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Sediments of the Southern Baltic Sea, their deposition and lithostratigraphy

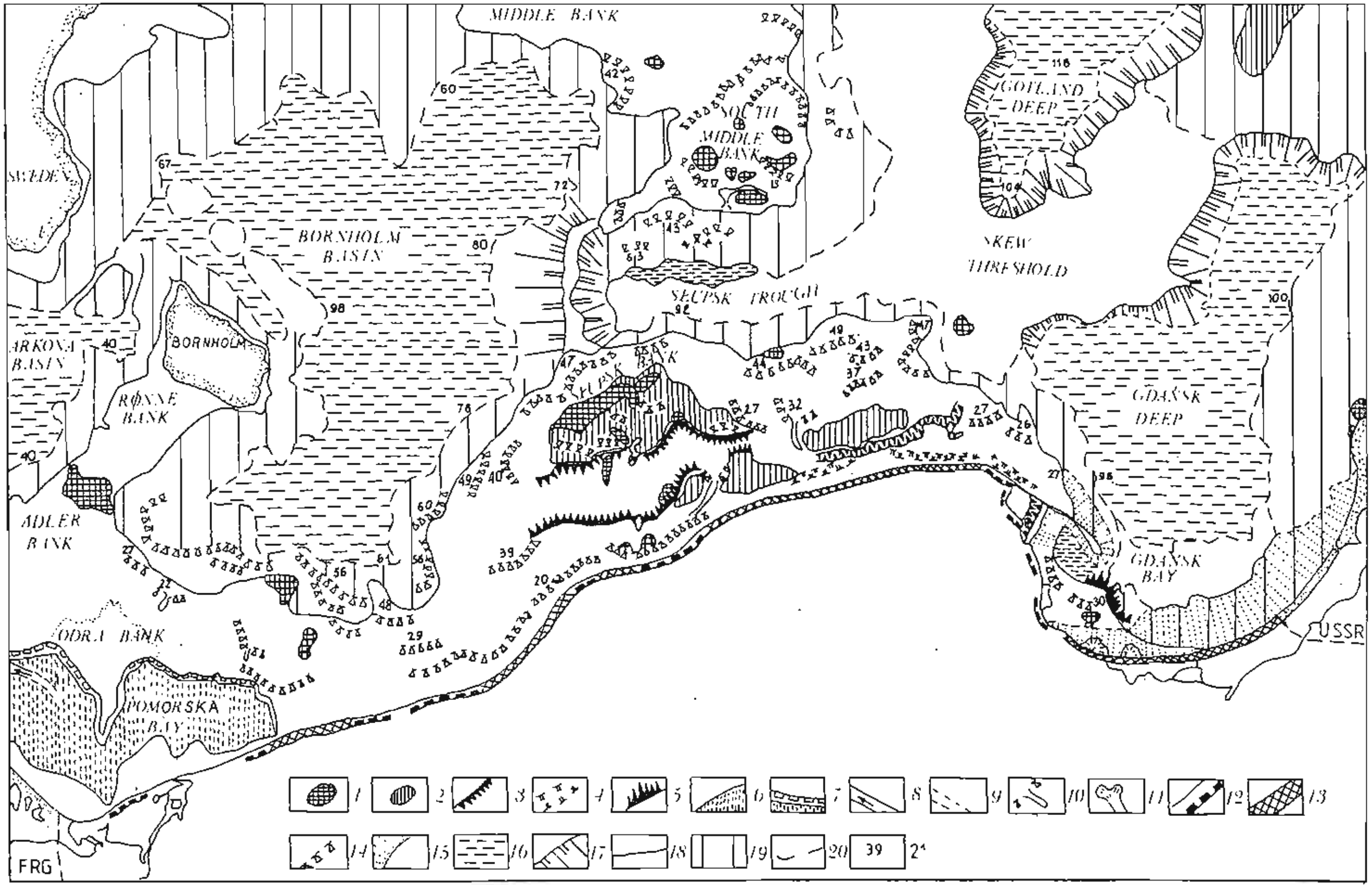
Evolution of the Baltic Sea in the Late Glacial and the Holoeene was first the effect of principal changes of climatic conditions, that determined a deglaciation. The latter caused land uplift and variations of sea water level. They influenced the duration of existing connections of the Baltic and the world oceans and thus, the changes of sedimentary enviroment.

GEOLOGIC REASONS FOR FORMATION AND DEVELOPMENT OF THE SOUTHERN BALTIC BASIN

In this area the Quaternary substratum is composed of Cambrian, Ordovician, Silurian, Devonian, Permian, Mesozoic and Tertiary rocks (R. Dadlez, 1976; W. Pożaryski et al., 1978; W.K. Gudelis, E. Jemelyanov, 1976; E. Rühle, 1982).

The Quaternary (Pleistocene and Holocene) deposits cover a washed bedrock surface. Their extent and thickness depend on its morphology, developed at the end of the Tertiary and partly remodelled due to denudation in a subaerial environment. Transformations of the bedrock morphology were then caused by successive ice sheet advances and the accompanied process of glacial erosion and deposition. In result a previous relief got smoothed and complexes of glacial and glaciofluvial features were formed (B. Rosa, 1968*a*). During the Late Glacial and the Holocene, a glacial landscape was partly transformed.

Varying transformation of a glacial relief and the scale of development of features of marine origin, resulted in a coexistence of various landform assemblages at the


MIDDLE BANK
SOUTH MIDDLE BANK
GOTLAND DEEP
SWEDEN
BORNHOLM BASIN
SKEW THRESHOLD
SŁUPSK TROUGH
ARKONA BASIN
BORNHOLM
RØNNE BANK
SŁUPSK BANK
GDAŃSK DEEP
ADLER BANK
GDAŃSK BAY
ODRA BANK
POMORSKA BAY
USSR
FRG

bottom, with relics of glacial, fluvial, lake and marine features (R. Pikies, 1976; R. Pikies, Sz. Uścinowicz, 1984; R. Kotliński et al., 1984) — Fig. 1.

Quaternary deposits form almost a continuous cover of considerably varying thickness (from several to over a hundred meters). In general, isopachytes run parallel and their contours agree with bottom depression shapes. Glacial and glaciofluvial deposits are the predominating genetic type. Locally there are also ice-dammed lakes and glacial-marine sediments (F.B. Pieczka, 1980).

At slopes of depths and depressions as well as on shoals, the Pleistocene mantle is represented by tills, frequently covered by glaciofluvial sediments. Locally, within convex bottom features the tills are exposed. In depths and depressions tills are concordantly overlain by the Late Glacial silty-clayey sediments or tills interbedded with silts, covered discordantly by the Holocene series.

Tills have varying grain size, mineral-petrographic and chemical compositions (W.K. Gudelis, E. Jemelyanov, 1976; R. Kotliński, 1984, 1985; R. Kotliński et al., 1984). Tills of the North-Polish Glaciation are expected to occur within the basins, where as at slopes and shallow sea areas there are also older tills. They were thermoluminescence dated e.g. in the Slupsk Sandbank area for 112 000±16 800 to 132 000± 16 800 years BP (R. Kramarska, A. Tomczak, 1986). Poorly consolidated tills and sandy glaciofluvial deposits have been relatively easily washed and transported within the reservoir. It caused a partial smoothing of convex bottom features and filling the ice marginal stream ways and depressions with sediments. Tills are usually mantled with gravel-sandy material. Locally tills are overlain by residual

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Fig. 1. Main morphologic elements of the Southern Baltic Sea (after R. Pikies, 1976)

Relics of glacial and glaciofluvial features: 1 — morainic hills and other elevations due to glacial deposition, 2 — morainic plateau, 3 — meltwater and thaw valleys, 4 — meltwater valleys almost completely buried, 5 — edge of the bottom in south-western Gdańsk Bay; relics of lake features: 6 — ancient lake areas,7 — lake cliffs; relics of fluvial features: 8 — fluvial valleys and directions of water flow, 9 — river valleys almost completely buried, 10 — slop cuts, 11 — alluvial fans (of the Vistula Delta inclusive); marine (depositional and abrasive) features: 12 — cliffs, abrasive fragments of the present coast, 13 — spits, accumulative fragments of the present coast, 14 — fragments of ancient shorelines (abrasive), 15 — spit accumulative slopes (Submarine), 16 — accumulative plains of deep-sea basins; 17 — slopes of various morphologic features; 18 — extent of a shallow-sea area; 19 — slope; 20 — extent of a deep-sea area; 21 — depth in meters b.s.l.

Główne elementy morfologiczne południowego Bałtyku według (R.Pikiesa, 1976)

Relikty form lodowcowych i wodnolodowcowych: 1 — wzniesienia morenowe i inne pozytywne formy akumulacji glacjalnej, 2 — wysoczyzna morenowa, 3 — doliny wód roztopowych i wytopiskowych, 4 — doliny wód roztopowych, prawie całkowicie pogrzebane, 5 — krawędź powierzchni dennej w południowo-zachodniej części Zatoki Gdańskiej; relikty form pochodzenia jeziornego: 6 — obszary dawnych jezior, 7 — klify jeziorne; relikty form pochodzenia rzecznego: 8 — doliny rzeczne i kierunki przepływu wód, 9. — doliny rzeczne, prawie całkowicie pogrzebane, 10 — dolinki zboczowe, 11 — stożki napływowe (również delty Wisły); formy pochodzenia morskiego (akumulacyjne i abrazyjne): 12 — klify, abrazyjne fragmenty współczesnego brzegu, 13 — mierzeje, akumulacyjne fragmenty współczesnego brzegu, 14 — fragmenty dawnych linii brzegowych (abrazyjne), 15 — stożki akumulacyjne mierzei (podwodne), 16 — równiny akumulacyjne basenów głębokomorskich; 17 — stożki różnych form morfologicznych; 18 — zasięg obszaru płytkomorskiego; 19 — skłon; 20 — zasięg obszaru głębokomorskiego, 21 — głębokość w m p.p.m.

