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LITHOLOGY AND GEOCHEMISTRY OF THE LATE GLACIAL AND HOLOCENE SEDIMENTS FROM GOSTYŃ LAKE (WESTERN POMERANIA, MYŚLIBÓRZ LAKELAND)

ANDRZEJ KORZENIOWSKI[1], DANIEL OKUPNY[2], ADAM MICHCZYŃSKI[3], JOANNA SŁAWIŃSKA[2], RYSZARD KRZYSZTOF BORÓWKA[2]

Abstract. Sediment geochemistry and lithology were studied in Gostyń Lake in the eastern part of the Myślibórz Lakeland (part of the Western Pomeranian Lake District). The research was undertaken because relatively shallow lake basins without ground supply contribute to the intensification of water circulation through evaporation. Late Glacial and Holocene phases in the evolution of Gostyń Lake were reconstructed based on selected geochemical indicators (Fe/Mn, S/Fe, Na/K, Mg/Ca, Cu/Zn, Na+K+Mg/Ca, Fe/Ca) as well as on the presence of human activity (Stone Age, Bronze Age, Early Iron Age and Roman Period). Also, the geochemical and archaeological data were correlated. Generally, the lithogeochemical composition variability in the Gostyń Lake deposits was found to be controlled by changes in: 1) the climate, related to the biogenic accumulation environment, 2) land cover in the Late Glacial and Holocene, and 3) human activities. Principal Component Analysis (PCA) revealed four major variable groups responsible for the changes: hydroclimatic variations which determined the type of sedimentary conditions during the Holocene climate optimum; changes in the organic matter provenance (along with conditions favouring sulphide precipitation); and denudation processes in the Gostyń Lake catchment. The methods used allowed the distribution of ancient settlement to be traced. Interpretation of the geochemical indicators (Fe/Mn, Cu/Zn, S/Fe, Ca/Fe) should involve many more factors which, in the relevant literature, are treated as measures of changes in redox conditions.

Key words: lakes, biogenic deposits, geochemistry, human impact, Holocene, western Poland

Introduction

Environmental reconstructions based on lake and peatland records often register changes on a regional scale, but local changes are driven by geological structure and lithology in the catchment, the morphology of the basin, the source of supply, and the catchment of surface and ground waters (Wojciechowski 2000; Błaszkiewicz 2007; Nowaczyk, Owsianny 2011; Płóciennik *et al.* 2015; Dietze *et al.* 2016; Okupny *et al.* 2016). Lake basins and peat bogs are important archives also of natural past geological and hydroclimatic evolution in the West Pomeranian Lake District (Jasnowski 1962; Borówka 1992; Latałowa 1992, 1999a; Malkiewicz, Tomaszewska 2009; Madeja 2012; Bloom 2015; Lamentowicz *et al.* 2015).

Shortly after the last ice sheet had melted, Western Pomerania was penetrated by Late Palaeolithic reindeer hunters. Indirect and direct traces of their activities, dated to 13,000–10,000 BP, were found in both the Polish and German parts of Pomerania, including the islands of Rügen, Wolin, Usedom and Chrząszczewska near Kamień Pomorski; recently, such traces have been discovered in the vicinity of Szczecin (Galiński 2015). There are also numerous traces of Mesolithic communities penetrating and colonising the Pomeranian environment, which was much more human-friendly during the first millennia of the Holocene (Galiński 1992). During the Late Palaeolithic and Mesolithic, anthropogenic environmental effects were negligible, as can be concluded from the lack of distinct changes in natural succession of vegetation in Western Pomerania found in palynological research at a number

[1] ul. Brzozowa 17, 66-416 Różanki, Poland.
[2] University of Szczecin, Institute of Marine and Environmental Sciences, ul. Mickiewicza 16, 70-383 Szczecin, Poland; e-mail: daniel.okupny@usz.edu.pl, ORCID: 0000-0002-8836-6044, ORCID: 0000-0002-1708-2722, ORCID: 0000-0002-7232-3453
[3] Silesian University of Technology, Institute of Physics – Centre for Science and Education, ul. Konarskiego 22B, 44-100 Gliwice, Poland; ORCID: 0000-0003-2795-6830

of sites, including the lakes Kołczewo and Racze on Wolin Island (Latałowa 1992, 1999a, b), Lake Święte 22 near Stargard (Malkiewicz 2009), Lake Chojna (Krupiński 1991), Lake Kwiecko (Madeja 2012), Lake Zarańskie (Noryśkiewicz 2014) and Lake Racze (Bloom 2015).

Human impact on the environment was more distinct in the Neolithic. In palynology, it is visible as an increasing contribution of NAP grains, accompanied by a reduced contribution of that of elm (*Ulmus* sp.), which is indicative of the emergence of open areas, mainly pastures and arable land (Latałowa 1992, 1999a; Bloom 2015). Very numerous Neolithic archaeological sites have also been discovered and described in the area since the mid-19th century (Siuchniński 1969, 1972), including in particular the most abundant traces of intensive development of the Funnel Beaker Culture (FBC). Most probably, the most spectacular sepulchral and/or cultural constructions, such as the very numerous megaliths that occur most abundantly in the southern part of the Pyrzyce Plain (Siuchniński 1972; Kulczycka-Leciejewiczowa 1996) or the rondel at Nowe Objezierze near Moryń that is being explored at present (Czerniak *et al.* 2019; Pędziszewska *et al.* 2019) should be associated with the FBC. Of hundreds of megaliths identified by German authors in the Pyrzyce Plain in the late 18th and early 19th centuries (Chmielewski 1952), only a few have persisted until now and are occasionally identified at present from the analysis of aerial photographs (Matuszewska, Szydłowski 2012). Regardless of this, the area is often taken into consideration in the discussion of the FBC genesis (Matuszewska 2019).

