
Environmental changes in the Fårö Deep (the Baltic Sea): lithology of sediments and diatom flora

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The Fårö Deep is situated north-east of the Gotland Island dividing the central part of the Baltic Sea. The sediment record shows all main stages of the Baltic Sea evolution in the Late Glacial and Holocene. This is verified by lithostratigraphic data and results of diatom flora analysis in the bottom sediment core PSh-5129 from the Fårö Deep. The homogeneous brownish grey clay at the bottom of the core marks the end of the glaciation when the Fårö Deep was part of a deep periglacial lake. The subsequently deposited clays with black interlayers and patches of Fe monosulphides underlying grey and greenish grey mud reflect dramatic changes in the environmental conditions. Analysis of sediment composition and diatom complexes confirmed that the alternation of lacustrine and marine conditions in the Fårö Deep in the Holocene followed the general evolution patterns of the Baltic Sea, yet with certain specific features. Due to a sophisticated water mass circulation during the Yoldia Sea stage, the marine influence was inconspicuous. Contrary to many sediment cores analysed from other parts of the Baltic Sea, the study sediment core contains only sparse and untypical diatom flora of the Litorina Sea.

Key words: bottom sediments, lithostratigraphy, diatom flora, lacustrine and marine environments, Baltic sea

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INTRODUCTION

The Baltic Sea evolution was marked by dramatic changes in the sedimentary environment controlled by the link between the Baltic Sea and the ocean. The principal features of these events were revealed and discussed in fundamental studies (Gudelis, Königsson, eds., 1979; Ignatius et al., 1981; Eronen, 1988; Winterhalter, 1992; Блажчишин, 1985; 1998 and others). The Baltic Sea stages alternating in the last 13–14 thousand years were distinguished. The Baltic Ice Lake formed in front of the retreating glacier continued for some time as a closed basin. When the glacier freed the central part of Sweden, the Baltic Ice Lake opened into the ocean. The water level

of the lake fell about 25 m (Svensson, 1991) and the basin turned into a marine one. The Yoldia Sea water salinity in the central Baltic deep could have been about 10‰ (Wastegård, Schoning, 1997). Yet the intensive glacier melting obstructed the inflow of ocean water through the narrow Swedish straits, and shortly, due to an isostatic uplift, the Baltic basin again converted into a fresh-water lake (Lake Ancylus). The cardinal changes of sedimentary environment in the Baltic Sea took place 8–7.8 thousand years ago (Agrell, 1979; Björck, 1995) when saline water (Litorina Sea) surged through the Danish straits from Kattegat, creating a long-lasting link with the North Sea.

The alternation of lacustrine and marine environments left clear marks in the composition of the Baltic

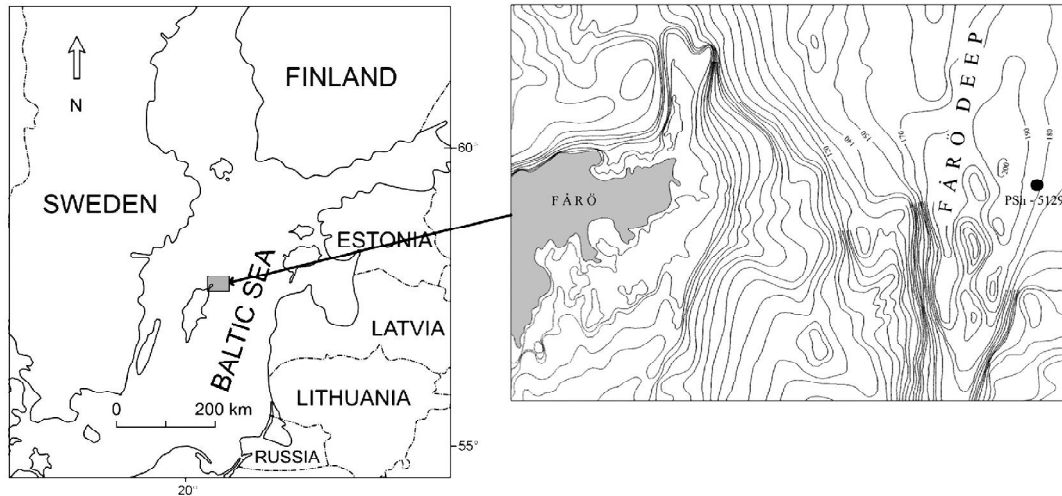


Fig. 1. Situation map of the study area. Bottom topography after Gelumbauskaitė (ed.), 1998
1 pav. Tyrimų rajono schema. Dugno batimetrija pagal Gelumbauskaitę (red.), 1998

