Oceanological and Hydrobiological Studies

International Journal of Oceanography and Hydrobiology

Volume 42, Issue 3

ISSN 1730-413X
eISSN 1897-3191

(336–346)
2013

VERSITA

DOI: 10.2478/s13545-013-0091-x
Review paper

Received: *November 13, 2012*
Accepted: *February 05, 2013*

A review of the diatom research in the Gulf of Gdańsk and Vistula Lagoon (southern Baltic Sea)

Małgorzata Witak*

Institute of Oceanography, University of Gdańsk
Piłsudskiego 46, 81-378 Gdynia, Poland

Key words: diatoms, review, Late Glacial, Holocene, Gulf of Gdańsk, Vistula Lagoon.

Abstract

The paper presents the history of diatom studies carried out in the Gulf of Gdańsk and the Vistula Lagoon since the beginning of the 20th century. One aspect of the research focuses on describing the structure of planktonic and benthic communities living in different parts of the area or occurring in their surface sediments as taphocoenoses. Other investigations concentrate on the fossil diatom flora, which is widely used in the research on the Late Glacial and Holocene to resolve paleogeographic, sedimentological and paleoecological problems.

INTRODUCTION

Diatoms are major components of algal assemblages in almost all aquatic habitats and are sensitive to numerous environmental factors. Their growth is influenced by the light availability, the thermal state of a basin, its hydrodynamics and the depth regime. Diatoms also respond to salinity fluctuations, dissolved oxygen content and the concentration of nutrients (Fritz et al. 1999, Hall and Smol 1999, Snoeijs 1999). Furthermore, a diatom record reflects other water quality characteristics, such as pH, alkalinity and saprobity (Round et al. 1990, Battarbee 2000). Changes in environmental parameters affect the variability in the structure of diatom assemblages. Such changes influence the abundance, the species composition and relationships within the diatom assemblages, which develop under a set of specific environmental parameters. Relationships between diatom taxa and environmental parameters serve as a basis for the development of bioindicator systems that rely on parameters such as salinity, pH, the trophic state and saprobity (Anderson and Vos 1992). These environmental factors are often affected by climate change and therefore diatom assemblages can be used as indicators of climate variability (Fritz et al. 1999, Anderson 2000, Korhola et al. 2000). Development of calibration methods resulted in establishing a bioindication system where particular environmental variables can be quantified, and tolerance and optimal ranges of a given taxon can be determined. The value of diatoms as bioindicators has been proved in studies of past sedimentary environments where a frustule is usually well preserved in the deposits. Detailed analysis of diatom taphocoenoses allows the interpretation and correlation of past events. Thus, the reconstruction of basin evolution is possible. Therefore, diatom

* e-mail: *oceman@univ.gda.pl*

analysis is one of the biostratigraphic methods that has been widely used to resolve the Late Quaternary paleogeographic, paleoceanographic and paleoecological problems (Battarbee 1986, Denys and de Wolf 1999, Sancetta 1999).

Diatom studies of the Late Glacial and Holocene stratigraphy have been conducted in the Gulf of Gdańsk and the Vistula Lagoon. Their evolution is strongly connected with the subsequent stages of the Baltic Sea development, i.e. Baltic Ice Lake (ca. 13.5 – 10.3 ^{14}C ka BP), Yoldia Sea (ca. 10.3 – 9.5 ^{14}C ka BP), Ancylus Lake (ca. 9.5 – 8.5 ^{14}C ka BP), Mastogloia Sea (ca. 8.5 – 7.5 ^{14}C ka BP), Littorina Sea (ca. 7.5 – 4.0 ^{14}C ka BP) and Post-Littorina Sea (the last 4.0 ^{14}C ka).

RECENT DIATOM FLORA OF THE GULF OF GDAŃSK

The first monograph on the occurrence of algae in the Gulf of Gdańsk was published by Lakowitz (1907) but it did not include an analysis of diatoms. Paul Schulz (1926) was a pioneer of diatomological investigations in this region; he published the first list of diatom taxa occurring in the coastal zone of the Gulf of Gdańsk (Fig. 1–3). He divided diatoms from this region into 7 salinity groups. Three of these groups included marine diatoms, i.e. the so-called "North Sea forms" occurring at the optimum salinity >30 psu, diatoms from waters of 12.5–30 psu and taxa occurring in waters with salinity of 7.9–12.5 psu. The remaining four groups included brackish-marine, brackish, brackish-freshwater and freshwater forms.

The research after 1945 focused on phytoplankton living in the different parts of the southern Baltic Sea. The composition of plankton was described in the Gulf of Gdańsk by Rumek (1948). This work was followed by description of seasonal variation in the phytoplankton abundance and species composition (Rumek 1950). Spatial and temporal distribution, and the structure of phytoplankton communities occurring in the open sea was described by Ringer (1970, 1973, 1990). The results of long-term studies focusing on floras occurring in the euphotic zone and in the bottom of the whole region were published by Pliński (1973, 1975, 1982, 1987, 1990, 1995). Other publications describing the distribution and composition of diatom assemblages in the Gulf of Gdańsk include Pliński (1988) and Pliński and Witkowski (2009). Structural changes in the phytoplankton observed in very shallow basins i.e. the Vistula Lagoon and the Puck Lagoon, resulting from the increasing eutrophication were extensively discussed by Pliński (1979). This problem was treated in many publications dealing with assemblages in the Gulf of Gdańsk (e.g. Pliński et al. 1982, Pliński et al. 1985, Pliński and Picińska 1986, Pliński 1992, Pliński et al. 1994, Niemkiewicz and Wrzołek 1998). The impact of trophic status changes on the microphytobenthos in Puck Bay was discussed by Fronczak and Pliński (1982) and Pliński and Florczyk (1984). Pliński and Kwiatkowski (1996) studied the relationship between the distribution of epipsammic diatoms and the environmental conditions in the shallow littoral of the Polish coast, including the Gulf of Gdańsk. Moreover, this area was included in the studies focused on the calibration of diatom species identified from the Baltic Sea (Snoeijs 1993, Snoeijs and Vilbaste 1994, Snoeijs and Potapova 1995, Snoeijs and Kasperovičienė 1996, Snoeijs and Balashova 1998).

