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LAST TWO MILLENNIA WATER LEVEL CHANGES OF THE MŁYNEK LAKE (NORTHERN POLAND) INFERRED FROM DIATOMS AND CHRYSOPHYTE CYSTS RECORD

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Abstract

A sediment core, 350 cm long recovered from Młynek Lake, northern of Poland (Warmia and Masuria Region) was analyzed with respect to their content of diatoms and chrysophyte cysts. The aim was to reconstruct the lake water level and climatic changes during the past 2500 years. The recognized diatom assemblages displayed marked floristic changes along the sediment core samples. The main change in diatom composition consists of a shift from an assemblage dominated by benthic *Fragilaria sensu lato* species through marked intervals to a planktonic one in distinct zones. A high proportion of benthic to plankton taxa has been reported as indicative for a lowering of the lake level with long ice cover in a cold dry climate and a shift from benthic to planktonic diatom taxa reflects arising water level with longest growing season and reduced ice cover on the lake during a warm wet climate. Multivariate statistical analysis included hierarchical ascending clustering distinguished four diatom ecological groups. The analyzed core section was divided into 11 diatom zones according to a distribution of ecological groups and variation in abundance of dominant species supported by ^{14}C data. The results displayed a developmental history of the Młynek Lake that can be divided into 6 main phases of alternating warm wet and cold dry shifts. A distinct dominance of planktonic eutrophic indicator diatoms accompanied by a low abundance of chrysophyte cysts indicates increased lake trophicity and a general trend for the increasing anthropogenic impact.

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Key words: Diatoms, chrysophyte, environment, water level, climate change, Młynek Lake, Poland

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INTRODUCTION

Holocene palaeoenvironmental reconstructions provide information on the natural variability of the climate system and provide longer-term perspectives on present climate trends (Bradley, 2008; Dobrowolski *et al.*, 2016). In the northern hemisphere numerous studies have been achieved on several naturally occurring archives as lakes and marine sediments, tree rings and ice cores, together with climate simulations, to understand the nature, timing and causes of the Holocene climate fluctuations (e.g., Davis *et al.*, 2003; Andersen *et al.*, 2004; Renssen *et al.*, 2005; Osborn and Briffa, 2006; Naughton *et al.*, 2007; Wanner *et al.*, 2008). In addition, the climate change during the last millennium had strong effect on human societies as historically documented for the Roman Warm Period (RWP), the Medieval Warm Period (MWP) and the Little Ice Age (LIA) (Jones and Mann, 2004; Abrantes *et al.*, 2005; Lebreiro *et al.*, 2006).

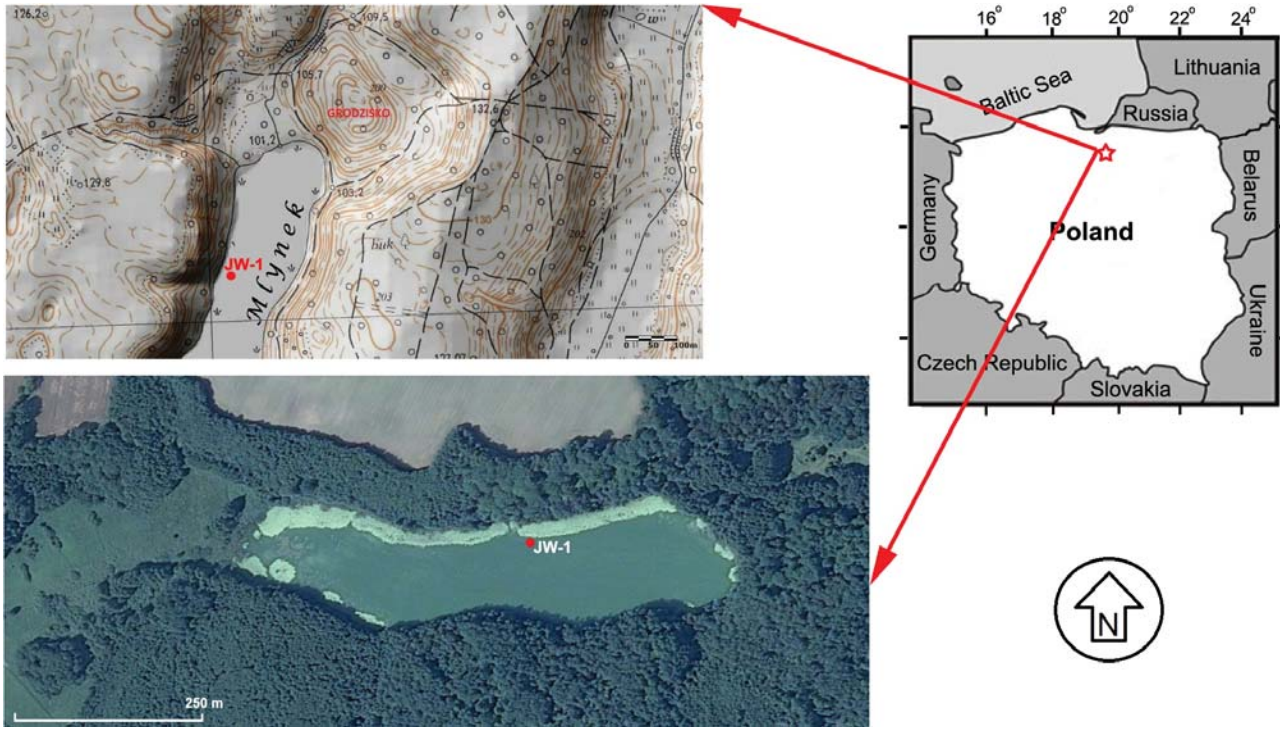

Fig. 1. Location map of the studied core JW-1, Młynek Lake.

Lake ecosystems are very sensitive to climate and environmental fluctuation. Therefore, lacustrine sediments are considered for an excellent natural archive of chemical, biological and physical characteristics of lakes, which in turn are used to reconstruct long-term climate and environmental fluctuations (Jones *et al.*, 2001). These sediments have long been used to reconstruct environmental changes driven by climate fluctuations (Last and Smol, 2001). Palaeolimnological studies using fossil diatoms have been applied in a wide range of investigations to infer long-term dynamics of lakes and their watersheds (Smol and Cumming, 2000). Diatoms are unicellular algae that have robust siliceous frustules, which are often well preserved in lake sediments. They are powerful indicators of past environmental changes due to their sensitivity to chemical and physical lake conditions, as well as their prevalence and high preservation potential in sediments (Battarbee *et al.*, 2001). Diatoms are mainly useful to estimate the lake trophic status (Hall and Smol, 1999), salinity gradient(Stager *et al.*, 2012), and acidification (Koinig *et al.*, 1998). Diatoms have been used also as proxy indicators to reconstruct Holocene climate changes in every continent. Applications of diatoms to climatic and hydrological studies are mostly conducted in (sub-) arctic and alpine regions (e.g., Moser *et al.*, 2000; Smol and Cumming, 2000). However, diatoms are sensitive to dissolved organic carbon concentrations (DOC) (Fallu and Pienitz, 1999), which are in turn strongly controlled by precipitation patterns (Schindler *et al.*, 1996). Several studies have investigated interactions between diatom assemblages and ice and snow cover in lakes, including the Arctic (e.g., Smol, 1988; Douglas and Smol, 1999), high-altitude regions as the Alps (e.g., Lotter and Bigler, 2000) and other continental regions including the Lake Baikal in central Asia (e.g., Mackay *et al.*, 2003).

