Geological Quarterly, 1998, 42 (3): 277–288

Origin and development of the Odra Bank in the light of the geologic structure and radiocarbon dating

Regina KRAMARSKA

Kramarska R. (1998) — Origin and development of the Odra Bank in the light of the geologic structure and radiocarbon dating. Geol. Quart., 42 (3): 277–288. Warszawa.

Sandy sediments of various origin and age dominate Quaternary geologic structure of the Odra Bank region. Three sediment series identified in numerous borehole section and dated using radiocarbon method represent sediments of the Interpleniglacial, the Late Vistulian Glaciation, and the Holocene. The oldest series composed of sands, locally silty sands with organic matter and coalified organic remains, formed in the Interpleniglacial of the Vistulian Glaciation. Younger series is represented by the marshy-lacustrine sediments, which formed in the Late Glacial and the Early Holocene. The youngest series is composed of marine sands. Stages of the region development were determined based on results of radiocarbon dating. Two dates are the most significant: 14 060 years BP, which indicates beginning of the peat accumulation in the studied region, and 5190 years BP, which indicates the beginning of the Littorina Sea transgression into the Odra Bank.

Regina Kramarska, Marine Geology Branch, Polish Geological Institute, Polna 62, 81-740 Sopot, Poland *(received: 26.02.1998; accepted: 16.03.1998).*

Key words: Southern Baltic, Odra Bank, Pomeranian Bay, Pleistocene, Holocene, fluvial, lacustrine and marine sediments, radiocarbon dating.

INTRODUCTION

Characteristics of the geologic structure of the near-surface layers of the western part of the southern Baltic Sea bottom, which includes an area between the Rewal meridian and the western border line of the Polish Exclusive Economic Zone (EEZ) (Fig. 1), and representation of development of this region during the Younger Pleistocene and the Holocene are goals of this study.

The sea bottom in the studied area is not significantly diversified. The Odra Bank, delimitted by the isobath of 10 m, is the main form. Border line between Poland and Germany divides the shoal into two parts. Smaller, southeastern part is located in the Polish EEZ. A small shallow delimited by the isobath 10 m also occurs along the eastern extension. This region is bordered from the south by a relatively steep slope delimited by isobaths from 17.5 (locally from 20 m) to 12.5 m. The bottom between the slope and the shoreline is distinguished by presence of small depressions or hills up to 3 m high. The northern slope inclines gently toward north-east and reaches depth of 30 m in the area of study.

These sedimentary series which could be dated using the radiocarbon method were subjects of consideration in this study. All identified organic occurrences or remains in this region of the Baltic Sea were subjected to radiocarbon dating in various studies conducted during several years.

First radiocarbon dates were obtained for samples collected in two cartographic borings (profiles R-74 and W-4). It should be noticed that dating of samples from the profile R-74, conducted in 1979 determined the first dates in the history of the bottom sediment study in the Polish Baltic Sea zone. The next series of dated sediments and shells was obtained in the reconnaissance and documentary works of heavy mineral concentrations (length of sounding borers up to 1 m, exceptionally 2.5 m). These works were initially conducted in the Polish Geological Institute, and subsequently by the Dredging and Underwater Works Company Ltd., under supervision of the author of this paper. The research data obtained at that time changed most significantly

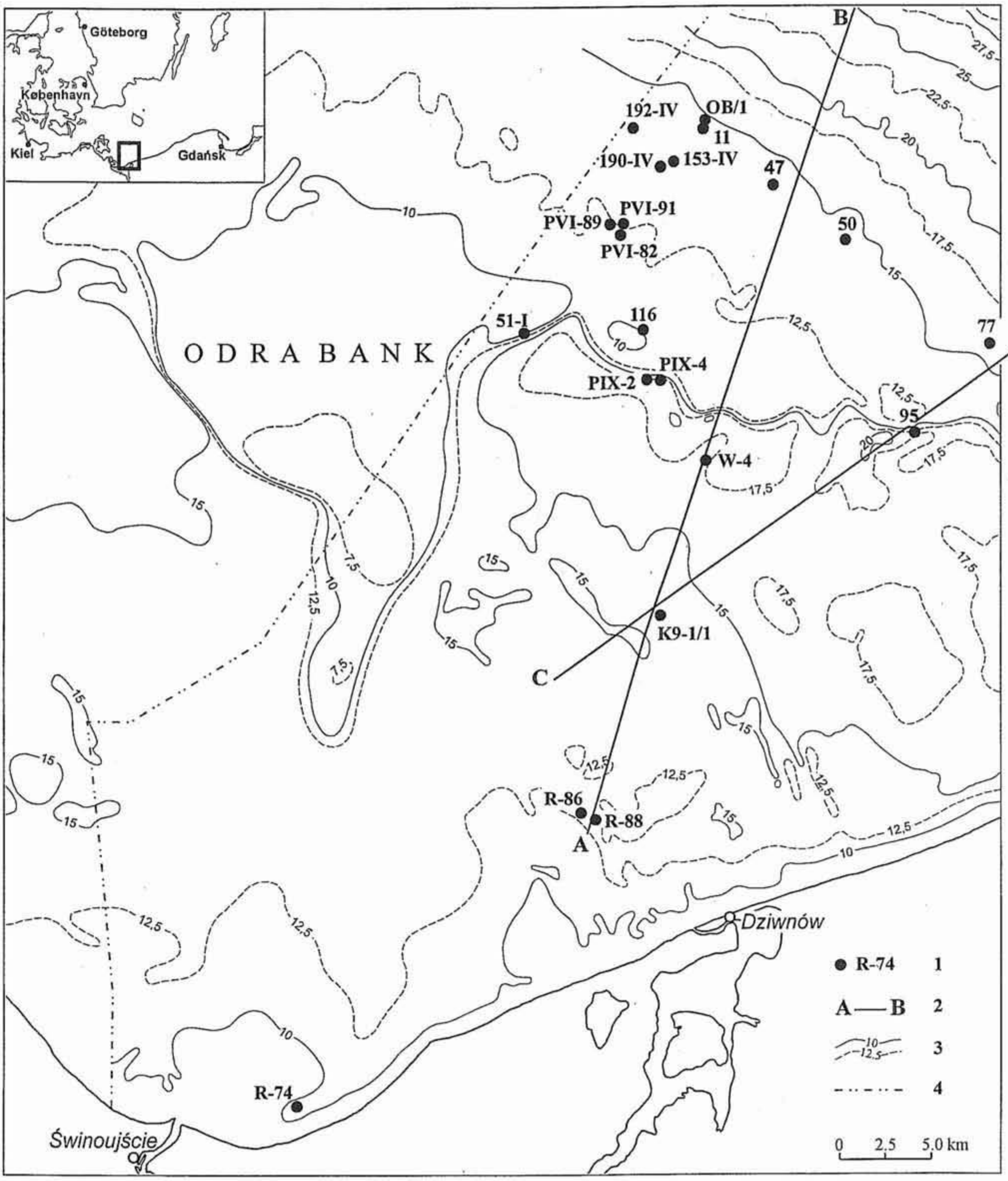

Fig. 1. Location of boreholes

1 — boreholes, 2 — geologic cross-sections, 3 — isobaths (interval 2.5 m), 4 — border line of the Polish Exclusive Economic Zone

Lokalizacja otworów wiertniczych

1 — otwory wiertnicze, 2 — linie przekrojów geologicznych, 3 — izobaty co 2,5 m, 4 — granica polskiej strefy ekonomicznej

recognition of the geologic structure of this region existing hitherto. Dating of samples of organic sediments from geologic-engineering borings drilled for the "Petrobaltic" drilling platform foundation (profiles R-86, R-88 and K9-1/1) and from test borings conducted by the Institut für Ostseeforschung in Warnemünde within cooperation framework with