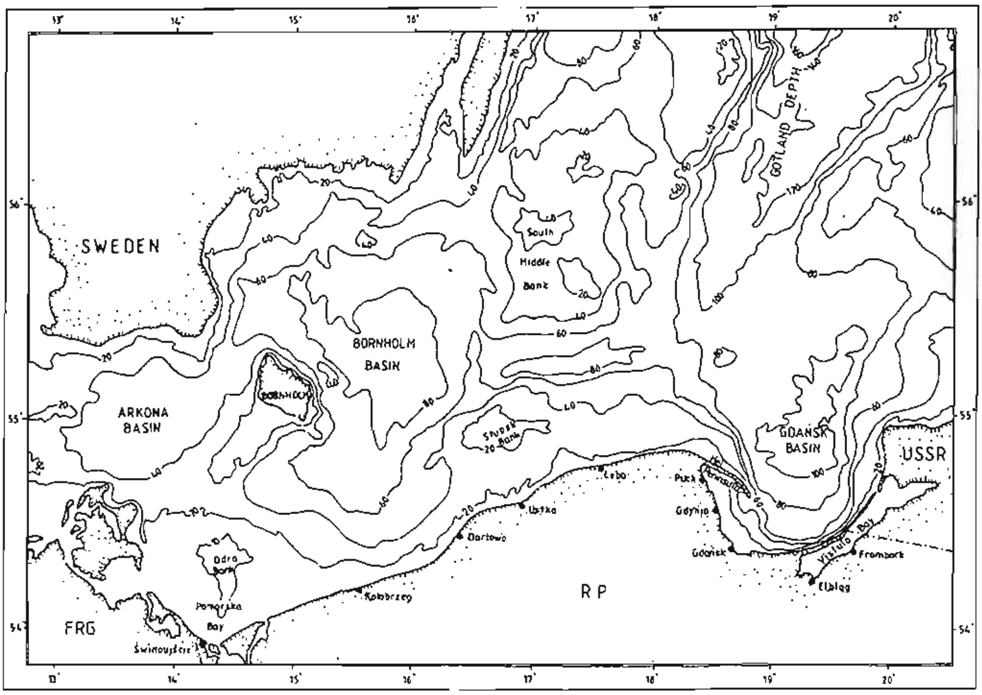


Fig. 2. Distribution of key regions of the Southern Baltic Sea on the schematic bathymetric background (isobath in meters)

Rozmieszczenie regionów starotypowych Bałtyku południowego na tle batymetrii (izobaty w metrach)

coarse-grained sediments, glaciofluvial sands or Late Glacial clays (R. Kotliński et al., 1984; Sz. Uścinowicz et al., 1984).

PRINCIPLES OF LITHOSTRATIGRAPHIC SUBDIVISION

An attempt of synthesis of previous investigations, new geologic data from seismoacoustic sounding and from boreholes, and detailed lithology analyses were the starting points for the description of changes of sedimentary conditions and finding the influence of these changes on sedimentary processes.

In the cited subdivisions a number of distinguished, Late Glacial and Holocene phases of the Baltic development and their durations are considerably different. Theses differences result from a progress of investigations, application of more up-to-date methods and also different criteria: mainly geomorphologic and hydrographic ones used by some authors, whereas stratigraphic and lithologic of the others

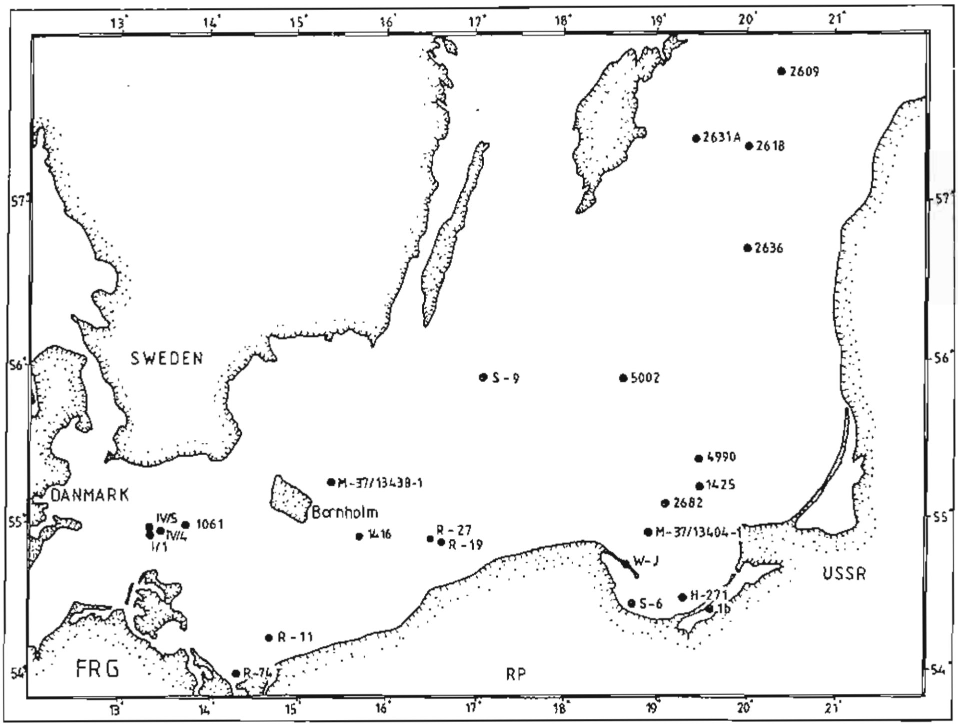


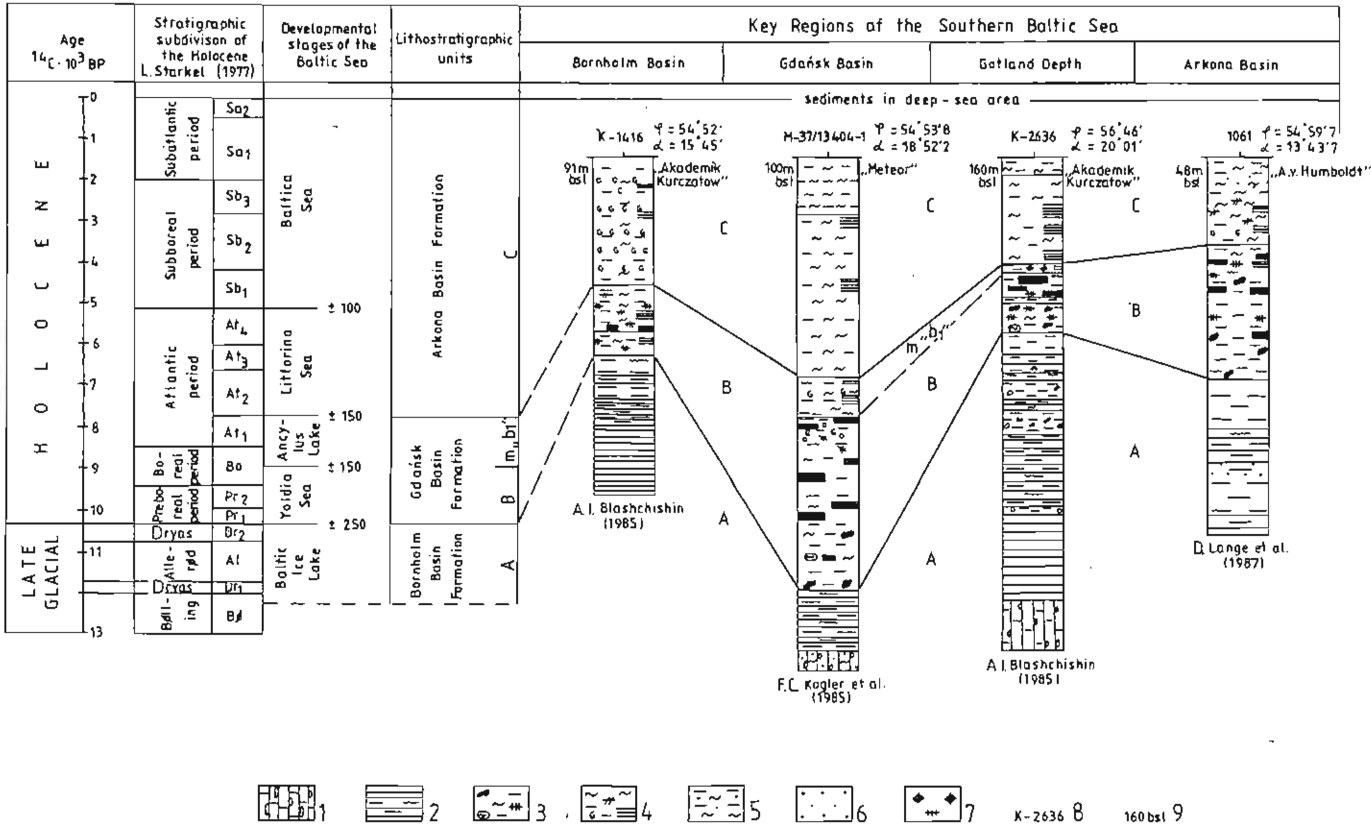
Fig. 3. Schematic location map of the analyzed core samples
Schematyczna mapa lokalizacji analizowanych rdzeni

(M.Sauramo, 1958; B.Rosa, 1968*b*, 1987; W.K.Gudelis, E.Jemelyanov, 1976; W.K.Gudelis, 1985; H. Kessel, A. Raukas, 1979; F.B.Pieczka, 1980; O.Kolp, 1982; E.Rühle, 1982; F.C.Kögler et al., 1985; R.Kotliński, 1989).

