ND	56	75	49	73	250	280
4	18	25	22	39	ND	ND	29	43	26	48	150	180
6	25	24	30	42	ND	ND	41	45	41	53	220	200
8	21	22	31	43	ND	ND	34	45	28	53	180	200
10	19	21	30	43	ND	ND	36	42	26	54	170	190
12	21	21	29	49	ND	ND	34	48	18	49	160	230
14	19	24	26	49	ND	ND	31	46	19	56	140	210
16	19	22	26	47	ND	ND	32	46	15	53	140	200
18	19	22	29	45	ND	ND	35	43	17	47	160	180
20	18	18	25	40	ND	ND	35	40	16	38	140	150
22	18	22	23	41	ND	ND	34	42	18	38	140	160
24	19	26	24	39	ND	ND	33	39	16	34	140	150
26	21	20	24	43	ND	ND	33	49	12	36	120	160
28	15	20	20	41	ND	ND	30	43	13	33	110	150
30	17	18	21	39	ND	ND	30	41	12	29	110	130
32	16	20	19	39	ND	ND	31	39	11	28	110	140
34	15	18	20	33	ND	ND	30	33	10	24	120	110

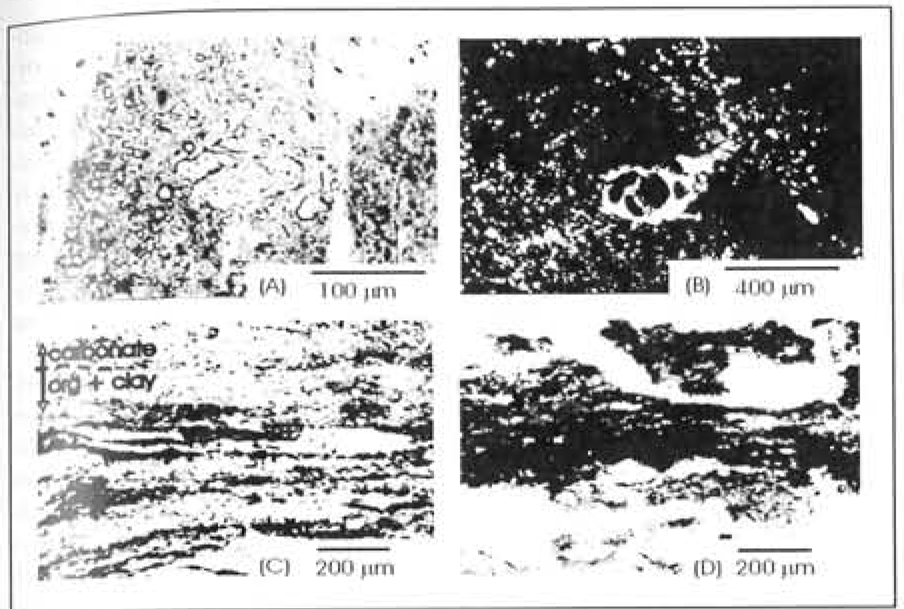

Fig. 4A. The partly dissolved carbonate twin rhomboedra, which has probably formed during an early diagenesis [BY-15, 24 cm, plane polarized light (PPL)].
Fig. 4B. Calcareous skeleton remnant [BY-15, 14 cm, crossed nicols].
Fig. 4C. Rhytmitic pyrite layers within a clay mineral/organic matter dominated layer. Note the contact with the carbonate layer [BY-15, 40 cm, PPL].
Fig. 4D. A massive sulfide layer. The carbonate/organic clay contact is not visible [BY-15, 42 cm, PPL].

Table 5. Dry weight (dw-%) and PO_4^{3-} "inorganic phosphate" data (mg/g dw); BY-15

cm	dw	**PO_4^{3-}**
2	6.2	1.9
4	8.3	3.4
6	10.6	4.4
8	17	3.2
10	18.2	3.6
12	16.8	5.1
14	19.9	3.2
16	22.9	2.8
18	19.5	3.6
20	21.9	3.8
22	22.8	3
24	19.4	3.8
26	23.2	2.8
28	23.5	2.8
30	24.2	3.2
32	21	3
34	21	3.1
36	25.1	3
38	23.6	3.1
40	28.5	5.3
42	23.1	4.4
44	26.4	3.5
46	26.5	3.1

The maximum of pore water Mn concentration (40 mg/l) is associated with the surface zone while the deeper layers contain only a few mg/l of Mn (Table 6). Evidently the surficial enrichment of Mn^{2+} is due to a rapid organic matter degradation and a subsequent reduction of Mn(IV) oxides. There was an oxygenated remnant in surface sediments. According to Widerlund & Roos (1994) this kind of zone can persist for some time in anoxic sediments.

The chemical composition of the $HAc\text{-}NH_4Ac$ extractable "carbonate" fraction does not show variation with respect to the concentrations of Mn, Ca and Mg (Table 6). The composition of the "carbonate" phase $(Mn_{0.70}Ca_{0.27}Mg_{0.03})CO_3$, in agreement with that of Jakobsen & Postma (1989) and Neumann et al. (1997), does not differ much from that estimated for samples from the Fårö deep [$(Mn_{0.72}Ca_{0.16}Mg_{0.12})CO_3$; Manheim 1961, 1982] or Landsort deep [$(Mn_{0.85}Ca_{0.10}Mg_{0.05})$ CO_3; Suess 1979, $(Mn_{0.77}Ca_{0.22}Mg_{0.01})$ CO_3; Lepland and Stevens 1998]. The XRD d-value (2.88 Å) indicates kutnahorite, Ca-rhodocrosite or dolomite. The $HAc\text{-}NH_4Ac$ extractable Fe differs greatly with those of Ca, Mg and Mn.

The presence of primary (during sedimentation) and early diagenetic carbonate particles are observed by PM (Fig. 4A-C). Primary carbonates occur as lenses, layers or concretions within silicates, sulfides and organic matter. The grain size of carbonate particles varies from few µm up to 300 µm, and many of globes, skeletons and euhedral particles (c.f. Peterstad & Aagaard 1985) seem to be corroded or partly dissolved. According to Jakobsen & Postma (1989), carbonates undergo dissolution and recrystallization events. Diagenetic changes of pore water Ca/Mn ratios are not observed (Table 6).

The low abundance of easily leachable Fe phases is consistent with the generally reducing surface sediment conditions (Fig. 5A). If calculated as Fe monosulfide, these reactive fractions can contain up to 2-3 mg/g FeS sediment. The silicate mineralogy is identical with that of EB-1 and contains most of weakly reactive iron phases. Framboidal pyrite is readily identified by PM and SEM as well as by chemical extractions (ca. 20-40 mg/g FeS_2) (Figs. 5C, 6A-D). The stoichiometrical "excess" of S relative to pyrite-iron (Fig. 5B, 5C) indicates that a substantial part of sulfur may occur as native (S^0) or organic state, in disagreement with the study of Boesen & Postma (1988). Although pyrite can be slightly non-stoichiometric ($FeS_{(2.05\text{-}2.25)}$; Bertolin et al., 1995), the large S-excess diagnosed in this study as well as total Fe/S behavior described by Salonen et al. (1995) indicate the existence of S^0 and/or organic S-compounds in the sediments.

Single pyrite framboids (10 mm) formed by small crystallites appear to be of synsedimentary origin. They mostly occur as individual rhytmites within single organic/detrital matter layers or as thicker massive individual layers (Fig. 4C, 4D; Fig. 6D). Diagenetic framboids (40 mm) occur as clusters (Fig. 6A-D). The partial dissolution of pyrite described by Cutter & Velinsky (1988) is not observed here. The lattice value (5.418 ± 0.005 Å) compares extremely well with 5.419 ± 0.003 Å reported for Littorina/Anchylus boundary pyrites in the Bothnian Sea postglacial sediments (Papunen 1968). Marcasite is not found in any of the samples examined. Usually this FeS_2-polyform occurs only in old sediments (Goldhaber & Kaplan, 1974).

Trace metal data (Table 7) indicate that only molybdenum appears to be associated with pyrite. The correlation between residual Mo and residual S is clear (r = 0.91). Mineral phosphate phases are not identified despite of somewhat even distribution of PO_4^{3-} content throughout the core (Table 5).

DISCUSSION

EB-1

The pore water S content is usually only a few percent of total S content (Fig. 2B). A major part of the sulfide precipitation evidently occurs during early diagenesis. The total surface carbon in the Bothnian Sea area 2.3 ± 1.0 % (Leivuori & Niemistö 1995) does not decrease significantly with depth in EB-1 area (Niemistö & Voipio 1981, Brügmann & Lange 1990). This probably suggests that the degradation of the reactive organic matter will be completed during early diagenesis. The redoxcline represents a boundary of an active bioturbation which allows for sulfate-ion transportation to the oxic-anoxic boundary. According to Berner (1984) and Jųrgensen (1989), the sulfate-reduction rate is intense within a few centimeter deep zone below the sediment surface because of an anaerobic degradation of organic matter and which decreases with depth.

It is controversial whether sulfur or iron limits sulfide formation in the Bothnian Sea. The reactive iron content probably limits sulfide precipitation in the EB-1 area at early stage of diagenesis. The content of the easily leachable (HAc-NH_4Ac) iron depends more on depositional conditions rather than diagenetic processes (Fig. 3). This is exactly the same depth where a FeS -S maximum occurs. The 20-25 cm zone may represent a remnant of an unusual high deposition of reactive species probably by storm events. On the other hand, permanent surface oxic conditions (Leivuori & Niemistö 1995) oxidize TOC to CO_2, thus inhibiting sulfide formation. The SO_4^{2-} does not appear to limit sulfide formation at an early stage of diagenesis (Table 3).

Table 6. SEA for K, Na, Ca, Mg, Mn and SO_4 -ions mg/g dw (Step I mg/l); (EB-1). SEA for Fe, see Figure 5A

	STEP I						STEP II					STEP III			STEP IV
cm	Na^+	K^+	Ca^{2+}	Mg^{2+}	Mn^{2+}	SO_4^{2-}	Na	K	Ca	Mg	Mn	Ca	Mg	Mn	Mn
2	4534	199	180	529	40.8	1168	3.4	0.6	2.4	2.5	2.8	0.4	0.1	0.6	6.4
4	4691	190	181	521	15.9	1032	1.8	0.6	3.2	2.3	4.5	17	0.8	55.5	1.8
6	4183	187	151	427	9.6	882	2	0.9	2.7	2.5	3.7	12.9	0.7	45.7	7
8	4064	210	135	373	6.8	838	1.6	1.1	2.2	2.2	2.2	8.7	0.5	27.7	7.3
10	4060	203	140	384	7.4	850	1.7	1.1	2	2	2.2	8.8	0.5	30.7	82.3
12	3508	189	101	307	2.4	652	1.8	1.2	2.1	2.2	2.6	8.9	0.6	32.6	40
14	3697	208	114	324	1	688	1.7	1.3	1.7	2.2	1.8	2.3	0.2	9.8	3.7
16	4161	236	133	369	1.8	825	1.7	1.4	1.6	2.1	1.4	1.4	0.2	5.5	1.5
18	3642	203	107	295	1	681	2	1.5	1.8	2.4	1.5	2.1	0.2	8.4	3.9
20	3984	-234	122	347	1.4	711	1.8	1.5	1.7	2.3	1.3	2.8	0.2	11.1	5.4
22	3964	239	109	316	2.5	781	1.5	1.3	1.5	2.1	1.3	1.6	0.2	6.7	2.9
24	3589	216	104	309	2.4	640	2.1	1.6	1.8	2.4	1.6	4.4	0.3	16.5	7.7
26	4109	248	125	371	1.8	734	1.8	1.4	1.5	2.1	1.5	1.8	0.2	7.3	3.3
28	3795	218	110	323	2.2	613	1.5	1.1	1.4	1.8	1.4	3	0.2	12	5.3
30	3915	225	114	343	2.2	666	1.6	1.1	1.5	1.9	1.5	7	0.4	24.8	26.6
32	3594	198	99	308	2.1	571	1.6	1.1	1.5	1.9	1.8	3.9	0.3	14.7	2.9
34	3771	212	108	312	1.8	577	1.7	1.3	1.7	2	1.6	5.7	0.4	20.6	5.6
36	3744	197	108	313	4	554	1.4	1	1.3	1.6	1.5	5	0.3	17.4	3.6
38	3761	191	112	330	5	536	1.5	0.9	1.4	1.7	1.5	6.5	0.4	22.4	21.6
40	3752	201	112	317	3.4	578	1.2	0.7	1.4	1.3	1.5	5.9	0.4	22.5	42
42	3583	192	108	327	3.6	515	1.6	1	1.5	1.8	1.5	5.8	0.4	20	21.6
44	3592	202	109	316	2.6	539	1.2	0.8	1.3	1.5	1.4	5.7	0.3	18.9	13.7
46	3687	205	109	310	1.9	506	1.2	0.8	1.3	1.5	1.4	6.3	0.4	19.8	12.7

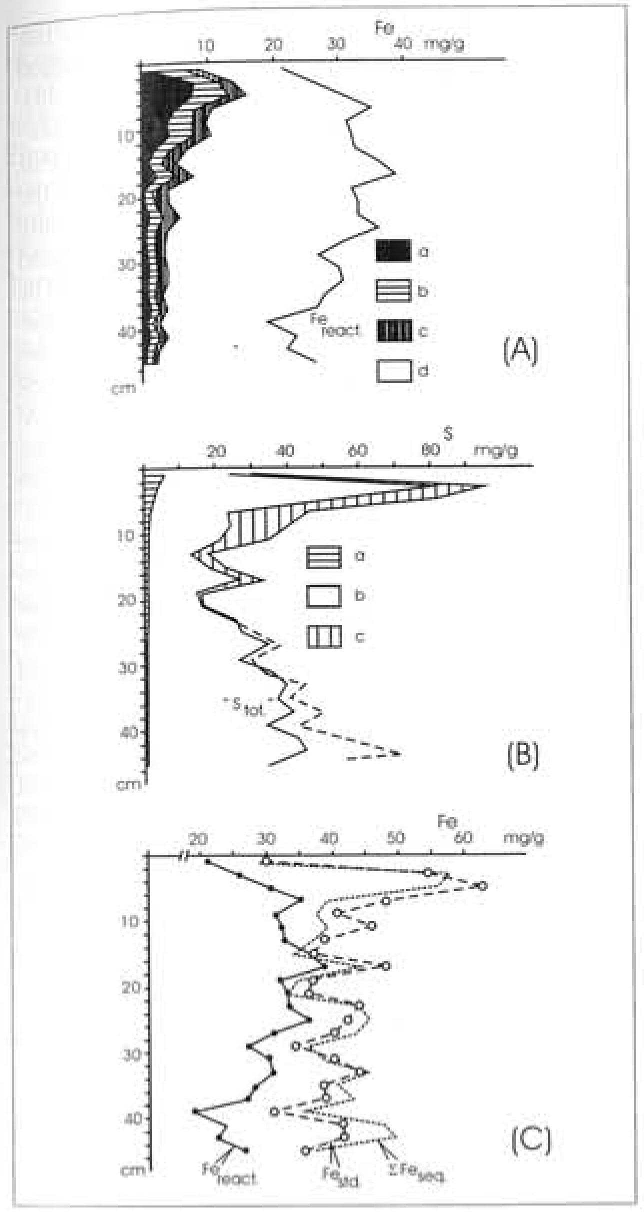

Fig. 5A. A "reactive iron" (BY-15). Symbols a, b and c denote Steps III, IV and V, respectively, see Table 1. Symbol d denotes HCl leachable "total reactive iron" subtracted by the Steps III, IV and V. Symbol d is attributed here as "sheet silicate -Fe".
Fig. 5B. Sulfur data (BY-15). Symbols a and b denote Steps I and VI, see Table 1. A remnant c phase is not the "real" FeS -S phase due to analytical uncertainties (see low Fe values in Figure 5A, phase c). Almost all S species occur as FeS_2, elemental or organic sulfur.
Fig. 5C. A comparison of "total Fe" from SEA (S Fe_{seq}) after correction, "total Fe" from separate, reference HCl-$KClO_3$ leaching (Fe_{std}) and HCl-leachable Fe (Fe_{react}); (BY-15). The difference of Fe_{std} and Fe_{react} is attributed to "FeS_2 -Fe".

Due to a lack of S^0, FeS is not converted to pyrite. Pyrite formation is contingent on the presence of S^0 (Berner 1970, Goldhaber & Kaplan 1974, Coleman & Raiswell 1995). Jfrgensen (1977) estimated that as much as 90 % of total reduced S can be re-oxidized to sulfate ion, which would partly explain the lack of S^0.

BY-15

The pore water S is < 10% of the total S content (Fig. 5B). Chloride-rich water affects pore water content at depths of about 5 cm (c.f. Neumann et al. 1997). The diffusion effect for authigenic mineral precipitation appears to be negligible relative to synsedimentary mineral formation. The general sulfur-carbonate -relationship appears to prevail in the Gotland Deep sediments (Fig. 5B, Table 6).

The notably strong maxima for sulfur and carbonate species in the surficial sediments may be due to stagnation period 1976-1993 in H_2S and HCO_3^--rich environment. It was, however, observed that the salt pulse itself may control authigenic mineral formation (Neumann et al. 1997, Sternbeck & Sohlenius 1997).

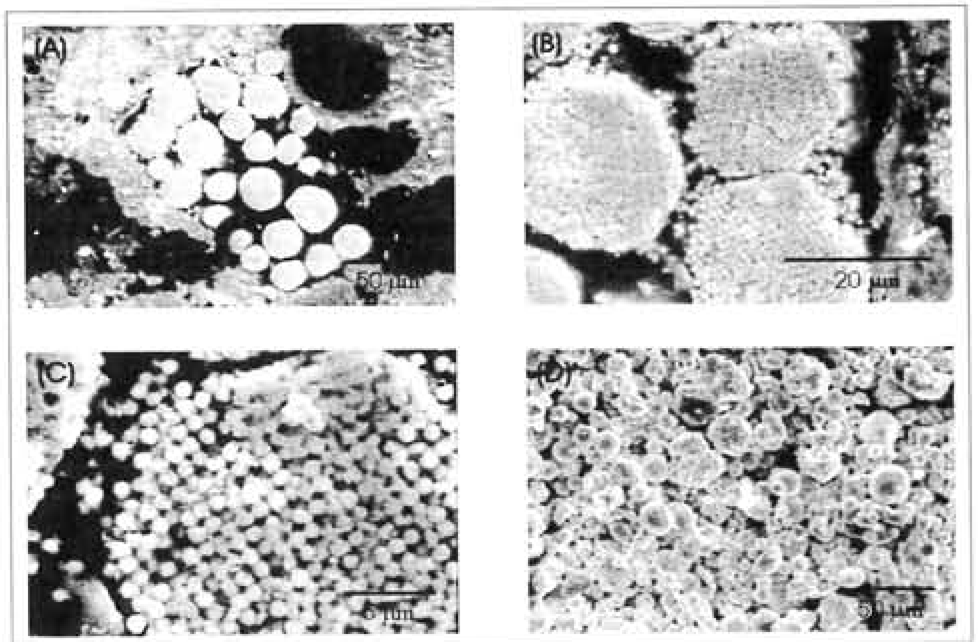

Fig. 6A. Diagenetically formed pyrite framboid cluster [BY-15, 14 cm, scanning electron microscope (SEM)].
Fig. 6B,C. Magnifications of 6A. The single crystallites appear to be subhedral in crystal form.
Fig. 6D. A pyrite collection after dense liquid separation. Smaller framboids appear to be synsedimentary origin while larger framboids are of diagenetic origin [BY-15, SEM].

In addition, Salonen et al. (1995) did not observe any surficial S maximum suggesting that the S formation took place after the inflow event. The saline water contributes authigenic mineral formation at BY-15 (c.f. Figs. 1 and 5).

The laminated sediments are interpreted to reflect the absence of bioturbation and the presence of anoxia (Jonsson et al. 1990, Sohlenius & Andren, 1995). They may be formed also by seasonal currents or even in sediments with permanently oxic surface and low biological productivity relative to the sedimentation rate (Morris et al. 1988, Widerlund & Roos 1994). Berner (1984) proposed that the low scatter of C to S indicates oxic surface conditions. Rhytmitic/massive pyrite layers are mostly associated with organic matter (e.g. Fig. 4C, D), suggesting the O_2/ H_2S fluctuations in the near-bottom water column.

The homogeneity is attributed to a bioturbation effect (Jonsson et al. 1990) or gas formation (Salonen et al. 1995). Although a clear lamination is absent in thin section samples at 14 and 24 cm depths, material does not show a random nature. The absence of clear pyrite - organic matter relationship suggests that the period may reflect longer periods of stagnation allowing greater scatter of organic matter and pyrite as proposed by Berner (1984), see also Boesen and Postma (1988).

According to Huckriede et al. (1996), the non-laminated part has been formed by extreme stagnation that gradually eliminates the salinity difference between the surface and bottom water masses, allowing mixing throughout the water column, colonialization and bioturbation of the bottom sediments by benthos. The present work indicates that the prolonged euxinic periods were not sufficiently long to weaken the halocline. Lepland & Stevens (1998) argued that the lack of lamination may be due to increased input of detrital material. It is possible that sporadical inflowing events have prevented the developing of extreme stagnation periods during the period of 14 and 24 cm PM samples.

The diagenetic FeS_2 framboids are larger in size than synsedimentary formed FeS_2 (Fig. 6D). It is possible that the supply of reactants present, e.g. reactive organic matter in the surface sediment simultaneously produces several pyrite growth centers, which would prevent further growth of single units. Diagenetic, weakly reactive organic matter would produce only local growth centers, allowing for larger framboid formation.

Table 7. Trace element data (mg/g dw); (EB-1). Step VI denotes "residual" (res.) fraction, e.g. pyrite, organic matter, silicate minerals. Steps I-VI denote "total" (tot.) fraction (HCl - $KClO_3$) which was done separately and assumed to represent the phases I-VI

	VI	I - VI	VI	I - VI	I	I-VI	VI	I - VI	VI	I-VI	VI	I - VI
cm	**Co (res.)**	**Co (tot.)**	**Cu (res.)**	**Cu (tot.)**	**Mo (res.)**	**Mo (tot.)**	**Ni (res.)**	**Ni (tot.)**	**Pb (res.)**	**Pb (tot.)**	**Zn (res.)**	**Zn (tot.)**
2	15	20	83	80	26	152	30	45	30	76	92	348
4	43	34	112	113	62	136	77	75	69	102	384	631
6	37	54	62	89	34	97	57	85	73	115	285	618
8	20	24	39	66	10	42	39	52	52	60	169	299
10	21	25	34	59	11	42	39	54	39	59	131	230
12	19	25	33	60	9	34	36	118	39	67	116	195
14	15	21	40	60	11	36	38	121	34	60	109	181
16	16	16	39	46	8	14	37	42	29	42	99	104
18	20	24	46	64	20	31	46	58	40	48	132	127
20	12	16	51	60	7	25	36	50	27	50	103	129
22	18	23	45	54	14	30	34	49	26	46	87	118
24	19	22	56	64	17	38	51	60	33	54	114	140
26	22	21	42	50	22	34	43	46	32	46	100	115
28	15	18	48	52	27	32	40	46	27	43	89	112
30	19	22	49	50	26	39	45	50	20	48	85	111
32	31	22	55	59	32	50	48	54	23	43	76	124
34	28	28	55	59	44	56	51	56	32	45	102	137
36	19	21	53	55	37	49	41	44	26	38	86	114
38	23	25	64	73	58	71	48	53	32	49	96	114
40	25	23	58	57	50	68	44	44	26	45	79	101
42	27	28	77	75	63	82	50	62	27	50	95	123
44	23	26	57	58	63	79	42	48	23	39	73	106
46	19	21	56	59	27	42	38	45	19	38	70	104

The sulfur species may limit the sulfide formation in the Gotland Deep area, in agreement with that of Huckriede et al. (1996) and disagreement with the studies of Boesen & Postma (1988) and Sternbeck & Sohlenius (1997). The pyrite-Fe correlates fairly with that of total S (r = 0.77) but the stoichiometrical imbalance for the S_{tot}/S_{pyrite} ratio (3.4 ± 1.9, n = 21) is clear. The element limitations for sulfide formation may only concern certain part of the cores (Lepland & Stevens 1998). Due to the low content of the HAc-NH_4Ac leachable iron content in the uppermost sediment (< 10 mg/g) it is controversial, whether sulfur limitation in BY 15 area applies generally. The small amounts of reactive HAc-NH_4Ac iron species generally in sediment indicate that almost all reactive iron is used up for sulfidization process. The slightly higher reactive-Fe content in surficial sediments indicates only minor diagenetic FeS_2 formation.

The FeS_2-S is 1 - 2 % at BY-15. The reduced-S content in continental shelf areas is usually <1 % (Jørgensen 1989) and in permanently euxinic Black Sea sediments in the range of 0.5 - 1.5 % (Berner 1984). The salinity (and the sulfate content) in the Baltic Proper is only about 1/3 from that of normal oxic and anoxic marine sediments. Obviously the high organic matter accumulation (8-9 % of C_{org}; see Niemistö & Voipio 1974, Emelyanov 1988) is mainly responsible for higher pyrite content in BY-15 sediments.

CONCLUSIONS

(1) The BY-15 sample contained 5-10 times more S than that of EB-1. The higher sulfate and TOC content (e.g. Niemistö & Voipio 1974, 1981, Emelyanov 1988, Brügmann & Lange 1990) contribute sulfide content at studied sites.

(2) The content of the easily leachable "reactive" Fe fractions (Steps III-V) is considerably bigger at EB-1 site (10-30 mg/g) relative to BY-15 (5-10 mg/g). Probably the permanent oxic surface conditions at EB-1 allows the reoxidation of Fe(II) which may prevent "less reactive" iron transformation toward "more reactive" iron phases. The intermittent anoxia at BY-15 maximizes iron reactivity toward sulfide formation, thus preventing general iron limitation.

(3) Sulfides occur mainly as FeS at EB-1 site while FeS_2 and S^0 or S_{org} contribute virtually at BY-15. Probably the lack of S^0 prevents the conversion of FeS into pyrite at EB-1. This may be due to reoxidation tendency at the redoxcline.

(4) Authigenic Mn-carbonates coexist with total and pyrite sulfur proportionally at BY-15 site. The carbonate-sulfide behavior may represent changing environmental conditions over longer time periods in the Gotland Deep. The permanent surface oxic conditions at EB-1 oxidize TOC to CO_2 preventing carbonate formation there.

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Late- and Postglacial palaeogeomorphology on the Klaipėda submarine slope, southeastern Baltic Sea

Leonora Živilė Gelumbauskaitė

Abstract

The palaeogeomorphology of the Late-glacial and Postglacial history is described using high-resolution seismoacoustic profiles. The Late–glacial and Holocene sequence is divided into six seismic units that calibrated with existing cores and boreholes. The Late Pleistocene glacial and Holocene history of the Klaipėda submarine slope is reconstructed and with known Quaternary sequence compared. Paleochannels imprinted in the Late-glacial section are examined and buried drainage system interpreted. The interdependence between sub-Quaternary surface deformation, the Late- and Postglacial depositional and erosional processes and recent marine processes are studied.

☐ *Palaeogeomorphology, Baltic Sea stages, Late-glacial, Postglacial, Holocene, seismic units, incisions, Klaipėda submarine slope, south-eastern Baltic Sea, Lithuania.*

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INTRODUCTION

Detailed bathymetry shows that study area is located on the gentle (gradients 0.2°-0.3°) north-eastern slope of the Gdansk Depression, named the Klaipėda submarine slope with three steps at the depths of 71, 52 and 27 m respectively.

Recent plain of the submarine slope was formed by the Holocene sea level fluctuations. The interpretation of the biostratigraphical and lithological data indicates that this area represents nearshore zone surface of the Litorina-Ancylus-Yoldia stages (Blazhchishin et al. 1985, Kabailienė 1997, Kessel and Raukas 1982). A basical profile line has cut submarine slope beginning at the depth of 12 m and ending at the depth of 83.5 m (Fig. 1).

At present, the submarine plain is determined as an accumulation zone, mostly influenced by the sediment drift carried out from the Nemunas River into the open sea via the Klaipėda Strait. Going westwards along the line, a composition of the bottom sediments changes from the near-shore zone to the base of depression in a very uneven manner (Timofeev et al. 1978, Repečka 1999). Fine sand (0.25-0.1 mm) deposits spread only on the submarine coastal zone to the depths of 15 m. Towards offshore, at the depths of 15–64 m, extended coarse aleurite (0.1-0.05 mm) is found mostly as prodelta deposits. The terrigenous material is distributed variable and at the depths from 43 to 48 m some small fine sand spots lie at the center of this zone.

Normally recent marine depositional conditions were observed deeper than 64 m only. From 64 to 70 m fine aleurite (0.05-0.01 mm), from 70 to 73 m aleurite-pelite mud (<0.01 mm) and from 73 to 83 m pelite mud deposits were found to occur.

MATERIAL AND METHODS

Many studies covered both the Quaternary history of the Baltic basin in general, and the southeastern part of the Baltic Sea, in particular (Winterhalter 1988, 1992, Gudelis and Koenigsson 1979, Sviridov et al. 1976, Sviridov 1983, 1991, Kabailienė and Raukas 1993). For the last years Late Glacial and Holocene history of the Baltic proper is studied in a rather comprehensive way (Sohlenius 1996, Andren 1999), but not much in the eastern part.

There are differing opinions about depositional processes, glacial isostasy/eustasy and tectonics movements, as well as the origin of the sub-Quaternary surface. A discussion mostly gives the genesis of the paleoincisions not only in this area, but also in all cases of the Baltic basin (Ehlers et al. 1984, Boulton and Hindmarsh 1987, Gaigalas 1976, Atzler 1997, Jurgens 1999, Savvaitov et al. 1999). A glacial geology, particularly genesis of the paleoincisions, is characterized also for other European seas (Saettem et al. 1992, Brew 1997; etc.)

Material for this paper was collected during INCO-COPERNICUS MASS project in 1997-1999. A main goal of this study was to reconstruct palaeogeomorphology of the Holocene sedimentary cover on the Klaipėda submarine slope, based on high-resolution seismic records and data evaluation of existing cores. An important task was also to compare data obtained with the whole Quaternary sequence and to assess an implication of the Quaternary depositional and erosion history from rather different conditions of the recent sedimentation.

Seismoacoustic profiling has been done by the subbottom profiler 3010-S (Maritime Institute, Gdansk) and by single channel seismic reflection equipment, based on a PAR-600B airgun (Stockholm University). The sound velocity in water was taken 1448 m/s and in the uppermost sediments assumed to be 1850m/s.

Such a geophysical and geological survey has been carried out along the basical W-E 70 km line. Subbottom profiler, side scan sonar, echosounder and sediment sampling were used to determine seabed characteristics. Penetration of the profiler record varied from 10 to 25 m beneath the seabed. The sediment sampling cores were taken in the different bottom sediment conditions ranging from sand to mud, at the depths of 34.7, 65 and 82 m. Subbottom profiling records were interpreted with respect to following seismic units.

