Evidence of cultural eutrophication of the Gulf of Gdańsk based on diatom analysis

by

Jarosław Pędziński*,
Małgorzata Witak

University of Gdańsk, Faculty of Oceanography and Geography, Institute of Oceanography, Department of Marine Geology, Al. M. Piłsudskiego 46, 81-378 Gdynia, Poland

* Corresponding author: *jaroslaw.pedzinski@ug.edu.pl*

Abstract

The objective of this study was to reconstruct the environmental changes in the Gulf of Gdańsk in the last 200 years. Four subbottom sediment cores were analyzed with respect to diatom flora and anthropogenic effects. The so-called "anthropogenic assemblage" – a result of cultural eutrophication – was observed in the surface sediments. Changes in the species composition may have been caused by the increased use of fertilizers, nitrogen loads and increasing organic matter concentration. Three phases (A, B and C) were distinguished based on the floristic spectrum, which clearly indicates trophic changes in the study area.

Introduction

Eutrophication is defined as an increased input of nutrients (nitrogen, phosphorus) or organic matter into an aquatic ecosystem, followed by increasing primary production (e.g. Nixon 1995). Eutrophication of water bodies is characterized by excessive growth of plants and algae due to the increased availability of limiting growth factors needed for photosynthesis, such as sunlight, carbon dioxide, and nutrient fertilizers (Schindler 2006). Eutrophication has been occurring naturally for over a million years as seas and other water bodies age and fill with sediments (Carpenter 1981).

Natural eutrophication is a long-term process, to some extent dependent on temperature, which occurs in all water bodies (e.g. ponds, lakes, seas, oceans). Initially, it is very beneficial for the development of plants and fish (Andrulewicz et al. 1998). Natural factors include seasonal cycles of assimilation and demineralization of nitrogen and phosphorus. These factors contribute to the process of natural eutrophication. It is a slow cycle that involves deposition and processing of organic matter from natural sources. The course of this process depends on the type of geological substrate, river network, climate and features in a catchment. This type of eutrophication is usually reversible and does not cause damage to the environment (Pliński 1979).

On the other hand, too large inflows of organic compounds contribute to progressive eutrophication (Leśniewska & Witak 2008; 2011). Cultural eutrophication occurs when the amount of nutrients in the water changes as a result of human activity and the rate of the eutrophication process increases significantly. The increased cultural eutrophication caused by anthropopressure is a pressing issue of the 20th and 21st centuries. Human activities have primarily accelerated the rate and extent of eutrophication through both point-source discharges and non-point source loadings of limiting nutrients, such as nitrogen and phosphorus, into aquatic ecosystems, which has dramatic consequences for drinking water sources, fisheries, and recreational water bodies (Carpenter et al. 1998). The main sources of eutrophication are agriculture, husbandry, industries, aquaculture, municipal sewage water, river run-off, erosion and atmospheric deposition (Stålnacke 1996; Elmgren & Larson 2001; Wassmann & Olli 2004).

The most conspicuous effect of cultural eutrophication is the formation of dense blooms of noxious phytoplankton, which reduces the transparency of water and its quality. Algal blooms reduce the penetration of light and, consequently, the growth of plants, causing their death in littoral zones (Lehtiniemi et al. 2005). Furthermore, the high rate of photosynthesis associated with eutrophication can deplete dissolved inorganic carbon resources and raise pH to extreme levels (Turner & Chislock 2010). When these dense algal blooms eventually die, microbial decomposition severely depletes dissolved oxygen, creating a hypoxic or anoxic "dead zone" lacking sufficient oxygen to support most organisms (Arend et al. 2011). Furthermore, such hypoxic events are particularly common in marine coastal environments surrounding large nutrient-rich rivers (Diaz & Rosenberg 1995). Consequently, eutrophication is a condition in an aquatic ecosystem where high nutrient concentrations stimulate the growth of algae, which leads to imbalanced functioning of the system, such as: (1) intense algal growth, (2) production of excess organic matter, (3) increase in oxygen consumption, (4) oxygen depletion with recurrent internal loadings of nutrients, and (5) death of benthic organisms, including fish (HELCOM 2007).

Eutrophication of marine waters is thoroughly described, both globally and regionally. Cultural and anthropogenic nutrient enrichment in the marine environment was discussed by e.g. Cloern (2001), Boesch (2002), de Jonge et al. (2002), and Wassmann & Olli (2004). The problem of eutrophication concerns not only the Baltic Sea (Håkanson & Bryhn 2008; Voss et al. 2011), but also other seas and coastal zones (Heisler et al. 2008; Pearl 2009; Smith & Schindler 2009). The Baltic Sea is a semi-enclosed brackish basin, considered to be one of the most contaminated seas. The coastal zone of the Baltic Sea is relatively small and shallow with limited water exchange. Therefore, this region is very sensitive to the impact of pollutants (Andrén 1999; Clark 2001). With 16 million people living in the immediate vicinity of the coastal zone and a total of 85 million living in the catchment area, the human impact on the Baltic Sea is significant (HELCOM 2002; Łysiak-Pastuszak et al. 2004). The largest inflow of riverine waters as well as the narrow and shallow entrance to the North Sea reduce the water exchange and contribute to the brackish character of the Baltic Sea. The largest rivers, such as the Vistula, the Neva, the Daugava, the Niemen and the Oder, supply the ecosystem with freshwater and a large amount of nutrients (Stålnacke 1996; Schernewski & Neumann 2005).

While at the beginning of the 19th century the Baltic Sea was a clean oligotrophic sea (Wulff et al. 2007; Österblom et al. 2007), it is now considered a strongly contaminated eutrophic basin (Andrén et al. 1999; Łysiak-Pastuszak et al. 2004). Since 1900, the amount of nitrogen introduced into the Baltic Sea has

increased four times and the amount of phosphorous – eight times (Larson et al. 1985; Glasby & Szefler 1998). The main sources of biogenic substances are waters of the Vistula River, which account for about 15% of the total phosphorus load and about 19% of the total nitrogen discharge from rivers into the Baltic Sea (Andrulewicz & Witek 2002). However, nutrient concentrations and loads supplied by the Vistula River have recently shown significant downward trends. The total concentration of phosphorus and nitrogen supplied by the waters of the Vistula River has decreased by about 15% and 20%, respectively (Pastuszak et al. 2012).

The Gulf of Gdańsk is considered to be a highly eutrophicated region, with the large-scale growth of filamentous brown algae and high concentrations of chlorophyll a as the main indicators (Kruk-Dowgiałło 1996; Olenina & Kavolyte 1997). Furthermore, extensive summer blooms of cyanobacteria were observed (Mazur-Marzec et al. 2006; Mazur-Marzec & Pliński 2009). The growth of phytoplankton organisms is the most frequently used indicator of eutrophication. Extensive cyanobacteria blooms seriously affect water quality as they cause deoxygenation and production of hydrogen sulfide, a process that is usually accompanied by unpleasant odor. Recent studies (2009–2011), however, indicate a gradual improvement in the trophic status of the Gulf of Gdańsk, as no reports of abundant or extensive cyanobacteria blooms have been presented lately. This should result in a lower risk of toxic cyanobacteria blooms (Mazur-Marzec et al. 2012).