Furthermore, the Chrysophytes algae are excellent indicators used in palaeolimnological reconstructions due to their sensitivity to different environmental and climatic factors, and their abundance and good preservation in lake sediments (Smol, 1995). Chrysophytes cysts are well known to respond to pH and alkalinity (Zeeb and Smol, 1995; Duff *et al.*, 1997). Air temperature and ice cover might be other important variables driving pH (Koinig *et al.*, 1998) and hence cyst assemblages. Water chemistry is known also to be one of the major factors controlling chrysophytes distribution (Hernandez-Almeida *et al.*, 2014).

The present study is focused on reconstruction of the Late Holocene climate-related environmental changes and lake level oscillations in the Młynek Lake area, northern part of Poland based on diatom and chrysophyte cysts analysis from the sediment record of the lake and supported by AMS radio carbon dating.

SITE DESCRIPTION

According to the physico-geographical division of Poland by Kondracki (2002), the Młynek Lake is located in the Iławskie Lakeland in northern Poland. It is a tunnel valley lake maintaining a NNE-SSW course, about 720 m long and 165 m wide at its maximum. The area of the Młynek

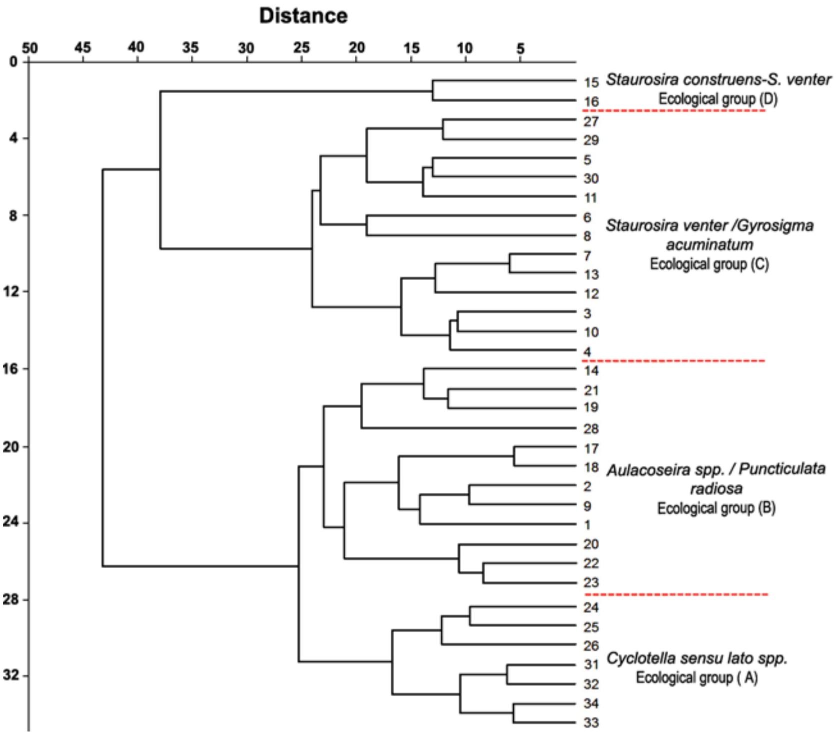

Fig. 2. Cluster analysis of the investigated samples based on the dominant and subdominant diatom taxa and showing the ecological diatom groups.

lake covers 7.5 ha (Choiński, 1991), its water surface rises to about 101 m a.s.l., but the maximum depth is just over 2 m. The lake is surrounded by a corrugated morainic plateau, located at 120–130 m a.s.l. On the upland surface, at the turning point from late to post glacial era, the dead ice melted creating drainage-less depressions of a longitudinal subglacial tunnel valley in which the Młynek Lake formed. The tunnel valley slopes are steep, incised to about 25 m depth, and up to 250 m wide. In the eastern vicinity of the Młynek Lake, there is a group of kame hills composed of fine sands and silts, reaching 200 m, although their height does not exceed a dozen meters or so. They were formed during the deglaciation at the termination of the Vistula Glaciation (Rabek and Narwojsz, 2006, 2008).

MATERIAL AND METHODS

Materials used in this study were obtained from the core JW-1, recovered from the middle-northern part of the Młynek Lake (coordinates: 53.82486 N, 019.72419 E). The sediments at 0.00–0.40 m depth are composed of gray-brown hydrated gyttja, at 0.40–1.10 m is gray-brown gyttja, 1.10– 1.45 m gray-brown very plastic gyttja, 1.45–1.80 m gray-brown, organic gyttja and 1.80–3.50 m gray-brown gyttja with organic matter.

Diatoms and Chrysophyte cysts were extracted from 1 g of dry sediment in each sample using the disintegration method in HCl and H_2O_2, according to the technique proposed by Zalat and Servant-Vildary (2007). For slide preparation, 0.1 ml of the final suspension was dried on cover slips and then mounted onto slides using Naphrax. Diatoms were identified to the species level using a Leica photomicroscope with digital camera and equipped with differential interference (DIC) optics at 1000× magnification with oil immersion. Identification and ecological information of the diatom species were based primarily upon the published literature (e.g., Patrick and Reimer, 1966, 1975; Kilham *et al.*, 1986; Krammer and Lange-Bertalot, 1986–1991; Denys, 1991–1992; Douglas and Smol, 1999; Witkowski *et al.*, 2000; Zalat and Servant-Vildary, 2005, 2007; Hofmann *et al.*, 2011; Zalat, 2015; Zalat *et al.*, 2017). Recent taxonomic advances have split many diatom taxa of the former genus *Fragilaria sensu lato* into several new genera, including *Fragilaria*, *Pseudostaurosira, Staurosira,* and *Staurosirella* spp. (Williams and Round, 1987). These new names herein collectively referred to as *Fragilaria sensu lato.* Chrysophyte cysts were described and enumerated following Duff *et al.* (1995, 1997), Pla (2001) and Wilkinson *et al.* (2002).