Western Pomerania is also an area of very numerous finds dated to later archaeological periods: to the Bronze Age and Early Iron Age, as well as to the Roman Period and the Early Middle Ages. Some are visible as legible remains of open-settlement township constructions or burial sites (Godłowski 1984; Kowalski, Kozłowska-Skoczka 2009/2010; Kaczmarek 2018).

All these archaeological sites attest to an intensive use of the Western Pomeranian natural environment since at least about 6000–5000 years BP. However, despite the abundance of archaeological evidence, the knowledge on the extent of environmental transformations in different parts of Western Pomerania in past ages is still far from complete. This gap should be bridged by multi-proxy-based exploration of natural archives, such as, in particular, sediments of inland sedimentation basins, lakes and peat bogs. Initial studies have already been carried out on a micro-region scale (Borówka 1992, 1994; Latałowa 1999a, b; Płaza *et al.* 2013/2015; Bloom 2015; Lamentowicz *et al.* 2019). The importance of such studies stems not only from their potential to assess changes in the vegetation cover, but also from the possibility to trace the effects of human activities on lacustrine and bog ecosystems; in addition, intensification of erosion-denudation processes as well as matter circulation can be followed at the scale of the sedimentation reservoir catchment.

The sites particularly useful for reconstructing climate changes and anthropogenic effects are sedimentation reservoirs subject to the evapotranspiration regime *sensu* Drwal (1973, 1974). Therefore, such sedimentation basins in recently glaciated areas have been targeted many times in studies aimed at assessing lacustrine responses to Late Glacial and Holocene changes in climate and human impact (Borówka 1990, 1994; Hulisz *et al.* 2012; Karasiewicz *et al.* 2014a, 2017; Mendyk *et al.* 2016).

This paper is aimed at presenting initial results of palaeo-environmental studies on lacustrine sediments of Gostyń Lake near Barlinek, in particular addressing changes in the sediment lithology and geochemistry on the geological time scale. Particular attention is paid to assessing human impact on the evolution of this sedimentation basin in the context of archaeological research carried out within the framework of the Polish National Record of Archaeological Sites (*Pol.* AZP – *Archeologiczne Zdjęcie Polski*).

Site description and coring

Gostyń Lake (φ 53°00'13" N; λ 15°09' 00" E; H – 82.1 m a.s.l.) is located on a morainic upland of the Myślibórz Lakeland, about 4.6 km NW of the centre of the town of Barlinek. Locally, lakes occupy up to 10% of the area (Fig. 1A). Gostyń Lake is a drainless morainic reservoir; its 7.8 km^2 catchment lies on an undulating morainic upland rising to 85–95 m a.s.l. and built by layers of Vistulian and Warthian glacial till up to 20 m thick (Sochan, Piotrowski 2004; Piotrowski, Sochan 2011). The Gostyń Lake basin, 940×500 m and 21.25 ha in size, is irregular, being wider in its northern part and narrowing to the south (Fig. 1B). Thus, the present surface area of the lake is three times larger than the mean size of drainless lakes calculated by Majdanowski (1950/51) for the River Oder catchment. The lake features three small islets, as well as submerged shallows vegetated by the common reed (*Phragmites australis*), bulrush (*Typha latifolia*), and common club-rush (*Schoenoplectus lacustris*). The mean and maximum depth of Gostyń are 1.5 and about 3.4 m, respectively. According to the most recent classification of lakes (Solheim *et al.* 2019), the lake belongs to the group of lowland mixed and unstratified water body, which are fairly rare in Europe.

