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The Vistula Lagoon evolution based on diatom records

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Abstract Five stages of development of the Vistula Lagoon were established based on the diatom flora preserved in 6 sediment cores. The study shows that the area originally had a terrestrial environment, whereas its later evolution is linked with the marine stages of the Baltic Sea. As a result of input of marine waters through the Vistula Spit, which is indirectly connected to Litorina transgressions, the shallow, eutrophic, brackish-water basin originated. In the next stage decrease in water level and salinity are noted. Moreover, symptoms of the Post-Litorina transgression were observed in the diatom record. Finally, the effects of the eutrophication are recorded in subfossil diatom flora. As a consequence of closing of the Nogat River inflow, the stronger influence of marine waters from the Baltic Sea are observed in the lagoon.

Keywords *Vistula Lagoon, paleoecology, Holocene, diatoms.*

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INTRODUCTION

The Vistula Lagoon has been the subject of numerous interdisciplinary studies focused on its post-glacial history (e.g. Brockmann 1954, Wypych & Nieczaj 1975, Uścinowicz & Zachowicz 1996). Other research concentrated on biostratigraphical methods, and the results obtained allowed to reconstruct the origin and development of the basin after its deglaciation (e.g. Przybyłowska-Lange 1974, Zachowicz 1985, Bogaczewicz-Adamczak & Miotk 1985).

The subsequent drillings in the lagoon and the Vistula Spit area were the subject of various analyses including granulometry, geochemistry, mineralogy of clay minerals, macro- and microfauna, palynology and radiocarbon datings. As a result several facies of the Late Pleistocene and Holocene sediments were distinguished (Zachowicz & Uścinowicz 1997). In addition, the diatom analyses of some sediment cores were completed (Witak et al. 2005, Jankowska et al. 2005). Based on the diatom spectra, the relative abundance of individual species and ecological groups, diatom assemblage zones were defined in each core. The research results supported by the lithological descriptions and ^{14}C dates allowed to characterise detailed environmental changes in different part of the Vistula Lagoon in the Middle and Late Holocene.

The present paper is an attempt to correlate results of the previous diatom studies. The best diatom records of 6 sediment cores are discussed here. The location of sampling sites give a good opportunity for investigating of changes of environmental conditions in the northern, central and the southern part of the Vistula Lagoon. In order to describe the changes in the environmental status, only those diatom taxa, which are good indicators of them, were chosen. Moreover, the distribution of halobian groups showed the salinity fluctuation in the lagoon was present. Therefore, using the diatom data and combining these results, we aim to improve the understanding of the Vistula Lagoon evolution in the Holocene.

MATERIAL AND METHODS

The material studied consists of six meters long sediment cores taken from the Vistula Lagoon area (Fig. 1). Piston cores were obtained in 1994 by the Polish Geological Institute, Branch of Marine Geology, Gdańsk.

Cores ZW 8 and ZW 12 were collected near the Vistula Spit at the water depths of 2.1 m and 2.3 m respectively, whereas boreholes ZW 10 and ZW 14 were drilled at the southern coast of the lagoon at the water depths of 1.8 m and 2.5 m. Cores ZW 4 and ZW 11 were taken in the central part of the basin at the water depth 2.7 and 3.4 m, respectively. The lithology of the cores is described in detail in Table 1.

For diatom analyses the cores were subdivided according to their lithology. Each lithological unit was sliced into 10–20 cm sections. Subsequently, samples were taken for diatom analysis according to Battarbee's (1986) method. Sediments were treated with 10% HCl in order to remove calcium carbonate, washed several times with distilled water and boiled in 30% H_2O_2. Finally, the samples were washed several times with distilled water. Permanent microscope slides were made using Naphrax ®. The diatom analyses were performed by means of a BIOLAR microscope using oil immersion 100x objectives.

In each sample at least 500 valves were counted in order to estimate percentage abundance of individual taxa. Identification was based on the works by Krammer & Lange-Bertalot (1986, 1988, 1991a, 1991b), Pankow (1990), Witkowski et al. (2000). Diatoms were divided into groups according to their salinity requirements based on the halobian system by Kolbe (1927). The diatom flora was divided into euhalobous, mesohalobous and oligohalobous taxa, these last being subdivided into halophilous, indifferent and halophobous ones. Additionally, in the diatom flora planktonic and benthic groups were distinguished (Round 1981). Ecological information was obtained from the literature (Krammer & Lange-Bertalot 1986, 1988, 1991a, 1991b; Denys 1991; Witkowski 1994). The content (in percentage) of halobian and habitat groups was counted in all cores.

RESULTS AND DISCUSSION

The diatom analyses of six sediment cores indicate that development of the Vistula Lagoon took place under changing environmental conditions. Based on the species composition, the relative abundance of the predominant taxa, salinity and habitat groups five stages can be distinguished in evolution of the basin (Figs. 2, 3, and 4). Moreover, the distribution of main taxa preserved in three cores located in different parts of the Vistula Lagoon is presented (Figs. 5a, 5b, and 5c).