Differences in dating for the climatic periods boundaries and, by the same token, between the Baltic Sea development phases reported by the Scandinavian (J.Mangerud et al., 1984; H.Voipio, 1981; S.Björck, S.Hakansson, 1982) and the Soviet scientists (W.K.Gudelis, 1985) are, for example, as follows:

— for the Middle and Late Holocene 2200 years;
— for the Lower Holocene boundary 200 years;
— the Bölling duration over 500 years;
— the Middle Dryas duration about 400 years;
— the Alleröd duration 200 years.

Recently, B.E.Berglund (1976) and others have recommended one climatic period 13 000 to 11 000 years ago for the Bölling, Middle Dryas and Alleröd.



Age $^{14}C \cdot 10^3$ BP
Stratigraphic subdivison of the Holocene L. Starkel (1977)
Developmental stages of the Baltic Sea
Lithostratigraphic units
Key Regions of the Southern Baltic Sea
Bornholm Basin
Gdańsk Basin
Gotland Depth
Arkona Basin
sediments in deep-sea area
HOLOCENE
LATE GLACIAL
Subatlantic period
Subboreal period
Atlantic period
Boreal period
Preboreal period
Dryas
Alleröd
Dryas
Bølling
Sa2
Sa1
Sb3
Sb2
Sb1
At4
At3
At2
At1
Bo
Pr2
Pr1
Dr2
Al
Dr1
Bø
Baltica Sea
Littorina Sea
Ancylus Lake
Yoldia Sea
Baltic Ice Lake
± 100
± 150
± 150
± 250
Arkona Basin Formation
Gdańsk Basin Formation
Bornholm Basin Formation
K-1416
91m bsl
„Akademik Kurczatow"
A. I. Blashchishin (1985)
H-37/13404-1
100m bsl
„Meteor"
F.C. Kogler et al. (1985)
K-2636
160m bsl
„Akademik Kurczatow"
A. I. Blashchishin (1985)
1061
48m bsl
„A.v. Humboldt"
D. Lange et al. (1987)
K-2636 8
160 bsl 9

In view of existing geological data certain opinion on the Baltic evolution, including that on the existence of the Late Glacial Yoldia, Echeneis and Mastogloia Seas, should be abandoned (H.Voipio, 1981; W.K.Gudelis, 1985).

In this paper the lithostratigraphic units were distinguished on the basis of diagnostic features of sediments formed in the Baltic basins (Fig. 2, 3), in which a sedimentary continuity was noted (F.C. Kögler, B.Larsen, 1979; H.Ignatius et al., 1981; A.I.Blashchishin, W.K.Lukashev, 1981; A.I.Blashchishin, 1982; F.C.Kögler et al., 1985). A lithostratigraphic succession in the basins indicates a certain regularity, what is expressed by the easy recognition of main units in the whole Baltic area, but borders of the lithostratigraphic units are not synchronized in every region (Fig.4).

The following basic lithostratigraphic unit can be distinguished in the Late Glacial and Holocene sediments of this basin (Fig. 5):

— the varved clay formation "A" of the Bornholm Basin;

— the homogenous clay formation with iron monosulphides "B" of the Gdańsk Basin with the cryptolaminated clay member of the Gotland Depth "b_1";

— silty clayey and silty organic formation "C" of the Arkona Basin.

In addition to the above basic units, the following ones have been distinguished in the shallow-sea zone:

— gyttja and peat bed "b_1'";

— gravel and sand member of the Vistula delta "b_1";

— sand and silt member of the Hel Peninsula "c_1";

— gyttja member of the Vistula Bay "c_1";

— sand bed of the Odra Bank "c_1'";

— gravel bed of the Słupsk Bank "c_1'".

The above units form the Baltic group an have been distinguished following the definitions contained in the work edited by J.E.Mojski (1985).

A formation constitutes in general a genetical homogenous assemblage of horizons, indicating a continuous sedimentation and distinct diagnostic features. A complex of these features and a scope of their variability within every unit form its characteristics, making it distinguished from the other units. Borders of the formation were fixed on a basis of a distinct change of the features, being the principal

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Fig. 4. Schematic sections of sediments in key regions

1 — till: 2 — varved clays (macro- and microlaminated); 3 — homogeneous clays with monosulphide concentrations; 4 — silty and silty-clayey organic sediments, strongly water- saturated; 5 — sandy silts, clays; 6 — sands: 7 — Fe-monosulphide; 8 — core no.; 9 — depth in the sampling site; A–C — formations: A – from the Bornholm Basin, B – from Gdańsk Basin, C – from the Arkona Basin, m "b1" – member from the Gotland Depth

Schematyczne profile osadów w regionach stratotypowych

1 — glina morenowa, 2 — iły wstęgowane (makro- i mikrolaminowane); 3 — iły homogeniczne ze skupieniami monosiarczków; 4 — osady mulaste i mulasto-ilaste, organiczne, silnie nawodnione; 5 — iły, mułki zapiaszczone; 6 — piaski; 7 — torf; 8 — numer rdzenia; 9 — głębokość w miejscu pobrania; A–C — formacje: A — z Basenu Bornholmskiego, B — z Basenu Gdańskiego , C — z Basenu Arkońskiego; m "b1" – ogniwo z Głębi Gotlandzkiej

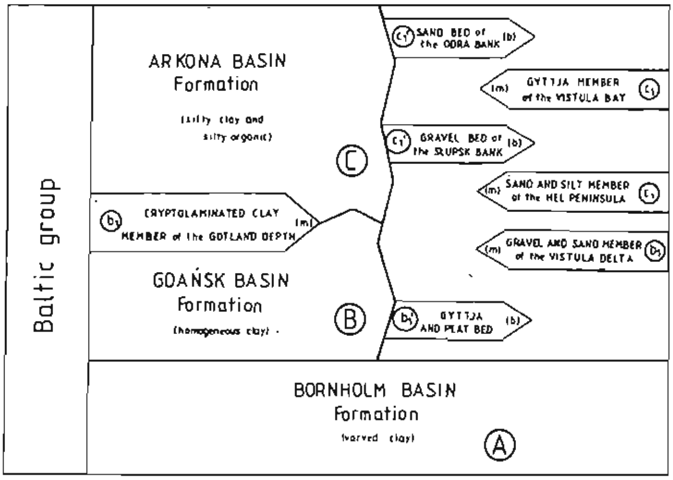


Fig. 5. Relations between lithostratigraphic units of the Southern Baltic Sea. Units are distinguished in agreement with definition J.E.Mojski (1985)

(b) — beds; (m) — member; A–C — formations

Relacje między jednostkami litostratygraficznymi Bałtyku południowego. Jednostki wyróżnione zgodnie z definicjami J. E. Mojskiego (1985)

(b) — warstwa, (m) — ogniwo; A–C — formacje

criterion for distinguishing them as e.g. structure and colour of sediments, acoustic reflection level. In the case of gradual change of features these borders were fixed in the places where a distinct change of proportions of the values of lithology features occurred, represented e.g. by the content of organic C, ratio C:N, content of carbonates, ratio of illite to chlorite, content of total sulphur, presence of authigenic siderite. Lower and upper borders of distinguished units can correspond with other time intervals in various regions (Fig. 4). The selected out basins and depths constitute the key regions, of which the limits are defined on the basis of sections and profiles. Members and layers form the secondary units within a formation. The distinguished member of cryptolaminated clays shows a certain lithologic peculiarity, that reflects a change of sedimentary conditions during the phase of Ancylus Lake. The layers of gravels from the Słupsk Sandbank and of sands from the Odra Sandbank were distinguished to underline a lithogenic individuality of isochronic units, noted in littoral area.

LITHOSTRATIGRAPHIC UNITS

The **Bornholm Basin Formation** forms the principal, Late Glacial lithostratigraphic unit and is represented by clayey and clayey-silty varved sediments (Fig. 6). They are gray and have a distinct varved diatectic structure, according to M. Sauramo (1958), at the bottom. In the top, these sediments are usually gray-brown and indicate a microvarved symmict structure or are homogenous. Varves are thinner towards the top, and grain sizes are smaller due to gradual reduction in sediment supply as the ice sheet retreated, and hydrologic conditions have changed (H.Ignatius et al., 1981). According to F.C.Kögler, B.Larsen (1979) changes in color and structure of sediments were probably caused by the inflow of saline waters.