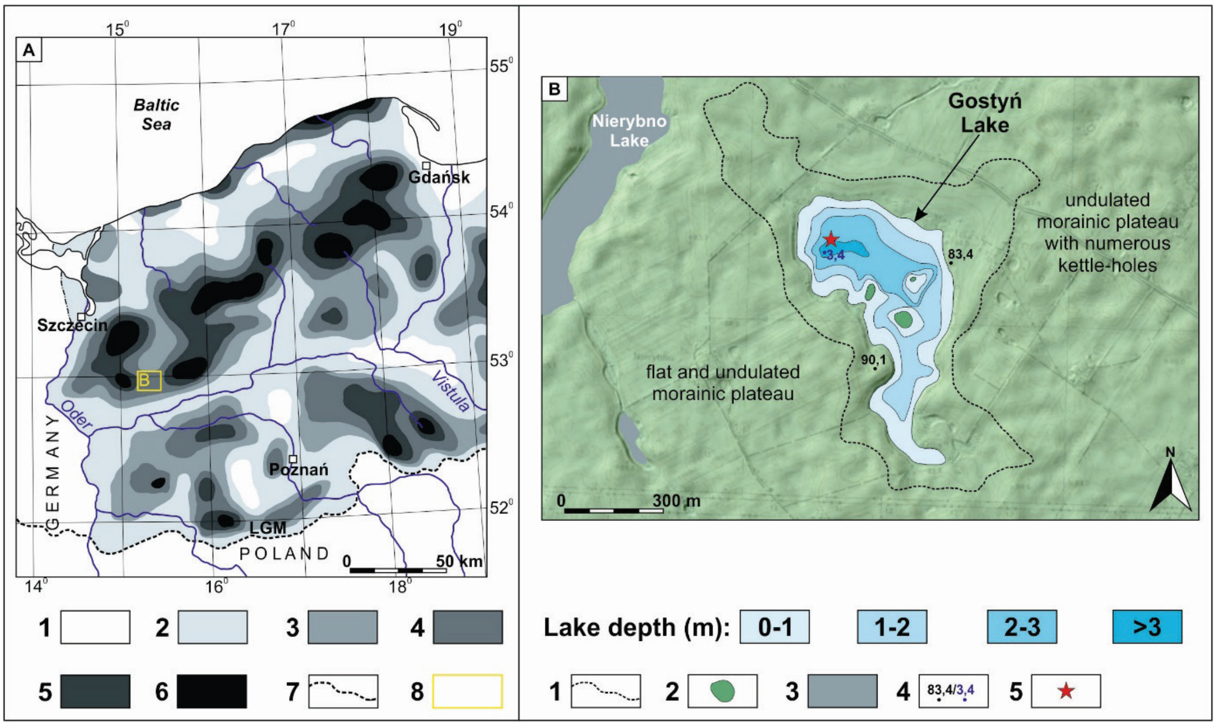

Fig. 1. Location of Gostyń Lake

A. Per cent contribution of lakes to the surface area of northern Poland after Majdanowski (1950/51)

1 – below 0.1%, 2 – to 1%, 3 – to 2%, 4 – to 3%, 5 – to 5%, 6 – to 10%, 7 – boundaries of the Last Glacial Maximum after Marks (2005), 8 – study area

B. Digital elevation of the catchment (based on LiDAR data), lake bathymetry and geomorphology of the surrounding area

1 – Gostyń Lake catchment boundary, 2 – islands; 3 – other lakes, 4 – maximum, minimum altitudes and maximum depth, 5 – coring site (GOS 1)

The small catchment of Gostyń Lake is located in an area with a low mean annual precipitation not exceeding 550 mm (Koźmiński *et al.* 2012). The growing season (April–September) is characterised by a precipitation deficit averaging 130–150 mm (Kołodziej 2008), the deficiency being alleviated, albeit in part only, by precipitation in autumn–winter. The persistence of the lake attests to the importance of water retention by the soil and supply from subsurface resources. The lake is flanked to the west, south and east by steep, though not particularly high (up to 1.5 m), escarpments supporting arable land, the northern shores being low-lying. To the north, west and south, the lake is surrounded by a wide rush belt which also connects the islets with the shores. The southern shallow embayment is almost entirely vegetated by yellow water lily communities. As shown by recent studies, changes in water level – like in other lakes in the northern part of Poland – are controlled primarily by local factors, with climatic effects playing a lesser role (Choiński *et al.* 2020). The results of archaeological study confirm the occurrence of many relicts in this area. In the area of 25 km^2 surrounding Gostyń Lake, 24 archaeological sites (with 54 archaeological factors) have been registered. Half of them date to Prehistory (mainly the Stone Age and Roman Period), and only one to the Medieval Period (Figs 2, 3).

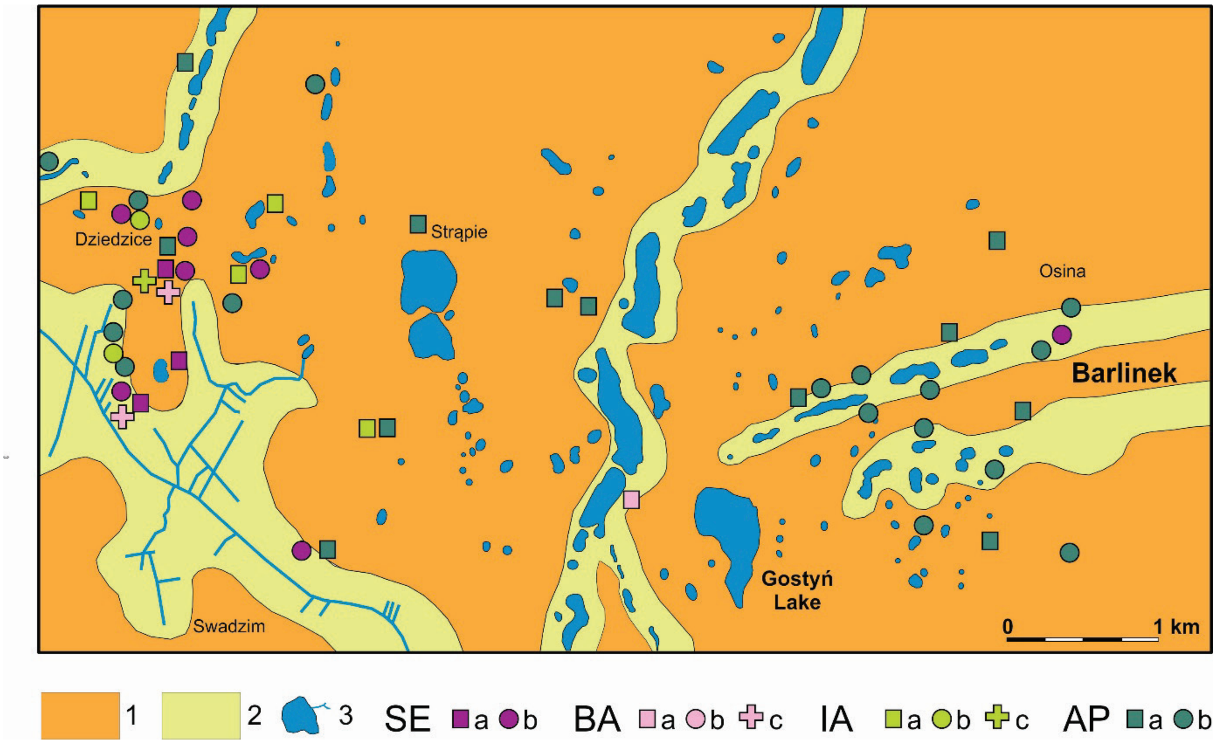

Fig. 2. Location of Prehistoric archaeological sites in the vicinity of Gostyń Lake after Kot (2013)

1 – morainic plateaus; 2 – tunnel valley bottom and water-logged meltwater depressions; 3 – lakes and streams; chronology of archaeological sites: SE – Stone Age, BA – Bronze Age, IA – Early Iron Age, AP – Roman Period; a – settlements; b – settlement traces; c – burial grounds