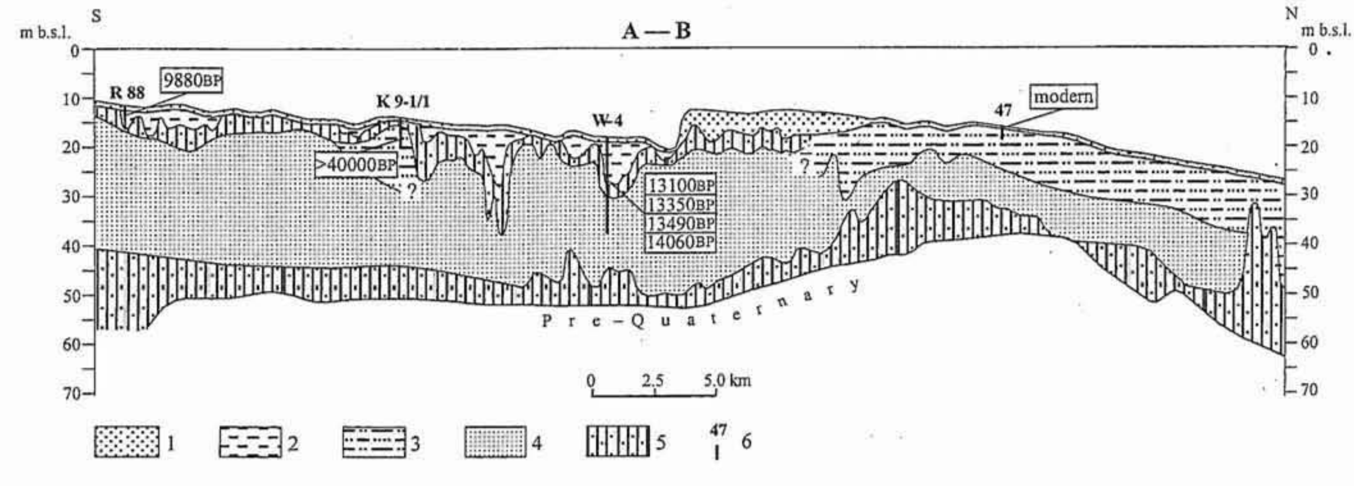

Fig. 2. Geologic cross-section A–B

Holocene: 1 — sands of Littorina and Post-Littorina seas; **Late Glacial–Holocene**: 2 — lacustrine silts and sands, locally peat; **Pleistocene**: 3 — Interpleniglacial riverain(?) sands and silts, 4 — glaciofluvial sands and gravels, 5 — till; 6 — boreholes with radiocarbon datings

Przekrój geologiczny A–B

Holocen: 1 — piaski morza litorynowego i politorynowego; **późny glacjał–holocen**: 2 — muły i piaski jeziorne, miejscami torfy; **plejstocen**: 3 — piaski i muły rzeczne(?) interpleniglacjału, 4 — piaski i żwiry wodnolodowcowe, 5 — gliny zwałowe; 6 — otwory wiertnicze z datami radiowęglowymi

the Marine Geology Branch of the Polish Geological Institute (profile OB/1), is considered supplementary.

As results of the study, in the period from 1979 to 1994, the author obtained 27 radiocarbon dates which refer to sediment samples in 17 profiles and 7 dates of shells in 7 boring profiles (Table 1). Location of the profiles is presented in Figure 1. All datings were conducted in the Radiocarbon Laboratory of the Silesian Technical University in Gliwice. Some dates documenting Late Glacial/Early Holocene period of the region development were published in the review cartographic publications (R. Kramarska, Z. Jurowska, 1991; R. Kramarska, 1995*a*), without elaborate analysis of results, however, because of the character of these publications.

A significant amount of results of lithological, faunal, and floral studies was also collected from sediments in the Odra Bank region. Detailed interpretation of these results will be presented in other publications — they where used here only for general description of sediments.

OUTLINE OF THE QUATENARY GEOLOGIC STRUCTURE

The bottom relief, geologic structure and natural resources considerations of an area designated as the Odra Bank region were subjects of studies conducted by the Polish Geological Institute during several years. Results of these studies are presented thoroughly in cartographic publications (Z. Jurowska, R. Kramarska, 1990; R. Kramarska, Z. Jurowska, 1991; J. E. Mojski, 1995). Earlier selected problems of the Quaternary which refer to lithology, stratigraphy and accumulations of heavy minerals were reflected only in few larger publications (Z. Jurowska, R. Kotliński, 1976; W. Wajda, 1982) and short published announcements (R. Kramarska, 1993*a*, 1994). The Odra Bank region is also mentioned in review works referring to larger areas of the Baltic Sea — more important include works of O. Kolp (1990) and B. Rosa (1967).

Sandy sediments of various origin dominate in the Quaternary geologic structure of the Odra Bank area (Figs. 2 and 3). Till sediments form two, locally discontinuous horizons. Older till — determined only in seismoacoustic study — lies directly on the Mesozoic bedrock. Younger — determined also in borings — lies shallow beneath the bottom. It extends as a thin layer from the shoreline toward the Odra Bank, and disappears probably on the northern slope of this form (Figs. 2 and 3). It appears again only in the bottom of the Bornholm Basin (Z. Jurowska, R. Kramarska, 1990). Layers of till are separated by the sandy sediments of thickness reaching even up to 30 m. Earlier there was no foundation for the more detailed stratification of this layer referring to its origin and age, thus based on analogy with the sea-coast, these sediments were designated as glaciofluvial sands and gravels of the Middle Polish Glaciation (R. Kramarska, Z. Jurowska, 1991). The upper part of the layer — occurring on the northern slope of the Odra Bank without the till cover — was included then into the marine Littorina cover. In the light of current study results, with a big probability one may accept that at least the uppermost part of the layer represents interstadial sediments (Grudziądz Interstadial = Interpleniglacial). The diversified surface of the upper till is leveled by marshy and lacustrine sediments accumulated in the Late Glacial and the Early Holocene in the region bordering the Odra Bank from the west.

The bottom surface is covered by a layer of Littorina and Post-Littorina sea sands. The layer is developed best on the Odra Bank and its extension towards south-east. This shoal