I. Terrestrial stage. The oldest sediments studied in the Vistula Lagoon were found in the lower part of the cores ZW 4, ZW 10 and ZW 14. They are represented by fine-grained sands with an admixture of organic mud including plant remnants and peat layers. According to Zachowicz & Uścinowicz (1997) these sediments originated from various environments and represent Early Holocene riverine, lacustrine

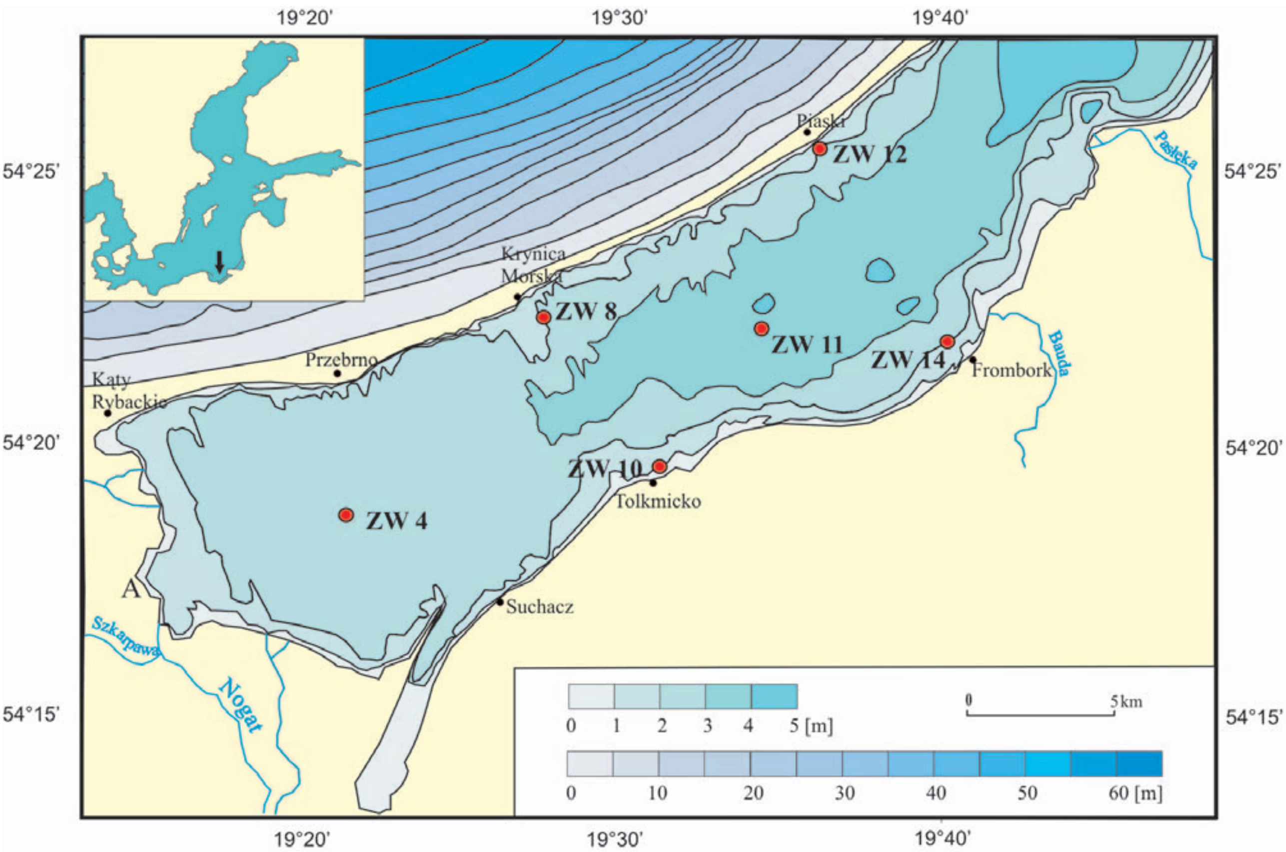

Fig. 1. Location of the sites cored in the Vistula Lagoon.

Table 1. Lithological description of cores (after Zachowicz et al. 1995)