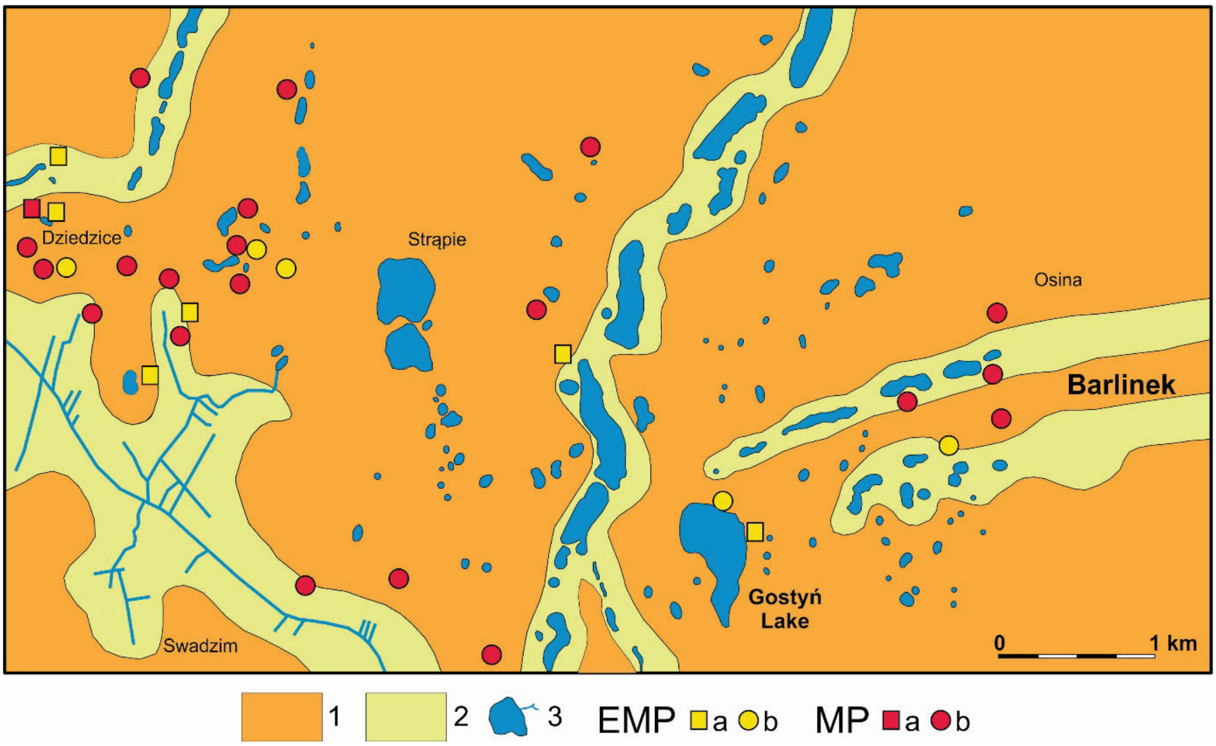

Fig. 3. Location of Medieval archaeological sites in the vicinity of Gostyń Lake after Kot (2013)

1 – morainic plateaus; 2 – tunnel valley bottom and water-logged meltwater depressions; 3 – lakes and streams; chronology of archaeological sites: EMP – Early Medieval Period, MP – Medieval Period; a – settlements, b – settlement traces

Methods

Field work

The sediment core was collected in the north of the lake, in the deepest area (Fig. 1). The field work was conducted in winter, whereby individual core segments could be collected from ice. The core segments were collected with a 10-cm-diameter, 50-cm-long Instorf corer. As opposed to tube corers, the Instorf corer does not compress sediment layers, and a 0.5-m-long half-cylinder core is retrieved undisturbed from the sediment. Following collection, each 0.5-m-long sediment segment was placed in a plastic trough and wrapped tightly with sheets of plastic to prevent desiccation. In the laboratory, the segments were divided into about 5-cm-long sections, with reference to lithological boundaries. Core GOS 1 (895 cm total length) yielded 179 samples.

Sample preparation and laboratory analyses

Geochemistry

Individual samples were freeze-dried in a Beta 1-8 LD plus lyophiliser by Christ. Following sediment homogenisation, about 2-g sediment samples dried at 105 ºC were analysed for loss on ignition (LOI) at 550 ºC to calculate percentage contributions of organic and mineral matter (Heiri *et al.* 2001). The ash remaining from combustion, devoid of organic matter, was dissolved in a Speedwave microwave mineraliser (Berghof) in 8 ml concentrated nitric acid, 2 ml 10% hydrochloric acid and 2 ml peroxide. The solution was assayed using atomic absorption spectrometry in an AAS SOLARR 969 spectrometer (Unicam), for contents of Na, K, Ca, Mg, Fe, Mn, Cu, Zn and Pb. Results were referred to 1 g sediment dry weight (d.w.). Air-dried sediment samples were analysed for contents of total carbon, total nitrogen, and total sulphur in a VARIOMAX CNS (Elementar). All the assays were performed at the Geochemical Laboratory, Institute of Marine and Environmental Sciences, University of Szczecin.

Radiocarbon dating

To develop the chronology of the sediments of the Gostyń Lake, five bulk samples were radiocarbon-dated using the liquid scintillation counting technique (LSC). All the samples were processed according to a standard protocol (Tudyka *et al.* 2015). The dates were calibrated with the calibration software OxCal 4.2 (Bronk Ramsey *et al.* 2010) using the IntCal13 calibration curve (Reimer *et al.* 2013).

Data visualisation and quantitative analysis

The data were processed using Microsoft Office Excel and PAST (Hammer *et al.* 2001) software; the latter was used to identify geochemical zones and to perform the Principal Components Analysis (PCA) to identify the major factors controlling changes in the sediment chemistry. The data were visualised using C2 graphic software (Juggins 2007) and CorelDRAW Graphics Suite X3.

