2,400 yrs. climate and human-induced environmental change recorded in sediments of Lake Młynek in northern Poland

Fabian Welc (1), Jerzy Nitychoruk (2), Leszek Marks (3), Krzysztof Bińka (3), Anna Rogóż-Matyszczak (2), Milena Obremska (4), Abdelfattah Zalat (5)

1. Institute of Archaeology, Cardinal Stefan Wyszynski University in Warsaw, Poland, e-mail: f.welc@uksw.edu.pl, corresponding author
2. Faculty of Economic and Technical Sciences, Pope John Paul II State Higher School of Education, Poland, e-mail: jerzy.nitychoruk@pswbp.pl, annarogoz@interia.pl
3. University of Warsaw, Faculty of Geology, Poland, e-mail: k.binka@uw.edu.pl, leszek.marks@uw.edu.pl
4. Polish Academy of Sciences, Institute of Geological Sciences, Poland, e-mail: mobremska@twarda.pan.pl
5. Tanta University, Faculty of Science, Tanta, Egypt, e-mail: abzalat@science.tanta.edu.eg

Abstract

In the densely forested Warmia and Masuria region (northern Poland) there are many endorheic small lakes characterized by their low sedimentation rate, which makes them excellent archives of the Holocene environmental and palaeoclimatic change. Lake Młynek, located near the village of Janiki Wielkie, was selected for multi-faceted palaeoenvironmental research supported with radiocarbon dates. Sediments from this lake also contain unique information about human impact on the environment, because a stronghold has been operating on its northern shore since the early Iron Age to the early Medieval period, giving the opportunity to correlate palaeoenvironmental data with phases of the human activity over the last 2,400 years. During the 3rd and 2nd centuries BC the lake was surrounded by a dense deciduous forest. From the 1st century BC to 2nd century AD the forest around the lake was much reduced, which can be associated with the first pre-Roman (La Tene) and Roman occupation phase evidenced by the construction of the stronghold located close to the lake. From the 2nd up to 9th century AD gradual restoration of the forest and a decline of human activity took place, along with lake deepening and the onset of a colder and humid climatic phase which corresponded to the global cooling episode known as the Bond 1 Event (1.5 ka BP). The next intensive phase of forest clearing around the lake occurred between the 9th – 13th century AD as result of human activity (Middle Age settlement phase of the stronghold). This period is marked by a warming, which has impacted and transformed the landscape likely over prints any signals of climate-driven environmental changes.

34

37

1. Introduction

Lake sediments are a useful source of proxies of past environmental and climate changes in the Holocene (see Brauer, 2004; Zolitschka, 2007; Wanner et al., 2008; Francus et al., 2013; Ojala et al., 2013; Welc, 2017). The main advantage of lakes for environmental reconstruction is the continuous and uninterrupted accumulation of their sediments. Well-dated lake sedimentary records allow for tracing of both long- and short-term climate changes in the Holocene (Smol et al., 2001; Tiljander et al., 2002; Valpola and Ojala, 2006; Czymzik et al., 2010; Elbert et al., 2012; Tylmann et al., 2012; Welc, 2017). Particularly valuable for palaeoclimate reconstructions are sequences from lakes without river inflow and outflow (Wetzel, 2001; Stankevica et al., 2015). As in most of Europe, many lakes in Poland have been heavily impacted by human activities within their catchments, resulting in many of them to become eutrophic in terms of their nutrient status (Cooke et al., 2005). Such intensive bio-productivity arising from nutrient enrichment results in the deposition of thick organic sedimentary sequences, mostly of organic gyttja composed of remains of aquatic plants, plankton and benthic organisms transformed by bacteria and mixed with mineral components supplied from the lake basin (Kurzo et al., 2004; Stankevica et al., 2015). There are ca. 1000 freshwater lakes of different sizes in the Warmia and Mazury Region in northern Poland (Fig. 1). Most of them are located within past glacial tunnel valleys formed by meltwater erosion at the termination of the Vistulian (Weichselian) Glaciation (ca. 115-12 ka BP). After deglaciation at the end of the Pleistocene these glacial tunnel valleys were partly filled with deposits and water, which persisted to the Holocene. Such lake basins have steep slopes and their bottom deposits are underlain by glaciofluvial sand, gravel and silt or glacial till (Kondracki, 2002; Gałązka, 2009). Many of these lakes are small (<1 ha), with stable sedimentation rates and without river inflow or outflow making them excellent sites for palaeoclimate reconstructions. Indeed, most of the climate reconstruction studies based mainly on pollen analysis are undertaken in this area (e.g., Kupryjanowicz, 2008; Kołaczek et al., 2013).

Lake Młynek is located near the village of Janiki Wielkie and it was selected for multi-faceted palaeoenvironmental research (pollen analysis, diatom, chrysophyte cysts, and geochemistry). It is hypothesized that the bottom sediments of this lake contain a unique record of

66 human impact on the surrounding environment, as a result of the location of an Iron Age stronghold

67 on the northern shore, which was active (though not continuously) up until the early Middle Ages

68 (Fig. 1). Due to archaeological research stratigraphic units distinguished on this site were divided

69 into seven main settlement phases: early Iron Age (I), stronghold abandoned after the early Iron

70 Age (II), early Middle Ages (III), stronghold abandoned in the early Middle Ages (IV), settlement

71 activity in the 11th – 13th centuries (V), stronghold definitely abandoned in the 14th century (VI)

72 (Nitychoruk and Welc, 2017; Rabiega et al., 2017).

73 This study provides an opportunity to reconstruct the transformation of the vegetation

74 around the lake that occurred under the influence of the climate (regional significance) and as a

75 result of human activity. Our results were correlated with geoarchaeological data to determine

76 mutual relations between environmental and climatic changes with development of human

77 settlement phases in the Warmia and Mazury (northern Poland) region during the last 2,400 years.

78

79 **2. Study area**

80 Lake Młynek is a small water body that occupies a glacial tunnel valley since the Holocene.

81 The lake is located in the Iława Lakeland in northern Poland, it is about 720 m long and 165 m

82 wide. The lake has an area of 7.5 ha, with its water level at ∼101 m a.s.l. and the maximum depth

83 is just over 2 m. Lake Młynek is surrounded by a morainic plateau at 120-130 m a.s.l and its

84 catchment consist is occupied by a dense forest (Fig. 1). In general, most of the Ilawa Lakeland is

85 covered with forest (41.5%), whereas meadows and synanthropic communities have a smaller

86 share. Among the habitats, a highly-productive mixed forest prevails. The basic components of the

87 Iława forest are pine (*Pinus*), oak (*Quercus)*, beech (*Fagus*), alder (*Alnus*), birch (*Betula*), in

88 smaller amounts there are spruce (*Picea*), larch (*Larix*), ash (*Fraxinus*), hornbeam (*Carpinus*),

89 maple (*Acer*) and linden (*Tilia*). Currently, the lake sits in a catchment that is characterized by a

90 transitional climate with influence of continental and maritime circulation. The growing season

91 lasts about 206 days, and the snow cover remains for 70-90 days. Average temperature values range

92 from approximately -4.0°C in February to above 17.0°C in July. Due to significant participation of

93 the polar air masses and a large number of natural water reservoirs, air humidity is relatively high,

94 ranging from 72% to 89%. Total annual precipitation ranges from 500 to 550 mm a year.

95 Southwestern winds dominate throughout a year, with westerly winds stronger in winter and the

96 highest wind speeds recorded during the winter months (Jutrzenka-Trzebiatowski and Polakowski,

97   1997; Stopa-Boryczka at al., 2013). It is important to note, that from the north, a small stream flows

98   into the lake Młynek, which is active in winter and dries up almost completely in summer (Fig. 1:

99   D). The stream is a result of irrigation related to the construction of a mill in the 15th century,

100 somewhere in the vicinity of the medieval stronghold located on the northern shore of the lake

101 (Semrau, 1935, Bińka et al., 2020).

102

103 **3.   Material and methods**

104 *3.1. Bathymetry*

105   Determination of lake bathymetry and thickness of bottom sediments is extremely

106 important in palaeolimnological research to help locate appropriate coring sites. This can be

107 achieved through the use of GPR sounding (Lin et al., 2009; Sambuelli et al., 2009; Sambuelli and

108 Silvia, 2012). In Poland winter is a particularly convenient season when the lake is covered with

109 ice, making GPR profiling much easier and improving access and speed of data collection (Hunter

110 et al., 2003). Measurements along and across the lake were carried out in 2017, directly on the lake

111 ice (Fig. 2). We used the radar system ProEx of the Malå Geoscience (www.malagpr.com.au/mala-

112 professional-explorer.html). A radar pulse was generated at a regular distance interval of 0.02 m

113 (900 samples were recorded from a single pulse). The time window of recording was between 250

114 and 300 ns. Prospection was done with use of a shielded monostatic antenna with 250 MHz nominal

115 frequency of the electromagnetic wave.

116

117 *3.2. Coring and sampling*

118   Based on the results of the GPR sounding,4 drillings were undertaken a ca. 2 m water depth

119 (Fig. 3) to collect cores following the Givelet et al. (2004) collecting protocol. A piston sampler

120 was used during drilling, which is very suitable for sampling in moderately cohesive sediments to

121 a depth of 5 m. The sampler set consists of a 200-cm long sonde, which is constructed from a thin-

122 walled, 40-mm diameter, stainless steel tube (https://en.eijkelkamp.com/products/sediment-

123 samplers/Piston-Sampler-set.html). Sediment cores were film-wrapped in 1 m plastic tubes and

124 transported to the laboratory. The cores (M1-4) were then subjected to magnetic susceptibility

125 measurements which enabled the selection of the core M-1, the longest and most continuous, to

126 carry out detailed analysis. The 3.5 m long core M-1 (geographic coordinates: 53.82486 N,

127 19.72419 E) was sub-sampled at 5 cm intervals and used for multi-proxy laboratory analyses.

128

3.3. Magnetic susceptibility (MS)

The cores from Lake Młynek were subjected to MS measurements using SM-30 magnetic susceptibility meter (ZH Instruments). Due to very high sensitivity (1 x 10^{-7} SI units) this device was provided with 8 kHz LC oscillator and its pick-up coil sensor was large enough to measure sufficiently high volume of sediments with very low MS. The measurements were done at every 5 cm along each core (M1-4).

135

3.4. Radiocarbon dating and age depth model

Radiocarbon dating was performed on 4 bulk samples from the core M-1, collected either from organic-rich gyttja or gyttja with dispersed organic matter (Table 1). The organic matter seems to have been derived both from aquatic and terrestrial sources. AMS dating was carried out by the Poznań Radiocarbon Laboratory in Poland (for methodology see Goslar et al., 2004). The construction of age-depth models required an assessment of several factors that could disturb constant accumulation of bottom deposits of Lake Młynek, such as those from sedimentary and post-sedimentary processes (including a varied rate of deposition and compaction, and the impact of bioturbation). The varied influx of material delivered to the lake from the adjacent area is a very important factor of disturbance. Therefore, a Bayesian age-depth model was chosen as it takes into account the sedimentation rate and its variability (Blaauw and Christen, 2005, 2011; Blaauw et al., 2007) (Fig. 4). The model was based on default settings, except for section thickness which was set at 0.05 cm given the length of this core. The Bacon model uses the IntCal3 curve (Reimer et al., 2013) to calibrate the radiocarbon data.

150

Table 1. List of radiocarbon determinations.

No.	Depth in m	Lab. reference	^{14}C yr. BP	Age calibrated 95% probability	Material dated
1	0.95-1.00	S/JW 1/2015/A	435 ± 30	1418 – 1494 AD	Bulk of gyttja
2	1.65-1.70	S/JW 1/2015/B	1015 ± 30	971 – 1048 AD	Bulk of gyttja
3	2.40-2.45	S/JW 1/2015/C	1730 ± 30	236 – 386 AD	Bulk of gyttja
4	3.45-3.50	S/JW 1/2015/D	2275 ± 30	401 – 351 BC	Bulk of gyttja

152

3.5. Palaeobotanical analysis

3.5.1 Pollen

The core M-1 was sampled every 5 cm for pollen analysis. 70 samples (ca. 10 g each) were treated with 5% HCl, boiled in 5% KOH and hot 30% HF. They were washed with 15% HCl and treated by the standard Erdtman's acetolysis. In each sample about 1000 pollen grains were counted using an optical microscope at 400x magnification.