Seismic records as strong reflectors, penetrated in the Late-glacial and Holocene sequence, register differences in lithology and allow distinguishing seismic units. Seismic units I, II, III, IV, V, VI were calibrated by shallow cores and seabed sampling in the area studied (Majore et al. 1997, Timofeev et al. 1978). Suc-

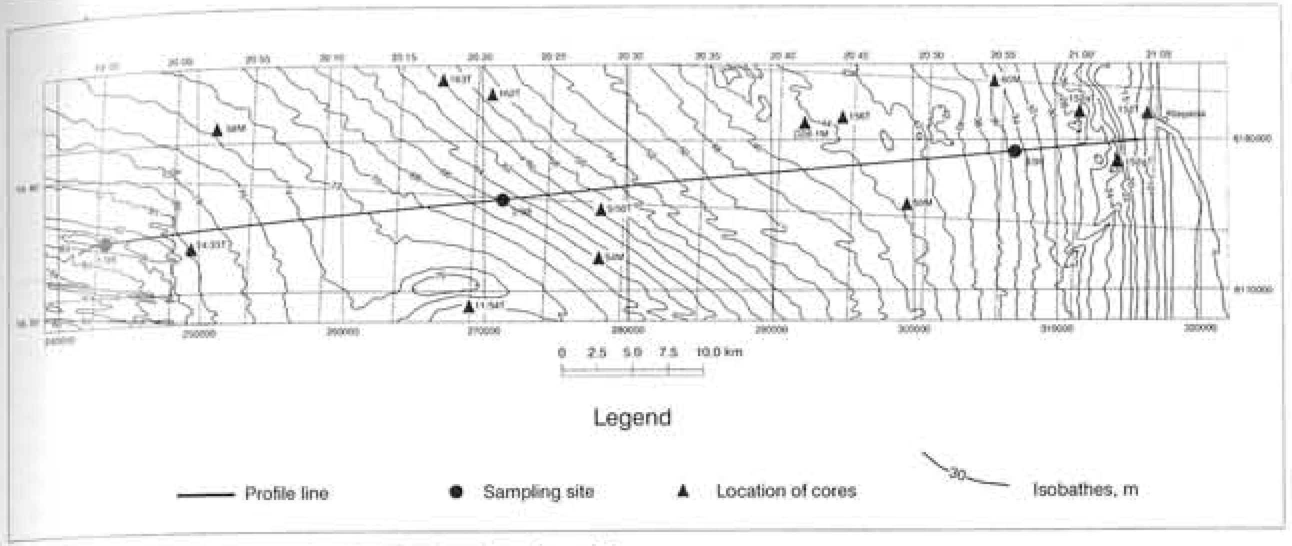

Fig. 1. Bottom topography of the Klaipėda submarine plain.

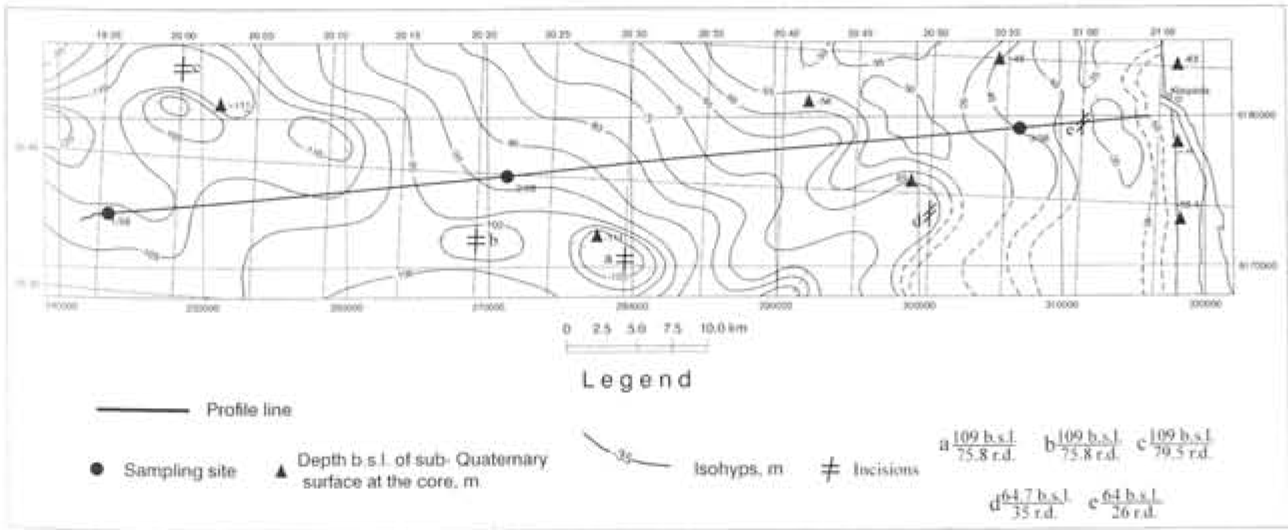

Fig. 2. Sub-Quaternary topography of the Klaipėda submarine plain.

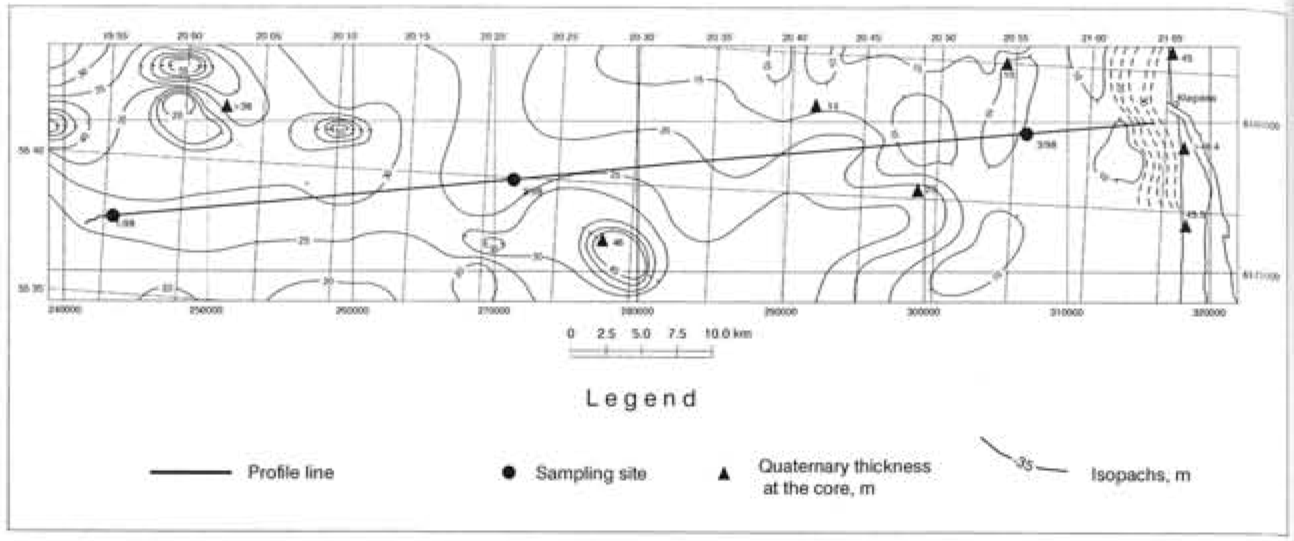

Fig. 3. Quaternary thickness of the Klaipėda submarine plain.

ceeding seismic units were interpreted from top to base: I-II as muddy-silty sediments (Postlitorina and Litorina stages), III-IV - homogenous and/ or laminated clayey-sandy sediments (Ancylus and Yoldia stages), V - laminated and homogenous glacial lacustrine clays (Baltic Ice Lake and Local Ice Lakes), and VI as loam till (Figs. 5, 6). These units were correlated with sub-Quaternary topography and Quaternary thickness compiled by interpretation of high resolution seismic data (Gelumbauskaitė 1997, 1999) (Figs. 2, 3).

The generalized geoseismic section was constructed and interpreted (Fig. 4).

RESULTS

Seismic unit I reflects chaotic internal structure and is more or less clearly seen on the whole recorded band (Fig. 5). Upper part of the seismic unit I has acoustic stratification on the bottom records, similar to tills, and differs from the other units. According to internal seismic reflectors this lithozone represents recessional glaciomoraine sediments. The top of this unit is uneven and for the whole seismic line is represented by five levels. Tracing eastwards along the seismic line, from deeper to shallow part of the basin, a lower level is distinguished at the depths of 83–71 m, the middle levels are determined at the depths of 70-52 and 48.6-44 m, and the upper levels - at the depths of 42-30, 30-26, and 25-12 m (Fig. 4). Along the traced unit I, the penetration of profile record of the lower and middle levels is 70-80 ms, and of the higher levels 35-40 ms (milisecond) approximately, where obstacle of the moraine, as cupola, push up and reaches present bottom surface. In the geoseismic section it makes the surfaces separated by steps of the relative depths of 21.1-14.6 m, 14.6-11.5 m, 11.5-6.6 and 6.6-2.0 m (Fig. 4). These levels have correlation with present and sub-Quaternary peneplain relief feature, compiled using study of high resolution seismic record and data of existing cores and sampling sites (see Figs. 1, 2, and 4).

Detailed bathymetry shows that submarine steps, distinguished on the present morphological expression, at the depths of 52 and 45 m, according to lithology and biostratigraphy data can be identified as steps, that represent shore lines of Yoldia and Ancylus lake regression. The shoreline of the first Litorina transgression is recognized at the depth of 27.0 m and is exposed on the slopes of the less steep hilly moraine relief. Steps on the sub-Quaternary relief represent three denudation surfaces at 100-90, 55-50, and 40-35 m b.s.l., marking peneplenization of Triassic, Jurassic and Cretaceous sedimentary rocks (Grigelis 1999).

Seismoacoustic profile demonstrates erosion character of the boundary between unit VI and overlying unit V. The erosion forms are found at the lower and the first of the upper levels. Bowl type erosion form was observed in the eastern part of the lower level, and channel segment was recognized at the first of the upper level surfaces (Fig. 4). The internal reflectors of the unit VI are rather short at the lower level and the erosion form, approximately at 10 m depth, is not sufficiently exposed. Comparison with the sub-Quaternary surface has showed a relationship between bowl type erosion form exposed in the upper part of the unit VI, lithozone of the till loam and paleochannel distinguished into sub-Quaternary relief, that cut through the lower level from east to west. For example, along segments a, b (seismic profiles 9403, 9402 at the sea depth 67 and 75.4 m; Fig. 2), there are two V-form channels recognized, approximately at 75.8 m relative and 109.1 m absolute depths and of 600-800 m width, inserted in the Upper Triassic surface, that is just eastward terminated by the limit of Triassic/Jurassic sedimentary systems, exposed on the seismic lines as cuestly relief (Bjerkeus et al. 1994, Gelumbauskaitė and Grigelis 1997).

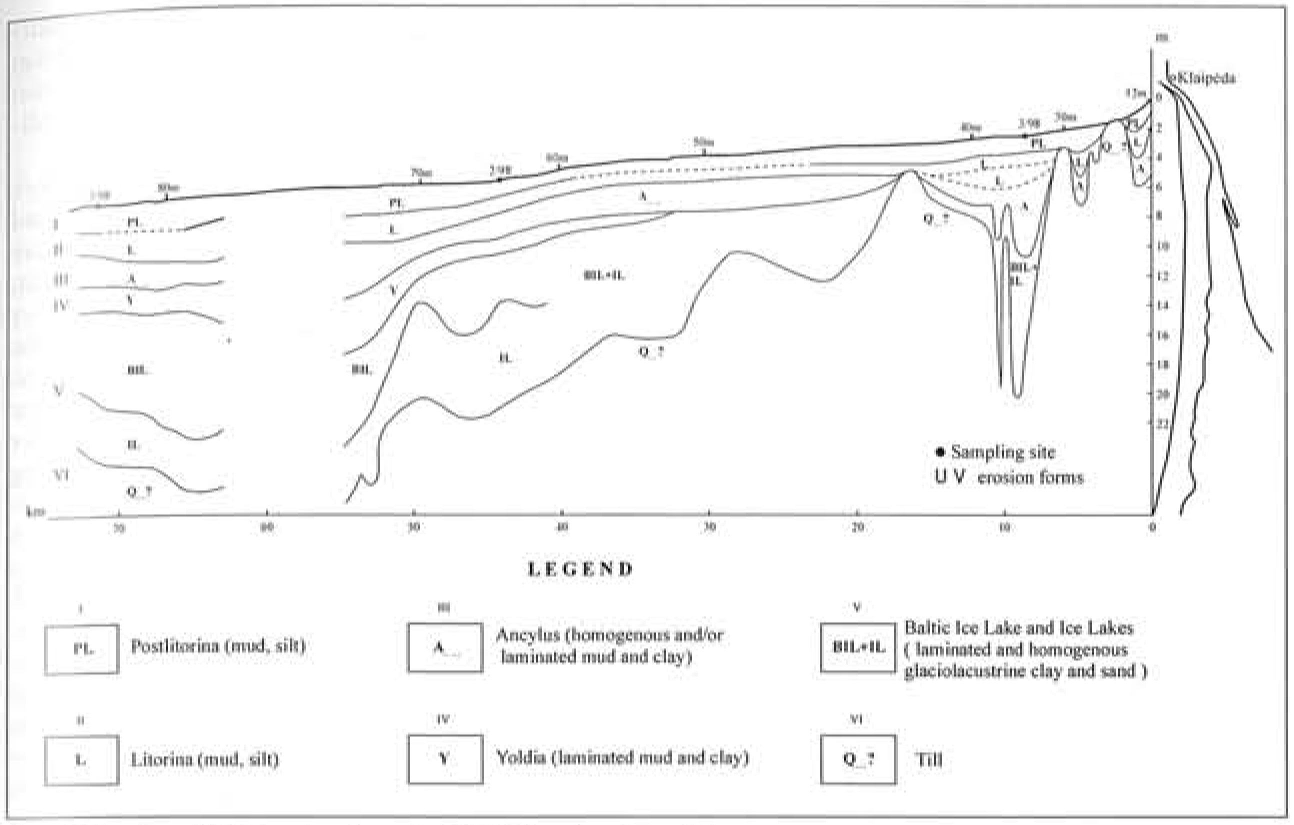

Fig. 4. Geoseismic W-E section along the Klaipėda submarine plain.

A similar morphology is recognized on the basical seismic profile segments, where the lower level is separated from the middle one by step, with the bowl type erosion forms expressed at the base of the step (Figs. 5, 6). In the borehole 54M (sea depth 65 m, ca. 1.5 km westwards from point a), there is a sub-Quaternary base achieved at the absolute depth of 111 m. The Quaternary sequence (46 m thick) consists of 10 m mud, 10 m clay, and 26 m till (Q_I, Q_{II}, Q_{III}) with silt interlayer (Q_{II}/Q_{III}). Hence, a channel (segment a; Fig. 2) is possibly infilled by the Lower and Middle Pleistocene tills and in the upper part is overlain by the interglacial Q_{II}/Q_{III} deposits. The seismic record shows that Late Weichselian till and younger sequence is overlain entirely. Third, the same channel segments are observed at the sea depth of 73.9 m (segment c, relative depth 79.5 m, absolute depth 109.1 m, width 800 m; Fig. 2), related to borehole 58M.

A different view can be seen in the shallow area, partly at the upper levels of the basical seismic line, where lower seismic units truncate. The incision is here distinct in the upper part of till loam, but, it is trending towards the coast in the pronounced, eroded depression. Here is a well-developed internal acoustic stratification. The present seismic line, at the sea depth of 38 m, has a V-shaped incision recognized, approximately 10-m deep and 220-m wide, cutting into erosion valley of the second generation (Fig. 6, 4). The incision is basically in the same location as the channel recognized on the sub-Quaternary surface and interpreted on the segment e (seismic line SP III 46-6; see Fig. 2). Here, the V-formed channel, approximately 500-m wide, is deeply inserted into Cretaceous substratum about 26 m (Gelumbauskaitė 1999). The same channel, as interpreted on the segment d (profile 9405), is inherited in the Jurassic substratum ca. 35.1 m and filled by till (Fig.2).

Unit V that overlies unit VI is recorded on the whole seismic line as a strong reflector, representing more or less one lithozone. The coherent, draping internal stratification is not likely developed under subglacial conditions, and confirms that this seismic unit consists of glaciolacustrine (IL - lower subunit, and BIL - upper subunit) clays. This seismic unit in the western part, at the lower level, is distinguished between 45-60 ms, that equals approximately to 9.5 m in thickness (in the area of the 1st location a lower interval is 4.2 m, and upper interval is up to 5.3 m, see Fig. 5).

Some boreholes are drilled close to the seismic line (Majore et al. 1997). For example, the borehole 58M (at a sea depth of 73.5 m, NW from basical line, in the traced channel on the sub-Quaternary surface) fixed thickness of clay up to 18 m. The boundary between subunits traces to the 2nd location (Fig. 4). The lithozone of the IL in the area of the 2nd location, at a sea depth of 65.0 m, is 7.2 m thick, and the lithozone of the BIL is 3.1 m thick. According to the data of the borehole 54M (at sea depth 66 m), thickness of clay sequence is 10 m. Going eastwards to the coast, the boundary between subunits discontinues.

The lower subunit, related to glaciolacustrine (IL) clays has more irregular, in same places chaotic internal or transparent structure specific for glaciofluvial deposition, that is claimed also by drilled cores. According to the core data, Late Glacial deposits in this area are mainly composed of sand, gravel and pebble (Kabailienė 1997).

The upper subunit is exposed well. The surface with coherent, draping internal stratification is recognized as lithozone of laminated clays formed during Late Glacial, the Baltic Ice Lake stage. The thickness of this surface reduces from the 2nd location followed to the coast. This surface is completely missing at a depth of 43 m, where obstacle of the moraine bodies is prominent in the present topography. At the highest levels Late Glacial deposits are recognized as infilling in two bowl type depressions within the depth ranges of 42.0-30.0 m and 30.0-27.0 m with the first one containing Late Glacial deposits approximately 8.0 m thick.

The boreholes and cores drilled offshore in the shallow area and in the Curonian Spit show very uneven and different Late Glacial—Holocene section, that constitutes different paleogeography conditions. According to the core data, in same places, for example at the station 156T, the Holocene thickness reaches only 50 cm. We have found a parallelism between Quaternary and Holocene thickness and sub-Quaternary morphology in this area. The Quaternary is less than 10 m thick, on the higher structural terrace reshaped by two ridges and there is a thin cover of the Holocene sedimentation spread (see Figs. 2, 3, 4).

The units IV and III overlying the unit V, are more homogenous in the seismic records as the units VI and V. Rather weak, but regular continuous reflectors are recognized on the whole seismic line. The coherent, laminated internal stratification is detected at the lower level, and irregular discontinuous reflections - at the middle level. Seismic unit IV correlates with the lithozone of Yoldia Sea. On the Lithuanian coast the Yoldia Sea transgression is characterized by a low water level, semi-brackish or only fresh-water basin varying in size. At the lower level, the 1st location shows this seismic surface between 60-65 ms, that equals to 1.6 m thickness (Fig. 5). Eastwards, the thickness increases to 3.85 m, but at 70 m depth, the unit IV, as units I, II, III, push up to 5 m, making a step. Farther eastwards, at the middle level, the thickness of the unit IV reduces to 1.0 m and at the depth 52 m completely wedge out (Fig. 4). According to the core data, deposits of the Yoldia Sea in this area are composed mainly of greyish mud with aleurite interlayer and approximately reaches only 1.0 m. For example, thickness of deposits at a sea depth of 70 m is 1.0 m (core 11/54T), at a sea depth of 59 m (core 9/50T) it is 1.59 m, and at a sea depth of 60 m (cores 163T, 162T) it exceeds 1.0 m. Completely the Yoldia marine deposits are absent in the supramarine, coastal area higher than 50 m deeps (Blazhchishin et al. 1976, Kabailienė 1997, Kessel and Raukas 1988). Hence, the segment at the middle level can be interpreted as submarine shore formation of the Yoldia Sea, mainly deposited by sand and traced at the depths of 70-52 m. The step, distinguished at a depth of 52 m, can be characterized a shore line of the Yoldia Sea.

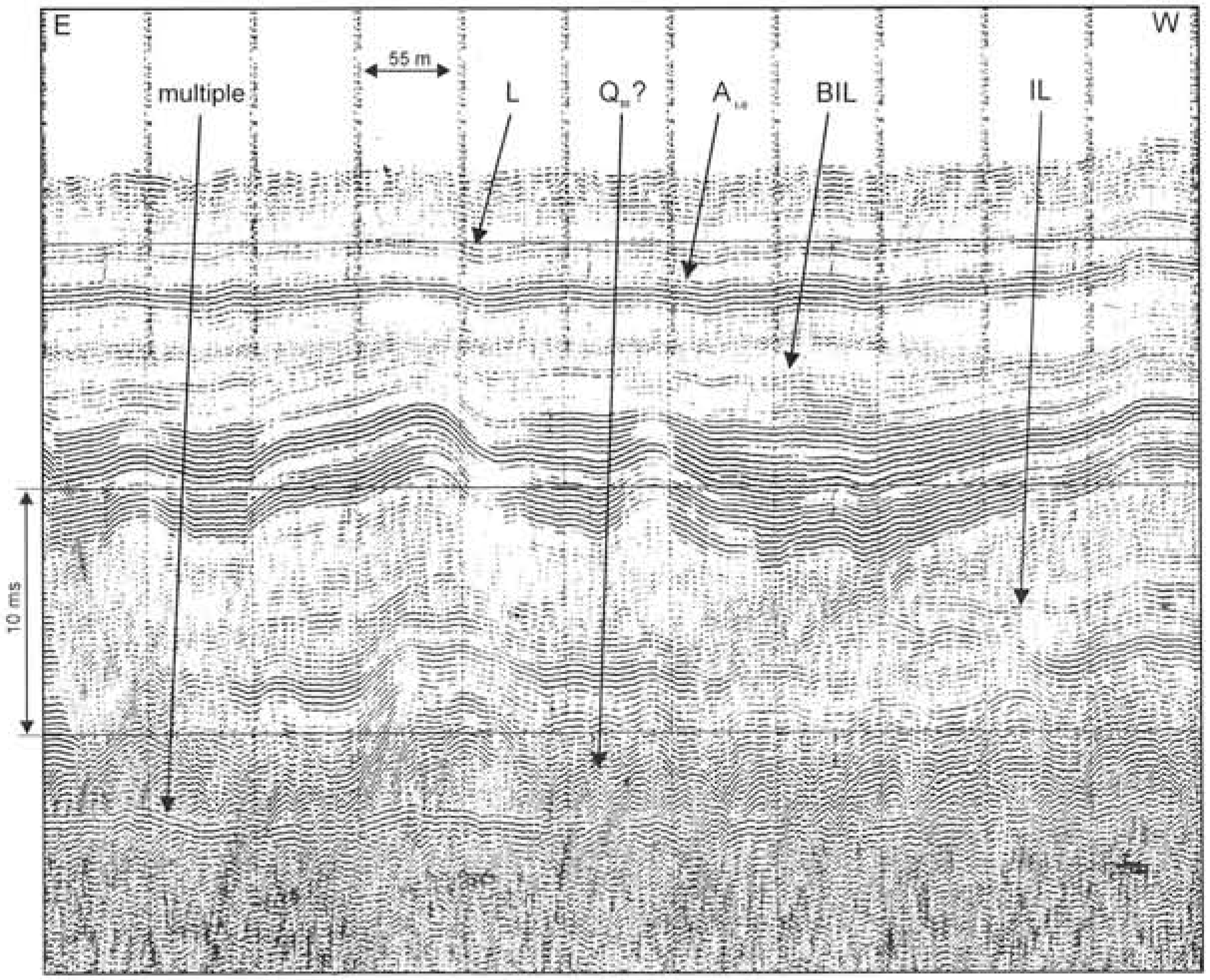

Fig. 5. Seismoacoustic profile, area of sampling site 1/98, depth 82.0 m.

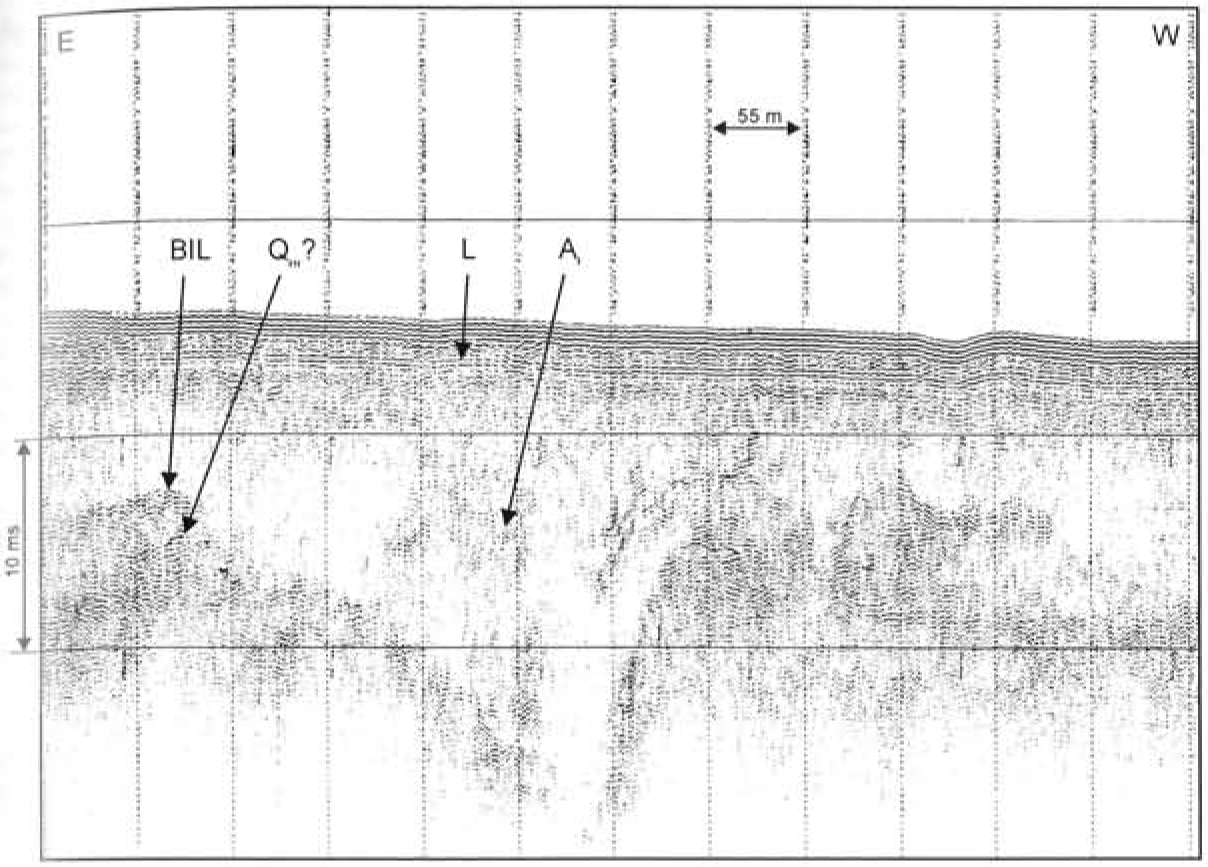

Fig. 6. Seismoacoustic profile, area of sampling site 3/98, depth 34.7 m.

The Unit III is distinct so well as the underlying unit IV. The boundary of units IV/III is commonly connected with regular continuous reflections and well recognized. The seismic unit III correlates with the lithozone of the Ancylus Lake phases. At the lower level, in the 1st location, seismic unit III lays between 62-66 ms (approximately 2.1 m thick; see Fig. 5). Going eastwards, the thickness increases up to 3.85 m, as all sesimic units at the the base of the step (see Fig.4). The seismic unit III is acoustically transparent up to the middle levels, mainly showing irregular discontinuous reflections. The thickness of Ancylus Lake phases varies from 1.7 to 2.0 m. According to the core data, the thickness of the Ancylus Lake deposits ranges at the lower level from 0.35 cm at the site 11/54T to 1.0 m at the site 162T, and reaches only 0.20 cm in the core 156T at the middle level, at the depth of 42.0 m. The boundary between sediments of transgression and regression phase in the internal acoustic stratification cannot be traced, but there is a recognized wedge-out of the first subunit at the depth of 45.0 m , and a downlap the second subunit of the Ancylus Lake lithozone at the depth of 43.0 m near moraine cupola (Fig. 4). The wedging-out of the first subzone at the depth of 45 m can be interpreted as a limit of the Ancylus Lake regression that is claimed by the biostratigraphy.

At the upper levels, unit III is distinguished in the bowl type depressions (Fig. 6).This lithofacies, infilling depressions to 5.0 m thick, has more faint, transparent reflections. Comparison of seismic data with biostratigraphy and geomorphology data indicates that lithozone corresponds to the shore zone of Ancylus Lake transgression. This interval can be interpreted as a result of sea level fluctuations with fluvial erosion in Boreal time into the shore zone faces.

Seismic unit II, overlying the unit III, and seismic unit I, overlying the unit II, are exposed on the upper part of seismic records (Figs. 5,6). The internal reflectors are similar in the units and have more or less homogenous: weak bedded structure on a whole-recorded band. The boundary reflectors of the units II/I have been identified well at the lower level and correlate with lithozones of the Litorina and Postlitorina seas, composed mainly of mud and silt at the lower and middle levels. In the area of the 1st location these seismic units are between 63-60 ms and 60-57 ms, respectively, and their thickness consist approximately L- 1.4 m/PL – 2.0 m. A similar thickness was found in the core 14/33T, where thickness of Postlitorina Sea deposits reaches 2.45 m and Litorina – only 1.0 m. These seismic units are acoustically transparent or have irregular reflections, and boundary between units II/I is not recognized at the depths from 56 m to 46 m at the middle levels. In the core 9/50T (depth –59 m), PL is 0.20 cm, L is 2.30 m.

The discontinuous irregular reflections of the units II and I are exposed at the highest levels. The units can be interpreted as lithozones into the shore facies of the Litorina-Postlitorina marine basins deposited mainly of sand. The lithozone of the Litorina Sea finally makes smooth relief of the depressions, and Postlitorina sediments, in this geoseismic section, equally overlay lithozone II. In the area of the 3rd location, where the boundary between L/PL is commonly diffused, general thickness reaches 3.2 (Fig. 4). According to the core data, the thickness of deposits varies from 0.20 cm at the site 156 to >4.0 m at the site 152b, and the surfaces are uneven here. Comparing with Quaternary thickness and sub-Quaternary morphology, the parallelism can be found between sub-Quaternary peneplaine ridges, Quaternary thickness and thickness of the post-glacial sedimentation pattern.

CONCLUSIONS

The Late-glacial history and Holocene sedimentation conditions on the Klaipėda submarine slope, the southeastern Baltic Sea, are studied using shallow seismic data and geological sampling, where very uneven sedimentation during Holocene sea level fluctuation, probably resulted from glacioisostasy/eustasy and tectonic adjustments due to depositions.

According to our data and correlation with the Pleistocene stratigraphic units in this area, the unit VI, recognized as till loam, is formed during the Baltija recessional phase of the Upper Nemunas glaciation (Late Weichselian). The surface expressed in three steps is related with sub-Quaternary and present morphology.

