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PALAEOENVIRONMENTAL CHANGES IN THE AREA OF THE SZCZECIN LAGOON (THE SOUTH WESTERN BALTIC SEA) AS RECORDED FROM DIATOMS

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Abstract

Analyses of diatom assemblages were performed in sediment cores from the Szczecin Lagoon area, as a part of a multidisciplinary research including seismoacoustic profiling and different types of palaeoecological and geological analyses: palynological, macrofossil, malacological, lithological, geochemical and sedimentological. Changes in the composition of a large spectrum of species of the local fauna and flora allowed the reconstruction of environmental conditions during the Late Glacial and Holocene in the Szczecin Lagoon. Succession of the diatom communities is the main topic of the present paper. In the Late Glacial sediments, the diatom flora was scarce and occurred only in core 42/99. In other cores, diatom assemblages characteristic for three phases of the Holocene development (limnic-swampy, marine/brackish-water and lagoonary) of the Szczecin Lagoon were distinguished. The Late Glacial (Older-Dryas (?), Allerød and Younger Dryas) record is incomplete and the flora is predominantly represented by *Actinocyclus normanii*, *Aulacoseira* spp, *Cocconeis placentula*, and *Fragilaria brevistriata*. The oldest Holocene sediments of the limnic-swampy type, are characterised by freshwater and halophilous diatoms (e.g. *Fragilaria brevistriata*, *Cocconeis placentula* and *Stephanodiscus hantzschii*). In the overlying marine sediments, only occasionally brackish-water taxa (e.g. *Planothidium delicatulum*, *Cocconeis hauniensis*) were observed. In the uppermost deposits formed in lagoonary conditions freshwater, halophilous and brackish-water species dominated (e.g. *Aulacoseira granulata*, *Cavinula scutelloides* and *Epithemia turgida*).

Key words: Diatoms (Bacillariophyceae), palaeoecology, Holocene, the Baltic Sea, Szczecin Lagoon

INTRODUCTION

Szczecin Lagoon is a large coastal water body constituting part of the Odra river mouth (Fig. 1) with distinctly limited water exchange with the Baltic Sea. This results from the presence, in the northern part, of a sand barrier system separating the lagoon from the Pomeranian Bay. The water balance arises from the freshwater incoming from the south (Odra river discharge) and the marine waters flowing in through the straits in the north. It makes Szczecin Lagoon a reservoir of the characteristic and unique environmental conditions. Changes in environmental conditions of the lagoon impact the living organisms assemblages in this area.

One of the most sensitive tools in the reconstruction of environmental changes is application of diatom analysis. Changes in diatom species composition are very useful in monitoring the status of recent aquatic environments and in deciphering past ecological conditions both in limnic (e.g. Marciniak 1981, Flower *et al.* 1997, Schönfelder, Steinberg this volume, Witoń, Witkowski 2003) and marine environments (*e.g.* Witkowski 1994, Andreen *et al.* 2000). Main indicator value of this group of algae lies in their ecological sensitivity to different environmental factors and for that reason they have a great potential value for studies of palaeogeography, palaeoecology and palaeoceanology. Reconstructions of the environmental changes extending back to the end of the last glaciation and relating to e.g. past sea-surface temperatures, pH, salinity, water depth and productivity is possible using ecological data on modern species and communities in reference to fossil diatom assemblages (*e.g.* Zielinski, Gersonde 1997, Snoeijs 1999).

The first report on diatoms from the Szczecin Lagoon was published in the 80's (Wypych 1980) but systematic studies in this area only started in the 90's of the 20th century

Fig. 1. Location of the study area.

(e.g. Andreen 1999, Borówka *et al.* 1999, 2002, Janke 2002, Witkowski *et al.* 2003a, b). The aim of the present paper is to reconstruct changes of environmental conditions in the Szczecin Lagoon during the Late Glacial and the Holocene as based on succession of the diatom assemblages. The interpretation of the diatomological analyses is supported by other palaeoecological results, namely palynological, macrofossil and malacological (Borówka *et al.* 2002, Latałowa, Święta 2003, Woziński *et al.* 2003).

REGIONAL SETTING

The Szczecin Lagoon is a large basin situated on the border of Poland and Germany (Fig. 1). It is a main link in the Odra River discharge with a surface area of 687 km^2. The study area constitutes a part of the so-called Szczecin syncline (Mikołajski 1966, Majewski 1980). The northern boundary of the Szczecin Lagoon separating it from the Baltic Sea, is formed by the Swina Bar, the back-delta of the Swina and Wolin and the Uznam Islands. In the south, a narrow channel closes the lagoon, this is the so-called Roztoka Odrzańska. The Szczecin Lagoon is a shallow water reservoir. Its maximum depth does not exceed 8.5 m and on the average it is *ca.* 3.5 m. The main part of the Lagoon has a relatively flat bottom with depths ranging from 4 to 6 m. These features make the basin resemble lagoonary reservoirs (Nichols, Allen 1981, Osadczuk 1999a, b). One specific feature of the Szczecin Lagoon recent morphology is an artificial navigational channel between Szczecin and Świnoujście with a depth of *ca.* 11 m. The Baltic Sea waters enter the Lagoon via this channel (Mikołajski 1966, Majewski 1980).

MATERIALS AND METHODS

The major subject of the study was the diatom flora occurring in the sediment cores from the Szczecin Lagoon. The diatom species composition was studied in 119 samples from 3 cores. Length of the cores ranged between 335 and 343 cm. Detailed analyses of diatom flora described in the present paper encompassed cores No 3/98, 39/99 and 42/99 (Fig. 1).

Subsamples for diatom analysis were treated in 150 ml beakers. After drying and weighting, they were treated with 10% hydrochloric acid to remove carbonates. Distilled water was added up to 150 ml and decanted after 12 hours, repeated several times. The samples were then boiled in 37% hydrogen peroxide to remove organic matter, washed four times until all peroxide and most of the clay fractions were removed. From the sample residue of 100 ml, a defined aliquot was taken from the centre of the homogenised suspension, randomly put on cover glasses and left to dry. Slides for diatom counting were mounted in Naphrax.

Diatom assemblages were examined quantitatively by counting at least 300 valves in transverse scans of each slide, using a Nikon Eclipse E600 light microscope at 1000x magnification. The counting results formed the basis for the diatom diagrams, presenting a vertical distribution of different ecological diatom groups. The following criteria were used for diatom grouping: habitat, salinity, trophy, saprobity, and pH.

The chronostratigraphy of the sediments was established by means of ^{14}C (both conventional and AMS methods) and pollen analysis. For the AMS datings, plant macrofossils and mollusc shells were selected from various levels (Latałowa, Borówka 2003). Pollen analysis was performed according to standard procedures (Faegri, Iversen 1989). Only selected data supporting determination of age of particular lithological layers are presented in the present paper. Full results of pollen analysis will be subject of a separate paper (Latałowa *et al.* in prep.).

RESULTS

Lithology of the profiles

The lithological description based mainly on physical properties of sediments has been supplemented by the most important data on records of leading plant and animal remains.