3.5.2   Diatom and Chrysophyte cysts analysis

70 samples were prepared for the analysis of diatoms and chrysophyte cysts. They were extracted from 1 g of dry sediment of 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 coverslips and then mounted onto slides using Naphrax. Diatoms were identified to species level using a Leica photomicroscope with a digital camera and equipped with differential interference contrast (DIC) optics at 1000x magnification with oil immersion. Identification and ecological information of the diatom species were based primarily upon the published literature (e.g. Kilham et al., 1986; Douglas and Smol, 1999; Witkowski et al., 2000; Hofmann et al., 2011). Recent taxonomic advances 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). Preliminary results of the diatom studies based on the core M-1 were already published by Zalat et al. (2018).

3.6. Geochemical analysis

ICP-OES spectrometer was used for determination of basic (Al, Ca, Mg, Na, K, Fe, P) and trace elements (As, Cd, Mn, Th, Ti, U, V, Zn). Powdered samples were mineralized in a closed microwave Anton Paar Multiwave PRO reaction system. Mineralization procedure was based on the procedure of Lacort & Camarero. Characteristics of lake sediments were determined by the extraction method of elements that are soluble in aquaregia (according to European Standard CEN/TC 308/WG 1/TG 1, slightly modified). Dry samples of about 0.2 g weight were transferred to the PTFE vessel and HNO_3, and HCL Merck Tracepur® was added. The vessels were placed in a rotor and loaded to a microwave. Finally, the samples were analysed in the Spectro Blue ICP

OES spectrometer at Regional Research Centre for Environment, Agricultural and Innovative Technologies, Pope John II State School of Higher Education in Biała Podlaska. Berndt Kraft Spectro Genesis ICAL solution and VHG SM68-1-500 Element Multi Standard 1 in 5% HNO_3 were used.

Total organic carbon (TOC) analysis was done after sample acidification to remove carbonates in the SHIMADZU SSM 5000A analyser with a solid sample combustion unit. The method was the catalytically aided combustion oxidation at 900°C with pre-acidification and oven temperature 200°C. A measuring range TC was 0.1 mg to 30 mg carbon. Sample amount was 1 g and aqueous content <0.5 g. Repeatability: S.D. ±1% of full-scale range (www.ssi.shimadzu.com/products/toc-analyzers/ssm-5000a).

All selected samples were analysed using a scanning electron microscope (SEM) HITACHI TM3000 with an energy dispersive spectrometer (EDS) SWIFT ED 3000 Oxford Instruments. The samples were not covered with any conductive material. Magnification range was x 20 to x 30 000. This method was used to perform basic microscopic observations of samples of the core M-1 with point determination of their chemical composition of major elements.

4. Results

4.1 Bathymetry

A georadar transect across the lake reflects both its bathymetry and composition of its bottom (Figs 2 - 3). The superficial layer of the transect is represented by lake ice, ca 25 cm thick and although it is almost not visible on radar images due to its thickness being smaller than a vertical resolution of measurements, beneath there are abundant horizontal multiple reflections of energy from the bottom of the ice. Two narrow and vertical zones with small diffraction hyperboles at 23 and 29 m of the transect indicate upward deformation of bottom sediments at the location sites of the sounding core and the core M-1 (Fig. 2a). The top of the underlying mineral deposits (so-called hard bottom) is indicated as a distinct downward-deflected reflection surface (Fig. 2b). In the central part of the lake, it occurs at 2.6 m depth (two-way travel time 290 ns) and indicates the top of the Holocene organic sediments. Unfortunately, beneath there is a signal-absorption zone (Fig. 2d), resulting from the fact that most sediments are composed of fine-grained organic material (gyttja). However, thickness of this layer was determined by drillings to about 5 m. A relief of the lake bottom in the GPR image reflects a cross-section of a buried glacial tunnel valley that was

217   eroded mainly in sandy and sandy-gravel deposits. Close to the lake shore (0 to 20 m in the

218   northwest and 110 to 140 m in the southeast), there are numerous oblique and chaotically parallel

219   reflection surfaces dipping towards the channel axis. They reflect bedding of the Pleistocene sandy-

220   gravel series that partly filled a subglacial channel (Fig. 2c).

221

222   *4.2. Magnetic susceptibility*

223   MS is highly dependent on lithology and grain size of deposits (Dearing, 1994; Sandgren

224   and Snowball, 2001). It reflects presence and size of ferromagnetic particles in a sample (Verosub

225   and Roberts, 1995). Increased content of ferromagnetic minerals such as magnetite, Fe-Ti oxides

226   or pyrrhotite generates higher MS whereas biotite, pyrite, carbonates and organics result in its lower

227   values. Total volume of magnetic minerals in lake sediments reflects mostly climatic changes in a

228   catchment (Bloemdal and deMenocal, 1989; Snowball, 1993; Peck et al., 1994). MS in the core M-

229   1 is varied but due to organic character of the sediments, its values are relatively low, from 0.002

230   to 0.034×10^{-7} units SI. In grey-brown gyttja with organic matter at 3.50 – 2.58 m depth, MS rises

231   and drops in turn from 0.01 to 0.02×10^{-7} SI. MS drops from 2.60 m depth, reaching a minimum at

232   1.63 m. Higher up, MS rises again, with the highest value at 1.35 m, then there is a minimum at

233   1.05 m and the next maximum at 0.69 m depth (Fig. 6).

234

235   *4.3. Chronology, lithology and sedimentation rate*

236   The age-depth model of the core M-1 from Lake Młynek indicates (Fig. 4) that the M-1

237   core chronologically covers the last 2,400 years. Bottom deposits of Młynek Lake are organic-

238   rich. The core M-1 is composed of grey-brown gyttja at 1.8 – 3.6 m depth (Fig. 5). At 1.45 – 1.80

239   m depth there is grey-brown gyttja-detritus and at 1.10 – 1.45 m depth algal gyttja is recorded.

240   The uppermost part of the core is composed of grey-brown (depth 0.4 – 1.1 m) and detritus gyttja

241   (0.0 – 0.4 m). The sedimentation rate was calculated based on the age-depth model. Results

242   reflect quite a stable sedimentary environment with a general rate of 1.5 mm a year. The rate is

243   stable at 3.40 – 1.77 m depth and equal ca 1.5 mm a year. It drops to 1 mm, then rises to 1.3 – 1.8

244   mm a year at 1.77 – 0.30 m. At 0.0 – 0.3 m the sedimentary rate is the highest and equal ca 3 mm

245   a year (Fig. 5).

246

247   *4.4. Pollen*

Based on percentage contents of main trees and terrestrial herbs five local pollen assemblage zones (LPAZ M1-M5) were established in the pollen sequence of the Lake Młynek. The pollen contents were determined based on changes in the percentage of individual taxa, confirmed by a cluster analysis (Fig. 9):

Zone	Depth [m]	Main features of pollen spectra
LPAZ M-1	345÷315 cm	Pollen grains of *Carpinus* reached 33.5% and *Alnus* 25%, *Pinus* and *Betula* are <20%. A top border of this zone is indicated by decline of *Carpinus*.
LPAZ M-2	315÷265 cm	The share of *Carpinus* drops significantly (<10%), contents of *Betula*, *Quercus* and *Corylus* are slightly raised. The percentages of Gramineae significantly increased up to 7.5%. There are continuous curves of *Cannabis/Humulus,* Chenopodiaceae, *Plantago lanceolate, Rumex acetosella* and *Secale cereale* and a top boundary is indicated by decline of Gramineae.
LPAZ M-3	195÷265 cm	At the beginning the curve of *Betula* raises to 24% but then drops <10%. The share of *Carpinus* and *Fagus* rises to 19% and 27%, respectively. Content of Gramineae decreased <2% and the curves of *Secale cereale, Plantago lanceolate* and *Rumex acetosella* disappear. There are only single pollen grains of Chenopodiaceae and C*annabis/Humulus.* A top boundary is indicated by a rise of Gramineae.
LPAZ M-4	195÷145 cm	Content of *Fagus* pollen began gradually decrease. The share of pollen grains of *Betula* increases and becomes stable at 22-27%. Content of the Gramineae pollen grains increases again to 7%. Curves of *Cannabis/Humulus, Plantago lanceolate, Rumex acetosella* and *Secale* raise and a top boundary is marked by a rapid rise of *Cannabis/Humulus.*
LPAZ M-5	145÷15 cm	Curves of main deciduous trees decline: *Carpinus* <9%, *Fagus* <5%, *Quercus* <5%, *Alnus* <15%, *Betula* <14% and content of *Pinus* increases to 40%. There is significant rise of Gramineae up to 15%. Percentages of *Cannabis/Humulus* reached absolute maxima (25%) but close to middle part of this zone their strong decline is observed (below 2-3%). The continuous curves of *Cerealia* undiff., *Centaurea cyanus, Plantago lanceolate, Rumex acetosella, Rumex acetosella* appeared, and single pollen grains of *Polygonum dumetorum, Polygonum aviculare* and *Urtica* were present.

4.5. Diatoms

Studies of the Lake Młynek bottom sediments revealed presence of more than 200 diatom taxa belonging to 54 genera (Zalat et al., 2018) (Fig. 8). Diatoms were generally abundant and well to moderately preserved in most samples, although with admixture of mechanically broken valves, especially in the topmost part of the core. Results of the diatom analysis and relative abundance of the most dominant taxa enabled subdivision of the M-1 core section into 11 diatom assemblage zones (Fig. 8) that reflected six phases of lake development (Zalat et al., 2018). Moreover, changes in chrysophyte cysts distributions along with variation in diatom composition could be related to

262   changes in pH, climate and trophic status. Stomatocysts can be used as the index of lake-level

263   changes, habitat availability, metal concentrations and salinity.

264

265   *4.6. Geochemistry*

266   Various factors influence distribution and accumulation of geochemical elements in lake

267   sediments. Most important are texture, mineral composition, oxidation/reduction state,

268   absorption/desorption and physical transportation processes (Ma et al., 2016). Curves of

269   representative elements are generally used to characterize sedimentary environments. Most

270   analysed elements do not indicate any clear trend with depth in the Lake Młynek. The curves of S

271   and TOC show significant rises at 2.0 – 1.4 m depth that are slightly correlated with decreased

272   contents of Al, Fe, K, Ca, Mg and MS (Fig. 6). Sulphur content is correlated with existence of iron

273   sulphides. In the studied core, Fe is positively correlated with Al and Ti (Fig. 7). Fe-Ti oxides are

274   noted in SEM EDS analysis. They are resistant to surface weathering and carry trace elements

275   (Bauer and Velde, 2014). At ca. 3 m, high frequency peaks of Al, K, Ca, Na, Mg, Fe and S occur

276   (Fig. 6).

277

278   **5. Discussion**

279   MS is generally low in biogenic sediments as gyttja, which is composed mainly of

280   microfossil skeletons e.g., diatoms and radiolarians (Thompson and Oldfield, 1986). In Lake

281   Młynek there is an apparent negative relationship between TOC and MS. Several intervals show

282   both higher percentages of TOC and lower MS values. Changes of MS in Lake Młynek sediments

283   record most probably an input of clay into the lake and diagenetic conditions in bottom sediments.

284   Iron oxides are presumably of detrital origin and were delivered to the basin through deep valleys

285   incised at the north-western shore. Concentration of ferromagnetic minerals is connected with

286   periodical intensive soil erosion around the lake. Their higher content depends also on diagenetic

287   processes in bottom sediments. Oxidation of organic matter in anoxic conditions (by iron-oxide-

288   reducing bacteria) results usually in increased content of ferromagnetic particles (small particles

289   are removed first). In opposite, oxygenation by heavy floods stops this process and small magnetic

290   particles are preserved (Jelinowska et al., 1997). At 1.40 m depth, TOC suddenly drops, probably

291   due to deforestation and then, MS significantly rises due to increasing input of terrestrial (non-

292 organic) material to the lake. Such coincidence clearly indicates that TOC is both of autochthonous

293 and allochthonous derivation (Fig. 6).