Progressive eutrophication in the study area is also visible in the diatom assemblage represented by diatoms with high edaphic requirements and dominated by pollution resistant taxa such as *Cyclotella atomus*, *C. choctawhatcheeana*, *C. meneghiniana*, *Stephanodiscus hantzschii* and *Thalassiosira levanderi*. These species are present in the so-called "anthropogenic assemblage" (e.g. Witkowski 1994; Witkowski & Pempkowiak 1995; Stachura-Suchoples 1999; Witak et al. 2006; Leśniewska & Witak 2008; 2011; Witak 2010).

However, the knowledge about cultural eutrophication in the Gulf of Gdańsk is still incomplete. Our research is important to gain knowledge about progressive eutrophication. The studied material consists of four sediment cores collected from different locations, depth and distance from the Vistula mouth.

The objectives of this study were (1) to determine the diversity and abundance of diatoms in four cores collected from different regions of the Gulf of Gdańsk, (2) to distinguish diatom assemblage zones (DAZ) based on floristic spectra and ecological groups in subbottom sediments, (3) to compare distinguished zones with respect to habitat, salinity, trophic status and saprobic preferences of the main species, and (4) to reconstruct trophic changes recorded in the diatom flora.

Materials and methods

Four sediment cores were collected in different parts of the Gulf of Gdańsk using the Niemistö corer during a cruise of ORP "Heweliusz" in 2014 organized by the Institute of Oceanography, University of Gdańsk (Dr. hab. Dorota Burska, Associate Professor). Core W9 was collected in the open part of the Gulf of Gdańsk, north of the Vistula mouth, and core ZP1 in the outer part of Puck Bay. Core UP10 was collected on the offshore side of the Hel Peninsula, whereas core GG was drilled in the Gdańsk Deep (Fig. 1). The core parameters are presented in Table 1.

Sediment samples were collected for diatom analysis at irregular intervals: first every 1 cm (to a depth of 5 cm), then every 2 cm (to a depth of 7 cm), every 3 cm and 5 cm at the end of the cores, respectively. Diatom samples were prepared according to standard methods (Battarbee 1986). The random settling technique was used (Bodén 1991) to estimate the concentration of siliceous microfossils per unit weight of dry sediment (absolute abundance). Quantitative analysis was carried out with a Nikon ECLIPSE400 microscope at a magnification of × 1000.

The counting method of Schrader and Gersonde (1978) was used. From 500 to 800 valves were counted

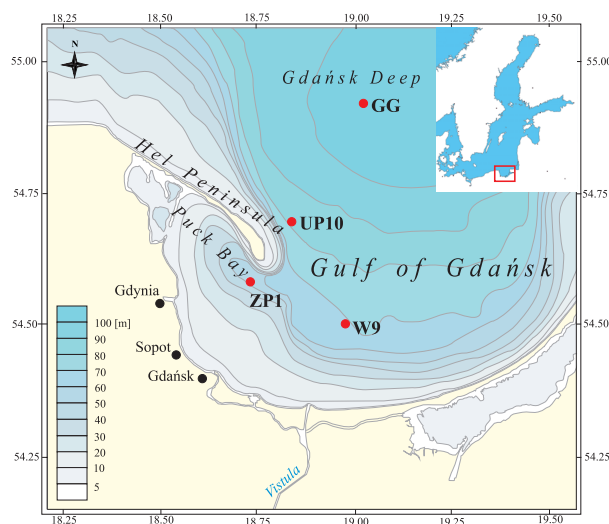**Figure 1**

Location of the analyzed cores

Table 1

Parameters of the analyzed cores

Core	φ	λ	Core length [cm]	Water depth [m]
W9	54.56	18.97	13	49.5
ZP1	54.59	18.73	28	50.2
UP10	54.67	18.89	35	79.7
GG	54.87	19.12	33	102

in each sample to estimate the percentage abundance of particular taxa. The raw counts were transformed into relative abundance of the total frustules counted. The taxonomy and ecological information (habitat, salinity, trophic and saprobic status) were primarily based on Hustedt (1927–1966), Krammer and Lange-Bertalot (1986; 1988; 1991a; 1991b), Pankow (1990), Denys (1991), Vos and de Wolf (1993), van Dam et al. *(*1994), Witkowski et al. (2000). However, for some marine or brackish-water species, occurring sometimes with a higher frequency, for example *Coscinodiscus granii*, *Fragilariopsis cylindrus*, *Pseudosolenia calcar-avis*, *Thalassiosira eccentrica*, trophic and saprobic preferences are unknown. Percentage content of all individual taxa as well as all ecological groups was estimated for each sample. Diatom assemblage zones (DAZ) in fossil sequences were defined using constrained hierarchical clustering, with clusters constrained by sample order. Diatom relative abundance data were square root transformed prior to cluster analysis in order to stabilize their variances. The analysis was performed using Tilia version 2.0.37 (Grimm 2011).

Results

Quantitative and qualitative analyses indicate that the diatom flora of subsurface muddy and silty sediments in the study area was generally abundant

and well preserved. In many samples, however, an admixture of broken frustules was observed, which greatly hindered their taxonomic identification. A total of 248 species, subspecies, varieties and forms belonging to 62 genera were identified in the studied material. However, the results show considerable differences in the number of identified taxa between the cores (Table 2). The list of the main diatom species and their ecological preferences is presented in Table 3.

A higher species diversity (146 species and 48 genera) was observed in core W9 collected in the north of the Vistula mouth. In this core, benthic, oligohalobous indifferent, eutraphentic and eu-mesotraphentic, as well as α- to β-mesosaprobous taxa constituted the largest group. Whereas, the lowest floristic diversity was determined in core GG collected in the Gdańsk Deep (115 species and 39 genera), where the number of taxa belonging to the ecological groups mentioned above was usually the lowest. Noteworthy is the highest diversity of planktic, euhalobous, oligotraphentic and oligosaprobous groups in core UP10 drilled north of the Hel Peninsula.

Due to the location of the cores, planktic taxa dominated in the whole studied material. Most of them belong to the euhalobous (marine) or mesohalobous (brackish-water) group and therefore they constitute an autochthonous community. Oligohalobous diatoms as well as halophilous, indifferent and freshwater taxa, tolerating low salinity, were also observed. Some of the freshwater diatoms are of riverine origin. They are transported by nutrient-rich waters of rivers, mainly through the Vistula River. Benthic taxa also belong to the allochthonous assemblage, as observed in cores GG and UP10 that come from the coastal zone of the Gulf of Gdańsk. Several zones were distinguished based on floristic changes observed in the vertical structures of the analyzed cores (Figs 2, 3, 4, 5).