Core	Depth (cm)	Lithology
ZW 4	0 – 230	silty mud
	230 – 565	silty mud with fragments of freshwater mollusc shells, at the depth 360-370, 380-390, 480-490 cm accumulation of shells
	565 – 597	muddy sand
	597 – 600	fine sand
ZW 8	0 – 6	Mud
	6 – 229	fine and medium sand, fragments of mollusc shells
	229 – 300	fine and medium sand, HCl+
	300 – 353	fine and medium sand, mollusc shell
	353 – 383	fine and medium sand, HCl+, fragments of shells
	383 – 408	medium and fine sand, at horizon 386 cm single grain of gravel
	408 – 600	medium and coarse sand, at horizon 494 cm single grain of gravel, mollusc shells
ZW 10	0 – 43	Mud
	43 – 209	mud with sandy interbeddings, HCL+, in the lower part shells of freshwater molluscs
	209 – 308	fine sand, at the bottom very fine sand, HCl+
	308 – 330	silt and sandy silt, HCl+, plant remains
	330 – 388	fine sand and muddy sand, in the lower part sandy silt, plant remains
	388 – 396	fine sand, HCl+, with irregular interbeddings of organic mud
	396 – 535	organic mud, laminated, with interbeddings of pat, sandy mud and fine sand HCL+, at horizons 409 – 422 cm, 437 – 442 cm and 490 – 500 cm peat
	535 – 595	fine sand with mud admixture, HCl+, plant remains
ZW 11	0 – 284	silty mud, at the depth: 32, 208, 228-230 cm single crumbs of shells
	284 – 600	silty mud, at the depth: 315-325, 356-362, 390-395 cm shells remnants and gastropods shells
ZW 12	0 – 83	silty mud
	83 – 130	fine sand
	130 – 355	medium sand, shells of freshwater molluscs
	355 – 403	mud, numerous shells of freshwater gastropods, at the depth 300 – 355 cm fragments of shells
	403 - 630	fine sand, in the lower part single shells of freshwater gastropods
ZW 14	0 – 260	sandy mud, with admixture of fine sands, numerous shells of freshwater molluscs
	260 – 360	irregular interbeddings of muddy sand, laminated and organic mud, numerous shells of freshwater molluscs
	360 – 597	irregular interbeddings of peat, organic mud, sand and sandy silt HCl +, at the depth 360 – 269 cm and 500 – 508 cm peat
	597 – 600	fine sand, HCl +

and swamp facies. Pollen data indicated that the terrestrial stage lasted at least up to the Early Atlantic chronozone (Zachowicz 1985). However, radiocarbon dating of peat layers taken from the southern part of the lagoon showed that land existed until the Middle Atlantic chronozone (Witak et al. 2005). According to Bogaczewicz-Adamczak & Miotk (1985) this area was at that time covered by mixed forests including elm, tilia and oak. The sediments studied were barren and did not contain diatoms. Nevertheless, the earlier diatom results showed the presence of rare freshwater, benthic diatoms in the Early Atlantic sediments of the core retrieved in the Frombork area (Bogaczewicz-Adamczak & Miotk 1985), which could be indicators of a small, shallow lake.

II. The Litorina transgression. The deposits formed during the second stage of basin development were found in all cores. Their thickness changed from ca. 4.0 m in the north and in the central part to ca. 1 m in the southern part of the lagoon. They are represented by fine and medium-grained sands in the vicinity of the Vistula Spit and by fine-grained sands in the south, whereas muddy sediments dominated in the central part. These deposits are very rich in freshwater mollusc shells and detritus.

Generally, the diatom flora of this section was abundant and well preserved, although an admixture of mechanically broken valves and detritus were noted in the cores taken from the Vistula Spit neighbourhood. In the lower part of these cores two layers were found to be barren. Additionally, in the bottom part of cores located in the central lagoon (ZW 4 and ZW 11) diatom flora is not preserved.

The species composition of this assemblage was strongly dominated by oligohalobous indifferent diatoms mainly represented by *Fragilaria* (sensu lato) spp.

Amongst them, F. *brevistriata* (syn. *Pseudostaurosira brevistriata*), *F. construens* (syn. *Staurosira construens*), *F. martyi* and *F. pinnata* (syn. *Staurosirella pinnata*) were the most abundant. Besides, *F. inflata* var. *istvanffyi* and *F. heidenii* were recorded here. These benthic euryhaline species occur in freshwater and brackish-water basins with alkaline meso- and eutrophic waters and high contents of oxygen (Denys 1991, Krammer & Lange-Bertalot 1991a). Moreover, freshwater diatoms belonging to genera *Amphora* (*A. copulata, A. inariensis, A. pediculus*) were noted, particularly often in the northern part of the lagoon (ZW 8 and ZW 12). These diatoms belong to euryhaline epiphytes and prefer alkaline waters rich in dissolved oxygen and nutrients (Denys 1991). A similar diatom assemblage including *Amphora* spp., and *Fragilaria* spp. was identified in the shallow littoral zone of the Litorina Sea in the Seagull Reef (Witak 2002). Besides, the same species were noted near Frombork by Bogaczewicz-Adamczak & Miotk 1985 and Przybyłowska-Lange 1974. The presence such a diatom flora in sediments indicates the existence of shallow brackish-water nutrient-rich basin. According to Zachowicz (1985), the origin of the Vistula Lagoon is indirectly connected to the Litorina Sea transgression. Eustatic sea level rise linked with climatic amelioration in the Atlantic chronozone caused the ground-water level rise and the basin was formed. Additionally, during the successive Litorina transgressions inflows of marine waters into lagoon appeared through the Vistula Spit, which was being formed at that time.