A bowl type erosion form is observed in the eastern part of the lower level of the unit VI, close to the step, it can be interpreted as an erosion form of the periglacial drainage, formed during Local Ice Lakes stage in the Bölling time. This erosion segment is located in the same place as palaeochannel segments a, b, c, inserted into the sub-Quaternary surface and recognized by many authors as Pra-Nemunas valley. The intercalibration with existing boreholes shows, that Lower and Middle Pleistocene tills and Middle/Upper Pleistocene interglacial sediments fill the paleochannel. The Late Weichselian sediments and younger sediments overlay the channels entirely. The channels reshaped Upper Triassic denudation surface on the Klaipėda submarine plain approximately to the depths of 60-80 m. They have the same face as the channels imprinted in the Upper Devonian sedimentary rock surface on the eastern slope of the Gotland depression (Bjerkéus et al. 1994, Gelumbauskaitė 1994, 1997).

The incision at the first of the upper levels, regarding its genesis, is more or less different from those at the lower level. This incision with roots in the Cretaceous substratum is less deep (approximately 30 m), and can be interpreted partly as subglacial, partly as periglacial erosion form, which appeared during the Late Glacial. During Holocene, until the first Litorina transgression, in the Pre-Boreal and Boreal time, a fresh fluvial valley seems to be formed at the lowermost level of the Yoldia Sea and Ancylus Lake stages.

According to our data, with regard to the form, depth, infilling and interrelationship of paleochannels, we cannot recognize that subglacial processes have formed them only.

The basin deposition of the Baltic Ice Lake, Yoldia Sea, Ancylus Lake transgression/regression phases was recognized at the lower level at the depths of 83-71 m and partly at the middle level at the depths of 70-60 m only. Going upwards, the deposits of the Yoldia Sea and Ancylus Lake were mainly composed of sand and can be interpreted as submarine shore formation. The unit IV and subunit III wedge out on the steps at the depth of 52 m and at the depth of 45 m, respectively. According to the biostratigraphy data, these lines are characterized as shore lines of the Yoldia Sea and Ancylus Lake regression. The shoreline of the first Litorina transgression is recognized at the depth of 27.0 m on the slopes of the less hilly moraine relief.

Reconstruction of the Postglacial and Holocene conditions based on the geoseismic section seems to be complicated mostly at the upper levels. Full section of the Holocene deposition is recognized in the small seabed depressions only. In the shoreface zone sedimentation pattern of the Litorina/Postlitorina seas fluctuates from 2.0 m to 0.0 m (at the depth of 26.5 m the Holocene cover wedges out to 0.0 m) and has no direct connection with the recent morphology and hydrodynamics. The deposition can be interpreted as having been associated with the tectonics that occurred after the glaciations.

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Palaeobaltic Middle Pleistocene Ulmale Sea in Latvia

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Abstract

The eastern part of palaeobaltic Ulmale Sea occupied the space of recent maritime area in Western Latvia and adjacent part of the Baltic Sea too in the Middle Pleistocene including Pulvernicki (Holsteinian) Interglacial as well as Early Kurzeme (Saalian) Glaciation (periglacial). The sediments of this palaeobasin (Ulmale Formation) with thickness from 0 to 70 m and more are widespread practically uninterrupted in the Quaternary of the northern part of the Western Latvia. The age of marine thickness is determined based on the composition and sequence of the spore and pollen complexes. The foraminifers, ostracodes and diatoms, contained in the sediments and their distribution features allow to consider, that a large part of this thickness had been formed in desalinated and freshwater conditions of the basin. The open sea conditions characterize the sediments of lower part of total marine thickness only, which are rich in foraminifers and marine species of diatoms. The sediments of the Ulmale Formation in the southern part of Western Latvia preserved only on separate sections along and entire palaeovalley incisions as well as on other small rare sections. The sediments of this Formation are preserved in the deep incisions and a deep depression in the area of the Baltic Sea too, where they occur within the Quaternary under two till layers, but in the area of elevations observed in the bedrock surface they are not preserved.

☐ *Intertill marine sediments, Middle Pleistocene, Holsteinian, Early Saalian, Ulmale Sea, Ulmale Formation, Western Latvia, Baltic Sea.*

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INTRODUCTION

The sediments, which far later were determined as marine formation of the Middle Pleistocene, are known in Latvia for a long time ago. These sediments, underlying gray till and often represented by strongly deformed layers of sand and silt, had been observed by A. Dreimanis in the bluff of the Baltic Sea in 1936 (Dreimanis 1936, 1999). However, at that time the marine origin, total thickness and area of the distribution, age and sequence of its in Quaternary were not studied.

For the first time the marine sediments represented by gray silt, containing shells of *Portlandia* and *Astarte* as well as the foraminifers, had been established in the Kolka borehole (northern part of Kurzeme Peninsula) by V. Ulsts and J. Majore in 1964 (Ulsts & Majore 1964).

The marine sediments with abundant shells of *Portlandia* and foraminifers were investigated in Central Latvia (Konshin, Savvaitov, Nedesheva & Dzilna 1969). The ESR determination (Dreimanis, Molodkov, Āboltiņš & Raukas 1998) allows to consider their age as Early Weichselian, however.

The numerable finds of single shells of *Portlandia arctica* Gray and basically their fragments in glacial sediments (tills and bedgravels) of Latvia were removed from the sediments of so-called Portlandia Sea (Riss-Würm) by the Last Ice Sheet (Zāns & Dreimanis 1936, Dreimanis 1949).

The largest area of the *in situ* distribution of the Middle Pleistocene intertill obvious marine sediments, the upper part of which had been observed by Dreimanis in 1936, is situated in the Western Latvia maritime region (Konshin & Savvaitov 1969, Savvaitov, Veinbergs, Krūkle 1971). This marine thickness occurs in the adjacent part of the Baltic Sea too. The marine sediments have the name of the Ulmale Formation (Danilāns 1973), but the sea itself may be called as the Ulmale Sea.

MATERIAL

Authors investigate the sediments of the Palaeobaltic Middle Pleistocene Ulmale Sea in Latvia since 1965. Original materials of these investigations in the onland area (the structure of Quaternary and the marine thickness, the data of studied spores-pollen spectra, diatoms and foraminifers, ostracodes in separated sections and their comparison between studied sections) are mainly used in the present paper. Original data of the interpretation seismic reflection profiling in some regions were also used, and for the first time they allowed to draw the distribution of the Ulmale Sea sediments in adjacent part of the Baltic Sea. Besides, all basic published materials of Latvian and Lithuanian researchers, who studied the intertill thickness of this Formation, are used and discussed by authors. According to all mentioned data, the structure, distribution, age, history and conditions of the formation of the sediments of the palaeobaltic Middle Pleistocene Ulmale Sea in Latvia are characterized below in detail.

ULMALE SEA SEDIMENTS

The regional features of the distribution of the Ulmale Formation sediments are close connected with the topography of the sub-Quaternary surface. Fig. 1 shows the principle scheme of total distribution of the Ulmale Formation sediments. The probably eastern boundary of the Ulmale Sea is also drawn on this scheme.

It is referred in the first place to the area of a large Ziemupe-Ovīši Depression in the bedrock surface located to north of Ziemupe. The onland part of this depression is about 112-115 km long and up to 20-25 km wide. The depression is opened towards the Baltic Sea, and stretching in a meridional direction. The altitudes of the bedrock surface within the onland depression limits decrease from plus 0-10 m (in edge part) to minus 60 m and even more (deep center part), but they reach less than minus 140-150 m in the incisions of the ancient valleys. The change of the Ulmale Formation thickness in this area, as a rule, is hardly connected with the altitudes of the bedrock surface. Maximal thickness of the marine sediments (to 70-80 m) is related to the deeper part (the region between Akmeņrags and Užava) of the Ziemupe-Ovīši Depression, as well as deep incisions of ancient valleys in the bedrock surface (to 90-120 m). The marine stratum is only about 10 m thick between Ventspils and Ovīši, where the altitudes of bedrock surface are about minus 10-30 m. The thickness decreased more and even absence of the marine sediments is observed in the eastern edge part of this Depression.

Besides, the occurrence of the Ulmale Sea sediments probably can be supposed in the southern maritime part of Western Latvia also. Here, in comparison to the northern region of Western Kurzeme, they occur in a small part of the Ulmale Sea only and are basically located in deep palaeoincisions and depressions. The thickness of the Ulmale Formation in the sections of the palaeoincisions reaches 73-105 m. Separate rare preserved remains of these sediments in the area of bedrock surface watersheds are about some meters thick only. The sub-Quaternary surface for the areas of the distribution of the Ulmale Formation sediments in southern regions of Western Latvia lies at the

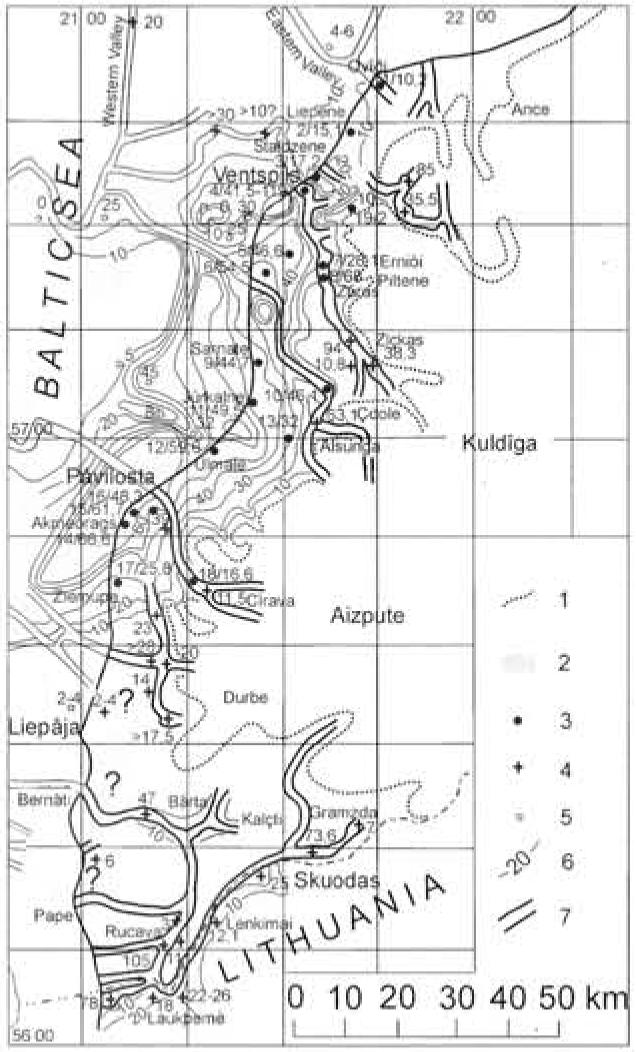


Fig. 1. The Ulmale Sea and Ulmale Sea Formation sediments distribution in the Western Latvia and adjacent part of the Baltic Sea (principal scheme). 1-probably eastern boundary of the Ulmale Sea; 2-areas with distributed sediments of the Ulmale Formation; 3-detail investigated borehole locations, number and thickness (m) of the Ulmale Formation: 1-Ovīši, 2-Liepene, 3-Staldzene, 4-Ventspils, 5-Varve, 6-Lībciems, 7-Zūras, 8-Erniņi, 9-Sarnate, 10-Dzintari, 11-Jūrkalne, 12-Ulmale, 13-Alsunga, 14-Akmeņrags, 15-Sudrabi, 16-Ozoli, 17-Ziemupe, 18-Cīrava, 19-Oši; 4-some another borehole locations with suggested sediments of the Ulmale Formation and its thickness (m); 5-thickness of the Ulmale Formation on the area of the Baltic Sea according to data of seismic reflection profiling (after A. Samburg and F. Kovalenko 1982, 1984, Juškevičs, V., Kondratjeva, S., Mūrnieks, A. & Mūrniece, S. 1997, 1998); 6-isopachytes of the Ulmale Formation (m); 7-incisions of ancient valleys or palaeochannels.

following altitudes: for bottom incisions - minus 105 m and for watershed areas - from minus 20 m to plus 0-10 m. The occurrence of the Ulmale Sea sediments can be supposed in the adjacent part of the northwestern Lithuania also. Here thickness of intertill formations observed is about 15-20m, and in palaeoincisions it reaches 80-85 m (Kondratienė 1971, Bitinas, Damušytė & Stančikaitė 1996).

The distribution of the Ulmale Sea sediments in the Latvian area of the Baltic Sea can be discussed in a schematic way only. Nearshore distribution of these sediments in adjacent part of the Baltic Sea in the area of 11-12 km wide has been investigated by A. Samburg and F. Kovaļenko in 1982 and 1984. These data were used for the compilation of geological maps for the areas of Liepāja and Ventspils sheets on a scale of 1:200000 by V. Juškevičs and S. Mūrniece also (Juškevičs, V., Kondratjeva, S., Mūrnieks, A. & Mūrniece, S. 1997, 1998). According to the abovementioned investigators, the sediments of the Ulmale Sea are widespread along the nearshore in the northern part only, but they are usually absent in the southern part. It seems, that the sediments of the Ulmale Formation in the bottom area of the Baltic Sea, adjacent to the southern part of Western Kurzeme, had been preserved from glacial exaration and basin abrasion in the Liepāja Depression and in the deep palaeoincisions only.

The distribution of thickness of the Ulmale Formation sediments in the bottom area of the northern part of adjacent Baltic Sea is complicated. The thickness of the Ulmale Formation sediments onland clearly is decreased and thinned out in the nearshore zone. The boundary of the Ulmale Formation thinning out is correlated with the position of the eastern slope of the Pāvilosta-Užava Elevation, but the Ulmale Formation sediments in the top area of this Elevation seem to be practically absent. Besides, the Ulmale Formation sediments in the areas of the Ventspils, Western and Eastern Ovīši Elevations are absent also. However, their strata in the sections of deep incisions (Eastern, Western, pra-Venta, pra-Užava, Aizpute palaeovalleys, *ect.*) and in the depression stretching along them.

The general stratigraphical position of the Ulmale Formation in the Quaternary has been well investigated in the onland part of the Ziemupe-Ovīši Depression. The marine strata in this region lie above bedrock surface or brown till of Letīža (Elsterian) Glaciation (from some meters to 15-20 m and over). The brown Late Letīža (Elsterian) limnoglacial clays (to some meters) are also often observed in local areas between marine sediments and Letīža till. The gray till of Kurzeme (Saalian) Glaciation (usually to some meters and seldom to 10-40 m) overlies the marine sediments as a rule. However, there are many sections known, where Kurzeme till is absent and the marine strata are overlain by younger sediments of the Late and Post Glacial. The different sediments - till of Latvia (Weichselian) Glaciation, Late Glacial silt and clay, Post Glacial sediments of the Baltic Sea Stages, *etc.* occur above Kurzeme moraine. The till of Latvia Glaciation in a large area of the maritime regions is washed out by waves of developing Baltic Ice Lake and Holocene Stages of the Baltic Sea too; therefore it had been preserved on separate sections only. The position of marine sediments between tills of Letīža and Kurzeme Glaciations is observed in the Quaternary of the ancient valley incisions too.

The Ulmale Formation sediments in a general geological section for the area of the southern part of Western Latvia lie between Kurzeme and Letīža tills. It can be seen in the regions of Rucava, Nica, south of Gramzda, etc., where the sediments of the Ulmale Formation are preserved within the incisions of the ancient valleys.

The sediments of the Ulmale Formation in the area of the Baltic Sea, preserved from glacial exaration in palaeovalley incisions on separate sections, lie under two layers of tills (Eastern and Western Valleys). The upper layer of the till belongs to Latvia Glaciation and lower - to Kurzeme Glaciation. The analogous stratigraphical position of intertill sediments had been dissected by borehole 37 in the Baltic Sea (Majore, Riņķe, Savvaitov & Veinbergs 1997). According to V. Juškevičs the thickness of the Ulmale Formation in the area of the Baltic Sea 15 km to northwestwards from Jūrkalne spreads under one till only (Kalniņa, L. 1999). The thickness of the intertill Ulmale Formation sediments in the sections of palaeovalleys known at the bottom of the Baltic Sea can reach and exceed 30 m.

The intertill sediments of the Middle Pleistocene (the OSL determinations - 127000±14000 - 145000±19000 BP) underlying Saalian till are shown by Bitinas, Repečka & Kalniņa also (1999).

The great deserts in the study of the Quaternary and the marine strata structure belong to S. Mūrniece, who had been mapping Pāvilosta area on large scales. Two lithologically different parts - lower one basically represented by silt, and upper one by sand are well distinguished within the intertill total basin thickness in the Piemares lowland between Akmeņrags and Sārnate (Juškevičs, Kondratjeva, Mūrnieks, Mūrniece 1998). The lower part is named Akmeņrags (Segliņš 1987 a, Meirons 1992, Kalniņa 1993, 1999, Dreimanis & Zelčs 1995) and the upper part - Jūrkalne (Meirons 1992, Kalniņa 1993, 1999, Dreimanis & Zelčs 1995) or Staldzene (Segliņš 1987 a).

BIOSTRATIGRAPHY

The marine sediment strata spreading in the maritime region between Ziemupe and Ovīši have been studied by many borehole cores and outcrops. The samples from drill cores have been analyzed by palynological method. The microfauna and diatoms, contained in the sediments, have been investigated too. Systematical pollen analyses and investigations of plant macrofossil assemblages are of utmost importance for the biostratigraphy of marine sediments. Pollen analyses for the studied sites were carried out by M. Neimane, V. Ozoliņa, L. Kovaļenko, I. Jakubovska, L. Kalniņa. The foraminifers, marine species of ostracoda and diatoms, contained in sediments, are certain indicators of marine genesis of the sediments (Konshin, Savvaitov 1969, Konshin, Savvaitov & Slobodin 1970, Veinbergs, Savvaitov, Krūkle 1971).

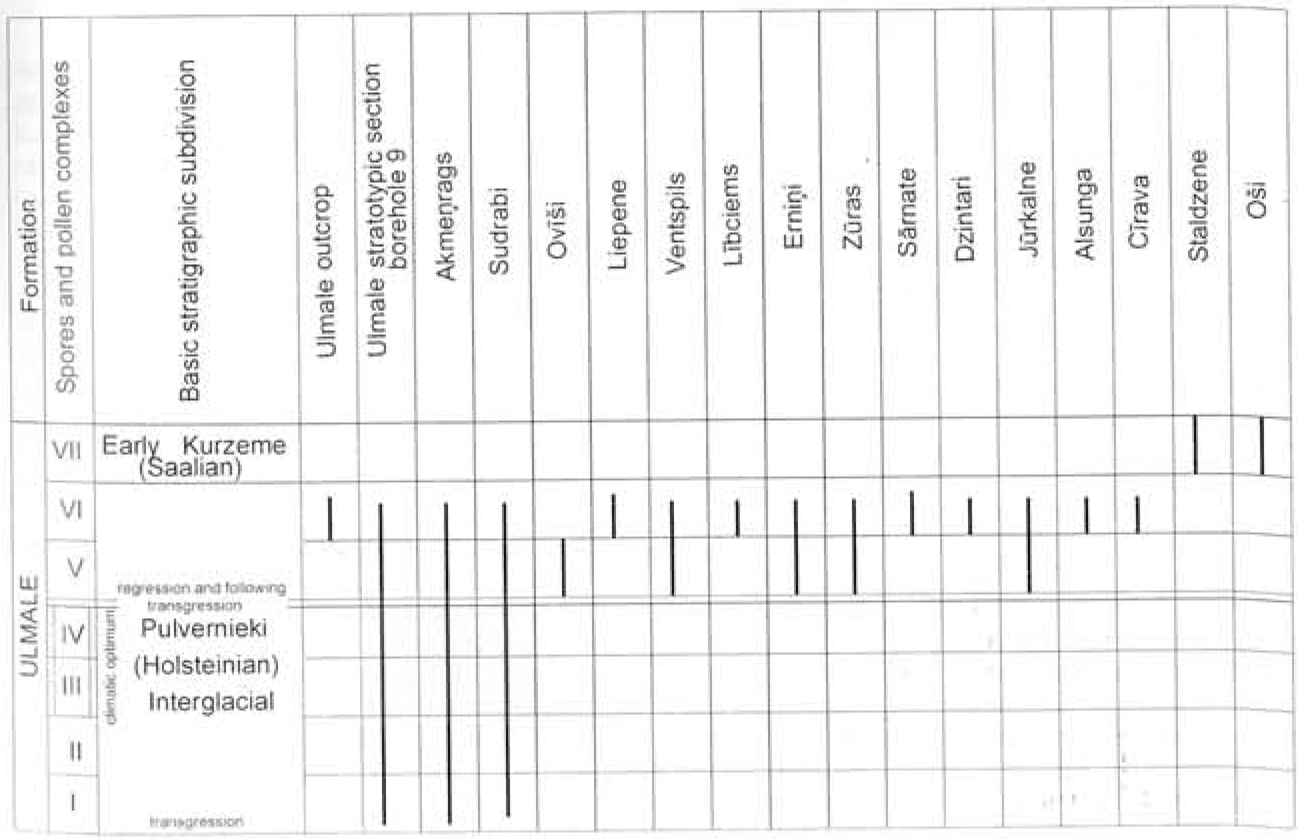
Seven spore and pollen complexes have been established in the total section of the marine sediment strata (from low to up): I-*Pinus, Betula, Artemisia*, II-*Pinus, Betula*, III-*Alnus, Carpinus, Corylus, Pinus, Betula, Quercetum mixtum*, IV-*Pinus, Alnus, Picea, Abies*, V-*Pinus*, *VI-Pinus, Betula*, VII-*Pinus, Betula, Artemisia, Chenopodiacea, Sellaginella selaginoides* Link. VI and VII complexes are subdivided into separate subcomplexes. Optimal complexes of the vegetation are III and IV (climatic optimum).

The correlative scheme of the sections investigated for Western Latvia between Ziemupe and Ovīši is shown in Table 1.

The Ulmale site (borehole 9 near Ulmale) is the section, where the stratigraphy of the marine strata was researched in first (Konshin, Savvaitov & Straume 1971). This section has principal significance for age determination and identification of the sediment genesis as well as it is the base for correlation of all investigated sections. According to the results of the Ulmale stratotypical section study there are six sequences of spore and pollen complexes (I-VI), characterizing the sediments of total marine thickness. It is obviously belonging to Pulvernieki (Holsteinian) Interglacial by the development of vegetation (Konshin, Savvaitov & Straume 1971). The optimal part of spore and pollen diagram is reflected by III and IV complexes. They are similar to the subzone P_{2b} and zone P_3 from stratotypical Pulvernieki section of the Pulvernieki (Holsteinian) Interglacial (Danilāns 1973). The list of the plant macrofossil assemblages from the sediments of the upper part of total marine thickness in the Ulmale section (VI spore and pollen complexes, Jūrkalne part of the Ulmale Formation) contains *Salix polaris, Salix herbacea, Salix reticulata, Betula nana, Dryas octopetala, Selaginella helvetica, Selaginella selaginoides, Sparganium hyperboreum* as well as *Azolla interglacialica* Nikit., *Caulinia goretskyi, Carex paucifloroides, Bransenia borysthenica, Ranunculus sceleratoides, Larix* sp., *Salvinia natans, Zannichellia palustris, Elatine hydropiper, Carpinus betulus* (Ceriņa 1987, 1993). These data allow to consider, that the upper part of the Ulmale Formation is related to the end of the Pulvernieki (Holsteinian) Interglacial as well as to following transitional and beginning stages of the Early Kurzeme (Saalian) time.

Practically analogous spore and pollen diagrams characterize the marine sediments dissected by boreholes in the region south of Ulmale. There are three

Table 1. Correlation of the Ulmale Formation between the sections by palynological data



Formation	Spores and pollen complexes	Basic stratigraphic subdivision	Ulmale outcrop	Ulmale stratotypic section borehole 9	Akmeņrags	Sudrabi	Ovīši	Liepene	Ventspils	Lībciems	Erniņi	Zūras	Sārnate	Dzintari	Jūrkalne	Alsunga	Cīrava	Staldzene	Oši
ULMALE	VII	Early Kurzeme (Saalian)																│	│
	VI		│	│	│	│		│	│	│	│	│	│	│	│	│	│		
	V	regression and following transgression		│	│	│	│		│		│	│			│				
	IV	climatic optimum Pulvernieki (Holsteinian) Interglacial		│	│	│													
	III			│	│	│													
	II			│	│	│													
	I	transgression		│	│	│													

researched sites known - Akmeņrags, Sudrabi and Ozoli (Segliņš 1987 a, b, Segliņš & Sakson 1987, Kalniņa 1993, 1999). The spore and pollen complexes of these sites are similar to those from earlier investigated and relatively near located Ulmale section. The optimum pollen complexes III and IV are also established here (Savvaitov, A., Veinbergs, I., Kalniņa L., Ceriņa, A., Jakubovska, I. & Stelle, V. 1998).

Moreover a group of spore and pollen diagrams characterize the uppermost part of the marine sediments, which can be observed in some rare sites only (Staldzene, *etc.*). The spectra of these diagrams are clearly distinguished by high amounts of herb pollen (*Artemisia*) and reflects the cooler (subarctic) climatic conditions, than those during VI complex. Probably this VII spore and pollen complex belongs to periglacial of Early Kurzeme (Saalian) Glaciation.

Irregular occurrence of foraminifers, diatoms and ostracodes is typical within the Ulmale Formation. Ostracodes and diatoms are represented by marine and freshwater species. Maximum and more often fixed amounts of the foraminifers are observed in the sediments limited by I, II and III spore and pollen complexes. Some higher quantities of foraminifers occur in the sediments characterized by V pollen complex also. The foraminifers in overlying sediments of the Ulmale section are not observed, but in the uppermost part of the site (borehole and outcropping) single foraminifers are found to occur. Here basically the freshwater diatoms are known, but rare marine diatoms are also found.

According to A. Charamisinova (1971), who had analyzed the samples from the Ulmale borehole, the maximal quantities of marine assemblage diatoms correspond to the sediments of III, IV and V pollen complexes. Underlying (II, I pollen complexes) and overlying sediments (VI complex) contain only sporadic marine diatoms.

Ostracodes in the marine thickness are very rare or single. They were found in Jūrkalne, Ventspils and Zūras-Erniņi boreholes sections, but the ostracodes of marine species - occurred only at the base of Jūrkalne section.

Besides the Ulmale site, the systematical investigations of the diatom complexes are known at Ozoli section. According to diatom assemblages identified by M. Sakson (Segliņš & Sakson 1987), there are sequenced parts distinguished in the common section, which had been formed during three stages (from low upwards): (1) marine transgression, (2) following desalination of the basin, and (3) conditions of the freshwater basin. The diatoms in all other investigated sections are poorly represented, but they are of mixed composition including freshwater, brackishwater and marine species (analyses after V. Kalnroze and V. Celma). They are observed in some separate sediment intervals VI and VII pollen complexes in Jūrkalne, Zūras-Erniņi, Ventspils, Staldzene, Liepene borehole sections.

The intertill sediments of the Ulmale Sea in southern part of the Western Kurzeme had been investigated in Rucava-Lauk¸eme region dissected here by series of boreholes (Segliņš 1988). The spore and pollen diagrams from this thickness were known after A. Dreimanis in 1944 and J. Straume in 1962. The new spore and pollen studies were carried out by O. Kondratienė and L. Kalniņa. The observed vegetation is of mixed composition. The subarctic forms *Betula nana, Alnaster, Rubus, Artemisia, etc.* and the warm forms *Azolla masula, etc.* are widespread here (Segliņš 1988). Earlier and new spore and pollen diagrams from intertill sediments of this region are similar to each other. They probably reflect the time of their formation in the upper part of Ulmale Formation. According to the pollen and spore data characterized the sediments in the northern region of Western Kurzeme can be VI spores and pollen complex. There are also foraminifers found in some intervals. According to A. Ceriņa, the plant macrofossil assemblage is of mixed composition similar to that from the upper part of the Ulmale Formation in the northern regions of Western Kurzeme, and it contains *Azolla interglacialica* Nikit. too.

The intertill sediments similar in thickness and analogous spore and pollen spectra are wide spread in Klaipeda-Kretinga region of Northwestern Lithuania (Kondratienė 1971, 1999). The intertill sediments of the Middle Pleistocene in this region are also fixed by A. Bitinas (1996), A. Bitinas, A. Damušytė (1998), A. Bitinas, A. Damušytė & M. Stančikaitė (1996).

PALAEOMARINE ULMALE BASIN

The total stratigraphical interval of the Middle Pleistocene, when the Ulmale palaeomarine basin had been developed and existed and the Ulmale Formation had been formed, includes complete Pulvernieki (Holsteinian) Interglacial (I, II, III, IV, V, VI pollen complexes) as well as the Early Kurzeme (Saalian) periglacial (VII pollen complex).

Due to transgression the Ulmale Sea flooded maritime regions of Western Latvia. The start of the transgression took place at the beginning of Pulvernieki (Holsteinian) Interglacial time. The sediments corresponding to the time of the transgressively developing Ulmale Sea are characterized by I, II, III and IV pollen complexes. This interval of geological section basically is represented by grew and green grew silts located in a deeper part of Ziemupe-Ovīši Depression area in the region of Ulmale-Akmeņrags and lies at the base of the Ulmale Formation strata. Besides, mentioned sediments of the marine thickness contain the largest amounts of the foraminifers and are more rich assemblage of the marine diatoms. The brown clay, underlying this basal part of the marine thickness, belongs to the sediments of Late Letīža (Elsterian) local Ice Lakes (Sudrabi Bed, Segliņš 1987 a).

The floor position of the marine sediments, characterized by V and VI pollen complexes, and located within incisions of the ancient deep valley (Ovīši, Ventspils, Zūras-Erniņi) has lower altitudes, than those of the adjacent area. This index shows, that between formation of the sediments IV and V pollen complexes took place the large-scale regression of the Ulmale Sea. The more ancient sediments within incisions during regression were outwashed by activity of cutting rivers, but at the time of following new transgression of the Ulmale Sea, these incisions and their watersheds areas were full up by sediments of V and VI pollen complexes. The new transgression of the Ulmale Sea had been characterized by more wide area of the distribution of the basin. During that time the Ulmale Sea occupied onshore part of the Western Latvia and was represented by relatively wide and shallow nearshore zone. According to dynamics of alongshore processes, this zone had been separated from open sea and therefore distinguished by desalinate and even freshwater conditions. There conditions favorable for formation of mainly sandy sediments existed, but in the deep incisions at that time the clayey sediments were deposited. The foraminifers, marine species of diatoms and ostracodes contained in sediments of this stage of the Ulmale Sea are poorly represented.

The sediments of VII spores and pollen complexes reflect the final stage of the Ulmale Sea, when Early Kurzeme (Saalian) Glaciation had been started. The sediments of this stage preserved in separate sites only. The Ulmale Sea, in comparison with previous stage, had been distinguished by relatively strong desalting of the waters.