294   The highest contents of detrital elements like Al, K, Ca and Mg are to be associated with

295 sudden delivery of clastic material to the lake e.g. during increasing flood or rainfall (Wirth, et al.,

296 2013). Especially Al is extremely immobile, that is why it should be regarded as a typical lithogenic

297 element (Price et al., 1999). Additionally, Al is a major constituent of soils and other sediments as

298 a structural element of clays. It has a strong positive correlation with many major elements (Fig.

299 7). The association between Al and other elements can be therefore used as the basis to compare

300 natural elemental contents in sediments and soils. Ca is well correlated with Al, originated mainly

301 from terrigenous bicarbonate inputs and was deposited in a lake as a solid carbonate (Miko et al.,

302 2003). Calcium is evidently more easily removed in solution from a mineral material and it is

303 highly concentrated in highly erosional periods (Mackereth, 1965).

304   The Fe/Ca ratio is considered as a eutrophication proxy. The highest ratio points out to low

305 oxygenation, eutrophic or dystrophic reservoirs (i.e. Kraska and Piotrowicz, 2000; Holmes and De

306 Decker, 2012), whereas the low Fe/Ca ratio in bottom sediments indicates oligotrophic character

307 of a lake. In the studied core sediments, Fe/Ca ratio varies from 0.808 (depth 3.05 m) to 3.677 (1.2

308 m). The ratio is low, indicating oligotrophic conditions in bottom sediments which gives conflicting

309 results with other data. The Fe/Ca ratio can be disturbed by detrital input to the lake (Fig. 6). The

310 dysaerobic conditions in the lake are confirmed with Th/U ratios (0.03 – 0.41) which are lower

311 than the critical value of 2 as indicated by Myers and Wignall (1987) and Wignall (1994). The ratio

312 of total Fe to total P ranges from 13.91 (1.6 m depth) to 30.82 (0.55 m). The values are typical for

313 other lakes in northern Poland, which vary from 3 to 180 according to Bojakowska (2016). The

314 release of P follows in reducing conditions. According to Ahlgren et al. (2011) is even up to ten

315 times greater than in aerobic conditions. However, there is a poor correlation with other redox

316 proxies i.e. Th/U (R=0.08). It can be caused by presence of Al which forms $Al(OH)_3$. In such

317 systems even though the redox state favours release of P from iron minerals, the P is immobilized

318 by binding with hydroxides. Thus, the presence of $Al(OH)_3$ can stop release of P even in an anoxic

319 hypolimnion (Hupfer and Lewandowski, 2008). It can be a case in the studied sediments as Al

320 shows positive correlation with P content (R=0.49). Except for Fe/Ca, all counted ratios point out

321 to anoxic conditions in all studied samples which is typical to eutrophic lakes. Nevertheless, as all

322 proxies are characterized by extreme values at the 3.05 m depth, they seem to depend on external

323 load of terrigenous material. It is confirmed with very good positive correlation between Fe and Al

324 (0.95), Fe and Ti (0.64) Mn and Al (0.46) or Mn and Ti (0.78).

325 The periphytic diatom species dominate the planktonic ones throughout the core. A high

326 proportion of periphyton to plankton assemblages was reported as indicative for a long-lasting ice-

327 cover (Karst-Riddoch et al., 2005) whereas a shift from benthic to planktonic diatom taxa is

328 considered for an ecological indicator that is generally interpreted in high-altitude lakes as record

329 of shorter winter and increased in temperatures. Common occurrence of benthic forms represented

330 by *Staurosira venter/Staurosirella pinnata* diatom assemblage indicates circumneutral to slightly

331 alkaline shallow water with lowering lake levels and prolonged ice cover. However, *Aulacoseira*

332 is the most dominant planktonic genus followed by *Cyclotella* and low frequency of

333 *Cyclostephanos*. Diatom preservation in the upper part of the core (depth 1.40 – 0.15 m) is moderate

334 to relatively poor and the recognized assemblage was represented by the occurrence of some

335 dissolved and teratological diatoms valves, in particular the topmost part of the core section (0.30-

336 0.15 m) (Zalat et al., 2018).

337

338 **6. *Phases of the Lake Młynek development***

339 Based mostly on results of palynological studies five main phases of the Lake Młynek

340 development in relation to the climate and human-induced environmental change were

341 distinguished (Fig. 10):

342 *5.1. Phase 1: 2,300 – 2,100 cal. BP (ca. 4 – 2/1 c. BC), depth: 3.45 – 3.15 m*

343 This phase is recorded in LPAZ M-1 which represents closed forest communities dominated

344 by hornbeam and alder, which colonized marshlands near lake shores. Plants of open stands are

345 only rarely noted as well as indicators of anthropogenic activity (e.g. *Plantago lanceolata*).

346 Vegetation at that time was relatively natural and not disturbed. Diatom assemblage at the

347 beginning (3.45 – 3.40 m depth) was distinguished by diatom subzone DZ1a (Fig. 8) that dominant

348 by the periphytic taxa such as *Staurosira construens, Staurosira venter, Staurosirella pinnata,*

349 *Gyrosigma acuminata* associated with the planktonic *Aulacoseira granulata, A. ambigua* and

350 *Puncticulata radiosa* which indicates a shallow and slightly alkaline lake. This interval was

351 followed by a great abundance of the planktonic alkaliphilous diatoms of subzone DZ 1b (3.35 –

352 3.15 m, fig.8) which was dominant by *Aulacoseira granulata, Cyclotella sensu lato* species,

353 *Cyclostephanos dubius* and *Stephanodiscus* species. The diatom assemblage explains a rising lake

354   level with increasing nutrients matter (Douglas & Smol 1999, Zalat 2015). The predominance of *A.*

355   *granulata* suggests a high trophic status of slightly alkaline freshwater environment with high silica

356   concentration (Kilham et al. 1986; Zalat et al., 2018). MS is high and corresponds to high contents

357   of Fe, Ti and Al, indicating increasing influx of terrigenous material, presumably activated by

358   intensive rainfalls.

359

360   *5.2. Phase 2: 2,100 – 1,830 cal. BP (ca. 1 c. BC – 2 c. AD), depth: 3.15 – 2.65 m*

361   During this phase 2 changes in the environment around the lake were caused by significant

362   human impact. This phase corresponds with the LPAZ M2, characterized by reduction and

363   fragmentation of the hornbeam-dominated forest. Birch, pine and hazel expanded under better

364   lighting conditions in a partly open forest. Mid-forest pastures occupied rather small-scale open

365   areas, as can be notified from higher percentages of *Plantago lanceolata* and other herbaceous

366   plants, e.g. Gramineae, *Artemisia* and *Rumex acetosa*/*acetosella*. Cultivated plants as *Cannabis* t.

367   and *Secale* are rare, however their occurrence is entirely consistent with other human indicators

368   present during this phase. This phase is commonly noted and similarly expressed in numerous

369   palynological sequences in neighbouring areas (see for example Noryśkiewicz, 1982, 1987, 2013;

370   Bińka et al., 1991; Ralska-Jasiewiczowa et al., 1998). Pollen data indicate that societies of that time

371   cultivated rye and probably hemp. It is the oldest settlement phase at Janiki Wielkie stronghold and

372   corresponds to the termination of the La Tène and the time of the early Roman period. Human

373   communities in the vicinity of the lake can be connected with settlements of the East-Baltic Kurgan

374   Culture (Rabiega et al., 2017). During this phase, planktonic diatoms were replaced by benthic

375   taxa, (DZ2) such as *Staurosira construens, S. venter*, and *Staurosirella pinnata* accompanied by a

376   significant abundance of *Gyrosigma acuminatum* indicating a lower lake level and dominance of

377   mesotrophic alkaline freshwater environment. The lower stands were interrupted by a short rise of

378   water level at 2.90 – 2.85 m where the abundance of planktonic eutrophic indicator *Aulacoseira*

379   spp. increased suddenly on expense of the benthic taxa. During this phase climatic conditions were

380   still similar to ones in the previous phase, but it was drier what is reflected by shallowing of the

381   lake. This phase can be correlated with the so-called Roman Climatic Optimum (see McCormick

382   et al., 2012).

383

384   *5.3. Phase 3: 1,830 – 1,150 cal. BP (ca. 2 – 9 c. AD), depth: 2.65 – 1.95 m*

This phase corresponds to LPAZ M3 when a forest restoration occurred. Absence of human indicator plants suggest that the settlement in the catchment was abandoned. There are also no traces of human activity nearby (Rabiega et al., 2017). Reduction of human impact and human-generated semi-open habitats, allowed for a short-term expansion of birch into empty, open areas, and later replaced by hornbeam that rebuilt its position to the level as in the LPAZ M1. Also, elm expanded again in a riparian forest. This restoration of the natural forest was followed by abrupt expansion of beech in the second half of the LPAZ M3. The area of open herbaceous plants communities, previously widespread, was limited.

Abundant planktonic diatoms including *Aulacoseira* spp., *Puncticulata radiosa*, and common occurrence of small *Cyclotella* spp. occurred in the lake (Fig. 8) what indicates its deepening, enhanced thermal stratification, reduced mixing and increased thermal stability (Zalat et al., 2018). Intensified development of a vegetation cover and higher lake water level are indicated by geochemical indices. A gradual drop of MS corresponds with decreased content of detrital elements as Fe, Ti, Al and K, accompanied by gradual increase of TOC and the proxy ratio Fe/Ca. Lower MS and content of Al (acting as a major constituent of soils) accompanied by the higher TOC suggest limited erosion, in spite of gradually higher precipitation in the lake catchment and therefore, a rise of its water level (Fig. 6). The climate in this phase has become more humid. Increased rainfall and decreased evaporation are reflected in lake sedimentation as the lake got deeper, resulting in reduced deposition and greater stability. This phase could be associated with a global cooling of the Bond Event 1 (1.5 ka BP) (Bond et al., 1997; Welc, 2019).

5.4 Phase 4: 1,150 – 780 cal. BP (ca. 9 – 13 c. AD), depth: 1.95-1.45 m.

This phase is correlated with the LPAZ M4 and was divided into two subphases 4a and 4b (Fig. 10). The subphase 4a marks the onset of another settlement phase, resulting in forest clearing, similarly as in the LPAZ M2. Disturbances took place firstly in a beech forest and less in a hornbeam-dominated one. The anthropogenic activity is reflected by presence of *Gramineae*, *Artemisia*, *Cannabis*/*Humulus*, *Plantago lanceolata*, *Rumex acetosella*, *Secale* and cerealia undiff. Diatom assemblages proves deepening of the lake (Zalat et al., 2018) as indicated by abundance of *Aulacoseira* associated with *Puncticulata radiosa* in the upper part of the diatom zone 5 at 1.85 – 1.70 m depth. The diatom assemblage suggests a rising lake level, higher trophy and stronger turbulent mixing conditions (Rühland et al., 2008; Zalat et al. 2018). Moreover, the greatest reduction of abundant *Fragilaria sensu lato* accompanied by abundant *A. granulata*, could resulted

416 from forest clearing around the lake. Higher TOC corresponds with lower content of detrital
417 material (Fe, Ti, Al and K) and lower MS, and it can reflect a progressing humidity (Fig. 6). This
418 phase can be correlated with the Migration Period and the early Middle Ages. A wooden-loamy
419 defence rampart was raised at the end of the phase in a settlement close to the lake (archaeological
420 phase III), after removal of a natural soil developed during abandonment of the site in the early
421 Roman Period. After a short period, this stronghold was destroyed. A charcoal from a fired wall
422 that represents destruction at the end of the archaeological phase IIIA, was dated at 1245 ± 25 cal.
423 BP i.e. 682-870 AD (95.4% probability) and 1090 ± 30 cal. BP i.e. 892-1014 AD (95.4%
424 probability) (Rabiega et al., 2017).