Table 1

List of radiocarbon datings of sediments and shells

Profile number	Sea depth [m b.s.l.]	Layer depth interval [m]	Sample type	Laboratory sample number	Age ^{14}C [BP]
			Series 1		
OB/1	15.7	2.30–2.45 1.10–1.25	floral detritus floral detritus	Gd-10 128 Gd-10 123	15 010±150 29 430±370
K9–1/1	14.4	4.3–4.5	floral detritus	Gd-10 180	> 40 000
77	15.6	0.18–0.38	organic silt	Gd-4841	>27 000
11	15.8	0.10–0.25 0.25–0.32	silty sand with organic matter silty sand with organic matter	Gd-6573 Gd-6572	32 030±770 34 700±1100
153-IV	12.7	0.23–0.31 0.70–0.80	silty sand weakly organic sand with organic matter laminas	Gd-10 038 Gd-9223	21 480±440 >45 000
190-IV	12.6	0.21–0.23	peat mat	Gd-10 039	22 780±660
192-IV	13.8	0.80–0.87	sand with organic matter laminas	Gd-7503	46 500 [(+ 5000) (–3200)]
			Series 2		
W-4	17.3	9.21–9.23 9.69–9.72 9.75–9.80 10.42–10.50	peat peat peat peat	Gd-4336 Gd-4335 Gd-2929 Gd-2928	13 100±300 13 350±270 13 490±190 14 060±220
R-86	13.0	2.50–2.60	peat	Gd-10 048	12 010±100
R-88	12.5	1.75–1.85	peat	Gd-10 049	9880±140
51-I	16.4	2.40–2.50	peat	Gd-7505	9500±80
R-74	10.0	1.20–1.35 1.35–1.50 1.50–1.78	peat peat peat	Gd-1043 Gd-1044 Gd-1042	7240±150 7695±120 8090±105
PIX-2	18.4	0.75–0.85	weakly organic silt	Gd-9309	8070±240
PIX-4	18.0	0.90–1.00	weakly organic clay	Gd-10 126	6630±140
PVI-82	11.3	72–80	floral detritus in lake-marl lake-marl (carbonaceous fraction)	Gd-9313 Gd-10 135	5100±200 6770±120
PVI-89	11.5	0.62–0.67	lake marl (carbonaceous fraction)	Gd-10 136	8410±120
PVI-91	12.3	0.40–0.50 0.75–0.85	floral detritus sand with weakly organic clay	Gd-9311 Gd-9327	16 200±570 9500±580
			Series 3		
47	13.5	0.10–0.17	marine shells	Gd-5980	modern
50	13.9	0.17–0,21	marine shells	Gd-6520	200±150
76	16.5	0.20–0.25	marine shells	Gd-6521	350±200
PVI-89	11.5	0.50–0.55	marine shells	Gd-10 137	4410±110
PIX-4	18.0	0.83–0.90	marine shells	Gd-7553	4510±50
116	9.6	0.15–0.20	marine shells	Gd-5979	1400±70
95	18.5	0.47–0.50	marine shells	Gd-6515	5190±130

extension delimited by isobaths of 12.5–13 m, is the relict of the spit bar from the Littorina transgression of the Baltic sea (R. Kramarska, Z. Jurowska, 1991).

LITHOLOGY AND RADIOCARBON AGE OF SEDIMENTS

Lithologic characteristics and radiocarbon dating includes generally sandy sediments, which with the upper till layer constitute the upper part of the Quaternary layer — recognized more precisely. Sandy sediments form three series:

— sands and sands with silty admixtures of not identified origin (possibly riverain), containing dispersed organic matter and carbonificated organic remains — radiocarbon dated from more than 45 000 to 21 480±440 years BP (series 1);

— sands and silty sands, locally with peat or lake marl marshy and lacustrine — radiocarbon dated from 14 060 to 5100±200 years BP (series-2);

— marine sands with numerous shell agglomerations, for which radiocarbon dates from 5190±130 years BP till recent were obtained (series 3).

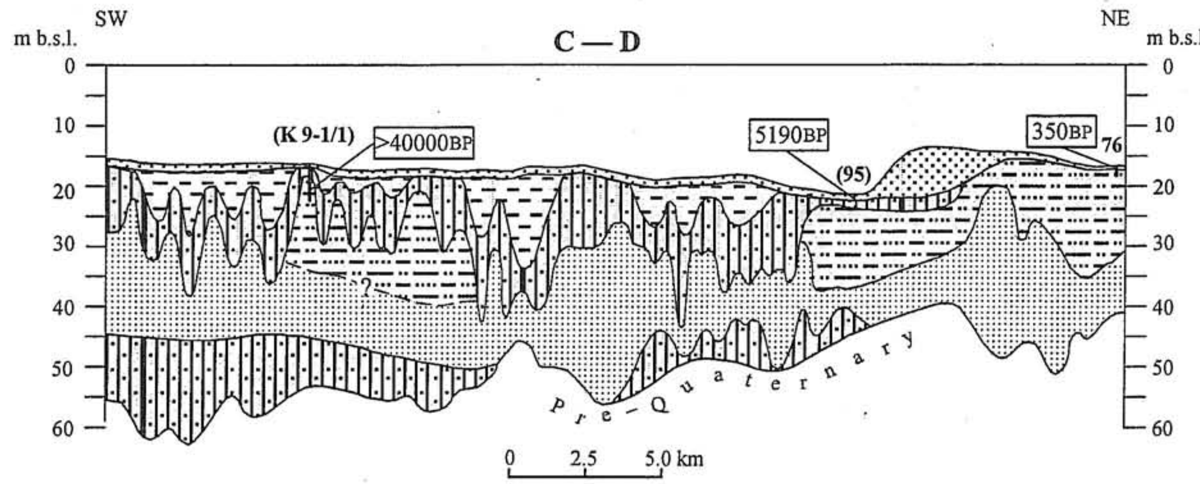

Fig. 3. Geologic cross-section C–D
For explanations see Fig. 2
Przekrój geologiczny C–D
Objaśnienia jak na fig. 2

Distribution of dates in the time scale, which refer to sediments of particular series, is presented in Figure 4. It should be emphasized that the distinguished sediment series were not determined in any of the cases in a single profile.

Series 1. Sediments radiocarbon dated as older than 21 000 years BP are documented in the numerous profiles on the northern slope of the Odra Bank. In most cases samples were collected from depths up to 1 m below the sea bottom, and only few profiles — including OB/1 — were obtained from depth slightly more than 5 m, but boring did not reach the layer bottom. Probably sediments of this age were identified also in the profile K9-1/1, south-west from the Odra Bank.

The distinguished series is lithologically diversified. In the lower part — studied in four profiles — fine-, medium- and locally coarse-grained sands dominate. Individual gravels of grey crystalline limestones were found in some places. The biggest accumulation of carbonificated fragments occur in the profile OB/1. They form two layers at a depth of 105–137 and 225–245 cm, respectively. Highly calcareous clay balls up to 3 cm in diameter occur at the bottom of the layer.

Sediments are stratified. Gentle laminas are most often underlined by accumulations of heavy minerals, coarser sand grains or carbonated floral detritus (profile OB/1). Lamination is parallel, most often diagonal or horizontal. Sediments do not display any lamination only along short segments.

Grain size composition of the described sediments of the lower layer part is characterized by a relatively narrow interval of mean grain size (Mz) — from 0.5 to 0.125 mm (1–3 φ). Sediments are predominantly well and moderately well sorted — values of standard deviation (σ_1) range from 0.35 to 0.7, exceptionally from 0.2 to about 1. Sands consist of grain populations transported *via* rolling, dragging, saltation, and grains deposited from graded suspension.

The upper part of the layer — studied in the profile OB/1 and in several shallow profiles — is composed of fine- and very fine-grained sands with silty sand interbeds. Sediment colour is grey-green. Two fractions dominate grain size composition i.e. 0.25–0.125 and 0.125–0.063 mm, respectively, occurring in varying proportions. Admixtures of silt fraction (0.063–0.004 mm) and even clay fraction (< 0.004 mm) exceed few percentages or more. Grains with diameters 0.5–0.25 mm range from few, rarely several percentages, and sometimes they are not present. Grains coarser than 0.5 mm do not occur — practically only floral detritus accumulates in this diameter range.

In addition to the detritus, weakly organic accumulations or laminas, and occasionally, as in the profile 190-IV, floral remains forming 2–3 cm thick peat mats, occur in the sediments. Fragments of wood, bark, branches, locally reaching up to 40 cm, occur frequently. Sediments are calcareous — contain detrital carbonates determined in the microscopic analyses.

Ten radiocarbon dates were determined for the sediments in seven profiles (Fig. 5). Dispersed organic matter which occurs in the silty-sandy sediments was dated in the profile 77 and samples from upper parts of profiles 11 and 153-IV, respectively. Carbonificated floral detritus aligned in regular laminas was dated in the lower parts of the profiles 11, 153-IV, and in the profiles 192-IV, K9-1/1, and OB/1, respectively. A mat-like interred of decomposed organic remains was dated in the profile 190-IV.