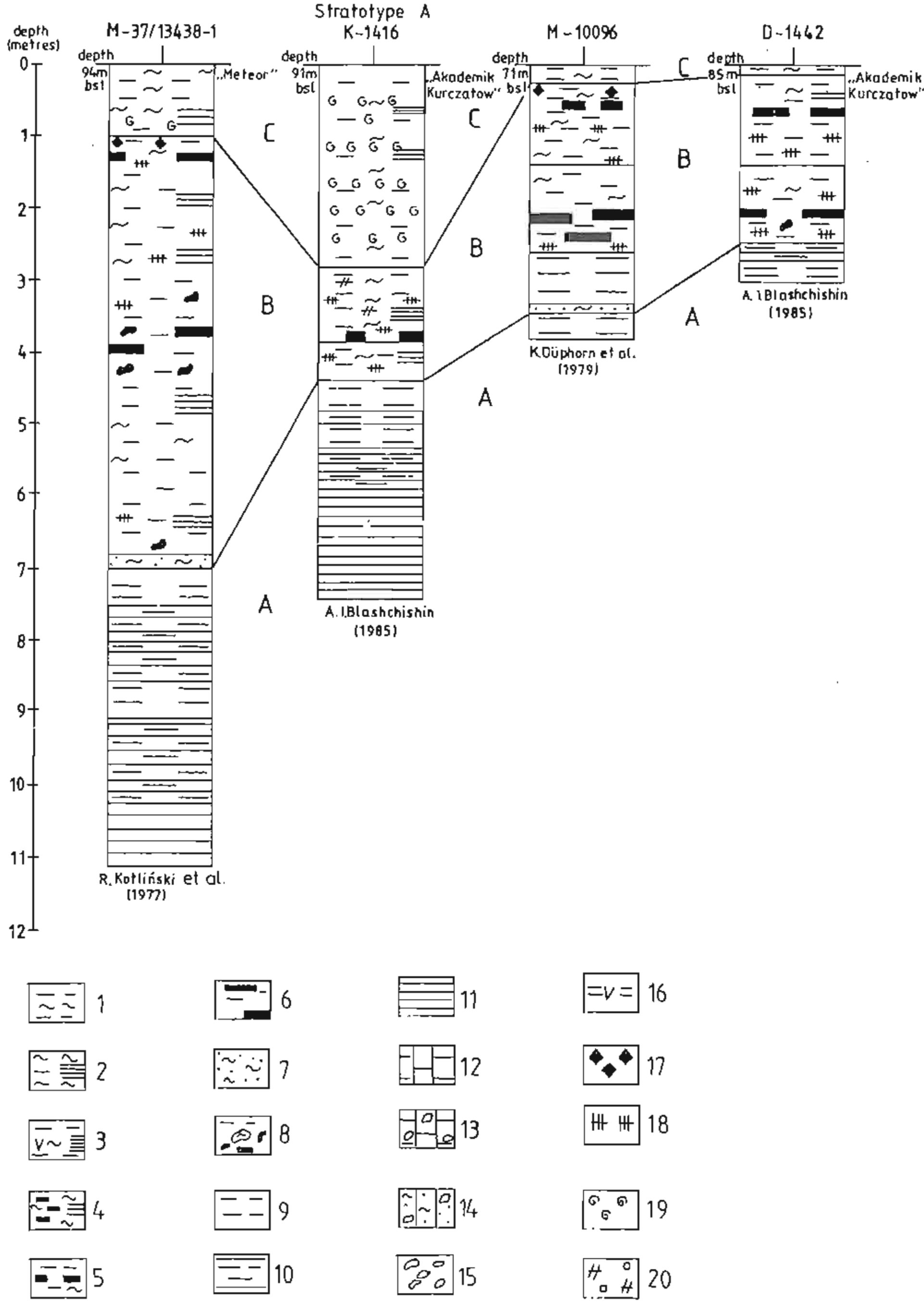
A low content of organic matter and many times greater content of carbonates (calcite and dolomite) are the specific features of these sediments, together with their color and structure, if compared with the overlaying Holocene deposits.

A quick melting of the ice sheet in the Southern Baltic Basin connected with a warming, was probably initiated at the beginning of the Bölling as proved by an absolute dating of a peat layer a cliff near Niechorze for 12 920±330 years BP (K.Kopczyńska-Lamparska, 1976). During the Bölling most of the area occurred inland, and in lakes the marshes lake sediments and peats were deposited (B.Rosa, 1987).

The deglaciation was accompanied by uplifting of land and rise of sea level. In this time a glacial ice melted in isolated reservoirs, of the Bornholm and Gdańsk basins and in the Slupsk Channel. Then, after these reservoirs were connected one with another, clayey and clayey-silty deposits were accumulated. A further retreat of the ice sheet resulted in a water overflow near Billingen, and in a sudden decrease of the water level of about 26–29 m (H.Ignatius et al., 1981). These changes caused in turn a connection with a worldwide sea and rapid inflow of saline waters to this reservoir what happened about 10 200 BP (E.Nilson, 1970).

The Gdańsk Basin Formation is the oldest lithostratigraphic unit of the Holocene represented by homogenous clayey and clayey-silty sediments (Fig. 7). They contain black amorphous spots and streaks of iron monosulphide. These sediments are best developed in the central part of the Bornholm Basin, Gdańsk Basin and Gotlandia Depth. The sediments that directly overlie the varved clays, have been probably deposited in a relatively shallow reservoir with oxidation conditions, as indicating by olive-gray and brown-gray colour of these sediments. Above, there are clayey-silty olive-brown deposits with laminas of monosulphides. They pass gradually upwards into clayey-silty cryptolaminated [1] blue-gray sediment that also contain concentrations of iron monosulphides. The origin of homogenous clays is not explained. A cyclic occurrence of lamina results probably from occasional changes in a palaeohydrochemic environment. In comparison with the underlying varved clays, the homogenous sediments have a varying content of the grain size below 0.002 mm, slightly higher content of organic carbon and many times lower contents of carbo-

[1] Cryptolaminated – sediments apparently homogenous, indicating a presence of laminas on X-ray photographs.


Stratotype A
depth (metres)
M-37/13438-1
K-1416
M-10096
D-1442
depth 94m bsl
„Meteor"
depth 91m bsl
„Akademik Kurczatow"
depth 71m bsl
depth 85m bsl
„Akademik Kurczatow"
A
B
C
R. Kotliński et al. (1977)
A. I. Blashchishin (1985)
K. Düphorn et al. (1979)
A. I. Blashchishin (1985)
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20

nates. They indicate also a higher apparent density and susceptibility. The high variability of the ratio C:N, a lower and quite stable value of the ratio illite: chlorite are the characteristic features, especially if compared with recent sediments above. A thickness of these sediments reaches 5 m in the Southern Baltic depths. Angular hiatuses of lamina and bioturbacies were noted within these sediments (F.C.Kögler et al., 1985).

In the top part of the formation of homogenous clays from the Gdańsk Basin the sequence of cryptolaminated clays from the Gotland Deep can be distinguished (Fig. 8). These sediments are composed of blue-gray cryptolaminated clays with black concentrations and streaks of iron monosulphides. They indicate also a high variability of the value C:N in a vertical section, distinct increase in contents of organic carbon and predominance of calcite over dolomite, if compared with the homogenous sediments that directly overlie the varved clays. Within these sediments there are pyrite and marcasite concentrations. These sediments were formed in a reservoir with a varying palaeohydrochemical environment.

Clayey and silty-clayey sediments of this formation have been in general deposited in a marine environment. A marine reservoir in this areas was formed during the Preboreal Period. In the same time a deposition of varved clays has been completed in the Southern Baltic Basin but still occurred in the Northern Baltic Basin, synchronously with the initiated deposition of homogenous clays in the south. During

Fig. 6. Sections of sediments in deep-sea area – Bornholm Basin

1 — silty clay, homogeneous, sapropelic, olive-gray to gray-green, gelatinuous; 2 — clayey silt, homogeneous or peaty, with laminae cycles, greenish-gray to dark gray, spongy, bioturbation evidence; 3 — silty clay, homogeneous, peaty, gray-black; 4 — silty clay, cryptolaminated, with Fe monosulphide concretions, gray-blue or dark-gray; 5 — silty clay, homogeneous, with laminae and Fe monosulphide concretions, olive-gray; 6— clay, homogeneous with thick Fe monosulphide laminae, olive-gray or dark gray-brown; 7 — silt, sandy, dark gray; 8 — clay homogeneous, gray or olive-gray with dark gray patchy Fe monosulphide concentrations and silt concentrations; 9 — clay, homogeneous, gray-brown, slightly limy; 10 — clay, microvarved, gray-brown, slightly limy; 11 — clay, brown-gray, varved and microvarved, limy; 12 — glacial clay, red-brown, limy; 13 — till, clayey, red-brown, limy; 14 — till, silty-sandy, red-brown, very limy; 15 — silty clay inclusions; 16 — peat, gyttja; 17 — pyrite; 18 — hydrotroilite; 19 — shell fragments; 20 — bioturbation evidence

Profile osadów w obszarze głębokomorskim Basenu Bornholmskiego

1 — ił mulasty, homogeniczny, sapropelowy, barwy oliwkowoszarej do zielonkawoszarej, galaretowaty; 2 — mułek ilasty, homogeniczny lub plamisty, z cyklami lamin, barwy zielonkawoszarej do ciemnoszarej, gąbczasty, ślady bioturbacji; 3 — ił mulasty, homogeniczny, zatorfiony, szaroczarny; 4 — ił mulasty, kryptolaminowany z mikrokonkrecjami monosiarczków Fe, barwy szaroniebieskiej lub ciemnoszarej; 5 — ił mulasty, homogeniczny z laminami i mikrokonkrecjami monosiarczków Fe, oliwkowoszary; 6 — ił homogeniczny z grubymi laminami monosiarczków Fe, oliwkowoszary lub ciemnoszarobrunatny; 7 — mułek piaszczysty, ciemnoszary; 8 — ił homogeniczny, barwy szarej lub oliwkowoszarej z ciemnoszarymi plamistymi skupieniami monosiarczków Fe i skupieniami mułków; 9 — ił homogeniczny, szarobrunatny, słabo wapnisty; 10 — ił mikrowarwowy, szarobrunatny, słabo wapnisty; 11 — ił brunatnoszary, warwowy i mikrowarwowy, wapnisty; 12 — ił glacjalny, czerwonobrunatny, wapnisty; 13 — glina zwałowa, ilasta, barwy czerwonobrunatnej, wapnista; 14 — glina zwałowa, mulasto-piaszczysta, czerwonobrunatna, silnie wapnista; 15 — wtrącenia gliny mulastej; 16 — torf, gytia; 17 — piryt; 18 — hydrotroilit; 19 — okruchy muszli; 20 — ślady bioturacji