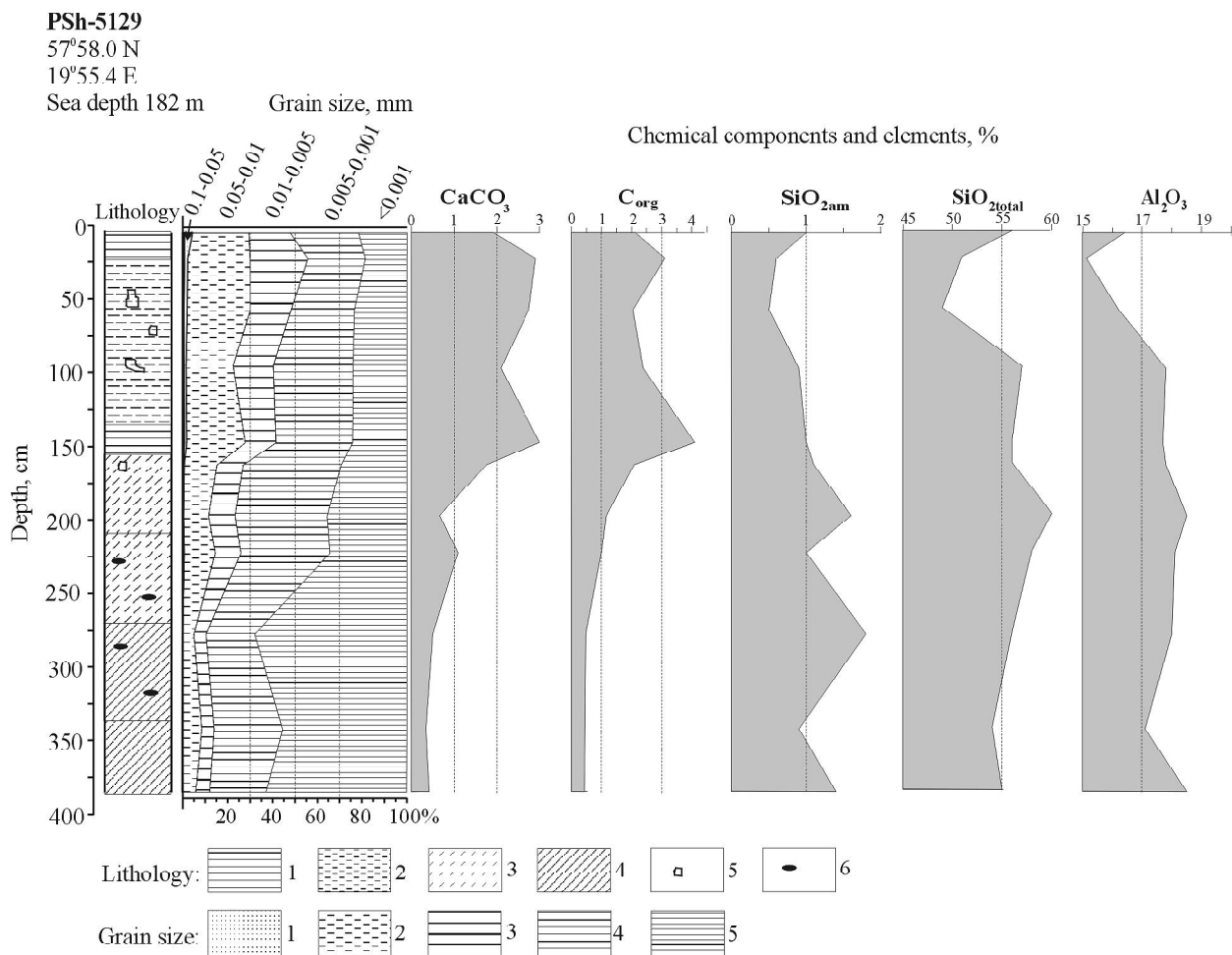


Fig. 2. Sediment core PSh-5129: lithology, grain size and distribution of chemical components.