Core 3/98

Layer no	Depth (cm)	Composition of sediments
1	343–232	fine brown detritus gyttja with large admixture of sand and silt; mollusc shells of the freshwater taxa (e.g. *Bithynia tentaculata*, *Valvata piscinalis*)
2	232–206	dark grey silty sand with admixture of organic matter gyttja

Layer no	Depth (cm)	Composition of sediments
3	206–70	brown to grey sand with large admixture of mollusc shell detritus (mainly *Cardium glaucum*) and various admixture of plant detritus
4	70–20	brown-grey silty fine detritus gyttja
5	20–0	black silty fine detritus gyttja

Core 39/99

Layer no	Depth (cm)	Composition of sediments
1	335–319	light grey-beige medium sand
2	319–311	dark-grey medium sand with admixture of fine and coarse plant detritus (e.g. *Carex* sp., *Urtica dioica*, *Lycopus europaeus*)
3	311–220	brown fine and coarse detritus gyttja with silt and sand; among botanical remains: *Typha* sp., *Schoenoplectus lacustris/tabernaemontani*, Characeae, *Najas minor*, *N. marina*, *Nuphar lutea*; among animal remains: Spongiae
4	220–160	dark-grey sand with admixture of coarse detritus incl. Diaspores of e.g. *Ruppia maritima*, *Zannichellia palustris*, *Typha* sp., *Najas marina*
5	160–102	dark-grey silty sand with large admixture of plant detritus (e.g. *Typha* sp., *Alnus glutinosa*, *Zannichellia palustris*)
6	102–80	black sand with admixture of fine detritus, remains of Spongiae and plant species characteristic of saline environment (*Ruppia maritima* and *Zannichellia palustris*
7	80–18	dark-grey-olive fine detritus gyttja with silt and fine sand; large amount of animal remains (Spongiae, *Daphnia* sp., Bryozoa)
8	18–0	black fine detritus gyttja with fine mineral matter; large amount of animal remains (Spongiae, *Daphnia* sp.

Core 42/99

Layer no	Depth (cm)	Composition of sediments
1	340–218	grey fluvial sand
2	218–200	dark brown, strongly humified and compressed *Carex* peat with admixture of medium sand
3	200–186	light grey medium sand with admixture of animal detritus (Spongiae, Oligochaeta)
4	186–144	brown fine and coarse detritus gyttja with admixture of silt and sand; among plant remains: *Menyanthes trifoliata*, *Comarum palustre*, *Nuphar lutea*, *Lemna gibba*, Characeae; animal taxa: Spongiae, Oligochaeta
5	144–110	light grey medium sand
6	110–60	dark grey fine sand with large admixture of fine detritus gyttja; numerous Spongiae remains
7	60–40	brown-olive fine detritus gyttja with large admixture of sand and silt; abundant remains of Spongiae and *Daphnia* sp.
8	40–10	Black fine detritus gyttja with silt and fine sand; large amount of animal remains (Spongiae, *Daphnia* sp.)

Chronostratigraphy of the profiles

In the present study, the basis for palynological dating of particular sediment sequences constitute pollen diagrams of the same profiles that are the subject of the diatom analyses presented in this paper (39/99 and 42/99); the additional palynological data come from the profile 1/98 representing the similar type of sediment sequence as in the profile 3/98 analysed in respect to diatom content.

In the pollen diagrams (Fig. 2 and 3), local pollen assemblage zones (lpaz) were distinguished based on the content of pollen of terrestrial plants and of trees in particular. The age of particular pollen units was determined by comparing with the reference pollen diagrams from the Wolin Island (Latałowa 1989, 1992).

Due to erosion of the older deposits and their subsequent redeposition, (particularly in the core 39/99) and the so-called reservoir effect radiocarbon dating in some sections of the profiles was less suitable. The rather well established radiocarbon dates were performed on samples of swamp and limnic deposits from the lower part of the profiles studied (below marine sediments). Due to reservoir effect the dates from *Cardium glaucum* shells (AMS method) are probably about 4 hundred years too old (cf. Heier-Nielsen *et al.* 1995). The AMS dates from macroscopic remains of terrestrial plants isolated from lagoonary sediments and of lagoonary sediment samples, as a rule, show distinctly older age than expected from pollen data (see Latałowa, Borówka 2003).

Core 3/98

The chronostratigraphy of this core is based on comparison of particular lithological layers in this profile with the adequate sections of the profile 1/98 dated according to the pollen diagram (Sikorski 2000). Both profiles are very similar in respect to the character and thickness of particular sections of sediments.

The bottom of the 3/98 core can be dated to the period between 8 and 7 thousands conv. ^{14}C years BP. This approximation is based on the similar thickness and composition of the limnic sediments in the 1/98 core dated as above. The topmost part of this limnic series at the limit with the sandy series (206 cm) is about 6400–6200 BP. Such age is deduced from both, the palynological estimation for the equivalent layer in the 1/98 core and the large set of ^{14}C dates provided for this sediment limit in various profiles taken in different parts of the Lagoon (Latałowa, Borówka 2003). The uppermost, about 80-cm layer of detritus gyttja started to accumulate probably between 2800–2400 BP. In the pollen diagrams from the 1/98 and 42/99 cores this layer coincides with the rise in beech (*Fagus sylvatica*) pollen curve that is dated in the reference diagrams from Wolin Island at 2800 conv. ^{14}C years BP. In this profile, the youngest diatom assemblage appears in the topmost 20 cm only. Comparing this layer with the adequate dates from other profiles, it appears that this section is probably incomplete. Formation of this diatom assemblage started not later than one thousand years ago.