Table 2

The number of diatom taxa in all ecological groups

Core	Total		Habitat		Salinity				Trophy							Saprobity						
	spec	gen	p	b	e	m	oh	oi	eut	eu-met	met	me-olt	olt	eu-dyt	ir	pos	α-mes	α-β-mes	β-mes	ols	ks	ir
All	248	62	65	183	59	47	29	113	64	32	12	3	17	5	135	3	28	7	67	15	1	127
W9	146	48	31	115	26	29	21	70	53	26	6	2	9	2	48	3	18	5	48	7	1	64
ZP1	138	48	34	104	37	28	20	53	48	18	7	–	8	-	57	3	16	5	38	5	1	70
UP10	133	40	49	84	37	26	10	60	42	17	6	1	13	2	52	2	12	5	32	12	–	70
GG	115	39	40	75	31	28	16	40	38	17	5	1	7	2	45	2	12	5	37	5	–	54

spec – species, gen – genera; **Habitat system (Round 1981):** p – plankton, b – benthos; **Salinity system (Kolbe 1927):** e – euhalobous (marine), m – mesohalobous (brackish water), oh – oligohalobous halophilous (slightly brackish water), oi – oligohalobous indifferent (freshwater); **Trophic system (Neumann 1932):** eut – eutraphentic, eu-met – eu-mesotraphentic, met – mesotraphentic, me-olt – meso-oligotraphentic, olt – oligotraphentic, eu-dyt – eu-dystraphentic, ir – irrelevant; **Saprobic system (Kolkwitz and Marsson 1908):** pos – polysaprobous, α-mes – α-mesosaprobous, α-β-mes – α-β-mesosaprobous, β-mes – β-mesosaprobous, ols – oligosaprobous, ks – xenosaprobous, ir – irrelevant

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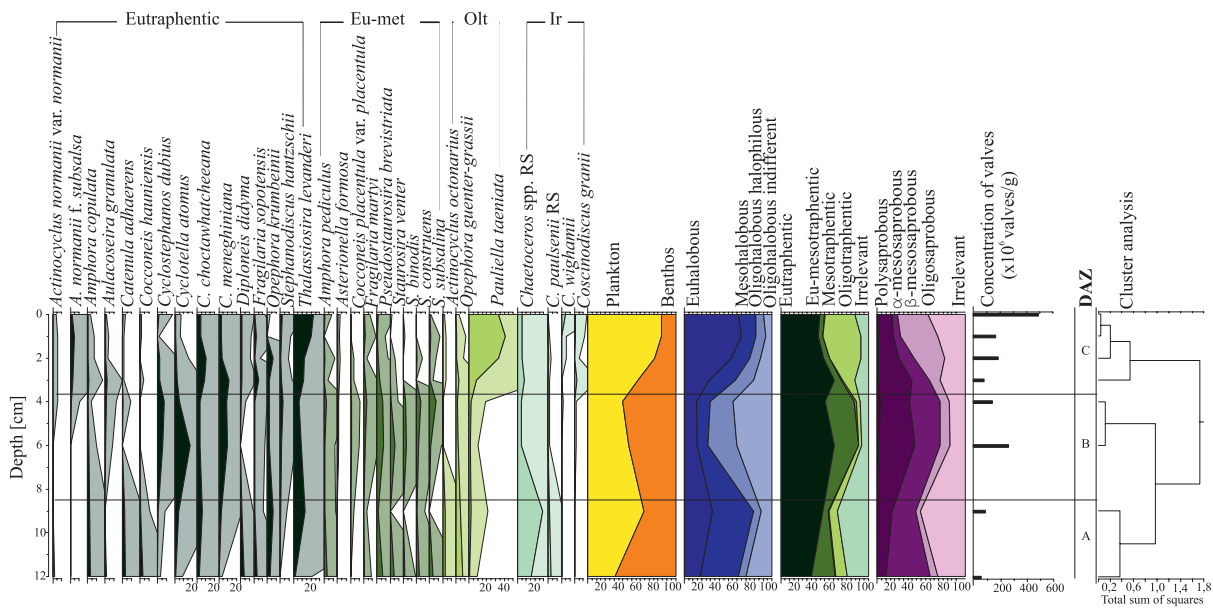**Core W9 (water depth 49.5 m)**

Figure 2

Diatom record of core W9, for explanations see Table 2
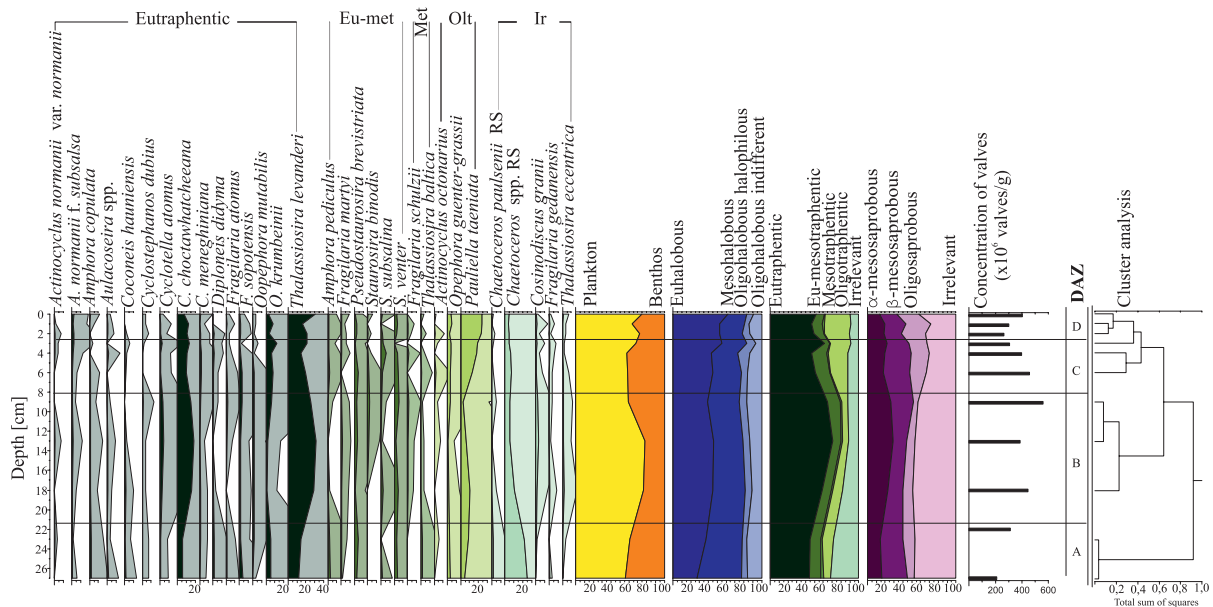
Core ZP1 (water depth 50.2 m)

Figure 3

Diatom record of core ZP1, for explanations see Table 2

Diatom biostratigraphy of core W9

W9-A *Chaetoceros* spp. RS – *Thalassiosira levanderi* DAZ (12–9 cm). The diatom community was rather rare but represented by numerous taxa