Lithology: 1 – greenish sapropelic microlaminated mud; 2 – grey mud; 3 – grey, bluish grey clay; 4 – brownish clay; 5 – patches; 6 – hydrotrillite.

Grain size, mm: 1 – 0.1–0.5; 2 – 0.05–0.01; 3 – 0.01–0.005; 4 – 0.005–0.001; 5 – <0.001.

2 pav. Nuosėdų sudėtis PSh-5129 kolonėlėje: litologija, granulometrija ir cheminių komponentų pasiskirstymas.

Litologija: 1 – žalsvas sapropelingas mikrosluoksniuotas dumblas, 2 – pilkas dumblas, 3 – pilkas, melsvai pilkas molis, 4 – rusvas molis, 5 – dėmėtumas, 6 – hidrotroilitas.

Granulimetrinė sudėtis, mm: 1 – 0,1–0,5; 2 – 0,05–0,01; 3 – 0,01–0,005; 4 – 0,005–0,001; 5 – <0,001

Sea sediments. Sediments of the same stage from different parts of the Baltic Sea, have some typical traits yet obviously differ in many physical, chemical and biological features. Lithostratigraphic sediment sections from various Baltic Sea deeps (Kalm et al., 1996; Sohlenius et al., 1996; Andrén, 1999; Andrén et al., 1999; Heinsalu et al., 2000; Trimonis, Savukynienė, 2000; Емельянов и др., 1995; 2001; Winterhalter, 2001 and others) prove that responses of various parts of the sea to changes in the sedimentary environment entailed by sea transgressions, isostatic phenomena and other events were different and usually regionally specific.

The aim of the present work was to reconstruct the palaeogeographic evolution of the Fårö Deep and to reveal the regional peculiarities of environmental changes, based on sedimentological and palaeobotanical data.

MATERIALS AND METHODS

The Fårö Deep is in the central part of the Baltic Sea north-east of Gotland Island (Fig. 1). Its greatest depth is 205 m.

The sediment core PSh-5129 (coordinates 57°58,025 N, 19°55,404 E, water depth 182 m) from the Fårö Deep was taken with a gravity corer during the expedition on the scientific research vessel "Professor Shtockman" (Russia) in 2004. The preliminary description of the sediments was accomplished during the expedition, and samples for laboratory analyses (grain size, chemical, palaeobotanical, etc.) were taken.

The lithological types of sediments (Fig. 2) were based on the results of grain size analysis by the standard pipette (settling in water) method. These results are presented as a percentage of different fractions and expressed in granulometric parameters – median diameter of grains (M_d) and sorting coefficient (S_o). The types of bottom sediments were based on the decimal classification of marine sediments (Безруков, Лисицын, 1960).

CO_2 and C_{org} concentrations in sediments were determined using an AH-7521 analyser, whereas the concentrations of SiO_2 and Al_2O_3 were determined by the X-ray-fluorescence method (Trimonis et al., 2006).

Sediment samples for laboratory diatom analysis were prepared using standardized methods (Battarbee, 1986). Carbonates were eliminated from the sediments using 10% hydrochloric acid solution, and organic matter was eliminated using hydrogen peroxide (30%). Clay particles were separated and eliminated by repeated washing and 2-h sedimentation. Diatoms were concentrated from the terrigenous material using a heavy liquid. The slides were prepared using Naphrax (light refraction index 1.73).

The microscopic analysis for the taxonomic description of species was performed using a Leica biological light microscope (magnification $\times 1000$). Atlases and books of diatoms were also used for description and ecological characteristics of diatom species (Snoeijs, 1993; Snoeijs, Vilbaste, 1994; Snoeijs, Potapova, 1995, etc.).

The percentage of diatom species was counted in all samples containing no less than 50 diatoms. The percentage diagram was compiled using TILIA (version 2) and TILIA–GRAPH (version 2.0 b.5) computer programs (Grimm, 1990; 1992).