For statistical analysis, in every rich-diatom slide, 1000 diatom valves were counted at 630x magnification in order to estimate percentage abundance of individual taxa. For samples with low-diatom concentrations, at least 300 valves were counted. Relative frequencies of every species were calculated as percentage of total diatom valves (%TDV)counted in each sample. It was calculated for estimation of ecological parameters such as life form-grouping, pH and salinity spectrum. The ratio of planktonic to benthic forms was calculated for each sample to estimate

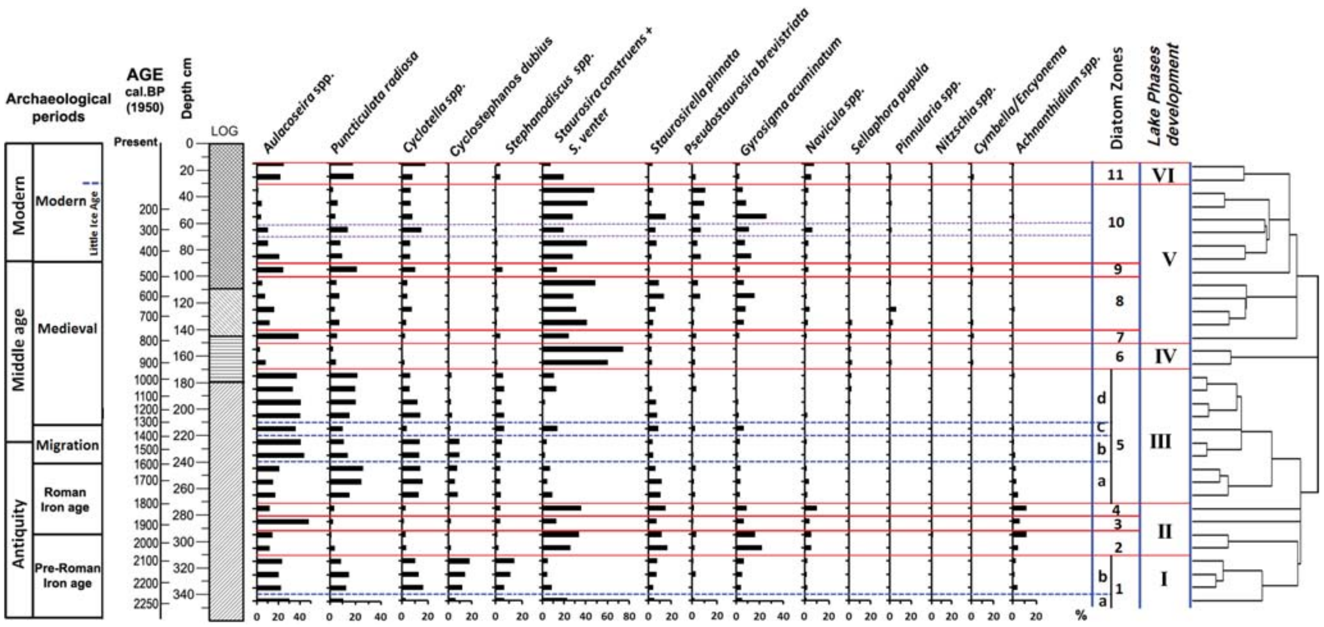

Fig. 3. Diatom stratigraphy of studied core JW-1, Młynek Lake, showing the diatom zones and lake phases development correlated with archaeological periods.

type of habitats and water level changes. The pH grouping of diatoms included three categories: acidophilous (pH <7 to 5.5), alkaliphilous (pH over 7 to 8.5) and alkalibiontic (pH over 8.5). The dominant species that have relative abundance over 5% of the total diatom valves in the examined samples were analyzed stratigraphically for the studied core section.

Multivariate statistical analysis achieved by the computer program PAST (Hammer *et al.*, 2001) was used to distinguish diatom ecological groups. Our calibration model included the diatom taxa that have relative abundance over 5% of the total diatom valves in at least 3 samples. Cluster analysis was carried out using Euclidean distance measure and the average clustering method of the investigated samples to distinguish the diatom ecological groups (Fig. 2).

Radiocarbon dating was performed for 4 bulk samples from the core JW-1, collected from organic-rich gyttja layers or gyttja with dispersed organic matter. The organic matter seemed to have been derived both from aquatic and terrestrial sources. AMS dating was done in the Poznań Radiocarbon Laboratory in Poland, where ^{14}C measurements were performed in graphite targets (Goslar *et al.*, 2004). Total number of ^{12}C, ^{13}C and ^{14}C atoms in a sample was measured, with content of ^{14}C using mass spectrometer by comparing intensities of ionic beams of ^{14}C, ^{13}C and ^{12}C. Conventional ^{14}C age was calculated using correction for isotopic fractionation according to Stuiver and Polach (1977). In a calculation procedure, uncertainty of radiocarbon age was determined with a use of counting statistics and standard deviation of partial $^{14}C/^{12}C$ results, resulting in the so-called 1-sigma uncertainty of conventional ^{14}C age. Calibration of ^{14}C age was performed, using OxCal ver. 4.2 software 10 (http://c14.arch.ox.ac.uk) designed by the Oxford Accelerator Unit and INTCAL13 calibration curve (Reimer *et al.*, 2013).

Interpolation of calibrated radiocarbon dates for the depth-time model was made using the Bacon.R software (Blaauw and Christen, 2011). Bacon is an approach to age-depth modeling that uses Bayesian statistics to reconstruct accumulation rate for deposits, through combining radiocarbon and other dates. Prior assumptions about accumulation rate and its variability over time are taken into account (Blaauw and Christen, 2005). Bacon divides a core into many thin vertical sections (by default of 5 cm thickness), and estimates the accumulation rate for each of these sections. Combined with an estimated starting date for the first section, these accumulation rates then form the age-depth model. I should be noted here that Bacon's calendar scale is cal BP (calendar years before AD 1950).

RESULTS

Diatoms communities during the last two millennia in the sediments of the Młynek Lake fluctuated between rich to frequent and very well to poorly preserved. A total of 215 diatom species and varieties representing 54 genera were identified. Of the recorded species, 58 diatom taxa were distributed regularly and 15 species were either common and/or abundant. The remaining taxa are infrequently distributed throughout the core samples. The relative abundances of the dominant and subdominant taxa have been synthesized in the form of stratigraphic diagrams (Fig. 3).

Most of the recognized taxa belonging to oligohalobous salinity group with very limited taxa less than 5% were considered as mesohalobous forms. The planktonic