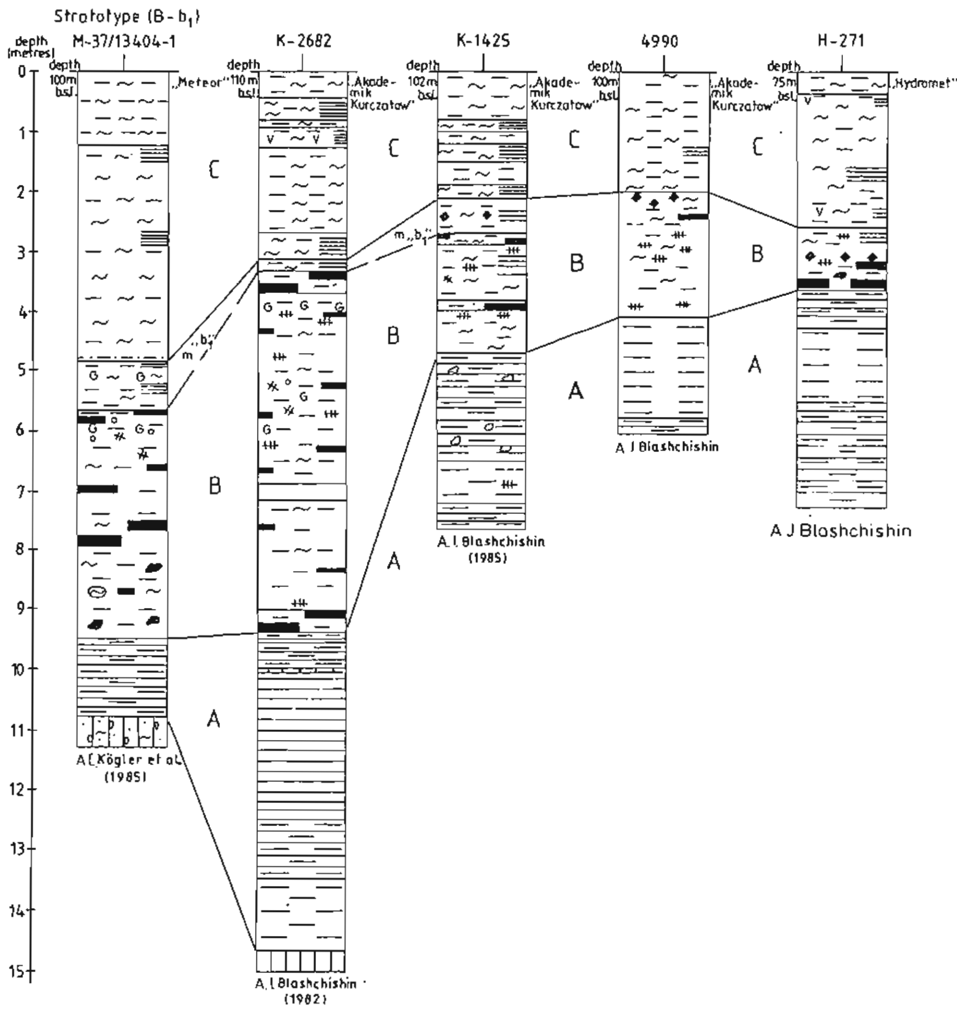


Fig. 7. Sections of sediments in deep-sea area – Gdańsk Basin

Explanations as in Fig. 6

Profile osadów w obszarze głębokomorskim Basenu Gdańskiego

Objaśnienia jak na Fig. 6

the Preboreal Period a northern part of the Yoldia Sea, still being influenced by the near ice sheet edge, indicated the arctic conditions, whereas the Southern Baltic Basin showed an increased biological productivity. The latter was suggested by an increase of organic matter content and presence of iron monoxides, and varving rate of sedimentation as proved by variation of grain size below 0.002 mm content and changes of the sediment colour. Changes in the environment are also reflected by

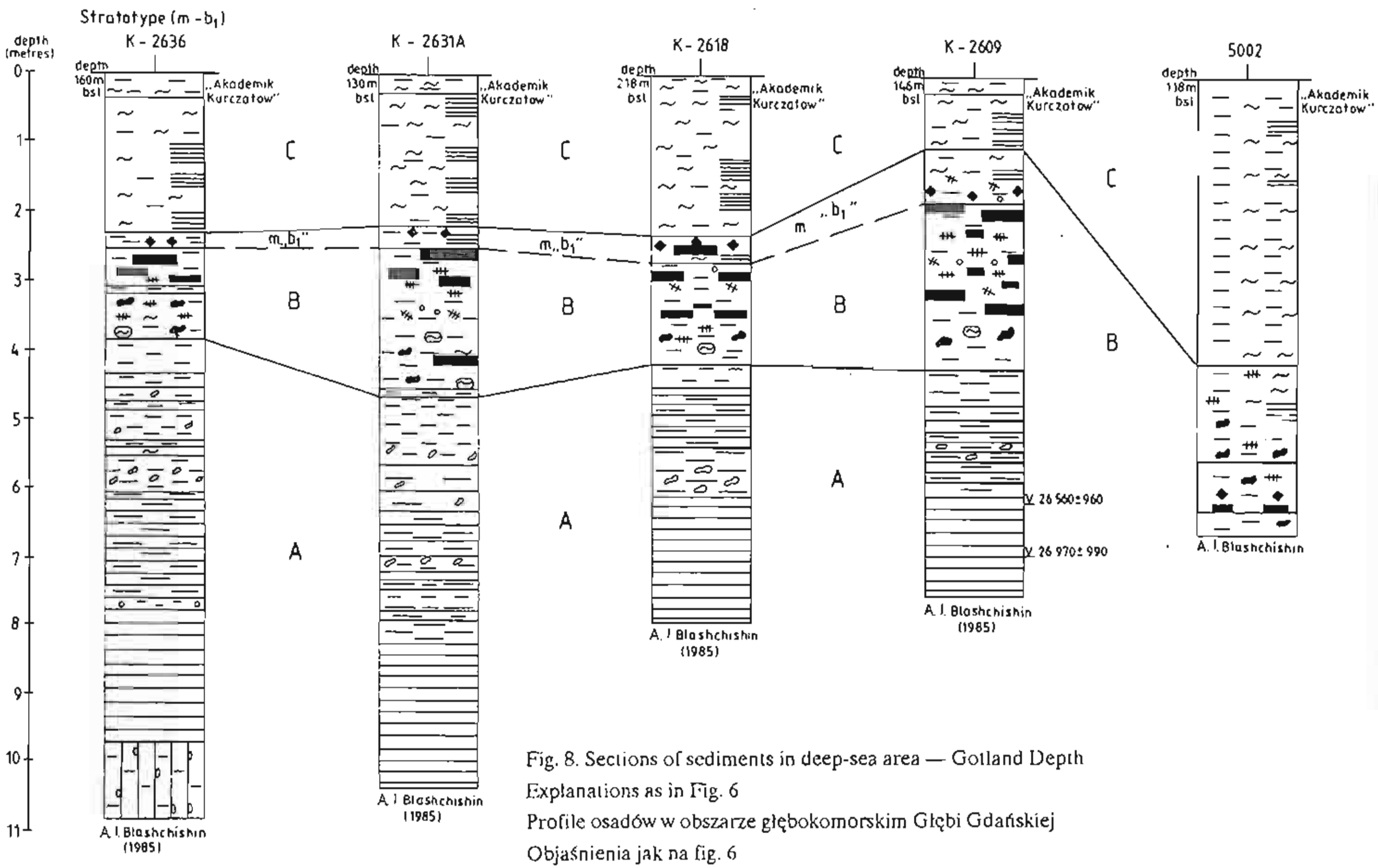


Fig. 8. Sections of sediments in deep-sea area — Gotland Depth
Explanations as in Fig. 6
Profile osadów w obszarze głębokomorskim Głębi Gdańskiej
Objaśnienia jak na fig. 6