For palaeogeographical purposes, the diatom species found in the sediments have been classified into two ecological groups (Hustedt, 1957). One of the groups is used for the description of water salinity. Marine (water salinity is $>30\text{‰}$), brackish (5–20‰) and freshwater ($<5\text{‰}$) diatoms are distinguished in this group. The other group is used for evaluation of the water basin depth in the past. It includes: 1) planktonic diatoms free-floating on the water surface, their abundance in sediments showing a deep water basin; 2) benthic diatoms living on the basin bottom; their abundance implying shallow littoral conditions.

Sediments of the Litorina Sea abound in diatom resting spores of the genus *Chaetoceros* Ehrenberg. They appear under conditions of a residual number of live diatom cells in plankton and elevated concentrations of nitrogen and phosphorus in water (Hargraves, French, 1983; Round et al., 1990). Spores of the genus *Chaetoceros* Ehrenberg were classified as a separate group and interpreted as marine planktonic diatoms (their percentage was calculated from the total of diatoms).

Lithostratigraphy

A detailed description of the sediment core PSh-5129 is given in Table. The lower part of the core is represented by slightly brownish clay. Its greater part (86–88%) is composed of fraction <0.005 mm including more than 50% of subcolloidal fraction (<0.001 mm). The M_d of the sediments is <0.001 mm. This layer is underlying an interval that begins with a 10-cm thick clay layer containing patches and small spots of amorphous Fe monosulphide (325–335 cm). Brownish grey clay with black sulphide streaks of different thickness composes an interval of 65 cm. According to grain size composition, this clay ($M_d <0.001$ mm) is also composed of very fine pelitic material, though grains of authigenous FeS corresponding to sand fraction can be tracked down (about 0.1%).

An interval of bluish-grey banded soft clay (160–217 cm) characteristic of Lake Ancyclus represents a distinct lithostratigraphic horizon with clear boundaries. Its grain size composition is absolutely different: the content of the subcolloidal fraction is half as low, yet the content of the coarse pelitic fraction (0.01–0.005 mm) is higher and the content of the fine silt fraction (0.05–0.01 mm) is almost double. The M_d of the sediments is 0.002–0.003 mm and their sorting (S_o) is 2.2–2.4.

Another important lithological boundary lies at a depth of 160 cm. The overlying grey mud is heterogeneous, laminated and microlaminated and contains higher concentrations of organic matter: C_{org} accounts up to 4% and $CaCO_3$ reaches 3% (in clays its highest concentration was 1.75%). The sediments of the Litorina Sea stage

Table. Lithological description of the core PSh-5129 from the Fårö Deep
Lentelė. Litologinis PSh-5129 kolonėlės iš Forio duburio aprašymas

Depth, cm	Sediment description	Stage of the sea
0–20	Pelitic mud greenish grey, homogeneous, very soft (considerable part of the layer is washed out)	Recent (PL)
20–42	Pelitic mud grey, dark grey, fine-spotted (black dots, interval 27–30 cm) and microlaminated (interval 30–40 cm). Lower boundary distinct, uneven	Litorina (L)
42–134	Pelitic mud grey, heterogeneous, soft, slightly elastic. Grey and dark grey banding weakly expressed. Dark grey mud layers predominate in 48–51 cm, 58–60 cm, 65–67 cm, 75–77 cm and 86–89 cm intervals. More often the uppermost parts of intervals are dark grey, downwards turn into small spotted (dotted type)	
134–160	Pelitic mud grey, greenish grey, heterogeneous, soft, slightly elastic. Sometimes microlaminated: alternation of greenish grey and black laminae. Very distinct microlamination in 140–141 cm, 144–154 cm and 157–160 cm intervals. The latter shows angular unconformity of the layers. Lower boundary sharp	
160–179	Clay grey, slightly bluish, mottled, soft. Mottled intervals slightly darker, indistinct. Lower boundary distinct, sloping	Ancylus (A)
179–217	Clay bluish grey, heterogenous, banded, soft. The uppermost part (179–193 cm) almost without banding, small patches and lenses predominate. Downwards gradual alternation of horizontal and subhorizontal dark grey bands is clear. Their width 4–8 mm. Lower boundary distinct (coincide with black layer)	
217–270	Clay grey, hydrotroilitic, moderate firm. The uppermost part almost without black interbeds, the largest content of hydrotroilitic lenses and patches in 235–262 cm interval. Gradual boundary	
270–335	Clay brownish grey with hydrotroilitic interbeds (270–275, 285–297, 325–335 cm). The rest of clay relatively homogeneous, moderate firm and firm	Yoldia (Y)
335–390	Clay grey (slightly brownish), homogeneous, very sticky	Baltic Ice Lake (BIL)