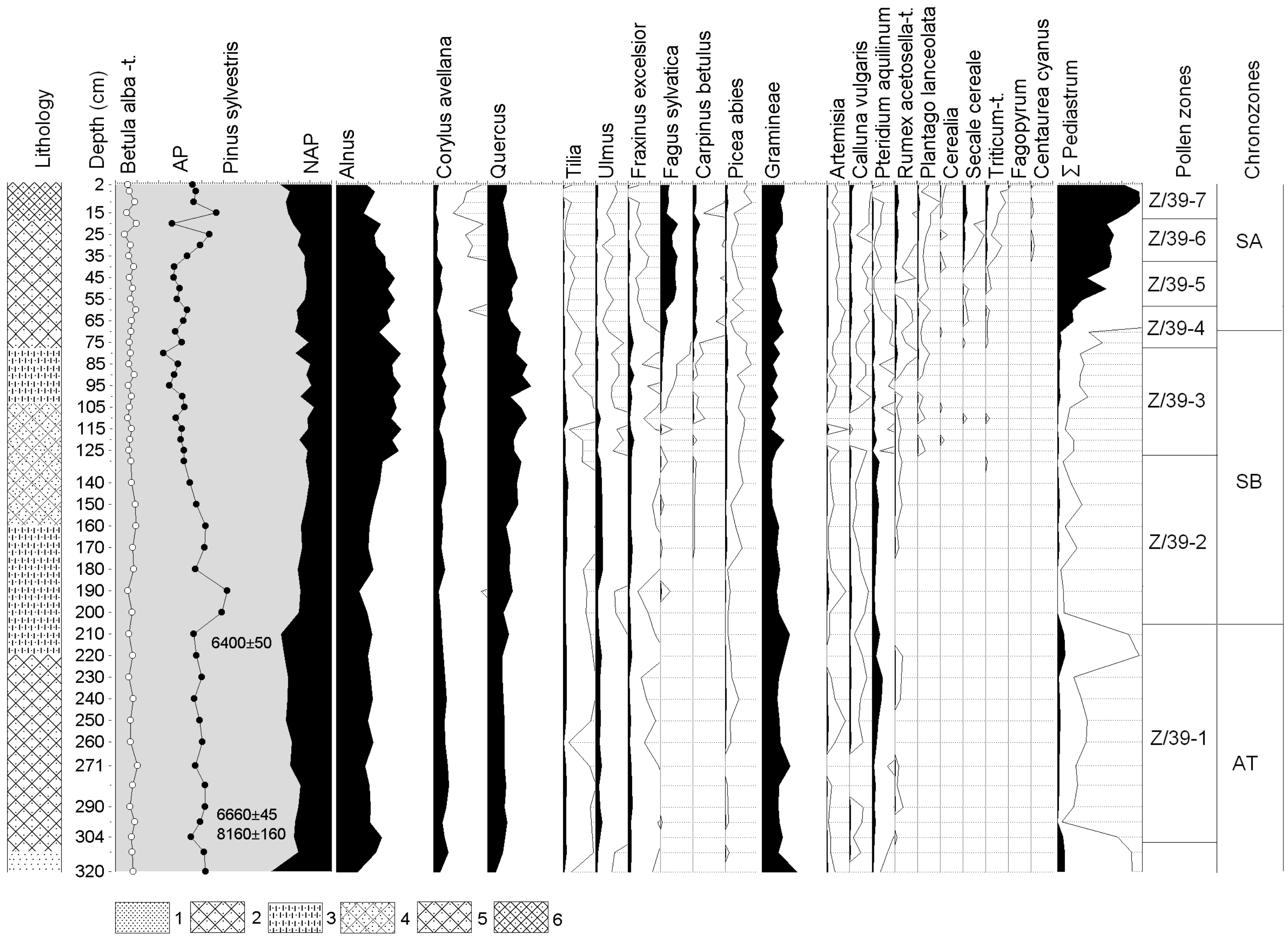

Fig. 2. Pollen diagram of core 39 from Szczecin Lagoon. Lithology: 1. dark-grey medium sand with admixture of plant detritus; 2. brown fine and coarse detritus gyttja with silt and sand; 3. sand with admixture of detritus; 4. dark-grey silty sand with large admixture of plant detritus; 5. dark-grey-olive fine detritus gyttja with silt and fine sand; 6. black fine detritus gyttja with fine mineral matter

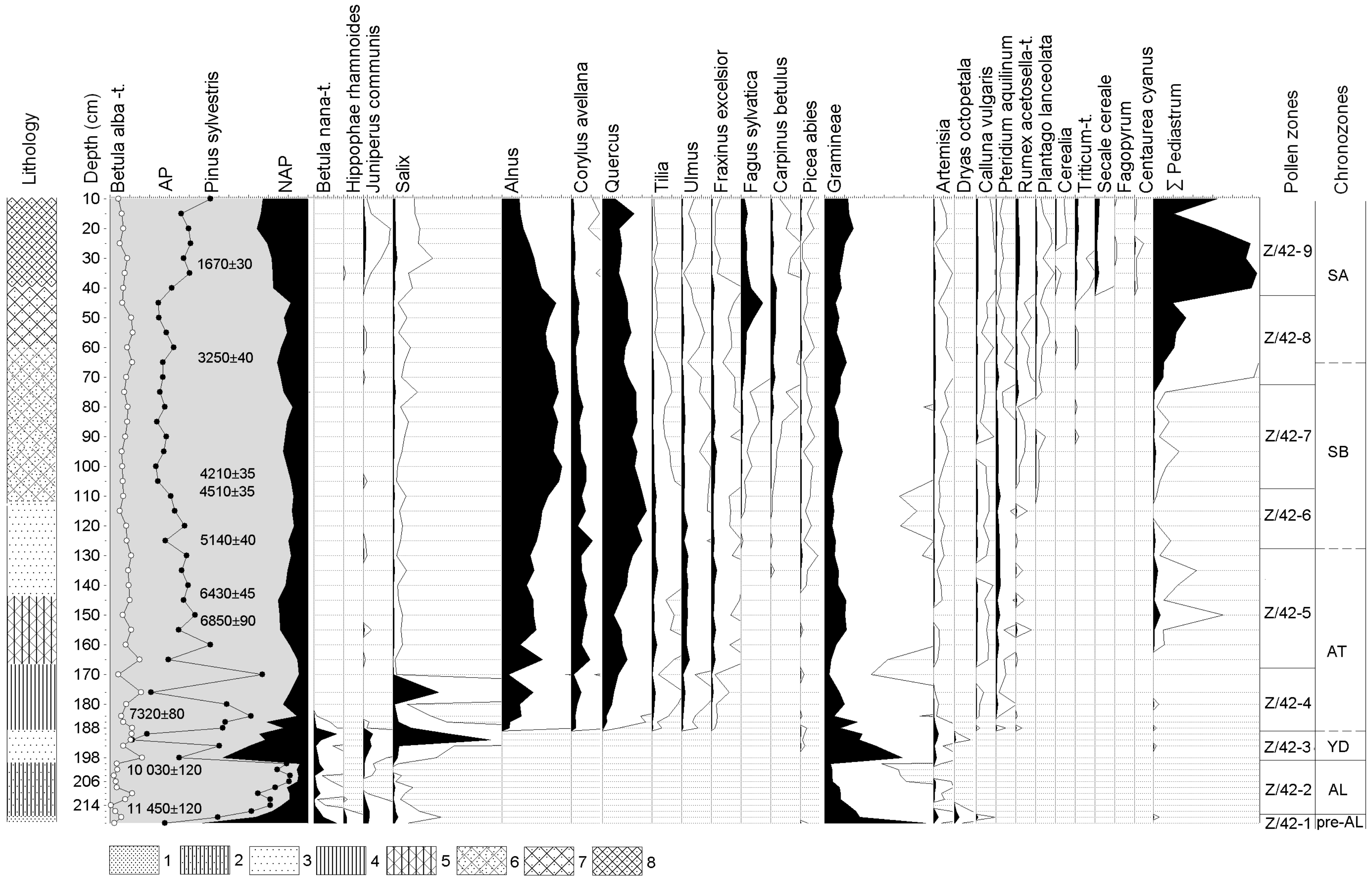

Fig. 3. Pollen diagram of core 42 from Szczecin Lagoon. Lithology: 1. grey fluvial sand; 2. dark brown peat with admixture of medium sand; 3. light grey medium sand; 4. brown fine detritus gyttja with admixture of silt and sand; 5. coarse detritus gyttja dark with admixture of silt and sand; 6. dark grey fine sand with large admixture of fine detritus gyttja 7. brown-olive fine detritus gyttja with large admixture of sand and silt; 8. black fine detritus gyttja with silt and fine sand.