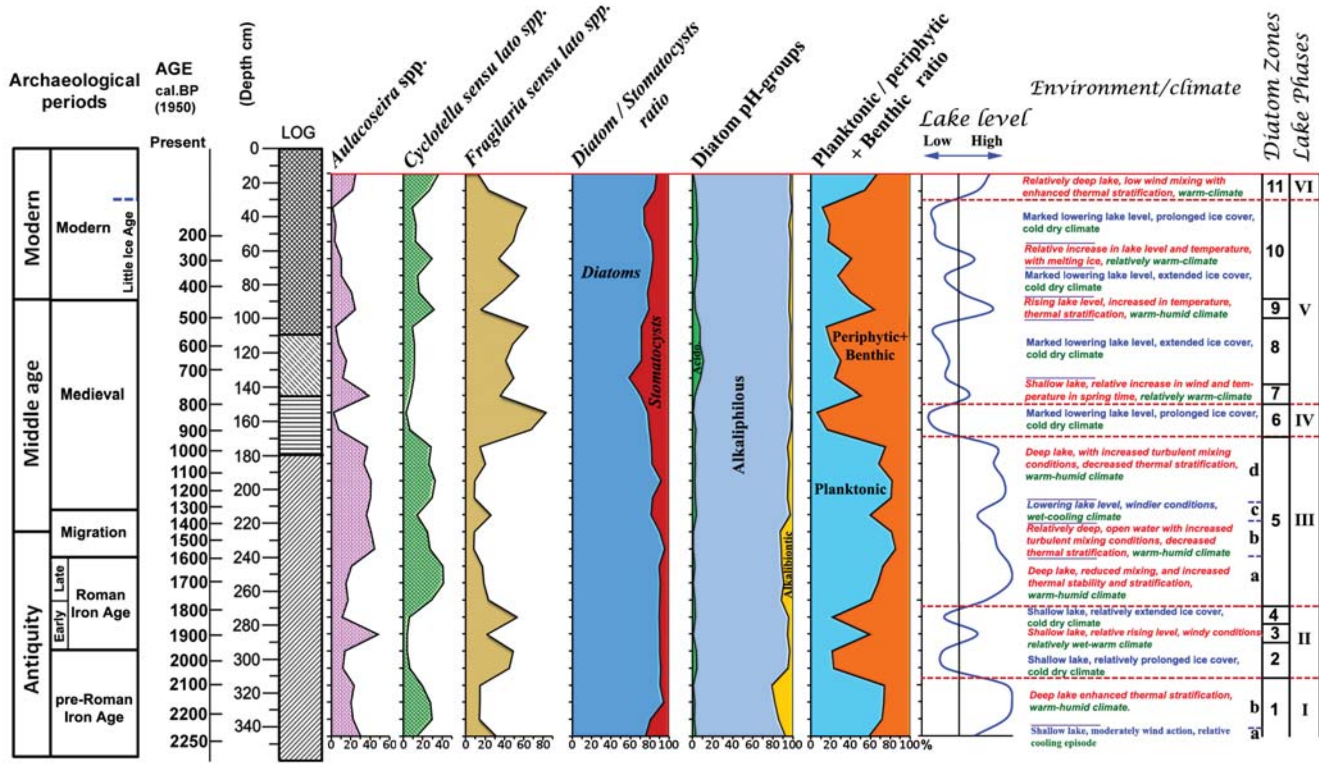

Fig. 4. Diagram showing the correlation between the relative abundance of the dominant diatom groups, diatom/stomatocysts ratio, pH-groups, planktonic/benthic ratio, lake level fluctuations, environment and climate with lake phases development.

taxa were dominant by *Aulacoseira* spp., followed by common of *Puncticulata radiosa*, small *Cyclotella* species and frequently of *Cyclostephanos dubius* and *Stephanodiscus* spp. The benthic species were represented by small *Fragilaria sensu lato* species including great abundance of *Staurosira venter, S. construens,* together with frequently occurrence of *Staurosirella pinnata* and *Pseudostaurosira brevistriata*, beside common appearance of *Gyrosigma acuminatum*. Other benthic species of the genera *Amphora*, *Navicula*, *Sellaphora*, *Cymbella*, *Encyonema*, *Nitzschia*, *Diploneis, Pinnularia* and *Surirella* were distributed sporadically. Most of the recorded diatoms preferring slightly alkaline to alkaline water occurred in the sediments. The most abundant taxa belonged to alkaliphilous group with relative frequency 78–95% of the total assemblage. Alkalibiontic diatoms ranged from 2 to 20%, while the frequency of acidophilous forms varied between 1.5 and 9.2% (Fig. 4).

Chrysophyte cysts were well preserved and relatively frequent distributed in the core sediments of Młynek Lake. A total of 26 stomatocysts including the ornamented and smooth types were recognized. These taxa have considerable potential as palaeoenvironmental and palaeoclimatic indicators in northern Europa and alpine regions. The changes in chrysophyte cysts distributions along with variation in diatom composition could be related to changes in lake-level, pH, metal concentrations, trophic status and climate.

Diatom ecological groups

In general, the diatom assemblages displayed marked floristic changes along the studied core samples, which reflect marked environmental and climatic changes during the past 2250 years. The main change in diatom composition consists of a shift from an assemblage dominated by benthic *Fragilaria sensu lato* species through marked intervals to a planktonic one in distinct zones. A high proportion of benthic to plankton has been reported as indicative for long ice-cover (Karst-Riddoch *et al.*, 2005), and a shift from benthic to planktonic diatom taxa, reflect trend to warming climate. Multivariate statistical analysis included hierarchical ascending clustering distinguished four diatom ecological groups (Fig. 2), which reflect marked environmental changes during the time of sediment deposition. Moreover, these ecological groups are used to divide the core section into eleven diatom zone belonging to six phases of lake development. These ecological groups as follows:

***Cyclotella sensu lato* spp. ecological group (A)**

A planktonic ecological group represented with frequency rating 60–77% of planktonic taxa. This ecological group was characterized by dominance of *Cyclotella sensu lato* species including great abundance of *Puncticulata ra-*

diosa (Lemmermann) Håkansson, *P. balatonis* (Pantocsek) Wojtal and Budzyska, in-combined with common to infrequent occurrence of small taxa such as *Cyclotella delicatula* Hustedt, *C. distinguenda* Hustedt, *C. ocellata* Pantocsek, *C. atomus* Hustedt, *C. meneghiniana* Kützing, *Discostella stelligera* (Cleve and Grunow) Houkand Klee and *D. woltereckii* (Hustedt) Houkand Klee. Other planktonic taxa are signified by considerable abundance of *Aulacoseira granulata* (Ehrenberg) Simonsen, *A. granulata* var. *angustissima* (O. Müller) Simonsen, *A. ambigua* (Grunow) Simonsen, *Cyclostephanos dubius* (Fricke) Round together with infrequently distribution of *Stephanodiscus hantzschii* Grunow, *S. minutulus* (Kützing) Cleve and Möllerand, *S. parvus* Stoermer and Håkansson. The benthic taxa are recorded in limited abundance.

Aulacoseira spp. / *Puncticulata radiosa* ecological group (B)

A second planktonic ecological group (65–86%) that characterized by great abundance of *Aulacoseira* spp. with relative frequency 38–45% of the total diatom community, accompanying with common occurrence of *Puncticulata radiosa* (12–22%) and sporadically distribution of small *Cyclotella* spp., *Cyclostephanos dubius* (Fricke) Round and *Stephanodiscus* spp. The benthic taxa are recorded by infrequently occurrence of *Sturosira venter* (Ehrenberg) Kobayashi and *S. construens* Ehrenberg by frequency less than 20% and rare occurrence of other benthic taxa.

Staurosira venter /*Gyrosigma acuminatum* ecological group (C)

An ecological group characterized by high abundance of benthic taxa with frequency 63–82% of the total assemblage. *Staurosira venter* (Ehrenberg) Kobayashi was the most dominant taxon (28–49%) together with common occurrence of *Gyrosigma acuminatum* (Kützing) Rabenhorst (8–25%) and infrequent abundance of *S. construens* Ehrenberg, *Staurosirella pinnata* (Ehrenberg) Williams and Round and *Pseudostaurosira brevistriata* (Grunow) Williams and Round. The planktonic taxa declined to less than 30% of the total assemblage and represented by infrequently occurrence of *Aulacoseira granulata* (Ehrenberg) Simonsen, *A. ambigua* (Grunow) Simonsen, *Puncticulata radiosa* (Lemmermann) Håkansson, *Cyclotella delicatula* Hustedt, *C. distinguenda* Hustedt, and *Discostella stelligera* (Cleve and Grunow) Houkand Klee.