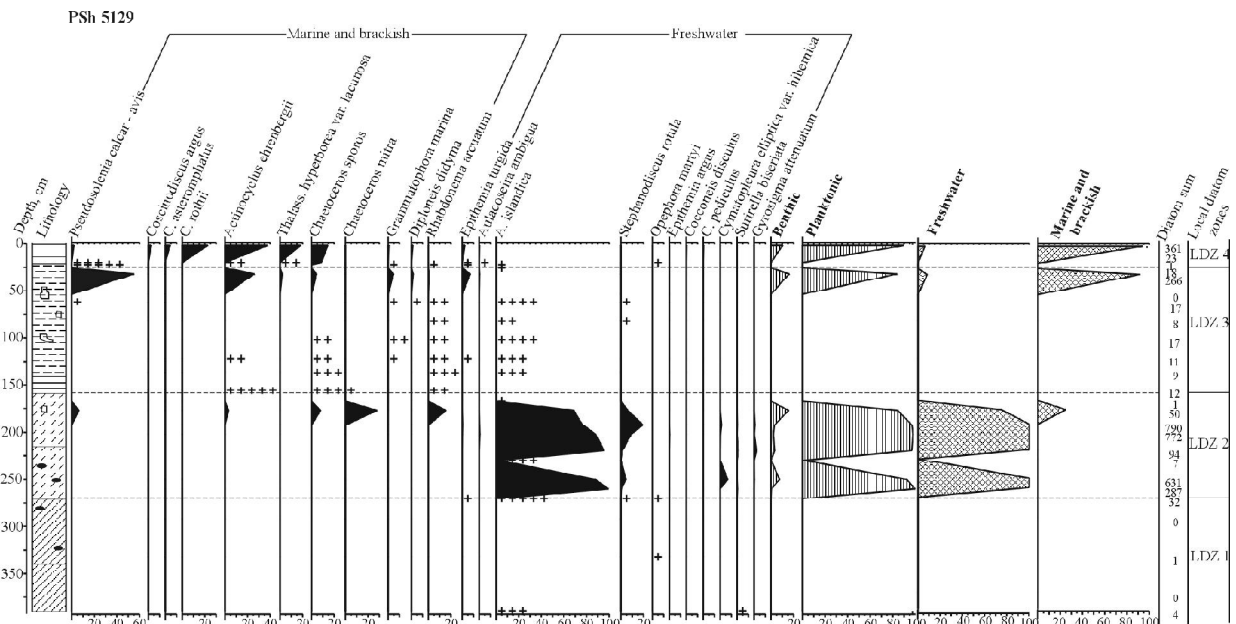


Fig. 3. Abbreviated diatom diagram of the core PSh-5129.

Legend of sediment lithology see in Fig. 2.

3 pav. Diatomėjų rūšinė sudėtis PSh-5129 nuosėdų kolonėleje.

Sutartiniai ženklai žr. 2 pav.

notably differ in grain size composition: higher concentrations of silt fractions (almost double value of fine silt), lower concentrations of subcolloidal fractions and a considerably greater content of fine sand grains. The Md ranges from 0.004 to 0.006 mm and S_0 is 3.0–4.1.

The upper layer of greenish grey very soft pelitic mud represents recent sediments. Its Md is 0.005 mm and $S_0 = 4.1$.

Diatom assemblage zones

According to species composition variations of the diatoms, four local diatom zones (LDZ) were distinguished in the sediment core PSh-5129 (Fig. 3).