Significant advances in knowledge about the distribution and composition of contemporary diatom assemblages in the Gulf of the Gdańsk was possible thanks to the research by Witkowski (1990, 1991a, 1994). The author provided detailed information about the ecological preferences and the distribution of key species in the sediments. Furthermore, several diatom assemblages typical of coastal shallows, sublittoral and deep water environments were discussed. Significant changes in the species composition and in the distribution of some diatom taxa caused by the inflow of strongly polluted Vistula waters, resulted in the development of the so-called "anthropogenic assemblage". The distribution of waste water entering the Gulf of Gdańsk in the Vistula run-off, as recorded by the diatom flora, has been studied by Stachura and Witkowski (1997). The distribution of subfossil diatom assemblages in ^{210}Pb dated sediments indicated that the eutrophication process caused by industrialization of the surrounding area may have lasted ca. 200 years (Witkowski and Pempkowiak 1995, Stachura-Suchoples 1998, 1999). Moreover, ecological preferences of the dominant taxa occurring in the surface sediments of the Gulf of Gdańsk were described by Stachura-Suchoples (2001). Based on the benthic diatom community, the problem of water quality in coastal streams was discussed in detail by Bogaczewicz-Adamczak and Koźlarska (1999), Bogaczewicz-Adamczak et al. (2001), Bogaczewicz-Adamczak and Dziengo (2003), Zgrundo (2004) and Zgrundo and Bogaczewicz-

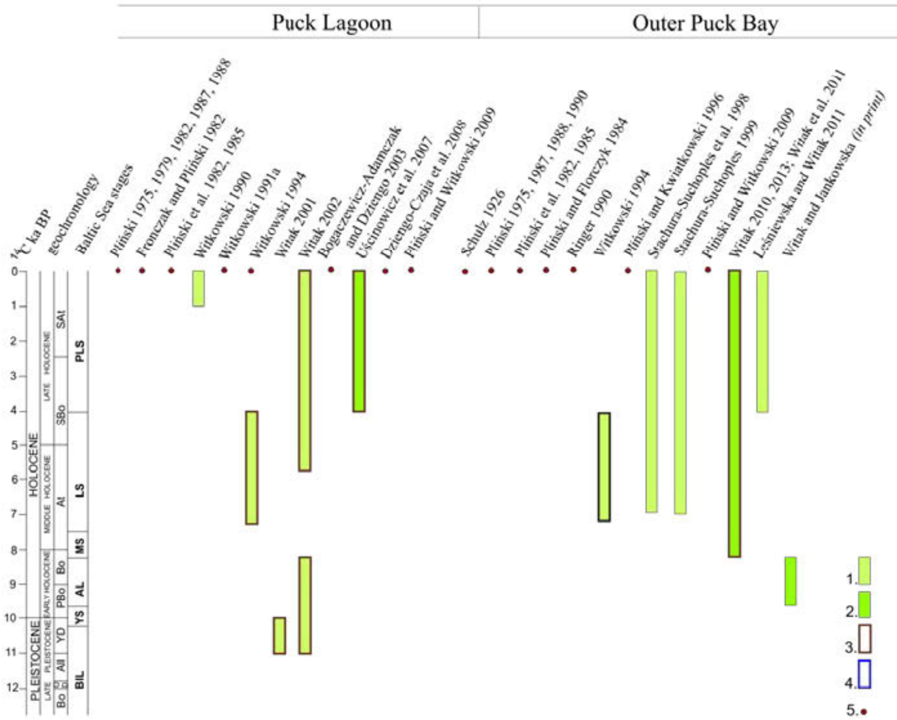

Fig. 1. Records of selected diatom studies of the Puck Lagoon and the Outer Puck Bay. 1 – diatom data, 2 – diatom and pollen data, 3 – ^{14}C data, 4 – ^{210}Pb data, 5 – recent diatoms; geochronology: Bo – Bölling, OD – Older Dryas, All – Alleröd, YD – Younger Dryas, PBo – Preboreal, Bo – Boreal, At – Atlantic, SBo – Subboreal, Sat – Subatlantic; Baltic Sea stages: BIL – Baltic Ice Lake, YS – Yoldia Sea, AL – Ancylus Lake, MS – Mastogloia Sea, LS – Littorina Sea, PLS – Post-Littorina Sea

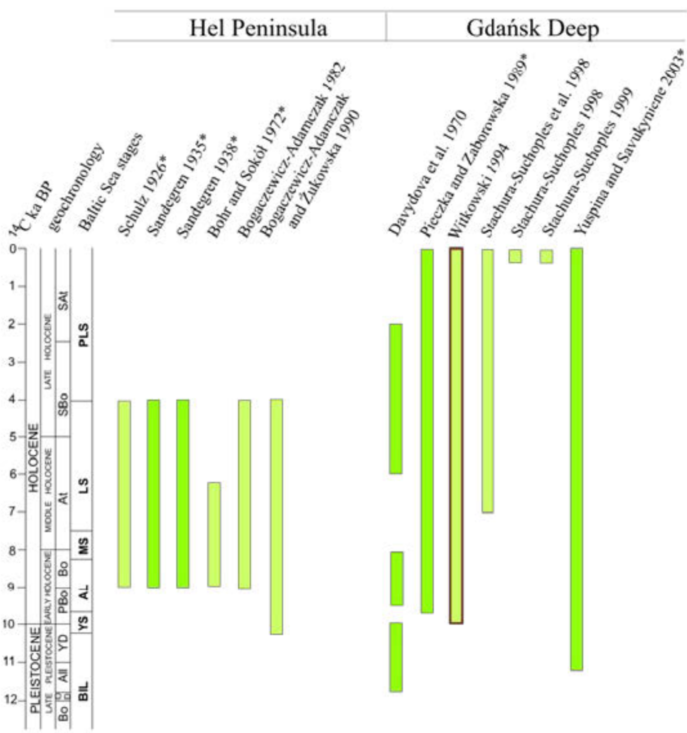

Fig. 2. Records in selected diatom researches of the Hel Peninsula and the Gdańsk Deep; *- author(s) did not distinguish the Mastogloia Sea stage; for explanations see Fig. 1

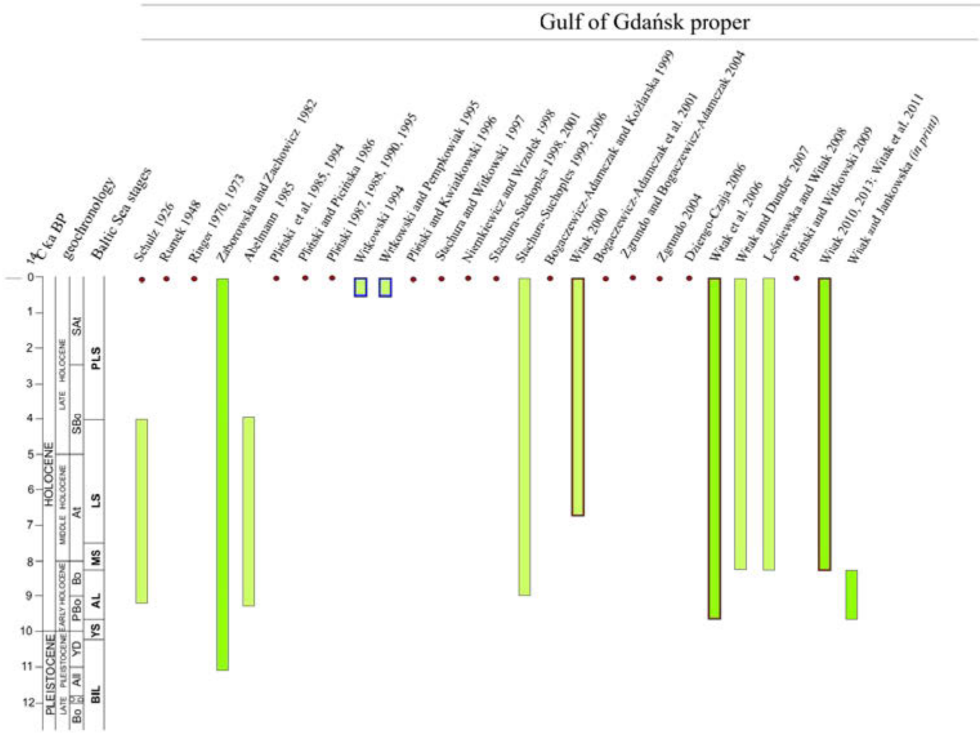

Fig. 3. Records of selected diatom studies in the Gulf of Gdańsk proper; for explanations see Fig. 1