Results

Lithology

In the study profile, the bog series overlies lacustrine deposits that show an up-core gradation from silt gyttja at the bottom, through algal gyttja, to coarse-detritus gyttja. The bog deposits are overlain mostly by fine-detritus gyttja (Table 1).

Table 1

Core GOS 1 sediment lithology

Depth (m)	Lithology
0.00–0.40	fine-detritus gyttja, olive in colour
0.40–1.20	detritus (occasionally coarse-detritus) gyttja, grey-brown in colour
1.20–3.03	fine-detritus gyttja, olive in colour
3.03–5.80	moss peat, dark-brown in colour
5.80–6.10	sedge peat, dark-brown in colour
6.10–6.40	coarse-detritus gyttja, olive in colour
6.40–8.45	algal gyttja, occasionally with admixtures of sand and silt, olive in colour
8.45–8.95	silt gyttja, grey-olive in colour

Core chronology

To follow the temporal evolution of the Gostyń Lake deposits, a radiocarbon dating-based age–depth model was developed using the OxCal v4.3.2 software (Bronk Ramsey, Lee 2013), for core GOS 1. The IntCal 13 calibration curve was used to calibrate the datings. The model was constructed using the PSequence command with k=0.5. The model was based on five radiocarbon datings determined at the Gliwice laboratory (Table 2) and a single dating, for the core surface, referring to the coring date. The model fit was 96%, evidencing the correctness of the assumptions. The timeframe produced by the model extends from the Younger Dryas to the present. The model is shown in Fig. 4.

Geochemistry

The geochemistry of the GOS 1 sediment profile is shown in Figs 5 and 6; the y axis represents the calibrated years b2k from the age–depth model. Local geochemical zones were identified with cluster analysis, with due consideration to the stratigraphic position of the samples. The analysis was performed with the following geochemical variables: LOI (a measure of the organic matter concentration), selected macro- and microelements (Na, K, Ca, Mg, Fe, Mn, Cu, Zn, Pb), and biogenic elements (C, N and S).

The results of the analysis produced five major geochemical zones (GZ I – GZ V); moreover, zones GZ I, GZ III and GZ IV could be subdivided into two sub-zones each (Figs 5, 6). The age and geochemical properties of the zones are described in Table 3.

Data interpretation and discussion

Factors controlling sediment chemistry

The PCA reduced the original 13 geochemical variables to four major components that, taken together, explained 88% of total data variance (Table 4). The PC1 axis (Fig. 7), which explained more than 50% of the total variance, is strongly positively correlated with the lithophile elements (Na, K, Mg, Fe), and negatively correlated with the organic matter, C, N. and Ca. It informs primarily on lithological differences in the sediments, as well as on changes in the mechanical denudation intensity (positive value), in contrast to the organic matter accumulation and chemical denudation (negative values). The available literature (Dean 1993; Koinig *et al.* 2003; Rydelek 2011; Woszczyk 2011) interprets lithophile components as proxies of denudation intensity, as they are supplied to lakes passively, in crystalline structures of quartz and aluminosilicates or as ions adsorbed on clayey minerals. The good agreement between changes in the relative extent of mechanical denudation in the Gostyń Lake catchment and the geochemical record in other biogenic accumulation reservoirs in the Polish Lowland (Okupny *et al.* 2013; Pleskot *et al.* 2018; Karasiewicz 2019) may be regarded as supporting the identification of post-glacial changes in the vegetation cover and land use. However, there is also evidence (Borówka 1992; Selvaray *et al.* 2016) that the accuracy and temporal resolution of the results may depend on the biogenic sediment accumulation rate.

Table 2

Results of ^{14}C dating of Gostyń Lake sediment bulk samples

Depth (m)	Material dated	Sample No.	^{14}C age (yrs BP)	Calibrated age range BP 95.4%
1.35–1.40	fine-detritus gyttja	GdS-4068	1,845±85	1,970–1,560
2.95–3.03	fine-detritus gyttja	GdS-4011	4,095±95	4,855–4,355
4.85–4.90	moss peat	GdS-4022	5,470±80	6,415–6,005
6.20–6.25	coarse-detritus gyttja	GdS-4016	6,290±75	7,420–7,005
8.70–8.75	silt gyttja	GdS-4063	10,460±100	12,650–12,030