Six dates have finite values and range from 21 480±440 to 45 500 [(+5000)(–3200)] years BP. It corresponds to the Interpleniglacial — the period of complicated climatic changes preceding the last advance of the Pleistocene ice sheet. Three infinite dates resulted either from trace amounts of ^{14}C isotope in a sample (profile 77) or from ^{14}C analysis

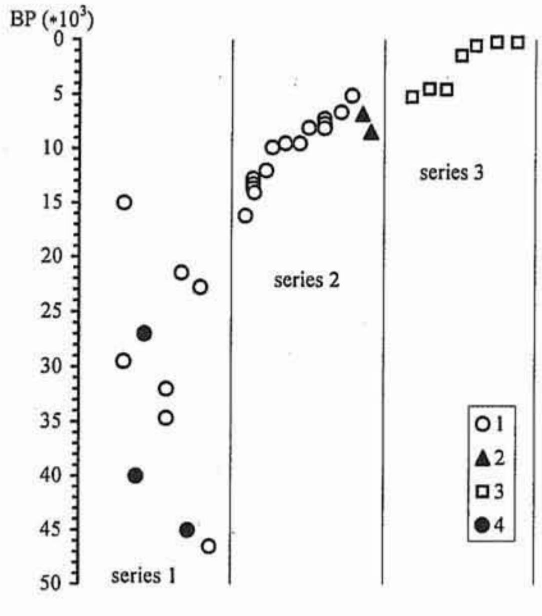

Fig. 4. Time distribution of radiocarbon dates
1 — dates of sediments and organic remains, 2 — dates of carbonaceous sediments, 3 — dates of marine mollusc shells, 4 — infinite dates (beyond the extend of radiocarbon dating)

Rozmieszczenie dat radiowęglowych w skali czasu
1 — daty osadów i szczątków organicznych, 2 — daty osadów węglanowych, 3 — daty muszli mięczaków morskich, 4 — daty nieskończone (poza zasięgiem metody radiowęglowej)

detection limit (profiles 153-IV and K9-1/1). Obtained values correspond though to previous six results.

Dating of samples in the profile OB/1, particularly of a lower sample, deserves special attention. Obtained date of 15 010±150 years BP is on the one hand younger from a date obtained for a sample in the upper layer (29 430±370 BP), on the other corresponds to a cold period, when an ice sheet was present in the Baltic region. It is difficult to determine reasons for this possible date rejuvenation. It is not very probably that this date, or even slightly older one, can be accepted in light of relatively numerous other dates, considering that the profile OB/1 has the same location as the profile 11, for which two dates, similar to age of an upper sample from the profile OB/1, were obtained.

Series 2. Sediments of this series — dated as the Late Glacial and the Early Holocene — are documented in many profiles from an area between the Odra Bank and a shoreline. Degree of sediments recognition is not uniform. Most of profiles are between 1 and 2.5 m deep, and bored only from 10 to 115 cm of marshy-lacustrine sediments. Sediments bottom was reached in three profiles: W-4, R-86 and R-88, where two latter are localized very close to each other, possibly within the same sedimentation basin. Thickness of penetrated sediments reaches 1.6 m in the profile R-88, 2.6 m in the profile R-86, and 10.0 m in the W-4 test hole (Fig. 5). A till was determined in the bottom of all of these cases, while character of a contact between marshy-lacustrine sediments and a till is diversified. In the profile W-4, organic sediments (peat) occur directly, without traces of erosion, on a glacial clayey interred covering a till. Therefore one may suggests, that peat formed on the "dead ice" block. In the profile R-86, grey mud, laminated with brown floral remains locally replaced by peat, occurs on the till surface. Grey clayey mud, laminated with light grey sandy mud with brown floral remains, occurs again above peat. Top of the till in profile R-88 is eroded and accentuated by presence of gravel.

The most complete profile of marshy-lacustrine sediments is known from the W-4 test hole. Despite the core absence from the interval 8.8–6.0 m, this is the longest identified profile in these sediments in the studied region. A lower part of the series, from 10.5 to 8.8 m, represented by the marshy sediments, is composed from clayey mud with a small (maximum upto 18%) admixture of the sandy fraction. Sediments are grey-green with steel-grey sulphide lamination, mainly in the interval between 10.5 and 9.85 m. Above, upto a depth of 9.15 m sulphides occur only in the form of small accumulations, however, a big amount of thread-like algae appears in the sediment, so that the sediment resembles algae mat. Three peat interlayers are present in this profile interval, at depth: 10.50–10.42, 9.80–9.69, and 9.23–9.21 m, respectively. Silts separating peat interlayers are strongly carbonaceous — sediments contain numerous clasts of mudstone with carbonaceous cement. Carbonificated and mineralized organic remains and well preserved fragments of plants also occur here frequently. In an upper part of the profile (from 6.0 to 0.5 m) coarser grains appear more frequently toward the layer top and sediments gradually change from silty sands, through very fine-grained sands, to fine-grained sands. Numerous floral remains occur in the layer bottom, but sediments generally contain organic material only in trace amounts. Sediments are also relatively less carbonaceous than these in the lower part of the profile.

Early Holocene limnic sediments were determined also on the northern slope of the Odra Bank in few, 1 m long probes (profiles PVI-82, PVI-89 and PVI-91) (Fig. 1). In contrast to sediments described above, they are represented by very fine-grained sands with interlayers of whitish carbonaceous mud (lake-marl), locally with fragments of non-decomposed floral remains (Fig. 6). Sea depths in an area of occurrence of these sediments are about 11–12.5 m and sediments occur only several to few tens of centimetres below the sea bottom. Thorough distribution of the sediments is not precisely identified, and their thickness is not known. It may be assumed that, based on distribution of points where these sediments were documented, the latter represent a local, small sedimentation basin.

Radiocarbon age of sediments of the series 2 was studied in 10 profiles, and determined 15 dates for organic carbon fraction and 2 dates for carbonaceous fraction (Fig. 6). In a profile W-4 — where dated organic sediments overlie directly, without traces of erosion, a layer of glacial clay covering a till — a radiocarbon date obtained for the lowest, rich in peat, layer of sediments is 14 060±220 years BP. This value, combined with three other dates representing higher parts of the profile: 13 490±190, 13 350±190, and 13 100±300 years BP, respectively, suggests very early period of conversion to peat-rich sediments, possibly even before melting of the "dead ice" block. The peat layer top, in profile R-86, occur-