The first inflows of marine waters onto the existing land are recorded in the northern part of the recent lagoon. This phenomenon could have changed the environmental conditions locally and caused the increase of salinity in the neighbourhood of the Vistula Spit in a short time. This suggestion is indicated by the presence of euhalobous and mesohalobous diatoms in the lower part of the cores ZW 8 and ZW 12. Amongst the marine flora *Diploneis smithii* var. *smithii*, *Fallacia forcipata* and *Nitzschia compressa* var. *compressa* were observed occasionally. The former species is common in the diatom assemblages preserved in the shallow water Litorina sediments of the Hel Peninsula (Bogaczewicz-Adamczak & Żukowska 1990), in Puck Bay (Witkowski 1994, Witak 2002) and in the Gdańsk Deep (Pieczka & Zaborowska 1989). *F. forcipata* and *N. compressa* are common in the sediments of the same age in Gulf of Gdańsk (Witkowski 1994). The brackish water flora occurred frequently and was

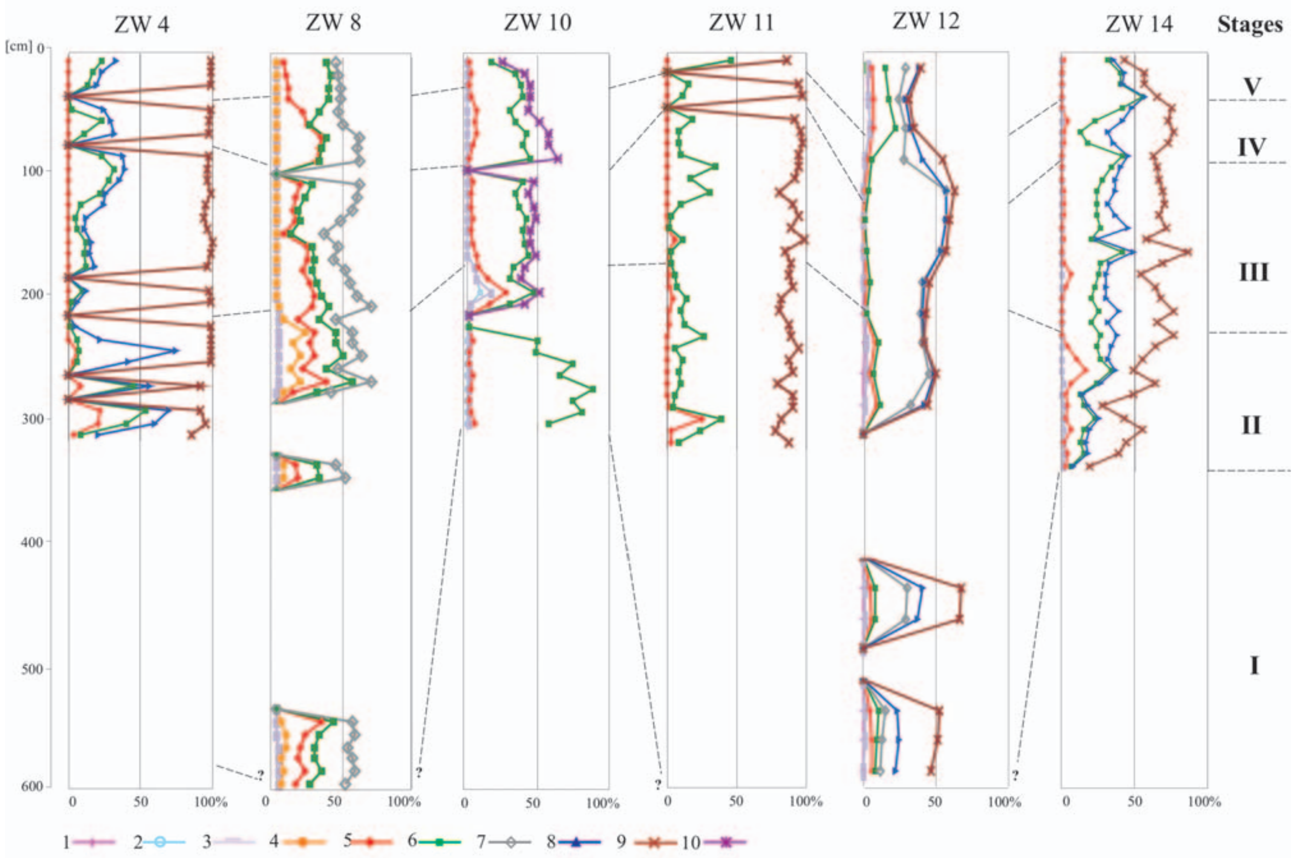

Fig. 2. Distribution of chosen taxa in cores; euhalobous: 1 – *Diploneis smithii* var. *smithii*; 2 – *Fallacia forcipata*; mesohalobous: 3 – *Campylodiscus* spp. 4 – *Opephora guenter-grassii*; oligohalobous halophilous: 5 – *Actinocyclus normanii* fo. *subsalsa*; oligohalobous indifferent: 6 – *Fragilaria* (sensu lato) spp., 7 – *Amphora* spp., 8 – *Stephanodiscus* spp., 9 – *Aulacoseira* spp., 10 – *Cyclotella atomus.*