Core 39/99

The chronostratigraphy of the 39/99 profile is based mainly on a pollen diagram (Fig. 2). The diagram, however, is not easy to interpret. Pollen curves are distinctly smoothed, probably mostly due to redeposition of older sediments. The other disadvantageous factor is the large distance to the land that leads to underrepresentation of pollen of most dry land taxa and discontinuity of sediments (hiatuses). In this situation the most indicative in respect to estimation of the age of particular layers are starting points of some of the pollen curves and their culminations. Because of reworking of the older sediments, all the AMS dates along the upper part of this profile indicate similar age ranging between 6,600 and 6,400 ^{14}C years BP and for this reason they are not included to the present paper.

The bottom of limnic sediments lies on a mineral, sandy bed. The two radiocarbon dates from two subsequent samples taken in this level (Gd-15078, 8160±160 and Poz-795, 6660±45) do not overlap, although in the light of palynological data from Wolin Island (Latałowa 1989, 1992) the younger one is more reliable. The age of the upper limit of the Z/39-1 lpaz is about 5 thousands years ^{14}C BP, but a kind of hiatus around this level can be expected. Due to comparison with the Wolin II profile (Latałowa 1992) the age of the upper limit of the Z/39-2 lpaz is determined as about 4 thousands years BP. The estimated date for the upper limit of the Z/39-3 lpaz is about 3000–2800 years BP (final decerase of *Tilia*, *Ulmus* and *Fraxinus* and a rise in *Fagus* and *Carpinus* pollen curves). The two upper pollen zones include the Migration Period (lpaz Z/39-5) – culmination of the *Fagus* curve, and the Medieval period (lpaz Z/39-6) – strong increase in all groups of anthropogenic indicators; it seems that the most recent sediments are missing in this profile.

Core 42/99

The core contains the Late-glacial and Holocene sediments interrupted by several hiatuses (Fig. 3). However, all types of sedimentary series present in the area of the Lagoon are represented. The first pollen record is from a thin layer of silty sand rich in organic matter overlying the fluvial sands. The pollen diagram (Z/42-1 lpaz) suggests its Older Dryas (pre-Allerød) age. The characteristic feature of the zone is high pollen content of herbs and *Betula nana* type and significant amount of *Juniperus* and *Hippophaë rhamnoides* pollen. The above lying layer of *Carex* peat representing fragment of the Allerød period (Z/42-2 lpaz) is covered by a layer of sand deposited during the Younger Dryas (Z/42-3 lpaz). The pollen sequence of the Allerød is characterised by decrease of NAP (herb pollen) and strong rise in the *Pinus* curve, while in the Younger Dryas an opposite pattern is observed.

Immediately on the Younger Dryas sands the middle-Holocene swampy-limnic deposits occur with a radiocarbon date of 7320±80 conv. years BP (Gd-12222) at the bottom of the sequence. Such age is not in contradiction with the pollen data. The upper limit of this type of the deposit lies between two radiocarbon dates: Gd-12217; 6850±90 and Poz-702, 6430±45 (AMS from *Cardium* shell). The latter one is probably slightly too old, however, it keeps the range of the general dating of the bottom of the marine series in the area of the Szczecin Lagoon (Borówka *et al.* 2000, Latałowa, Borówka 2003). The palynological data from the marine section of sediments do not illustrate the continuous succession. However, the three AMS dates from *Cardium* shells (Poz-703, 5140±40, Poz-706, 4510±35 and Poz-705, 4210±35 conv. years BP), with the reservation of their about 400 years older age due to the reservoir effect, establish well the chronological position of this series. It shows an increase of organic matter content in sediments at about 4 thousands years BP. The estimation of age in the upper part of the profile is based exclusively on pollen data. Both radiocarbon dates (AMS from sediment samples) are distinctly too old. According to the pollen diagram, the age of the upper limit of the Z/42-6 lpaz should be about 3000–2800 years BP, while the upper limit of the Z/42-7 lpaz is about 1000 years BP.

Succession of diatom assemblages

Despite the lack of the continuous sedimentary record (presence of hiatuses), profile 42/99 was considered the most interesting. This was due to the fact that in the lowermost part of this core Late-Glacial sediments occurred and the whole core was in general characterised by relatively low content of the re-deposited material. In general, core 42/99 encompasses the Late Glacial and Holocene, whereas 3/98 and 39/99 Middle and Late Holocene.

The total number of diatom taxa identified in all samples studied amounted to 455. In almost all cores studied, except for 42/99, a similar distribution of diatoms within the sediment profile was observed. An abundant diatom flora was present in the lowermost and in the topmost (50–60 cm) parts of the cores. In their middle part a drastic decrease in diatom abundance was recorded. The most characteristic examples of a diatom succession in the area of Szczecin Lagoon were described in cores 3/98 (Figs 4a, 4b) and 39/99 (Figs 5A, 5B).

Core 3/98

Altogether 235 diatom taxa have been identified in the sediments of the core 3/98. These were mostly benthic forms (210 taxa). In general diatom flora of this core is characterised by significant shifts in species composition. Based on changes in the diatom ecological groups, three diatom assemblage zones (DAZ 3/98/1 – 3/98/3) were distinguished (Figs 4A, 4B).

DAZ 3/98/1 encompassed sediments from the depth interval of 343–206 cm. Diatom valves were abundant and well preserved. In the DAZ 3/98/1 strong dominance of benthic over planktonic diatoms was observed. The distribution of both habitat groups showed distinct opposite tendency. Contents of benthic forms generally increased upwards, whereas of planktonic ones decreased. *A. crenulata* and *A. granulata* represented the planktonic taxa with the highest abundance. With respect to halobous preferences dominant were freshwater species (up to 70.5%) represented by *Amphora pediculus*, *Aulacoseira crenulata*, *A. granulata*, *Fragilaria brevistriata*, *F. pinnata*, *Melosira varians*. Halophilous taxa (*e.g. Epithemia sorex*, *E. turgida*, *Rhopalodia gibba*) were less abundant. With regard to pH preferences, alkaliphilous followed by alkalibiontic diatoms dominated with percentages