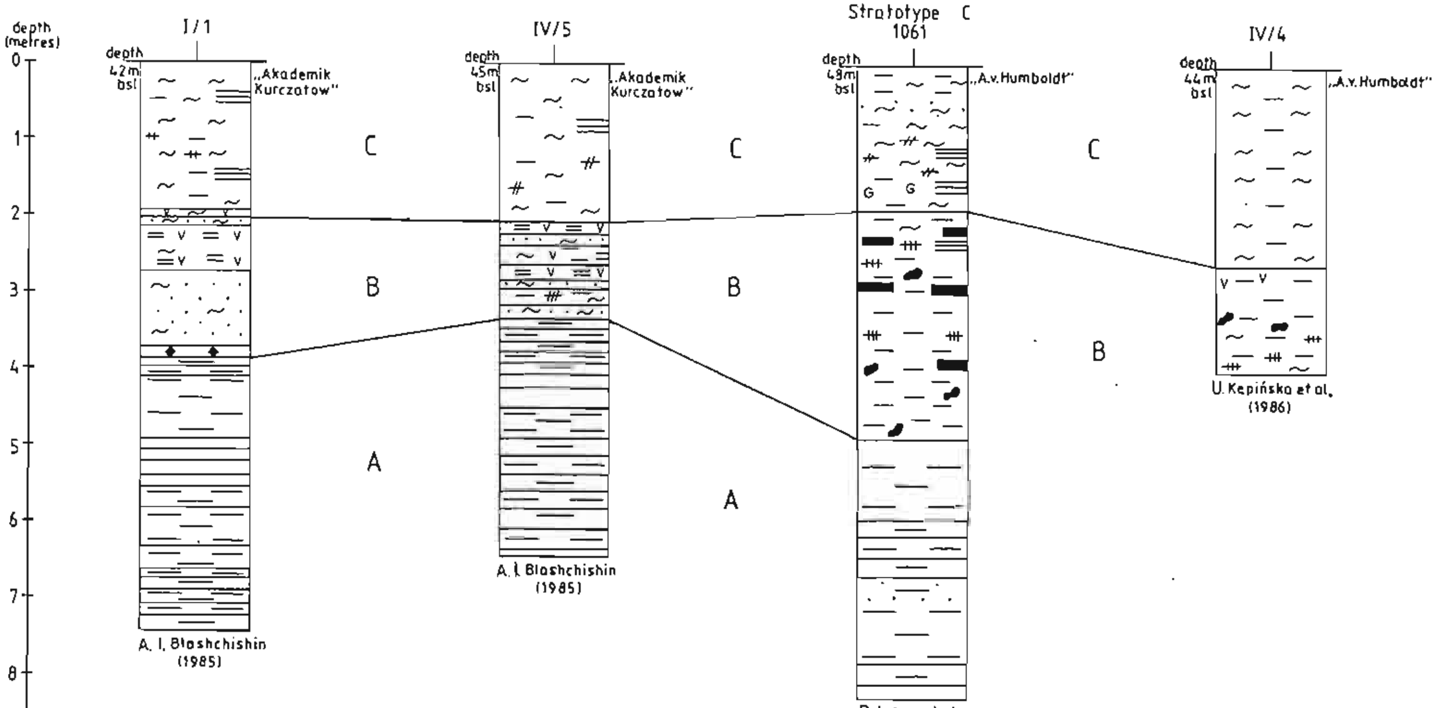


Fig. 9. Section of sediments in deep-sea area — Arkona Basin

Explanations as in Fig. 6

Profile osadów w obszarze głębokomorskim Basenu Arkońskiego

Objaśnienia jak na fig. 6

varying values of the ratio C:N. At the end of the Preboreal Period a quicker land uplift is referred to a water rise, resulted in a disconnection with the sea. Therefore, an inflow of "new" saline waters was restricted and so, a general water salinity decreased and the reservoir was transformed into a saline lake. Shallowing of the lake is proved by an increased content of sand in sediments. During the Ancylus lake phase the cryptolaminated blue-gray clays were deposited. The ice sheet retreated in this time outside the reservoir area. At the end of the Boreal Period a more intensified land uplift in the north than in the southern Baltic area resulted in a transgression of the lake southwards and in the opening of the connection with the sea trough the Sound in Denmark and quick inflow of saline waters (H.Ignatius et al., 1981).

The present marine sediments have been deposited during the Atlantic, Subboreal and Subatlantic periods i.e. during the phases of the Littorina and Baltic seas. Modern sedimentary conditions in the Baltic reservoir are determined by a structural distribution of water masses, relatively low content of salts in bottom water layers, low saturation with oxygen and high concentration of biogenic elements and lithology of sediments of the bottom and littoral zone, depth and morphology of the bottom, and also volume and type of sediment provided to the sea (E. Seibold, 1971; R. Kotliński, 1976).

A development of present marine sediments is synchronize in two sedimentary areas i.e. deep-sea and shallow-sea ones. Their border is defined by a location of a pycnocline that determines extents of silty and clayey grain sizes. The upper extent of the pycnocline occurs at various depths, about 45–40 m in the Arkona Basin and about 70 m in the Gotland Depth. The sedimentary rate of the Holocene deposits in individual basins is varying and depends on current velocities, greater in central parts of the depths and lower at the slopes. At present the greatest sedimentary rates are characteristic for silty and silty-clayey sediments (H. Ignatius et al., 1981). In the shallow-sea zone wind waving, depth and morphology of the bottom, type of sediments in a substrata in a littoral zone are the real sedimentary factors. A detailed lithofacial description of present sediments is enclosed in the paper of Sz.Uścinowicz et al. (1984).

DEEP SEA AREA

The A r k o n a B a s i n F o r m a t i o n is represented by present silty and silty-clayey dark gray-green to black sediments with a high content of organic matter and a lower value of the ratio C:N (Fig. 9). These sediments are mushy and very intensively water saturated. They are best developed in the Gotlandia and Gdańsk depths where they are up to about 7 m thick. Their deposition started after the Atlantic transgression of a sea, ended with its maximum level during the so-called Littorina sea phase. During the Subboreal and Subatlantic periods a sea level was subjected to insignificant fluctuactions. A rapid change of sedimentary conditions at the beginning of the Atlantic Period is expressed by a sharp contact of homogenous and present sediments, and also indicated in seismograms of the acoustic reflection level (Fig. 10) [2].

Silty and silty-clayey deposits have been accumulated in a deep-sea area from a suspended matter in zones of poor action of inner waves on the bottom. Sedimentary processes are strictly connected with water stratification, that is connected among other with the oxygen content and biological productivity. A water convection practically occurs within the upper stratum what results in a negative influence (due to long-lasting stagnation of bottom water) on decomposition of organic matter in sediments. These processes consume the oxygen in water, whereas a mineralization of organic matter in sediments forms accumulations of biogenic salts. A sulphuretted hydrogen, liberated during decomposition of organic compounds and reduction of sulphates, is concentrated in anaerobic zones.

Such sediments are easily recognizable due to high (over 50%) content of silts (0.062–0.002 mm) and considerable content of organic matter. The sediments of the oxidizing environment are gray, olive-gray and seldom gray-black. On the other hand, the sediments of the reducing environment are dark gray or black, with an intensive smell of sulphuretted hydrogen. Silty and silty-clayey sediments have considerably different physical features and mineral content in separate parts of the reservoir. They are also regionally varying if occurrence of some components is concerned. Illite, chlorites and quartz are common. Besides, a montmorillonite and a beidellite, sporadically iron hydroxides, were noted in sediments of the Bornholm Basin (Z.Śliwiński, Sz.Uścinowicz, 1983). The sediments of the Gdańsk Depth contain traces of montmorillonite, kaolinite and smectiles. There are also mixed-packet minerals: illite-smectile, chlorite-vermiculite (Z.Śliwiński, 1979; F.B.Pieczka, 1980; F.C.Kögler et al., 1985). The quantitive content of clay minerals in sediments is connected of the grain size below 0.062 mm. These sediments are specific for a presence of authigenic siderite, increase of sulphur content and high concentration of organic matter if compared with homogenize deposits.

SHALLOW SEA AREA

Present marine gravels and sands with admixture of gravels occur usually in the zone to 25-30 m deep. These deposits form fields of varying sizes and shapes and are up to about 2 m thick (R. Kotliński, 1983; R. Kotliński, M. Masłowska, 1984). They have varying grain sizes, usually poor and extremely poor sorting, seldom good one, and frequently a grain size below 0.125 mm is absent. A petrographic composition is

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[2] Photographs from the originals done by P.Przeździecki.