(81 species and 31 genera). Most frustules were poorly preserved. The poor state of preservation and the high degree of fragmentation of frustules was probably caused by mechanical and chemical destruction. The lower part of the zone was dominated
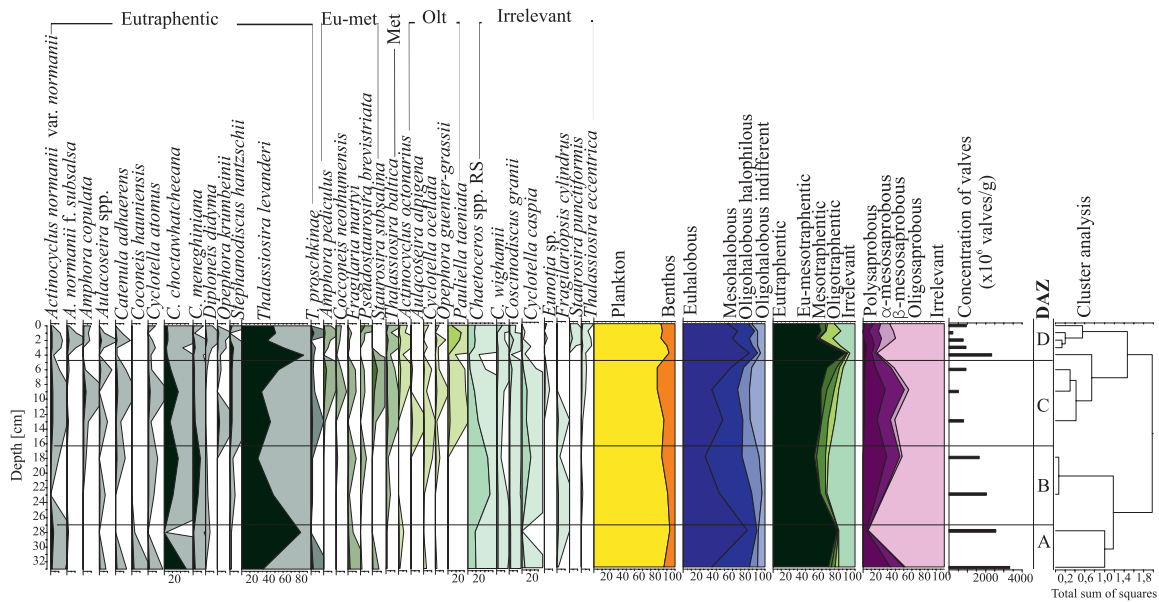
Core UP10 (water depth 79.7 m)

Figure 4

Diatom record of core UP10, for explanations see Table 2

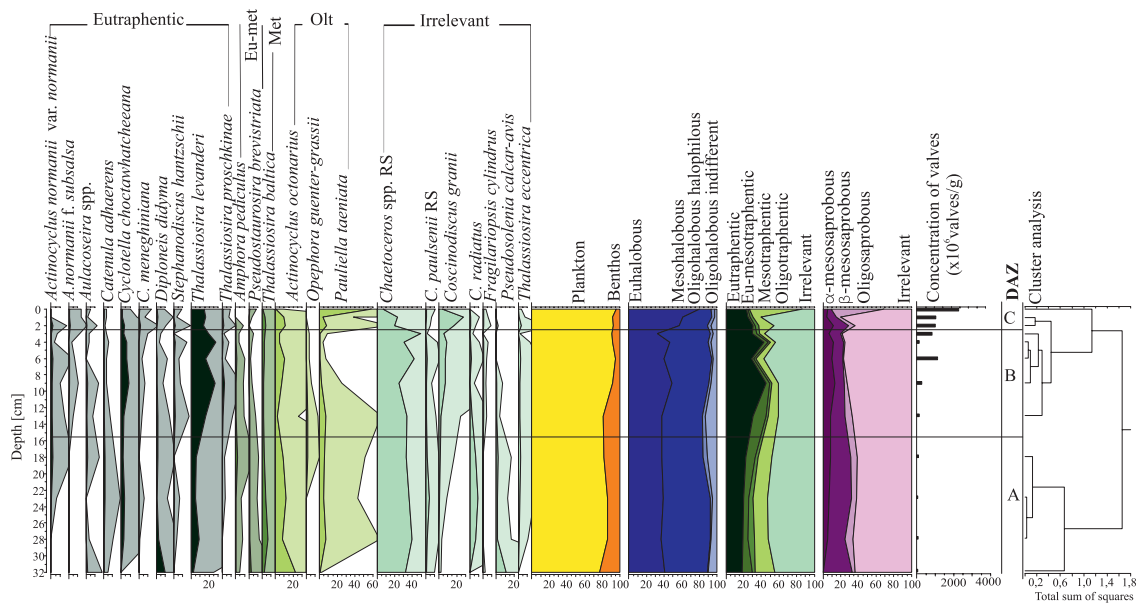Core GG (water depth 102 m)

Figure 5

Diatom record of core GG, for explanations see Table 2

by benthic species (ca. 60%), including mainly eutraphentic (*Amphora copulata*, *Catenula adhaerens*, *Opephora krumbeinii*, *Thalassiosira levanderi*) and eu-mesotraphentic diatoms (*Amphora pediculus*, *Cocconeis placentula* var. *placentula*, *Staurosira binodis*, *S. construens*, *S. subsalina*, *S. venter*; Fig. 2). All these taxa belong to the β-mesosaprobous group. However, they are known from waters of either low or high salinity. The increase in the number of planktic taxa was observed in the upper part of the zone (up to ca. 60%), which is associated with a higher content of *Chaetoceros* spp. RS. They were accompanied by

Table 3

Autecology of the main diatom taxa recorded in the sediment cores of the study area