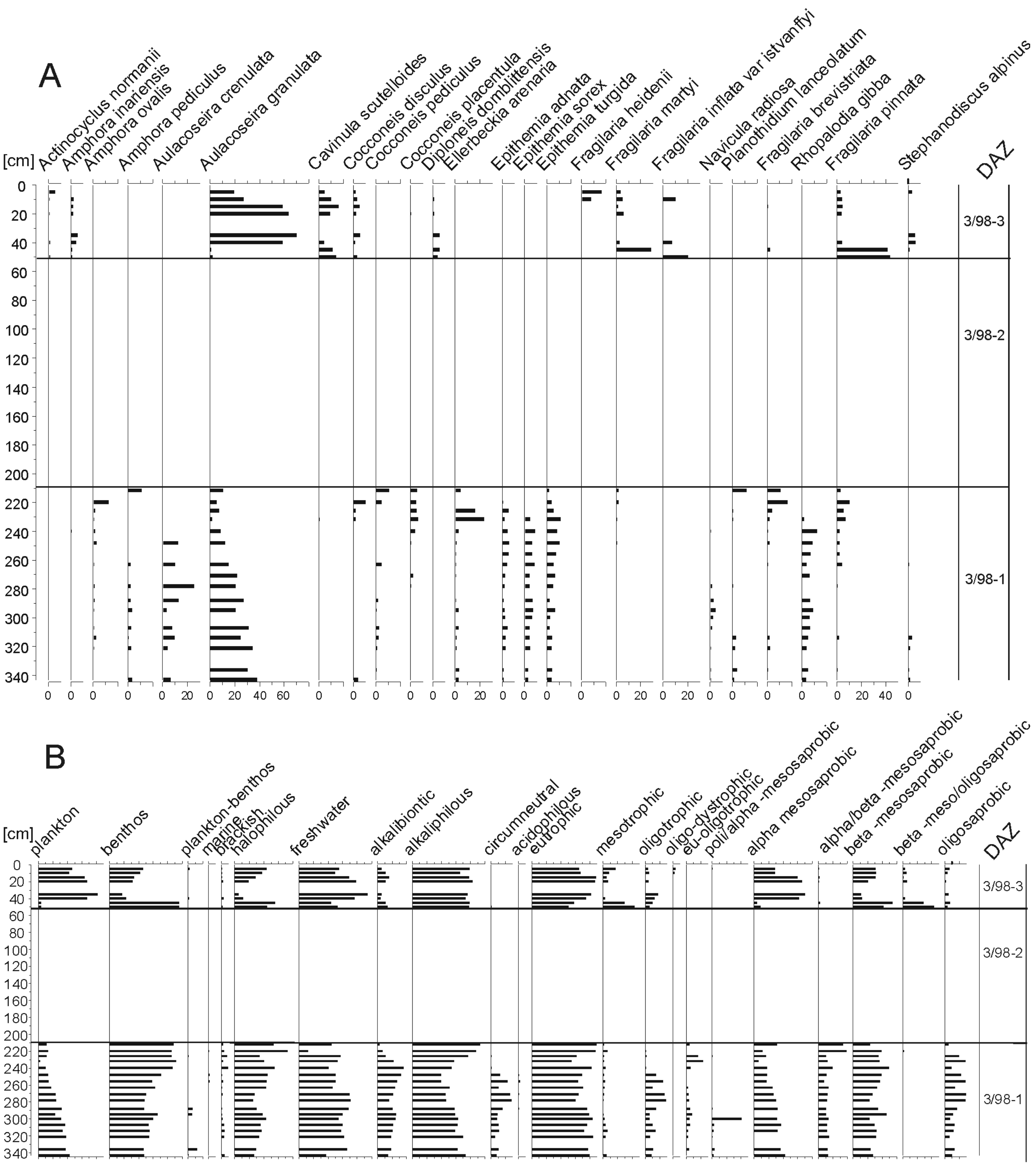

Fig. 4. **A:** Distribution of dominant diatom species in the sediments of core No 3/98. **B:** Distribution of diatom ecological groups in the sediments of core No 3/98.

reaching *ca.* 60% and 30% respectively. They were represented by *e.g. Amphora pediculus*, *Fragilaria brevistriata*, *Cocconeis placentula*, *Aulacoseira granulata*. With respect to trophic conditions, eutraphentic species were the most abundant group. Their total content ranged from 60 to more than 80%. Included in this group were *e.g. Fragilaria pinnata*, *Rhopalodia gibba*, *Epithemia sorex*. In the lower and middle part of the zone, increased contents of circumneutral taxa were observed coinciding with similar tendency in oligotraphentic taxa. In the uppermost part of the zone, both groups have almost completely disappeared. Single valves of marine and brackish-water species have been found in this DAZ (*e.g. Navicula crucicula*, *Lyrella abrupta*) at a depth of 220–226 cm and 206–212 cm.

DAZ 3/98/2 occurred between 206 and 20 cm of the profile. The sediment of this DAZ was characterised by an oc-

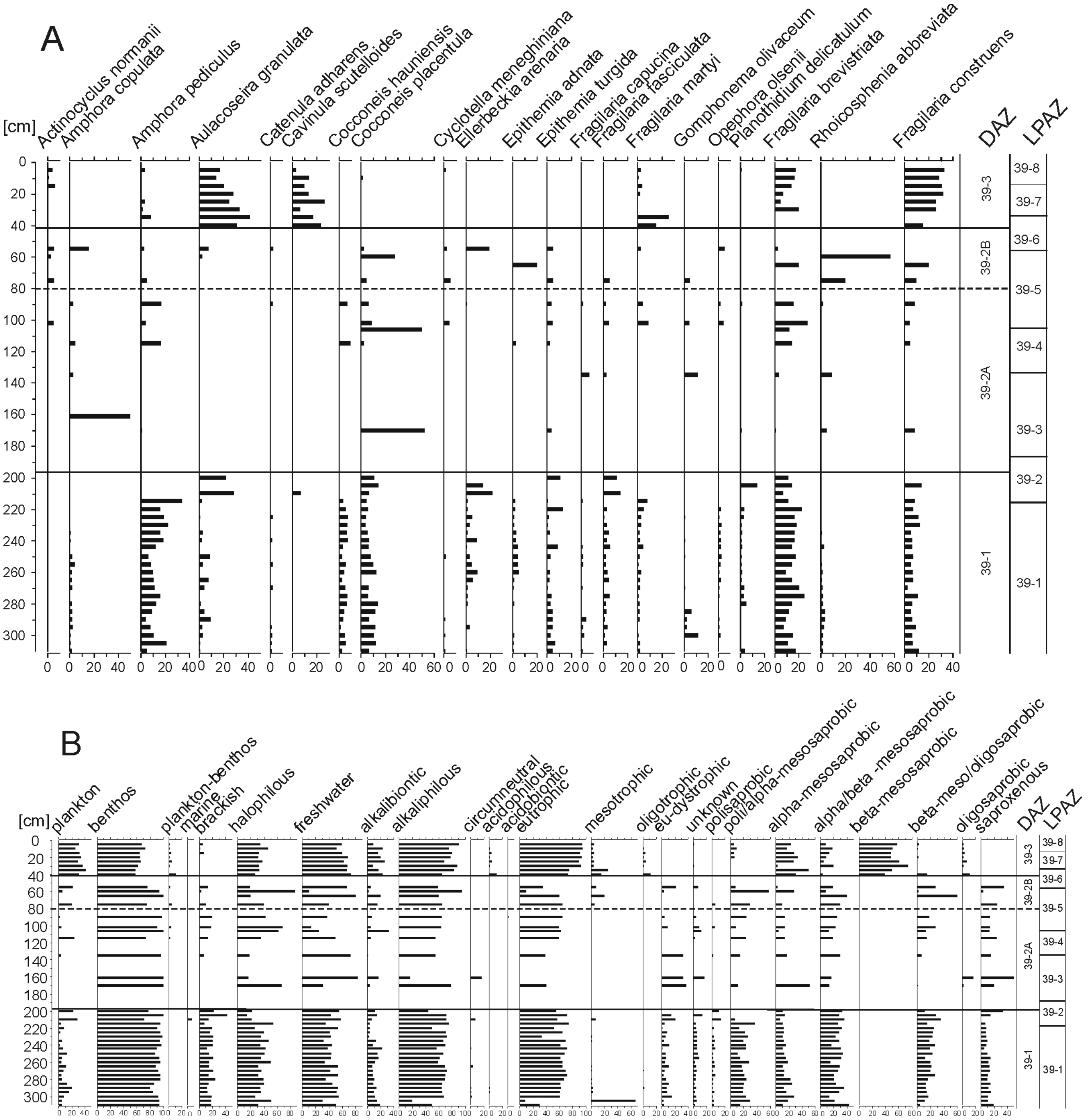

Fig. 5. **A:** Distribution of dominant diatom species in the sediments of core No 39. **B:** Distribution of diatom ecological groups in the sediments of core No 39.

currence of *Cardium glaucum* shells and nearly complete absence of diatom valves. Fragmented valves of brackish-water and some freshwater taxa occurred sporadically.