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Early post-glacial environmental changes in the western Gulf of Finland based on diatom and lithostratigraphy of sediment core B–51

Atko Heinsalu, Tuula Kohonen, Boris Winterhalter

Abstract

A long sediment core (B–51) from the western Gulf of Finland, the Baltic Sea was investigated using diatom analysis and sediment lithostratigraphy. The core covers the sedimentation history from the late Baltic Ice Lake stage to the beginning of the Litorina Sea stage. The occurrence of a thin sequence with black bands and lenses of Fe-monosulphides has been associated with a short-term brackish Yoldia Sea phase when the offshore area of the Gulf of Finland was characterised by highly stratified water column with a turbid freshwater surface layer above dense brackish bottom water. Increase in the diatom abundance in the sediment record probably correlates with the onset of the Ancylus Lake stage. The increase in grain size and in the abundance of littoral diatoms resuspended and transported into the deeper areas is associated with the culmination of the Ancylus Lake transgression and the following drainage. A stratified water column with saline water in the deepest parts and a very low salinity in the surface water was characteristic of the Gulf of Finland during the Initial Litorina Sea phase. Increased surface water salinity and anoxic bottom conditions correspond to the beginning of the Litorina Sea stage.

☐ Palaeoenvironment, diatom analysis, Yoldia Sea, Ancylus Lake, Litorina Sea, Baltic Sea, Gulf of Finland.

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INTRODUCTION

The Baltic Sea basin has experienced several successions of freshwater and brackish-water stages since the last deglaciation. The Baltic Ice Lake occupied the basin following the retreat of the Fennoscandian Ice Sheet and ended up with its partial drainage at Mt. Billingen in south central Sweden 11,565 GRIP years BP (Andrén et al. 1999). Varved clays and silts accumulated in front of the receding ice margin.

The following Yoldia Sea stage (11,565–10,700 calendar yr BP) marks the period when the ocean had a connection with the Baltic Sea basin across south central Sweden (Björck 1995). According to recent sediment studies in the Baltic Sea proper, the Yoldia Sea stage can be divided into two freshwater phases and a short brackish-water phase in between (Svensson 1989). The sediments deposited during this time show significant differences depending on the distance of the site to the retreating ice margin. Thinly laminated clay varves were deposited close to the ice margin, while further away, more or less homogeneous grey silty clays accumulated (Winterhalter 1992). A thin sequence with black bands and small lenses of amorphous Fe-monosulphides has been associated with the brackish Yoldia Sea phase (Huckriede et al. 1996, Lepland et al. 1999). This brackish-water phase lasted for about 60–120 years (Wastegård et al. 1995).

The rapid land uplift, which raised the passages in south-central Sweden above the ocean level at 10,700 calendar yr BP, and caused the water level to rise in the Baltic Sea basin, is defined as the onset of the Ancylus Lake (Andrén et al. 2000a). During the first half of this stage, the Ancylus Lake was dammed-up, and the transgression culminated at 10,200 calendar yr BP (S. Björck et al. 2001). A rapid lowering of the

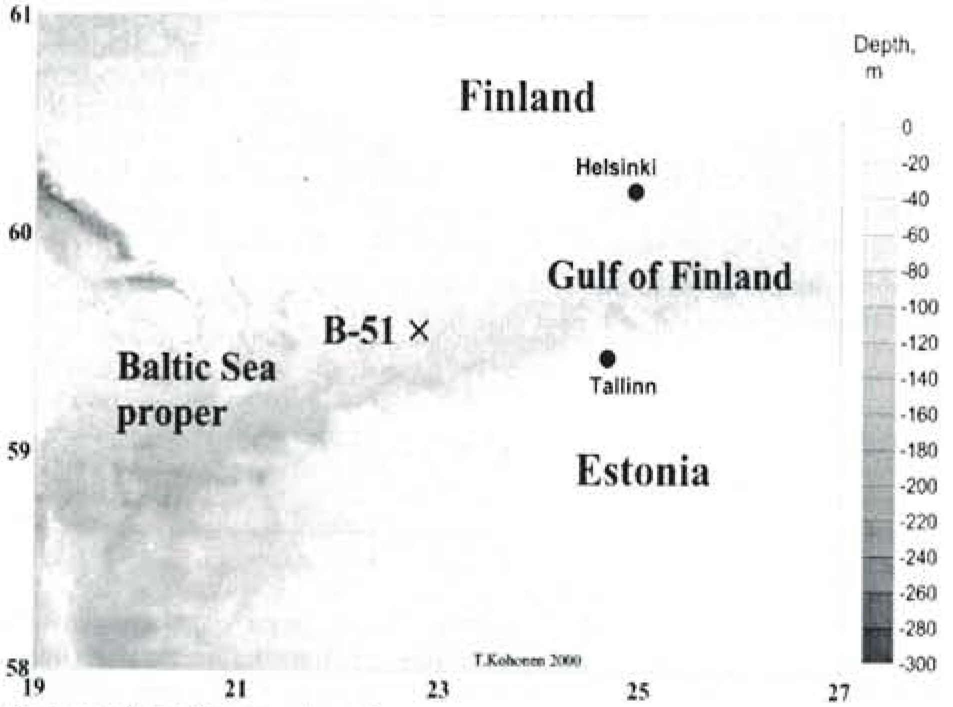

Fig 1. Location of the sampling site.

Ancylus Lake followed shortly after the culmination, when the dammed waters found a new southern outlet and the 'non-dammed' phase of the Ancylus Lake began (Björck 1995). However, the position of this freshwater outlet has not yet been located (Jensen et al. 1999). The Ancylus Lake sediments consist typically of two units. The occurrence of black bands or staining of ferrous sulphides is characteristic for the lower Ancylus Lake clays, while the upper unit consists of bluish homogeneous clays (Ignatius et al. 1981).

Eustatic rise of the ocean level led to intermittent inflows of saline water over the sills of the Danish Straits into the Baltic Sea basin at c. 8500–8200 ^{14}C yr BP (Eronen et al. 1990). The period between 8500–7500 ^{14}C yr BP is regarded as a transitional phase between the Ancylus Lake and the fully brackish Litorina Sea. In the littoral sediments this phase, often called the Mastogloia Sea, is properly defined by diatom assemblages that prefer low salinity. In offshore cores this transitional phase is characterised by a low abundance of diatoms and is referred to as the Initial Litorina Sea (Andrén 1999). The lithostratigraphic boundary between the Ancylus Lake and the Litorina Sea sediments is generally marked by a clear and rapid increase in the content of organic carbon and a change from homogeneous clays to laminated gyttja clays (Winterhalter 1992).

The Gulf of Finland (GOF) is a west to east elongated large sub-basin in the north-eastern Baltic Sea (Fig. 1). The surface area of the GOF is 29,571 km^2, its mean depth is 37 m and the maximum recorded depth is 123 m. The surface water salinity varies from 5–7‰ in the western GOF to about 1–3‰ in the east, while the bottom water salinity in the western part of the basin reaches values of 8–9‰ (Alenius et al. 1998). The GOF is a direct continuation of the Baltic Sea proper without any notable sill, thus being directly influenced by the bottom waters of the Baltic Sea proper. In the western GOF a permanent halocline prevails throughout the year at the depth of 60–80 m, towards the east the difference between surface and bottom salinity decreases (Alenius et al. 1998).

Diatoms are sensitive indicators of surface water salinity and diatom analysis has been frequently used for determining the palaeoenvironmental conditions of the different stages of the Baltic Sea (e.g. Alhonen 1971, Abelmann 1985). Still, not enough attention has been paid to diatom studies of the offshore sediments in the GOF and those cores investigated have been often incomplete (Kessel et al. 1973, Dzhinoridze 1986, Åker et al. 1988, Sakson 1993). In this paper results of diatom analysis and sediment lithostratigraphy of a long core (core B–51) from the entrance of the GOF is presented. The aim of the present study was to reconstruct early post-glacial palaeoenvironmental conditions for the GOF with special emphasis to the possible detection of the brackish Yoldia Sea deposits.

MATERIAL AND METHODS

The sediment core B–51 was taken in 1997 in the westernmost part of the GOF at the location 59°33.738' N, 22°47.125' E, with a water depth of 68 m (Fig. 1). The location was selected on the basis of an interpreted acoustic profile acquired with a GeoChirp subbottom profiler together with a DESO 25 echosounder during a cruise of r/v Petr Kottsov in 1996.

A 726-cm long sediment core was taken with a vibro-hammer corer from r/v Geola. A 7-cm long section of the sediment core was lost during core extraction. The core (diameter 110 mm) was cut lengthwise into two halves onboard the ship. Additional 2 cm had to be rejected in the middle due to disturbance while cutting. The visible lithology of the sediment profile was described and photographed on board the vessel. Sub-samples were taken for microfossil studies and for determination of sediment physical parameters. The water content (as weight loss on drying at 105°C), humus content (as weight loss on ignition at 550°C), and grain size (with Micromeritics Sedigraph 5000 D after removal of organic matter with H_2O_2 and 2N HCl at 75°C) of the sub-samples were analysed.

Preparation for diatom analysis followed Battarbee (1986). The relative abundance of diatoms was estimated by counting the number of diatom valves per cover glass transect. Diatoms were grouped in accordance with their living habitats into planktonic and periphytic (epiphytic and benthic diatoms) taxa, and with respect to salinity preferences into brackish-marine, brackish-water and freshwater taxa. Freshwater diatoms have been subdivided into large-lake, small-lake and indifferent taxa respectively. Diatom taxonomy and ecological information is mainly based on Snoeijs et al. (1993–1998), Krammer & Lange-Bertalot (1986–1991), Mölder & Tynni (1967–1973) and Tynni (1975–1980).

RESULTS

Acoustic profile and lithostratigraphy

The three lithological units typical of the Baltic Sea can be identified in acoustic profiles from the western Gulf of Finland: 1. glacial clays and silts; 2. the Yoldia Sea and the Ancylus Lake ('transitional') clays; and 3. the Litorina Sea and recent sediments (see Kohonen & Winterhalter 1999). In the echosounding profile (redrawn in Fig. 2) all three units can be clearly discerned at the sampling site, although only a short section of the Litorina Sea sediments has escaped subsequent erosion. In surrounding areas erosion has been more intense exposing both 'transitional' and glacial clays. The erosion of sediments deposited originally in deep water is due to crustal rebound following deglaciation, which has brought the sea floor up to the wave base.

A detailed lithostratigraphy of the core B–51 is presented in Table 1. The colour coding refers to the Munsell system.

The lowest part of the core consists of varved clay typically mirroring seasonal variations in the amount of melt water and suspended mineral matter entering the basin. These varved clays are overlain by a 10 cm thick layer of clay, which is stained black with lenses and granules of amorphous Fe-monosulphide. A similar layer has also been recognised in cores taken some 10 nautical miles southeast of Helsinki from a water depth of 40–50 m (Åker et al. 1988). Higher up in the sequence thin black FeS layers are observed at 520 cm increasing upwards in thickness. This black stained sulphide clay is overlain by homogeneous clay rich in small pyrite concretions. The next major litholologic boundary is at 57 cm, where the homogeneous grey clay is overlain by a thinly laminated gyttja clay sequence.

Except for some ice-rafted dropstones in the glacial clay sequence, all analysed sub-samples of the core B–51 consisted of clay and silt fractions. The grain size distribution of the core B–51 is presented as per-

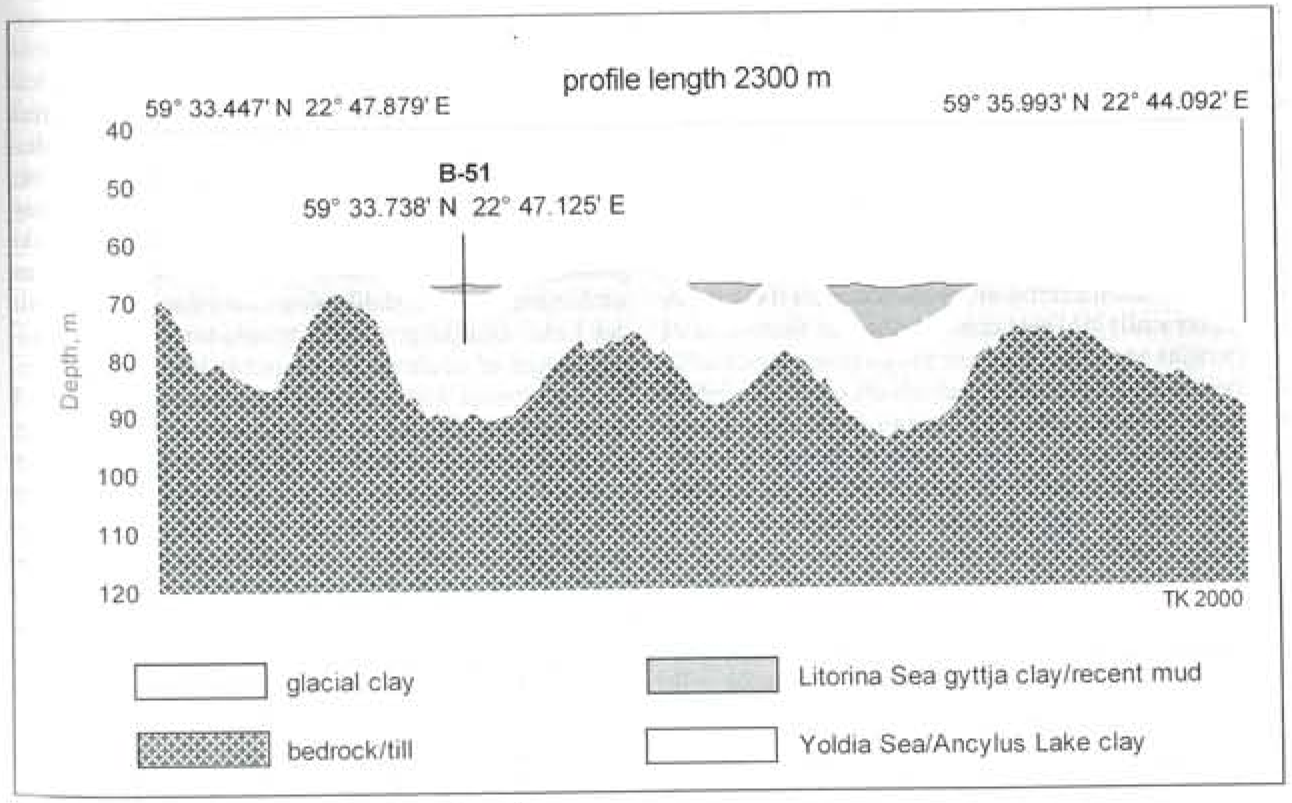

Fig. 2. Interpreted acoustic profile from the study area.

Table 1. Lithological description of the core B–51 from the entrance of the Gulf of Finland

Depth, cm	Sediment	Notes	Colour
0–25	gyttja clay	thin laminations	greenish grey (5 GY 4/1–5 GY 6/1)
25–42	gyttja clay	mottled, sulphide spots; burrows; at 34 cm a distinct thin brown layer with a sharp lower boundary	greenish grey (5 GY 4/1–5 GY 6/1)
42–57	gyttja clay	dark grey and reddish brown thin laminations	greenish grey (5 GY 4/1–5 GY 6/1)
57–132	clay	sulphide spots except in the lowermost 2 cm; at 57–65 cm mottled sediment with burrows (bioturbation); branchlike <2 mm-long nodules (pyrite concretions) at 75–131 cm	dark greenish grey (5 GY 4/1), greenish grey (5 GY 6/1)
132–141		no sample	
141–144	clay	homogeneous; pyrite concretions	bluish grey (bluish 5 GY 4/1)
144–215	clay	sulphide-rich especially at top; sulphide granules at 231, 265 cm; pyrite concretions; a few light coloured bands at the top	brownish grey (5 YR 4/1), olive grey (5 Y 4/1) with black mottling
215–383	clay	more sulphide bands than below	brownish grey (5 YR 4/1), olive grey (5 Y 4/1) with black banding
383–520	clay	sulphide lenses, which gradually thicken upwards; stones at 453–509 cm	brownish grey (5 YR 4/1), olive grey (5 Y 4/1)
520–592	clay	brown, greenish and black layers <1–4 mm; towards the upper part the layers become thinner and more indistinct	dark greenish grey (5 GY 4/1)
592–606	clay	homogeneous, with sulphide granules at 601–604 cm	dark greenish grey (5 GY 4/1)
606–616	clay	black sulphide layers <1–2 mm	dark greenish grey (5 GY 4/1)
616–631	clay	thin (<1 mm) indistinct varves	brownish (5 Y 4/1), dark greenish grey (5 GY 4/1)
631–726	clay	distinct varves (1–10 mm); dropstones with diameter up to 3 mm; disturbed layers at 632, 645, 650–652, 659, 670–672 and 719–726 cm	brownish olive grey (5 Y 4/1), greyish olive green (5 GY 3/2), olive grey (5 Y 3/2)

centage of <0.002 mm fraction (Fig. 3). In the lowermost part of the core more than 90% of the grains consists of <0.002 mm fraction. The proportional abundance of silt is highest at 386 cm.

No traces of recent mud, indicative of present day sediment accumulation could be detected in the acoustic profiles from the coring site. The topmost sediments in the core represent the early Litorina Sea deposits. Deposits from accumulation areas have high content of water and organic matter. Sediment from areas of active deposition exhibit in Swedish studies (Håkanson 1986) typically a water content of more than 75% of wet weight and a weight loss on ignition of over 10% of dry weight. In a Finnish study (Vartiainen et al. 1997) the same parameters are >70% and >9% respectively. In the top of the core B–51 both water content and loss on ignition was below these values (Fig. 3), indicating that the youngest sediments are absent.

DIATOM STRATIGRAPHY

The diatom analysis was carried out within the 19–650 cm core-depth interval, and the stratigraphy was divided into six diatom assemblage zones (DAZ; Table 2, Fig. 4). The bottommost part of the sediment core was devoid of diatoms.

ENVIRONMENTAL HISTORY

The Baltic Ice Lake

Varved clays of the Baltic Ice Lake are usually barren of diatoms in the GOF (Åker at al. 1988) and no diatoms were observed in the lowermost section of core B–51. A poor diatom flora, indicating freshwater conditions has been observed in a sediment core from Lake Ladoga (Abramova et al. 1967), which was an embayment of the Baltic Sea basin during the Baltic Ice Lake. Diatom productivity was low during the initial stages of deglaciation probably because of extensive ice cover and high turbidity from silt and clay introduced by meltwater from the retreating ice sheet. Diatom scarcity can also be attributed to the very high sedimentation rates causing a pronounced dilution effect. Diatoms were more common in the distal areas of the Baltic Ice Lake, in southern Baltic Sea basin, where alkaliphilous freshwater flora indicating higher conductivity have been recorded (Jensen et al. 1997).

The Yoldia Sea

Immediately after the drainage of the Baltic Ice Lake narrow straits west of Lake Vättern were the only passages between the ocean and the Baltic Sea basin (Fredén 1988). Freshwater outflow from the rapidly melting ice sheet was probably strong enough to prevent major marine water ingression. Furthermore, the deep basin of Lake Vättern acted as a trap for dense saline water, which occasionally flowed over the sills, but salt water never penetrated further east (J. Björck et al. 2001). Therefore, the initial Yoldia Sea phase was characterised by freshwater conditions (Svensson 1989) and brackish water inflow to the Baltic Sea basin occurred for a short spell after the retreat of the ice edge across the Närke Strait at c. 11,300 calendar yr BP (Wastegård et al. 1998, Björck 1999). Most probably indistinctly varved clays in the core B–51 were deposited in the GOF during the initial freshwater phase of the Yoldia Sea. Strong meltwater input from the retreating ice sheet produced vast amounts of fine-grained suspension. High turbidity and low transparency of the surface water was unfavourable for the photosynthesis of diatoms, and furthermore high accumulation rates made diatoms very sparse in the sediments and possibly undetectable for diatom analysis. Large-lake diatom assemblages found in several pre-isolation sediment records in northern Estonia suggests that freshwater environmental conditions occurred in the littoral areas along the southern coast of the GOF at the beginning of the Yoldia Sea (Heinsalu 2000).

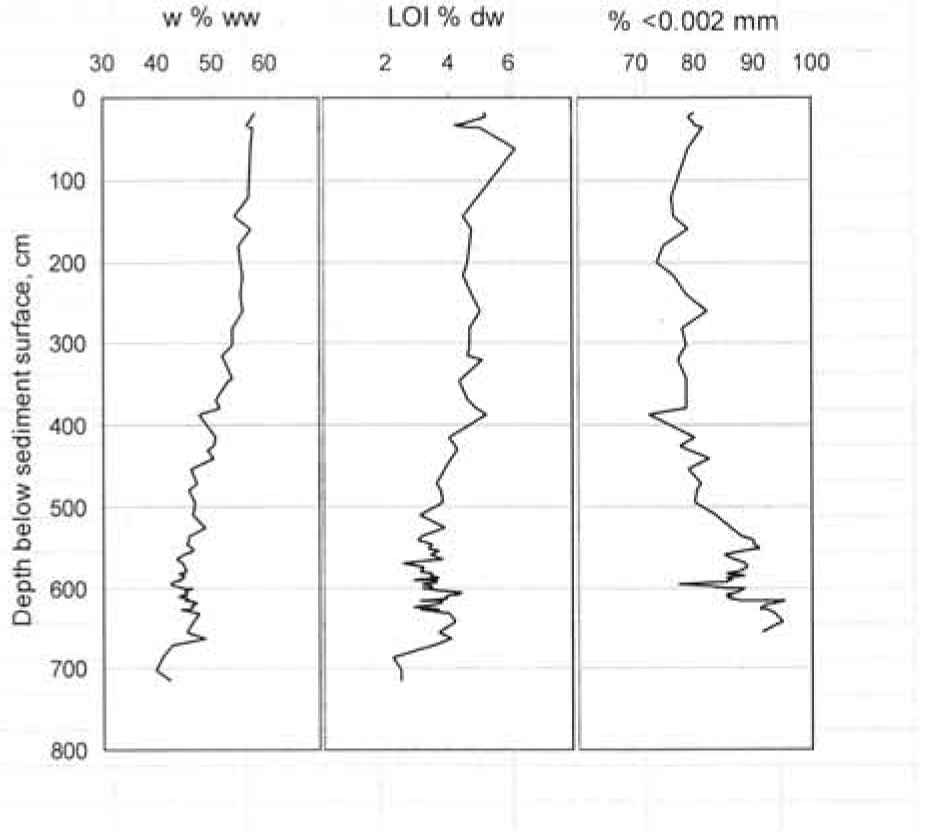

Fig. 3. Down core variations of water content (w) as % of wet weight, loss on ignition (LOI) as % of dry weight and % of the grains <0.002 mm for the core B–51.

The finds of arctic molluscs *Portlandia arctica* (De Geer 1913, Brunnberg & Possnert 1992) and a transition from a grey diatactic to a reddish symmict varved clay (Brunnberg 1995) east of the inflow area indicate saline water ingression into the Baltic Sea basin during the middle phase of the Yoldia Sea. Benthic foraminifer and ostracod assemblages in the sediments at the Närke Strait and further east in the northern Baltic Sea proper suggests a bottom water salinity of c. 10‰ for the brackish phase of the Yoldia Sea (Wastegård 1997, Wastegård & Schoning 1997). Diatom records from the Landsort Deep (Lepland et al. 1999) and the Gotland Deep (Abelmann 1985, Sohlenius et al. 1996, Andrén et al. 2000a) display a peak of planktonic brackish-water diatom *Thalassiosira baltica* and thus slightly brackish-water conditions occurred also in the surface water layer.

The crucial question in the history of the Yoldia Sea is how far east from the inflow area did the saline water pulse penetrate. Indistinct varved clays are overlain by a layer of clay stained with iron sulphides in the core B–51. The formation of FeS precipitation can indicate the presence of saline and anoxic bottom water (Huckriede et al. 1996). Occurrence of planktonic large-lake diatoms *Aulacoseira islandica* and *Stephanodiscus neoastraea* in DAZ B51A indicate non-saline surface waters at the entrance of the GOF. However, a distinct change in the diatom assemblages in northern Estonia, where in several littoral pre-isolation sequences large-lake diatoms are replaced by brackish-water diatoms (Heinsalu 2000), confirms the existence of brackish-water conditions in the GOF for a short period during the Yoldia Sea. Mixing of the water column and circulation of brackish-water up to the surface along certain stretches of the coast is interpreted as a consequence of upwelling (Heinsalu 2000). In addition, littoral sediment sequences of the Yoldia Sea with brackish-water diatoms have been recorded also from the eastern part of the GOF (Saarnisto et al. 1999) and from southern Finland (Valovirta 1965, Tynni 1966). Similar periphytic brackish-water taxa

Table 2. Diatom assemblage zones of the core B–51 from the entrance of the Gulf of Finland

Depth, cm	DAZ	Description of the DAZ	Baltic Sea stage/phase
19–57	B51F	Brackish-marine and brackish-water planktonic diatoms predominate, their relative abundance increases within the zone. *Actinocyclus octonarius* Ehrenberg, *Thalassiosira baltica* (Grunow) Ostenfeld, and *T. eccentrica* (Ehrenberg) Cleve are dominant species. *Coscinodiscus asteromphalus* Ehrenberg, *Cyclotella choctawhatcheeana* Prasad and *Chaetoceros* spp. resting spores are present in lower values. The frequency of large-lake planktonic diatoms *Aulacoseira islandica* (O. Müller) Simonsen and *Stephanodiscus neoastraea* Håkansson et Hickel is decreasing within the zone.	Litorina Sea stage
57–145	B51E	At the lower boundary of the zone, the relative abundance of large-lake diatoms distinctly decreases. Brackish-water periphytic diatoms, such as *Diploneis smithii*, *Rhoicosphenia curvata* (Kützing) Grunow, *Epithemia turgida* var. *westermanni* (Ehrenberg) Grunow and *Mastogloia smithii* Thwaites, increase towards the upper part of the zone. The importance of large-lake and other freshwater littoral diatoms is higher than in the DAZ *B51D*.	Initial Litorina Sea phase
145–385	B51D	Large-lake periphytic diatoms decline distinctly at the lower boundary of the zone. The relative abundance of large-lake planktonic diatoms is high, however decreases towards the upper boundary of the zone. *Aulacoseira islandica* decreases throughout the zone, and simultaneously *Stephanodiscus neoastraea* and *S. medius* Håkansson increase, reaching a maximum abundance at core-depth of 215 cm and then decreasing towards the upper boundary of the zone. *S. minutulus* (Kützing) Cleve et Möller, *Aulacoseira subarctica* (O. Müller) Haworth, *Cyclotella iris* Brun et Héribaud and *C. comta* (Ehrenberg) Kützing are present in low values.	Ancylus Lake, non-dammed phase
385–520	B51C	The abundance of diatoms increases dramatically at the lower boundary of the zone, and remains high throughout the rest of the core. Altogether 540 diatom valves were counted in two cover slip traverses. Large-lake planktonic taxa are still the dominant group of diatoms, but their importance continuously decreases towards the upper part of the zone. At the same time the importance of large-lake periphytic taxa increases. *Aulacoseira islandica* is still a dominant species of the assemblage. *Stephanodiscus neoastraea* and *S. medius* are continuously present at low values. *Diploneis domblittensis* (Grunow) Cleve, *Martyana martyi* (Héribaud) Round, *Gyrosigma attenuatum* (Kützing) Rabenhorst and *Cymatopleura elliptica* (Brébisson) W. Smith are the most common periphytic diatoms.	Ancylus Lake, up-dammed phase
520–606	B51B	The abundance of diatoms is very small. In the upper and lower part of the zone the number of counted diatoms in one slide reaches to 100–160 valves. The dominant species are *Aulacoseira islandica* and *Stephanodiscus neoastraea*. A few large-lake periphytic diatoms, such as *Encyonema prostratum* (Berkeley) Kützing, *Cocconeis disculus* (Schumann) Cleve, *Diploneis domblittensis* and *Martyana martyi* occur.	Yoldia Sea, final fresh water phase
606–616	B51A	Very poor in diatoms. In six levels, altogether 3 to 40 diatom valves were observed per slide. The most common species are large-lake planktonic diatom *Aulacoseira islandica*, *Stephanodiscus neoastraea* and *S. medius*. Some brackish-water periphytic taxa, such as *Diploneis smithii* (Brébisson) Cleve and *Campylodiscus echeneis* Ehrenberg are present.	Yoldia Sea, brackish phase

such as *Diploneis smithii*, *D. interrupta* and *Campylodiscus echeneis* in *DAZ B51A* are likely transported to the offshore area from the littoral zone. Correlation of diatom data from the core B–51 with those from the coastal areas indicate that the brackish-water pulse did penetrate into the GOF. However, in more offshore settings the water column remained highly stratified with a freshwater surface layer overlying the dense brackish deep-water.

It has been suggested that the final phase of the Yoldia Sea, following the short brackish-water phase, was characterised by freshwater palaeoenvironmental conditions, at least in the Baltic Sea proper (Wastegård et al. 1995, Andrén 1999). The absolute abundance of diatoms is small and indicates low productivity in the offshore areas (Abelmann 1985, Andrén et al. 2000b). In the GOF similar environmental conditions have been registered on the Island of Suursaari (Heinsalu et al. 2000) and in northern Estonia (Heinsalu 2000). Homogeneous grey clay at the core-depth of 520–606 cm corresponds to *DAZ B51B*. Both overall low abundance of large-lake diatoms and disappearance of periphytic brackish-water diatoms imply correlation of that zone with the final freshwater phase of the Yoldia Sea. A relatively high rate of sedimentation indicates that meltwater flux from the ice sheet might still influence the area at the entrance of the GOF and allows interpreting the apparently low diatom productivity with low illuminance in the photic zone and dilution through rapid sediment accumulation.