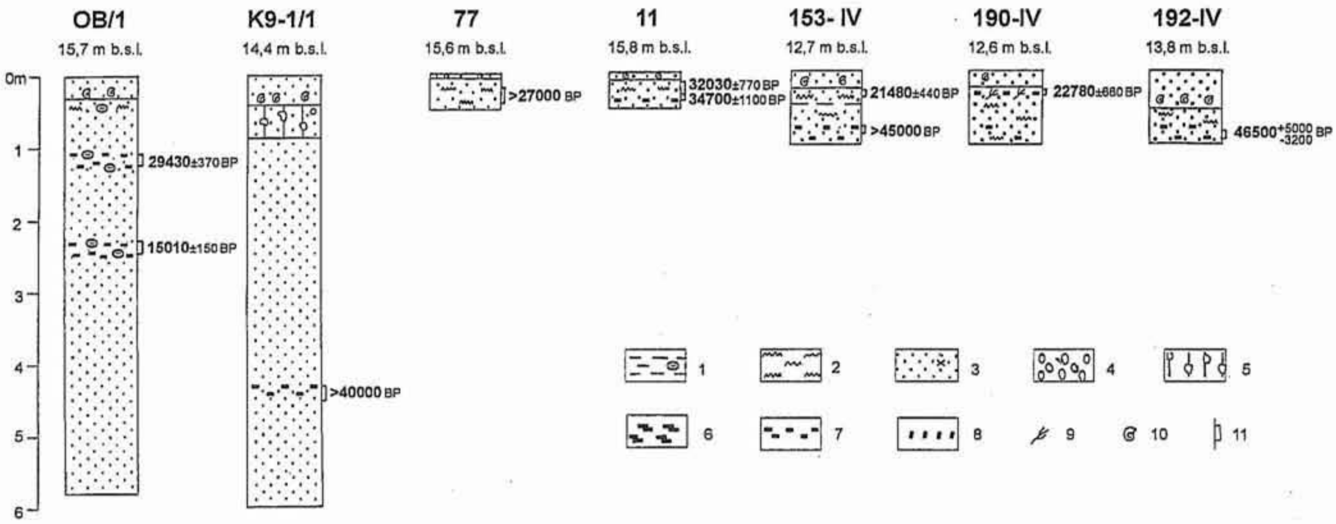

Fig. 5. Lithologic profiles of the series 1 sediments with results of radiocarbon datings
1 — clays, locally clay balls, 2 — silts, 3 — sands, locally with heavy minerals, 4 — gravels, 5 — tills, 6 — peats, 7 — organic matter, 8 — lake marl, 9 — floral remains, 10 — fauna, 11 — samples radiocarbon dated

Profile litologiczne osadów serii 1 z wynikami datowania ^{14}C
1 — iły lub toczeńce iłu, 2 — muły, 3 — piaski, miejscami z udziałem minerałów ciężkich, 4 — żwiry, 5 — gliny, 6 — torfy, 7 — materia organiczna, 8 — kreda jeziorna, 9 — szczątki roślinne, 10 — fauna, 11 — próbki datowane metodą ^{14}C

ring between grey mud interlayers laminated by brown organic matter is dated 12 010±100 years BP. Sediments dated in a borehole R-88 were deposited probably after a short period of erosion of the till surface. Radiocarbon date obtained in this profile for peat-rich mud is 9880±140 years BP. A similar date — 9500±80 years BP — was obtained for the peat layer drilled in the bottom of the profile 51-I. Subsequently younger dates: 8070±240 and 6630±140 years BP, indicating the end of the Boreal Period and beginning of the Atlantic Period, were collected from profiles PIX-2 and PIX-4 located at the base of the southern slope of the Odra Bank. Studied samples represent weakly organic clayey sediments occurring directly beneath marine sand cover. Dates 8090±105–7240±150 years BP were determined for peat-rich silts in the profile R-74, located in the Pomeranian Bay in the vicinity of the current coast-line.

Interlayers of carbonaceous clays (lake-marl) containing locally fragments of non-decomposed floral remains were dated from limnic sediments in the northern slope of the Odra Bank. Dates 8410±120 (profile PVI-89) and 6770±120 years BP (profile PVI-82) were obtained for the carbonaceous interlayers. Floral remains present in the carbonaceous layer were dated additionally in the profile PVI-82. Date 5100±200 years BP was obtained for this sample. Based on these results, it was possible to determine apparent age of the carbonaceous sediments. In the studied case, age of the sample determined based on the $CaCO_3$ is older by about 1600 years in comparison to radiocarbon date of floral remains. Similar value of an apparent age should be considered for a sample from the profile PVI-89.

Date 5100±200 years BP (profile PVI-82) is the youngest one in marshy-lacustrine sediments in the studied area. It corresponds with a period of the Littorina Sea maximum transgression, and it should be assumed that it defines the end of marshy-lacustrine sedimentation in the Odra Bank area.

In addition to numerous datings described, one should also pay attention to two dates obtained for samples from the profile PVI-91. Radiocarbon age for a lower sample — 9500±580 years BP — corresponds well with other dates from this area. Date 16 200±570 years BP obtained for a sample from a higher layer results probably from admixture of an older carbon from older sediment redeposition and does not determine age of the sediment deposition. Dated sample is composed from rhythmically interlayered sands and carbonificated floral detritus.

Series 3. Marine sands form variable in thickness a cover at the bottom. The greatest thickness is associated with submerged, relict bay-bar, which forms an extension of the Odra Bank towards south-east. Border lines of this form are determined by isobaths 12.5–13.0 m (Fig. 1). The bay-bar converts gradually to an abrasion or abrasion-accumulation plain. From the south is limited by a slope, which upper edge is located at a depth of 10 (western part of this form) or 12.5 m (eastern part of the bar). The base of the slope is delimited by isobath 17.5, locally 20 m.

The whole thickness of a layer of sands within the accumulation coast relict has not been penetrated. Numerous borings up to 3 m deep were drilled for heavy minerals documentation and the bottom of the layer was not reached. Only on the southern slope of this form (in the profile 51-I) and at the base of the slope (in the profiles PIX-2, PIX-4 and 95) the bottom of the layer was reached at a depth 18.5–19.0 m b.s.l. It may be concluded that thickness of marine sands associated with submerged bay-bar reaches maximum 10 m. This thickness represents only a southern, near-edge part of this form.

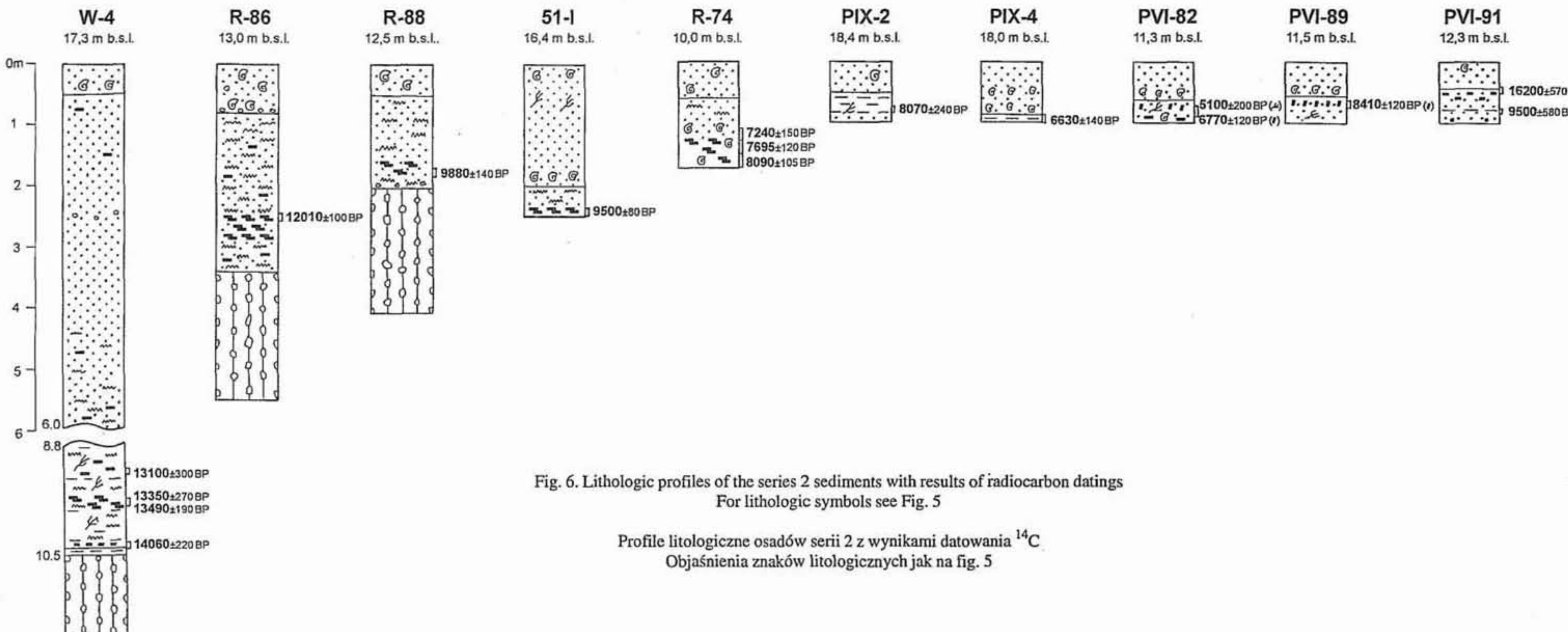

Fig. 6. Lithologic profiles of the series 2 sediments with results of radiocarbon datings
For lithologic symbols see Fig. 5