425 Human impact declines during the subphase 4b (1.70 – 1.45 m depth) onwards. At this time
426 birch and less intensively poplar occupied temporarily abandoned open areas, especially toward
427 the end of the zone, when a human activity was less intensive. Alder became more abundant,
428 probably expanding into exposed marginal areas of the lake. The subphase 4b, corresponds to the
429 diatom zone 6 (Fig. 8) which is characterized by abundant benthic *Fragilaria sensu lato* with
430 sporadic occurrence of planktonic taxa. A high proportion of benthic to plankton assemblages was
431 reported as indicative for a long-lasting ice-cover (Karst-Riddoch et al., 2005). As well as, a great
432 abundance of the benthic *Staurosira venter* and *Staurosira construens* with marked decline in the
433 planktonic diatoms such as *Aulacoseira* spp. and *Puncticulata radiosa* reflects lowering water
434 level and slight alkaline freshwater, lower nutrient concentrations and low silica content (Kilham
435 et al. 1986; Stevens et al., 2006; Zalat et al., 2018).

436 In the stronghold at the lake shore, the next phase of human activity took place at the end of
437 the 11th century AD when a new rampart was raised. Wooden constructions were also built, traces
438 of which were excavated in the gate passage. The settlement was finally abandoned presumably
439 in the first half of the 13th century and then, its ramparts were strongly eroded, with their material
440 moving towards a yard and the moat (Rabiega et al., 2017). The subphase 4b is characterized by
441 climate change towards a gradual warming, which confirms gradual shallowing of the lake and
442 increased rate of sedimentation. Human impact on the environment in this subphase is already so
443 great that reconstruction of a climate change is not clear. There is no doubt, however, that this is a
444 warm period, which should be correlated with the Medieval Warm Period (MWP) (Mann et al.,
445 2009).

446 *5.5. Phase 5: 780 – 0 cal. BP (13 c. AD – present time), depth: 1.45 - 0 m*

447 This phase starts about 1200 AD and is connected with the early Modern Period. Cultivation
448 and treatment of hemp has been terminated but cultivation of cereals and presence of synanthropic
449 plants indicate human activity near the lake. The water level is not high and slightly changes, which
450 is evident by great abundance of the benthic diatom taxa over the planktonic forms (DZ 8-10, fig.
451 8). There is a drop of TOC and rise of MS caused by increasing input of terrestrial material at 1.4
452 m depth, resulting presumably from human deforestation. The small watercourse which enters the
453 lake from the north–east appeared most probably during this phase and had a strong impact on the
454 its water environment (see, Bińka et al, 2020). As it was mentioned before, in 15 c. AD a mill was
455 built near the lake and damming of the water in the mill reservoir probably contributed to periodical
456 blooms of dinoflagellate populations in Lake Młynek. Major blooms of *Tetraedron* which usually
457 precede blooms of the dinoflagellate, were most probably the main factor that contributed to the
458 decline of settlement on the stronghold near the shore of the lake (Bińka et al, 2020). This zone is
459 also characterized by increased precipitation which is reflected by significantly more intensive
460 terrestrial inflow to the lake and is confirmed by quasi-linear correlation of MS with contents of Fe
461 and Ti in sediments (Fig. 6). The modern lake is shallow (2-3 m) and gradually overgrowing.
462 Summing up, the phase 5 is marked by intensive human activity around the lake and therefore,
463 most environmental and climate changes are obliterated.
464

465 ### *7. Development of Lake Młynek – a regional background*
466 The above scenario seems to be confirmed by earlier palaeoenvironmental research carried
467 out in the south-western part of the Warmia-Masuria Lakeland (Kupryjanowicz, 2008; Kołaczek
468 et al., 2013). Previous studies of the lakes sediments in this region were based mainly on pollen
469 analysis and enable to compare Lake Młynek record with other sequences.
470 The closest Lake Woryty (Pawlikowski et al,.1982, Noryśkiewicz and Ralska-
471 Jasiewiczowa, 1989, Ralska-Jasiewiczowa and Latałowa, 1996), just 35 km to the east, is a
472 reference one. Palaeoenvironmental records delivered by Lake Młynek core are very similar to the
473 Woryty palynological succession with distinctive human impact during the Roman Period and the
474 Medieval Ages, however, a detailed comparison is difficult, because of the low resolution of the
475 pollen spectrum obtained at Woryty.
476 The second site is Lake Drużno, located in the Vistula Delta, 35 km to the north of Młynek
477 Lake (Zachowicz et al., 1982; Zachowicz and Kępińska, 1987; Miotk-Szpiganowicz et al., 2008).

478　　　Unfortunately, the low resolution and the lack of reliable age-depth model of the lake　comparison

479　　　also very difficult. Despite of this and also due to habitat differences between Lake Drużno and

480　　　Lake Młynek, pollen records obtained at both sites are very similar and comprise human indicators

481　　　during the Roman Period and human impact during the Medieval time.

482　　　　　　The pollen spectrum from Lake Łańskie (Madeja, 2013), located 55 km to the south-east

483　　　from Lake Młynek, shows higher content of pine and lower share of beech than in the case of Lake

484　　　Młynek. Such divergences are probably not only due to different location and environmental

485　　　conditions in the lake vicinity but also depend on different size of these lakes. Lake Młynek is a

486　　　very small (0.7 km^2) mid-forest basin, whereas Lake Łańskie is over 10 km^2 large and contains

487　　　mostly a regional pollen record. Based on periodical appearances of human plant indicators and

488　　　archaeological data between 300 BC and 800 AD, three human phases of West Baltic Barrow,

489　　　Wielbark and Prussian cultures were distinguished (Madeja, 2013). In the pollen diagram from

490　　　Lake Młynek (phase 2), the first culture is indicated, including termination of the La Tene and the

491　　　Roman Period. Significant growth of human indicators from the beginning of 11th century is visible

492　　　in diagrams from both sites. A more local record from Lake Młynek is marked especially by high

493　　　content of *Humulus*/*Cannabis* (to 25%) in 13-15th centuries AD. In the sediments of Lake Łańskie,

494　　　hemp occurred discontinuously and was <1%.

495　　　　　　The pollen records from Lake Młynek are similar to the ones from the Masurian Lakes:

496　　　Wojnowo, Miłkowskie and Jędzelek, located over 100 km to the east (Wacnik et al., 2014).

497　　　Recorded episodes of human impact on vegetation during the Roman Period and Medieval time

498　　　are separated by 500-600 years long intervals without cultivation and with natural reforestation

499　　　(indicated by strong share of birch which is a pioneer tree). Similar lasting of human withdrawal

500　　　in the Lake Młynek section began and terminated earlier than recorded in the lakes Wojnowo and

501　　　Miłkowskie. Another history of human activity is represented in a record from Lake Salęt (Szal et

502　　　al., 2014b). Pollen grains of cultivated and ruderal plants are noted continuously from the early

503　　　Iron Age to the early Medieval time. In opposite to the pollen record from the lakes Młynek,

504　　　Wojnowo and Miłkowskie, the suggested constant settlement in the neighbourhood of the Lake

505　　　Salęt was interrupted by a single very short decline of human impact at 880-980 AD (Szal et al.,

506　　　2014a). Numerous pollen data are available from the area adjacent in the south-west in the Brodnica

507　　　Lake District, including Strażym Lake (Noryśkiewicz, 1987; Noryśkiewicz and Ralska-

508　　　Jasiewiczowa, 1989), Oleczno Lake (Filbrandt-Czaja, 1999; Filbrandt-Czaja et al., 2003) and the

509 Chełmno Lakeland (Noryśkiewicz, 2013). Pollen records from this region also suggest intensive
510 settlements during La Tene, Roman and Medieval periods.

511 Pollen record from other sites located to the east of Lake Młynek indicates mostly
512 differences in a beech content. The *Fagus silvatica* content changes to the north-east and its
513 significantly high content in Lake Młynek sediments represents a very local record in a small lake.
514 Decline of *Fagus sylvatica* depend on a continental climate and is noted in pollen diagrams from
515 the lakes: Salęt (Szal et al., 2014a), Mikołajki (Ralska-Jasiewiczowa, 1989), Żabińskie (Wacnik et
516 al., 2016) and Wigry (Kupryjanowicz, 2007). A decline of beech is accompanied by a rise of *Picea*
517 *abies*. A record of human activity in pollen spectra from eastern Poland was noted at many sites.

518

519 **8. Conclusions**

520 Based on results of performed laboratory analysis, supplemented with archaeological data,
521 five main environmental phases of the Lake Młynek development were distinguished (Fig. 10).
522 Radiocarbon ages enabled detailed chronology whereas pollen data and stratigraphy of the
523 stronghold to the north-east of the lake made correlation of human activity with environmental data
524 possible for the last 2300 years. From the 1st century BC to 2nd century AD the forest around the
525 lake was much reduced, what can be associated with pre-Roman and Roman occupation phase
526 (attested also on the stronghold located close to the lake). From the 2nd to 9th century AD is attested
527 gradual restoration of the forest and decline of human activity along with a lake deepening due to
528 the advent of more wet climatic conditions. This colder and humid phase corresponded to the Bond
529 1 Event (1.5 ka BP) cooling episode. Intensive forest clearing around the lake occurred in the 9th –
530 13th century AD as result of next phase human activity. This period is marked by warming
531 confirmed by a gradual shallowing of the lake (Middle Age Warm Period). Since 14th century AD
532 strong human impact transformed the local landscape, especially by construction and activity mill
533 and creating of a small artificial lake in 15th century AD. This caused that possible climate-induced
534 natural environmental changes are not so clear. We can conclude that environmental
535 transformations recorded in bottom lake sediments of Lake Młynek were highly dependent on
536 human activity and were especially intensive in the Roman and Middle Age periods due to
537 favourable climatic conditions. It is important to add here that transformations of Lake Młynek,
538 reconstructed based on diatom analysis, not only indicate changes of the lake water level and

correspond with a human impact but also determine episodes of more humid climate during coolings.

References

Ahlgren, J., Reitzel, K., De Brabandere, H., Gogoll, A., Rydin, E.: Release of organic P forms from lake sediments, Water Research 45, 565-72, 2011.

Bauer, A., Velde, B.: Geochemistry at the Earth's Surface Movement of Chemical Elements. Springer – Verlag, Berlin-Heidelberg, 2014.

Bińka, K., Cieśla, A., Łącka, B., Madeyska, T., Marciniak, B., Szeroczyńska, K., Więckowski, K.: The development of Błędowo Lake (Central Poland) - A palaeoecological study, Studia Geologica Polonica 100, 1-83, 1991.

Bińka, K., Welc, F., Nitychoruk, J., Sieradz, D., Lewczuk, A: Unique finds in palynological spectra: acetolyze resistant vegetative forms of freshwater dinofagellate based on the Lake Młynek record from northeastern Poland, Studia Quaternaria 37/2, 59-67, 2020.

Blaauw, M., Christen, J.A.: Flexible Palaeoclimate Age-Depth Models Using an Autoregressive Gamma Process, Bayesian Analysis 6/3, 457–474, 2011

Blaauw, M., Christen, J.A., Mauquoy, D., van der Plicht, J., Bennett, K.D.: Testing the timing of radiocarbon dated events between proxy archives, The Holocene 17, 283-288, 2007.

Bloemdal, J., deMenocal, P.: Evidence for a change in the periodicity of tropical climate cycles at 2.4 Myr from whole – core magnetic susceptibility measurements, Nature 342, 897-900, 1989.

Bojakowska, I.: Phosphorous in lake sediments of Poland – results of monitoring research, Limnological Review, 16, 15-25, 2016.

Brauer, A.: Annually laminated lake sediments and their palaeoclimatic relevance. In: The Climate in Historical Times. Towards a Synthesis of Holocene Proxy Data and Climate Models. GKSS School of Environmental Research, 111-129, edited by: Fischer, H., Kumke, T., Lohmann, G., Flöser, G., Miller, H., von Storch, H., Negendank, J.F.W., Springer Verlag, 2004.

570   Brauer, A., Dulski, P., Mangili, C., Mingram, J., Liu, J.: The potential of varves in high-resolution
571   palaeolimnological studies, PAGES News 17 (3), 96-98, 2009.

572   Brenner M., Whitmore T.J., Curtis J.H., Hodell D.A., Schelske, C.L.: Stable isotope (d13C and
573   d15N) signatures of sedimented organic matter as indicators of historic lake trophic state, J.
574   Paleolimnol., 22, 205-221, 1999.