The Ancylus Lake

Due to the fact that freshwater conditions prevailed in the GOF already in the late Yoldia Sea a lithostratigraphic boundary between the Yoldia Sea and the Ancylus Lake sediments in offshore areas is hardly detectable. However, several studies reveal high pelagic primary production of diatoms at the beginning of the Ancylus Lake (Abelmann 1985, Andrén et al. 2000b). The diatom record at the entrance of the GOF indicates an abrupt increase in the abundance of dia-

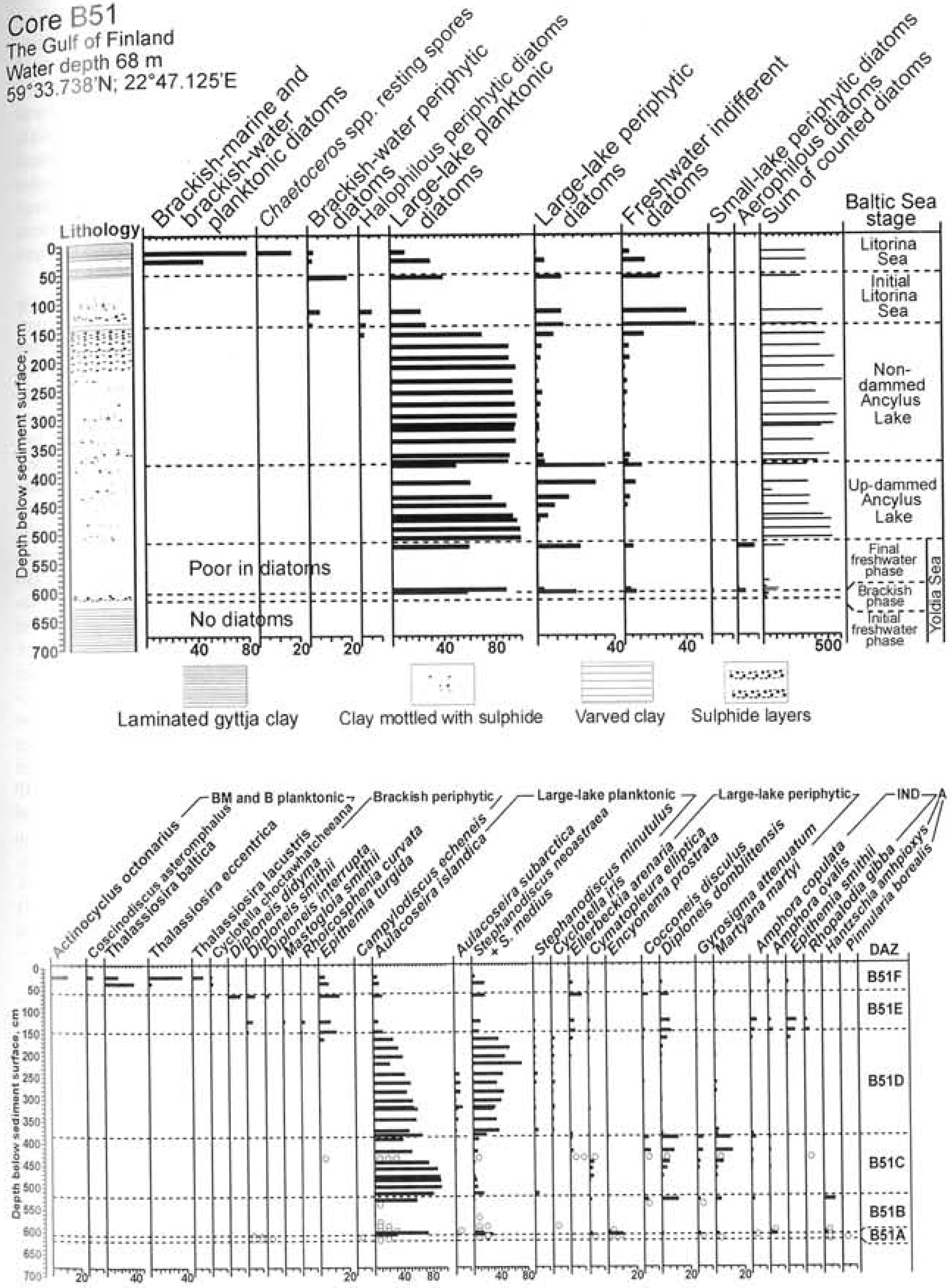

Fig. 4. Diatom stratigraphy of the core B–51 from the entrance of the Gulf of Finland. Abbreviations: BM – brackish-marine diatoms, B – brackish-water diatoms, IND – freshwater indifferent periphytic diatoms, A – aerophilous diatoms. The grey dots mark the levels whereas diatom abundance was small and no percentage calculations were carried out.

toms at the core-depth of 520 cm *(DAZ B51C)*. The large-lake planktonic diatom *Aulacoseira islandica* dominates. The increase in diatom abundance coincides with the appearance of black ferrous mono-sulphide staining in the sediment. The initiation of the diatom bloom in pelagic areas of the GOF during the beginning of the Ancylus Lake is interpreted as a result of a marked decrease in the supply of sediment from the greatly diminished ice cap and therefore reduced turbidity and enhanced transparency of the water column. A rising water level induced abrasion of soils in the coastal regions and increased transport of nutrients and dissolved silica into the pelagic area. This coincided with the rise of the temperature towards the second half of the Preboreal. Progressively, the increased percentage of periphytic diatoms in *DAZ B51C* infers that littoral sediments were reworked and transported into the deeper parts of the basin, thus supporting the idea of water-level instability during the up-dammed Ancylus Lake phase and the following drainage. This is in good agreement with the stratigraphic position of slightly coarser sediment particles, which probably derived from near-shore erosion (Fig. 3).

A rapid regression caused by the drainage of the Ancylus Lake has been detected in the shore displacement data around the Baltic (e.g. Björck 1995). The period after the drainage, when the Baltic Sea basin was more or less at level with the World ocean, but the narrow connection prevented saltwater inflow, has been named the non-dammed Ancylus Lake phase (Björck 1995). High values of planktonic diatoms in *DAZ B51D* refer to decreased resuspension from the littoral areas. *Aulacoseira islandica*, is considered to be a cold stenothermal species (e.g. Stoermer et al. 1981), often flourishes after breakup of winter ice in spring. However, *A. islandica* predominates in previous zones. In DAZ B51D planktonic diatom diversity increases which is perhaps induced by higher temperatures in the surface water layer. The moderate increase of *Stephanodiscus* species, likewise, indicates a somewhat higher trophic state of the basin.

The Litorina Sea

Soon after the establishment of ocean connection through the Danish Straits the first indications of saline water penetration into the Baltic Sea basin appeared in the areas close to the entrance. Berglund and Sandgren (1996) have reported slightly brackish conditions along the coast of Blekinge, southern Sweden at 8800 ^{14}C yr BP. This can be equivalent to a weak brackish-water inflow into the Bornholm basin at about 8900 ^{14}C yr BP (Andrén et al. 2000b). However, this environmental change in the sediment record is time transgressive. In southern Finland the coastal waters became brackish at about 8000 ^{14}C yr BP (Hyvärinen 1984). This slow spread of brackish water across the Baltic Sea basin can be explained by the limited water exchange between the Kattegat and the landlocked Baltic Sea basin. The inflow of saline water occurred probably in several pulses (Andrén et al. 2000a). Due to the density difference between the marine water crossing the threshold and the freshwater Ancylus Lake, the saline water would obviously flow as a bottom near current. Moreover, vertical mixing of water was prevented by a permanent halocline, and checked horizontally by the bottom topography. The sills separating the various sub-basins were obstacles for the spread of saline water into the central and marginal basins.

In the core B–51 *DAZ B51E* differs from the previous zone by the low abundance of planktonic diatoms and an increase of periphytic diatoms, the latter being easily transported for long distances from their littoral habitats. The gradually increasing littoral brackish-water diatoms suggest that slightly saline conditions prevailed along the coast of the GOF. Apparently low abundance of diatoms during the Initial Litorina Sea phase has been registered all over the Baltic Sea basin (Andrén 1999). Heiskanen (1998) suggests that increasing eutrophication combined with a warming climate may result in a decrease in the share of diatoms from the pelagic system in the northern Baltic Sea. Dinoflagellates, due to their mobility, can overcome diatoms during calm and warm spring weather, because planktonic diatoms sink rapidly from the photic layer. In addition, the vernal dinoflagellates promote a greater retention of nutrients in the pelagic system, which provides a firm start for the cyanobacterial blooms in the summer. Primary production of the Baltic Sea proper became nitrogen-limited shortly after the Ancylus Lake/Litorina Sea transition at c. 8500 ^{14}C yr BP (Westman 1998). The presence of fossil cyanobacterial pigments indicates intense cyanobacterial blooms in the basin in the early stages of the Litorina Sea at c. 7500 ^{14}C BP (Bianchi et al. 2000, Kowalewska et al. 1999). The data above suggest that the GOF probably must have had a stratified water column with saline water in the deepest parts and probably with low salinity in the surface water.

The appearance and high values of brackish-marine planktonic diatoms in *DAZ B51F*, the increase of loss on ignition values, and the simultaneous change from clay to laminated gyttja clay suggest that the surface water salinity of the GOF increased considerably and consequently, the difference in the salinity through the water column diminished. The strong influx of saline water from the Kattegat could have changed significantly the hydrological conditions in the Baltic Sea basin. According to Åker at al. (1988) that event probably took place c. 7500 ^{14}C yr BP.

Due to the decrease in water depth as a result of crustal uplift active deposition in the study area ceased and even erosion of formerly deposited sediment may have taken place during the latter part of the Litorina Sea stage (Kohonen & Winterhalter 1999).

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Main associations of microelements in sediments from the Šventoji-Nida area, southeastern Baltic Sea

Rolandas Radzevičius

Abstract

The investigations have been carried out in the Lithuanian part of the Baltic Sea offshore zone (the Šventoji-Nida area). A Dc-Arc ES analysis was performed to determine microelement concentrations in the sediments. Based on the median diameter (Md, mm) of the sediments, the analyzed samples have been subdivided into four sets. Three main trends in the distribution of microelements were established in the sediments, according to the median values of the microelements in the four sets. Two main microelement associations were revealed in the sediments, i.e. clastogenic and natural-technogenic. The summary index of concentration coefficient of Ti, Zr (Zd_{Ti-Zr}) and Ga, Pb (Zd_{Ga-Pb}) was calculated. A comparison between Zd_{Ti-Zr} and Zd_{Ga-Pb} values shows that the accumulation of the microelements related to the clastogenic association is less dependent on grain size in the study area.

☐ *Baltic Sea, sediment, microelement, association, paragenetic relationship, concentration coefficient index (Zd).*

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INTRODUCTION

The investigation area covers the Lithuanian part of the Baltic Sea offshore zone (Fig. 1). This zone is restricted by 20°30' longitude in the west; its northern boundary extends along 56°05' latitude, and southern boundary coincides with the Lithuanian-Russian frontier. The investigation area is located in the eastern part of the Central Baltic Sea (Grigelis (Ed.) 1991). Here the sea depth does not exceed 70 m. Along the coast, the near-shore zone extends at the depths of 0-10-25 m, while offshore the zone is limited by the Palanga ridge (at 10-35 m depth) in the north and the Kuršių plateau (at 20-50m depth) in the south of the investigation area. The Pra-Nemunas channel separates these bottom relief forms.

Sedimentary material is washed out from relict deposits and carried out from the Kuršių Marios Lagoon; under the impact of hydrodynamic factors it forms various types of sediments (Gudelis & Emelyanov (eds.) 1976, Gulbinskas 1995, Repečka 1997). Boulders, pebbles, gravel, coarse sand, medium sand, fine sand, coarse aleurite and muddy sediments are distributed in the studied area. Fine sand and coarse aleurite sediments are widespread here (Fig. 2). Coarse-grained sediments (median diameter more than 0.25 mm) are closely related to plateaus and fine-grained sediments (median diameter less than 0.05 mm) are spread locally in the deepest part (sea depth more than 65 m) of the studied area.

Element distribution in the sediments depends on grain size, mineral composition, organic matter content etc. (Blazhchishin & Emelyanov 1977, Emelyanov 1986). In general, element concentrations are higher in the fine-grained sediments than in the coarse-grained sediments because fine-sized particles (less than 0.01 mm) and organic matter play the main role in the transport of many chemical elements. On the other hand, some chemical elements concentrate in the sandy sediments.

The aim of this study was to determine main microelement associations in four sediment groups; to determine microelements representing main associations in the sediments and to locate zones of their concentration.

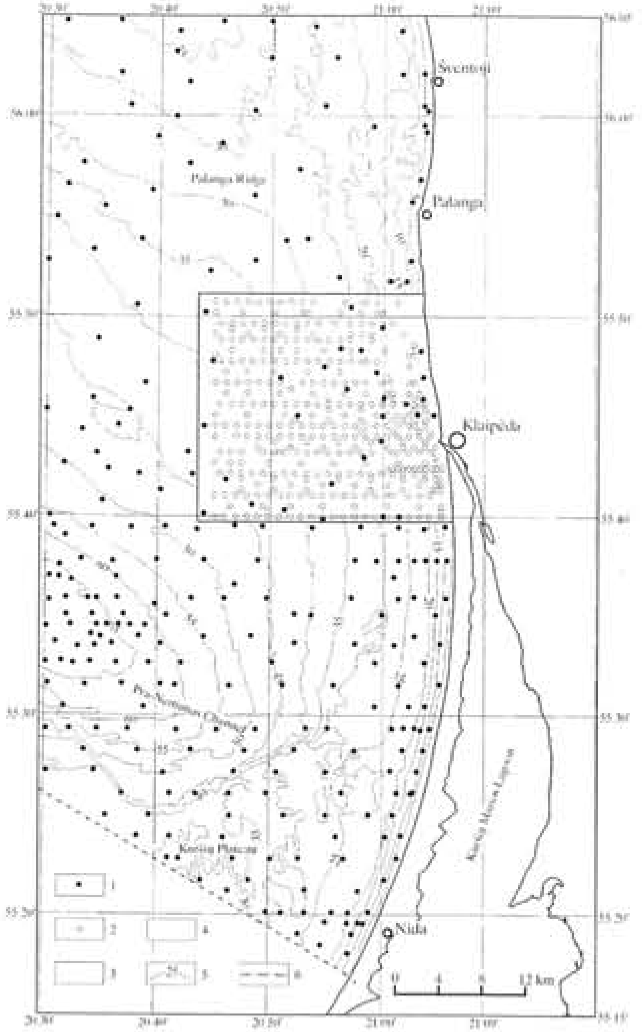

Fig. 1. Geography of investigation area, showing location of sample sites. 1 – samples collected in 1993-1999, 2 – samples collected in 1990-1991, 3 – A zone, 4 – B zone, 5 – isobathes, m, 6 – Lithuanian-Russian boundary. Note: Isobathes are taken from Gelumbauskaitė (Ed.) 1998.

METHODS AND DATA

The data used in this paper were collected during the marine geological mapping (in 1993-1999) at a scale of 1:50,000 in the Lithuanian part of the Baltic Sea offshore area. The bottom surface sediments were sampled by Van Veen grab (sandy sediments) and Niemistö gravity corer (muddy sediments).

Grain-size composition of the surface bottom sediments was measured by dry sieving (Analizette 3 Vibrator Sieve Shaker) and pipette (Petelin 1976) methods. Grain-size analyses were performed at the Institute of Geology, Department of Baltic Marine Geology, Lithuania.

Chemical analyses were undertaken for smaller than 1 mm fraction of 274 samples of the sediments (Fig. 1). Determination of microelements (Li, B, Ga, P, Mn, Ti, V, Cr, Co, Ni, Cu, Zn, Pb, Mo, Ag, Sn, Zr, Nb, Y, La, Yb, Sc, Ba) was performed by atomic emission spectrometry (DC-Arc Emission Spectrometry) using DFS-13 spectrograph and MD-1000 microdensitometer. The international standards OOKO 151, 152, 153, 301, 302 and 303 were used for quality control. Concentration of elements obtained by DC-Arc ES was recalculated to a dry matter. Chemical analysis was carried out at the Institute of Geology, Laboratory of Spectroscopic Analysis, Lithuania. Also the results of chemical analyses (377 in total) obtained during the geological mapping at a scale 1:50,000 carried out by J. Savickas (1990-1991) were used in this study (unpublished data).

Based on the median diameter (Md, mm) of the sediments, the analysed samples have been subdivided into four sets, i.e. 1st set with Md more than 0.25 mm, 2nd one with Md=0.25-0.1 mm, 3rd one with Md=0.1-0.05 mm, and 4th one with Md less than 0.05 mm. These sets were studied by means of statistical method, i.e. descriptive and principal components factor analysis was performed using SPSS WIN software. The factor analysis was used to reveal microelement associations (e.g. Kazhdan & Guskov 1990, Baltakis 1993, Jimenez-Espinoza et al. 1993, Sanchez Bellon et al. 1997, Zinkute 1998, Kadūnas et al. 1999).

Before proceeding the statistical analysis, the logarithmic values of microelement concentrations were taken, because microelement distribution in the lithosphere is described by logarithmic low (Ahrens 1954, Ahrens 1954, Ahrens 1957). For easy readability, the obtained statistical results presented in Table 1 and 2 are non-logarithmic. Figures were compiled using SURFER and CorelDraw softwares.

"Background" median values for all microelements were calculated separately in four sediment groups (sets) in order to remove the influence of sediment grain-size composition. Calculations were performed using method of consecutive elimination of anomalies outside the interval (x-2d, (x+2d, where x - arithmetic mean, d - standard deviation) employing SIGMA software. More details about the calculation of median ("background") values and SIGMA software can be find elsewhere (e.g. Zinkutė 1998, Zinkutė 1999).

Both the fine sand (2nd set) and coarse aleurite (3rd set) sediments were subdivided into two sets in order to remove the influence of sample scattering in the study area (Fig. 1). Weighted average values of each element were calculated according to the formula:

$$Md^* = \frac{P_A * Md_A + P_B * Md_B}{100}$$

where:

P – area of the zones, %,

Md – an element median ("background") value in a zone determined by method of consecutive elimination of anomalies,

A, B – the zones (Fig. 2).

The weighted average values serve as the "background" values for microelement distribution in the fine sand and coarse aleurite sediments.

"Background" median values of microelements were used to calculate summary indexes of a concentration coefficient (Zd). The summary index shows how many concentration coefficients of the microelement groups exceed background level. This coefficient is very wide used for technogenous geochemistry exploration as an index of the contamination (Saet 1990, Radzevičius et al. 1997, Kadūnas 1998, Zinkutė 1998, Kadūnas et al. 1999).

The summary index of concentration coefficients (Zd) was calculated according to formula:

$$Zd = \sum_{i=1}^{n} Kk_i - (n-1), \text{ here } Kk_i = \frac{C_i}{C_f}$$

where:

Kk_i – coefficient of concentration,

C_i – chemical element concentration in the analysed sample,

C_f – background value of a chemical element,

n – number of chemical elements

DISCUSSION

The distribution of the sediment median diameter (Md) shows (Fig. 2) that coarse sand, medium sand, fine sand and coarse aleurite sediments prevail in the studied area. The fine-grained sediments (Md less than 0.05 mm) are distributed locally at a depth of 65 m (and deeper).

According to the previous investigations (Blazhchishin & Emelyanov 1977, Gudelis & Emelyanov (eds.) 1976, Emelyanov 1986), such sediment grain-size composition predetermines a significant decrease in lithogenic element (Li, Ga, Cu, Co, V, Ni etc.) association and a significant increase in clastogenic element (Ti, Zr, Nb, Y, La, Yb) association (Baltakis 1993, Radzevičius 1993, Kadūnas 1999).

From the data given in Table 1, it was possible to establish main trends in the distribution of microelements in the sediments of the investigated area. The values of microelement concentrations are rather diverse in the studied area. Ti, Zr, Mn, P, Ba show extremely high variation in four sediment groups. Maximum median values of most microelements are found in the fine-grained sediments (Md less than 0.05 mm), while these of Ti, Zr, Nb, Y, La, Yb, Mn are mostly

Table 1. Values of microelements in the sediments, ppm

El.	Sediments															
	Coarse-grained (Md > 0.25 mm)				Fine sand (Md = 0.25-0.1 mm)				Coarse aleurite (Md = 0.1-0.05 mm)				Fine-grained (Md <0.05 mm)			
	N = 36				N = 261				N = 330				N = 24			
	Min	Max	Mz	Md	Min	Max	Mz	Md	Min	Max	Mz	Md	Min	Max	Mz	Md
Li	2.9	13.9	8.8	8.9	1.2	19.2	7.5	7.3	2.8	21.6	8.6	8.6	2.8	30.0	18.8	19.0
B	11.9	47.3	19.7	16.6	14.8	137.6	38.4	34.5	10.9	75.9	47.7	47.2	31.4	96.1	59.0	60.3
Ga	1.5	11.9	3.8	3.5	1.0	10.0	3.0	2.8	1.3	9.0	3.3	3.0	1.4	12.0	7.0	7.1
P	286	1097	653	696	297	1782	683	690	270	1180	498	443	246	1080	644	639
Mn	99	435	221	204	62	2772	314	238	65	895	330	303	89	838	263	182
Ti	449	3663	983	746	476	22770	3644	2182	679	11800	4168	3760	969	3478	2217	2231
V	6.9	41.5	16.1	14.4	9.1	79.3	25.6	23.7	6.8	72.5	29.8	28.0	9.3	132.7	56.3	55.2
Cr	9.6	49.3	19.0	16.9	10.9	178.2	42.4	34.5	10.8	123.3	47.8	47.9	19.6	115.3	68.1	70.0
Co	1.8	4.4	2.4	2.1	1.2	6.0	2.8	2.6	1.8	6.6	3.5	3.4	1.1	10.0	5.3	5.2
Ni	4.6	12.9	7.3	6.7	3.6	27.6	7.5	6.9	3.6	26.0	9.3	8.9	3.7	47.6	26.4	27.1
Cu	0.5	7.7	1.8	1.0	0.5	59.3	5.0	4.0	1.8	49.4	5.2	4.9	2.0	30.0	18.4	21.7
Zn	9.6	38.6	13.9	9.9	4.2	317.1	21.0	9.9	8.9	79.9	29.9	33.5	9.7	115.3	51.5	44.6
Pb	6.0	25.7	9.1	8.3	4.5	49.5	10.0	8.8	0.5	39.0	10.7	9.6	5.1	67.7	32.6	37.4
Mo	0.39	0.93	0.50	0.50	0.31	1.67	0.47	0.40	0.35	2.36	0.49	0.39	0.35	4.28	1.55	1.56
Ag	0.029	0.693	0.096	0.068	0.013	0.992	0.092	0.069	0.028	0.307	0.074	0.069	0.057	0.553	0.222	0.200
Sn	0.6	3.8	1.8	2.0	0.5	31.9	2.3	2.0	0.5	6.5	1.5	1.5	0.6	5.2	3.0	3.3
Zr	9	1188	143	44	18	24750	1244	554	40	9830	1420	1178	73	1283	273	233
Nb	6.0	23.7	13.5	13.7	3.6	55.4	19.3	16.9	3.0	43.7	19.5	19.6	3.6	18.6	10.4	9.7
Y	3.0	34.7	11.5	9.9	3.8	99.0	22.3	15.8	4.4	88.5	23.4	22.6	5.6	35.4	14.3	14.0
La	5.0	46.3	16.1	14.9	3.5	129.4	23.1	16.8	4.9	98.3	24.0	21.5	5.0	31.0	16.7	16.2
Yb	0.3	2.4	0.9	0.8	0.3	12.9	2.8	2.0	0.3	10.3	2.6	2.4	0.4	2.5	1.6	1.6
Sc	0.7	7.9	1.3	0.7	0.6	11.9	2.4	2.4	0.4	10.2	3.3	3.4	0.7	13.4	6.9	8.2
Ba	169	573	314	296	38	1431	263	277	87	713	330	333	88	507	366	386

Note: N – number of samples Min – minimum, Max – maximum, Mz – arithmetic mean, Md – median.

concentrated in coarse aleurite (Md=0.1-0.05 mm) sediments. Minimum median values were found in the coarse-grained sediments (Md more than 0.25 mm) with the exception of Li, Ga, Ba, P. These microelements are in smaller concentrations in fine sand sediments if compared to coarse-grained sediments. The uneven distribution of microelements in the sediments depends on many factors, particularly on the origin of sedimentary matter (Gudelis & Emelyanov (eds.) 1976, Blazhchishin & Emelyanov 1977, Emelyanov 1986). Fine-sized fractions are the main factor controlling concentrations of most microelements (e.g. Li, B, Ga, V, Cr, Co, Ni, Cu, Pb, Mo, Ag, Sn) in the sediments. Higher concentrations of Ti, Zr, Nb, Y, La, Yb, Mn depend on the amount of weathering-resistant accessory minerals in the sandy and coarse aleurite sediments. Higher concentrations of P, Ba are probably related to fragments of calcareous rocks and mollusc shells. Higher concentrations of Li, Ga are found in clay minerals of the coarse-grained sediments when they occur next to till outcrops.

The "background" median values of microelements are presented in Table 2. Similar trends of microelements are established after consecutive elimination of anomaly concentration. "Background" median values of B, V, Cr, Co, Ni, Cu, Pb, Mo, Ag and Sn gradually increase from coarse-grained sediments to fine-grained sediments. Higher concentrations of Ti, Zr, Nb, Y, La, Yb and Mn are in the coarse aleurite sediments. Median values of Li, Ga, Ba and P are higher in the coarse-grained sediments comparing to the fine sand sediments but they are the highest (except P) in the fine-grained sediments.

A comparison between the primary median (Table 1) and "background" median values (Table 2) shows that they are almost equal for most of microelements in the coarse-grained sediments. The microelements exhibit a lognormal distribution. "Background" median values of the microelements (B, Mn, Ti, V, Cr, Zr and Y) are obviously lower. They show a distribution skewed towards lower values. As in the coarse-grained sediments, two microelement groups were distinguished according to median values in the fine sand sediments. "Background" median values of Li, B, P, Mn, Ti, Cr, Co, Ni, Zr, Y, Sc and Ba obviously lower in the fine sand sediments. All other median values of microelement are quite similar.

Table 2. Median values of microelements in the sediments, ppm

El.	Sediments												
	Coarse-grained (Md >0.25 mm)		Fine sand (Md = 0.25-0.1 mm)					Coarse aleurite (Md = 0.1-0.05 mm)					Fine-grained (Md <0.05 mm)	
			B zone		A zone			B zone		A zone				
	Md N=36	n	Md N=163	n	Md N=98	n	**Md***	Md N=36	n	Md N=294	n	**Md***	**Md N=24**	n
Li	**8.9**	33	6.8	144	7.9	97	**7.0**	7.9	36	8.8	255	**8.1**	**22.5**	20
B	**14.9**	28	29.6	158	40.5	95	**31.3**	41.8	30	49.0	264	**42.9**	**59.9**	24
Ga	**3.5**	34	2.8	145	2.6	88	**2.8**	4.3	36	2.9	276	**4.1**	**8.4**	19
P	**696**	36	722	152	499	95	**687**	699	36	420	235	**656**	**620**	24
Mn	**199**	30	190	157	256	86	**200**	184	30	307	267	**203**	**168**	17
Ti	**713**	32	1870	153	2970	93	**2040**	2398	32	4126	263	**2666**	**2246**	23
V	**13.9**	27	23.8	163	21.8	94	**23.5**	35.0	35	27.4	294	**33.8**	**56.2**	22
Cr	**15.9**	29	30.8	154	36.6	91	**31.7**	53.0	34	49.1	246	**52.4**	**76.6**	20
Co	**2.0**	27	2.3	144	3.1	80	**2.4**	3.5	35	3.4	248	**3.5**	**5.2**	19
Ni	**6.6**	35	6.4	158	7.9	84	**6.6**	9.6	34	9.0	234	**9.5**	**30.3**	22
Cu	**1.0**	27	3.7	151	4.9	92	**3.9**	6.0	34	4.8	272	**5.8**	**22.8**	16
Zn	**9.9**	30	9.8	119	22.7	97	**11.8**	9.9	36	34.1	294	**13.6**	**45.0**	19
Pb	**8.2**	29	8.3	133	8.6	93	**8.3**	14.4	36	9.2	256	**13.6**	**35.7**	24
Mo	**0.50**	34	0.40	127	0.40	81	**0.40**	0.40	36	0.39	253	**0.40**	**1.53**	24
Ag	**0.068**	31	0.07	123	0.069	68	**0.070**	0.108	36	0.069	246	**0.102**	**0.190**	24
Sn	**2.0**	25	2.2	132	1.3	94	**2.0**	2.4	32	1.4	294	**2.2**	**3.3**	22
Zr	**41**	34	397	163	781	95	**456**	538	36	1433	246	**676**	**216**	21
Nb	**13.5**	36	16.9	131	16.8	91	**16.9**	15.5	36	20.3	235	**16.3**	**9.4**	18
Y	**9.4**	28	14.7	149	13.6	92	**14.5**	14.6	32	23.6	294	**16.0**	**14.6**	19
La	**14.9**	28	16.8	128	16.8	98	**16.8**	21.5	33	22.4	267	**21.6**	**16.2**	23
Yb	**0.8**	33	2.0	149	2.0	94	**2.0**	2.1	33	2.4	275	**2.1**	**1.6**	22
Sc	**0.7**	25	2.0	163	2.9	98	**2.1**	3.2	36	3.4	222	**3.2**	**9.3**	13
Ba	**296**	36	248	162	297	85	**255**	336	35	335	285	**336**	**391**	22

Note: N – number of samples. Element values evaluated after consecutive elimination of anomalies at minimum average square deviation value; Md – median value, Md* - weighted average value, n – number of samples after elimination, bolding indicate the median values accepted as the background values.

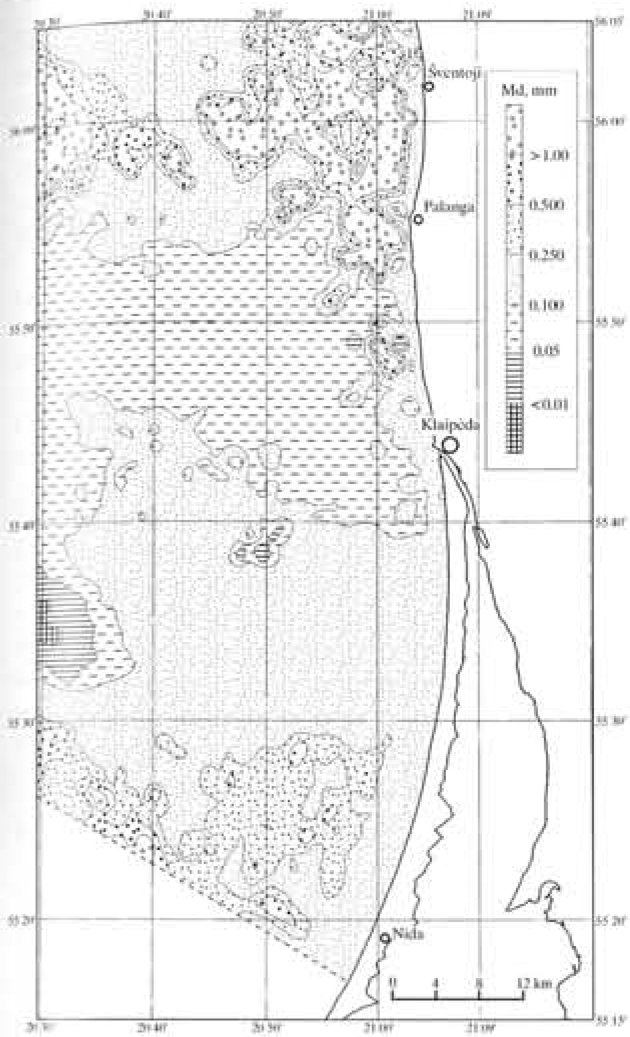

Fig. 2. Md (mm) of bottom surface sediments.

Three microelement groups were distinguished in the coarse aleurite sediments. The first group comprises "background" median values of microelements (B, Mn, Ti, Zn, Zr, Nb, Y and Yb), which are lower than primary median values. The "background" values of the second group of microelements (Ga, P, V, Cr, Ni, Cu, Pb, Ag and Sn) are higher. A microelement distribution is skewed towards higher values. All other microelements make up the third group. Microelements distributed lognormally. In the fine-grained sediments three microelement groups were distinguished. B, P, Mn, Pb, Mo, Ag, Zr and Nb have shown lower, while Li, Ga, Ti, V, Cr, Ni, Cu, Zn, Y, Sc and Ba have shown higher "background" median values than primary median values. Median values of Co, Sn, La and Yb are similar.

Factor analysis was applied to determine main associations of microelements in the sediments. The factor analysis was performed separately for the four sediment groups. The first main associations are presented in Table 3. Other microelement associations are not presented because they are, as a rule, statistically insignificant and reflect specific geochemical processes. A relationship between elements is formed artificially due to low (close to analysis detection limit) element concentrations, systematic error of the analyses or because of some limitations of the applied method (Kadūnas 1999).