represented mostly by *Opephora guenter-grassii*. This epipsammic form is one of the main components of littoral assemblage in Litorina sediments in the Puck Bay (Witak 2002) and the Gulf of Gdańsk (Witkowski 1994, Witak 2000). Besides, in the northern and southern part of the lagoon characteristic taxa of the Litorina stage C*ampylodiscus clypeus* and *C. echeneis* were noted. According to Alhonen (1971), mass occurrences of these taxa in the marine littoral zone are associated with the salinity rise in the initial Litorina stage (the so-called clypeus lagoons). *Campylodiscus* spp. was encountered in the Litorina Sea sediments in Vistula Lagoon (Przybyłowska-Lange 1974, Bogaczewicz-Adamczak and Miotk 1985), in the Gdańsk Basin (Pieczka & Zaborowska 1989) and in the Gulf of Gdańsk (Witkowski 1994).

The temporary contact with saline waters is also shown by the occurrence of oligohalobous halophilous form, *Actinocyclus normanii* fo. *subsalsa*. This taxon belongs to the euryhaline plankton forms occurring in marine littoral zones, estuaries and inland waters rich in nutrients with high conductivity (Denys 1991, Krammer & Lange-Bertalot 1991a). It was reported as an indicator of Litorina transgressions recorded in lagoonary facies (Witak et al. 2005).

Mass diatom occurrence in all studied cores was noted at the depth of ca. 300 cm b.s.l., which means that the next marine water inflow reached the southern part of the lagoon. The maximum content of euhalobous in ZW 10, mesohalobous in ZW 8 and ZW 12 and oligohalobous halophilous in ZW 4, ZW 11 and ZW 14 might indicate the maximum salinity of the Vistula Lagoon. Results of pollen data (Zachowicz 1985) supported by radiocarbon dating (Witak et al. 2005) indicate that this phenomenon corresponds to the Late Atlantic – Early Subboreal chronozone. Stratigraphic position of these sediments suggests that the basin expanded southwards due to the rising sea level during maximum the Litorina transgression named by some authors as the Litorina III phase (Gudelis 1997). Analogous effects were registered at many sites in the coastal zone of the Southern Baltic Sea at that time. Marine waters influx dated 6.0-5.0 ^{14}C ka BP was recorded in diatom taphocenoses of numerous coastal lakes of the middle part of Polish coast (e.g. Miotk & Bogaczewicz-Adamczak 1986), in the Szczecin Lagoon (Borówka et al. 2005), in the Puck Bay (Witak 2002), and also in Jastarnia in the Hel Peninsula (Bogaczewicz-Adamczak, 1982).

III. Slightly brackish-water/ freshwater lagoon. The diatom flora of the third stage of the lagoon evolution corresponds to sediments occurring at the depths between ca 220-200 cm and ca. 100–70 cm b.s.l. Deposits are represented by fine-grained sands in the northern part of the basin and by silty mud in the central and the southern part of it. Witak et al. (2005) discussed that these sediments were deposited in the Subboreal chronozone. This suggestion is supported by the previous biostratigraphical studies in this area (Przybyłowska-Lange 1974, Bogaczewicz-Adamczak & Miotk 1985).

The diatom assemblage of the stage was abundant and well preserved, however, an admixture of broken frustules was present. The flora is characterised by decrease of the content of diatoms preferring

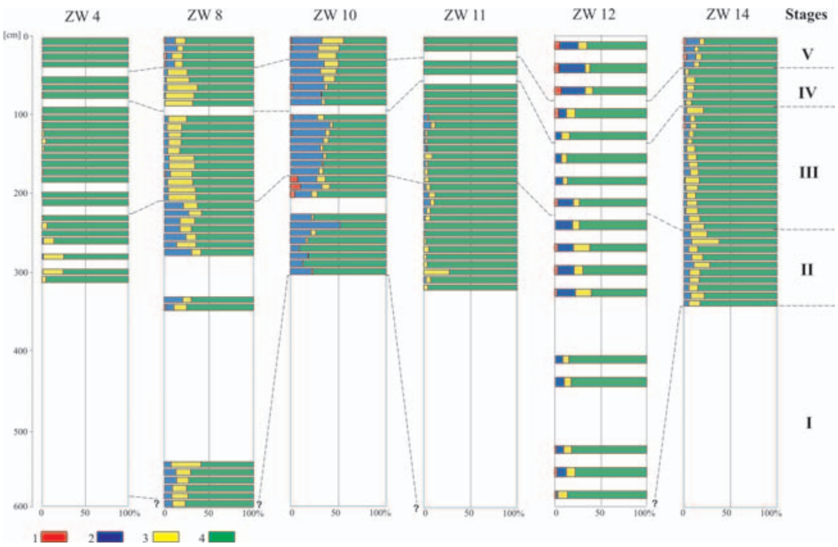

Fig. 3. Distribution of halobian groups: 1 – euhalobous, 2 – mesohalobous, 3 – oligohalobous halophilous, 4 – oligohalobous indifferent.