LDZ 1. It comprises an interval of 270–390 cm. Diatoms in this interval are sparse. They are represented by a few freshwater diatoms characteristic of a large oligotrophic lake.

LDZ 2. The interval of 160–270 cm is predominated by freshwater diatoms. At a depth of 217–270 cm planktonic freshwater *Aulacoseira islandica* (O.Müller) Simonsen and *Stephanodiscus rotula* (Kützing) Hendeby somewhere account for 100%. The interval of 160–217 cm contains a small amount (up to 3%) of freshwater benthic diatoms predominated by *Opephora martyi* Heriboud, *Epithemia argus* Kützing, *Surirella biseriata* Kützing, *Gyrosigma attenuatum* (Kützing) Rabenhorst. In the upper part of the interval (160–180 cm), brackish diatoms account for up to 25%. They are predominated by planktonic *Pseudosolenia calcar-avis* Schultze, *Actinocyclus ehrenbergii* Ralfs and benthic *Rhabdonema arcuatum* (Lyngbyae) Kützing and *Chaetoceros* sp. diatom spores.

LDZ 3. The content of diatoms is small at the depth 25–160 cm. Most of them belong to the ecological group of brackish diatoms. Benthic *Rhabdonema arcuatum* and *Grammatophora marina* (Lyngbyae) Kützing, planktonic *Actinocyclus normanii*, *Chaetoceros* sp. diatom spores prevail. Unusually, also large numbers of freshwater planktonic *Aulacoseira islandica* and *Stephanodiscus rotula* are found. The upper part of the interval (25–50 cm) is predominated by planktonic marine *Pseudosolenia calcar-avis* (up to 60%) and *Actinocyclus ehrenbergii*.

LDZ 4. It represents an interval of surface sediments (0–25 cm). It is predominated by the brackish planktonic diatoms *Actinocyclus ehrenbergii*, *Coscinodiscus rothii* (Ehrenberg) Grunow, *Thalassiosira hyperborea* var. *lacunosa* (Berg) Hasle. This diatom complex is typical of the present Baltic Sea in which water salinity is slightly lower than in the Litorina Sea stage.

DISCUSSION

The variation of sediment types and diatom complexes in the core PSh-5129 shows that sedimentation conditions in the Fårö Deep underwent considerable changes. A layer of very homogeneous grey clay with brownish tint formed in the Late Glacial. The Fårö Deep at that time was part of a large periglacial lake where intensive for-

mation of glacial sediments took place. This time interval is classified as the Baltic Ice Lake stage. During this period, layers of microlaminated, banded and homogeneous clays were deposited. Classifying them as a lithostratigraphic complex, A. I. Blazhchishin (Блажчишин, 1985) pointed out that the upper parts of the Late Glacial sediment sections contain layers (up to 1 m thick) of light brownish, brownish grey and even grey homogeneous clays. Their formation is associated with the highest level of the Baltic Ice Lake.

The deep lake conditions are reflected by very fine-grained clay in the bottom of the core PSh-5129 (335–390 cm). The Md of clay does not reach 0.001 mm, whereas the sum of pelitic fractions exceeds 90%. Though diatoms are sparse (LDZ 1), their comparison with diatoms in other sediment sections of this time shows lacustrine sedimentation conditions. Diatom flora is absent in clays of the Gotland Deep (Емельянов и др., 1995) and in the northern part of the Baltic Sea (Heinsalu et al., 2000). Representatives of planktonic freshwater diatoms were traced down only in varved clays of the West Gotland Basin (Емельянов и др., 2001). They imply that the lake was freshwater and deep. It is assumed that sparse diatom flora or its absence in the Late Glacial sediments of the Baltic Sea was predetermined by a low productivity, unfavourable climate conditions and glacial melt water turbidity, because sedimentation rates were high (Heinsalu et al., 2000).

Appearance of hydrotroilite interlayers and patches in the interval of 325–335 cm mirrors a change of sedimentation conditions. The change occurred when the water drained away from the dammed lake. Its water level fell down rather rapidly, because the subsidence of the Billingen region in Central Sweden created good conditions for opening of the lake to the ocean. This time span coincides with the beginning of the Holocene (Preboreal) and marks the onset of the Yoldia Sea stage.