Diatom taxa	Habitat	Salinity	Trophy	Saprobity
Actinocyclus normanii var. *normanii* (Gregory) Hustedt	p	oi	eut	α-mes
A. normanii f. *subsalsa* (Juhlin-Dannfelt) Hustedt	p	oh	eut	α-mes
A. octonarius Ehrenberg	p	e	olt	β-mes
Amphora copulata (Kützing) Schoeneman et Archibald	b	oi	eut	α-β-mes
A. pediculus (Kützing) Grunow	b	oi	eu-met	β-mes
Aulacoseira granulata (Ehrenberg) Simonsen	p	oi	eut	α-mes
Cyclotella atomus Hustedt	p	oh	eut	α-mes
C. caspia Grunow	p	oh	ir	ir
C. choctawhatcheeana Prasad	p	m	eut	α-mes
C. meneghiniana Kützing	b	oh	eut	α-mes
Cocconeis hauniensis Witkowski	b	m	eut	β-mes
C. neothumensis Krammer	b	oi	eu-met	ols
C. placentula var. *placentula* Ehrenberg	b	oi	eu-met	β-mes
Catenula adhaerens Mereschkovsky	b	e	eut	β-mes
Chaetoceros paulsenii RS Ostenfeld	p	m	ir	ir
Chaetoceros wighamii Brightwell	p	m	ir	ir
Coscinodiscus granii Gough	p	e	ir	ir
C. radiatus Ehrenberg	p	e	ir	ir
Cyclostephanos dubius (Fricke) Round	p	oi	eut	α-mes
Diploneis didyma (Ehrenberg) Cleve	b	m	eut	ir
Fragilaria atomus Hustedt	b	m	eut	ir
F. gedanensis Witkowski	b	m	ir	ir
F. martyi (Héribaud) Lange-Bertalot	b	oi	eu-met	β-mes
F. schulzii Brockman	b	m	met	ir
F. sopotensis Witkowski et Lange- Bertalot	b	m	eut	α-mes
Fragilariopsis cylindrus (Grunow) Krieger	b	e	ir	ir
Opephora guenter-grassii (Witkowski et Lange-Bertalot) Sabbe et Vyverman	b	m	olt	β-mes
O. krumbeinii Witkowski, Witak et Stachura	b	e	eut	β-mes
O. mutabilis (Witkowski et Lange-Bertalot) Sabbe et Vyverman	b	m	eut	β-mes
Pauliella taeniata (Grunow) Round et Basson	p	e	olt	ols
Pseudosolenia calcar-avis (Schultze) Sundström	p	e	ir	ir
Pseudostaurosira brevistriata Williams et Round	b	oi	eu-met	ols
Staurosira binodis (Ehrenberg) Lange-Bertalot	b	oi	eu-met	β-mes
S. construens (Ehrenberg) Williams et Round	b	oi	eu-met	β-mes
S. punctiformis Witkowski, Metzeltin et Lange-Bertalot	b	oh	ir	ir
S. subsalina (Hustedt) Lange-Bertalot	b	oh	eu-met	β-mes
S. venter (Ehrenberg) Cleve et Möller	b	oi	eu-met	β-mes
Stephanodiscus hantzschii Grunow	p	oi	eut	pos
Thalassiosira baltica (Grunow) Ostenfeld	p	m	met	β-mes
T. eccentrica (Ehrenberg) Cleve	p	e	ir	ir
T. levanderi Van Goor	p	e	eut	ir
T. proschkinae Makarova	p	m	eut	ir

Habitat: p – plankton, b – benthos; **Salinity:** e – euhalobous (marine), m – mesohalobous (brackish water), oh – oligohalobous halophilous (slightly brackish water), oi – oligohalobous indifferent (freshwater); **Trophic:** eut – eutraphentic, eu-met – eu-mesotraphentic, met – mesotraphentic, olt – oligotraphentic, ir – irrelevant; **Saprobic:** pos – polysaprobous, α-mes – α-mesosaprobous, α-β-mes – α-β-mesosaprobous, β-mes – β-mesosaprobous, ols – oligosaprobous, ir – irrelevant

eutraphentic, α-mesosaprobous species *Cyclotella atomus, C. choctawhatcheeana* and *Cyclostephanos dubius*. The overall frequency of eutraphentic species increased toward the upper part of the zone from 30 to 50%, whereas the frequency of the eu-mesotraphentic group decreased from 25 to 10%. The concentration of valves was generally low and in the range of 59–92 × 10^6 valves g^{-1}.

W9-B *Cyclotella atomus – Cyclotella meneghiniana – Thalassiosira levanderi* **DAZ** (9–4 cm). The diatom flora was quantitatively rich (88 species and 40

genera) and much better preserved than in the lower section containing biogenic detritus. A clear increase in the frequency of diatoms preferring a high content of nutrients and organic matter was observed in the upward direction of the zone. In the planktic group, brackish-water *Chaetoceros* spp. RS dominated in the bottom part. They were replaced by oligohalobous, eutraphentic, α-mesosaprobous species, i.e. *Aulacoseira granulata*, *Cyclostephanos dubius* and *Cyclotella atomus*. The stable abundance (ca. 10%) of marine *Thalassiosira levanderi* was observed throughout the zone. Amongst benthic diatoms, *Cyclotella meneghiniana* representing the eutraphentic group and *Staurosira* spp. belonging to eu-mesotraphentic, β-mesosaprobous taxa occurred in large numbers in the upper part of the zone. The concentration of valves was higher than in the previous section (121–257 × 10^6 valves g^{-1}).

W9-C *Pauliella taeniata – Thalassiosira levanderi* **DAZ** (4–0 cm). The diatom taphocoenosis was abundant, quite well preserved and represented by 88 species belonging to 36 genera. The most striking feature of the diatom assemblage is a clear increase in the frequency of oligotraphentic and oligosaprobous taxa toward the upper part of the zone. The phenomenon is associated with the replacement of diatoms thriving in eutrophic conditions, i.e. *Actinocyclus normanii*, *Aulacoseira granulata*, *Cyclostephanos dubius*, *Cyclotella atomus*, *C. choctawhatcheeana*, *Stephanodiscus hantzschii*, by taxa well adapted to low concentrations of nutrients, i.e. *Pauliella taeniata*, which reached a maximum frequency of 40%. The important component of the plankton was also *Thalassiosira levanderi* (10–20%) belonging to the eutraphentic group. The diatom concentration ranged from 80 in the bottom part to 492 × 10^6 valves g^{-1} in the upper part of the zone.

Diatom biostratigraphy of core ZP1

ZP1-A *Chaetoceros* **spp. RS –** *Thalassiosira levanderi* **DAZ** (27–22 cm). The diatom assemblage of this zone was quantitatively rich (75 species and 32 genera) and generally well preserved. However, some valves were mechanically or/and chemically destroyed. Brackish-water *Chaetoceros* spp. RS and marine *Thalassiosira levanderi* were the most important components of the planktic group (65–70%; Fig. 3). They were accompanied by eutraphentic, α-mesosaprobous taxa, i.e. *Cyclotella atomus*, *C. choctawhatcheeana* and by oligotraphentic and oligosaprobous species *Pauliella taeniata*. Benthic diatoms were represented mostly by *Amphora*

copulata, *A. pediculus*, *Fragilaria sopotensis*, *Opephora krumbeinii*, *Pseudostaurosira brevistriata* and *Staurosira venter*, which prefer waters rich in nutrients and organic matter. The diatom concentration was relatively high and amounted to 211–313 × 10^6 valves g^{-1}.

ZP1-B *Thalassiosira levanderi – Cyclotella choctawhatcheeana* **DAZ** (22–8 cm). The diatom flora was represented by a species-rich (79 species and 33 genera) and well-preserved assemblage. *Chaetoceros* spp. RS and *Pauliella taeniata* were replaced by *Cyclotella atomus*, *C. choctawhatcheeana* and *Thalassiosira levanderi* in the upper part of the zone. In total, the frequency of plankton increased to ca. 80%. Benthic diatoms, mostly eutraphentic and eu-mesotraphentic α- to β-mesosaprobous, were represented by *Amphora* spp., *Cocconeis* spp., *Fragilaria* spp., *Opephora* spp. and *Staurosira* spp. Their frequency was higher (3–5%) at the bottom and at the top of the zone. The diatom concentration ranged from 387 to 562 × 10^6 valves g^{-1} in the upper part of the zone.