Adamczak (2004). As evidenced by the study of recent diatom flora in the western coastal zone of the Puck Lagoon, the occurrence of teratological forms reflects the declining water quality in this region (Dziengo-Czaja et al. 2008). Moreover, differences between recent and subfossil diatom assemblages along the Sopot-Hel transect and the role of fossilization processes in the reconstruction of paleoenvironments were discussed by Dziengo-Czaja (2006). Long-term studies of the species composition of diatom assemblages in the Gulf of Gdańsk resulted in the identification and description of many new species listed in Table 1 (Witkowski 1991b, 1993a, 1993b, 1993c, 1994, Witkowski and Lange-Bertalot 1993, Witkowski et al. 1995, 1997, 1998, 2000, Lange-Bertalot et al. 2003).

Diatom biostratigraphy in the Gulf of Gdańsk

Schulz (1926) was the first diatomist who used fossil diatoms to resolve paleogeographic and paleoecological problems in the Gulf of Gdańsk (Fig. 2, 3). The author described the species composition of assemblages from the Ancylus Lake and Littorina Sea occurred in the sediments collected in the vicinity of Hel, Gdańsk and the Vistula Delta Plain. Diatom studies were continued by other researchers in the 1930s, but only in the Hel Peninsula region.

Hel Peninsula

Sediments of this sandy barrier, with macro- and microfossils, were very appealing for interpretation of the past events because of the unique Holocene sequence (>100 m-thick) of the peninsula. Results of diatom analysis supported by pollen data obtained from the Holocene sediments retrieved from deep boreholes in Hel and Jurata, served as a basis for the identification of the Ancylus and the Littorina sections (Sandegren 1935, 1938). These papers have expanded our knowledge about the geological structure of the Hel Peninsula and its development in relation to the Baltic Sea stages. Studies of postglacial development of the Hel Peninsula initiated before World War II were continued in the 1970s. Several sedimentary units were distinguished based on sedimentological analysis performed on the 100 m long core in Hel (Bohr and Sokół 1972). Sediments of the lowermost part of the borehole corresponded to the glacial period and the Baltic Ice Lake stage. Two complexes of freshwater forms that occurred in

Table 1

New diatom taxa identified in the Gulf of Gdańsk

Species	Location type
Achnanthes leonardii Witkowski et Lange-Bertalot 2000	Puck Lagoon
Achnanthes vistuliana Witkowski 1994	the Gulf of Gdańsk Dead Vistula
Cocconeis hauniensis Witkowski 1993	Puck Bay
Dickeia resistans Witkowski, Lange-Bertalot et Metzeltin 2000	Puck Bay
Fallacia cassubiae Witkowski 1991	Puck Bay
Fallacia clepsidroides Witkowski 1994	Puck Bay
Fragilaria amicorum Witkowski et Lange-Bertalot 1993	Puck Lagoon
Fragilaria bronkei Witkowski, Lange-Bertalot et Metzeltin 2000	the Gulf of Gdańsk
Fragilaria cassubica Witkowski et Lange-Bertalot 1993	Puck Bay
Fragilaria eichhornii Witkowski et Lange-Bertalot 1995	Puck Bay
Fragilaria gedanensis Witkowski 1993	Puck Bay
Fragilaria guenter-grassii Witkowski et Lange-Bertalot 1993	Puck Bay
Fragilaria geocollegarum Witkowski et Lange-Bertalot 1995	Puck Bay
Fragilaria improbula Witkowski et Lange-Bertalot 1995	the Gulf of Gdańsk
Fragilaria neoelliptica Witkowski 1994	the Gulf of Gdańsk
Fragilaria polonica Witak et Lange-Bertalot 1995	Puck Lagoon
Fragilaria sopotensis Witkowski et Lange-Bertalot 1993	Puck Lagoon
Hippodonta caotica Witkowski, Lange-Bertalot et Metzeltin 2000	the Gulf of Gdańsk
Karayevia temniskovae Witkowski, Lange-Bertalot et Bąk 2006	Hel Peninsula
Navicula aleksandrae Lange-Bertalot, Bogaczewicz-Adamczak et Witkowski 2003	the Gulf of Gdańsk the Haffner stream mouth
Navicula bourrellyivera Lange-Bertalot, Witkowski et Stachura 1998	Puck Lagoon
Navicula bozenae Lange-Bertalot, Witkowski et Zgrundo 2003	the Gulf of Gdańsk the Haffner stream mouth
Navicula germanopolonica Witkowski et Lange-Bertalot 1993	the Gulf of Gdańsk
Navicula hanseatica Lange-Bertalot et Stachura 1998	Puck Lagoon
Navicula iserentantii Lange-Bertalot et Witkowski 2000	Puck Bay
Navicula margaritiana Witkowski 1994	Puck Lagoon
Navicula paul-schulzii Witkowski et Lange-Bertalot 1994	Puck Bay
Navicula rajmundii Witkowski, Lange-Bertalot et Metzeltin 2000	Puck Bay
Navicula specululum Witkowski 1994	Puck Bay
Navicula stachurae Witkowski, Lange-Bertalot et Metzeltin 2000	the Gulf of Gdańsk
Navicula starmachii Witkowski et Lange-Bertalot 1994	the Gulf of Gdańsk
Navicula viminoidess spp. *cosmomarina* Lange-Bertalot, Witkowski Bogaczewicz-Adamczak et Zgrundo 2003	the Gulf of Gdańsk the Haffner stream mouth
Navicula wiktoriae Witkowski et Lange-Bertalot 1994	the Gulf of Gdańsk
Opephora horstiana Witkowski 1994	Puck Bay
Opephora krumbeinii Witkowski, Witak et Stachura 1999	the Gulf of Gdańsk
Planothidium sopotense Lange-Bertalot et Dziengo 2004	the Gulf of Gdańsk
Staurophora anuschkae Witkowski 2000	the Gulf of Gdańsk Dead Vistula
Staurosira punctiformis Witkowski, Lange-Bertalot et Metzeltin 2000	Vistula Lagoon

the deposits of the central section were replaced by predominantly marine and brackish-water assemblages. The fossil diatom assemblages reflect the latest phase of the Ancylus Lake and the beginning of the Littorina Sea (Bohr and Sokół 1972). The analysis of diatom flora, preserved in a core extracted from the site in Jastarnia, indicate the occurrence of deposits from the Mastogloia Sea stage, which are located between limnic sediments of Ancylus and marine sediments of the Littorina stages (Bogaczewicz-Adamczak 1982). Our knowledge on fossil diatom assemblages of the Hel Peninsula was completed by analyses of the 112 m long sediment core from Jurata (Bogaczewicz-Adamczak and Żukowska 1990). Five stratigraphic units in the Holocene sequence (the Yoldia Sea, Ancylus Lake, Mastogloia Sea, Littorina Sea and the Post-Littorina Sea) were distinguished based on sedimentological and diatomological analysis.