575   Czymzik, M., Dulski, P., Plessen, B., von Grafenstein, U., Naumann, R., Brauer, A.: A 450-year
576   record of spring-summer flood layers in annually laminated sediments from Lake Ammersee
577   (southern Germany), Water Resour. Res., 46, W11528, 2010.

578   Dearing, J. A.: Environmental magnetic susceptibility: using the Bartington MS2, 1994.

579   Douglas, M.S.V., Smol, J.P.: Freshwater diatoms as indicators of environmental change in the High
580   Arctic, 227–244, in: The Diatoms: Applications for the Environmental and Earth Sciences,
581   edited by: Stoermer, E.F., Smol, J.P., Cambridge Univ. Press, Cambridge, 1999.

582   Duff, K.E., Zeeb, B.A., Smol, J.P.: Atlas of Chrysophycean Cysts, 2. Kluwer Academic Publishers,
583   Dordecht-Boston-London, 1995.

584   Duff, K.E., Zeeb, B.A., Smol, J.P.: Chrysophyte cyst biogeographical and ecological distributions:
585   a synthesis, Journal Biogeography 24, 791–812, 1997

586   Elbert, J., Grosjean, M., von Gunten, L., Urrutia, R., Fischer, D., Wartenburger, R., Ariztegui, D.,
587   Fujak, M., Hamann, Y.: Quantitative high-resolution winter (JJA) precipitation reconstruction
588   from varved sediments of Lago Plomo 47°S, Patagonian Andes, AD 1530-2001, Holocene 22
589   (4), 465-474, 2012.

590   Filbrandt-Czaja A.: Zmiany szaty roślinnej okolic jeziora Oleczno w późnym holocenie pod
591   wpływem czynników naturalnych i antropogenicznych, in: Studia nad osadnictwem
592   średniowiecznym ziemi chełmińskiej 3, 61–68, edited by: W. Chudziak, Toruń, 1999.

593   Filbrandt-Czaja A., Noryśkiewicz B., Piernik A.: Intensification gradient of settlement processes
594   in pollen diagrams from Dobrzyńsko-Olsztyńskie Lake District, Ecol. Quest., 3, 125-137, 2003.

595   Snowball, I.: Mineral magnetic properties of Holocne lake sediments and soils form the Karsa
596   Valley, Lappland, Sweden, and their relevance to paleoenvironmental reconstruction, Terra
597   Nova 5, 258-270, 1993.

598   Francus, P., von Suchodoletz, H., Dietze, M., Donner, R.V., Bouchard, F., Roy, A.-J., Fagot, M.,
599   Verschuren, D., Kröopelin, S.: Varved sediments of Lake Yoa (Ounianga Kebir, Chad) reveal

progressive drying of the Sahara during the last 6100 years, Sedimentology 60 (4), 911-934, 2013.

Gałązka, D.: Szczegółowa mapa geologiczna Polski 1:50 000, ark. Iława (210). Centr. Arch. Geol. Państw. Inst. Geol., [Detailed Geological Map of Poland, scale 1:50 000, Iława sheet (210). Warsaw, 2009.

Givelet, N., Le Roux, G., Cheburkin, A., Chen, B., Frank, J., Goodsite, M. E., Kempter, H., Krachler, M., Noernberg, T., Rausch, N., Rheinberger, S., Roos-Barraclough, F., Sapkota, A., Scholzb, Ch., Shotyk, W.: Suggested protocol for collecting, handling and preparing peat cores and peat samples for physical, chemical, mineralogical and isotopic analyses. J. Environ. Monit., 6, 481–492, 2004.

Hofmann, G., Werum, M., Lange-Bertalot, H.: Diatomeen im Süßwasser-Benthos von Mitteleuropa. A.R.G. GantnerVerlag, Rugell, Liechtenstein, 1–908, 2011.

Holmes J.A., De Decker P.: The chemical composition of ostracod shells: application in Quaternary paleoclimatology, in: Ostracoda as proxies for Quaternary climate change, Developments in Quaternary Science 12, 131-140, edited by: Horne D., Holmes J.A., Rodriguez-Lazaro J. & Viehberg F., 2012.

Hunter, L. E., Delaney, A. J., Lawson, D. E. Davis, L.; Downhole GPR for high-resolution analysis of material properties near Fairbanks, Alaska, in: Ground Penetrating Radar in Sediments, Geological Society, Special Publications 211, 275-285, edited by: Bristow, C. S., Jol, H. M., London, 2003.

Ivanić, M., Lojen, S., Grozić, D., Jurina, I., Škapin, S.D., Troskot-Čorbić, T., Mikac, N., Juračić, M.: Geochemistry of sedimentary organic matter and trace elements in modern lake sediments from transitional karstic land–sea environment of the Neretva River delta (Kuti Lake, Croatia), Quaternary International 494, 286-299, 2018.

Jelinowska, A., Tucholka, P., Wieckowski, K.: Magnetic properties of sediments in a Polish lake: evidence of a relation between the rock-magnetic record and environmental changes in Late Pleistocene and Holocene sediments, Geophys. J. Int., 129,727-736, 1997.

Karst-Riddoch, T.L., Pisaric, M.F.J., Smol, J.P.: Diatom responses to 20th century climate-related environmental changes in high elevation mountain lakes of the northern Canadian Cordillera, Journal of Paleolimnology 33, 265–282, 2005.

630 Kilham, P., Kilham, S.S., Hecky, R.E.: Hypothesized resource relationships among African
631   planktonic diatoms, Limnology and Oceanography 31, 1169–1181, 1986.

632 Jutrzenka – Trzebiatowski, A., Hołdyński, A.: Roślinność rzeczywista Parku Krajobrazowego
633   Pojezierza Iławskiego. Akademia Rolniczo-Techniczna. Olsztyn: 1–36, 1997.

634 Kołaczek, P., Kuprjanowicz, M., Karpińska-Kołaczek, M., Szal, M., Winter, H., Danel, W.,
635   Pochocka-Szwarc, K, Stachowicz-Rybka, R.: The Late Glacial and Holocene development of
636   vegetation in the area of a fossil lake in the Skaliska Basin (north-eastern Poland) inferred from
637   pollen analysis and radiocarbon dating, Acta Palaeobot., 53(1), 23–52, 2013.

638 Kondracki, J.: Geografia regionalna Polski. Wyd. Nauk. PWN, Warszawa, 2002.

639 Kraska M., Piotrowicz R.: Lobelia lakes: specificity, trophy, vegetation and protection, in:
640   protection of beds and wetlands of Pomerania region 3, 48-52, edited by: Malinowski B., 2000.

641 Kuprjanowicz, M.: Badania palinologiczne w Polsce północno-wschodniej, in: Człowiek i jego
642   środowisko (Polska północno-wschodnia w holocenie), Botanical Guidebooks 30, 77–95, edited
643   by: Wacnik A., Madeyska, 2008.

644 Kupryjanowicz, M.: Postglacial development of vegetation in the vicinity of the Wigry Lake,
645   Geochronometria 27, 53-66, 2007.

646 Lin, Y.T., Schuettpelz, C.C., Wu, C.H., and Fratta, D.: A combined acoustic and electromagnetic
647   wave-based techniques for bathymetry and subbottom profiling in shallow waters, Journal of
648   Applied Geophysics, 68, 203–218, 2009.

649 Ma, L., Wu, J., Abuduwaili, L., Liu, W.: Geochemical Responses to Anthropogenic and Natural
650   Influences in Ebinur Lake Sediments of Arid Northwest China, Plos One, 13/11(5):e0155819:
651   doi: 10.137, 2016.

652 Madeja J.: Vegetation changes and human activity around Lake Łańskie (Olsztyn Lake District,
653   NE Poland) from the mid Holocene, based on palynological study, Acta Palaeobotanica 53(2),
654   235–261, 2013.

655 Mann, M. E., Zhang, Z., Rutherford, S., et al.: (2009). Global Signatures and Dynamical Origins
656   of the Little Ice Age and Medieval Climate Anomaly, Science 326 (5957), 1256–60, 2009.

657 McCormick, M., Büntgen, U., Cane, M.A., Cook, E.R., Harper, K., Huybers, P., Litt, T., Manning,
658   S.W., Mayewski, P. A., More, A.F.M., Nicolussi, K., Tegel, W.: Climate Change during and
659   after the Roman Empire: Reconstructing the Past from Scientific and Historical Evidence,
660   Journal of Interdisciplinary History 43:2 (Autumn, 2012), 169–220.

661 Miotk-Szpiganowicz, G., Zachowicz, J., Uścinowicz, S.: Review and reinterpretation of the pollen

662   and diatom data from the deposits of the Southern Baltic lagoons, Polish Geological Institute

663   Special Papers, 23, 45–70, 2008.

664 Myers, K.J., Wignall, P.: Understanding Jurassic Organic-rich Mudrocks—New Concepts using

665   Gamma-ray Spectrometry and Palaeoecology: Examples from the Kimmeridge Clay of Dorset

666   and the Jet Rock of Yorkshire, in: Marine Clastic Sedimentology, 172-189, edited by: J.K.,

667   Legett, G., Zauffa,1987.

668 Nitychoruk, J. Welc, F.: Janiki Wielkie. Środowisko fizyczno-geograficzne, in: Katalog Grodzisk

669   Warmii i Mazur, tom 2, 153 – 155, edited by: Kobyliński, Z., Warszawa, 2017.

670 Noryśkiewicz, B.: Lake Steklin – a reference site for the Dobrzyń-Chełmno Lake District, N

671   Poland, Report on palaeoecological studies for the IGCP-Project No. 158B, Acta Palaeobot.,

672   22(1), 65-83, 1982.

673 Noryśkiewicz A. M.: Historia roślinności i osadnictwa Ziemi Chełmińskiej w późnym holocenie,

674   Studium palinologiczne, Toruń, 2013.

675 Noryśkiewicz, B.: History of vegetation during the Late-Glacial and Holocene in Brodnica Lake

676   District in light of pollen analysis of Lake Strażym deposits, Acta Palaeobot., 27(1), 283-304,

677   1987.

678 Noryśkiewicz, B., Ralska-Jasiewiczowa, M.: Type region P-w: Dobrzyń-Olsztyn lake District,

679   Acta Palaeobotanica 29(2), 85-93, 1989.

680 Ojala, A.E.K., Kosonen, E., Weckström, J., Korkonen, S., Korhola, A.: Seasonal formation of

681   clastic-biogenic varves: the potential for palaeoenvironmental interpretations, GFF, Special

682   issue: Varve Genesis Chronol., Paleoclimate 135 (3/4), 237-247, 2013.

683 Pawlikowski M., Ralska-Jasiewiczowa M., Schönborn W., Stupnicka E., Szeroczyńska K.:

684 Woryty near Gietrzwałd, Olsztyn Lake District, NE Poland – history and lake development during

685   the last 12000 years, Acta Palaeobotanica 22(1), 85-116, 1982.

686 Peck, J. A., King, J. W., Colman, S. M., Kravchinsky, V. A.:1994. A rock magnetic record from

687   lake Baikal, Syberia: Evidence for Late Quaternary climate change, Earth. Planet. Sci. Lett.,

688   122, 221-238, 1994.

689 Rabiega, K., Rutyna, M., Wach, D.: Janiki Wielkie. Badania Archeologiczne, w: Katalog Grodzisk

690   Warmii i Mazur, tom 2. Warszawa, 155–174, edited by: Kobyliński, Z., Warszawa, 2017.

691   Ralska-Jasiewiczowa M.: Type region P-x: Masurian Great Lake Dystrykt. Acta Palaeobotanica

692   29(2), 95-100, 1989.

693   Ralska-Jasiewiczowa M., Latałowa A.: Poland, in: Palaeoecological events during the Last 15,000

694   years: Regional Synthesis of Palaeoecological Studies of Lakes and Mires in Europe, 403-472,

695   edited by: Berglund, B.E., Birks H.J.B., Ralska-Jasiewiczowa, M., Wright H.E., John Wiley &

696   Sons: Chichester, 1996.

697   Ralska-Jasiewiczowa M, Goslar T, Madeyska T, Starkel L.: Lake Gościąż, Central Poland, a

698   monographic study, W. Szafer Institute of Botany, Polish Academy of Sciences, Kraków, 1998.