ZP1-C *Thalassiosira levanderi – Cyclotella choctawhatcheeana – Opephora krumbeinii* **DAZ** (8–3 cm). The diatom flora was generally well preserved and represented by 81 species belonging to 35 genera. The decrease in the content of the planktic group is correlated with the lower frequency of brackish-water *Chaetoceros* spp. RS and *Cyclotella choctawhatcheeana*, as well as marine *Thalassiosira levanderi*. At the same time, there was a significant increase from 5 to 20% in the abundance of the oligotraphentic and oligosaprobous species, *Pauliella taeniata*. In the benthic group, eutraphentic and eu-mesotraphentic species were observed commonly. Amongst them, *Opephora guenter-grassii*, *O. krumbeinii* and *Staurosira venter* were most frequently observed. The diatom concentration decreased from 458 to 307 × 10^6 valves g^{-1}.

ZP1-D *Pauliella taeniata – Thalassiosira levanderi* **DAZ** (3–0 cm). The diatom community was abundant, well preserved and diverse, comprising 79 species and 28 genera. The planktic group reached its maximum frequency (30%). The most characteristic feature is the gradual increase in the frequency of marine species *Pauliella taeniata* and *Thalassiosira levanderi* up to 25%. The benthic group was represented by the same taxa as in the previous zone, but their content was usually lower. The diatom concentration increased from 263 in the lower part to 403 × 10^6 valves g^{-1} in the surface layer.

Diatom biostratigraphy of core UP10

UP10-A *Thalassiosira levanderi – Cyclotella choctawhatcheeana* **DAZ** (33–27 cm). The diatom taphocoenosis was abundant, very well preserved, but the floristic diversity was rather low – with 53 species and 25 genera. Planktic forms occurred in large numbers (up to 90%) in the zone (Fig. 4). The main components were marine *Thalassiosira levanderi*, brackish-water *Chaetoceros* spp. RS and *Cyclotella choctawhatcheeana*. Benthic species were observed sporadically. Only *Amphora pediculus*, *Catenula adhaerens*, *Cyclotella meneghiniana* and *Fragilaria martyi* reached a frequency of 2%. Most diatoms found in the zone belong to the eutraphentic, α- to β-mesosaprobous group. The concentration of valves was very high, i.e. $3323–2564 \times 10^6$ valves g^{-1}.

UP10-B *Thalassiosira levanderi – Cyclotella choctawhatcheeana – Chaetoceros* **spp. RS DAZ** (27–17 cm). The diatom flora was represented by a well-preserved, species-poor assemblage, in which 25 genera and 45 species were identified. The most striking features of the assemblage are visible changes in the plankton structure. The content of *Thalassiosira levanderi* clearly decreased in the upward direction of the zone, whereas other planktic taxa, i.e. *Cyclotella caspia*, *C. choctawhatcheeana* and *Chaetoceros* spp. RS, were found more often. Benthic diatoms were still very rare, with the exception of *Cyclotella meneghiniana*, the content of which exceeded 5%. Noteworthy is the occurrence of the cold-water marine species *Fragilariopsis cylindrus* in this zone. The diatom concentration decreased from 2053 at the bottom to 1651×10^6 valves g^{-1} at the top of the section.

UP10-C *Thalassiosira levanderi – Cyclotella choctawhatcheeana – Staurosira subsalina* **DAZ** (17–5 cm). The diatom assemblage comprised 86 species representing 34 poorly preserved genera. Planktic species were abundant (up to 90%) and dominated by the marine species *Thalassiosira levanderi*, the frequency of which increased up to 75% in the upper part of the zone. *Chaetoceros* spp. RS, *Cyclotella caspia* and *C. choctawhatcheeana* showed the opposite tendency. Other planktic species, *Actinocyclus normanii* var. *normanii*, *Coscinodiscus granii*, *Pauliella taeniata* and *Stephanodiscus hantzschii*, were observed sporadically. Benthic diatoms occurred more often than in the previous zone. They were represented mainly by *Amphora copulata*, *A. pediculus*, *Catenula adhaerens*, *Cocconeis neothumensis*, *Cyclotella meneghiniana*, *Staurosira subsalina*, which developed well in eutrophic and mesosaprobic conditions. Marine cold-water *Fragilariopsis cylindrus* was observed in the lower part of the zone. The diatom concentration ranged from 514 to 920×10^6 valves g^{-1} in the upper part of the zone.

UP10-D *Pauliella taeniata – Thalassiosira levanderi* **DAZ** (5–0 cm). The diatom flora of this zone was rather rare and represented by a diverse assemblage comprising 78 species and 30 genera. Diatoms were well preserved, but many frustules were mechanically and/or chemically destroyed. Planktic diatoms dominated and their total frequency reached 80–92%. The main components of this group were marine taxa: *Thalassiosira levanderi*, *Pauliella taeniata* and *Coscinodiscus granii*. They were accompanied by taxa that prefer lower salinity, i.e. *Actinocyclus normanii* var. *normanii*, *Actinocyclus normanii* f. *subsalsa*, *Chaetoceros wighamii*, *Cyclotella choctawhatcheeana*, the frequency of which did not exceed 5%. In the benthic group, *Amphora* spp., *Cyclotella meneghiniana*, *Diploneis didyma*, *Opephora* spp. and *Staurosira* spp. were most frequently observed. The concentration of valves ranged from 209 to 2328×10^6 valves g^{-1}.

Diatom biostratigraphy of core GG

GG-A *Chaetoceros* **spp. RS –** *Actinocyclus octonarius – Pseudosolenia calcar-avis* **DAZ** (32–15 cm). Diatoms were very rare in the taphocoenosis, but represented by 80 species belonging to 34 genera. They were poorly preserved and many broken valves were observed. The diatom flora was dominated by planktic species, whose total frequency reached 85% (Fig. 5). The main component was *Chaetoceros* spp. RS (30–40%), accompanied by marine species, including oligotraphentic *Actinocyclus octonarius* and *Pauliella taeniata* as well as *Coscinodiscus* spp., whose trophic preferences are irrelevant. *Pseudosolenia calcar-avis* was often observed in the lowest part of the zone. Benthic taxa were rare and included freshwater *Amphora pediculus*, *Pseudostaurosira brevistriata*, brackish-water *Opephora guenter-grassii* and marine *Catenula adhaerens*. Most of them prefer eutrophic β-mesosaprobic conditions. The concentration of valves is very low and ranged from 31 to 69×10^6 valves g^{-1}.

GG-B *Chaetoceros* **spp. RS –** *Thalassiosira levanderi* **DAZ** (15–3 cm). The diatom taphocoenosis was in a poor state of preservation, but represented by as many as 72 species belonging 30 genera. Half of all diatoms were represented by resting spores of *Chaetoceros*. The frequency of marine species *Thalassiosira levanderi* gradually increased

toward the upper part of the zone. In addition, *Actinocyclus octonarius*, *Coscinodiscus granii*, *Cyclotella choctawhatcheeana* were abundant in the planktic group. The benthic group was observed very rarely, particularly in the middle and upper part of the zone. The diatom concentration increased from 96 at the bottom to 1136×10^6 valves g^{-1} at the top of the zone.