Puck Lagoon

Based on the diatomological analysis, also palaeoecological studies were conducted in the Puck

Lagoon, which is enclosed by the Hel Peninsula (Fig. 1). The geological setting of the Puck Lagoon, however, offers rather limited opportunity for discussion on the past ecological changes. This problem is particularly important in the shallowest, inner part of the lagoon, which was a land until the Littorina transgression ca. 5.5 ^{14}C ka BP (Witkowski and Witak 1993). Studies of microbial mats dominated by cyanobacteria, green algae and diatoms in the coastal shallows of the NW Puck Lagoon indicate that their origin is associated with the water level rise dated to the beginning of the last millennium (Witkowski 1990). Diverse diatom flora was discovered in Littorina sediments collected from the deeper part of the Puck Lagoon (Witkowski 1994). Older fossil diatom flora was discussed by Witak (2001). Well preserved and abundant diatom assemblages occur in the Late Glacial sediments collected from the Rzucewo Deep – one of the depression in the Puck Lagoon. The diatom assemblage was dominated by small *Fragilaria* spp. (*sensu lato*) accompanied by nordic-alpine forms, which indicates that a shallow oligotrophic lake existed in the study area ca. 11.0 ^{14}C ka BP. This record was completed with further investigations, which showed an increase in the trophic state in the Early Holocene (Witak 2002). Terrestrialization resulted in acidification of the lake water and formation of a peat bog. Diatom records indicated the inundation of the Rzucewo Deep and the remaining Puck Lagoon during the Littorina transgression ca. 5.5 ^{14}C ka BP and eventually, the development of brackish-water conditions. The Littorina and Post-Littorina stages were also distinguished in the subsurface sediments of another depression – the Kuźnica Deep. The evolution of the lagoon's littoral zone in the Late Holocene was discussed in detail based on the diatom studies supplemented with radiocarbon and pollen data (Witak 2002). A list of diatom indicators typical of the Littorina and Post-Littorina transgression was published by Witak and Bogaczewicz-Adamczak (2006) after analysis of fossil diatom assemblages preserved in cores retrieved from the Gulf of Gdańsk and the Vistula Lagoon. The most recent diatom, pollen and radiocarbon data of sediment sequences from the western coasts of the Puck Lagoon provide evidence for periodic sea-level oscillations related to climatic fluctuations in the Subboreal and Subatlantic chronozones (Uścinowicz et al. 2007).

Outer Puck Bay

The diatom record corresponding to the Littorina stage in the western part of the Outer Puck Bay was described by Witkowski (1994). Furthermore, Littorina and Post-Littorina diatom assemblages were recorded by Stachura-Suchoples (1999) in a core retrieved from the central part of the bay. The same material, supplemented with a core taken from the Gdańsk Deep, was included in the discussion on the application of *Chaetoceros* resting spores as bioindicators of palaeoenvironmental changes (Stachura-Suchoples et al. 1998).

Gulf of Gdańsk proper

Much older diatom flora was observed in the deeper part of the Gulf of Gdańsk by Zaborowska and Zachowicz (1982) (Fig. 3). Pollen data indicate that the diatom record includes the Late Glacial and the whole Holocene. Mostly freshwater diatoms of the Baltic Ice Lake, Yoldia Sea and Ancylus Lake occur in the lower part of this core corresponding to the Younger Dryas, Preboreal and Boreal chronozones, respectively. Diatoms of the transition stage of the Mastogloia Sea occur towards the top of the latter core in the older part of the Atlantic chronozone. Ultimately, marine-brackish-water flora provides evidence for the Littorina Sea transgression that occurred in the Late Atlantic chronozone. Abelmann (1985) studied a sediment core retrieved from the deeper part of the Gulf of Gdańsk. Results of this study indicate the presence of limnic facies of the Ancylus Lake, transition facies of the Mastogloia Sea and marine deposits of the Littorina Sea. Interesting information on past ecology, bathymetry and salinity is provided by the diatom analysis of sediment cores from the area located between the Hel Peninsula and Gdańsk – the Gdynia region. The diatom flora, typical of the Ancylus Lake stage, was reported by Stachura-Suchoples (1999, 2006) and Witak et al. 2006. This last freshwater stage in the Baltic Sea development was discussed in detail by Witak and Jankowska (*in print*). The diatom assemblages of three sediment cores permitted the reconstruction of Early Holocene evolution of the SE Gulf of Gdańsk with respect to bathymetry, pH, the trophic and saprobic status. Additionally, the authors were able to distinguish three stages of the Ancylus Lake: (1) a very shallow, nutrient-rich, strongly alkaline basin with the average amount of organic matter, affected by Vistula River waters in the vicinity of today's Hel Peninsula in the Preboreal/Boreal chronozone; (2) an increase in the trophic and saprobic status as a result of stronger input from the riverine waters due to climatic amelioration in the Boreal chronozone; and (3) a signal of water level lowering in the regression of the Ancylus Lake in the Late Boreal. Diatom assemblages typical of the Mastogloia Sea occurred in the above cores and in the cores analyzed by Witak and Dunder (2007). Furthermore, reconstructions of the spatial and temporal development of the Gulf of Gdańsk in the Littorina and Post-Littorina Sea, based on the fossil diatom flora preserved in the Late Holocene sediments were published (Stachura-Suchoples 1999, 2006, Witak 2000, Witak and Dunder 2007, Leśniewska and Witak 2008). The impact of the Vistula River on the paleohydrology of the area was also discussed in the aforementioned publications.

Gdańsk Deep

Postglacial migrations of the Baltic shoreline and related transgressive-regressive cycles, documented by biostratigraphic methods, caused many difficulties in the reconstruction of past events, particularly in the littoral zone of the basin. However, diatom assemblages from the sediments deposited in the pelagic part present much greater potential for drawing inferences on these issues (Fig. 2). The diatom assemblages of the Baltic Ice Lake occurred in cores retrieved from the Late Glacial limnic deposits of the Gdańsk Deep (Davydova et al. 1970, Yuspina and Savukyniene 2003). Diatom records of the whole Holocene published by Ignatius and Tynni (1978) were completed by Pieczka and Zaborowska (1989). The authors also proposed a list of indicator taxa for the Baltic Sea stages in the Holocene. This list was modified by Witkowski (1994), who defined the Mastogloia Sea stage in the deep-water sediments of the Gdańsk Deep.

Diatom biostratigraphy of the Vistula Lagoon

The postglacial history of the Vistula Lagoon development has gained scientific interest since the 1930s and 1940s (Fig. 4). Gross (1941) was the first who applied biostratigraphic methods in the reconstruction of environmental changes in the lagoon. He distinguished two stratigraphic units based on the diatom and pollen distribution in the sediment cores retrieved from the western part of the lagoon: the lower unit, dated to the Ancylus and Early Littorina stages, when the basin was isolated with no connection to the Baltic Sea and the upper unit related to the Late Littorina stage, when saline waters of the open sea inundated the basin. Brockmann (1954) discussed the origin and development of the Vistula Lagoon during the Holocene. His analysis involved both recent and fossil diatom assemblages preserved in 15 sediment cores retrieved from different parts of the lagoon and in 9 cores retrieved from the Vistula Spit. This work includes a discussion on taxonomy and ecological preferences of the most important species, and a comparison of the fossil and recent diatom assemblages recorded in the lagoon and in the coastal zone of the Baltic Sea. In addition, diatom taxa indicative of the Ancylus and Littorina stages of the Vistula Lagoon were listed in this publication.