The factor analysis of the coarse-grained sediments (Md more than 0.25 mm) shows how Cu, B, Co, Zn, Zr, Ti, Ni, Cr, Mn and V are linked up in the first association. Nb, Y, Yb, and partially Ti, Cr, V, La, Mn form the second, while Pb, Ga, V, Sn, and partially Ba form the third associations. The first and second associations are clastogenic. The elements forming these associations are related to weathering-resistant minerals. Ti, Zr, Nb, Y, Yb and La are typical clastogenic microelements (Baltakis 1993, Kadūnas 1998) belonging to the two associations. This fact probably indicates that coarse-grained sediments are highly effected by weathering processes. Microelements (Ga, Pb, V, Sn and Ba) forming the third association are related to sediment-forming minerals and may partly have been originated from technogenic load.

The obtained associations are similar in the fine sand (Md=0.25-0.1 mm) and coarse aleurite (Md=0.1-0.05 mm) sediments (Table 3). Clastogenic association is the first main association in these sediments. This fact indicates that sediments are strongly differentiated by

Table 3. Associations of microelements in the sediments of Baltic Sea (Šventoji-Nida area)

Sediments	Associations (factors)		
	F1	F2	F3
Coarse-grained (Md>0.25 mm)	Cu-B-Co-Zn-Zr-Ti-Ni-Cr-Mn-(V)-[-Sn]	Nb-Y-Yb-(Ti-Cr-V-La-Mn)	Pb-Ga-V-Sn-(Ba)
Fine sand (Md=0.25-0.1 mm)	Ti-Mn-Zr-Cr-Y-Yb-La-B-Nb-V-Zn-(Co-Sc)	Pb-Ga-Ni-Cu-Co	P-[-Ba]-[-Li]-[-Ni]-[-Zn]
Coarse aleurite (Md=0.1-0.05 mm)	Ti-Y-Yb-Mn-Zr-Cr-Nb-B-La-(V-Sc-Co)v	Ga-Pb-Cu-Sn-P-Co	Li-Zn-Ni-Ba-(Ga)-[-P]
Fine-grained (Md<0.05 mm)	Pb-Cr-Sn-Ni-Li-V-Mo-Zn-Ag-Cu-Ga-B-Co-Sc-P-Yb-(Ba)	Nb-Ti-Zr-(Yb-Y)	La-Mn-Ba-Y-(Co)-[-P]

Note: [-Zn] – element negative loading, (Co) – element with the main part of quantity making up the loading of another factor.

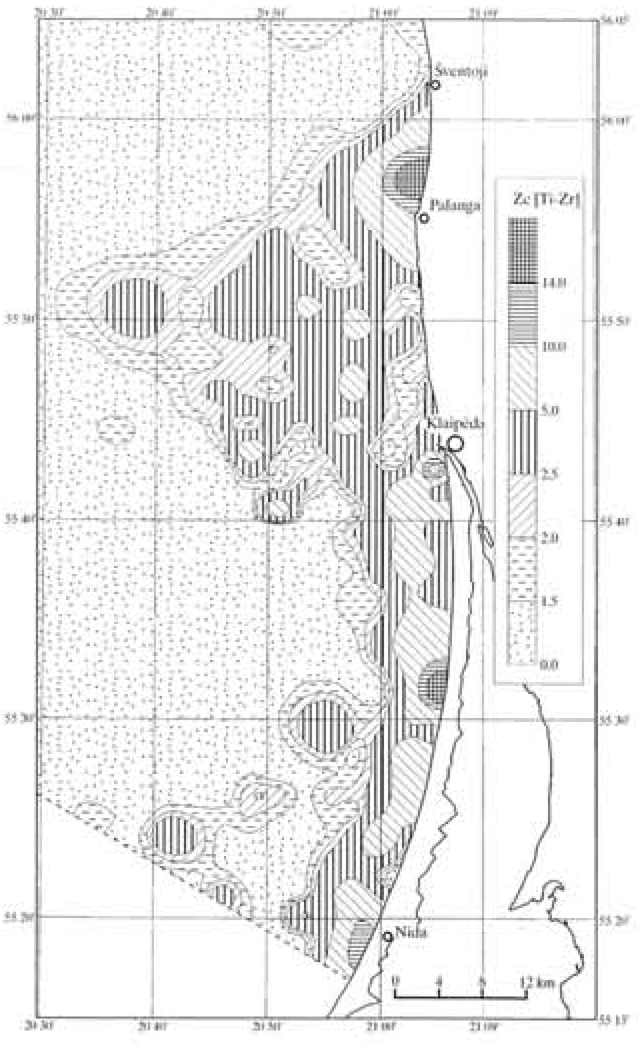

Fig. 3. Association of Zr-Ti in the sediments.

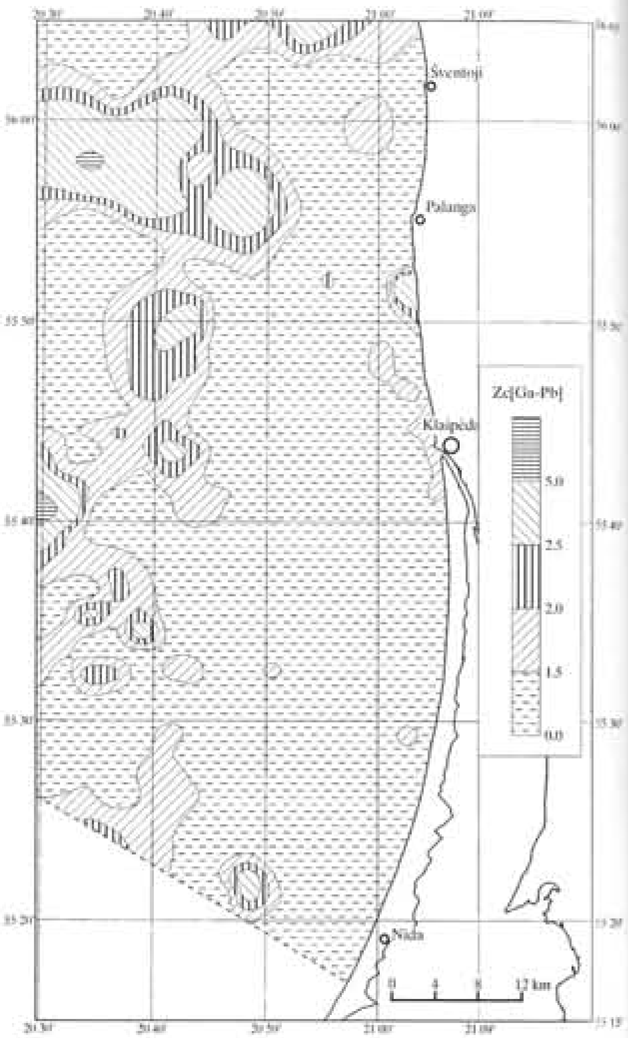

Fig. 4. Association of Ga-Pb in the sediments.

mechanical processes. Ti, Mn, Zr, Cr, Y, Yb, La, B, Nb, V, Zn and partially Co, Sc form a clastogenic association in the fine sand sediments. A part of these microelements (e.g. Zn and V) transit into other associations in the coarse aleurite sediments The second association is formed by Ga, Pb, Ni, Cu and Co in the fine sand sediments, or by Ga, Pb, Cu, Co, P and Sn in the coarse aleurite sediments. This association is a natural-technogenic association, elements being related to various minerals, organic matter and technogenic load (Baltakis 1993, Radzevičius & Zinkutė, 1998, Kadūnas 1998). Both associations are typical for the fine sand and coarse aleurite sediments, which are not mechanically mixed and heavily polluted in the study area.

The factor analysis reveals three associations in the fine-grained sediments (Md less than 0.05 mm). The first association is lithogenic. The elements (Pb, Cr, Sn, Ni, Li, V, Mo, Zn, Ag, Cu, Ga, B, Co, Sc, P, Yb and Ba) forming the lithogenic association are related to fine-sized particles. Nb, Ti, Zr and partially Yb, Y form the second clastogenic association.

In respect with the results of the factor analysis, Ti and Zr are strongly linked between themselves in the clastogenic association, whereas Ga and Pb are closely bounded in the natural-technogenic association. Such regularities were observed in the all sediments.

Ti and Zr are main microelements of the clastogenic association. Significant correlation between Ti and Zr was established in the all sediment groups. The linear relationship ($r>0.70$) was observed in the coarse-grained, fine sand and coarse aleurite sediments. Higher correlation coefficient ($r>0.70$) indicates paragenetic relationship between microelements (Burkov 1968, Kadūnas 1999). A paragenetic relationship between Ti and Zr ($r=0.62$) disintegrates in the fine-grained sediments. The disintegration of the paragenetic relationship between Ti and Zr depends on Ti amount that is related to fine-sized particles.

The summary index (Zd_{Ti-Zr}) of concentration coefficient of Ti and Zr was calculated. Zd_{Ti-Zr} values vary from 1 to 15 (Fig. 3.). The Zd_{Ti-Zr} values more than 2.0 indicate the zones of Ti and Zr association concentration. These zones are distinguishable in eastern part of the study area. It occurs along the coastline. The western boundary nearly coincides with the 25 m isobath in the south, towards the north, at the Klaipėda latitude the western boundary occurs at the 35-40 m isobath. At the Šventoji this zone is so narrows that it cannot be distinguished according to the available data. Zones where Zd_{Ti-Zr} values are higher than 5 occur at the depth not exceeding 25 m. A formation of these zones was probably related to the accumulation of heavy accessory minerals.

Ga and Pb are the main microelements of the natural-technogenic association. The correlation between these microelements is significant. The paragenetic relationship (correlation coefficient more than 0.70) was found in the all sediments. The summary index (Zd_{Ga-Pb}) of concentration coefficients of Ga and Pb varies from 1 to 6 in the sediments (Fig. 4.).The Zd_{Ga-Pb} distribution is very complicated comparing to the Zd_{Ti-Zr} distribution. The Zd_{Ga-Pb} values are obviously lower and rarely exceeding 2.0. Besides, the areas with Zd_{Ga-Pb} more than 2.0 are small and form locally separate zones in the western part of the study area. These facts clearly indicate that significance of this association is quite low. The concentration of the microelements belonging to the natural-technogenic association is inauspicious condition in the study area.

CONCLUSIONS

The data obtained by DC-Arc emission spectrometry of sediments from Lithuanian part of the Baltic Sea (The Šventoji-Nida area) were subdivided into four sets. These sets were studied by means of statistics.

The "background" median values of microelements were calculated in each sediment group (set) separately in order to remove the influence of sediment grain-size composition on microelement distribution.

Factor analysis based on the geochemical data establishes two main associations of microelements in the sediments. The first one association is clastogenic, the second one – natural-technogenic. These associations are characterised by most stable links in the sediments.

Ti and Zr were chosen as typical microelements representing clastogenic association, while Ga and Pb were considered to be the main microelements of the natural-technogenic association. Summary indexes of concentration coefficient for Ti-Zr (Zd_{Ti-Zr}) and Ga-Pb (Zd_{Ga-Pb}) were calculated. A comparison between values of Ti-Zr (Zd_{Ti-Zr}) and Ga-Pb (Zd_{Ga-Pb}) revealed that microelements of clastogenic association are less dependent on grain-size composition and more intensively concentrated in the study area.

The joint use of factor analysis and summary index of concentration coefficient allowed us to determine main associations of microelements and to characterise geochemical anomalies of the associations of microelements, which is more interesting from a geochemical point of view.

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Nearshore facies of the southern shore of the Baltic Ice Lake - example from Tromper Wiek (Rügen Island)

Klaus Schwarzer, Markus Diesing, Babette Trieschmann

Abstract

Sedimentological investigations (sidescan-sonar and shallow seismic surveys, vibrocoring, grab sampling) have been carried out in Tromper Wiek (southwestern Baltic Sea). Based on seismostratigraphic and lithological results five depositional sequences could be distinguished: E1c-glacial till, E2-glaciofluvial sediments, E3a-deposits of the Baltic Ice Lake, E4-Ancylus-lake deposits, E5-Litorina stage deposits. A beach ridge system with an associated lagoon attributed to the Baltic Ice Lake final transgression (10.3 ka BP) was mapped out. Due to high rates of sea level rise this system was not completely reworked during the Litorina transgression. The bedding conditions of the beach ridge-lagoon system point to a discontinuous development by overstepping of an older outer beach ridge and the construction of an inner younger one. The maximum water level of the final Baltic Ice Lake transgression is estimated to about 13—14 m bsl.

☐ *Baltic Ice Lake, beach-ridge, lagoon, water-level highstand, sequence stratigraphy.*

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INTRODUCTION

A rapid rise of the global sea level has been observed from drillings in coral reefs (Fairbanks 1989, Bard et al. 1990, 1996) and siliciclastic systems (Hanebuth et al. 2000) since the world-wide lowstand during the last glacial maximum. The sea level was monotonously increasing, exhibiting two intervals of rapid rise, which are attributed to melt water pulses (Fairbanks 1989, Hanebuth et al. 2000). Unlike these low-latitude locations, being remote from ice sheets, the water-level history of the Baltic Sea and its precursors are somewhat different and more complex due to the interaction of eustatic, isostatic and tectonic processes. Especially during the period 13-9 ka BP (all dates mentioned in the text are non-calibrated radiocarbon ages) major changes in its oceanography and related water-level history occurred: The Baltic Sea evolved from an ice-dammed melt-water lake (Baltic Ice Lake, 12.6-10.3 ka BP) to a fresh-water lake (Ancylus Lake, 9.5-8.0 ka BP), interrupted by a period of marine ingression (Yoldia Sea, 10.3—9.5 ka BP). Björck (1995) presents a detailed summary of the Baltic Sea development between 13-8 ka BP.

Considerable progress was achieved during the last decade concerning the knowledge about the paleogeography and the lake level maximum of the Baltic Ice Lake in the southwestern Baltic Sea area. Its extension to the west seems to be considerably wider than previously suggested. Jensen & Stecher (1992) described coastal deposits of freshwater origin in Fakse Bay (Zealand, Denmark) which were interpreted as marginal deposits of the Baltic Ice Lake during a transgression maximum of about 13 m bsl, dated to approximately 10.5 ka BP. Furthermore, Bennike & Jensen (1995) showed evidence of nearshore Baltic Ice Lake deposits from the same area associated with two water-level highstands, one of 13-15 m bsl dated to approximately 12.5-12.2 ka BP and a second one of 13 m bsl dated 10.6-10.3 ka BP, respectively. According to Jensen et al. (1997), the Baltic Ice Lake extended into Mecklenburg Bay and Kiel Bay during the transgression maximum at 10.3 ka BP. In Mecklenburg Bay the lake level maximum was estimated to about 20 m bsl.

Lemke et al. (1998) described deposits of the Baltic Ice Lake in Tromper Wiek (Rügen Island, Germany) in the range of 20 m bsl. AMS ^{14}C-data of the upper part of the section ascribed them to the transgression maximum at 10.3 ka BP. The depth difference of the lake level maximum to Fakse Bay was explained by different isostatic rebound rates.

Therefore two phases of water-level highstand, an "initial" and a "final" phase of the Baltic Ice Lake, separated by a water level lowstand seem to have occurred in the south-western part of the Baltic Ice Lake. This first stage in the evolution of the Baltic Sea was finished by its final drainage approximately 10.3 ka BP. The water level decreased about 25 m (Björck 1995).

Besides areas with raised shorelines in the northern part of the Baltic Sea, only little information is available concerning the sedimentary facies of marginal deposits of the Baltic Ice Lake. This is because deposits of former shorelines are often eroded along the southern coastline of the Baltic Sea during the Litorina transgression. Nevertheless, evidence of drowned, former coastlines is reported from other areas, e.g. from the northern North Sea (Hovland & Dukkefoss 1981, Rokoengen et al. 1982) and the US East Coast (Rampino & Sanders 1981, Stubblefield et al. 1984, Oldale 1985). The preservation of beach ridges is often attributed to "overstepping", favoured by a rapid sea-level rise (Rampino & Sanders 1981, Oldale 1985, Forbes et al. 1991). According to Carter (1988) high sediment influx, interplay between landward and seaward transport processes and barrier stranding on pre-existing submarine topographic features can be the reason for overstepping as well.

Drowned barrier beach ridge- and associated back-barrier lagoon/pond deposits of the Baltic Ice Lake were described by Jensen & Stecher (1992) from the southern part of Fakse Bay. Here beach ridge deposits consist of medium to coarse sand with variable pebble content in a coarsening upward sequence. The lagoonal part is built up by a laminated alteration of clay-silt deposits, interrupted by sand layers. Within the clay-silt deposits freshwater bivalves were found. In the northern part of the bay, barrier spit deposits were found consisting of medium sand with pebbles in a laminated structure (Jensen 1995). The sediments of an associated inshore basin are built up by massive and laminated medium sand, interlayered with laminated to heterolithic clay-silt.

SETTING

The study area Tromper Wiek is a semi-enclosed headland bay in the north-eastern part of Rügen island (NE-Germany) (Fig. 1). The two headlands (Wittow and Jasmund) are built up by Upper Cretaceous and Late Quarternary (Weichselian) deposits. These headlands are connected by a dune overtopped beach barrier named Schaabe which separates the „Große Jasmunder Bodden" from Tromper Wiek. The water depth in the study site ranges between 5 and 25 m bsl.

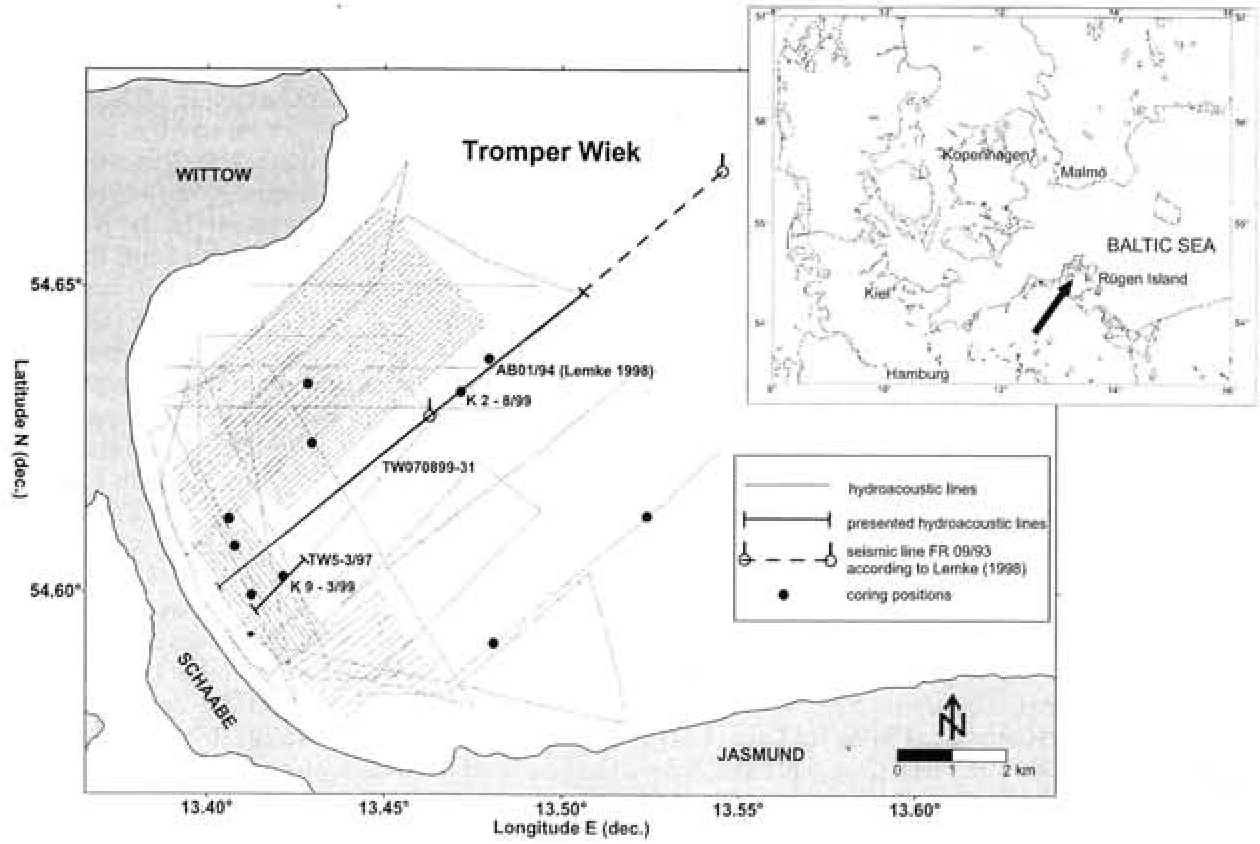

Fig. 1. Location of the study area Tromper Wiek.

METHODS

Data from hydroacoustic surveys (boomer, sidescan sonar) and sediment samples (vibrocorer, grab sampler) were collected between 1997 and 1999 onboard the research vessel „LITORINA". All positioning was done by DGPS which allowed an accuracy in the range of 0-10 m. The equipment for the hydroacoustic measurements consisted of an EG&G Uniboom shallow seismic boomer system (0.3-15 kHz) and a Klein 595 sidescan sonar (100 and 500 kHz). The hydroacoustic data were collected concurrently. The shallow seismic reflection pulses were amplified, filtered and printed on paper using an EPC 9802 graphic recorder and were as well recorded on tape. The maximum penetration depth of the boomer system was 20-30 m with 0.3 m vertical resolution. Before interpreting shallow seismic profiles, thickness of sediment facies units and level of reflectors below sea bottom were calculated using an average sound velocity of 1500 m/s for water and sediment according to Lemke (1998).

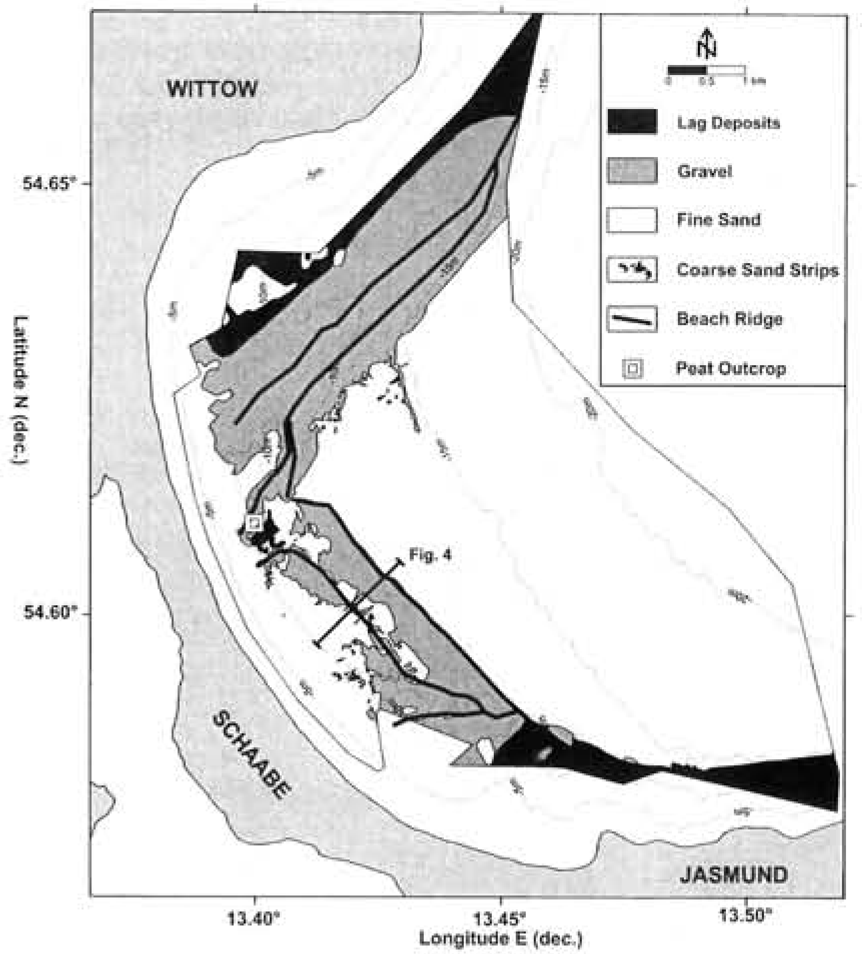

Fig. 2. Sediment distribution patterns and location of the drowned beach ridges within the study area.

Seismic interpretation is based on the principles of seismic stratigraphy (Vail 1987) investigating the development of depositional sequences and systems tracts by identifying discontinuities of reflector terminations and analysing seismic facies within each seismic sequence (Van Wagoner et al. 1987). Seismic facies is characterised by seismic reflection patterns including reflector configuration, continuity, amplitude, frequency and external form, from which geological interpretation of environmental setting or depositional processes and estimation of lithology is allowed.

Sidescan sonar data were collected employing the 500 kHz channels (beam width 0.2°) and a range of 75 m to each side. This allows for high-resolution images of the seafloor with a transverse resolution of 0.26 m.

Sediment samples were taken using a HELCOM-standard grab sampler. Detailed visual description as well as grain-size analysis was performed. For further groundtruthing of the sidescan sonar data underwater video observations and sediment descriptions by scuba divers were carried out. Based on first preliminary interpretations of the boomer data 3 m long vibro cores were taken to get lithological and sedimentological information of the subsurface and to identify sediment facies units in the collected shallow seismic data.

RESULTS

Based on sidescan sonographies sediment distribution patterns of the seafloor were elaborated (Fig. 2). In front of Wittow and Jasmund cliff coasts the seafloor is covered with heterogeneous sediment comprising grain sizes from sand to boulders. Small-scale patches of rippled sand are observed within these areas. This sediment type is interpreted as residuals of glacial till (lag deposits).

Adjacent to these lag deposits the seafloor is covered with gravel deposits; the water-depth ranges here between 8 and 14 m below sea-level. Prominent morphological ridges occur within these gravel fields. Observations by scuba divers revealed that these ridges are composed of well-rounded pebbles and cobbles up to 25 cm in diameter. In front of Schaabe spit fine sands are located in water depths down to 10 m bsl and in excess of 14 m bsl in the inner part of the bay. Within these fine sand areas and close to the gravel fields, small-scale strips of coarse sand can be recognised. Additionally, a peat outcrop was found surrounded by a gravel field (Fig. 2).

Based on boomer surveys five seismostratigraphic units can be recognised (Fig. 3). According to Jensen

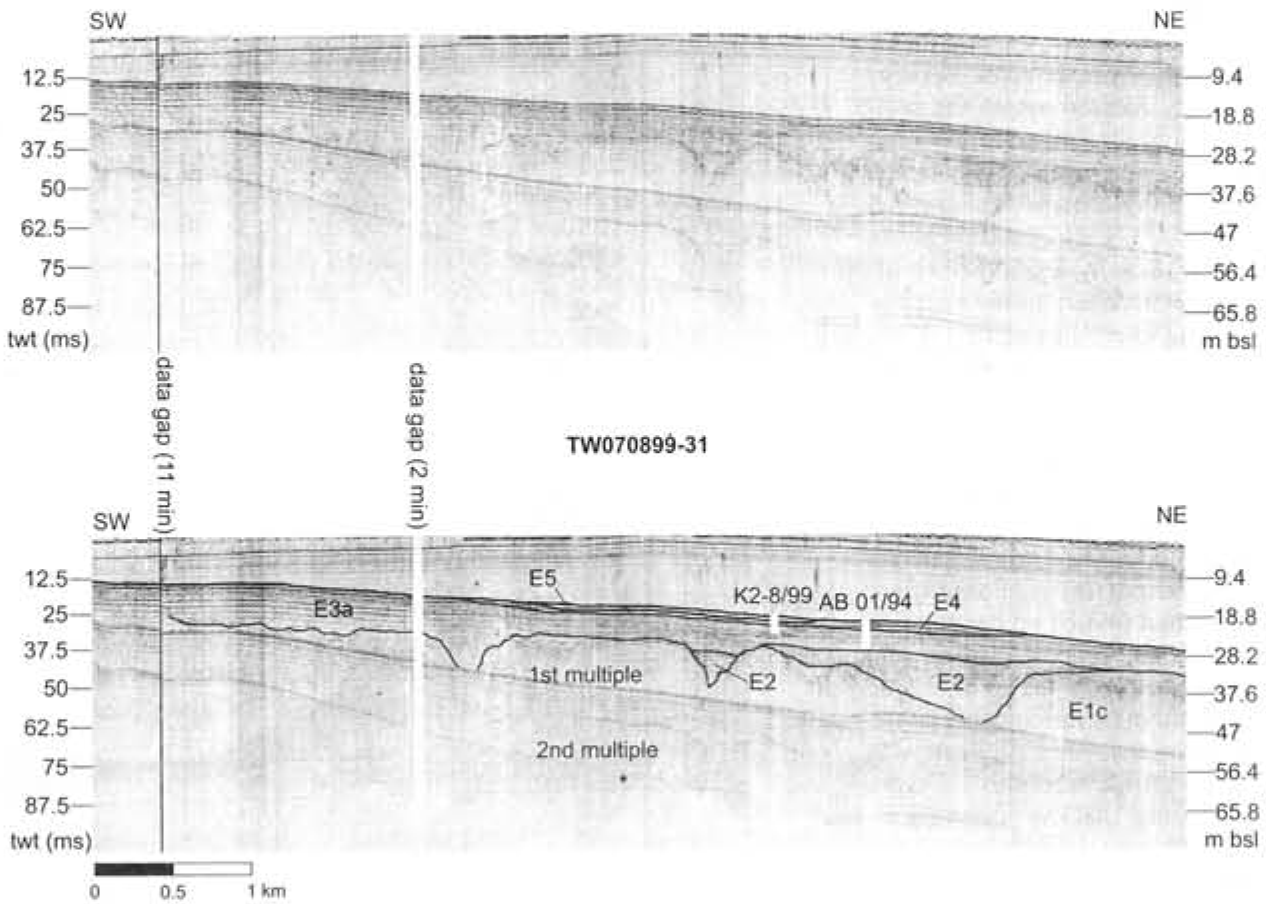

Fig. 3. Seismic profile TW070899-31 (for location see Fig. 1). The explanation of the seismic sequences is given in the text. Core AB01/94 was taken by Lemke et al. (1998).

et al. (1997), Lemke (1998) and Lemke et al. (1998) they are named E1c, E2, E3a, E4 and E5. In the following text we focus mainly on sequence E3a, the other sequences are described concisely.

Sequence E1c shows an internal chaotic reflector configuration. Its distinct upper sequence boundary reflector can be observed in most of the seismic profiles. This sequence consists of till and is covered by lag deposits in the NW and S of the research area. In the central part of Tromper Wiek the till surface dips to a depth of more than 40 m bsl. According to Lemke (1998) till of sequence E1c was deposited during the third glacial advance of the Weichselian.

In the central part of Tromper Wiek the till surface is structured by incised channels. In the seismic records a parallel to wavy reflector configuration and a well-developed discordant upper boundary characterises the channel filling sediment which is sequence E2. The thickness of this sequence can reach more than 15 m depending on the depth of the channels. According to Lemke et al. (1998) these sediments are of glaciofluvial origin and were deposited after the final retreat of the Weichselian glaciers during the initial phase of the Baltic Ice Lake.