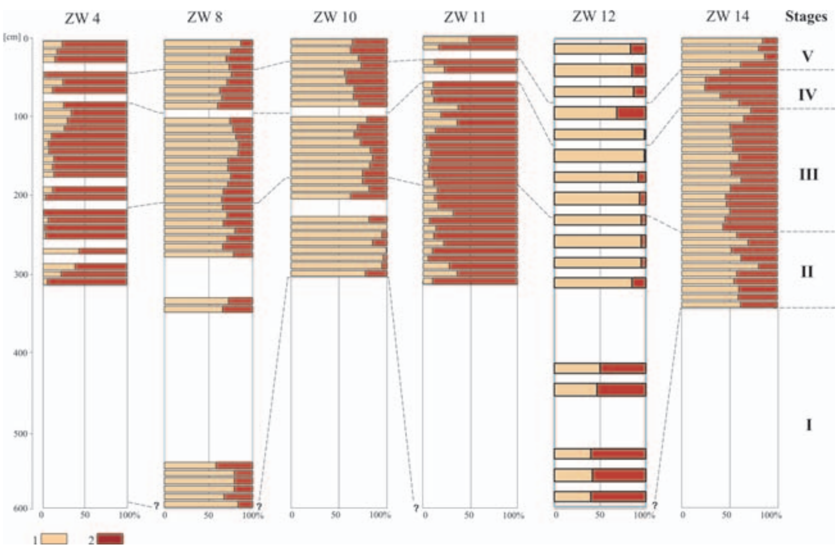

Fig. 4. Distribution of habitat groups: 1- benthos, 2 – plankton.

saline habitats, which are replaced by freshwater taxa. As a result in cores taken from the central part of the lagoon (ZW 4 and ZW 11) almost all diatoms belonged to oligohalobous indifferent, whereas in the rest of sediments the proportion of freshwater diatoms was higher. In the vicinity of the Vistula Spit (ZW 8 and ZW 12) freshwater diatoms were mostly represented by *Amphora* spp. They were accompanied by *Fragilaria* (sensu lato) spp. In contrast, the latter genus dominated in the diatom flora occurring in the southern part of the lagoon. The predominance of freshwater and euryhaline taxa with combination of rare occurrence of marine and brackish-water taxa suggests that the flora developed under slightly brackish-water conditions. Decreasing of the basin salinity is probably cased by limited input of brackish-water of the Post-Litorina Sea. Simultaneously, the higher content of benthic and periphytic diatoms typical for very shallow littoral zone may indicate a fall in the lagoon water level. The same phenomenon was observed by Przybyłowska-Lange (1974) and Bogaczewicz-Adamczak & Miotk (1985).

Additionally, representatives of genus *Aulacoseira* were observed very often in the cores ZW 4, ZW 11 and ZW 14. Amongst them, *A. granulata* and *A. italica* were most commonly recorded. Both taxa belong to the freshwater plankton occurring in eutrophic alkaline waters (e.g. Denys 1991). According to Witkowski (1994) these taxa are abundant in the Vistula and their distribution conforms to the direction of Vistula water spreading within the Gulf of Gdańsk. Their high frequency in the core ZW 4 may indicate the major role of Nogat river waters in the hydrological development of the eastern part of the Vistula Lagoon. The abundance of *Aulacoseira* spp. in ZW 11 and ZW 14 is probably caused by Bauda river influx in the vicinity of Frombork. The sporadic occurrence of these species in ZW 12 as well as their lack in ZW 10 and ZW 8 may suggest that river waters inflow could change the salinity of lagoon locally. Thus, in the river mouth area the basin was probably freshwater. On the other hand, a high abundance of *A. normanii* fo. *subsalsa* in assemblage near Krynica Morska (ZW 8) may indicate the local inflow of Post-Litorina waters through the Vistula Spit, which resulted in a slight salinity increase in this area. Some differences in species composition of the diatom assemblage recorded in particular cores indicate the spatial differentiation of environmental conditions within the basin studied.