The influence of the Littorina Sea transgression on the paleoecology of the Vistula Lagoon was discussed by Przybyłowska-Lange (1974). The author distinguished three stages of the basin development based on the diatom record; (1) a basin with higher salinity related to three Littorina transgressions through the barrier of the Vistula Spit, assigned to the Atlantic chronozone, (2) a freshwater eutrophic, slightly deeper lake with stable ecological conditions dated to the Subboreal chronozone and (3) a shallow freshwater eutrophic basin with periodic inflows of marine waters linked to the Subatlantic transgression of the Post-Littorina Sea. Furthermore, the diatom flora in the subbotom sediments of the Vistula Lagoon reflected the consequences brought by blockage of the Nogat River in 1915. A reconstruction of the lagoon development is supplemented with the diatom data from sediment cores retrieved in the Druzno Lake (Przybyłowska-Lange 1976). The fossil diatom assemblages reveal that three marine transgressions in the Atlantic and Subboreal chronozones reached the area of the Elbląg Upland south of the Vistula Lagoon. According to the author, the Druzno Lake was considered to be a remnant of the Vistula Lagoon embayment, and was isolated by the Nogat River delta deposits in the Late Subatlantic chronozone.

Diatom and pollen analysis supported by ^{14}C dates permitted the reconstruction of environmental changes in the Vistula Lagoon in the Late Glacial and Holocene (Bogaczewicz-Adamczak and Miotk 1985a). The authors postulated the existence of a shallow lake in the Alleröd chronozone. The core

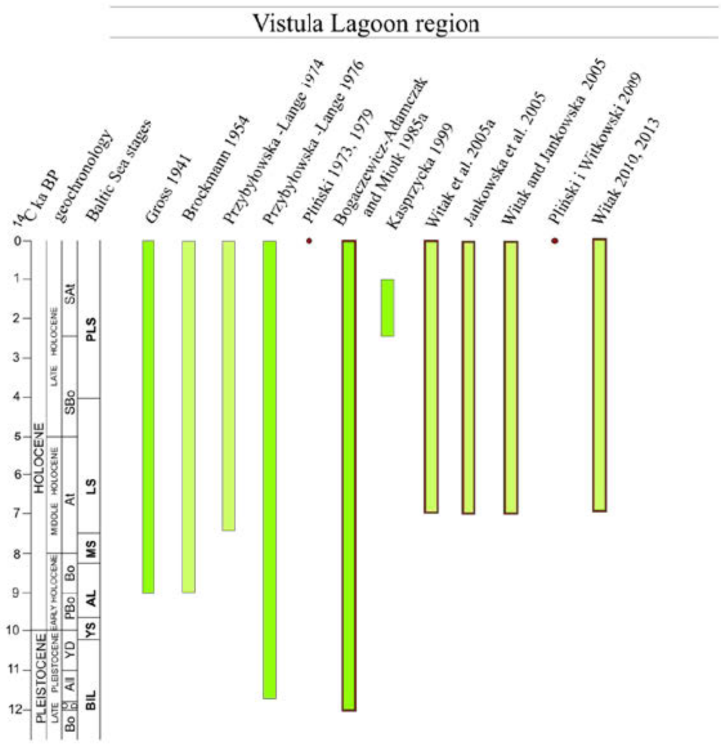

Fig. 4. Record in selected diatom researches of the Vistula Lagoon; for explanations see Fig. 1

studied by these authors was rich in well-preserved diatom assemblages. Planktonic diatoms accompanied by euhalobous and mesohalobous taxa, typical of the Littorina Sea, are abundant in the sediment of the Vistula Lagoon dated to the second part of the Atlantic chronozone. The salinity of this basin and its water level decreased in the Subboreal chronozone. The coastline migrated southward and then westward as a result of Subatlantic transgression, and the Vistula Lagoon had the largest area in its history. This phenomenon was also described by Kasprzycka (1999). The author observed diatoms in the cores retrieved from the Vistula Delta Plain. The development of various parts of the Vistula Lagoon during the Holocene was also discussed by Witak et al. (2005a) and Jankowska et al. (2005). The importance of the inflow of the marine waters through the Vistula Spit during the Littorina and Post-Littorina transgressions was discussed by Witak and Jankowska (2005).

Finally, multi-directional reconstruction of spatial and temporal development of the Gulf of Gdańsk and the Vistula Lagoon with the emphasis on the role of global (climatic fluctuations, eustatic sea-level changes), regional (transgressive/regressive cycles, development of sandy barriers) and local factors (river input) in the last 8 ka ^{14}C yr was described by Witak (2010). The fossil diatom assemblages occurred in 15 sediment cores supported by ^{14}C data and pollen analysis indicated several shifts in the environmental state of the study area. They were linked to subsequent stages of the Baltic Sea development, i.e. the Mastogloia Sea, the Littorina Sea and the Post-Littorina Sea. Moreover, the so-called anthropogenic diatom assemblage was identified in the subbotom sediments. Statistical analysis of the diatom assemblage zones distinguished in all cores showed significant differences in the diatom assemblages of the Gulf of Gdańsk and the Vistula Lagoon. The fossil diatom assemblages of these regions differed in their floristic diversity, the abundance of the dominant taxa, the diatom ecological groups and the preservation state. The low similarity level between the two separate clusters corresponding to both regions reflects significant palaeoecological differences between them. Diatom biofacies defined in the Gulf of Gdańsk were generally associated with the age of sediments. Only assemblages from the Mastogloia Sea were scattered in the cluster, which could be related to poor preservation of diatoms. On the contrary, diatom biofacies in the Vistula Lagoon indicate their stronger connection with the spatial factor than the temporal one. The cluster structure proves that the location of the sampling sites played a key role in this area. Such differences probably resulted from the paleogeography of both areas. Diatom analysis showed that inflows of open sea waters were much stronger in the Gulf of Gdańsk compared to the Vistula Lagoon, which developed behind the barrier of the Vistula Spit. In both cases, however, their past hydrology regime was affected by a substantial influx of riverine waters. To sum up, four intervals were defined in the evolution of both areas (Witak 2013): (1) Mastogloia Sea stage, (2) Littorina Sea stage, (3) Post-Littorina Sea stage and (4) current environmental changes associated with the progressive anthropopressure and eutrophication processes.

REFERENCES

Abelmann, A. (1985). Palökologische und ökostratigraphische Untersuchungen von Diatomeenassoziationen an holozänen Sedimenten der zentralen Ostsee. *Berichte -Reports. Geologisch-Paläontologisches Institut der Universität Kiel*, 9, 200 pp, (in German).

Anderson, N.J (2000). Miniview: Diatoms, temperature and climatic change. *European Journal of Phycology,* 35, 307-314.

Anderson, N.J. & Vos P. (1992). Learning from the past: diatoms as paleoecological indicators of changes in marine environments. *Netherlands Journal of Aquatic Ecology,* 26(1), 19-30.