699   Rühland K, Paterson A.M., Smol J.P.: Hemispheric-scale patterns of climate-related shifts in

700   planktonic diatoms from North American and European lakes. Global Change Biology 14,

701   2740– 2754, 2008

702   Sambuelli, L., Silvia, S.: Case study: A GPR survey on a morainic lake in northern Italy for

703   bathymetry, water volume and sediment characterization, Journal of Applied Geophysics 81,

704   48-56, 2012.

705   Sambuelli, L., Calzoni, C., Pesenti, M.: Case history: Waterborne GPR survey for estimation

706   bottom-sediment variability: A survey on the Po River, Turin, Italy, Geophysics 74, 95–102,

707   2009.

708   Sandgren, P., Snowball, I.: Application of mineral magnetic techniques to Paleolimnology, in:

709   Tracking environmental change using lake sediments, Physical and geochemical methods 2,

710   edited by: Last, W., Smol, J., Kluwer Academic Publishers. Netherlands, 2001.

711   Semrau, A.: Mitteilungen des Coppernicus-Vereins für Wissenschaft und Kunst zu Thorn. Heft 42. Elbing.

712   1939.

713   Smol, J.P., Birks, J.B., Last, W.M.: Tracking Environmental Change Using Lake Sediments,

714   Terrestrial, Algal and Siliceous Indicators 3, 371, Springer Verlag, 2001.

715   Snowball, I. F.: Mineral magnetic properties of Holocene lake sediments and soils from the Karsa

716   valley, Lappland, Sweden, and their relevance to palaeoenvironmental reconstruction, Terra

717   Nova 5, 258 – 270, 1993.

718   Stankevica, K., Kalnina, L., Klavins, M., Cerina, A., Ustupe, L., Kaup, E.: Reconstruction of the

719   Holocene Palaeoenvironmental Conditions Accordingly to the Multiproxy Sedimentary

720   Records from Lake Pilvelis, Latvia, Quaternary International 386, 102-15, 2015.

721   Stevens L.R., Stone J.R., Campbell J, Fritz S.C.: A 2200-yr record of hydrologic variability from
722   Foy Lake, Montana, USA, inferred from diatom and geochemical data. Quaternary Research
723   65, 264–274, 2006

724   Stopa-Boryczka, M., Boryczka, J., Wawer, J., Grabowska, K., Dobrowolska, M., Osowiec, M.,
725   Błażek, E., Skrzypczuk, J., Grzęda.: Climate of north–eastern Poland based on J. Kondracki and
726   J. Ostrowski`s Physiographic division. Atlas of interdependence of meteorological and
727   geographical parameters in Poland. Warsaw University, Warsaw, 2013.

728   Szal M., Kupryjanowicz M., Wyczółkowski M.: Late Holocene changes in vegetation of the
729   Mrągowo Lakeland (NE Poland) as registered in the pollen record from Lake Salęt, Studia
730   Quaternaria, 31(1), 51–60, 2014a.

731   Szal M., Kupryjanowicz M., Wyczółkowski M., Tylmann W.: The Iron Age in the Mrągowo Lake
732   District, Masuria, NE Poland: the Salęt settlement microregion as an example of long-lasting
733   human impact on vegetation. Veget. Hist. Archaeobot., 23, 419–437, 2014b.

734   Thompson, R., Oldfield, F.: Environmental magnetism, Allen and Unwin London, 1986.

735   Tiljander, M., Ojala, A.E.K., Saarinen, T., Snowball, I.: Documentation of the physical properties
736   of annually laminated (varved) sediments at a sub-annual to decadal resolution for
737   environmental interpretation, Quat. Int., 88 (1), 5-12, 2002.

738   Tylmann, W., Szpakowska, K., Ohlendorf, C., Woszczyk, M., Zolitschka, B.: Conditions for
739   deposition of annually laminated sediments in small meromictic lakes: a case study of Lake
740   Suminko (northern Poland), J. Paleolimnol., 47 (1), 55-70, 2012.

741   Valpola, S.E., Ojala, A.E.K.: Post-glacial sedimentation rate and patterns in six lakes of the
742   Kokemöaenjoki upper watercourse, Finland, Boreal Environ. Res., 11, 195-211, 2006.

743   Verosub, K. L., Roberts, A. P.: Environmental Magnetism: past, present and future, Journal of
744   Geophysical Research 100, 2175-2192, 1995.

745   Wacnik A, Tylmann W, Bonk A et al., Determining the responses of vegetation to natural processes
746   and human impacts in north-eastern Poland during the last millennium: Combined pollen,
747   geochemical and historical data, Vegetation History and Archaeobotany. Epub ahead of print
748   17 March. DOI: 10.1007/s00334-016-0565-z, 2016.

749   Wacnik A., Kupryjanowicz M., Mueller-Bieniek A., Karczewski M., Cywa K.: The environmental
750   and cultural contexts of the late Iron Age and medieval settlement in the Mazurian Lake District,

751 NE Poland: combined palaeobotanical and archaeological data, Veget. Hist. Archaeobot., 23,

752 439–459, 2014.

753 Welc, F.: Lake sediments and geoarchaeology (editorial), Studia Quaternaria 34(1), 3-8, 2017.

754 Welc, F.: Geoarchaeological evidence of late and post-Antiquity (5th-9th c. AD) climate changes

755 recorded at the Roman site in Plemići Bay (Zadar region, Croatia), Studia Quaternaria 36 (1),

756 3–17, 2019.

757 Wetzel, R.G.: Past productivity: paleolimnology, in: Limnology. Lake and River Ecosystems, third

758 ed., edited by: Wetzel, R.G., Elsevier, Oxford, 785-804, 2001.

759 Wilkinson, A.N., Zeeb, B.A., Smol, J.P.: Atlas of chrysophycean cysts, Kluwer Academic

760 Publishers, Dordecht, 2002.

761 Williams, D.M., Round, F.E.: Revision of the genus Fragilaria, Diatom Research 2, 267–288, 1987.

762 Wirth S.B., Gilli A., Niemann H., Dahl T.W., Ravasi D., Sax N., Hamann Y., Peduzzi R., Peduzzi

763 S., Tonolla M., Lehmann M.F., Anselmetti F.S.: Combining sedimentological, trace metal (Mn,

764 Mo) and molecular evidence for reconstructing past water-column redox conditions: the

765 example of meromictic Lake Cadagno (Swiss Alps), Geochimica et Cosmochimica Acta, 120,

766 220-238, 2013.

767 Witkowski, A., Lange-Bertalot, H., Metzeltin, D.: Diatom flora of marine coasts, I. Iconographia

768 Diatomologica 7, 1–925, 2000.

769 Zachowicz J., Kępińska U.: The palaeoecological development of Lake Drużno (Vistula Deltaic

770 Area), Acta Palaeobotanica 27(1), 227-249, 1987.

771 Zachowicz J., Przybyłowska-Lange W., Nagler J.: The Late-glacial and Holocene vegetational

772 history of the Żulawy region, N Poland, A. Biostratigraphic study of Lake Drużno sediments,

773 Acta Palaeobotanica 22(1), 141-161, 1982.

774 Zalat, A.A.: Holocene diatom assemblages and their palaeoenvironmental interpretations in

775 Fayoum Depression, Western Desert, Egypt. Quaternary International 369, 86–98, 2015.

776 Zalat, A., Welc, F., Nitychoruk, J., Marsk, L., Chodyka, M., Zbucki, Ł.: Last two millennia water

777 level changes of the Młynek Lake (Northern Poland) inferred from diatoms and chrysophyte

778 cysts record, Studia Quaternaria 35 (2), 77 – 89, 2018.

779 Zolitschka, B.: Varved lake sediments, in: Encyclopedia of Quaternary Science, edited by: Elias,

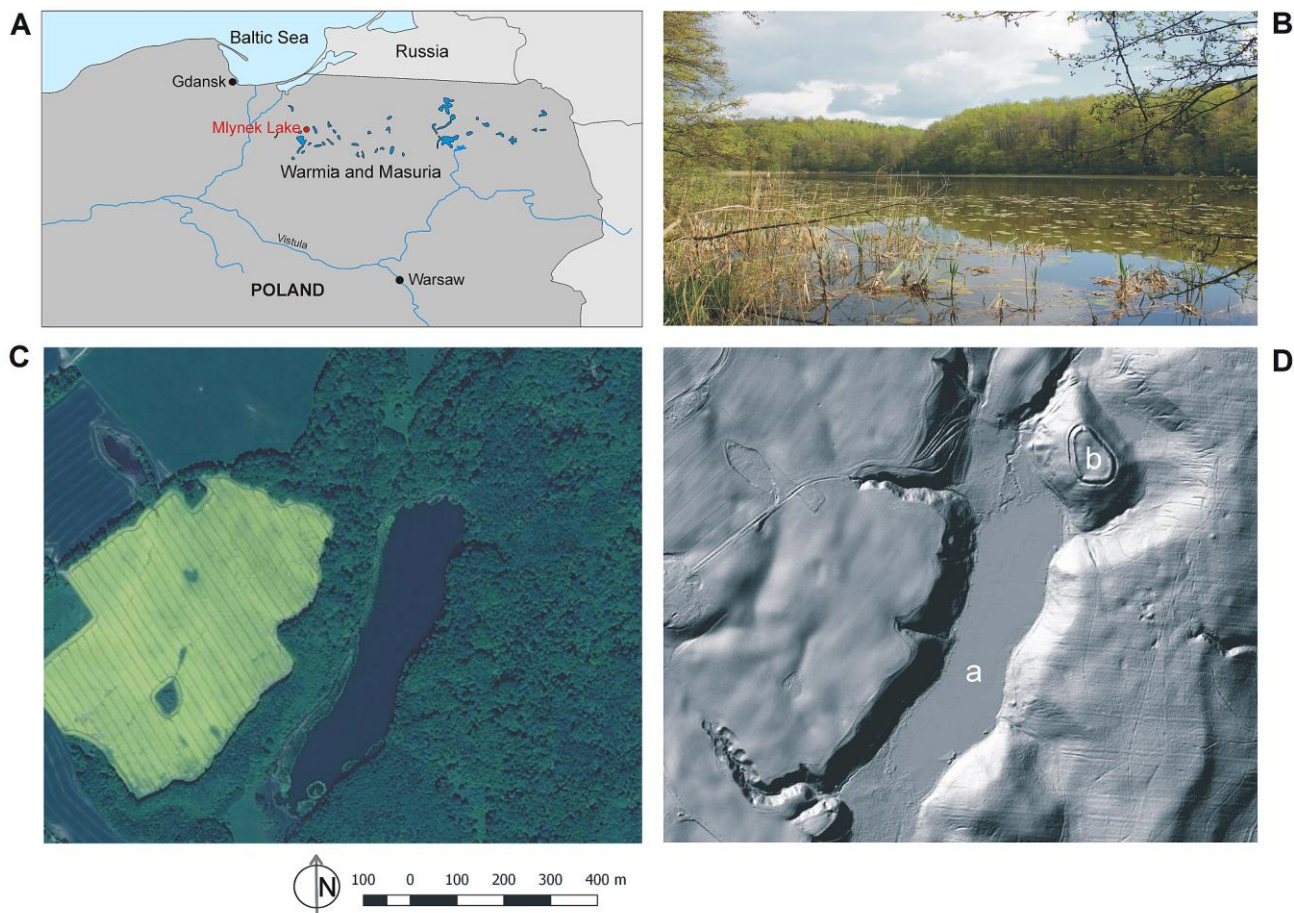780 S.A., Elsevier, Amsterdam, 3105-3114, 2007.