Profile litologiczne osadów serii 2 z wynikami datowania ^{14}C
Objaśnienia znaków litologicznych jak na fig. 5

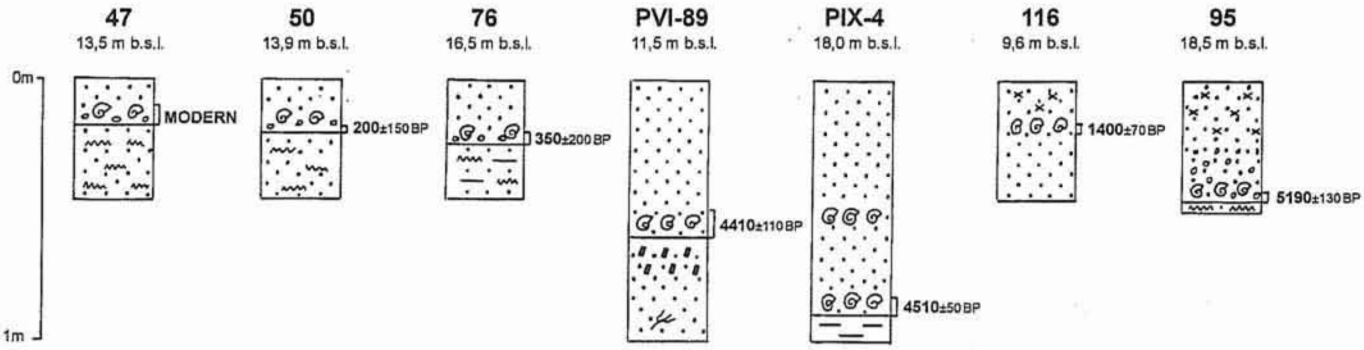

Fig. 7. Lithologic profiles of the series 3 sediments with results of radiocarbon datings
For lithologic symbols see Fig. 5

Profile litologiczne osadów serii 3 z wynikami datowania ^{14}C
Objaśnienia znaków litologicznych jak na fig. 5

Accumulations of heavy minerals and outwash-type shell layers are characteristic features of the sandy cover of the Odra Bank. Shell layers are typical in profiles where considerable accumulations of heavy minerals do not occur, or they mark a lower boundary of larger, macroscopically identifiable accumulations of heavy minerals. Shell outwash forms are represented mainly by *Cardium glaucum* and only individual shells of *Macoma baltica. Cardium* shells are predominantly well preserved, characterized by strong structure, distinct ornamentation, and dimensions reaching 1 cm. Shell layers occur occasionally few times in the same profile, however, the most distinct and widespread is a layer at a depth of about 20 to 25 cm beneath the bottom.

Outside the relict bay-bar, the marine sand cover has a very limited thickness, rarely exceeding 1 m. Minimum thickness, determined in numerous profiles in the northern part of the area, is only 20 cm. An erosional layer consisting of coarse-grained sand, often with admixture gravel grains and a large amount of broken and whole mollusc shells, mainly *Cardium glaucum*, more rarely *C. edule*, *Macoma baltica* and *Mya truncata* and snail *Hydrobia* sp.

Marine sediments in the Odra Bank region are characterized by their exceptional grain size composition uniformity and a high degree of mineralogical sorting. These features distinguish them from sands of other origin which occur at the base of marine cover. Marine sediments are represented almost entirely by fine-grained sands with a large (up to 70%) majority of 0.25–0.125 mm fraction. Fractions 0.5–0.25 and 0.125–0.063 mm occur in amounts between few to more than 10%. Other fractions occur in amounts less than 1%. This grain size distribution, with one fraction dominant, determines good, locally very good or relatively good degree of sorting of marine sands in the Odra Bank region.

A high degree of mineralogical selection of these sands, which distinguish them from sands of different origin, is manifested by absence of weak, not resistant to transport related degradation, components. These sediments are typically depleted from carbonates and sedimentary rock clasts. They contain instead elevated amounts of heavy minerals, which occasionally form accumulations. These accumulations are associated with an edge of the submerged bar-bay, particularly in the westernmost part of the bar above the isobath 10 m (R. Kramarska, 1993*b*)

Marine mollusc shells, separated from erosional layers of the bottom part of a marine sandy cover or from shell outwash forms occurring within this cover, were radiocarbon dated. Age of shells was determined in seven profiles (Fig. 7). The oldest date 5190±130 years BP was determined for a shell in a sample from the profile 95, located at the base of the relict bay-bar. Shell horizon occurs at the bottom of marine sediments, at a depth of about 50 cm beneath the bottom. This layer is composed mainly from a mollusc (*Mytilus edulis*), which broken in considerable degree shells give sediments violet colouring. In addition of mollusc (*Mytilus edulis*), shells of other molluscs (*Cardium glaucum* and *Macoma baltica*) and snail *Hydrobia ulvae* are also present.

The profile PIX-4 is similarly located and representing analogous geologic setting, and radiocarbon date of a similar shell sample is 4510±50 years BP. Marine mollusc shells within the erosional layer covering limnic sediments, in the profile PVI-89, at a landward site of the relict bay-bar, have also a similar age of 4410±110 years BP.

Next date was obtained for the shell outwash consisting mainly of *Cardium* shells in the core 116. It was collected in one of shallower areas of the Odra Bank, where sea depth is 9.2 m. Shell layer occurs 0.15–0.20 cm beneath the bottom and separates sands enriched in heavy minerals upto 4.2% (at the top) from sands without considerable concentrations, occurring below the shell outwash. Shells are accompanied by slightly coarser sand and individual gravel grains. Radiocarbon date obtained for this layer: 1400±70 years BP, represents an episode of intensive dynamic sea activity and determines beginning of formation heavy mineral accumulations, at least in the studied area.

Dates of shells from the erosional layer separating continental Interpleniglacial sediments from marine sands on the northern slope of the Odra Bank (profiles 47, 50 and 76) are more recent (younger than a thousand years). They document next, recent stage of the area development and associated periodical storms, during which interstadial sediments occurring at a shallow depth below the bottom are eroded.

DISCUSSION AND COMMENTS

The best recognized period of development of geologic structure in the Odra Bank area, based on radiocarbon dating, includes younger part of the Vistulian Glaciation period (Interpleniglacial, Upper Pleniglacial, Late Glacial) and the Holocene, which is a period from about 58 000 years BP (J. E. Mojski, 1997).

Changes of climatic conditions, in the result of which the Scandinavian ice sheet disappeared almost entirely, initiated beginning of this period. Climatic warming lasted about 25 000 years and was characterized by fluctuations — at least two short warmer periods separated by a longer cooler period are determined. This time is documented by numerous observations in Europe, which suggests that both warming periods can be interpreted as interstadials (J. E. Mojski, 1993). In Poland this period of changes in climatic conditions corresponds with the Interpleniglacial (Grudziądz Interstadial).