Sequence E3a, superimposing sequence E1c and the channel filling sequence E2, shows a continuous, parallel internal reflector configuration in the distal part of Tromper Wiek while in the south-western proximal part of the research area the reflectors become more indistinct but still show characteristic continuous internal parallel reflections. The upper boundary of sequence E3a is discordant while the lower boundary is concordant in the central part of Tromper Wiek. At the lateral margins of sequence E3a reflectors are onlapping on sequence E1c. Sequence E3a follows the glacial morphology and its maximum thickness reaches approximately 15 m. In the seismic record deposits of sequence E3a occur up to a depth of 9 m bsl.

According to Lemke (1998) and Lemke et al. (1998) the silty respectively fine sand sediments of sequence E3a reveal AMS-^{14}C ages of 10570 ± 50 a BP and 10100 ± 120 a BP in the upper section of the sequence (core AB01/94, Fig.3). They were deposited during the final water level highstand of the Baltic Ice Lake.

In the western part of Tromper Wiek prominent morphological ridges can be recognised (Fig. 4). Within these ridges subparallel to chaotic internal reflections with erosional truncation at their surfaces can be observed. Reflectors of sequence E3a are onlapping on these structures as progading clinoforms. West of these ridges the internal reflections show a parallel to wavy configuration. In cores a clayey to silty fine laminated material interrupted by several thin sandy layers was observed. The material belongs to a lagoonal facies. In sediment core K 9-3/99 sandy lagoonal deposits are interlayered with thin layers of silt, 1 - 2 cm in thickness. Vertical roots of Phragmites pass through these sequences.

Bathymetric, sonographic and seismic records and sediment cores (Fig. 4), all collected in the inner part of Tromper Wiek, point to a partly eroded beach ridge-lagoon-system. In the seismic record TW 5-3/97 this system can be recognised showing a characteristic outer beach ridge damming a lagoon (see western part of the profile, Fig. 4). An inner beach ridge on top of the former lagoonal sediments can be observed as well. In relation to the outer ridge this second beach ridge is situated closer to the ancient shoreline.

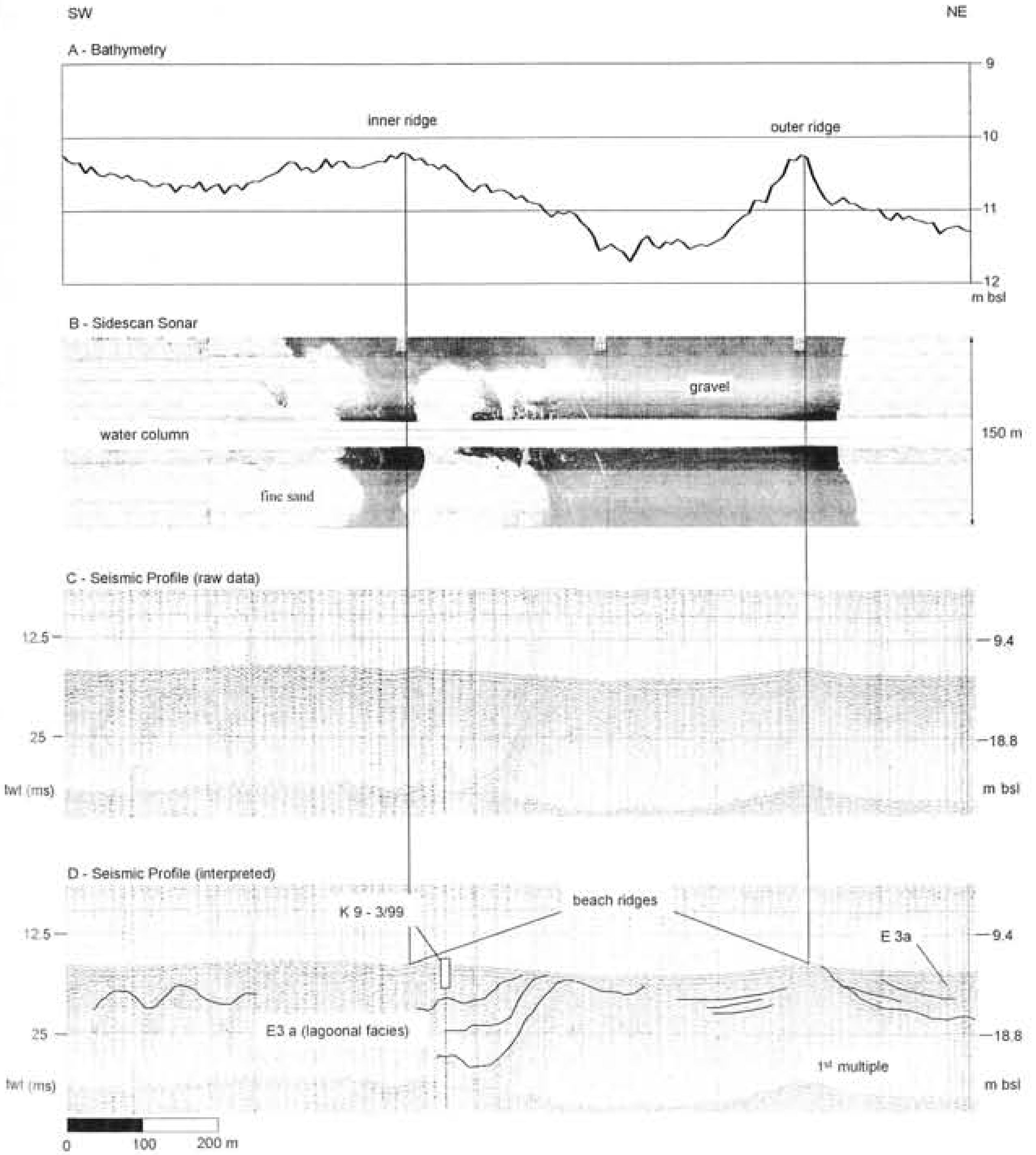

Fig. 4. Seismic profile TW5-3/97 (for location see Figs 1 and 2): A: In the morphological profile two ridges are visible. B: The sidescan sonar image shows that the morphological ridges are built up by gravel deposits. C: Boomer profile without interpretation. D: Interpreted seismic profile: The outer beach ridge and an associated lagoon are clearly visible. The inner beach ridge is located on top of lagoonal deposits. Sediments of sequence E3a terminate onlap on the beach ridge.

Sequence E4 is restricted to the central part of Tromper Wiek reaching up to 16 m bsl. The maximum thickness of this layer is 3 m. Only few parallel reflectors, concordant to the lower boundary, can be observed. This sequence is following the morphology of the underlying sequence E3a. From sediment cores it is known that thin layers of organic material appear in-between grey silty fine sand which is the main component. A peat sample taken from sediments of sequence E4 was dated by conventional radiocarbon-method to 9590 ± 140 a BP (Lemke 1998, Lemke et al. 1998). According to Lemke (1998) these sediments were deposited during the Ancylus Lake transgression.

Sequence E 5 can be observed in two areas within Tromper Wiek. The maximum thickness of this layer is up to two meters. In the seismic records it appears transparent with an indistinct lower boundary. According to Lemke (1998) and Lemke et al. (1998) sediments of sequence E5 were accumulated during Littorina and post-Littorina stages. In seismic records of the south-western part of Tromper Wiek a marked sediment complex with distinct prograding internal reflector configuration extending towards Großer Jasmunder Bodden is observed. According to the results of Schumacher & Bayerl (1997) this sediment complex was deposited during the Littorina transgression.

DISCUSSION

Evidence of a drowned, former beach ridge-lagoon system assigned to the Baltic Ice Lake stage was presented (Fig. 5). There is still uncertainty on the mechanisms of drowning and preservation of beach ridges although it is often attributed to a rapid rise in water level (Rampino & Sanders 1981, Oldale 1985). The beach ridges observed in Tromper Wiek were finally drowned during Litorina transgression. According to the shoreline displacement curve of Rügen Island (Schumacher & Bayerl 1997, 1999) a rapid sea-level rise from 15 to 6 m bsl, which is 13 mm/a, occurred between 8000 and 7300 a BP. The final drowning of the beach ridges possibly took place during this time. This rapid rise during the initial phase of the Litorina transgression might have favoured, at least partly, the preservation of the beach ridges.

An additional factor for the preservation potential of the ridges that has to be taken into consideration is the grain size. The clasts building up the ridges consist of granules (2-4 mm), pebbles (4 -- 64 mm) and cobbles (64 -- 256 mm). Schrottke (1999) presented an example from the Heiligenhafen area (western Baltic Sea) where such coarse sediments resist erosion in a nearshore, wave dominated area for hundreds of years.

According to ^{14}C data of the upper section of sequence E3a, Tromper Wiek was affected by the final transgression of the Baltic Ice Lake during the Younger Dryas chronozone. In the course of this transgression, the outer beach ridge and an associated lagoon developed in the south-western part of the bay. The beach ridge was attached to Jasmund peninsula cliff coast in the south (Fig. 2). The coastline of the peninsula was located some hundred meters northwards due to the lower water level. Erosion of glacial till from the cliff coast as well as from the adjacent seafloor provided material to build up the beach ridge system which separated a lagoon from the open Baltic Ice Lake. Within this sheltered environment fine-grained and laminated lagoonal sediments were deposited. The depth within the lagoon was up to 10 m.

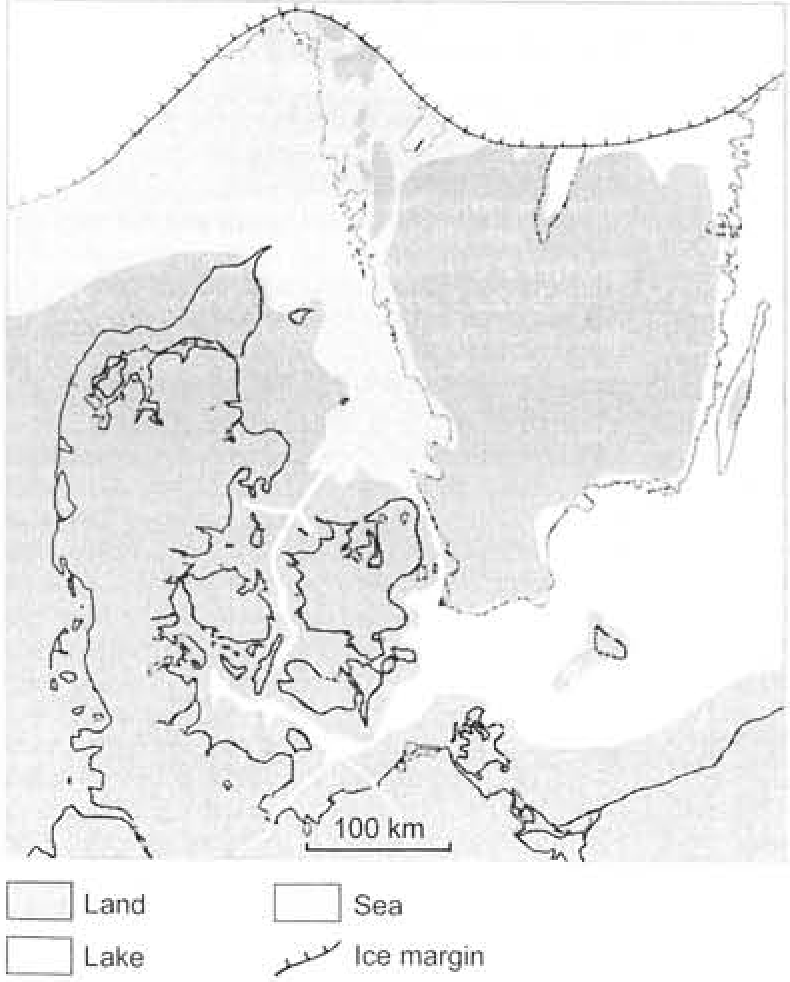

Fig. 5. Palaeogeographical map of the south-western Baltic Sea during the highstand of the final Baltic Ice Lake transgression phase 10.3 ka BP (Jensen at al. 1997, slightly modified).

In a second phase an inner beach ridge, a little bit higher in elevation was built upon the lagoonal deposits approximately 350-500 m further onshore (Figs. 2 and 4). This probably happened under a slightly higher lake level. The inner ridge, situated upon lagoonal sediments, which were deposited in the shelter of the outer ridge, indicates a discontinuous development of the geomorphological coastal features.

This discontinuous evolution may be explained by overstepping of the outer beach ridge during the Baltic Ice Lake final transgression. Overstepping might be caused by high rates of water-level rise (Rampino & Sanders 1981, Oldale 1985, Forbes et al. 1991) or, more precisely, an accelerated rise of water level leaving those barriers with slow response times behind (Carter 1988). Barriers consisting of gravel and boulder are the most likely to be overstepped (Carter 1988). There is a lack of knowledge on rates of water-level rise and phases of acceleration or retardation of the Baltic Ice Lake final transgression. Nevertheless Jensen & Stecher (1992) calculated a relative rate of water-level rise of 3 mm/a during the period 11500—10000 a BP. This corresponds to the rate of sea-level rise reported by Forbes et al. (1991) who observed overstepping of a gravel barrier. Sufficiently high rates of water-level rise combined with the coarseness of the beach ridge sediments might have favoured overstepping of the outer beach ridge.

There is less information on the development of the beach ridges in the northwest of Tromper Wiek due to the fact that the massive and widespread surficial gravel layer hampered penetration of seismic waves into the subsurface. No adjacent lagoon was found until now but a peat outcrop (Fig. 2) was detected by sidescan sonar investigations. This peat probably developed in a sheltered environment between two beach ridges.

Beach ridges themselves are somewhat unreliable for an exact indication of water level as the height of their crests have no simple relationship to the water level (Orford et al. 1991). Moreover, the beach ridges have been partly eroded during Litorina transgression as indicated by erosional truncation at their surfaces.

Lagoonal deposits of sequence E3a assigned to the Baltic Ice Lake final transgression were found up to a maximum height of 9 m bsl in Tromper Wiek. This is considerably higher than the value proposed by Lemke et al. (1998) being in the range of 20 m bsl. As we have indeed detected the paleo-coastline of the Baltic Ice Lake in Tromper Wiek, our value seems to be more reliable as an upper limit of sediments deposited during the final Baltic Ice Lake transgression. Assuming a thickness of the water column of at least 1-2 m above the lagoonal deposits, the corresponding water-level can be estimated to around 7-8 m bsl. Taking into account an uplift of 6 m between 7000 and 5000 a BP for Rügen Island, as reported by Schumacher & Bayerl (1999), the maximum water-level of the Baltic Ice Lake during the final transgression around 10.3 ka BP was around 13 — 14 m bsl. This value fits well to the results presented by Jensen & Stecher (1992) from Fakse Bay, where they determined a transgression maximum of 13 m bsl. Fakse Bay and Tromper Wiek might therefore have experienced no differential isostatic rebound as often assumed and shown in isobase maps of the southern Baltic (e.g. Kolp 1979, Striggow & Till 1987). Further verification of this conclusion would have considerable consequences with regard to the interpretation of similar sequences in the western Baltic Sea.

CONCLUSIONS

The applied hydroacoustic (sidescan-sonar, boomer) and sedimentological (grabsampler, vibrocorer) methods have proved to be powerful tools in investigating subaqueous Pleistocene and Holocene sediments. Based on these investigations the following conclusions can be drawn:

A coarse clastic barrier beach ridge-lagoon system of the final Baltic Ice Lake transgression has been detected in Tromper Wiek. This finding proves and extends the results of Lemke et al. (1998). Preservation of the beach ridges despite Litorina transgression is probably due to a high rate of sea-level rise and coarseness of the ridge material. The configuration of the beach ridge-lagoon system in the south-western part of Tromper Wiek points to a discontinuous development possibly implying overstepping of the outer ridge. A water-level of approximately 13—14 m bsl during the final Baltic Ice Lake transgression maximum can be deduced from the maximum elevation of lagoonal deposits, taking into account an uplift of 6 m between 7000 and 5000 a BP (Schumacher & Bayerl 1999).

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Baltica

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Sedimentation in the Northern Baltic Sea Basin

Egidijus Trimonis, Nijolė Savukynienė

Abstract

Sedimentation in the Northern Baltic Sea Basin is analysed on the ground of new palynological and sedimentological data. This region is a very sophisticated province of interaction of two large morphostructures of the Baltic Sea. According to spores-pollen spectrum the Northern Baltic Sea Basin had already been occupied by the Baltic Ice Lake in the Older Dryas. During later stages of the Baltic Sea development the marine (or lacustrine) sedimentation did not discontinue. The sediment stratum of the Northern Baltic Sea Basin is heterogenous due to the environmental changes, which took place here.

☐ *Northern Baltic Sea Basin, spores-pollen diagram, bottom sediments, grain-size, climatic periods, sea stages, environment.*

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INTRODUCTION

The northern part of the Baltic Sea is distinguished for its complicated bottom relief and composition of sediments. It was conditioned by the geological history of this region, when the Baltic Crystalline Shield and the Baltic Syneclise – these two largest morphostructures of the region – had undergone different tectonic processes as far back as Paleozoic. In Quaternary glaciotectonics played an important role showing up distinctly old tectonic faults and newly generated moraine ridges. Now the bottom in the Northern Baltic Sea is characterized by considerable unevenness of relief – steep cliffs, deep exarational and erosional valleys. They were only partly softened by an intensive sediment accumulation, which followed the ice sheet regression at the end of the Pleistocene.

The main traits of geological processes in the Northern Baltic Sea after the glaciation were the same as in the other parts of the sea (Gudelis 1976), however the previous course of development is responsible for peculiarities of relief and sediment cover formation of this region. It was proved by geological-geophysical investigations (Flodén 1980, Söderberg 1988, Trimonis & Sviridov 1994, Noormets & Flodén 1999) including underwater observations (Emelyanov et al. 1995, 1996).

Besides many sediment cores have been analysed, but a complete cycle of sedimentation beginning with the late glaciation has been recorded in none of them (Kleimenova 1988). Therefore, the palynological and sedimentological studies of cores presented in this article partly fills the existing gap.

MATERIAL AND METHODS

The sedimentological and palynological analysis of bottom sediments was made on two cores obtained during the r/v *Shelf* expedition (Trimonis & Sviridov 1994). The core Sh-2135 (59°10.9' N, 21°01.0' E, sea depth 120 m) and the core Sh-2144 (59°21.8' N, 20°40.8' E, sea depth 66 m) are in the middle of the SE-NW lithological cross section of the Northern Baltic Sea Basin (Fig.1). The sedimentological examination was made by E.Trimonis, the palynological analysis – by N.Savukynienė.

The lithological composition of bottom sediments was determined according to visual core description and smear slides studying. The grain-size analysis was made using standard pipette (settling in water) method. Results are presented in percents. Granulometric types of sediments are distinguished on the basis of predominant fraction and median diameter using decimal clas-

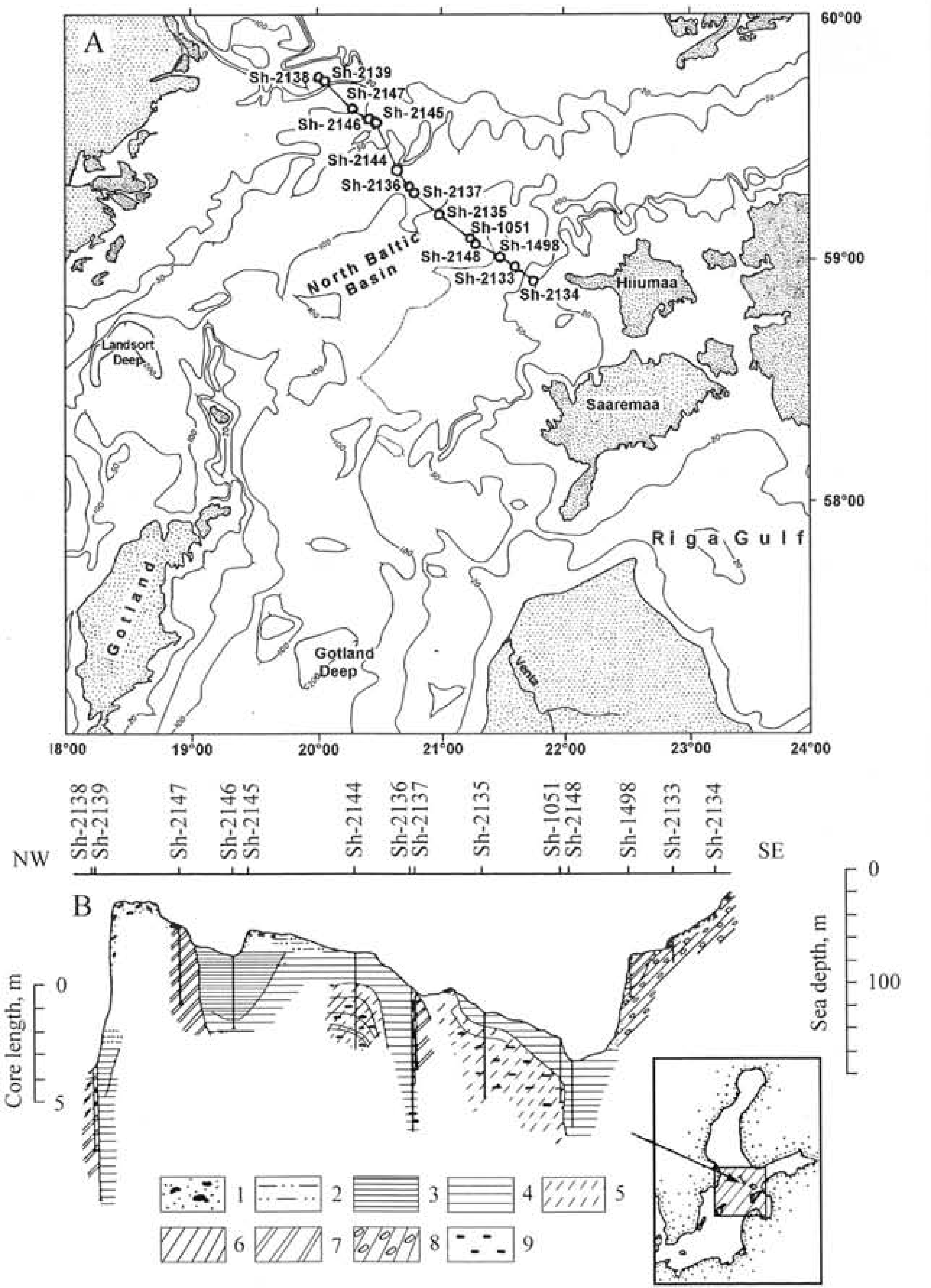

Fig. 1. Location of sampling sites (A) and bottom sediments along a transect (B) from the northern part of the Baltic Sea. 1 – sand, gravel and pebble; 2 – coarse silt; 3 – microlaminated pelitic mud; 4 – greenish grey mud; 5 – bluish grey and grey clay; 6 – brownish grey clay; 7 – varved clay; 8 – morainic clay; 9 – hydrotroilitic layers and patches.

sification of marine sediments (Bezrukov & Lisitzin 1960).

Samples for microscopic spores and pollen analysis were taken every 5 cm in both cores. Separation and acetolysis methods were used for treatment of spores and pollen; the content of pollen per 1 g of dry material was calculated using formula suggested by M.Kabailienė (1979). Results are presented in percentage diagrams using computer programs TILIA and TILIA GRAPH, where the percentage composition of pollen was calculated from the total sum of tree, shrub and grass pollen (Figs. 2 and 3).

The content of pollen in the sediments of the both cores differs considerably. The pollen concentration ranges from 20000 to 60000 per 1 g of dry matter in the upper parts of the cores composed of pelitic mud. Deeper, in clayey sediments, the pollen concentration is only 2000-7000 (interval 210-250 cm in core Sh-2144 and 90-230 cm in core Sh-2135) and in some intervals – as low as 150-200 p/g (345—380 cm in core Sh-2144 and 250-300 cm in core Sh-2135). The tree pollen dominate almost in all samples. The content of spores is rather high, whereas the poorest one is the spectrum of grass pollen.

RESULTS AND DISCUSSION

The thickness of clay and terrigenous mud in the cores is 373-435 cm (Figs. 2 and 3). It represents the upper part of the Late Quaternary. The lower part is composed of a reddish grey loam (morainic deposits) with patches of fine-grained sand and debris of carbonaceous rocks and granites. Due to rough the pre-Quaternary surface the Quaternary sediments were deposited very unevenly – the thickness of their stratum ranges from 0 to a few tens metres and the average mostly is 5-10 m (Trimonis & Sviridov 1994).

The Quaternary sediments are deposited directly on the rough surface of the Archean-Proterozoic crystalline rocks along most of the profile (Fig.1). In its southern part (between st. Sh-2148 and st. Sh-2134) the pre-Quaternary surface has an escarpment relief with steep slopes. The Quaternary sediments are deposited on the Cambrian-Ordovician terrigenous and carbonaceus rocks, which are exposed on the surface of steep slopes (Emelyanov et al. 1995).

The unconsolidated sediments of the Late Pleistocene-Holocene cover almost the whole bottom surface. However, in the areas of strong erosion (mostly bottom elevations) this layer is very thin or absent. In such cases the moraines or the pre-Quaternary deposits are covered with coarse-grained clastic matter – boulders, gravel with sand (st. Sh-2133, st. Sh-2134) (Fig.1).

In the Younger Dryas the receding Scandinavian ice sheet still covered a considerable part of the Northern Baltic Sea area. The standstills of the ice sheet and its edge fluctuations generated thick morainic ridges, which have been traced in the northern part of the Baltic Sea by seismic investigations (Söderberg 1988). They represent an underwater continuation of the Salpausselka morainic ridges examined in detail in Finland.

The investigated northern part of the Baltic Sea was already a water filled basin with intensive accumulation of sedimentary matter during the Older Dryas. The pollen analysis in the sediment sequence of cores Sh-2144 and Sh-2135 revealed that the lower intervals (340-426 cm in core Sh-2144 and 360-370 cm in core Sh-2135) may be ascribed to early deglaciation (Baltic Ice Lake stage). *Betula* and *Pinus* pollen dominate in the spores-pollen spectrum (44-56% and 30-70% respectively), whereas *Picea, Alnus, Corylus* (redeposited ?) pollen are solitary. Among grasses we can mention *Artemisia*, Chenopodiaceae, Poaceae, *Helianthemum*, Asteraceae, *Hippophae, Dryas octoetala*, among spores plants – Polypodiaceae, Sphagnales spores dominate and *Lycopodium annotinum, L. clavatum, Ophioglossum vulgatum, Selaginella selaginoides* - are found in solitary cases. *Pinus* and Polypodiaceae pollen dominate only in the interval of 390-400 cm (core Sh-2144) pollen spectrum and it can be ascribed to the Allerod.

The Late Pleistocene glacial sediments of core Sh-2144 are composed of bluish grey clay with dark grey patches and lenses enriched with iron monosulphides (hydrotroillite) and one thicker interlayer (interval 372-390 cm), which consists of brownish grey clay with mottled texture. The sediments of the same age (Baltic Ice Lake stage) in core Sh-2135 are represented by grey clay with a fairly large portion of hydrotroillite.

The composition of sediments shows that sedimentation in the periglacial water basin for a greater part of the time took place under reducing conditions and sufficient amount of active organic material. The mechanical differentiation of sedimentary matter was intensive and calm environment dominated in the basin. The main part of sediments is composed of pelitic fractions (74.2 – 84.9%), whereas sand and coarse aleurite make up only 0.2 – 0.7%. Still more thinly dispersed clay accumulated in deeper water (st. Sh-2135). The sum of pelitic fractions in its composition exceeds 90% including the bulk (>60%) of subcolloidal fraction (<0.001 mm).

However the accumulation of sedimentary matter was not even – during different time spans the hydrodynamic environment in the basin would become very active. The interlayer of brownish grey clay (core Sh-2144, interval 372-390 cm) formed in a basin with good aeration and stormy hydrodynamic environment. This interval bears evidences of pollen redeposition.

According to palynological data the thickest sediment layer was deposited in the Early Holocene. The Northern Baltic Sea Basin became the area of intensive accumulation of bluish grey (core Sh-2144) and

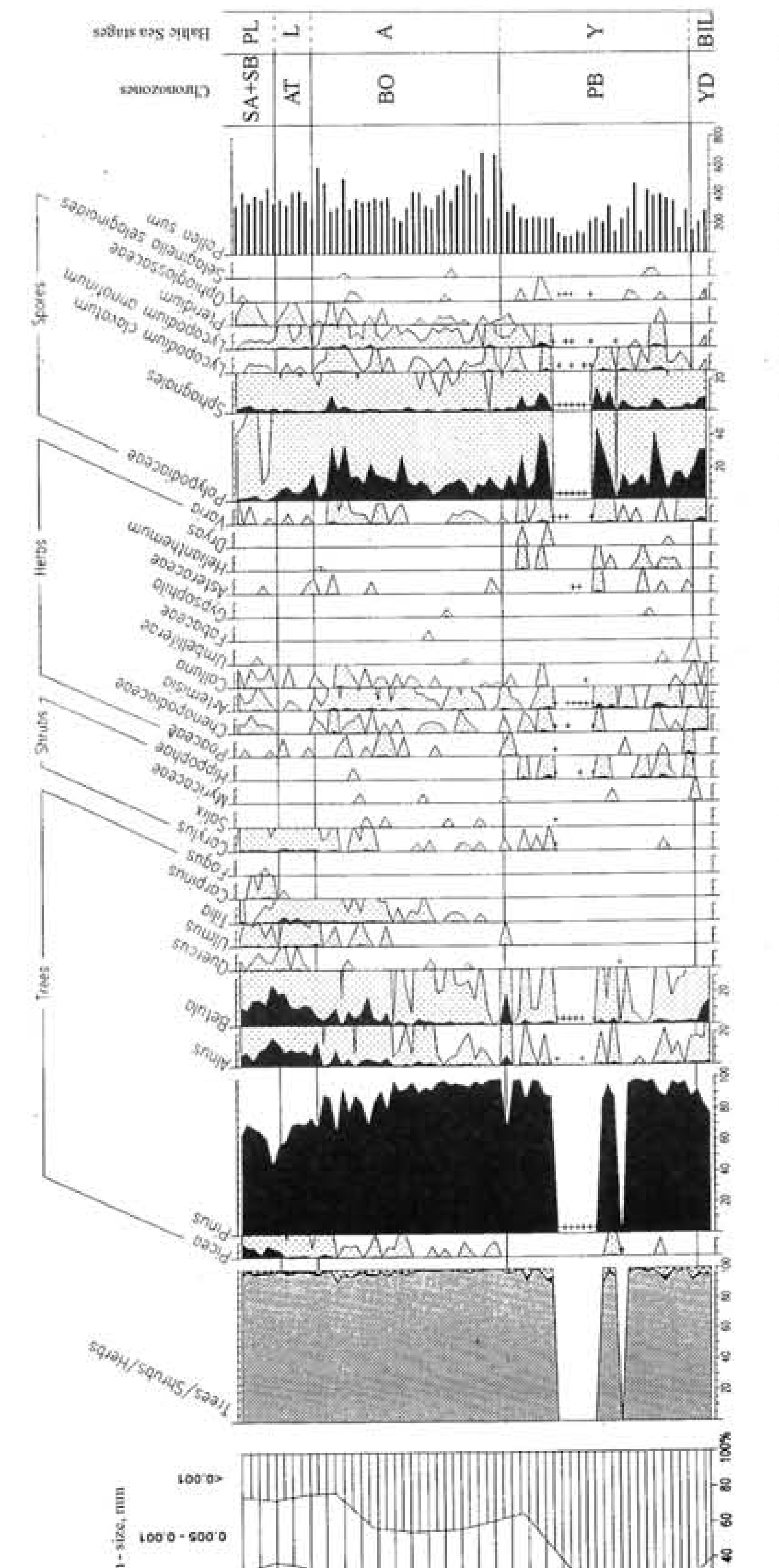

Fig. 2. Lithology, grain-size and spores-pollen diagram of core Sh-2135. Chronozones: SA – Subatlantic, SB – Subboreal, AT – Atlantic, BO – Boreal, PB – Preboreal, YD – Younger Dryas, AL – Allerod, OD – Older Dryas. Baltic Sea stages: PL – Postlitorina, L – Litorina, A – Ancylus, Y – Yoldia, BIL – Baltic Ice Lake. For the legend see Fig. 1.