781

ILUSTRATIONS

783

784

785

786

787

788
Fig. 1. A - location of Lake Młynek in the Warmia and Mazury Region (north-eastern Poland) (Drawing; Fabian Welc).

B – view of the Młynek Lake from the north-west (Photo: Fabian Welc), C – satellite image of the lake (open source:
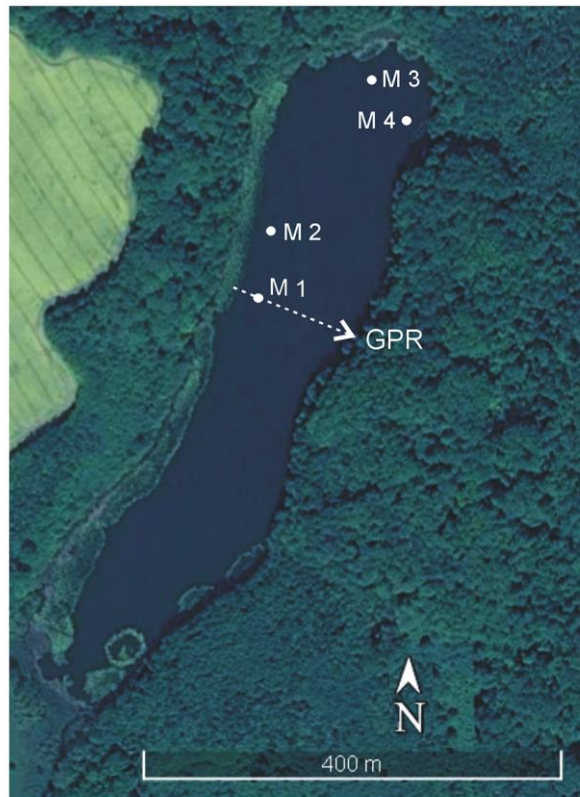
©Google Earth： www.google.com/intl/pl/earth). D – LIDAR image of the lake: a – lake basin, b – Janiki Wielkie

archaeological site established in early Iron Age (open source: ©Geoportal Poland：www.geoportal.gov.pl).

793
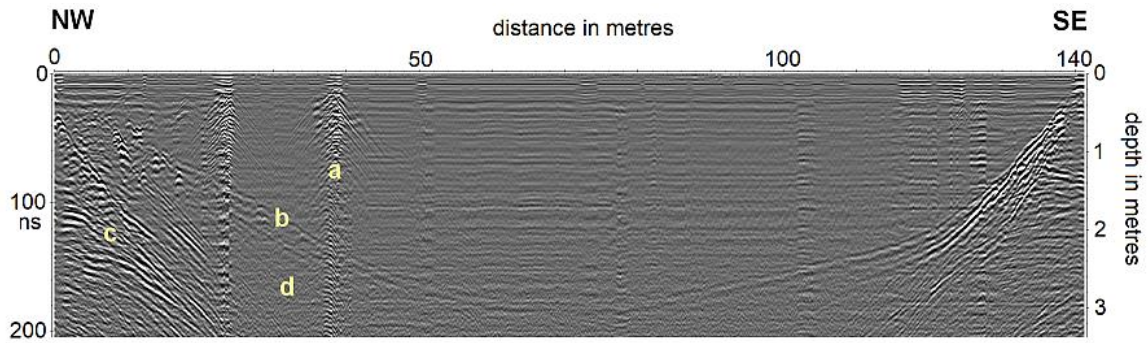
Fig. 2. GPR reflection profile across Lake Młynek (cf. Fig. 2), a – drilling M-1, b – upper boundary of the so-called hard bottom, c –stratified glaciofluvial sandy-gravel beds beneath the lake sediments, d – attenuation zone of electromagnetic waves connected with occurrence of organic sediment (gyttja) (measurements, processing and interpretation: Fabian Welc).

Fig. 3. Młynek Lake: A – location of drillings M 1-4 and transect of GPR sounding (open source: Google Earth©: www.google.com/intl/pl/earth/).
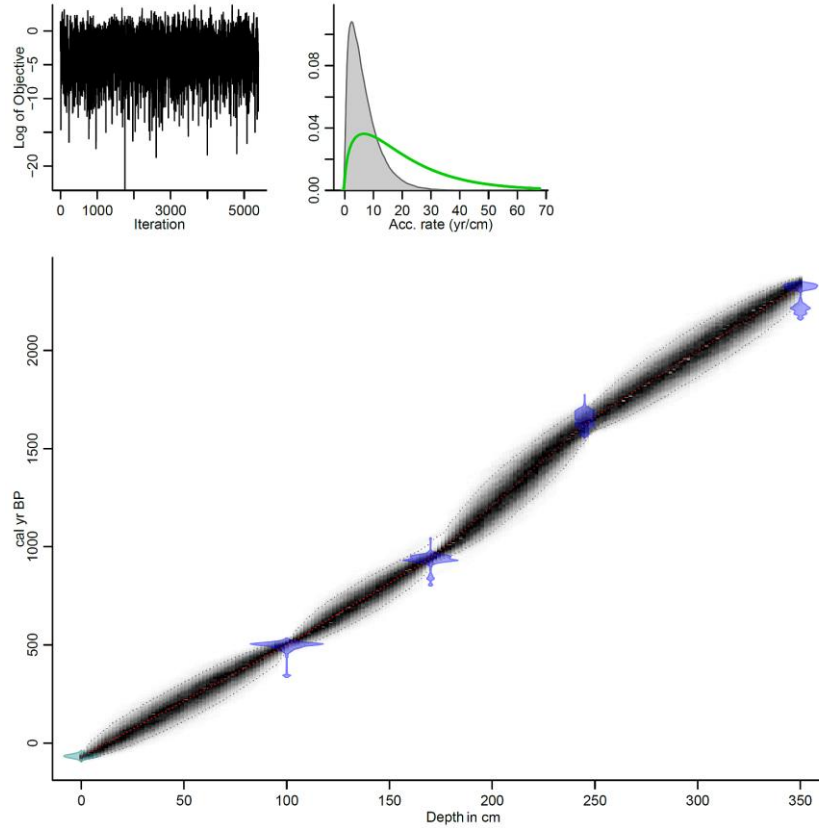
811 Fig. 4. Age-depth model of the core M-1 from the Lake Młynek sediments. Good runs of a stationary distribution are
812 shown in the upper left panel, green curves and grey histograms in the upper right panel present distributions for the
813 sediment accumulation rate. The main bottom panel shows the calibrated 14C dates (transparent blue) and the age-
814 depth model (darker gray areas) which are indicating calendar ages. Grey stippled lines show 95% confidence intervals
815 and the red curve shows the 'best' model based on the weighted mean age for each depth. The model was created by
816 F. Welc using the open Bacon software (Blaauw and Christen, 2011).

817
818
819
820
821
822
823
824
825

826
827
828
829
830
831
832
833
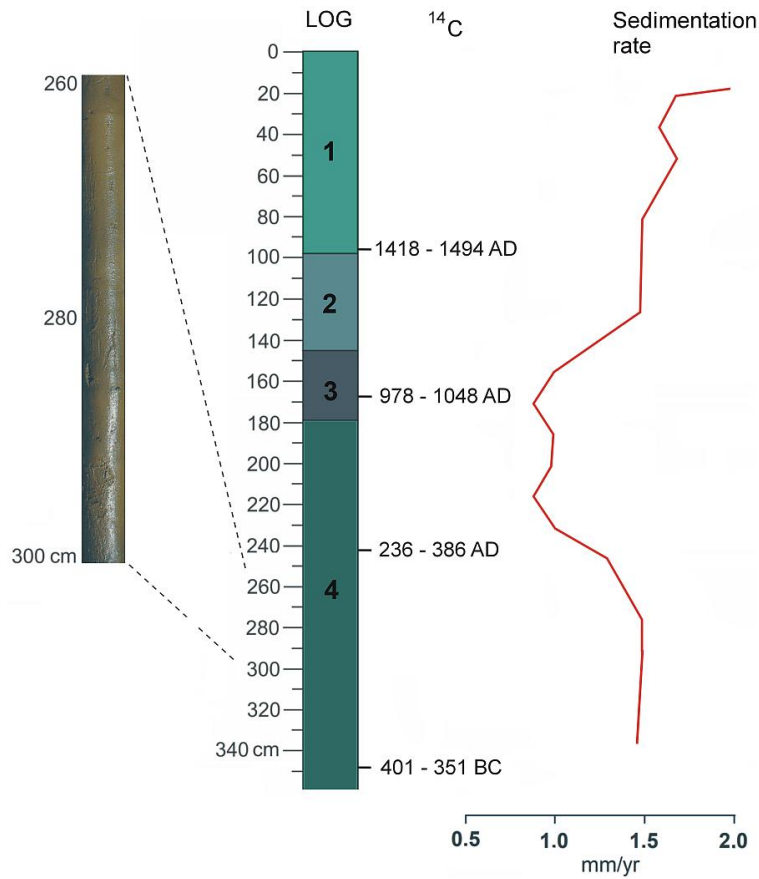
Fig. 5. Lithology of the M-1 borehole with radiocarbon determinations with 95% confidence, close up - photo of the log at 2.6 - 3.0 m depth and sedimentary rate (mm/year) estimated based on the age/depth model. Description of LOG: 1 - hydrated – detritus type gyttja, 2 - very plastic - algal gyttja, 3 - gray-brown peaty - detritus gyttja, 4 - gray-brown gyttja (Photo and drawing: Fabian Welc).

839
840
841
842
843
844

845

846

847

848
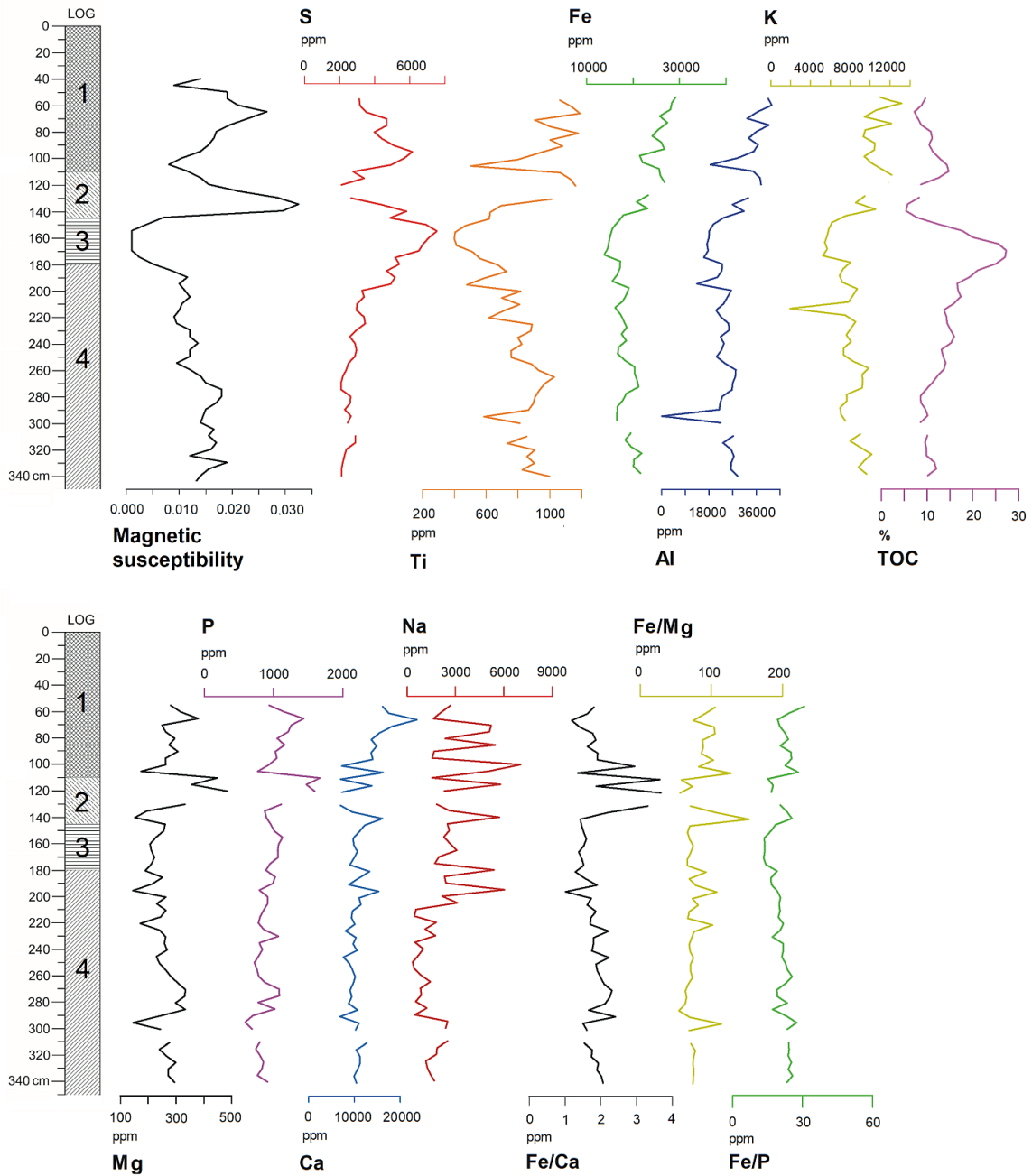
Fig. 6. Concentration depth curves for selected elements and TOC in the core M-1 of Lake Młynek sediments. Description of LOG: 1 - hydrated – detritus type gyttja, 2 - very plastic - algal gyttja, 3 - gray-brown peaty - detritus gyttja, 4 - gray-brown gyttja (Drawing: Fabian Welc).