During the interstadial, when a small glacier ice cover existed only in the northern part of Scandinavia, depression in the Baltic area was occupied by the Baltic Lake (E. Lagerlund, 1987). Lake waters filled the Gdańsk Basin, Słupsk Trough, and Bornholm Basin. Some opinions state that the lake had two saline phases with cool Boreal and Arctic fauna and spread out onto areas of the Lower Vistula region and the Elbląg Elevation (A. Makowska, 1986). Marine transgressions during this period are known from southwestern Norway (B. G. Andersen *et al.*, 1981). Shallow water area of the current Baltic Sea was, however, a land extending up to Scania and the Danish Straights. The Odra Bank — a part of this land — was an area of aquatic accumulation, probably fluvial. Fine- and medium-grained sands (transported in graded suspension and *via* saltation, dragging, and rolling) formed series of few to more than 10 m thickness and characteristic sedimentary structure — horizontal parallel lamination, locally displaying weakly cross-bedding. Other types of sediments which formed at that time, were fine- and very fine-grained sands with weakly organic silty laminas, locally with clay balls, carbonificated floral detritus and wood fragments. Sediments — excluding one location with ostracods and one more with mixed fresh water and marine fauna — do not contain fossils. They neither contain diatomic flora. It seams that they may represent sediments of alluvial flats or meandering false channels. Weakly-organic sediments and carbonificated organic remains were dated using radiocarbon method in few locations. Values determined include interval from 46 500[(+5000)(–3200)] to 21 480±440 years BP. Not all dates have finite values and one of them is questionable (profile OB/1). This comment indicates purposefulness of further studies of sediments in the Odra Bank area, particularly considering the fact that degree of recognition is not sufficient to present palaeogeography of the study area during the Grudziądz Interstadial. Additional difficulty in the final determination of sediments stratigraphy is the fact that it was not possible to determine sediment sequence in a vertical profile. The whole thickness of sediments categorized within the Grudziądz Interstadial was not drilled in the Odra Bank region, and these sediments occur in a considerable area only under a thin, few centimetre thick, layer of recent marine sands. The profile K9-1/1 is an exception, where they are covered by a till, however, here additional radiocarbon datings are needed because of the infinite value obtained in this study. The closest location of similar lithologically sediments of the same age, but covered by Younger Pleistocene sediments, are known from the Gardno–Łeba Lowland (K. Rotnicki, R. K. Borówka, 1994), and also from the Szczecin Lowland (M. Kurzawa, 1993).

The next stage of development — about 20 000 years ago until the Oldest Dryas — associated with ice sheet advance into an area of the southern Baltic, which included also an area of the Odra Bank. Locally preserved till of a small thickness, rarely exceeding 5 m, remained from this cold period.

The last deglaciation of the southern Baltic started from ice sheet retreat from a line delimited by the Gardno moraines. Then, in the Oldest Dryas, about 14 000 years ago, the ice sheet margin was located to the north from Kołobrzeg and the Odra Bank (S. Uścinowicz, 1995). In the Bornholm Basin, at a sea depth of 52 m, a marginal zone was identified and dated 16 300±2400 years using termoluminescence method (R. Kramarska, Z. Jurowska, 1991). Further to the west, the ice sheet margin went through Scania marking the maximum extent of the Halland-West-Skåne phase (E. Lagerlund, M. Houmark-Nielsen, 1993). The Pomeranian Bay and the area of Odra Bank were released from glacier ice the earliest in the southern Baltic. Deglaciation was areal with important role of dissecting of the marginal glacier zone by meltwaters. Subsequently, blocks of "dead ice" formed, and marshes and enrichment in peat started about 14 000 years ago. It is well documented in the boring profile W-4. Marshy sediments with peat formed also in Bölling (profile R-86) and more commonly — at least at this stage of recognition of this area — in the Preboreal and Boreal periods (profiles R-88, 51-I and R-74). In time, marshes transform into local lakes. They were though shallow basins with still deposition of silty sediments, locally silty-sandy or silty-clayey. Development of these lakes lasted until the Atlantic Period in the Holocene. At that time land part of the Pomeranian Bay was drained by the Pra-Odra, which as is postulated (B. Rosa, 1967), was drained into the Arkona Basin.

Land period of development in this area ended only slightly more than 5000 years ago. Until then, sedimentation under continental conditions survived on the northern slopes of the shoal, in local basins with carbonaceous sediments (profiles PVI-82, PVI-89 and PVI-91). The youngest radiocarbon date obtained from organic remains present in these sediments is 5100±200 years BP. It is possible, however, that even earlier, about 7000 years ago, marine conditions influenced the

Pomeranian Bay area. In some profiles (profiles R-74 and R-88) a mixed, fresh water and marine fauna appeared (R. Kramarska, 1995*a*). Possibly, already at that time, a lagoon existed here, separated by the barrier of Odra Bank from marine Littorina Sea basin. Nevertheless, intermediate phase with brackish conditions occurred.

Date of 5100 years BP obtained for fresh water sediments corresponds with date of 5190±130 years BP (profile 95), which is the oldest data obtained for marine shells and documents Littorina Sea transgression in the Odra Bank area. This period of the area development is characterized by erosional process significantly dominating over accumulation. Erosional surfaces commonly present at the top of older sediments document these processes. This erosional surface is commonly covered by abrasion pavement consisting of coarser, than in upper profile parts, sand grains with admixture of gravel grains and accumulations of shells and their fragments. Erosional processes in some locations lasted yet till beginning of the Subboreal Period, which is documented in the layer with dated shells in profiles PVI-89 and PIX-4. A sand cover consisting mainly of fine-grained sands started to form with increase of sea level and transgression progress. The Odra Bank yet remains for a longer time a bay-bar barrier separating transgressive sea from the lagoon, which existed between the shoal and a current coast-line. This lagoon also included the Szczecin Lagoon at the end of the Atlantic Period (A. Majewski, 1980).

From the Subboreal Period, when sea reached a level similar to the present-day one, substantial processes which modified the bottom morphology ended, and only the surface modelling continues. Insignificant fluctuations of sea level or maybe catastrophic storm surges leave shell horizons of the outwash type in sediments. Intensified sea activity was noted about 1400 years ago through forming of a shell horizon in shallow areas of the Odra Bank (profile 116). It corresponds with the Baltic "Subatlantic transgression" dated along the Polish coast for about 1500 years ago. Predominance of abrasion processes on the northern bank slope has lasted also till a present-day period and is documented in radiocarbon dating of shells in erosional layers of the profiles 47, 50 and 76.

Sands of Post-Littorina Sea — influenced by frequent redeposition caused by waves and currents — reach a high degree of selection of grain and mineral-petrographic composition. In process of selective introduction of a specific grain size into motion, components not resistant to mechanical destruction are eliminated from sediments. This process leads subsequently to formation of heavy minerals accumulations. These accumulations within the old bay-bar coast-line in the Odra Bank belong to the richest in the southern Baltic Sea.

Translated by Marek Matyjasik

REFERENCES

ANDERSEN B. G., NYDAL R., WANGEN O. P., OSTMO S. R. (1981) — Weichselian before 15 000 years B.P. at Jaeren-Karmöy in south-western Norway. Boreas, **10**, p. 297–314, no. 4.

JUROWSKA Z., KOTLIŃSKI R. (1976) — Lithological characteristic of the surface deposits of Ławica Odrzana (in Polish with English summary). Kwart. Geol., **20**, p. 675–682, no. 3.

JUROWSKA Z., KRAMARSKA R. (1990) — Mapa geologiczna dna Bałtyku w skali 1:200 000, arkusz Dziwnów, Szczecin. Państw. Inst. Geol. Warszawa.