Staurosira venter /*S. construens*ecological group (D)

This ecological group was characterized by marked decline in abundance of planktonic taxa to less than 15% and absolute abundance of the benthic diatoms (85–91%) with maximum occurrence of *Staurosira venter* (Ehrenberg) Kobayashi and *S. construens* Ehrenberg. While, *Staurosirella pinnata* (Ehrenberg) Williams and Round and *Pseudostaurosira brevistriata* (Grunow) Williams and Round were distributed sporadically.

Diatom stratigraphy

The investigated core section was divided into 11 diatom zones according to hierarchical ascending clustering and the distribution of ecological groups.

DZ 1 (3.45–3.15 m): this zone was dominated by planktonic diatoms of the ecological group (A) with relative abundance from 60 to 74%. It is divided into two subzones. The first one (1a) occupies the interval depth 340–345 cm and characterized by co-abundance of *Aulacoseira* taxa and *Fragilaria sensu lato* species with decline in abundance of *Cyclotella* taxa. The second subzone includes the interval depth 315–335 cm. *Aulacoseira* spp. are common including the eutrophic indicator *A. granulata*, *A. granulata* var. *angustissima*, and *A. ambigua*, accompanying with *Puncticulata radiosa* and *Cyclostephanos dubius*. Other planktonic diatoms are distributed frequently. The benthic *Fragilaria sensu lato* species (*Staurosira construens*, *S. venter*, *Staurosirella pinnata*) and *Gyrosigma acuminatum* are recorded in less abundance with relative frequency 5–10%. Diatom frustules were well preserved and high concentration in this zone. Low abundance of Chrysophyta cysts with high to moderate diatom/cysts ratio (3.2–17) was recorded.

DZ 2 (3.10–2.95 m): the benthic diatoms of the ecological group (C) were most abundant with relative frequency 77–79%. The small *Fragilaria sensu lato* species were dominant (42.7%), e.g., *Staurosira construens*, *S. venter*, and *Staurosirella pinnata* with low abundance of *Pseudostaurosira brevistriata*. Other benthic taxa such as *Gyrosigma acuminatum* reached frequency 17–22% together with infrequently distribution of some *Navicula* spp. and *Achnanthidium* spp. Planktonic species declined in frequency between 21–23% and represented by frequently occurrence of *Aulacoseira granulata* together with sporadically of *Puncticulata radiosa*and small *Cyclotella* spp. Preservation and concentration of diatom frustules were moderate. Diatom/cysts ratio was relatively high (9.7–10.3) with common smooth forms than ornamented taxa.

DZ 3 (2.90–2.85 m): short interval was characterized by predominance of planktonic taxa of the ecological group (B) with relative frequency 61%. *Aulacoseira* spp. show great abundance (48%) with reduction in occurrence of other planktonic diatoms such as *Puncticulata radiosa*, small *Cyclotella* spp. and *Stephanodiscus* spp. The small benthic taxa including *Staurosira construens, S. venter*, *Staurosirella pinnata* declined in frequency to 20% together with sporadic occurrence of *Gyrosigma acuminatum, Navicula* spp. and *Achnanthidium* spp. Well preserved and high concentration of diatom frustules was observed in this zone. Diatom/cysts ratio was relatively high (8.5) with common smooth forms than ornamented taxa.

DZ 4 (2.80–2.75 m): another short interval represented by diatom assemblage of the ecological group (C). Planktonic taxa *Aulacoseira* spp. declined suddenly in its abundance to 12% on expense of benthic small *Fragilaria sensu lato* species, which predominated again with relative frequency 54%, associated with frequently appearance of *Gyrosigma acuminatum*. The benthic taxa constitute 78.3% of the total diatom assemblage. Preservation of diatom frustules was moderate with high concentration. Diatom/cysts ratio was relatively high (9.2) with common smooth forms than ornamented taxa.

DZ 5 (2.70–1.75 m): great abundance of planktonic taxa associated with reducing amount of the benthic forms distinguished this zone. According to the relative abundance of the planktonic *Aulacoseira* spp. and *Puncticulata radiosa*, this zone is subdivided into 4 subzones. The subzone (5a) at the depth 2.45–2.70 m was characterized by diatom taxa of the ecological group (A). Planktonic taxa were dominant (62.5–73%), *Puncticulata radiosa* increased relatively in their frequency over *Aulacoseira* spp. Other *Cyclotella* spp. are distributed frequently. The benthic *Fragilaria sensu lato* species declined in abundance together with sporadic occurrence of other benthic forms. The second subzone (5b) occupied the depth interval 2.20–2.40 m, and signified by decline in abundance of *Puncticulata radiosa* with great abundance of *Aulacoseira* taxa of long chains frustules, while the other planktonic taxa were spread frequently. The benthic taxa are distributed sporadically in this subzone. Short period of small thickness at depth 2.20–2.10 m was characteristic the third subzone (5c). Marked decline in *Cyclotella sensu lato* species associated with relative decrease in abundance of *Aulacoseira* taxa and frequently occurrence of *Fragilaria sensu lato* taxa with significance amount of *Stephanodiscus* spp. The fourth subzone (5d) occupied the depth interval from 2.05–1.70 m, which is characterized by high abundance of planktonic taxa. *Aulacoseira* species are predominant again with common occurrence of *Puncticulata radiosa* and irregular abundance of *Cyclotella* spp. The benthic forms are very limited. In general, well preserved and high concentration of diatom frustules was detected in this zone (DZ 5). Diatom/cysts ratio was relatively moderate (4.5–11) with common smooth forms than ornamented taxa.

DZ 6 (1.70–1.55 m): most of the prevailing planktonic species of the previous zone are replaced by benthic taxa of *Fragilaria sensu lato* species became dominant by frequency rating 70–84%. *Staurosira venter* and *S. construens* are the predominant taxa in this zone. Marked decline in the planktonic diatoms (7–15%) including infrequent *Aulacoseira* spp. and *Puncticulata radiosa*. Diatom frustules were preserved well with high concentration. Diatom/cysts ratio was moderate (3.5–4), with relatively common ornamented cysts over the smooth taxa.

DZ 7 (1.50–1.45 m): short interval was distinguished by diatoms of the ecological group (B). Planktonic taxa represented by *Aulacoseira* spp. increased relatively in abundance (41%) on expense of the benthic *Fragilaria sensu lato* species (30%). Well preserved and high concentration of diatom frustules was distinguished in this zone. Diatom/cysts ratio was low (2.4) with common smooth forms over the ornamented.

DZ 8 (1.40–1.05 m): the planktonic *Aulacoseira* spp. and *Puncticulata radiosa* decreased clearly with increasing abundance of *Fragilaria sensu lato* (45–65%) in this zone, *Staurosira construens* and *S. venter* had maximum abundance (32–49%) with low frequency of *Staurosirella pinnata* and *Pseudostaurosira brevistriata.* Preservation of the frustules was moderate to poor with some teratological diatoms and relatively low concentration. Diatom/cysts ratio was low and relatively stable (2.1–2.5) with common smooth forms.