853
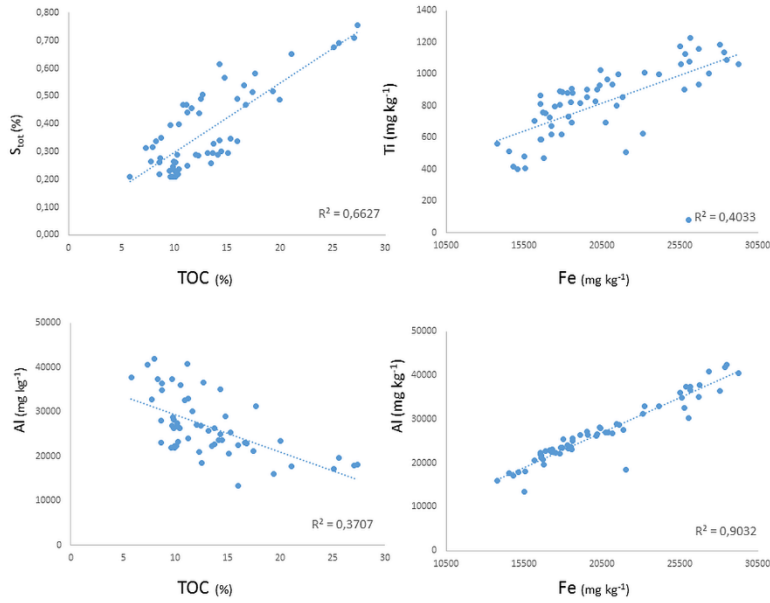
Fig. 7. Scatter plot showing the correlation in the core M-1 between S and TOC, Al and TOC, Ti and Fe, and Ti and
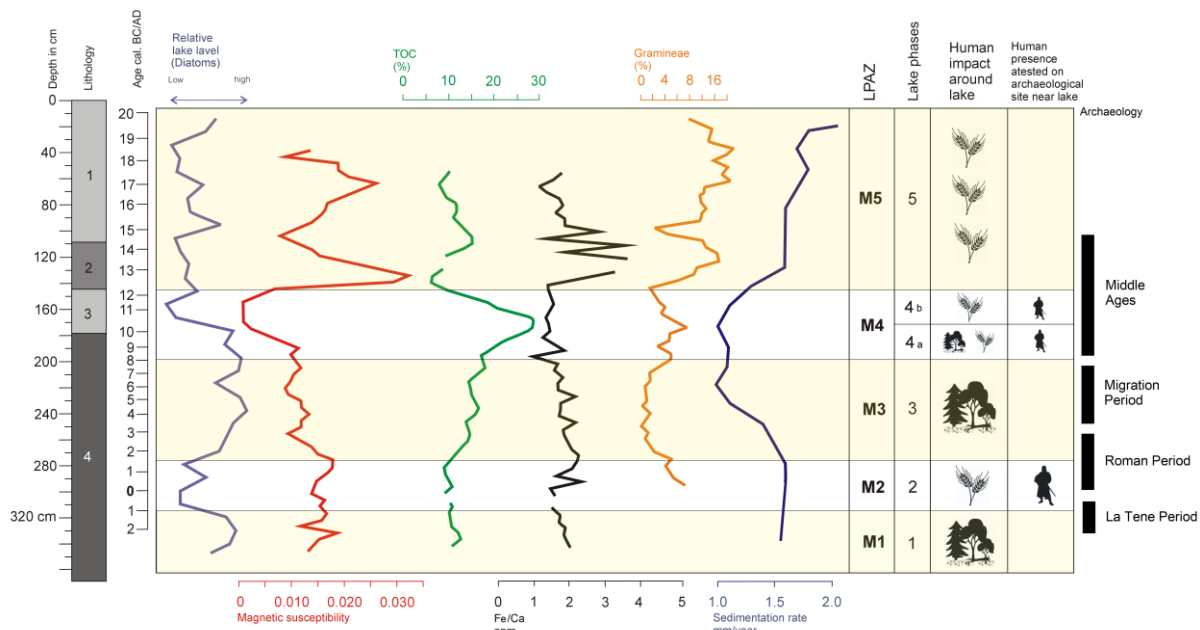
Fe. (Drawing: Anna Rogóż-Matyszczak)

856
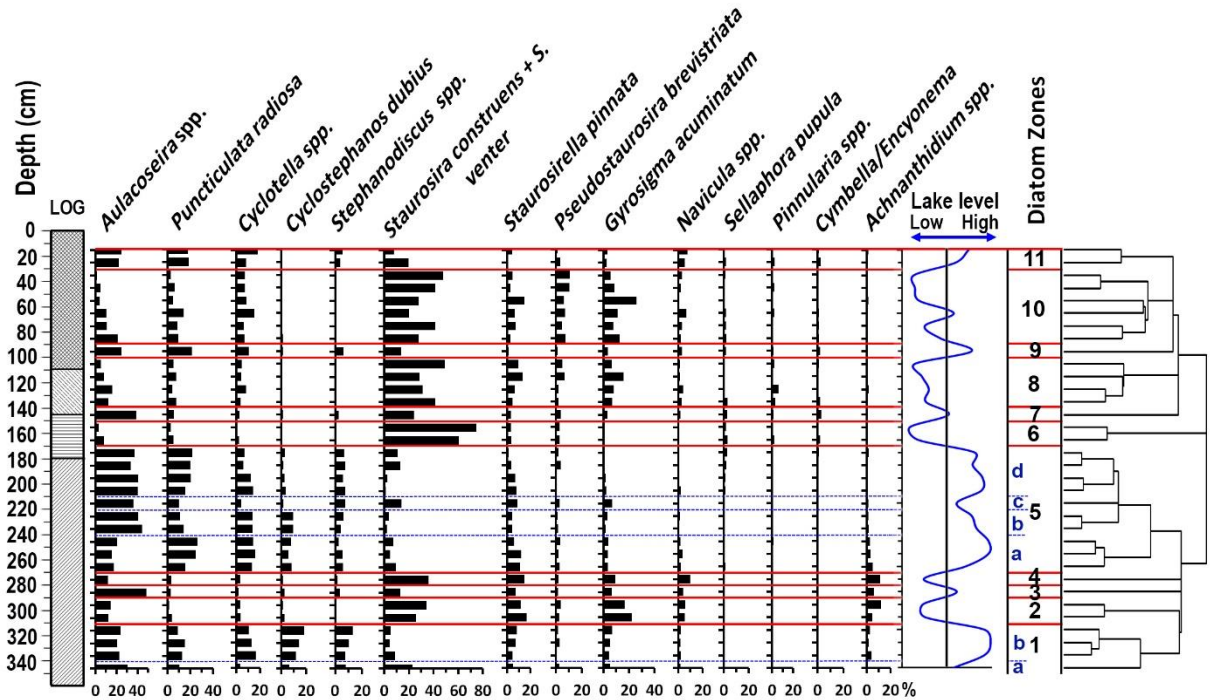
Fig. 8. Diatom stratigraphy of the core M-1, showing diatom zones and lake phases and relative water level changes

estimated on relation between planktonic and benthonic diatom taxa (Interpretation and drawing: Abdelfattah Zalat).
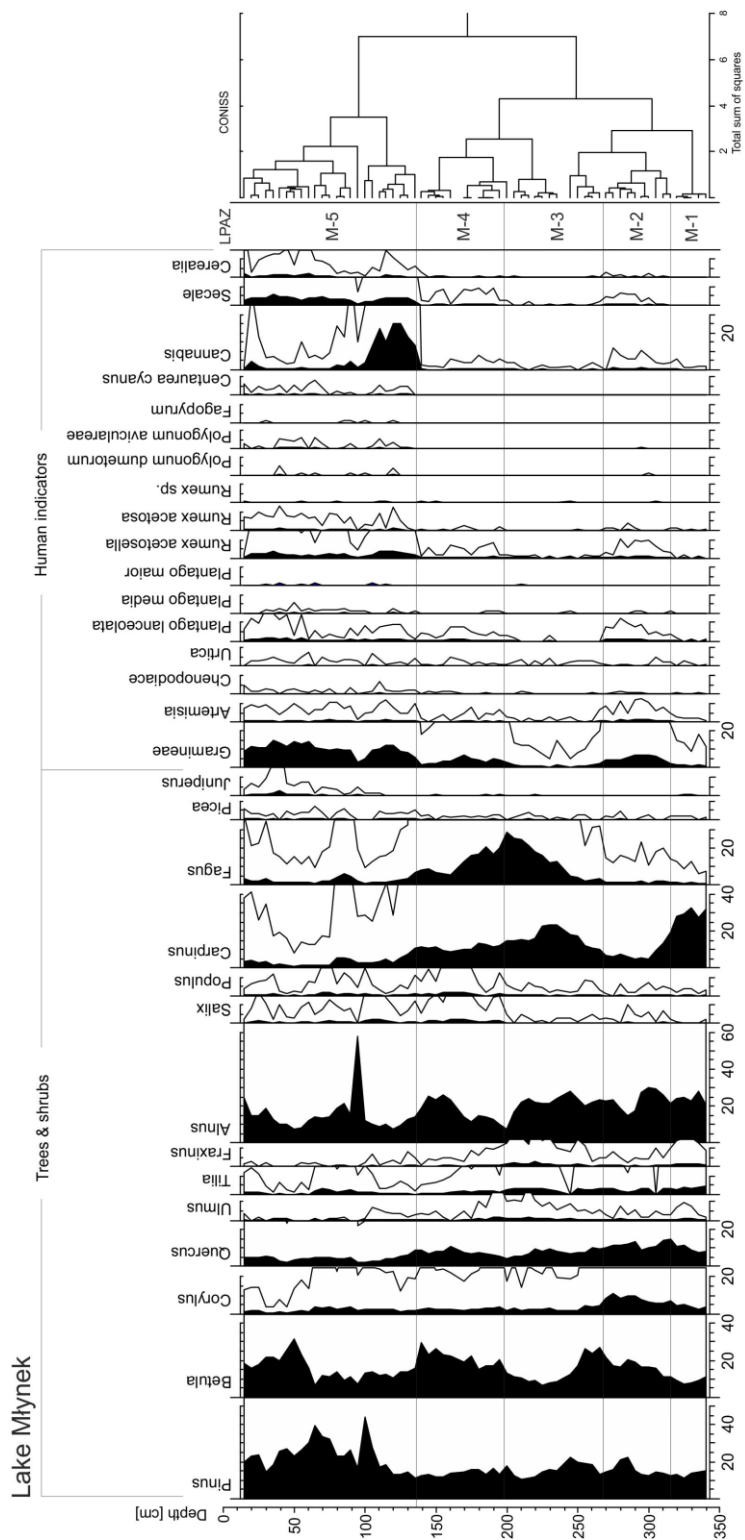
Fig. 9. Percentage pollen diagram from core M-1 – selected taxa.

865

866 Fig. 10. Diagram with selected palaeoenvironmental proxies including lithology (1 - hydrated – detritus type gyttja, 2
867 - very plastic - algal gyttja, 3 - gray-brown peaty - detritus gyttja, 4 - gray-brown gyttja) with phases of human activity
868 in the vicinity of Lake Młynek, supplemented by archaeological chronology for Poland (Drawing: Fabian Welc).