DAZ 3/98/3 included the recent and subfossil sediments. Freshwater taxa dominated this part of the core (up to 96.2%) and were represented by *e.g. Aulacoseira granulata*, *Fragilaria pinnata*, *Fragilaria martyi*. At a depth of 20–10 cm, planktonic species reached their greatest values while from the depth of 10 cm benthic taxa dominated. Between 5 and 10 cm single marine diatoms represented by *Lyrella abrupta* appeared. With respect to trophic preferences, eutraphentic forms (66.5%) dominated, represented by *Cavinula scutelloides, Aulacoseira granulata,* and *Fragilaria pinnata*. Within pH groups, the most abundant were alkaliphilous taxa (63.9%) with *Fragilaria construens*, *Aulacoseira islandica*, *Cocconeis disculus* as the most abundant (Figs 4A, 4B).

Core 39/99

In the sediments from core 39/99, 247 species representing a total of 52 genera (12 centric and 40 pennate) were identified. Based on changes in distribution of diatom ecological groups and in species composition, three diatom assemblage zones (DAZ 39/99/1-39/99/3 and two zubzones) were distinguished (Figs 5A, 5B).

DAZ 39/99/1 The sediments of the DAZ 39/99/1 (320–200 cm) encompassed the most of the Atlantic period (lpaz Z/39-1 and part of the lpaz Z/39-2). The upper limit of lapz Z/39-1 is dated to *ca.* 5000 ^{14}C conv. years BP. Benthic diatoms, especially taxa representing the genera of *Fragilaria*, *Cocconeis*, and *Epithemia* dominated. Planktonic forms occurred in low quantities and were mainly represented by taxa of the genera *Aulacoseira* and *Stephanodiscus*. With regard to halobous preferences, freshwater and halophilous forms dominated. Their relative abundance reached 60% (Figs 5A, 5B).

DAZ 39/99/2 sediments (200–40 cm) were deposited during the Subboreal and a part of the Subatlantic periods (upper part of lpaz Z/39-2 to Z/39-5). In this DAZ two subzones were distinguished. The DAZ 39/99/2A encompasses the sediment depth of *ca.* 200–80 cm and corresponds to the second part of the lpaz Z/39-2-lpaz and Z/39-3 lpaz. A high content of sand was characteristic for sediments of this subzone. The DAZ 39/99/2B included the sediment section of 80 to 40 cm and corresponded to the lpaz Z/39-4 and Z/39-5. In DAZ39/99/2B the sediment again changes to gyttja. The lpaz Z/39-5 is dated to the Migration Period. Another characteristic feature of the whole DAZ39/99/2 was the very low abundance of diatoms. Some of the samples analysed were completely barren. The taxa identified in sub-zone 39/99/2A, e.g. *Cocconeis hauniensis*, *Fragilaria fasciculata, Opephora olsenii* and *Planothidium delicatulum*, were scarce and usually, the valves were fragmented. Although the abundance of diatoms was very low, their salinity preferences were distinct and brackish water forms dominated (up to 20%, Figs 5A, 5B), whereas in sub-zone DAZ39/99/2B freshwater and halophilous forms dominated. Included in this group were *Ampora libyca*, *Cocconeis placentula*, *Ellerbeckia arenaria* and *Rhoicosphenia abbreviata*. With respect to trophic conditions and pH, eutraphentic and alkaliphilous forms strongly dominated.

DAZ 39/99/3. This zone covers the uppermost part of the core (40–0 cm) and encompassed the lpaz Z/39-6 dated to the Early Medieval period. The sediment of DAZ 39/99/3 was mainly composed of algal gyttja with some mineral matter admixture. The content of benthic taxa shows a distinct decrease while of planktonic one opposite tendency and increases to *ca.* 30–40 %. Within the habitat groups benthic forms were the most abundant diatoms and represented by *e.g. Cavinula scutelloides*, *Fragilaria brevistriata*, *F. construens* and *F. martyi* in the lowermost part of the DAZ. Planktonic forms were represented by e.g. *Actinocyclus normanii* and *Aulacoseira granulata* with the latter species reaching relative abundant to *ca.* 40 %. With respect to salinity preferences freshwater with maximum abundance up to 60% and halophilous (max. up to 40%) taxa dominated (Figs 5A, 5B).

The diatom flora in the material studied showed a marked similarity with regard to ecological preference. In the entire core, alkaliphilous forms dominated with maximum relative abundance of 70%. *Fragilaria brevistriata*, *Planothidium delicatulum*, and *Aulacoseira granulata* represented them. Alkalibiontic taxa (*e.g. Diploneis didyma*, *Stephanodiscus hantzschii*) were less abundant and reached up to 30%. Dominance of eutraphentic diatoms was characteristic in all samples (max. up to 75%), mostly represented by *Aulacoseira granulata*, *Fragilaria brevistriata*, and *Fragilaria pinnata*. A group of species with undefined trophic requirements formed a major component (max. up to 64%). In this group, *Fragilaria martyi* and *Melosira dickiei* formed the largest percentages. The contribution of the most abundant saprobity groups amounted to 63% of β-mesosaprobic (*Aulacoseira granulata* and *Fragilaria martyi*) and 15% of α-me-sosaprobic (*Cyclotella meneghiniana*, *Rhoicosphenia abbreviata* Figs 5A, 5B).

Core 42/99

In this core the diatom flora was distributed unequally. Beginning from the depth of 55 cm down, sediments of some stratigraphic units were barren while in other only a few samples contained diatoms. In several samples of the lowermost part of the core, diatoms appeared in low quantities. Altogether 120 diatom species have been identified in core 42/99. A single diatom assemblage zone (DAZ 42/99/1) was distinguished in the core studied.