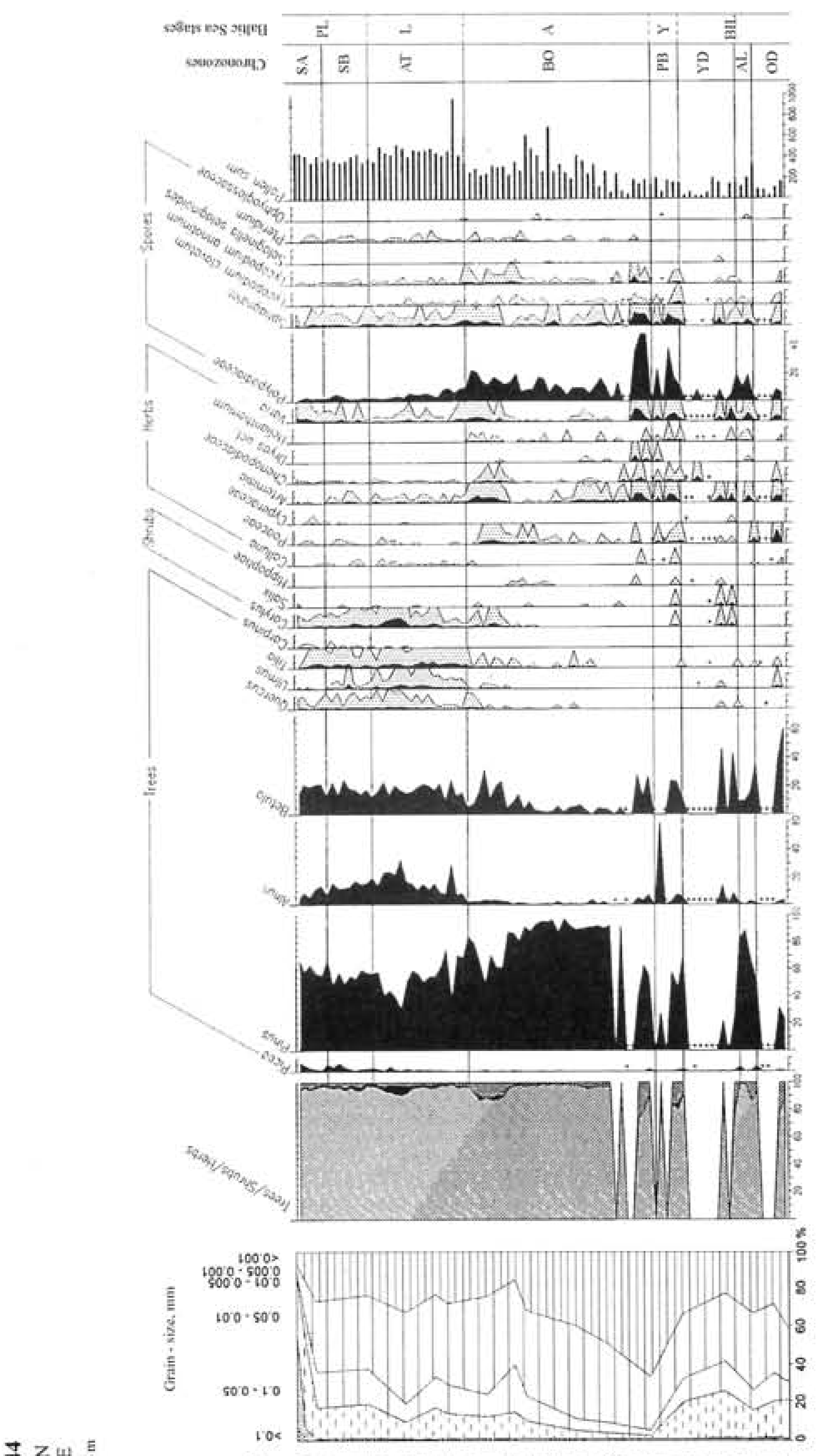

Fig. 3. Lithology, grain-size and spores-pollen diagram of core Sh-2144. Chronozones and the Baltic Sea stages abbreviations see Fig. 2. For the legend see Fig. 1.

grey (core Sh-2144) clay enriched with hydrotroillite when the ice sheet retreated finally. Sediment intervals 315-340 cm (st. Sh-2144) and 210-360 cm (st. Sh-2135) are dated to the Preboreal. The content of tree pollen decreased to 40-60%, grasses – to 6-10%, whereas the amount of spores increased considerably (to 60%) in the spores-pollen spectrum of these intervals. Among the group of tree pollen the portion of *Pinus* decreased, whereas *Betula* (up to 30%) and *Alnus* increased. The grass spectrum changed but a little. However the content of Polypodiaceae, Sphagnales, etc. increased considerably (st. Sh-2135).

According to grain-size composition the most fine-grained sedimentary matter was deposited during the Preboreal. Accumulation presumably took place in a slowly deepening basin during the Yoldia transgression. Clays are composed almost only of pelitic fractions (>98%) including even up to 81-87% of subcolloidal fraction. At the end of the Preboreal (interval 220-225 cm of core Sh-2135) the greater changes of grain-size composition of sediments occurred. Though the total amount of pelitic fractions decreased negligibly (to 94.4%) a distinct redistribution took place within them. The content of subcolloidal fraction decreased up to 34.6%, whereas the content of medium pelite fraction increased (up to 47.2%). At the same time the content of coarser fractions increased, particularly the fine aleurite fraction. Presumably these changes were related to the gradual transition of the Yoldia Sea to a new stage (Ancylus Lake) and lowering of water level in the Baltic Sea (Eronen, 1988). All this brought somewhat nearer the sources of sedimentary matter and entailing in this way changes of sedimentation.

The beginning of the Ancylus stage in the sediment sequence of core Sh-2144 has a distinct lithological boundary – the bluish grey clay (Yoldia Sea) is covered with a light brown clay. But deeper in the sea (st. Sh-2135) no considerable changes could be traced. In spores-pollen spectrum some changes is reflected by an increased concentration of spores and pollen (up to 5000-6000 p/g) in the Boreal. Tree pollen are dominating. At the early part of the Boreal the prevalence of *Pinus* pollen is absolute (up to 95%); the concentration of grass pollen and spores are somewhat lower. This period is represented by sediment intervals 185-315 cm (st. Sh-2144) and 100-210 cm (st. Sh-2135).

Later in the Boreal when climate became more temperate and humid the concentration of *Alnus*, *Betula* and *Corylus* pollen increased. Small amounts of *Picea*, *Ulmus* and *Tilia* pollen were found. The concentrations of grass pollen – Poaceae, *Artemisia*, Ericaceae as well as Polypodiaceae, *Sphagnales*, *L. clavatum*, *Pteridium* spores also increased. This period is represented by interval 150-185 cm in core Sh-2144 and interval 55-100 cm in core Sh-2135. A light grey homogenous (microlaminated in some places) clay was deposited in the deeper part of the basin. At a somewhat smaller depth (st. Sh-2144) bluish grey clay with characteristic small patches of iron sulphides was formed.

Judging from grain-size composition of sediments the course of sedimentation during the Boreal was uneven. At the first half of this period the sedimentary environment was very similar as at the end of the Yoldia stage because the accumulating thinly dispersed sedimentary matter was principally of the same composition. The same can be said about site Sh-2144, where the sum of pelitic fractions in some intervals of the Ancylus Lake sediments was as high as 98%. Core Sh-2144 includes a 130 cm thick clay layer. Its brown colour implies that sedimentation took place under the conditions of activated aeration in near-bottom water layer.

By far thinner layers developed during the second half of the Boreal. Besides, the grain-size composition of clays deposited during this period it is characterized by smaller amounts of pelitic fractions (85.2-87.8%), lower concentration of subcolloidal and evident increase of the portion of fine aleurite matter. The relative slowing down of the sedimentation rates and weaker differentiation processes of sedimentary matter were presumably related with the beginning of the Litorina transgression.

The beginning of the Litorina stage in the sediment sequence of the Baltic Sea can be easily traced by their lithological composition. The interval 65-150 cm of core Sh-2144 is composed of a very characteristic greenish grey microlaminated pelitic mud with an increased content of organic matter. The grey (up to dark grey) pelitic mud of the same time was distinguished in core Sh-2135 (interval 32-55 cm). The spores and pollen confirm that these sediments were deposited during the Atlantic climatic period. The spectrum is distinguished by a great qualitative and quantitative diversity of pollen including maximal concentration of broad-leaved trees (*Quercus* and *Tilia* in particular), *Alnus* and *Corylus*. The concentration of grass pollen and spores decreased. The *Pinus* curve reaches up to only 60%, *Alnus* – 30%, *Betula* – 20%.

The pelitic mud has the same grain-size composition as at the end of the Ancylus stage. The pelitic fractions compose the main part of sediments – from 80.5 to 90.4% with the dominating medium pelite fraction. The amount of aleurite particles somewhat increased. Thus, the differentiation of sedimentary matter even slightly decreased. Presumably the sedimentation took place under the conditions of still lasting transgression – very slow and without considerable changes.

In the Subboreal the pollen concentration of broad-leaved trees, *Alnus* and *Corylus* decreased, but at the same time the content of *Picea*, *Pinus* and grass pollen increased. There also appeared pollen of *Carpinus* and *Fagus*. This period is represented by an interval (25-65 cm) of greenish grey pelitic microlaminated mud in core Sh-2144. Due to the thinness of the sediment layer (0-32 cm) it is rather difficult to identify the boundary between the Subboreal and the Subatlantic climatic periods in core Sh-2135. Besides neither the lithological nor the grain-size composition of pelitic mud in this interval shows any changes.

The Subatlantic period is represented by the interval 3-25 cm composed of fine aleurite mud deposited above greenish grey clay in core Sh-2144. Coarse silt with a small concentration of pelitic fractions (17%) is at the top (interval 0-3 cm) of this core. The spores-pollen spectrum of these sediments corresponds to the composition of recent vegetation on the land. Thus, the recent sedimentation on the Northern Baltic Sea Basin slope (site Sh-2144) takes place under conditions of very active hydrodynamics.

In deeper water (site Sh-2135) the accumulation processes have not undergone any changes since the end of the Boreal. The surficial sediments are composed of greenish grey or dark grey (st. Sh-2148) pelitic mud with an increased amount of organic matter.

CONCLUSIONS

The accumulation processes on the slope of the Northern Baltic Sea Basin began no later than the Older Dryas. The spores-pollen spectrum of two cores made it possible to distinguish all climatic periods after the Dryas till now. The spores-pollen spectrum of the Northern Baltic Sea Basin virtually coincides with corresponding spectra from other parts of the Baltic Sea (Kleimenova 1988, Kabailienė 1998). Therefore, the sediment layers representing the different stages of the Baltic Sea were revealed in the sediment sequence of this region.

The lithological and grain-size composition of bottom sediments were changing gradually. The most fine-grained sediments accumulated in the Yoldia Sea. During later stages the sediments gradually coarsened and the changes in grain-size was more distinct in its pelitic part. For most of the time sedimentation took place in calm reducing environment, which still prevails in this basin today. Active hydrodynamic conditions and a better aeration of near bottom water occurred on the slope of the Northern Baltic Sea Basin only at certain periods (Baltic Ice Lake and Ancylus stages).

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BALTICA POSTER PAGE

Many authors in marine geology and geophysics are familiar with the problems of publishing large-size figures especially such as sidescan images and seismic records, with satisfactory quality and size in journal articles. Because of space and format limitations in accordance with the publisher's instructions and the envisaged volume of the article, authors frequently have to restrict the number and size of figures, often more than they think to be bearable. The story ends in most cases with a compromise, the author adapting himself to the circumstances, which generally means to show many figures, but in too small sizes and therefore coupled with loss of information. But what about his very best records having outstanding quality, which show more of the interesting details than can be seen in the article's examples? Even if the author may already have presented them in a conference poster, he may estimate the incorporation of these records in an article of suitable size as a too high barrier, and so they will be banned perpetually into the archives and be lost to the scientific community.

Especially in the case of high-resolution side-scan sonar, the presentation as large-size figures seems a need, which can be elucidated by a simple calculation. The actual resolution of targets with these systems is about 20 cm, corresponding in the normal paper scale of the records to 1 mm. To transfer this on a printed presentation, a resolution of 0.5 m would normally be tolerated. Since these systems have a record width between 20 and 40 cm, the tolerable size reduction for printing should be between 1.0 (= no reduction) and 0.5. Actually, such small reductions will be rarely found in the literature, and thus the power of these systems is little exploited for scientific communication.

As an innovation to alleviate this problem, and to encourage the authors to publish such records, *BALTICA* now offers a regular column called *„Baltica Poster Page“* (see here: Werner, F., p. 85-87). Eventually, X-ray radiographs (in digitised format) could also be considered. The volume of this column should be comparable to the text volume of a normal poster, corresponding to three pages in the journal format at maximum. One page (or a double page) should be reserved to the selected record with the size 18 x 24 cm, the rest for a short description of the related subject, a thorough explanation of the main figure, eventually one or two small auxiliary figures (map, diagram), conclusions, and a few references.

The *Baltica* with its large-size page format and its endeavours for excellent print quality appears as an adequate place for such a column. Considering the reader community with its common regional interest, the topic of The Poster Page should normally be related to the region of the Baltic Sea, although records of other regions may also be considered, if they address a problem related to the Baltic region.

The Editor

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Baltica 13 (2000) 85-87

New aspects of sand waves (Fehmarn Belt, western Baltic) by using high-resolving sonography

Friedrich Werner

Abstract

The complex surface morphology of sand waves as only being revealed by high-resolution side-scan sonar (ca 20 cm) is demonstrated in a sonography section of a fluviatile-type sand-wave field in the Fehmarn Belt. The migration is only active during strong inflow phases, and its process is taking place by increments of slide events on the lee-side slopes. This may modify the conventional model of internal structures with uniform cross-bedding of sand waves.

☐ *Western Baltic, high-resolving side-scan sonar, sand waves.*

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INTRODUCTION

The dynamics of sand waves have been intensely studied in the past including mapping of their by side-scan sonar. However, high-resolving systems (resolution ca. 20 cm) have rarely been applied, and the published sonographies were mostly too small in scale to detect much of the important details. The high-resolution sonography from the Fehmarn Belt (Fig. 1) gives an example of the details of their complex bedforms and how they may be used to better understand their dynamics.

The Fehmarn Belt is one of the main straits of the estuarine-type water exchange in the western Baltic where generally the outflow of low salinity water (>15%) in the upper section is dominating, whilst high-salinity inflow is concentrated in the lower part (Wyrtki 1953). The dynamics of the water exchange in all these straits is strongly dependent on the meteorological conditions which due to water level differences in the adjacent sea basins generate high current speeds affecting the sea bed (Dietrich & Schott 1974). Therefore, most of the straits show current-induced bedforms such as sand waves or others (Fig. 2; Kuijpers 1985). In the Darss Sill area (Fig. 2-1), sand waves reach maximum values with 5 meters (Lemke et al. 1994). Where both in- and outflow obtain high velocities, the typical tidal-type profiles with symmetric and concave slopes occur (Allen 1982), like occurring in the Darss Sill and Great Belt areas (Fig. 2-4, Werner & Newton 1975). In contrast, due to Coriolis forces, on the southern side of the Fehmarn Belt (Fig. 2-3, Werner et al. 1974) the inflow is steadily superior to the outflow, and the sand waves show the fluviatile form type (Allen 1982), i.e. strongly asymmetric profiles, rounded crests at their highest elevation, and steep lee-side slopes.

METHODS

The side-scan sonography of Fig. 1 has been produced 1986 with a KLEIN Hydroscan recorder Model 521 (paper width 40 cm, wet paper printing, manually setting of tuning and TVG) and a towfish 422S (500 kHz frequency, horizontal beam angle 0.2°). The towing velocity of 2.9 knots yielded a practically undistorted scale relation. In the first side-scan sonar survey of the Fehmarn Belt sand-wave field of 1972 (Werner et al. 1974), a 100 kHz/1.0° EG&G system has been used. Diver observations for checking sonographic structures, vibrocore investigations, sampling for granulometry, and boomer profiles have been made in both surveys.

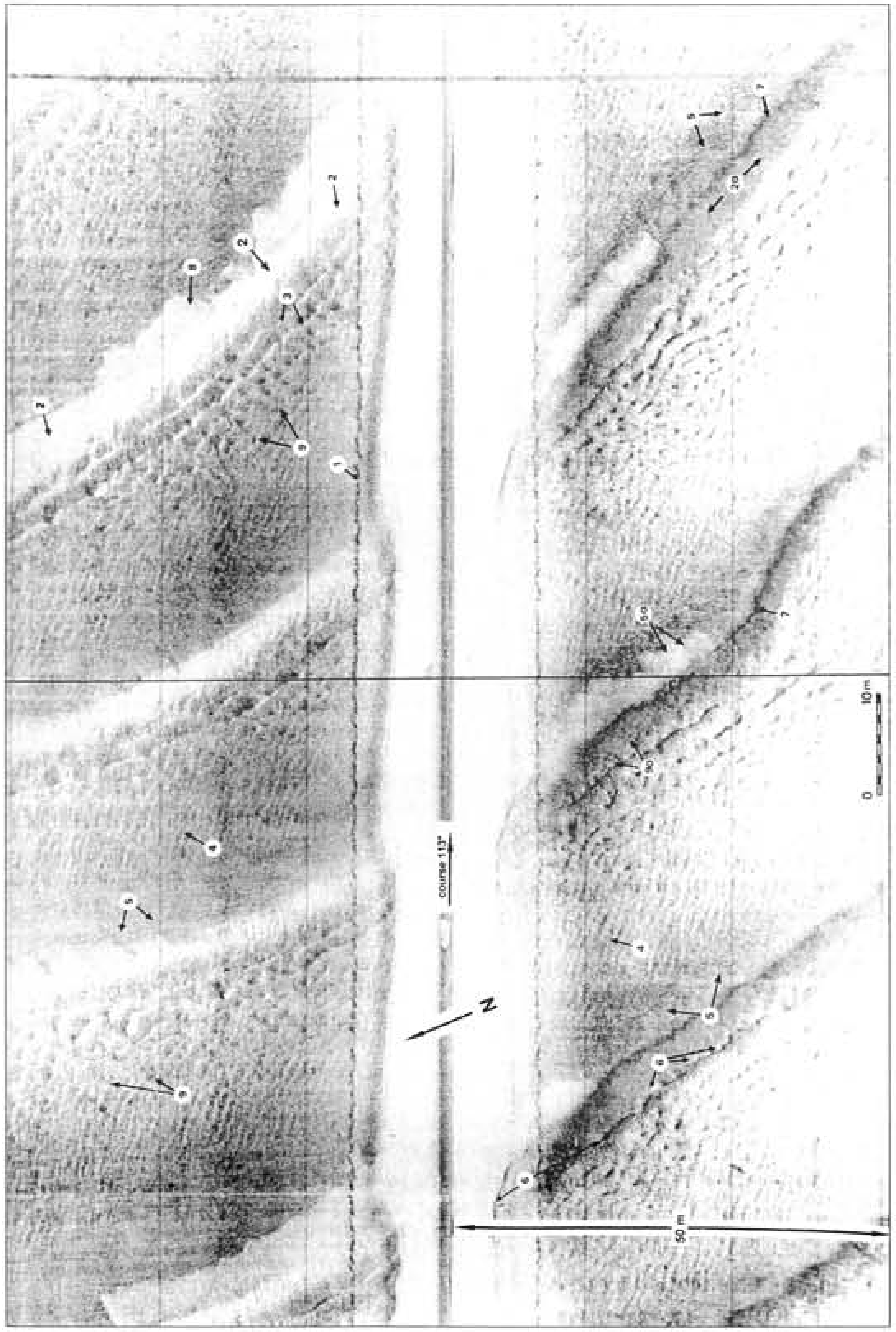

Fig. 1. Side-scan sonograph showing typical section of Fehmarn Belt sand-wave field at a water depth of 17 m. Bathymeteric upslope direction (s. Fig. 2): downward. 1: water surface reflection, 2: acoustic shadow of lee-side slope (note increasing length toward distal margin), 2a: strong (= dark) high-angle insonification on lee-side slope, 3: straight trains of crest-parallel dunes: near-crest effect, 4: dune fields on the middle slope: characteristically striking oblique to main current, 5: current ripples in sand-wave troughs, ca 35-45 cm spacing, striking ± parallel to sand-wave crests, 5a: ditto, lying upon slided sediment, 6: oversteepened dune relics on sand-wave crests, 7: shell-debris stripes at slope toe, 8: slided sediment (low reflectivity probably due to settling of suspended fine sediment), 9: current-parallel structures of various kinds. – Reduction from original record: x 0.42. Geographical position of Figure: 54°34.3'N/11°04.6'E.

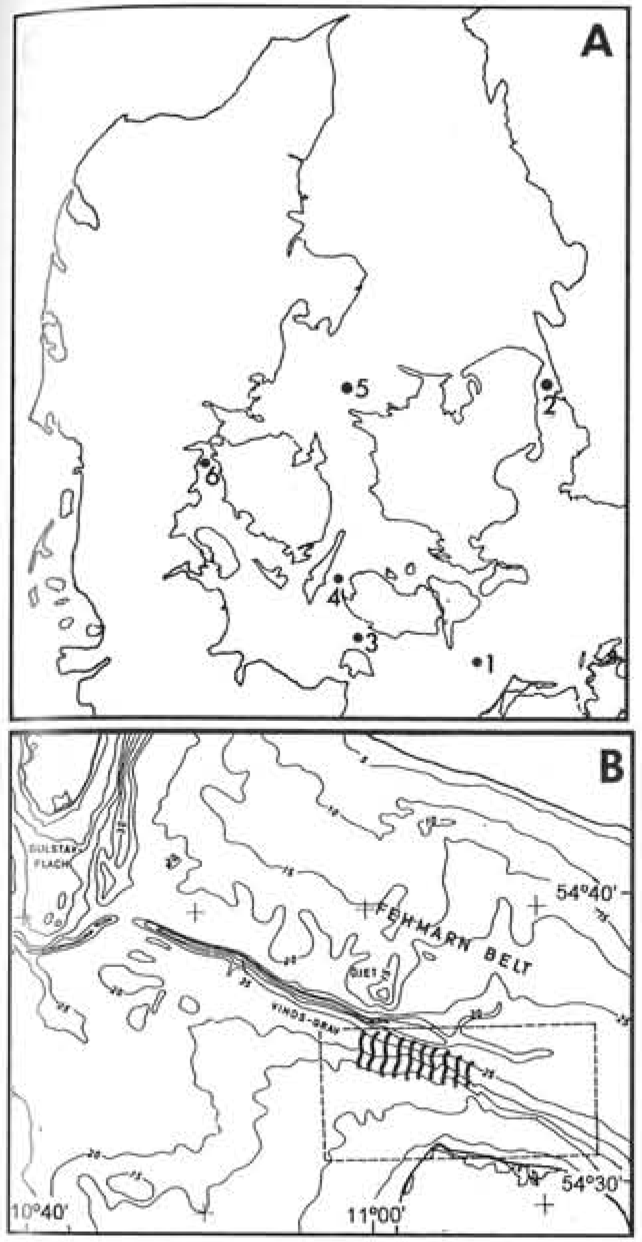

Fig. 2. A. Main water-exchange straits with sand-wave fields in the western Baltic as numbered in text. B. Fehmarn Belt, bathymetry with study area of sand-wave field.

RESULTS

The sand-waves with spacing between 20 and 70 m and heights between 0.8 m and 2.2 m extend between 12 and 23 m of water depth in a field of 9 x 1.5 km. Their true lee-slope angle is about 30° (Fig. 1). In 1972, the sand-wave field was found to be densely settled by various pelecypods all over the stoss slope including the crest, even by the large and slow-growing *Arctica islandica* (Werner et al. 1974), and the stoss slopes of the sand waves did only show sparsely and blurred dune fields. It was believed therefore, that the sand waves would not migrate for longer periods. In the 1986 survey, however, where Fig. 1 is a part of, the imagery was much more differentiated. All stoss slopes were completely covered with dunes (Fig. 1-4) whose orientations differ as common for sand waves (Allen 1982). Additionally, the small-scale current ripples parallel-oriented to the main crests (Fig. 1-5) occur in other profiles also on the middle stoss slopes and are therefore not effects of the lee vortice backflows. Yet they indicate the recent mobility of the sand-wave field. Sliding structures by sediment avalanches off the lee slopes (Fig. 1-8), formerly not observed, but now widespread, also are such indications. They may explain the discontinuous cross-bedding of the internal structure found in the vibrocores.

CONCLUSIONS

Monitoring of sand-wave fields like in the Fehmarn Belt with its discontinuous mobility and sensitively reacting morphology may be used as a tool in studying the development of storm intensity and frequency in the context with the global change problem.

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The palaeoenvironment of the Baltic Sea – a sub-project of BASYS

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The Baltic Sea is said to be one of the best-studied marine areas of the World. However, the attempts to evaluate its future development, in view of the heavy loads imposed on it by increasing urbanisation of the surrounding land areas, have shown serious gaps in our knowledge. The Institute of Baltic Sea Research in Warnemünde invited scientists from circum-Baltic Sea countries to attend a series of workshops in the early and mid-1990s to define these gaps and to propose steps to ameliorate the situation. The final outcome of these workshops was a proposal, the Baltic Sea Systems Study (BASYS), addressed to the European Union for funding from the Marine Science and Technology Programme Mast-III. In the final outcome, 75 principal investigators, from 50 partner institutes, from 13 countries were involved in signing the multi-million 3-year BASYS program approved by the EU and scheduled to start on August 1st 1996.

The main objective of BASYS was to (a) improve the understanding of the susceptibility of the Baltic Sea to external forcing both by natural and manmade processes, (b) to quantify past and present fluxes of key elements, and (c) to differentiate between the effects of climate variability and human interventions. To achieve these objectives a systems approach was chosen, based on a multitude of scientific activities and close international co-operation with special emphasis on modern analyses of variables sampled in the field, data processing and modelling tools. Although, the bulk of the work addressed present day processes, e.g. fluxes of biogenic and non-biogenic matter into and within the system on seasonal and annual scales in the pelagial and the benthal from the coast-line to the deep basins, the evaluation of the natural variability in the ecosystem could only be based on the analysis of historical data on climate, hydrography, chemistry and biology. For this purpose the study of the palaeoenvironment was made an integral part of BASYS.

After lengthy discussions it was decided that the palaeoenvironmental part of the project would be based on a very detailed study of carefully chosen coring sites in three different basins, the Bornholm Basin (BB), the Gotland Basin (GB), and the North Central Basin (NCB). The rationale of this approach was based on:

Firstly, it was understood that the widespread and generally accepted assumption, that sedimentation in deep basins is a continuous process and laterally uniform, was grossly erroneous. Furthermore, international monitoring programs were known to rely heavily on the use of sediments from deep basins. The old sampling sites had, however, often been chosen more-or-less by chance and were still assumed to show a continuous sedimentation record over the last decades or so. The representability of these sampling sites has been seriously questioned. Thus, it was concluded that the uniformity of sedimentation in deep basins should be carefully studied and the best possible locations identified for at least a few internationally acceptable reference stations.

Secondly, the environmental monitoring programs, using short sediment cores, often fail to cover a sufficiently long time span. This may lead to hasty and erroneous conclusions as to the state of the Sea and especially as to measures to be taken for further amelioration. During the past 10-12 thousand years the Baltic Sea has gone through several lacustrine and marine phases. The sediments deposited during the past stages, being exposed to differential erosion, may still have a considerable impact on the chemical and physical characteristics of the material in the short cores used for monitoring. It is imperative that, parallel with the study of recent and sub-recent sediments, also older sediments should be studied to better understand the inter-relationship between natural and man-made influence on the marine environment and how these changes are manifested in the sedimentary record.

Thirdly, scientists concerned with environmental monitoring have given very little consideration to the study of element mobilisation and fixation in the sediments. Considering the great variability in the bedrock geology surrounding the Baltic Sea it is most obvious that the concentration of e.g. heavy metals and other elements will differ enormously from region to region due to purely natural reasons. Thus the effect of anthropogenic input of biologically detrimental elements into the marine environment can be evaluated only if based on a sound understanding of diagenetic processes and on the proper use of weak solvents to differentiate between bio-available (soluble) and non-available elements.

With the above rationale in mind and in accordance with the research plan adopted for BASYS, the state of the Baltic Sea environment during the last 8000 years was reconstructed from long cores taken from the three chosen deep basins in the Baltic Sea (Bornholm Basin, Gotland Basin and the North Central Basin). The accurately dated cores showed compositional peculiarities that could be correlated with well-known climatic events, e.g. the warm medieval period when Vikings were known to have inhabited Greenland. The sediments, especially from the Gotland Basin, showed the effects of major inflows of saltier North Sea water through the Danish Straits. These inflow events were found to correlate with the North Atlantic Oscillation (NAO), the shifting of the relative positions of low and high pressures in the North Atlantic. Thus, the development of anoxic conditions in the deep basins could be associated to climatic phenomena and not necessarily blamed on industrial activities. The detailed study of the cores also showed that algal blooms (cyanobacteria or blue green algae) have been a common phenomenon in the Baltic Sea for at least the last 7000 to 8000 years, so here again man is not to be blamed. It was also observed that the input of heavy metals by industry is visible in the upper parts of the sediments as a clear increase in such metals as cadmium, lead, zinc, etc. Due to the environmental restrictions imposed by most circum-Baltic countries and the collapse of the Soviet/Russian industry the most recent sediments showed a clear decline in the concentrations of these heavy metals.

Many of the new results emanating from BASYS have been published in the annual reports and in scientific papers published in various journals (many of the references can be seen on the BASYS web-site: http://www.io-warnemuende.de/Projects/Basys/en_home.html), but there is still much data that needs to be processed and turned into proper publications. For this reason the publisher of BALTICA and the co-ordinator of BASYS sub-project on the palaeoenvironment have decided that the next volume (Vol. 14) will be dedicated to the geological aspects of the BASYS project. Authors are encouraged to submit their manuscripts to the Editor by the end of May 2001. BALTICA instructions to authors is announced on the web-site: http://www.geologin.lt/baltica.

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