DZ 9 (1.00–0.95 m): short interval was characterized by diatoms of the ecological group (B). Planktonic taxa increased in abundance (66.7%) with predominance of *Aulacoseira granulata, A. ambigua* and *Puncticulata radiosa.* The benthic *Fragilaria sensu lato* species decreased suddenly in this zone to 16%. Concentration and preservation of the frustules was moderate. Diatom/cysts ratio was relatively moderate (3.8) with common smooth forms.

DZ 10 (0.90–0.35 m): diatom assemblage of the ecological group (C) was distinguished in this zone. There are obvious fluctuations in the abundance of *Fragilaria sensu lato* species that dominant this zone with *Gyrosigma acuminatum*, found in considerable amount. The benthic forms constitute 61–84.5% of the total assemblage, including great abundance of *Staurosira venter* and *S. construens* together with frequent distribution of *Staurosirella pinnata* and *Pseudostaurosira brevistriata*. The planktonic forms declined in their abundance in-between 16–39% and represented by low occurrence of *Aulacoseira* spp., *Puncticulata radiosa* and few small *Cyclotella* spp. Preservation of the frustules moderate with some teratological diatoms. Diatom/cysts ratio was relatively moderate (2.9–5.2) with common smooth forms over the ornamented.

DZ 11 (0.30–0.15 m): marked decline in abundance of benthic taxa accompanied with increased abundance of planktonic forms (62–70%) was observed in this zone. Diatom assemblage of the ecological group (B) reappeared again with great abundance of *Aulacoseira* spp. and *Puncticulata radiosa* associated with reduced abundance of *Fragilaria sensu lato* species. Preservation of the frustules was moderate to poor with many teratological diatoms and moderate diatom concentration. Diatom/cysts ratio was high and common smooth forms over the ornamented.

DISCUSSION

The diatom stratigraphy of the Młynek Lake sediments reflects distinct changes in the natural environment during the past 2250 years. There are marked fluctuations in abundance of small benthic *Fragilaria sensu lato* species and the planktonic *Aulacoseira* taxa together with small *Cyclotella* spp. in the sediment record. Many palaeolimnological studies of the Arctic lakes suggested that changes in the relative abundances between planktonic and small benthic fragilarioid taxa may have been a response to changes in duration of winter ice cover (Smol, 1988; Douglas and Smol, 2010). Other palaeolimnological studies have reported conspicuous and abrupt shifts in *Cyclotella–Aulacoseira–Fragilaria* species as a result to sharp shifts in high magnitude fluctuations in past climate (e.g., Schmidt *et al*., 2012; Jones *et al*., 2013). Distribution patterns of *Cyclotella–Fragilaria– Aulacoseira* diatom assemblages in the lake sediment record are often related to the phenology of the lake ice, thermal stratification and mixing regimes, the depth of the epilimnion, and the development of subsurface habitats (Lotter and Bigler, 2000).

The warmer climate and strengthening of thermal stratification favor small-celled *Cyclotella*/*Discostella* taxa that have relatively high surface area to volume ratios (Winder *et al*., 2009). However, the fragilarioid spp. show the highest accumulation rates in the sediment traps during the ice-covered period. Several authors attributed this cycle in diatom life strategy to climate-mediated changes in the duration of ice cover and thermal stratification patterns (e.g., Smol, 1988; Douglas and Smol, 1999, 2010; Schmidt *et al*., 2012). According to these results, the ratio between planktonic diatoms *Aulacoseira* and *Cyclotella* species and the benthic *Fragilaria* species gives good information on the length and extent of the ice cover and climatic changes.

First distinguished period in the investigated lake encompassed the phases I and II and the lowest part of the third phase of lake development during the Iron Age and Roman Period (2250 BC – 350 AD). The first phase (I) started at the basal part of the core at the depth to 345–315 cm, and encompassed the interval between ca. 250–88 BC. The diatom assemblage of DZ 1 was characteristic for this phase, which was subdivided into 2 stages. The first stage contained the subzone (1a), distinguished by co-abundance of *Aulacoseira* taxa and *Fragilaria sensu lato* species with declined abundance of *Cyclotella* taxa. The assemblage reflects shallow slightly alkaline lake with moderately wind action during relatively cooling episode. The second subzone (1b) was distinguished by maximum abundance of the planktonic diatoms with dominance of *Aulacoseira* spp., together with common *Puncticulata radiosa* and small *Cyclotella* spp. The benthic *Fragilaria sensu lato* species are reduced in their occurrence. Great abundance of planktonic taxa is indicative of a rising lake level. Common occurrence of *A. granulata* suggests high trophic status of slightly alkaline freshwater environment with high silica concentration. The synchronous increases in small planktonic *Cyclotella* diatoms accompanied by concurrent relative decreases in benthic taxa suggest changes indicating longer ice-free periods and enhanced thermal stratification. During this time, alkalibiontic *Cyclostephanos dubius* shows relatively common frequency probably as a response to increased temperature and nutrients in the lake**.** The diatom/cysts ratio was high, which denotes rising water lake level accompanied by increased trophicity. It is supported by abundance of eutrophic indicator *Aulacoseira granulata*. Moreover, *Aulacoseira* taxa are also used as indicators of wind-induced mixing in the lake. Their common occurrence suggests stabilized conditions, remaining wet and windy conditions with increased turbulence and upwelling in the reservoir.

The second phase of lake development encompassed the interval from ca. 88 BC to 150 AD at 315–270 cm depth. Marked environmental change was recorded at the beginning of this phase at the depth 315–290 cm. The planktonic diatoms reduced abruptly in their relative occurrence with increasing in abundance of benthic fragilarioid taxa accompanied with common of *Gyrosigma acuminatum*. The diatom assemblage reflects a lowering lake level, mesotrophic alkaline freshwater environment through the period ca. 80 BC to 60 AD. Ecological conditions in this period were unfavorable for a development of planktonic diatoms and chrysophyte algae because of a low water level in the lake, and benthic diatoms dominated in bottom sediments. This period was followed by short rising water level episode of about 33 years, started from 26 to ca. 59 AD, since the abundance of planktonic eutrophic indicator *Aulacoseira* spp. increased suddenly on expense of the benthic fragilarioid taxa at 2.90–2.85 m depth. Low occurrence of stomatocysts with great abundance of *Aulacoseira* spp. reflects the lake eutrophication. Planktonic diatoms dropped abruptly from 60 to 125 AD, at the termination of the second phase of lake development. During this period, the benthic taxa including *Fragilaria sensu lato* species, *Gyrosigma acuminatum*, *Navicula* spp. and *Achnanthidium* spp. were abundant. The diatom assemblage suggests lowering water level of the alkaline freshwater lake with relatively extended ice cover periods during the cold dry climate. The marked dropping in the abundance of *Aulacoseira* taxa and *Puncticulata radiosa* indicate declined in nutrients concentration with silica content and the lake became mesotrophic.