DAZ 42/99/1 encompassed the sediment interval of 60–10 cm representing the last *ca.* 2 thousands years. The sediment of this DAZ included the second part of the lpaz Z/42-7 and the lpaz Z/42-8 (Fig. 3). In DAZ 42/99/1 benthic taxa dominated (up to 60%) and were represented by *e.g. Fragilaria brevistriata*, *F. construens*, *F. pinnata* and *Cavinula scutelloides*. Planktonic species made up to 40%, and these were *e.g. Aulacoseira granulata*, *A. ambigua*, *Stephanodiscus alpinus* and *S. hantzschii*. With respect to halobous preferences, freshwater species dominated and reached 70–80% (max. 90%) with particularly abundant *Aulacoseira granulata*, *Cavinula scutelloides* and *Fragilaria brevistriata*. Halophilous taxa (e.g. *Actinocyclus normanii*, *Cyclotella meneghiniana*) were less abundant (up to 20%). Brackish-water taxa were represented mostly by e.g. *Opephora olsenii*. Their relative abundance, except the uppermost sample (10 cm depth) did not exceed 10%. The contribution of the remaining halobous groups was indistinct and did not reach 1%. With respect to pH preferences, alkaliphilous taxa (*e.g. Aulacoseira granulata*, *Fragilaria pinnata*, *Fragilaria brevistriata*) with maximum abundance up to 90% and of alkalibiontic taxa (*e.g. Cavinula scutelloides*, *Stephanodiscus hantzschii* and *Opephora olsenii*), which constituted up to 10% dominated. Dominance of eutraphentic diatoms was characteristic in all samples (with maximum abundance up to 80–90%), mostly represented by *e.g. Aulacoseira granulata*, *Fragilaria brevistriata*, *Cavinula scutelloides*, and *Cyclostephanos dubius*. Eutrophic-dystrophic species formed a major component (max. up to 7.8%). Among them most frequently occurred *Stephanodiscus alpinus*. With respect to saprobity preferences, β-mesosaprobic taxa dominated (up to 72%). In this group, *Cavinula scutelloides*, *Aulacoseira italica,* and *Cocconeis disculus* formed the largest share. In relatively high quantities (up to 25%), oligosaprobic species occurred and were represented by *Diploneis domblittensis* and *Fragilaria brevistriata* (Figs 6A, 6B).

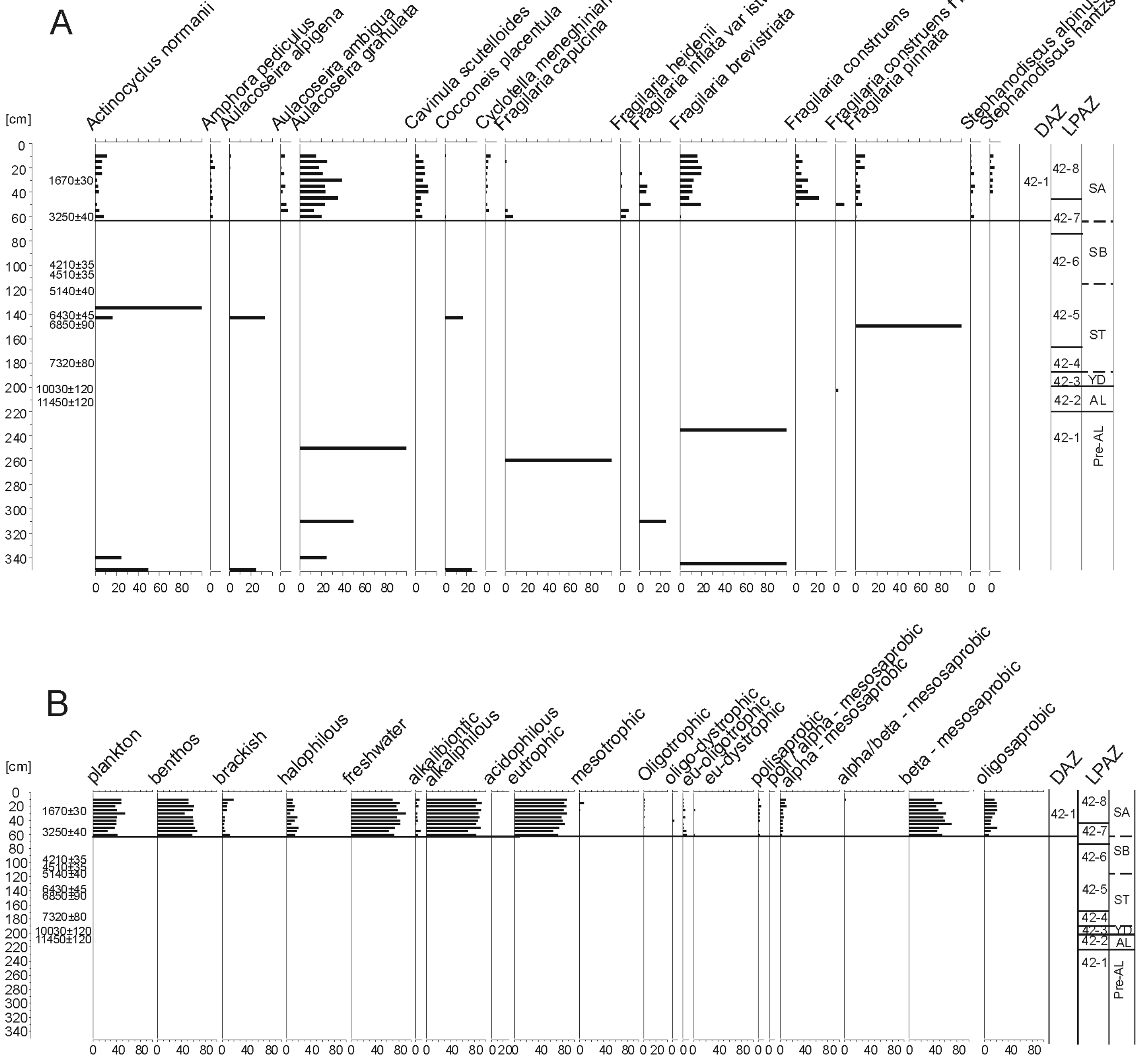

Fig. 6. *A:* Distribution of dominant diatom species in the sediments of core No 42. **B:** Distribution of diatom ecological groups in the sediments of core No 42.

In the lower part of the core diatoms occurred only in some samples with major sediment intervals forming hiatuses in the diatom record. Therefore no DAZ were distinguished in this part of the profile. Of these sections relatively well developed was diatom flora occurring in the Allerød sediments (lpaz Z/42-2). Included in this group are *Actinocyclus normanii*, *Aulacoseira granulata*, *Cocconeis placentula* and *Fragilaria brevistriata*.

DISCUSSION

The Szczecin Lagoon is an area influenced by the Odra River and by the saline waters of the Baltic Sea. Such a transition zone between different water masses creates specific life conditions and offers interesting opportunities for environmental and ecological studies. Successive changes in species composition of the diatom flora from sediment cores allowed quite a reliable reconstruction of changing conditions during the Late Glacial and Holocene history of the lagoon. Unlike the Holocene, the Late Glacial diatom flora is only found occasionally and provides a limited insight into the palaeogeography of this developmental stage of the Szczecin Lagoon. So far only a single core (42/99) contained the Late Glacial (Pre-Allerřd, Allerød and Younger Dryas) diatoms. This is quite different from other known studies of the Late Glacial deposits. Diatom floras from this period were encountered in a number of studies in Europe (*e.g.* Marciniak 1981, Jensen *et al.* 1997, Bogaczewicz-Adamczak 2001, Witak 2002), United States (e.g. Stoermer *et al.* 1988), Near East (*e.g.* Lake Zeribar in Iran, Snyder *et al.* 2001). Interesting, however, is that the flora occurring in core 42/99 represents various aquatic environments, including riverine ones, whereas the other floras referred to are found exclusively in lacustrine sediments. The presence of diatoms in these deposits may imply that in generally harsh sedimentary environment there existed kind of niches which favoured the survival of diatoms in the fossil record. The most interesting phenomenon is the occurrence of *Actinocyclus normanii* in Late Glacial fluvial sediments. A diatom species widespread in modern eutrophicated European rivers which is nowadays thought to be an invasive form (e.g. Danube, Main, Rhine; Kiss *et al.* 1990). The appearance of this species in some European rivers is well dated. In river Havel in Berlin it was found in the early 1900s. This species is also abundant in brackish waters of the Baltic Sea (Witkowski 1994) and of other coastal areas including Northern Atlantic (e.g. Metzeltin, Witkowski 1996). In core 42/99 this species appeared at least 3 times in the geological record. At first it was found in the lowermost part of the core in riverine sediments below the Allerød (lpaz Z/42-1). The second time it occurred at the depth interval of 130–140 cm. This sediment represents lpaz Z/42-5 and the level can be dated approximately at about 6 thousands years BP. Therefore the sediment with *A. normanii* is related to the onset of the marine transgression in the area of the Szczecin Lagoon. The third appearance of *A. normanii* is related to the uppermost 60 cm of the sediment and represents lagoonary deposits. Results of our study with respect to *A. normanii* show that taxa believed to be invasive and related to the human introduction in last decades might have already occurred in certain geographical regions in this particular case Central Europe.