IV. The Post-Litorina transgression. The next stage of lagoon development is recorded in the sediments

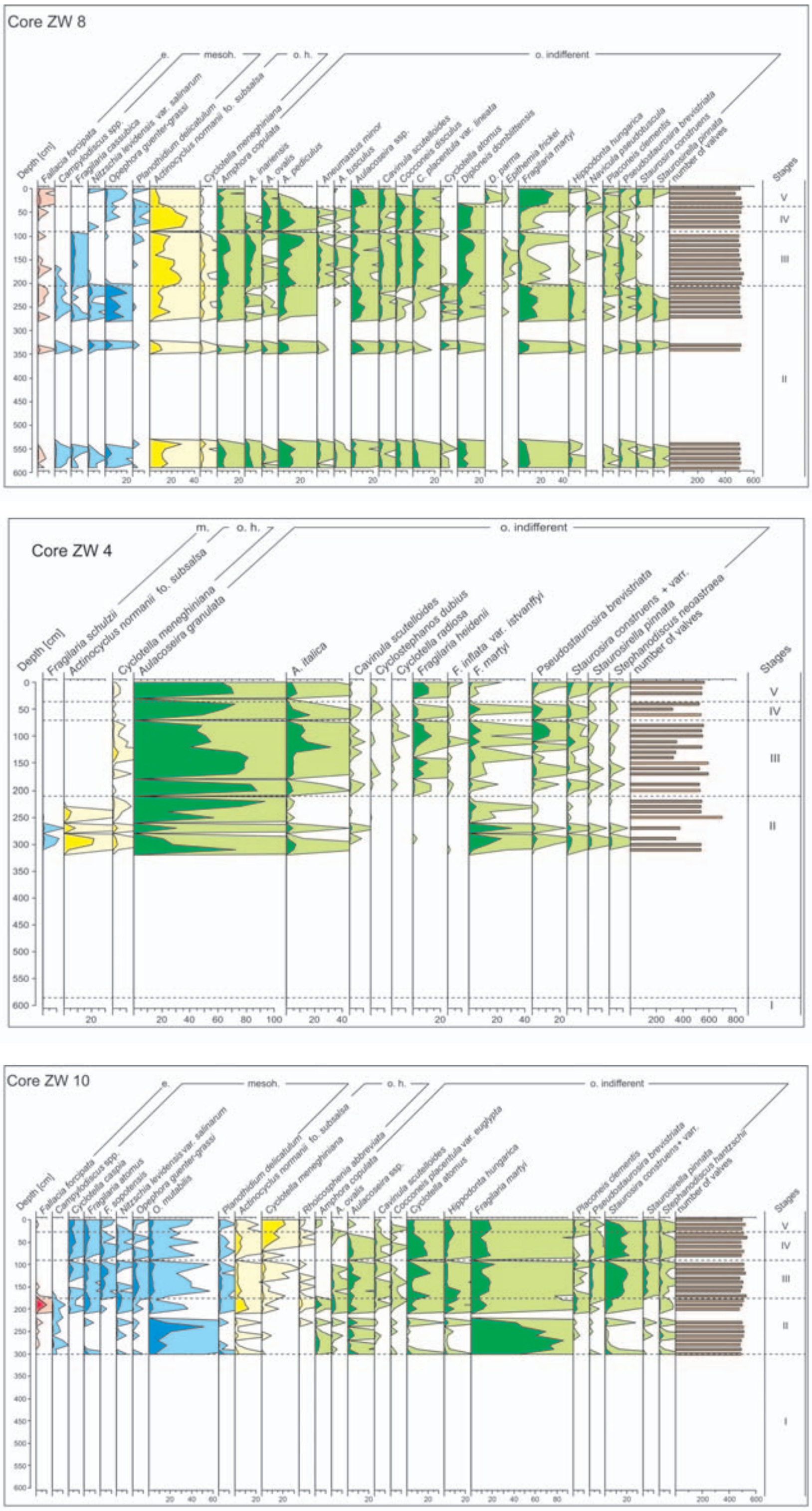

Fig. 5. Distribution of main taxa in cores: a – ZW 8; b – ZW 4; c – ZW 10.

occurring in the different depths. The base has been found between the depth of 120 cm (ZW 12) and 60 cm (ZW11), whereas the top lies between the depth of 90 cm (ZW 12) and 20 cm (ZW 11). The deposits consist mainly of muds, including silty and sandy ones, which cover the central part of lagoon and its southern coast. However, near the Vistula Spit coast sandy sediment prevails. Moreover, in ZW 8, ZW 12 and ZW 14 interbbedings with fragments and whole shells of freshwater gastropods and bivalves are observed very often.

In the sediments of all cores a quantitative increase of planktonic diatoms was recorded. Amongst them, *Actinocyclus* spp., *Cyclotella* spp. and *Stephanodiscus* spp. occurred the most often. A maximum frequency of *A. normanii* fo. *subsalsa* for the core ZW 8 was encountered in the Krynica Morska area, while in core ZW 10 this taxon was associated by a mesohalobous, *Cyclotella caspia*, and a halophilous species*, C. meneghiniana*. In the rest cores representatives of genus *Stephanodiscus*, belonging to oligohalobous indifferent, prevailed. First of all, an increased abundance of *S. neoastrea* was also observed in the diatom assemblages. This species was accompanied by *S. medius* and *S. rotula* in core ZW 14. Similar changes in the diatom flora were noted in the vicinity of Frombork by Przybyłowska-Lange (1974) and Bogaczewicz-Adamczak & Miotk (1985). Results of the previous diatom study also indicate the abundance of planktonic forms, mostly represented by *S. astrea* (lit. cit.).