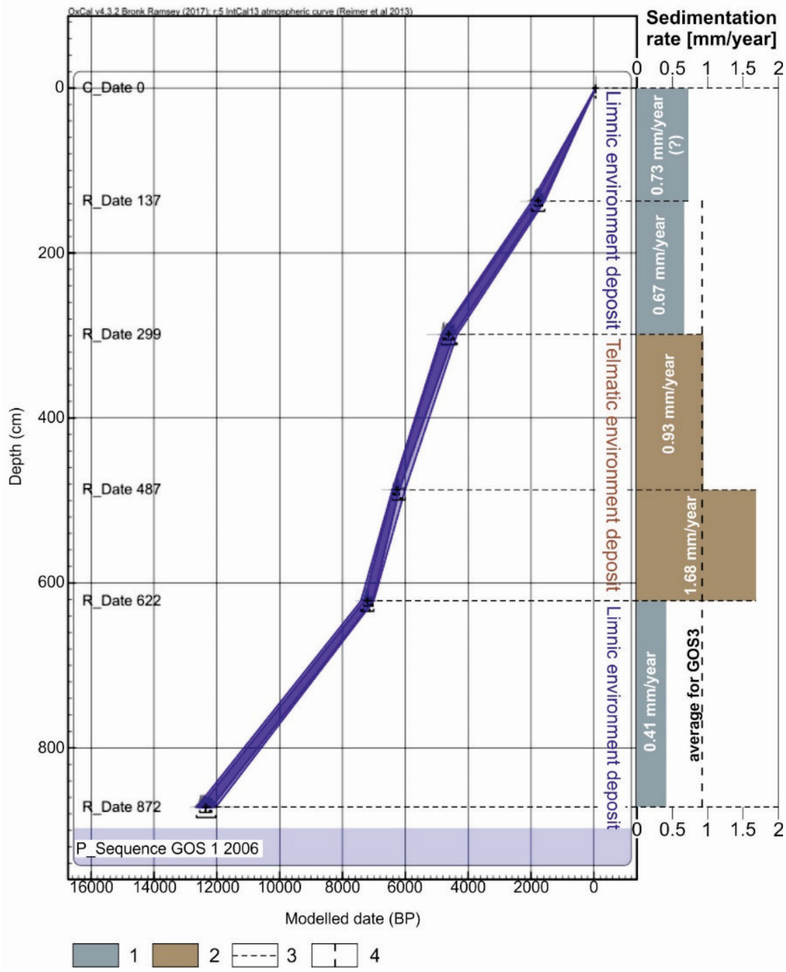

Fig. 4. Age–depth model of the GOS 1 profile from Gostyń Lake

1 – lake sediments, 2 – peat sediments, 3 – average sedimentation rate for selected sections, 4 – average sedimentation rate for all core

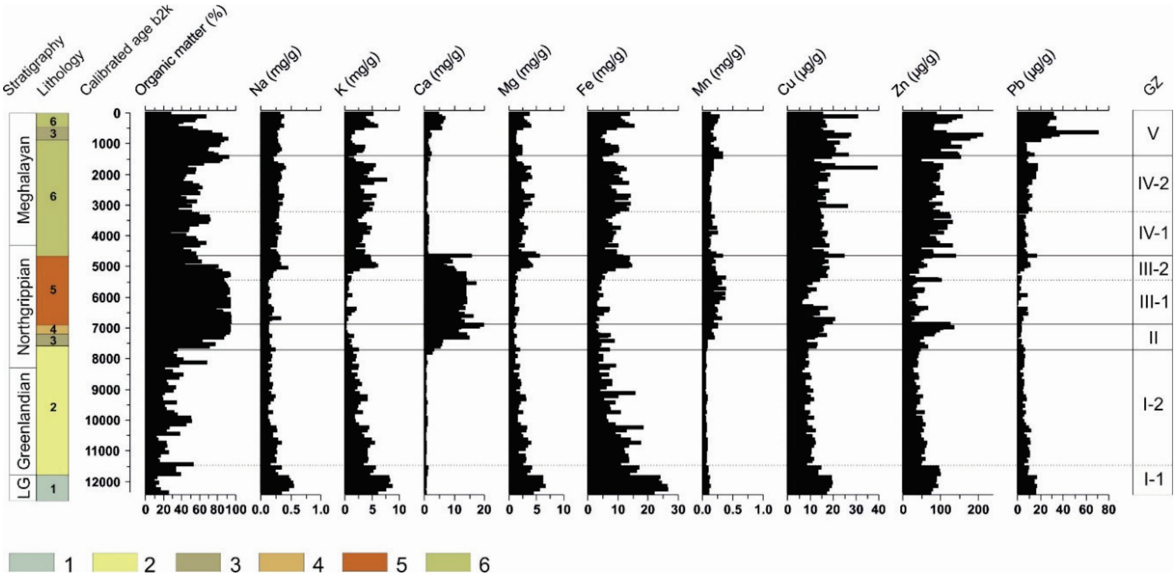

Fig. 5. Core GOS 1. Stratigraphic variability of organic matter concentration and contents of selected major and trace elements

1 – silt gyttja, 2 – algal gyttja, 3 – coarse-detritus gyttja, 4 – sedge peat, 5 – moss peat, 6 – fine-detritus gyttja; GZ – geochemical zones and sub-zones

Table 3

Detailed description of geochemical characteristics of sediments within identified geochemical zones and sub-zones