The third phase of lake evolution (ca. 158–972 AD) can be subdivided into 4 stages based on relative abundance of the planktonic diatom taxa, corresponding with the diatom zone (DZ 5). The first stage comprised the first diatom subzone (DZ 5a) at 270–245 cm depth that period between ca. 158–400 AD. Distinct environmental shift took placed during this period. The diatom assemblage of the subzone (DZ 5a) was represented by great abundance of planktonic *Puncticulata radiosa*,accompanied by common occurrence of *Aulacoseira* spp., small *Cyclotella* spp. and considerable amount of the alkalibiontic taxon *Cyclostephanos dubius*. The clear increasing in the abundance of planktonic taxa, in particular *Cyclotella sensu lato* spp. with concurrent relative decreasing in benthic taxa including fragilarioid species suggest a climate warming and changes as evidence of longer ice-free periods and enhanced thermal stratification. Increased abundance of *Cyclotella sensu lato* species over than the *Aulacoseira* taxa reflect nutrient-poor or moderate to form mesotrophic lake, reduced mixing, stratification and increased thermal stability that favour planktonic diatoms.

The second stage of the phase III of lake development covered period interval 400–500 AD and encompassed the depth 240–220 cm. During this stage, the diatom assemblage of the subzone (DZ 5b) was characterized by reduced occurrence of *Puncticulata radiosa* associated with increasing abundance of *Aulacoseira* spp. The other remaining planktonic taxa such as small *Cyclotella* spp., *Cyclostephanos dubius* and *Stephanodiscus* spp. are represented in considerable amounts. The dominance of *Aulacoseira* spp, usually found in shallow, eutrophic, slightly alkaline (pH optimum around >7 to 8) wetlands during warm windy periods (Zalat and Servant-Vildary, 2007; Zalat, 2015; Zalat *et al.*, 2017; Marks *et al.*, 2018). Consequently, the diatom assemblage of the second stage of the phase III reflects relative gradually decreasing lake level with increased trophicity, slightly alkaline open freshwater environment and stronger turbulent mixing conditions during warm humid climate. This is followed by a short episode 550–600 AD at depth 215 cm, where the fragilarioid taxa increased relatively at the expense of *Cyclotella* spp. associated with common occurrence of *Aulacoseira* taxa. The diatom assemblage reflects a lowering of the lake level during windier conditions and a relative dry cool climate. The phase III of the lake development is terminated by the diatom subzone (DZ 5d), through the period 650–972 AD. The re-dominance of *Cyclotella* spp. with great abundance of *Aulacoseira* taxa reflects a rising lake level with increased turbulent mixing conditions, relative decreasing thermal stratification in a warm humid climate.

The fourth phase of lake evolution occurred in the period from 1050 to 1150 AD at 170–150 cm depth. It was characterized by DZ 6, distinguished based on absolute abundance of the benthic *Fragilaria sensu lato* species with sporadic occurrence of planktonic taxa less than 10% of the total assemblage. The chrysophyte cysts increased relatively but had still a lower frequency than the diatoms. Dominance of benthic small fragilarioid diatoms reflects coldest dry climate period from 1050 to 1150 AD and the lake was shallow, alkaline freshwater, had lower nutrient concentrations with low silica content and extent of ice cover. The steep decrease in temperature for about 100 years in our record is in agreement with documentary winter temperature reconstructions in literature, showing that for the period between 1090 and 1179 AD winter temperatures within the WMP were similar to the ones during the Little Ice Age (LIA) (Pfister *et al.*, 1998). This cold episode could correspond to the Great Winter of 1076/1077 AD, which affected all of Western Europe, including northeastern Spain (Pfister *et al.*, 1998; Pla and Catalan, 2005). Moreover, there are many evidences of glacier advances between 1050 and 1150 AD (Grove and Switsur, 1994), namely in the Alps (Holzhauser *et al.*, 2005), Alaska (Wiles *et al.*, 1995), North and South Patagonia, British Columbia (Luckman and Villalba, 2001) and Greenland (Geirsdottir *et al.*, 2000). Some of these advances were of small extent, but others, were very prominent for instance those in the Alps and southeastern Tibet. Therefore, the period of glacier advances between 1050 and 1150 AD seems to be of global extent and roughly coincides with the so-called Oort minimum of solar activity.

Phase V of Młynek Lake evolution occupied the interval 1170–1820 AD. At the beginning of this phase, a marked environmental change occurred during a short episode at around 1170–1200 AD at 150–145 cm depth. The diatom assemblage DZ 7 was distinguished by relative decline in abundance of the benthic *Fragilaria sensu lato* species in-combined with increasing abundance of *Aulacoseira* spp. and frequent occurrence of Chrysophyta cysts. Re-dominance of the planktonic *Aulacoseira* spp. at the expense of the benthic taxa reflects a free ice cover episode that led to slightly rising water level of a shallow, slightly alkaline freshwater lake with increased the eutrophication during relatively warm wet climate.

A steep decreased temperature for about 170 years from 1250 to 1420 AD occurred and the diatom community of DZ 8 at 140–105 cm depth was flourished. In this zone, benthic diatoms including fragilarioid spp. dominated with relatively common occurrence of chrysophyte cysts and clear decline in the planktonic diatom taxa. Recognized stomatocysts types 5, 33, 157 and 212 are known to be common in cold water (Duff *et al.*, 1995). A high abundance of benthic fragilarioid diatoms and common chrysophyte cysts reflect cooler and dry conditions of shallow alkaline lake with lower nutrient concentrations and longer duration of extent ice cover. This colder period in particular between AD 1350 and AD 1450 corresponds to large explosive volcanic eruptions and solar minima (Breitenmoser *et al.*, 2012; Anchukaitis *et al.*, 2013). There is a marked evidence of volcanic effects on length of winter conditions in Poland, found in the context of the volcanic eruption at AD 1258, when total solar irradiance (TSI) values were high but volcanic forcing strong (Stothers, 2000). Moreover, the cold period around 1350 AD in our record (DZ 8) agrees with the very cold winters 1352–1355 AD, recorded in the GISP2 ice core (Stuiver *et al.*, 1995), low temperatures reconstructed for the Northern Hemisphere (Mann, 2002) and the estimated low radiation (Bard *et al.*, 2000).

After this cold phase, a short episode of warming at 1500 AD occurred. The diatom assemblage DZ 9 was characteristic for this event at 100–95 cm depth. There is apparent decline in abundance of the benthic fragilarioid taxa associated with great abundance of planktonic diatoms as *Aulacoseira* spp. and *Puncticulata radiosa* with frequent occurrence of small *Cyclotella* spp. The diatom assemblage suggests climate warming and changes as evidence of ice-free episode including rising lake level, increased trophic state of the lake and stronger turbulent mixing conditions. The predominance of alkaliphilous diatom taxa with low abundance of chrysophyte cysts indicates eutrophic, slightly alkaline freshwater environment during the early episode of the Late Middle Age. This warm event (ca. 1500–1550 AD) occurred during the Little Ice Age and coincides well with data from the European lakes (e.g., Lotter and Bigler, 2000; Magny, 2004). An evidence from Poland, based on stable carbon isotopes, also shows a warm-wet event at that time (Skrzypek and Jędrysek, 2000).