GG-C *Pauliella taeniata* – *Chaetoceros* spp. RS – *Coscinodiscus granii* DAZ (3–0 cm). The diatom community was well preserved, abundant and represented by diverse flora (72 species and 28 genera). Planktic taxa accounted for over 90% of the assemblage. Marine species – *Coscinodiscus granii*, *Pauliella taeniata* and *Thalassiosira levanderi* – were the main component. Freshwater species, *Aulacoseira* spp. and *Stephanodiscus hantzschii*, were rarely encountered. Oligohalobous halophilous taxa were represented by *Actinocyclus normanii* f. *subsalsa* and *Cyclotella meneghiniana*. Oligotraphentic and oligosaprobous diatoms (*Pauliella taeniata*, *Actinocyclus octonarius*) reached the highest frequency in this zone. The diatom concentration was very high and ranged from 1006 to 2268×10^6 valves g^{-1} in the surface layer.

Discussion

The results of the diatom analysis of all sediment cores enable the discussion on environmental changes in the Gulf of Gdańsk. Three different phases were distinguished in the study area based on the species composition, the relative abundance of the dominant taxa and the frequency of the ecological groups (Fig. 6).

Phase A

The first phase is recorded in the deepest sediments of all cores GG-I DAZ, UP10-I DAZ, ZP1-I DAZ and W9-I DAZ. The diatom flora preserved in these sediments was represented by planktic species. In cores W9 and ZP1, benthic forms were common in the bottom part of this phase. The diatom assemblages described in all zones were dominated by eutraphentic and eu-mesotraphentic species. Furthermore, diatoms with high edaphic requirements, such as *Actinocyclus normanii* var. *normanii* (α- mesosaprobous), *Amphora copulata* (α-β-mesosaprobous), *Catenula adhaerens* (β-mesosaprobous), *Cyclotella choctawhatcheeana* (α-mesosaprobous), *Diploneis didyma* (irrelevant), *Opephora krumbeinii* (β-mesosaprobous), were observed quite often. An important diatom was *Cyclotella choctawhatcheeana* (α- mesosaprobous). The
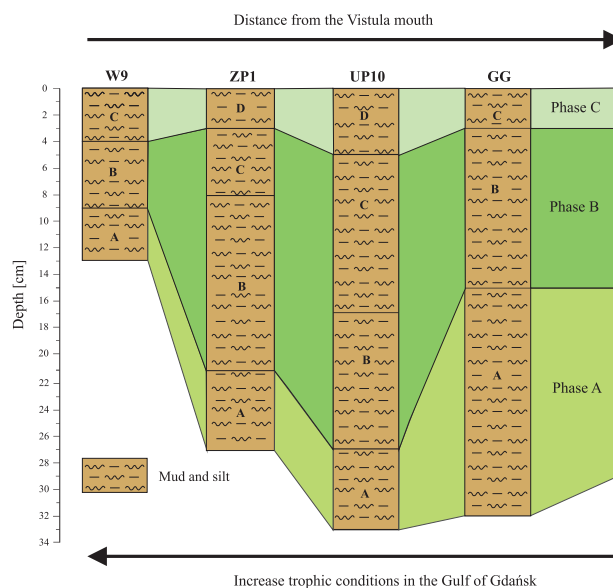

Figure 6

Correlation between the diatom assemblage zones distinguished in the cores

eu-mesotraphentic group was dominated by *Amphora pediculus* (β-mesosaprobous), *Pseudostaurosira brevistriata* (oligosaprobous) and *Thalassiosira baltica* (β-mesosaprobous), accompanied by *Fragilaria martyi* (β-mesosaprobous), *Staurosira construens* (β-mesosaprobous), *S. subsalina* (β-mesosaprobous), and *S. venter* (β-mesosaprobous). Resting spores of *Chaetoceros* were very common. According to Hajdu and Larsson (1990), *Chaetoceros* spp. RS dominate in the spring bloom after a cold winter in the Baltic Sea. However, ecological (e.g. trophic and saprobic) preferences of the taxon, are still unknown.

The main features of the diatom taphocoenoses preserved in the lower parts of the cores indicate the human impact. The high frequency of diatoms with high edaphic requirements observed in phase A can be related to urbanization and increased use of fertilizers in agriculture (Kowalkowski et al. 2012; Pastuszak et al. 2012) and industrialization of the catchment area. On the other hand, the eutraphentic species occurred in the Gdańsk Deep (core GG) with the lowest abundance. The diatom flora in this region was represented mainly by oligotraphentic taxa, which prefer clean waters and a low content of nutrients in pelagic zone, i.e. *Actinocyclus octonarius* and *Pauliella taeniata* in the water column and *Opephora guenter-grassii* in the benthic group. This shift indicates that changes in the diatom assemblages are directly associated with the distance from the Vistula estuary, which is the main source of biogenic substances in the studied area. The relation between the trophic and

saprobic groups indicates that waters in the first phase were rich in biogenic compounds and organic matter. The concentration of diatom valves was generally the lowest and ranged from 31 to 69×10^6 valves g^{-1} with one maximum of 3323×10^6 valves g^{-1} in UP10-A. The low concentration in the deepest part of the cores could result from the dissolution of valves in the water column and mechanical destruction.

Phase B

The second phase of environmental changes in the study area is described on the basis of the diatom flora of GG-II DAZ, UP10-II DAZ, UP10-III DAZ, ZP1-II DAZ, ZP1-III DAZ and W9-II DAZ. In phase B, significant changes in ecological groups, i.e. the trophic and saprobic ones, were observed. A very strong human impact on the species composition is documented in the planktic group with mainly small-sized forms. This fact can be associated with the decreasing depth of the euphotic zone, which is a result of the eutrophication process (Andrén et al. 1999; Witak 2010). The significant increase in the abundance of eutraphentic, eu-mesotraphentic and α- mesosaprobous taxa was observed in all diatom assemblages.

One of the most important species, especially in DAZ W9-II, was *Cyclotella meneghiniana*, considered to be one of the most typical indicators of anthropogenic assemblages (Witkowski 1994; Witkowski & Pempkowiak 1995; Leśniewska & Witak 2008; Witak 2010; Witak & Pędziński 2018). The species prefers eutrophic and hypertrophic conditions and tolerates polluted waters (van Dam et al. 1994; Stachura-Suchoples 2001). It was accompanied by *Cyclotella atomus* and *C. choctawhatcheeana*. Both species are eutraphentic/α-mesosaprobous and are abundant in waters with higher concentrations of phosphorous and inorganic nitrogen, moderately polluted, containing decaying organic matter (Stachura-Suchoples 2001; Bąk 2004). The small-celled cosmopolitan species, *C. choctawhatcheeana*, was confirmed to be one of the most tolerant diatoms in the study area (Witkowski 1994; Stachura-Suchoples 1999; 2001). *Cyclotella atomus* was abundant in core W9 collected to the north of the Vistula mouth. This taxon often occurs in bays and near estuaries, where the content of biogenic substances and organic matter is high in the water column.