Battarbee, R.W. (1986). Diatom analysis. In B.E. Berglund (Ed.), *Handbook of Holocene paleoecology and paleohydrology* (pp. 527-570). London: John Wiley & Sons Ltd.

Battarbee, R.W. (2000). Palaeolimnological approaches to climate change, with special regard to the biological record. *Quaternary Science Reviews,* 19, 107–124.

Bogaczewicz-Adamczak, B. (1982). Novyi diatomovyi analiz osadotchnoy tolshtchi Gelskogo Poluostrova. *Peribalticum*, 2, 185-93, (in Russian).

Bogaczewicz-Adamczak, B. & Dziengo M., 2003, Using benthic diatom communities and diatom indices to assess water pollution in the Puck Bay (southern Baltic Sea) littoral zone. *Oceanological and Hydrobiological Studies*, 32(4), 131-157.

Bogaczewicz-Adamczak, B., Klosińska D. & Zgrundo A. (2001). Diatoms as indicators of water pollution in the coastal zone of the Gulf of Gdańsk (southern Baltic Sea). *Oceanological Studies*, 30 (3-4), 59-75.

Bogaczewicz-Adamczak, B. & Koźlarska I. (1999). The evaluation of water quality in the Swelinia stream on the basis of diatom analysis. *Oceanological Studies*, 27 (1-2), 59-71.

Bogaczewicz-Adamczak, B. & Miotk G. (1985). Z biostratygrafii osadów Zalewu Wiślanego. *Peribalticum*, 3, 79-96, (in Polish).

Bogaczewicz-Adamczak, B. & Żukowska A. (1990). Okrzemki kopalne z osadów w Juracie. *Przewodnik 61 Zjazdu PTG*, 71-74, (in Polish).

Bohr, R. & Sokól M. (1972). The fossil diatom flora from the sediments of the Hel Peninsula. International Conference in Poland, 22-26 September 1972, (pp. 20-23). Sopot: Wydawnictwa Geologiczna, Warszawa

Brockmann, C. (1954). Die Diatomeen in den Ablagerungen der Ostpreussischen Haffe. *Meyniana*, 3, 1-95, (in German).

Davydova, N.N., Dzsinoridze R.N., Kvasov D.D., Masicka G. & Spiridonova E.A. (1970). Novyie dannyie po stratigrafii donnykh otlozhenyi Yuzhnoj Baltiki. *Baltica*, 4, 33-43, (in Russian).

Denys, L. & De Wolf H. (1999). Diatoms as indicators of coastal paleoenvironments and relative sea-level change. In E.F. Stoermer & J.P. Smol (Eds), *The diatoms. Application for the Environmental and Earth Sciences,* (pp. 277-298), Cambridge: Cambridge University Press.

Dziengo-Czaja, M., (2006). Ubytek informacji biologicznej w osadach Zatoki Gdańskiej w świetle badań współczesnej i kopalnej flory okrzemkowej. PhD Thesis; University of Gdańsk: 1-125, (in Polish).

Dziengo-Czaja, M., Koss J. & Matuszak A., (2008). Teratological forms of diatoms (Bacillariophyceae) as indicators of water pollution in the western part of Puck Bay (southern Baltic Sea). *Oceanological and Hydrobiological Studies*, 37 (2), 119-132.

Fritz, S.C., Cumming B.F., Gasse F. & Laird K.R. (1999). Diatoms as indicators of hydrological and climatic change in saline lakes. Applications and uses of diatoms: prologue. In E.F. Stoermer & J.P. Smol (Eds), *The diatoms. Application for the Environmental and Earth Sciences,* (pp. 41-72), Cambridge: Cambridge University Press.

Fronczak, M. & Pliński M. (1982). Ecological characteristic of fouling microflora in Puck Bay. *Zeszyty Naukowe UG. Oceanografia,* 9, 49-64, (in Polish).

Gross, H. (1941). Beitrag zur Entwicklungsgeschichte des Frischen Haffs. *Geologie das Meere und Binnengewässer*, 5 (1), 1-38.

Hall, R.I. & Smol J.P. 1999. Diatoms as indicators of lake eutrophication. In E.F. Stoermer & J.P. Smol (Eds), *The diatoms. Application for the Environmental and Earth Sciences,* (pp. 128-168), Cambridge: Cambridge University Press.

Ignatius, H. & Tynni R. (1978). Itämeren vaiheet ja piilevätutkimus. *Turun yliopiston maaperägeologian osaston julkaisuja*, 36, 1-26.

Jankowska, D., Witak M. & Huszczo D. (2005) Paleoecological changes of the Vistula Lagoon in the last 7000 y BP based on the diatom flora. *Oceanological and Hydrobiological Studies*, 34(4), 109-29.

Kasprzycka, M. (1999). Tło paleogeograficzne osadnictwa Żuław Elbląskich w pierwszym tysiącleciu naszej ery. *ADALBERTUS* 5, 1-194, (in Polish).

Korhola, A., Weckström J., Holmström L.& Erästö P. (2000). A quantitative Holocene climatic record from diatoms in northern Fennoscandia. *Quaternary Research,* 54, 284-294.

Lakowitz, K. (1907). *Die Algenflora der Danziger Bucht. Ein Beitrag zur Kenntnis der Ostseeflora. Danzig.* (in German).

Lange-Bertalot, H., Witkowski A., & Bogaczewicz-Adamczak B. (2003). Rare and new so-called taxa of *Navicula* s. str. in the Gulf of Gdańsk and its freshwater effluents. *Limnologica*, 33, 258-270.

Leśniewska, M. & Witak M. (2008). Holocene diatom biostratigraphy of the SW Gulf of Gdańsk, southern Baltic Sea (part III). *Oceanological and Hydrobiological Studies*, 37 (4), 35-52.

Niemkiewicz, E. & Wrzolek L. (1998). Phytoplankton as eutrophication indicators in the Gulf of Gdańsk water. *Oceanological Studies*, 27 (4), 77-92.

Pieczka F.B. & Zaborowska K. (1989). Litologia i stratygrafia rdzenia 6/HI/67 z Basenu Gdańskiego, *Studia i Materiały Oceanologiczne*, 56, 323-330, (in Polish).

Pliński, M. (1973). Badania nad glonami poludniowego Baltyku oraz Zalewu Szczecińskiego i Zalewu Wiślanego, *Zeszyty Naukowe Wydz. BiNoZ UG, Oceanografia*, 1, 59-72, (in Polish).

Pliński, M. (1975). The algae in the surface water of the Bay of Puck (Baltic) in the vegetation period of 1972. *Botanica Marina*, 18, 183-186.

Pliński, M. (1979). Kierunki zmian strukturalnych w fitoplanktonie estuariów Baltyku Południowego, *Rozprawy i Monografie UG*, 15, 1-136, (in Polish).

Pliński, M. (1982). Rozmieszczenie i biomasa fitobentosu Zatoki Puckiej wewnętrznej, *Studia i Materiały Oceanologiczne*, 39, 53-68, (in Polish).

Pliński, M. (1987). Roślinność. In B. Augustowski (Ed.), *Bałtyk Południowy* (pp. 321-346), Wrocław, Warszawa, Kraków, Gdańsk, Łódź: Wydawnictwo PAN, (in Polish).