The Yoldia Sea sediments (270–335 cm) are characterized by black lens-shaped interlayers in brownish grey clay, which differed but little from glacial sediments. Clay also accumulated in a deep water basin. Yet the water column must have been stratified and the deeper water horizon was more saline. This environment was favourable for sulphate-reduction processes and formation of microconcretions of Fe sulphides (Емельянов и др., 2001). Their appearance can be traced in the changed granulometric composition of sediments, i. e. a higher content of silt and sand fractions. Yet it is difficult to judge about the changes of water salinity, because diatoms are almost absent in clays (Fig. 3). The changed sedimentation conditions were presumably unfavourable for their growth and preservation in sediments. Only a few freshwater and no brackish diatoms were found in sediments. This fact proves the mixing of fresh and saline water, which was temporary and unstable, because the link with the ocean was rather limited. This is proven by previous research works (Svensson, 1989; Sohlenius et al., 1996, etc.).

Sedimentation conditions in the Fårö Deep gained a certain stability when the basin became isolated again (Lake Ancylus). These environmental changes are reflected in diatom assemblage (LDZ 2). The number of diatoms sharply increases from the depth of 270 cm and above. Many planktonic freshwater diatoms appear (*Aulacoseira islandica*, *Stephanodiscus rotula*, etc.), which are characteristic of Lake Ancylus (Клейменова и др., 1978) and imply freshwater deep lake conditions.

Clays of Lake Ancylus comprise two distinct layers: grey hydrotrillite clay (217–270 cm) is underlying bluish grey patched clay (160–217 cm). The differences imply that the initial sedimentation conditions changed. This is proven by certain changes of diatom complex. The lower clay layer is predominated by freshwater planktonic diatoms. The upper bluish grey layer contains a greater number of benthic freshwater diatom species. These changes might have marked regression of the Lake Ancylus at the end of Boreal. Analogous sub-types of lacustrine clays characteristic of the Ancylus stage were identified also in other parts of the Baltic Sea (Ignatius et al., 1981; Блажчишин, 1985; Емельянов и др., 2001).

The composition of the diatoms changed at the end of the Ancylus Lake stage. Brackish planktonic diatoms *Pseudosolenia calcar-avis*, *Actinocyclus ehrenbergii* appeared (though not in abundance), implying that water salinity was gradually increasing. About 8–7.8 thousand years ago (Björck, 1995), the Baltic Sea again opened to the ocean (North Sea) through the Danish Straits, marking the beginning of the Litorina transgression. These events are clearly reflected in the composition of bottom sediments.

Pelitic mud replaced clays in the Fårö Deep. The heterogeneous composition of the mud (Table) could imply that sedimentation conditions changed frequently. This can be proven by the above-mentioned changes of grain size and chemical composition of sediments. Besides, the diatom complex characterizing the Litorina Sea stage (LDZ 3) is also rather variable. Spores of *Chaetoceros* diatoms characteristic of the Litorina Sea stage, found in the upper clay layer, imply complicated sedimentation conditions under which spores found their way to the sediments of Lake Ancylus. This is also proven by quite abundant planktonic freshwater diatoms found in the Litorina Sea mud. All the mentioned circumstances and the small content of diatoms in the Litorina Sea sediments indicate unfavourable conditions for diatom preservation.

Pelitic dark grey mud with a relatively rich flora of *Pseudosolenia calcar-avis* (up to 60%) and *Actinocyclus normanii* diatoms (25–50 cm) correspond best to marine conditions. The upper part of the section composed of greyish green mud represents recent deepwater Baltic Sea sediments. Their diatom complex (LDZ 4) implies a relative decrease of water salinity.

CONCLUSIONS

The changes of sedimentation environment in the Fårö Deep in the Late Glacial and Holocene followed a similar pattern as in the central part of the Baltic Sea, with the only difference that here some evolution stages of the sea are weakly expressed (Yoldia Sea stage). Yet in general, the lithology and diatom complexes (LDZ) of bottom sediments reflect well the general trends of the Baltic Sea evolution. Sediments of the Litorina Sea with sparse and untypical diatomic flora can be pointed out as a specific feature of sedimentation in the Fårö Deep. Many sediment sections of the Litorina Sea stage in the central part of the Baltic Sea abound in diatoms reflecting marine conditions.