The highest abundance of *Thalassiosira levanderi*, a very common marine planktic species in the surface sediments, is a very important observation. This taxon was considered tolerant of increased concentrations of phosphorus and nitrogen and is the main component

of the anthropogenic assemblage in the Gulf of Gdańsk (Witkowski 1994; Witkowski & Pempkowiak 1995; Witak 2000). *Opephora krumbeinii*, a small-sized species, was frequently observed in the benthic group, particularly in the upper part of ZP1-C DAZ. *Opephora krumbeinii* is known as a eutraphentic, β-mesosaprobic form. Eu-mesotraphentic species were also found in the oligohalobous group, i.e. *Pseudostaurosira brevistriata* (oligosaprobous)*, Staurosira subsalina* (β-mesosaprobous), *S. venter* (β-mesosaprobous). The highest frequency of these species was recorded in the vicinity of the Vistula mouth (core W9) and in the Outer Puck Bay (core ZP1). In this phase, resting spores of *Chaetoceros* spp. were most abundant. According to Grimm & Gill (1994), the occurrence of *Chaetoceros* spp. RS is associated with nutrient depletion toward the termination of a phytoplankton bloom. The abundance of eutraphentic/eu-mesotraphentic and pollution-tolerant taxa indicates a strong human impact and the most intensive cultural eutrophication in this phase. This is related to increased amounts of biogenic substances supplied by rivers, mainly the Vistula, since the 1980s. Excessive loads of biogenic salts come from the use of fertilizers in agriculture, urbanization, soil erosion, domestic, animal livestock and industrial sewage disposal leading to the degradation of water quality. As a consequence, nutrient enrichment leads to increased primary production and reduced light penetration, oxygen depletion, changes in biochemical cycles and biological structures, including the loss of biodiversity. The diatom valve concentration was generally higher compared to the previous interval with an amount of $96–2053 \times 10^6$ valves g^{-1}. This indicates that the diatoms were generally well preserved. The high concentration of diatoms may also be related to the high content of available biogenic substances. However, valves were sometimes mechanically and/or chemically destroyed, making it difficult to count them.

Phase C

The last phase C is recorded in GG-III DAZ, UP10-IV DAZ, ZP1-IV DAZ and W9-III DAZ. The most characteristic feature of these taphocoenoses is the abundance of marine forms, i.e. *Thalasiossira levanderi, Opephora krumbeinii*, which belong to the eutraphentic group. On the other hand, the highest frequency of *Pauliella taeniata, Actinocyclus octonarius* and *Opephora guenter-grassii* was observed. These species occurred in waters with low concentrations of phosphorous and inorganic nitrogen and developed in slightly polluted waters (Stachura-Suchoples 1999;

Bogaczewicz-Adamczak & Dziengo 2003).

The frequency of the cosmopolitan neritic planktic species, i.e. *Actinocyclus octonarius* (oligotraphentic, β-mesosaprobous), was high in GG-III DAZ. *Coscinodiscus granii* was often found and proved to be the dominant diatom blooming in early autumn, while *Pauliella taeniata, Thalassiosira levanderi* and *Chaetoceros* spp. RS dominate in the spring bloom after cold winters with extensive ice cover (Hasle & Syversten et al. 1997; Andrén et al. 2000). The most important component of this phase is *Pauliella taeniata*, which dominates in the spring bloom (Hajdu & Larson 1990).

Irrespective of the location, *Pauliella taeniata* was most frequently observed in the uppermost part of all cores. Perhaps the highest frequency of this species observed only in the upper parts of the cores results from the very low preservation potential (Denys 1991). *Pauliella taeniata* has a delicate, thin frustule and rarely occurs in the fossil state (Witak 2010). Such a high content of this taxon in the superficial sediments may be related to ice cover. It is an arctic species associated with the sea ice (Haecky et al. 1998) and an indicator of ice-cover conditions in the Baltic Sea. According to Höglander et al. (2004), this species occurs with a lower frequency in the spring bloom when the ice cover is limited. During harsh winters, characterized by the presence of thick ice cover, a high frequency of *Pauliella taeniata* was observed. These changes may have been induced by the shift in the NAO (North Atlantic Oscillation) index from a negative to positive phase (Tuovinen et al. 2010).

Another explanation of the abundance of *Pauliella taeniata* in the uppermost part of all cores may be related to the trophic conditions in the Gulf of Gdańsk. Undoubtedly, the changes in the trophic status in the Gulf of Gdańsk were caused by the use of fertilizers in agriculture and progressing urbanization of the catchment. Differences in the trophic status may result from the reduced use of fertilizers in the 1990s.

As a result, the gradual improvement in the water quality in the Gulf of Gdańsk has been observed. Therefore, the higher frequency of *Pauliella taeniata* could be related to these environmental changes. This hypothesis is confirmed by research conducted by Mazur-Marzec et al. (2012). The results show that symptoms of eutrophication are regressing. Recent studies have shown lower frequency and lower intensity of cyanobacterial blooms. This shift may be an indication of ongoing changes induced by the reduced nutrient loading and/or climate change. The diatom valve concentration was similar to the previous phase with a range of $80–2268 \times 10^6$ valves g^{-1}. This demonstrates good conditions during the fossilization process, which is due to the relatively short exposure of the surface and shallow subsurface (0–4 cm) sediments to the chemical dissolution and mechanical destruction.

Conclusions

The diatomological studies of four cores show abundant and diverse flora, which indicates the variability of ecological conditions in this area. Based on the species composition, the relative abundance of the dominant taxa and the frequency of the ecological groups, three phases can be distinguished, which provide the basis for reconstructing the environmental conditions of the study area. The diatom taphocoenoses from the lowest part of all cores correspond to phase A. In this phase, the diatom flora was represented mainly by eutraphentic and eu-mesotraphentic taxa, which proves the availability of biogenic salts in the catchment. However, the content of biogenic substances decreases in the Gdańsk Deep, as evidenced by the high frequency of oligotraphentic forms.

In the second phase B, the significant increase of diatoms with high edaphic requirements was observed. The distribution of subfossil diatom assemblages indicates that intensive industrialization and inflow of riverine waters lead to changes in the trophic status. In this phase, the high content of eutraphentic diatoms was observed in anthropogenic assemblages of the analyzed sediments. The anthropogenic diatom assemblage in the Gulf of Gdańsk was characterized by a decline in the floristic diversity, the abundance and the larger number of pollution-tolerant taxa represented by small-sized planktic and benthic diatoms.

The final phase C was separated in the upper parts of the analyzed cores. The diatom flora was represented by oligotraphentic taxa, which is probably associated with a decline in trophic conditions and a gradual improvement in the water quality in the study area. This hypothesis is confirmed by the increased frequency of *Pauliella taeniata*. However, our knowledge about this species is still incomplete. Therefore, higher-resolution research is needed to provide an explanation for eutrophication/oligotrophication or perhaps climate change in the Gulf of Gdańsk.

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