The temperature dropped again and the climate changed into cold-dry through the next period from 1520 to 1820 AD. A colder climate was indicated during this period by diatom assemblage DZ 10, which is distinguished by a prominent lower abundance of the planktonic taxa and increased abundance of small *Fragilaria sensu lato* taxa, together with common appearance of *Gyrosigma acuminatum*. The highest diatom/cysts value with maximum development of benthic fragilarioid taxa and low frequency of planktonic diatoms it being indicative of lowering water level in the Młynek Lake with prolonged ice cover over the time period 1520 to 1820 AD. The lake was characterized by alkaline freshwater environment with poor to moderate nutrient concentrations. A short episode at ca. 1750 AD denotes relatively warm climate with relative higher water level of a shallow lake as interruption in this cold phase. Comparison with other European cold-season reconstructions indicates that phases with the highest abundance of *Fragilaria sensu lato* species are contemporaneous with the Little Ice Age in the Alps and thus suggest a longer ice-cover on the lake during this cold phase (Wanner *et al.*, 2000). Therefore, our data explain that the fifth phase of Młynek Lake was simultaneous with the Little Ice Age.

This cold period was identified by Grove (2004) as a time interval from 1300 to 1850 AD, which is composed of several periods when glacial extents were larger. The glacial advances during the LIA have been identified in all parts of the world. In the Alps, the LIA consisted of three major periods of glacial advance with moderate retreat in-between (Wanner *et al.*, 2000; Holzhauser *et al.*, 2005). Even though the peaks of glacier activity, centered at 1300, 1450, 1650, 1850 AD in the Alps, Alaska and Rocky Mountains, roughly correspond to the Wolf, Spörer, Maunder and Dalton minima (Wiles *et al.*, 2004; Holzhauser *et al.*, 2005). Moreover, a brief cooling phase can be documented between 1689–1699 AD that matches with a 11 years cool phase described in the Tatra Mountains in Poland (Niedźwiedź, 2010). The very strong cooling (long winters) in the second half of the 15th century and persistently severe winter conditions in Poland until ca 1700 AD coincided with high pressure conditions of the Siberian High (Meeker and Mayewski, 2002) and transport of cold continental air to eastern Poland.

A conspicuous environmental and climatic change was observed in the last phase VI of the Młynek Lake development from 1850 to 1935 AD, represented by the topmost samples at 30–15 cm depth. At the beginning ca. 1850 AD, there was an almost complete shift from diatom assemblage consisting mainly of benthic *Fragilaria sensu lato* taxa of DZ 10 to planktonic taxa including eutrophic indicator *Aulacoseira* spp., *Puncticulata radiosa* associated with other small *Cyclotella* taxa of DZ 11. This change in diatom communities continued to the recent time, which indicated a longer growing season, due to climate warming. The alkaliphilous diatom taxa reached about 95% and the chrysophyte cysts were represented in a low amount. The diatom assemblage reflected slightly alkaline freshwater environment with relative rising lake level and increased nutrient concentrations during warm climate. Moreover, the pronounced occurrence of *Cyclotella sensu lato* species with concurrent relative decline in benthic taxa suggests ice-free periods and enhanced thermal stratification. Our record agree well with a large survey on arctic and subarctic lakes by Smol *et al.* (2005), who found recent (post-1850) increased abundances of small planktonic *Cyclotella* taxa at the expense of *Fragilaria* spp., linking these changes to reduced ice cover and/or enhanced thermal stratification. This has been supported also by Rühland *et al.* (2008), who found similar changes in diatom assemblages not only in arctic and subarctic Canada but also in alpine and temperate lakes.

Increasing warming after the mid-19th century is consistent with a reduced number of volcanic eruptions, increasing insolation and anthropogenic greenhouse effect (Hegerl *et al.*, 2007; Jones *et al.*, 2013), since the increasing in temperatures is simultaneous with industrialization during the last century (Mann *et al.*, 1999). Furthermore, our record explained that the variations in diatom species abundance, loss of biodiversity, dominant eutrophic taxa and presence of teratological diatoms with poor to moderate preservation encountered in the sediment samples after 1900 AD to present are likely due to increasing in human activity and anthropogenic nutrient additions to the lake system.

CONCLUSIONS

A sediment record, 350 cm long obtained from the Młynek Lake in northern Poland has been investigated in detail by diatom and chrysophyte cysts analysis to gain knowledge of environmental and climatic changes in the last 2250 years. The documented diatom assemblages in the sediment record reveal their sensitivity to climate-related environmental changes over the last two millennia. Multivariate statistical analysis distinguished four diatom ecological groups, which are used to divide the core section into eleven diatom zone. Results of the diatom analysis, supported by ^{14}C data explained 6 different phases of lake development through its history. The first phase I was encompassed the period from 250 to 88 BC that belonged to La Tène Cage. The diatom assemblage reflected the base of the core section at 245 cm depth was deposited in shallow slightly alkaline water during the relatively cooling climate. After that, the lake environment shifted to a deep, enhanced thermal stratification during a warm-humid climate. The phase II (88 BC – 150 AD) was characterized by a cold climate, interrupted by a short warming episode of about 33 years from 26 to ca. 59 AD. The diatom assemblage reflected lowering of the lake level of a mesotrophic alkaline freshwater environment during a cold dry climate. This was followed by a short episode with a warm-humid climate, where the *Aulacoseira* spp. became dominant. Clear declining in temperature and extent ice cover occurred again at the end of the second phase of lake development, associated with predominance of *Fragilaria sensu lato* spp. The phase III of the lake history was distinguished by rising lake level during a warm period from 158 to 972 AD, with increasing trend in temperature and free ice cover. This warm phase was interrupted by a short episode ca. 550–600 AD, characterized by a diatom assemblage that suggested lowering of the lake level during windier conditions and a relative dry cooling climate. The phase IV covered the period from 1050 to 1150 AD, characterized by absolute abundance of the benthic *Fragilaria sensu lato* species which reflected coldest climate and the shallow, alkaline freshwater lake with extensive ice cover. The phase V was the coldest period in the lake history that occupied the interval of 1170–1820 AD. It was interrupted by short episodes of relatively warm climate at ca. 1170–1200, 1500 and 1750 AD. The recorded diatom assemblage with relatively common chrysophyte cysts reflected cooler and dry conditions of shallow, alkaline freshwater environment with extensive ice cover. In addition, the assemblage of warmer climate reflected a slightly rising lake level of freshwater environment with increased eutrophication. Finally, recent history of the Młynek Lake (ca. 1850 to 1930 AD) is represented by the phase VI. Diatom communities indicate warming, relative rising of the lake level, slightly alkaline freshwater environment with longer growing season and increased nutrient concentrations. In this phase, diatom abundance and preservation declined, with dominant eutrophic taxa and presence of many teratological diatoms, which may linked to increasing anthropogenic activities in recent time.

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