Diatom analyses of cores 3/98 and 39/99 (cf. also core 3/96 in Borówka *et al.* 2002, Witkowski 2003a) (except core 42/99 which has interesting, but mostly fragmentary record) revealed three distinct developmental stages of the Szczecin Lagoon. The results of the diatom analyses are supported by the results of the palynological, macrofossil and malacological studies. In the Early and Middle Holocene, the Szczecin Lagoon basin was filled in with limnic-swampy deposits. Swamps composed of telmatic and aquatic flora and fauna developed (Latałowa, Święta 2003, Borówka *et al.* 2002). Borówka *et al.* (1999) and Witkowski *et al.* (2003a, b) showed that abundant epiphytic diatoms occur in this part of the sediment. This may point to an existence of shallow-water limnic reservoirs. Studies of malacofauna (Borówka *et al.* 2000, Woziński *et al.* 2003) and macroscopic remains (Latałowa, Święta 2003) confirm these findings. In the cores studied the occurrence of freshwater and halophilous diatom taxa *e.g. Fragilaria brevistriata*, *Stephanodiscus hantzschii*, and *Cyclotella meneghiniana* characterises a series of limnic-swampy deposits. This stage of the Szczecin Lagoon formation covers the time span from the beginning of the Holocene to *ca.* 6200 ^{14}C years BP (Borówka *et al.* 2002).

In the sediments overlying the lowermost diatom assemblage zone, diatoms are very poorly represented. This phenomenon is apparently related to a shallow marine embayment having been formed here after the Littorina transgression at the end of the Middle Holocene (Borówka *et al.* 2002, Woziński *et al.* 2003). The marine origin of the series in question is clearly confirmed by malacological analysis. The biometric characteristics of the bivalve *Cardium glaucum* showed that at this time the salinity of the so-called "Szczecin Bay" was higher than in the recent Pomeranian Bay (Bo- rówka *et al.* 2000). Microscopic Foraminifers and cysts of Dinophyceae abundantly present in the pollen slides confirm the brackish-marine environment (Latałowa 2003). Diatom valves found in these deposits are characteristic of the marine littoral zone (Witkowski 1991, 1994). In the samples analysed, usually single, fragmented specimens were observed *e.g. Fragilaria fasciculata*, *Catenula adhaevens* and *Cocconeis hauniensis*. A high content of sandy sediments and the action of waves and currents may have caused this.

The beginning of the uppermost stage of the Szczecin Lagoon formation DAZ 3/98/3, 39/99/3 and 42/99/1 is related to the late phase of isolation from marine influences in the Late Holocene (*ca.* 2 800 BP). Abrasion processes on the morainic shores of the Uznam/Usedom and Wolin Islands caused the development of a sand barrier in the area of the recent Swina Barrier (Keilhack 1911–1912, Prusinkiewicz, Noryśkiewicz 1966, Osadczuk K. 2002). The isolation of the lagoon from marine waters resulted in a change of the deposition processes. The lagoonary sediments contain predominantly freshwater diatom taxa *e.g. Aulacoseira granulata*, *Ellerbeckia arenaria*, *Fragilaria construens*. The accumulation of this type of deposits has continued in the Szczecin Lagoon until today (Borówka *et al.* 2002).

Diatoms are one of the best indicators of salinity changes (Simonsen 1962, Witkowski 1994, Snyder *et al.* 2001, Witkowski *et al.* 2004). In the material studied, changes in the environmental conditions caused variations in the diatom composition with regard to salinity but in all samples freshwater forms were the most abundant.

In the most recent time the chemical discharge from the industrialised and urbanised Odra River basin resulted in a strong increase of eutrophication in the Szczecin Lagoon (Mutko 1994). The result of this process is a large quantity of diatoms typical of eutrophicated waters in the material studied. Their percentage increases towards the top of the sediments studied. *Cyclotella meneghiniana*, *Stephanodiscus hantzschii* and *Actinocyclus normanii* are the most abundant. These taxa are considered the best indicators for determining the trophic status of an aquatic environment (Lange-Bertalot 1979, Witkowski 1994, Andreen *et al.* 1999, Bąk 2004). An increased influx of organic pollutants into the Szczecin Lagoon waters is also recognisable from the diatom record.

Environmental changes both of natural and of human origin distinctly affected the species composition of the diatom flora in the Szczecin Lagoon. The number of taxa identified in our material amounted to 455. When compared to the number of diatom taxa in recent Szczecin Lagoon, the difference is relatively low. Bąk (2004) identified in the recent Szczecin Lagoon 521 taxa. She also identified a number of taxa which were only present either in recent flora or in the sedimentary material. 256 of these taxa appeared only in the recent flora while 82 of them occurred infrequently in the sediments and were absent in modern diatom flora of the Szczecin Lagoon.

CONCLUSIONS

Generally diatom assemblages identified in the sediment cores studied enabled a reconstruction of the environmental and ecological conditions during Holocene in the Szczecin Lagoon basin. Unlike the Holocene, the diatom record in the Late Glacial was fragmentary, but some interesting information is also gained from the present diatom analysis.

1. Domination of benthic fresh water forms in the lowermost part of the cores studied reveals that Szczecin Lagoon was from the very beginning a shallow lacustrine/swampy (flow through) basin with minor influences of saline waters from the Pomeranian Bay. After the *Littorina* transgression the Lagoon constituted an open marine bay. The last development stage is the isolation of the Szczecin Lagoon from direct marine influences. These three stages are also reflected in changes of the diatom species composition.

2. The distinct majority of the species identified is characteristic of eutrophicated waters. This testifies to the eutrophic nature of the Szczecin Lagoon waters since the early developmental stage in the Early Holocene.

3. Increasing pollution and eutrophication of the Szczecin Lagoon waters is recorded in the uppermost sediments. The diatom assemblage of these sediments is dominated by resistant taxa indicative for human impact with *Aulacoseira granulata*, *Stephanodiscus hantzschii* and *Cyclotella meneghiniana* as representative forms.

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