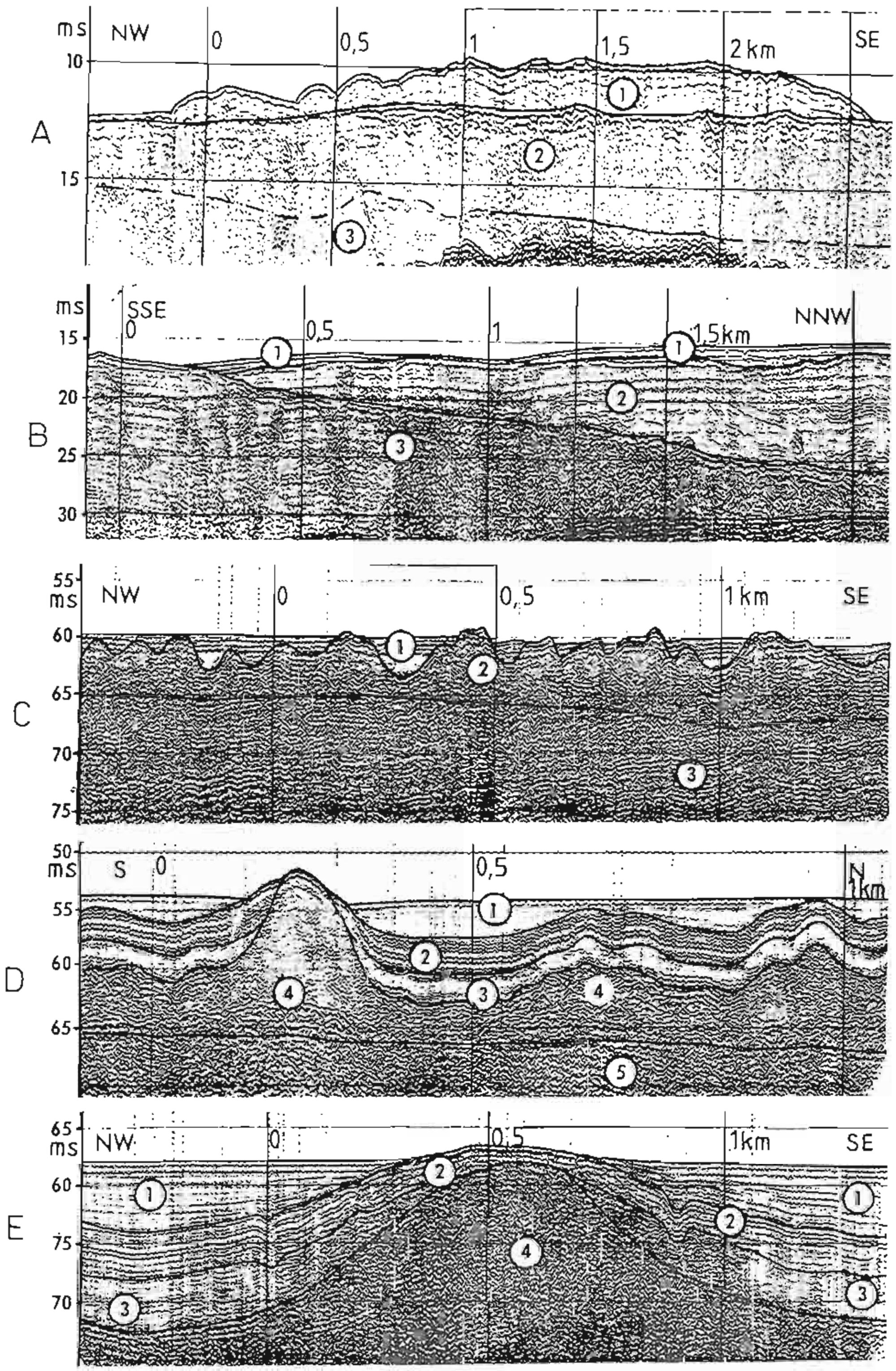
predominated by three groups of components i.e. gravels of crystalline rocks, Paleozoic limestones and sandstones, and in grain sizes below 5 mm also by quartz. Flints, lidites and siltstones are of minor significance (R.Kotliński, 1983, 1984, 1985; R.Kotliński et al., 1984). The offshore sand limit is not simple; in general it gets wider from the west eastwards. Fine-grained sands are noted at a depth of 55–60 m on a slope of the Bornholm Basin an even at about 80 m in the Gdańsk Basin. They usually overlie directly the Pleistocene tills of the Late Glacial clays. The thickness of these sediments is considerably varying; it depends on substrata morphology and local hydrodynamics conditions. It changes from several centimeters on slopes of basins to several meters in sandy areas of shoals (Z.Jurowska, R.Kotliński, 1976; R.Kotliński, 1985). In the Hel Peninsula these sands are thick and e.g. in the Jastarnia borehole reach about 30 m. In this borehole a peat sample from a depth of 5 m was radiocarbon dated for 5370±95 BP (B.Bogaczewicz-Adamczak, 1982). Sands of the Hel Peninsula are of spit origin.

An occurrence of poor prevailing grain size of 2.0–0.5 mm and admixture of gravels of over 2.0 mm, constituting 1–10%, form the characteristic feature of coarse-grained sands. They are usually noted at depths of 10–25 m, close to residual coarse sediments. Medium-grained sands possess a grain diameter (Mz) of 1.5 to 2.0 ϕ mean and good sorting, and contents of heavy minerals in a grain size of 0.25–0.125 mm over 1%. These sediments are usually noted at depth intervals from 10–12 to 25–30 m.

Fine-grained sands are predominated by the grain size of 0.25–0.062 m, have a mean or good sorting and higher content of heavy minerals in the grain size of 0.65–0.125 mm. These sediments occur at depths from 25–30 m to about 50–60 m and were deposited in areas with weak bottom currents. They form vast covers with varying thickness, from several centimeters to about 3 m, dependent on distance from parent area and intensity of transporting currents. On the other hand the sands at depths from about 8–10 to 25–30 m are redeposited in the zone of transformation of wind waves. They form mobile bottom areas of various shapes and sizes and are arranged in characteristic structures at sea bottom (R.Kotliński, Sz.Uścinowicz, 1980).

Sands on a submarine bank slope at depths of 0–10 m are washed away, redeposited or accumulated under the influence of breaking wind waves and bottom currents.

Fine-grained sands enriched in heavy minerals and occurring in the shallow-sea area contain over 2% of heavy minerals in the predominant fraction of 0.25–0.125 mm and have a very good sorting. This sediments are usually noted at a depth of 12–22 m where they form a layer about 30 to 10 cm thick, depending on extent of redeposition connected with waving intensity and reservoir depth (R.Kotliński, 1981). Within this layer there are lamina with heavy mineral content to 50–80% in weight. The sands enriched in heavy minerals are also noted in some fragments of a submarine bank slope at depths from 0 to 10 m (Sz.Uścinowicz et al., 1984).


A
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D
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S
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1km
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Quartz and feldspars (to 5%) are predominating components of sands (R.Kotliński, 1981, 1984, 1985; R.Kotliński et al., 1984; M.Michałowska, Sz.Uścinowicz, 1984). Amidst the heavy minerals there are mainly transparent ones, represented by garnets amphiboles, epidotes, pyroxenes, chlorites and biotite. The others (staurolite, disthene, tourmaline, sillimanite, andalusite, zircon, rutile, vesuvianite, apatite) are of secondary importance.

Fig. 10. Characteristic fragments of seismograms received with a use of apparatus "UNIBOOM" – EG and G.Vertical scale described in single time. For depth of distinguished units or their thicknesses the approximate values of sound velocity in water (1.45 m/s) and in sediments (1.6–1.8 m/s) can be applied

A — Occurrence of marine sands in the so-called Koszalin Bay. These sands (1) cover an uneven top surface of tills (2). The latter form a continuous complex and mantle the Neogene series (3). Top surface of the Tertiary deposits is usually smooth and seldom wavy. Sands form the so-called "littoral cover". An occurrence of these sediments is typical for a shallow-sea area, submarine shoals inclusive

B — Occurrence of marine sands (1) in ice-dam clays (2) formed in as isolated reservoir to the southeast of the Słupsk Sandbank. The clays overlie discordantly the till (3)

C — Outcrops of the Late Glacial clays (2) in sea bottom — Oblique Threshold. Depressions filled with silty-clayey sediments (1) lying discordantly, formed probably during the present development of the Baltic Sea. The sub-Quaternary sequence (3) is noted on seismograms

D — Outcrops of tills in the bottom of the Bornholm Basin (4). The till is concordantly overlain by varved clays (3), overlain by homogeneous clays (2). The latter are discordantly overlain by present silty-clayey organic sediments (1). A distinct acoustic reflection horizon at the border *Ancylus- Litorina*. Under the till there are Mesozoic . The basement probably composed of sandstone of Cretaceous age (5)

E — Outcrops in a bottom of the Gdańsk Depth, probably of homogeneous clays (2), underlain by a till (4). The latter is concordantly overlain by the Late Glacial clays (3), covered by homogeneous clays (2) that are covered discordantly by present silty-clayey sediments (1). A distinct border *Ancylus-Litorina*

Charakterystyczne fragmenty sejsmogramów uzyskane zestawem aparatury "UNIBOOM" – EG and G. Skala pionowa opisana w czasie pojedynczym. Przy określeniu głębokości zalegania wyróżnionych jednostek lub ich miąższości do przeliczeń można zastosować przybliżone wartości prędkości dźwięku w wodzie (1,45 m/sek), a w osadach (1,6–1,8 m/sek)

A — Charakter zalegania piasków morskich w rejonie tzw. "Zatoki Koszalińskiej". Piaski morskie (1) pokrywają nierówną powierzchnię stropową glin zwałowych (2), które tworzą kompleks ciągły i leżą na osadach neogeńskich (3). Powierzchnia stropowa osadów trzeciorzędowych jest z reguły wyrównana, rzadziej falista. Piaski tworzą tzw. pokrywę litoralną. Sposób zalegania osadów jest typowy dla regionu płytkomorskiego oraz ławic podwodnych

B — Charakter zalegania piasków morskich (1) na iłach zastoiskowych (2) powstałych w izolowanym zbiorniku w SE części od Ławicy Słupskiej. Iły pokrywają niezgodnie glinę zwałową (3)

C — Wychodnie na powierzchni dna morskiego iłów późnoglacjalnych (2) – Próg Ukośny. Zagłębienia wypełnione leżącymi dyskordantnie osadami mulasto-ilastymi (1) powstałymi prawdopodobnie w okresie współczesnym rozwoju Bałtyku. Na sejsmogramach zaznacza się podłoże podczwartorzędowe (3)

D — Wychodnie na powierzchni dna glin morenowych w rejonie Basenu Bornholmskiego (4). Na glinie leżą zgodnie późnoglacjalne iły wstęgowe (3) przykryte iłami homogenicznymi (2). Nad iłami homogenicznymi (2) leżą dyskordatnie współczesne osady mulasto-ilaste organiczne (1). Wyraźnie widoczny akustyczny poziom odbicia na granicy *Ancylus-Litorina*. Pod gliną zwałową występują osady mezozoiczne prawdopodobnie piaskowce kredowe (5)

E — Wychodnie na powierzchni dna głębi Gdańskiej prawdopodobnie iłów homogenicznych (2) pokrywających glinę morenową (4). Na powierzchni glin morenowych leżą zgodnie iły późnoglacjalne (3) pokryte iłami homogenicznymi (2), które pokrywają zalegające niezgodnie współczesne osady mulasto-ilaste (1). Wyraźna granica *Ancylus-Litorina*

There are also non-transparent minerals, rock pieces, glauconite and carbonate minerals. The noted quantitive and qualitative variation is firstly the effect of redeposition that occurred many a time, caused by wave-wind currents (R.Kotliński, 1981, 1985).