Pliński, M. (1988). *Glony Zatoki Gdańskiej.* Część IV. Okrzemki, Gdańsk: Wydawnictwo UG, (in Polish).

Pliński, M. (1990). Important ecological features of the Polish coastal zone of the Baltic Sea. *Limnologica*, 20, 39-45.

Pliński, M. (1992). Vegetation. *Studia i Materiały Oceanologiczne*, 61, 181-190, (in Polish).

Pliński, M. (1995). Phytoplankton of the Gulf of Gdańsk in 1992 and 1993. *Oceanologia*, 37, 123-135.

Pliński, M. & Florczyk I. (1984). Changes in the phytoplankton resulting from the eutrophication of the Puck Bay. *Limnologia*, 15, 325-327.

Pliński, M. Florczyk I. & Picińska J. (1985). Skład i liczebność fitoplanktonu Zatoki Gdańskiej Właściwej. *Studia i Materiały Oceanologiczne*, 46, 23-64, (in Polish with English summary).
Pliński, M., Janik J. & Gliczyński T. (1994). Biomasa fitoplanktonu Zatoki Gdańskiej w latach 1986 i 1987, *Zeszyty Naukowe UG Oceanografia*, 13, 61-68, (in Polish).
Pliński, M & Kwiatkowski J. (1996). Microphytobenthos of the shallow littoral of the southern Baltic. *Oceanological Studies*, 4, 65-77.
Pliński, M. & Picińska J. (1986). The dynamics of seasonal change of the phytoplankton biomass in the Gulf of Gdańsk. *Oceanologia*, 23, 77-83.
Pliński, M., Sobolewska B. & Mielczarek M. (1982). Skład i liczebność fitoplanktonu zachodniej części Zatoki Gdańskiej. *Studia i Materiały Oceanologiczne*, 39, 35-75, (in Polish with English Summary).
Pliński, M. & Witkowski A. (2009). *Diatoms – Bacillariophyta. Part one: centric diatoms*, In M. Pliński (Ed.), *Flora of the Gulf of Gdańsk and adjacent waters (southern Baltic), 4/1,* Gdańsk: Wydawnictwo Uniwersytetu Gdańskiego, pp. 223, (in Polish with the English key for identification to the genus)
Przybyłowska-Lange, W. (1974). Rozwój Zalewu Wiślanego w świetle analizy okrzemkowej. *Prace IMGW*, 2, 129-162, (in Polish).
Przybyłowska-Lange, W. (1976). Diatoms of lake deposits from the Polish, Baltic Coast. I. Lake Druzno. *Acta Palaeobotonica*, 17, 35-74.
Ringer, Z. (1970). Skład fitoplanktonu południowego Bałtyku w latach 1967-68. *Studia i Materiały MIR, Gdynia,* 7 (A), 1-31, (in Polish).
Ringer, Z. (1973). Fitoplankton południowego Bałtyku na tle warunków hydrologicznych. *Studia i Materiały MIR, Gdynia,* 11 (A), 1-89, (in Polish).
Ringer, Z. (1990). Roślinność. In A. Majewski (Ed.), *Zatoka Gdańska* (pp. 361-373) Warszawa: Wydawnictwa Geologiczne, (in Polish).
Round, F.E. Crawford R.M. & Mann D.G. (1990). *The diatoms. Biology and morphology of the genera*. Cambridge: Cambridge University Press.
Rumek, A. (1948). Lista gatunków fitoplantonu powierzchniowego Zatoki Gdańskiej. *Biuletyn Morskiego Laboratorium Rybackiego*, 4, 139-141, (in Polish).
Rumek, A. (1950). Sezonowe występowanie gatunków w fitoplanktonie Zatoki Gdańskiej. *Biuletyn Morskiego Laboratorium Rybackiego*, 5, 145-149, (in Polish).
Sancetta, C. (1982). Distribution of diatom species in surface sediments of the Bering and Okhotsk seas. *Micropaleontology,* 28, 3, 221-257.
Sandegren, R. (1935). O kopalnej mikroflorze z wiercenia na Helu i o zmianach postglacjalnych poziomu Bałtyku. *Sprawozdania PIG*, 8 (3), 51-63, (in Polish).
Sandegren, R. (1938). Über die fossilen Mikroflora aus den Bohrungen bei Bad Hel und Jurata auf der Halbinsel Hel. *Geologiska Föreningen i Stockholm Förhandlingar,* 60 (4), 601-611, (in German).
Schulz, P. (1926,). Die Kieselalgen der Danziger Bucht mit Einschluss derjenigen aus glazialen und postglazialen Sedimenten. *Botanischer Archive Königsberg*, 13 (3-4), 149-327, (in German).
Snoeijs, P. (1993). *Intercalibration and distribution of diatom species in the Baltic Sea,* Volume 1, *The Baltic Marine Biologist Publication*, 16a. Uppsala: Opulus Press.
Snoeijs, P. (1999). Diatoms and environmental changes in brackish waters. In E.F. Stoermer & J.P. Smol (Eds), *The Diatoms: Applications for the Environmental and Earth Science* (pp. 298-333). Cambridge: Cambridge University Press.
Snoeijs, P. & Balashova N. (1998). *Intercalibration and distribution of diatom species in the Baltic Sea,* Volume 5, *The Baltic Marine Biologist Publication*, 16e. Uppsala: Opulus Press.
Snoeijs, P. & Kasperoviciene J. (1996). *Intercalibration and distribution of diatom species in the Baltic Sea,* Volume 4, *The Baltic Marine Biologist Publication*, 16d. Uppsala: Opulus Press.
Snoeijs, P. & Potapova M. (1995). *Intercalibration and distribution of diatom species in the Baltic Sea,* Volume 3, *The Baltic Marine Biologist Publication*, 16c. Uppsala: Opulus Press.
Snoeijs, P. & Vilbaste S. (1994). *Intercalibration and distribution of diatom species in the Baltic Sea,* Volume 2, *The Baltic Marine Biologist Publication*, 16b. Uppsala: Opulus Press.
Stachura, K. & Witkowski A. (1997). Response of the Gulf of Gdańsk diatom flora to the sewage run-off from the Vistula river. *Fragmenta Floristica Geobotanica* 42(2), 517-545.
Stachura-Suchoples, K. (1998). The last 200 years as revealed by diatom analysis – preliminary results. *Proceedings of the 15th International Diatom Symposium*, 209-226.
Stachura-Suchoples, K., (1999). Diatoms as indicators of Vistula river influence on the paleoecology of the Gulf of Gdańsk. PhD thesis, University of Gdańsk, pp.172, (in Polish)
Stachura-Suchoples, K., (2001). Bioindicative values of dominant diatom species from the Gulf of Gdańsk, Southern Baltic Sea, Poland, In R. Jahn, J.P.Kociolek, A. Witkowski & Compére P. (Eds), *Lange-Bertalot-Festschrift* (pp. 477-490). Ruggell, Lichtenstein: Gantner Verlag.
Stachura-Suchoples, K. (2006). Diatoms as indicators of the influence of the Vistula River inflow on the Gulf of Gdańsk during the Holocene. In Ognjanova-Rumenova N.& Manoylov K., (Eds.), *Advances in phycological studies, Festschrift in Honour of Prof. Dobrina Temniskova-Topalov* (pp. 283-291), Sofia-Moscow: PENSOFT Publishers & University Publishing House.
Stachura-Suchoples, K., Zgrundo A. & Witkowski A. (1998). Occurrence and significance of *Chaetoceros* (Bacillariophycae) resting spores in the Holocene sediments of the Baltic Sea. *Oceanological Studies*, 2, 87-92.
Stachura, K. & Witkowski A. (1997). Response of the Gulf of Gdańsk diatom flora to the sewage run-off from the Vistula river. *Fragmenta Floristica Geobotanica* 42 (2), 517-545.
Uścinowicz, S., Zachowicz J., Miotk-Szpiganowicz G. & Witkowski A. (2007). Southern Baltic sea-level oscillations: New radiocarbon pollen and diatom proof of the Puck Lagoon (Poland). *The Geological Society of America, Special Paper*, 426, 143-158.
Witak, M. (2000). A diatom record of Late Holocene environmental changes in the Gulf of Gdańsk. *Oceanological Studies*, 29(2), 57-74.
Witak, M. (2002). Postglacial history of the development of the Puck Lagoon (the Gulf of Gdańsk, Southern Baltic Sea) based on the diatom flora. *Diatom Monographs 2*. Ruggell, Lichtenstein: Gantner Verlag.
Witak, M. (2010). Application of diatom biofacies in reconstructing sedimentary basins evolution. The records from the southern Baltic Sea differentiated by the extent of the Holocene marine transgressions and human impact. *Diatom Monographs 12*. Ruggell, Lichtenstein: Gantner Verlag.
Witak M. (2013). Diatom biofacies in the SW Gulf of Gdańsk and the Vistula Lagoon (the southern Baltic Sea) as indicators of the basin evolution in the Middle and Late Holocene. *Oceanological and Hydrobiological Studies*, 42(1), 70-88
Witak M., Bogaczewicz-Adamczak B., 2006, Diatoms as indicators of the Littorina and Post-Littorina transgressions in the Polish coastal zone, *Proceedings of the 18th International Diatom Symposium* (pp. 479-497). Bristol: Biopress Limited.
Witak, M. & Dunder J. (2007). Holocene diatom biostratygraphy of the SW Gulf of Gdańsk, Southern Baltic Sea (part II). *Oceanological and Hydrobiological Studies*, 36(3), 3-20
Witak, M. & Jankowska D. (2005). The Vistula Lagoon evolution based on diatom records. *BALTICA*, 18(2), 68-76.
Witak, M., Boryń K. & Mayer A. (2005). Holocene environment changes recorded by diatom stratigraphy in the Vistula Lagoon. *Oceanological and Hydrobiological Studies*, 34(2), 111-33.
Witak, M., Jankowska D. & Piekarek-Jankowska H. (2006). Holocene diatom biostratigraphy of the SW Gulf of Gdańsk, Southern Baltic Sea (part I). *Oceanological and Hydrobiological Studies*, 35(4), 307-329.
Witak, M. & Jankowska D. (in print). Ancylus Lake stage in the Gulf of Gdańsk (southern Baltic Sea) based on the diatom taphocoenoses, In P. Kociolek, M. Kulikovsky, D.M. Harwood & J.Witkowski (Eds.), *Strelnikova – Festschrift*. Ruggell, Lichtenstein: Gantner Verlag.
Witkowski, A. (1990). Fossilization processes of the microbial mat developing in clastic sediments of the Puck Bay (Southern Baltic Sea). *Acta Geologica Polonica*, 40 (1-2), 1-27.
Witkowski, A. (1991a). Diatoms of the Puck Bay coastal shallows (Poland, Southern Baltic). *Nordic Journal of Botany*, 11, 689-701.
Witkowski, A. (1991b). *Fallacia cassubiae* sp. nov., a new brackish-water diatom from the Puck Bay (Southern Baltic Sea), Poland. *Diatom Research*, 6, 401-409.
Witkowski, A. (1993a). *Fragilaria gedanensis* sp. nov. (Bacillariophyceae), a new epipsammic diatom species from the Baltic Sea. *Nova Hedwigia*, 56, 497-503.