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APLINKOS SĄLYGŲ KAITA FORIO DUBURYJE (BALTIJOS JŪRA): NUOSĖDŲ LITOLOGIJĄ IR DIATOMĖJŲ FLORA

Santrauka

Forio duburio, esančio į šiaurės rytus nuo Gotlando salos, kuri dalija Centrinę Baltijos jūros dalį, raidoje užfiksuoti visi svarbiausi Baltijos jūros vystymosi etapai poledynmečiu ir holocene. Tai rodo dugno nuosėdų kolonėlės PSh-5129 (koordinatės 57°58,025 N, 19°55,404 E, jūros gylys 182 m) iš Forio duburio nuosėdų litostratigrafiniai ir diatomėjų floros tyrimai.

Vienalytis rusvai pilkas molis nuosėdų pjūvio apačioje atitinka ledynmečio pabaigą, kai Forio duburys buvo gilaus priedyninio ežero dalimi. Vėliau susiklostė moliai su juodais Fe monosulfidų tarpsluoksniais ir lęšiais, o virš jų – pilkas ir žalsvai pilkas dumblas, atspindintis ryškius aplinkos sąlygų pasikeitimus holocene. Pagal diatomėjų rūšinės sudėties pokyčius išskirtos keturios vietinės diatomėjų zonos (VDZ).

Nuosėdų sudėties ir diatomėjų kompleksų analizė patvirtino, kad ežerinių ir jūrinių sąlygų kaita Forio duburyje poledynmečiu ir holocene atitiko bendras Centrinės Baltijos raidos tendencijas, bet turėjo savo ypatumų. Rusvai pilką vienalytį molį ir virš jo esantį 65 cm storio molio sluoksnį su Fe monosulfidais apibūdina tas pats diatomėjų kompleksas, kuris labai negausus ir neišryškina jūrinių sąlygų. Be to, pažymėtinos Litorinos jūros nuosėdos su negausia ir nelabai būdinga diato-

mėjų flora. Daugelyje centrinės Baltijos jūros dalies pūvių šio laikotarpio nuosėdose gausu diatomėjų, atspindinčių jūrinės Litorinos stadijos sąlygas.

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ИЗМЕНЕНИЯ УСЛОВИЙ ВО ВПАДИНЕ ФОРЁ (БАЛТИЙСКОЕ МОРЕ): ЛИТОЛОГИЯ ОСАДКОВ И ДИАТОМОВАЯ ФЛОРА

Резюме

Во впадине Форё, расположенной северо-восточнее острова Готланд, разделяющего центральную часть Балтийского моря, запечатлены все основные этапы развития Балтийского моря в послеледниковье и в голоцене. Это показали литостратиграфические и диатомовые исследования донных осадков в колонке PSh-5129 (координаты 57°58,025 N, 19°55,404 E, глубина моря 182 м) из впадины Форё.

Однородная коричневатая-серая глина внизу осадочного разреза соответствует концу ледниковья, когда впадина Форё была частью глубокого приледникового озера.

Залегающая выше глина с черными прослоями и линзами железистых моносльфидов, а над ней серый и зеленовато-серый ил свидетельствует о существенных изменениях условий среды в голоцене. По данным изменений видового состава диатомовой флоры в осадках выделены четыре местные диатомовые зоны (МДЗ).

Анализ состава осадков и заключенных в них комплексов диатомей подтвердил, что смена озерных и морских условий во впадине Форё в послеледниковье и в голоцене соответствовала общим тенденциям развития центральной Балтики, но при этом имела свои особенности. Однородная коричневатая-серая глина и над ней залегающий 65-сантиметровый слой глины с железистыми моносльфидами характеризуются одним и тем же диатомовым комплексом, малочисленным и не подтверждающим существования морских условий. Кроме того, следует отметить, что осадки Литоринового моря здесь имеют скудную диатомовую флору. Во многих других разрезах из центральной части Балтийского моря в литориновых илах много диатомей, характерных для морских условий.