KOLP O. (1990) — The Ancylus Lake Phase of the Post-Glacial evolution of the Baltic Sea. Quest. Geogr., **13/14**, p. 69–86. UAM. Poznań.

KRAMARSKA R. (1993*a*) — Odra Bank — new geological data. The Baltic. Third Marine Geological Conference. Abstract of Papers, Sopot, p. 76.

KRAMARSKA R. (1993*b*) — Poszukiwanie i rozpoznawanie złóż minerałów ciężkich w rejonie Ławicy Odrzanej — opracowanie i ocena wyników fazy 1 i 2. PRCiP Gdańsk. Centr. Arch. Geol. Państw. Inst. Geol. Warszawa–Sopot.

KRAMARSKA R. (1994) — Syntetyczny profil stratygraficzny rejonu Ławicy Odrzanej. Mat. Konf. "Geologia i geomorfologia Pobrzeża i południowego Bałtyku", p. 35–36. WSP. Słupsk.

KRAMARSKA R. (1995*a*) — Quaternary geological profiles (I). Pl. XVII. In: Geological Atlas of the Southern Baltic (ed. J. E. Mojski). Państw. Inst. Geol. Warszawa– Sopot.

KRAMARSKA R. (1995*b*) — Korelacja litologiczna i stratygraficzna osadów czwartorzędowych w rejonie Ławicy Odrzanej. Centr. Arch. Geol. Państw. Inst. Geol. Warszawa–Sopot.

KRAMARSKA R., JUROWSKA Z. (1991) — Objaśnienia do Mapy geologicznej dna Bałtyku w skali 1:200 000, arkusz Dziwnów, Szczecin. Państw. Inst. Geol. Warszawa.

KURZAWA M. (1993) — Objaśnienia do Szczegółowej mapy geologicznej Polski w skali 1:50 000, arkusz Żelisławiec. Państ. Inst. Geol. Warszawa.

LAGERLUND E. (1987) — An alternative Weichselian glaciation model, with special reference to the glacial history of Skåne, South Sweden. Boreas, **16**, p. 433–459.

LAGERLUND E., HOUMARK-NIELSEN M. (1993) — Timing and pattern of the last deglaciation in the Kattegat region, southwest Skandinavia. Boreas, **22**, p. 337–347.

MAJEWSKI A. ed. (1980) — Zalew Szczeciński. IMiGW. Wyd. Komunikacji i Łączności. Warszawa.

MAKOWSKA A. (1986) — Pleistocene seas in Poland — sediments, age and palaeogeography (in Polish with English summary). Pr. Inst. Geol., **120**.

MOJSKI J. E. (1993) — Europa w plejstocenie; ewolucja środowiska przyrodniczego. Wyd. PAE. Warszawa.

MOJSKI J. E. ed. (1995) — Geological Atlas of the Southern Baltic 1:500 000. Państw. Inst. Geol. Warszawa.

MOJSKI J. E. (1997) — Small stratigraphic units of Vistulian in the Southern Baltic area. The Late Pleistocene in eastern Europe: Stratigraphy, paleoenvironment and climate. Abstract Volume and Excursion Guide of the INQUA–SEQS Symposium, p. 39–40. Vilnius.

ROSA B. (1967) — Analiza morfologiczna dna południowego Bałtyku. UMK. Toruń.

ROTNICKI K., BORÓWKA R. K. (1994) — Stratigraphy, paleogeography and dating of the North Polish Stage in the Gardno–Łeba coastal plain. Guide–Book of the Symposium on Change of Coastal Zones, p. 84–88. UAM. Poznań.

UŚCINOWICZ S. (1995) — Evolution of the Southern Baltic during the Late Glacial and Holocene. Pl. XXVII. In: Geological Atlas of the Southern Baltic (ed. J. E. Mojski). Państw. Inst. Geol. Warszawa–Sopot.

WAJDA W. (1982) — Ławica Odry w świetle nowych badań geologicznych. Peribalticum II, p. 171–183. GTN Ossolineum. Wrocław.

GENEZA I ROZWÓJ REJONU ŁAWICY ODRZANEJ W ŚWIETLE BUDOWY GEOLOGICZNEJ I DATOWANIA OSADÓW METODĄ RADIOWĘGLA

Streszczenie

W budowie geologicznej czwartorzędu rejonu Ławicy Odrzanej przeważają osady piaszczyste różnej genezy i wieku (fig. 1–3). Trzy serie osadów rozpoznane w licznych profilach wierceń i datowane metodą radiowęgla (tab. 1, fig. 4–7) reprezentują osady interpleniglacjału i późnego glacjału zlodowacenia wisły oraz holocenu.

Seria 1, zbudowana z piasków, miejscami z domieszką mułków, z rozproszoną substancją organiczną i zwęglonymi szczątkami organicznymi, występuje na północnym stoku Ławicy Odrzanej pod cienką pokrywą piasków morskich. Na podstawie datowań metodą radiowęgla seria ta została uznana za osady interpleniglacjalne utworzone prawdopodobnie w środowisku rzecznym. Rozpoznany na obecnym etapie badań tylko strop warstwy — maksymalnie do głębokości 6 m — nie daje podstaw do rozważań paleogeograficznych. Pojedyncze stanowisko z małżoraczkami i brak okrzemek w osadach dodatkowo utrudniają jednoznaczne określenie genezy osadów i środowiska sedymentacji.

Seria 2 złożona z piasków i piasków mulistych, miejscami z torfem lub kredą jeziorną, rozpoznana została między Ławicą Odrzaną a brzegiem morskim i lokalnie na północnym skłonie ławicy (fig. 1, 6). Bagienno-jeziorne osady tej serii wypełniają zagłębienia w powierzchni glin zwałowych. Datowanie radiowęglowe osadów dokumentuje okres tworzenia się torfów i rozwój jezior od późnego glacjału aż do transgresji morza litorynowego w okresie atlantyckim. Szczególne znaczenie dla paleogeografii i historii rozwoju obszaru w tym okresie mają daty 14 060± 220 i 5100±200 lat BP — najstarsza i najmłodsza data radiowęglowa osadów serii 2 (fig. 6). Pierwsza z dat, uzyskana dla najniższej próbki torfów w profilu W-4, świadczy o bardzo wczesnej deglacjacji tej części Bałtyku. Druga wyznacza schyłek lądowego okresu rozwoju Ławicy Odrzanej.

Kolejną **serię 3** budują holoceńskie piaski morskie z licznymi odsypami muszlowymi i lokalnymi koncentracjami minerałów ciężkich (fig. 1, 7). Pokrywa piasków morskich najlepiej rozwinięta jest w najpłytszych rejonach dna. Jest to przede wszystkim Ławica Odrzana oraz jej przedłużenie w kierunku południowo-wschodnim — relikt brzegu mierzejowego. Data radiowęglowa 5190±130 lat BP, uzyskana dla skorupek małżów morskich wyseparowanych ze spągowych partii morskiej pokrywy piaszczystej w profilu 95 (fig. 3, 7), dokumentująca obecność morza u południowych zboczy bariery mierzejowej Ławicy Odrzanej, pozostaje w ścisłym związku z wcześniej wspomnianą datą wyznaczającą schyłek rozwoju jezior na ławicy. Istotne znaczenie mają też współczesne daty (młodsze niż tysiąc lat) muszli z warstwy erozyjnej leżącej w stropie osadów zaliczonych do interpleniglacjału. Dokumentują one współczesny etap rozwoju obszaru odznaczający się ograniczoną akumulacją osadów morskich i erozją płytko zalegających osadów starszych.