Components of the present sediments are generally of terrigene origin, coming mainly from the Pleistocene glacial deposits. If compared with terrigene deposits, the present sediments contain a slight admixture of biogenic components. Variations in contents of these sediments indicate that bottom fragments without the occasional supply with terrigene material have not been the ground for development of benthonic features. A small productivity of benthos has been connected with hydrometeorologic conditions (oxygenation, water temperature, salinity, intensive action of waves on the bottom). These conditions were the principal reason for development and extents so, a shell detritus is usually dispersed in these sediments.

Sediments lying on the bottom form three groups: the ones of a residual product that are generally represented by a coarse material; redeposited sediments, being a product of washing near the source of the material, composed usually of sands and sands with gravels (migrating deposits); sediments resulting from the present accumulation, represented by sands and silts, formed due to mixing of redeposited material and the one, transported into the basin by another way (components of aeolian and fluvial origin). No distinct correlation of lithology of residual sediments with their location and present sedimentary environment forms a characteristic feature of them. On the other hand, features of sediments of the present marine accumulation reflect in general the conditions prevailing during their development and indicate a strict connection with the place of their present occurrence (R.Kotliński, 1984).

Sediments formed in the area examined show, on the one hand, lithological similarities, but on the other distinct facial differences. Their therefore difficult separation and lithostratigraphic correlation is additionally impeded by hiatuses noted frequently in numerous sequences. And also, due to the isostatic rise of the shallow-sea, the completely developed sequences synchronous with the sea level changes, have not been preserved. But the substantial changes in depositional conditions related to the palaeogeographic evolution of the Baltic Sea are reflected defined lithological horizons. The following can be regarded as lithostratigraphic horizons of the rank of lower order units within formations (fig. 11):

— the Preboreal peat and gyttja bed;

— the Boreal peat bed.

Of similar rank can also be eolian, deltaic and lagoonal sediments reported from numerous sequences in a defined area. Therefore, in the deep-sea area, distinctive of defined bottom zones are sequences reflecting different lithofacies conditions. The most typical ones for given depositional conditions are:

— shoal sediments;

— the lagoonal assemblage of the Vistula Bay;

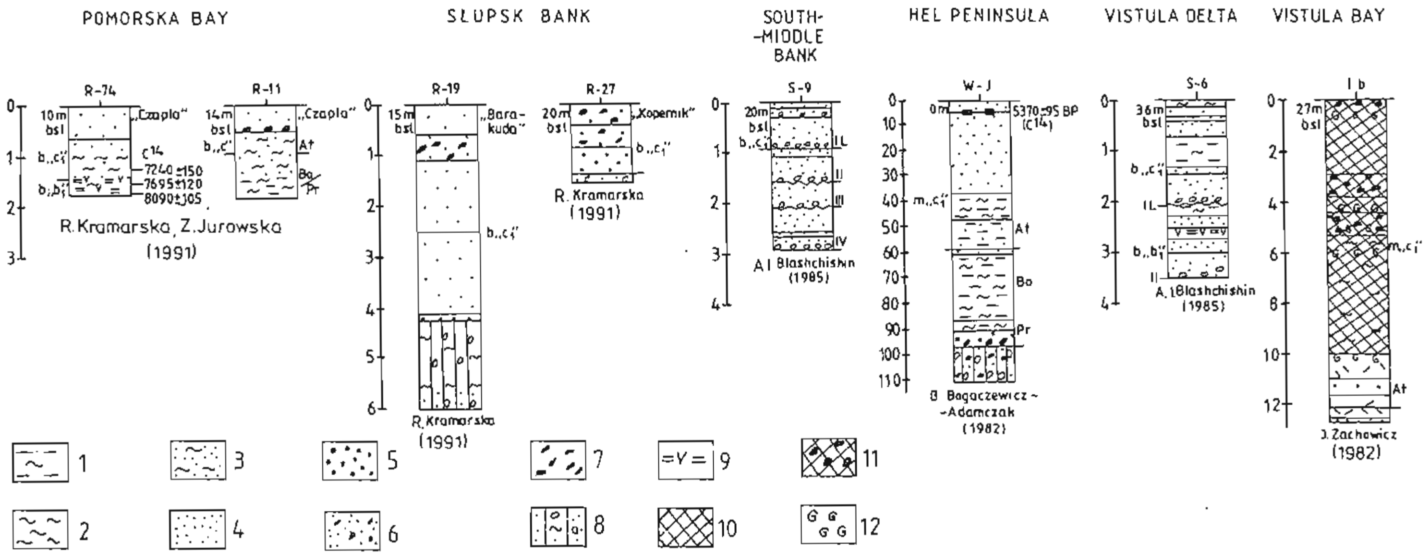

Fig. 11. Sections of sediments in shallow-sea area

1 – silty clay; 2 – silt; 3 – silty sand; 4 – fine-grained sand; 5 – coarse-grained sand; 6 – sand with gravel; 7 – gravel; 8 – till, silty-sandy; 9 – peat; 10 – detritus gyttja; 11– limy gyttja, peat detritus; 12 – shells; 13 – ^{14}C age in ka BP; periods: Pr – Preboreal, Bo – Boreal, At – Atlantic, Sb – Subboreal, Sa – Subatlantic

Profile osadów w obszarze płytkomorskim

1 – ił mulasty; 2 – mułek; 3 – piasek mulasty; 4 – piasek drobnoziarnisty; 5 – piasek gruboziarnisty; 6 – piasek żwirowaty; 7 – żwir; 8 – glina zwałowa mulasto-piaszczysta; 9 – torf; 10 – gytia detrytusowa; 11 – gytia wapienna, detrytus roślinny; 12 – muszle; ^{14}C – wiek w ka BP; okresy: Pr – preborealny, Bo – borealny, At – atlantycki, Sb – subborealny, Sa – subatlantycki

— fine-grained eolian sands;

— coarse-clastic sediments of the transgressive horizons the gravel bed of the Słupsk Bank or the gravel-sand assemblage of the South Middle Bank;

— abrasive morainic pavement on tills;

— sand and gravel member of the Vistula Delta;

— sand-bar assemblages.

For the South-Middle Bank distinctive is a sedimentary assemblage of the ancient shorelines represented by four transgressive-regressive cycles. Each of them commences with a gravel and terminates with a fine-grained sand horizon. The upper gravel horizon corresponding to the Littorina transgression is correlated with the Vistula delta gravel (A.I.Blashchishin, 1985).

The formation of the Odra Bank sediments and its topography are the resultant of processes acting in the marine environment. Detailed lithological characteristic and origin of the Odra Bank sands are reported, among others, in the following papers: Z.Jurowska, R. Kotliński (1976); W.Wajda (1982).

As indicated by the ^{14}C age of an approximately 60 cm thick peat bed form the vicinity of Międzyzdroje found to be 8090±105 BP and 7200±105 BP at the bottom and top respectively (R.Kramarska, 1980), in the Pomorze Bay area the formation of the sandy cover commenced during the Littorina Period.

The Słupsk Bank constitutes a submarine morainic plateau, in its bottom occur Pleistocene and Holocene marine sediments (Littorina and Baltica). The variability of the lithological features within the Słupsk Bank results from processes affecting the bottom during the Atlantic, Subboreal and Subatlantic periods. The degree of reworking and distribution of the marine sediments are related to processes acting during the initial marine invasion phase in this area and to intensive currents in the then surf zone. Detailed characteristics of gravel and sand of the Słupsk Bank are given in the paper by R.Kotliński (1985).

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OSADY POŁUDNIOWEGO BAŁTYKU — WARUNKI FORMOWANIA I LITOSTRATYGRAFIA

Streszczenie

Osady Bałtyku południowego formowane były w późnym glacjale i w holocenie, w zmieniających się warunkach sedymentacji. Wyróżnione podstawowe jednostki litostratygraficzne są rozpoznawalne na obszarze całego Morza Bałtyckiego, przy czym wykazują one zmienną miąższość a ich granice w poszczególnych regionach nie są synchroniczne. Osady każdej z tych jednostek tworzą jednorodny genetycznie zespół poziomów odznaczający się ciągłością sedymentacji i wyraźnymi cechami diagnostycznymi. Zmienność cech litologicznych osadów jest odbiciem zmian warunków i tempa sedymentacji w regionach. Podstawową – późnoglacjalną – jednostkę stanowi formacja z Basenu Bornholmskiego, reprezentowana przez osady ilaste wstęgowane, formowane w zbiorniku pozostającym w bezpośrednim zasięgu topniejącego lądolodu. Najstarszą jednostkę holocenu stanowi formacja z Basenu Gdańskiego, którą tworzą osady ilasto-mulaste, homogeniczne ze skupieniami siarczków żelaza. Osady te formowane były w okresie preborealnym i borealnym, w fazie morza yoldiowego i jeziora ancylusowego. Współczesne osady morskie, zaliczone do formacji z Głębi Arkońskiej oraz osady przybrzeżno-zalewowe, tworzyły się synchronicznie w dwóch obszarach sedymentacyjnych – głębokomorskim i płytkomorskim. Ich formowanie rozpoczęło się w okresie atlantyckim i trwa do dziś, tj. obejmuje fazę morza litorynowego i współczesnego nam morza baltica.

klimatycznego holocenu. Osady tarasu zalewowego doliny Samicy pod Przeciwnicą powstały niemal współcześnie (790±70 lat BP).

Liczne luki stratygrafiezne, obejmujące długie okresy (głównie interstadialne i interglacjalne) plejstocenu, świadczą o intensywności procesów niszczących. Prawdopodobnie intensywność ta miała związek z wielkopromiennym wypiętrzaniem środkowej części Wielkopolski w plejstocenie i lokalnie z nasileniem procesów neotektonicznych.