Geochemical zone and sub-zone	Depth (m) Age (years b2k)	Description
GZ I-1	8.80–8.40 ~12,300–11,500	Representing silt gyttja accumulation phase, at the transition of the Younger Dryas to the Holocene; maximum contents of lithophile elements (Na, K, Mg and Fe); higher contents of Mn, Cu, Zn and Pb than those in GZ I-2; substantial contributions of OM and biogenic elements (C, N and S); maximum values of mechanical denudation intensity indicators (Mg/Ca and Na+K+Mg/Ca).
GZ I-2	8.40–6.45 ~11,500–7650	Representing algal gyttja accumulation phase, with occasional admixtures of sand and silt; characteristic but relatively low contents of OM, total carbon and total nitrogen, at a somewhat elevated concentration of total sulphur; gradual reduction in lithophile elements (Na, K, Mg and Fe); stable but relatively low contents of Ca, Mn, Cu, Zn and Pb; distinct tendency towards reduction of mechanical denudation indicators (Mg/Ca and Na+K+Mg/Ca) and Fe/Mn ratio.
GZ II	6.45–5.70 ~7,650–6,850	Representing accumulation of coarse-detritus gyttja and sedge peat. Rapid increase in contents of OM and biogenic elements (particularly sulphur). Increased contents of Ca, Mn, Cu and Zn, accompanied by declining content of potassium as well as fairly stable but low contents of Na, Mg, Fe and Pb. Increased values of chemical denudation indicators (Na/K and Ca/Mg ratios) and almost negligible indicators of mechanical denudation. Distinct reduction of Fe/Mn and increased C/N ratio.
GZ III-1	5.70–4.00 ~6850–5450	Coinciding with moss peat accumulation phase. Highest contents of OM (up to about 90%) and total carbon. Variable but fairly high concentration of total nitrogen (3–4%) and fairly stable concentration of sulphur (to about 0.5%). Relatively high and fairly stable content of Ca (about 15 mg/g) and gradually increasing content of Mn (from 0.2 to 0.4 mg/g). Low contents of lithophile elements (Na, K, Mg and Fe) and Pb. Variable contents of Cu and Zn. High but declining values of chemical denudation indicators (Na/K and Ca/Mg ratios) as well as low but stable values of mechanical denudation indicators (Mg/Ca and Na+K+Mg/Ca) and Fe/Mn. C/N ratio fluctuating from about 15 to 22.
GZ III-2	4.00–3.03 ~5,450–4,650	Representing the uppermost layer of moss peat. Reduction in OM concentration (from 90 to 50%), in contents of biogenic elements (C, N, S) as well as Ca and Mn. Distinct increase in contents of lithophile elements (Na, K, Mg and Fe) as well as Cu, Zn and Pb. Distinct reduction in values of chemical denudation indicators (Na/K and Ca/Mg ratios) at a slight increase in mechanical denudation ones (Mg/Ca and Na+K+Mg/Ca) and Fe/Mn. Fairly high but variable C/N ratio (15–25).
GZ IV-1	3,03–2.20 ~4,650–3,250	Representing the lower part of the fine-detritus gyttja layer. Variable OM concentration (usually 40–75%) and biogenic element contents. Rapid decline in Ca content and gradual increase in that of Zn. Contents of most lithophile elements somewhat lower than in GZ III-2. Higher values of mechanical denudation indicators resulting primarily from rapid reduction in Ca content. Periodical increases of Fe/Mn above 50 suggesting hypoxia/anoxia. C/N ratio decline to about 10.
GZ IV-2	2.20–1.10 ~3,250–1,450	Representing the upper part of the fine-detritus gyttja layer. Variable OM concentrations (usually 40–60%), peaking (~90%) in uppermost part of the zone and correlated with variable contents of biogenic elements. Somewhat higher contents of lithophile elements (K, Mg, Fe) and Pb, and lower contents of Ca and Mn compared to those in GZ IV-1. Variable, although decidedly higher values of mechanical denudation indicators and Fe/Mn ratio. Distinct increase in C/N ratio in uppermost layer, correlated with maximum OM and total carbon contents.
GZ V	1.10–0.00 ~1,450–0	Representing the uppermost layers of lacustrine deposits developed as fine- and coarse-detritus gyttja. Variable but usually high contents of OM and biogenic elements. Variable contents of lithophile elements (Na, K, Mg and Fe), but somewhat lower than in GZ IV-2. Clearly higher contents of Ca, Mn and trace metals, particularly Pb. Declining values of mechanical denudation indicators; distinct increase in values of chemical denudation indicators (Na/K and Ca/Mg). Gradual increase in Fe/Mn ratio attesting to persistence of oxygen deficiency. C/N ratio stabilised at about 10–12.

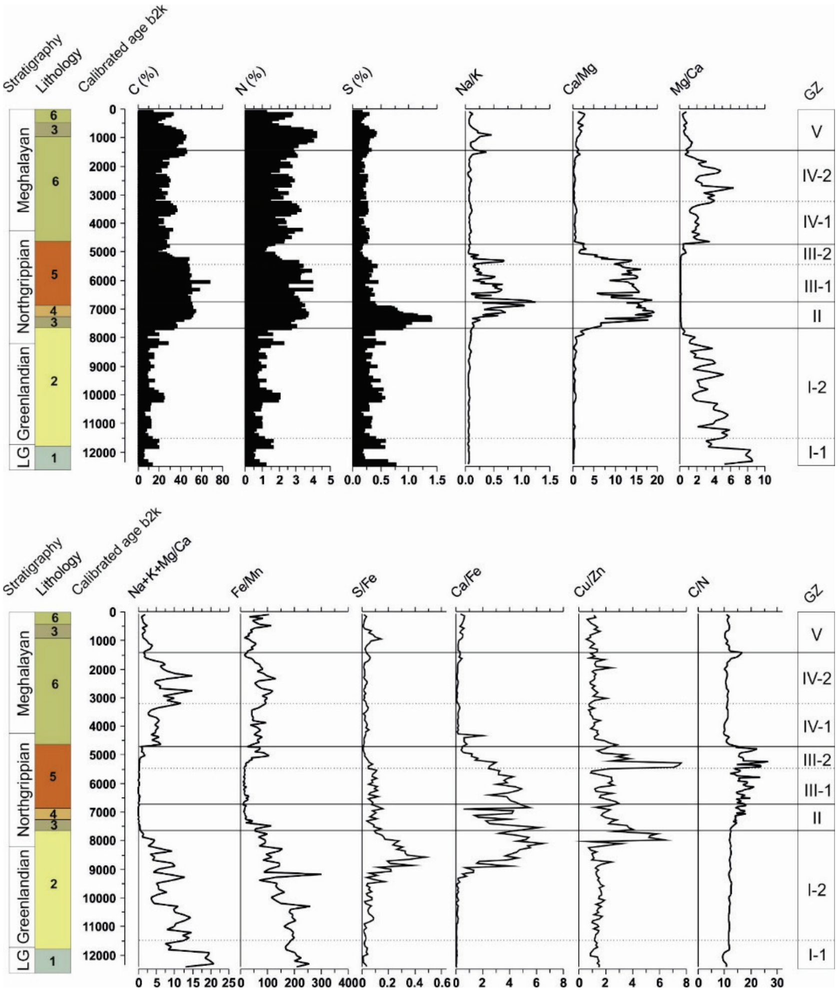

Fig. 6. Core GOS 1. Stratigraphic variability of biophilic elements and selected geochemical indicators