Such a diatom flora indicates a short-term rise in the lagoon water level, probably related to the Subatlantic Post-Litorina Sea transgression. The change of the environmental conditions is supported by the occurrence of the gaps in the diatom records noted in sediments of western part of the lagoon. On the other hand, the Post-Litorina transgression could cause the intensification of marine inflow through the Vistula Spit and as a consequence a local small rise in the water salinity. This phenomenon is recorded by a slight increase in the abundance of mesohalobous benthic diatoms (*Nitzschia levidensis* var. *salinarum*) in cores ZW 8 and ZW 12 (Witak et al. 2005). This taxon was accompanied by *Fragilaria atomus* and *F. sopotensis* in core ZW 10 (lit. cit). The diatom flora of the rest cores did not show changes in salinity. Probably the rise in water salinity was reduced due to intense discharge of riverine waters, which is evidenced by a high content of *Aulacoseira* spp.

V. Brackish-water eutrophic lagoon. The muddy sediments of the last stage have been found in the upper part of all cores. Their thickness changes from 20 cm in the central part of lagoon to 60 cm near Frombork and Krynica Morska. The diatom flora preserved in the subbotom deposits was well preserved, abundant, and representative of many taxa. In all cores the most striking feature was decreasing of frequency of planktonic forms. Generally, freshwater benthic taxa occurred commonly in subfossil assemblages. Amongst them, *Fragilaria* (sensu lato) spp. was the most important component in all floras. This group was mostly represented by *F. construens* (syn. *Staurosira construens*) and *F. martyi.* Besides, in ZW 8 and ZW 12 *Amphora copulata, A. inariensis* and *A. pediculus* were noted often. The increased content of benthic and periphytic diatoms in subfossil sediments (e.g. *Amphora* spp., *Fragilaria* spp.) was also observed by Bogaczewicz-Adamczak & Miotk (1985). An abundant occurrence of these eutraphentic taxa indicates a distinct increase in the trophy of Vistula Lagoon in the last stage of development. An intensive eutrophication of water basin is show also by the occurrence of small planktonic species e.g. *Cyclotella atomus*, *C. caspia*, *Stephanodiscus hantzschii*. These are pollution-tolerant taxa and their distribution is associated with wastewater discharge (Stachura & Witkowski 1997). According to Andrèn (1995) the dominance of small centric diatoms indicates a decrease of euphotic zone depth due to eutrophication. Such a flora with diatoms typical of waters rich in nutrients and organic matter was observed in subsurface sediments of the Gulf of Gdańsk (Witak 2000), Gdańsk Deep (Witkowski 1994), Gdańsk Basin and Oder Rinne (Andrèn et al. 1999).

Simultaneously, in the northern and southern part of lagoon a high content of marine and brackish-water taxa was observed. The first group was represented by *Fallacia forcipata* and *Diploneis smithii,* whereas the second one by *Nitzschia levidensis* var. *salinarum*, *Opephora guenter-grassii* and *Opephora mutabilis* (Witak et al. 2005). The distinct increase of water salinity noted here must be connected with the construction of a dam in 1915, which strongly reduced the discharge of Nogat river waters into the lagoon. As a consequence, the share of river waters in the general water balance of the Vistula Lagoon decreased tenfold (Mikulski 1960), while the inflow of marine waters increased. This phenomenon is clearly expressed in the neighbourhood of Piaski, Krynica Morska and Tolkmicko. However, near Frombork the increase in salinity can be partly reduced by Bauda river inflow. Nevertheless, in the diatom flora occurred in sediments of central part of lagoon euhalobous and mesohalobous were not observed. It looks like, that ecological results of closing of Nogat river are only recorded by distinct decrease of frequency of riverine taxa *Aulacoseira granulata* and *A. italica*.

CONCLUSIONS

The diatom floras preserved in sediment cores from the Vistula Lagoon indicate that its development took place under changing environmental conditions during the Holocene. The area originally had a terrestrial environment, whereas its later evolution was linked with marine stages of the Baltic Sea. The basin formation is heterochronic and indirectly associated with the consecutive Litorina Sea transgressions in the Atlantic chronozone. The first inflows of marine waters through the Vistula Spit barrier reached the northern part of the recent lagoon. Next, the aquatic environment had been extended over the whole of the basin, which is related to the maximum of the Litorina transgression in the Late Atlantic – Early Subboreal period. However, the intensive rise of the groundwater at that time can be also the reason of the lagoon formation. In the next stage of basin development corresponded to the Subboreal chronozone decrease of the salinity was noted. This phenomenon is related to limited inflow of brackish-water of the Post-Litorina Sea and the intensive riverine discharge. Due to the Subatlantic Post-Litorina Sea transgression a short-time lagoon level rise was observed. The intensification of open-sea water influx through the Vistula Spit caused locally increase of the salinity in the northern part of the basin, whereas this phenomenon was reduced by discharge of riverine waters in its central part. The last change of the environmental status is recorded in the subbotom sediments. As a result of strongly reduction of Nogat river water inflow the hydrological regime of the lagoon is shaped mostly by input of the Baltic Sea waters. Moreover, effects of the eutrophication are registered in the superficial deposits.

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