Springer

Witkowski, A. (1993b). *Cocconeis hauniensis* sp. nov., a new epipsammic diatom species from Puck Bay (Southern Baltic Sea), Poland. *Nordic Journal of Botany*, 13, 467-471.
Witkowski, A. (1993c). *Fallacia florinae* (Moeller) com. nov., a marine, epipsammic diatom. *Diatom Research*, 8, 215-218.
Witkowski, A. (1994). Recent and fossil diatom flora of the Gulf of Gdańsk, Southern Baltic Sea. *Biblioteca Diatomologica*, 28, 1-313.
Witkowski, A. & Lange-Bertalot, H. (1993). Established and new diatom taxa related to *Fragilaria schulzii* Brockmann. *Limnologica*, 23, 59-70.
Witkowski, A., Pempkowiak J. (1995). Reconstructing the development of human impact from diatoms and ^{210}Pb sediment dating (The Gulf of Gdańsk - Southern Baltic Sea). *Geographia Polonica*, 65, 63-78.
Witkowski, A., Lange-Bertalot H., & Metzeltin D. (2000). Diatom flora of marine coasts I. *Iconographica Diatomologica*, 7, 1- 925.
Witkowski, A., Lange-Bertalot H., Witak M. (1995). Diatom taxa of unusual structure belonging to the genus Fragilaria*, Fragmenta Floristica Geobotanica* 40 (2), 729-741.
Witkowski, A., Lange-Bertalot H. & Stachura K. (1998). New and confused species in the genus *Navicula* (Bacillariophyceae) and the cosequences of restrictive generic circumscription. *Cryptogamie Algologie*, 19 (1-2), 83-108.
Witkowski, A., Metzeltin D., Lange-Bertalot H., & Bafana G. (1997). *Fogedia* gen. nov. (Bacillariophyceae) a new naviculoid genus from the marine littoral. *Nova Hedwigia*, 65 (1-4), 79-98.
Witkowski, A., & Witak M. (1993). Budowa geologiczna dna zatoki. In K. Korzeniewski (Ed.), *Zatoka Pucka.*(pp. 309-315). Gdańsk: Instytut Oceanografii UG,(in Polish).
Yuspina, L. & Savukyniene N. (2003). Biostratigraphy of bottom sediments of the Gdańsk Basin. In E.M. Emelyanov (Ed.), *Geology of the Gdańsk Basin, Baltic Sea* (pp. 118-134). Kaliningrad: Yantarny Skaz.
Zaborowska, K. & Zachowicz J. (1982). Voprosy biostratigrafii donnykh otlozhenyi Gdanskoy Buchty. *Peribalticum*, 2, 195-201, (in Russian).
Zgrundo, A. (2004). Ocena wpływu potoków na stan środowiska w przybrzeżnej strefie Zatoki Gdańskiej na podstawie analizy okrzemkowej. PhD Thesis; University of Gdańsk: 1-163. (in Polish).
Zgrundo, A., & Bogaczewicz-Adamczak B. (2004). Applicability of diatom indices for monitoring water quality in coastal streams in the Gulf of Gdańsk region, northern Poland. *Oceanological and Hydrobiological Studies*, 33 (3), 31-46.