for explanation see Fig. 5

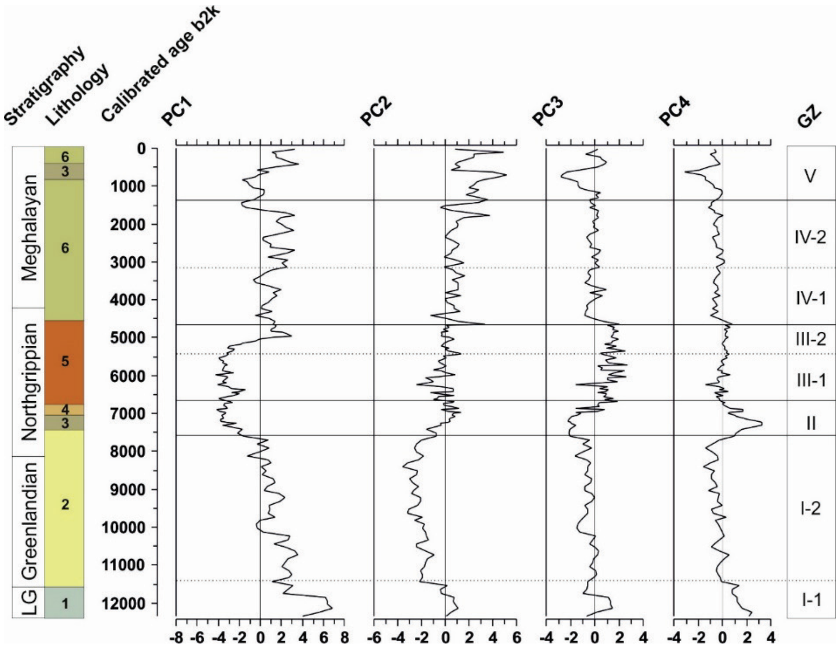

Fig. 7. Core GOS 1. Stratigraphic variability of the four principal components

for explanations see Fig. 5

Table 4

Results of Principal Components Analysis (PCA) for contents of selected major and trace elements in core GOS 1 sediment

Element	PC1	PC2	PC3	PC4
Organic matter	**-0.891**	0.365	0.081	0.022
Na	**0.805**	0.464	0.178	0.093
K	**0.951**	0.080	0.118	0.148
Ca	**-0.760**	0.104	**0.421**	0.337
Mg	**0.898**	0.141	0.221	0.250
Fe	**0.899**	0.047	0.120	0.337
Mn	-0.463	**0.560**	**0.580**	0.108
Cu	0.313	**0.816**	-0.064	0.092
Zn	0.324	**0.766**	**-0.394**	-0.089
Pb	0.483	**0.523**	-0,174	-0.320
Total C	**-0.889**	0.382	0.035	0.082
Total N	**-0.717**	**0.547**	-0.256	-0.044
Total S	-0.301	-0.077	**-0.593**	**0.734**
Variance explained (%)	50.65	20.60	9.52	7.27
Cumulative variance explained (%)	50.65	71.25	80.77	88.04

The PC2 axis, which explained 20.6% of the total variance, is positively correlated with contents of trace metals (mainly Cu and Zn and, to a lower extent, Mn and Pb) as well as the total nitrogen content. Thus, it may be presumed that PC2 informs on changes associated with human impact, reflecting the supply of additional amounts of metals used in ancient history. Higher nitrogen concentrations may be associated with a growing importance of animal husbandry. Analysis of variability in the first two principal components shows their positive values, appearing from the bottom of GZ III-2 (Fig. 7), i.e., since ~5,450 b2k (3450 BC), to be associated with variations in the anthropogenic effects on the Gostyń Lake catchment environment. Human impact induced changes in the mechanical denudation intensity, probably coupled with transformations of the vegetation cover, the changes being initially associated with growing animal husbandry and later on with plant cultivation. Such interpretation is completely in agreement with results of palynological and geochemical analyses of the sediment from Racze Lake on the Pyrzyce Lowland (Bloom 2015). That lake, too, showed a substantial increase – since about 3550 BC – in the mineral matter concentration, accompanied by an increase in contents of the lithophile elements (Na, K, Mg, Fe). The changes in the geochemical proxies referred to occurred during a period of distinct transformation of the land cover and fire activity in NW Poland and East Germany (Fig. 8D). The role of the latter factor was dealt with by, *inter alia*, Tobolski (1976) in the context of changes in the woodland structure (e.g., *Fagus sylvatica* and *Pinus sylvestris* as important sylvigenic drivers). In addition, the elevated trace element contents and a concomitant increase in the Mg content recorded in the Suwałki Lakeland water basins are typical of lakes with catchments in morainic areas. The PCA conducted by Bojakowska and Gliwicz (2012) for NE Poland suggested this was a geogenic factor.

The PC3 axis, which explained 9.5% of the total variance, was positively correlated with the Mn and Ca contents, a negative correlation being seen with those of sulphur and zinc (Table 4). Therefore, PC3 may be taken as informing on changes in redox conditions prevailing during the Gostyń sediment accumulation. Positive values of PC3 appear in the geochemical zones GZ III-1 and GZ III-2, i.e., when the sedimentary basin experienced subaerial sedentation of moss peat, featuring elevated contents of Mn and Ca (Fig. 5). At the same time, the Fe/Mn ratio in those layers were the lowest (Fig. 6), indicating a domination of oxidising conditions. Negative values of PC3 were observed in the geochemical zone GZ II and in the middle part of GZ V (Fig. 7), where the total sulphur contents were elevated (Fig. 6). High sulphur contents are primarily associated with anaerobic decomposition of organic remains, usually mediated by anaerobic bacteria. Some of the hydrogen sulphide pool formed then reacts with trace metal compounds, which induces precipitation of authigenic sulphur minerals, primarily framboid forms of pyrite (Sawłowicz 1993,

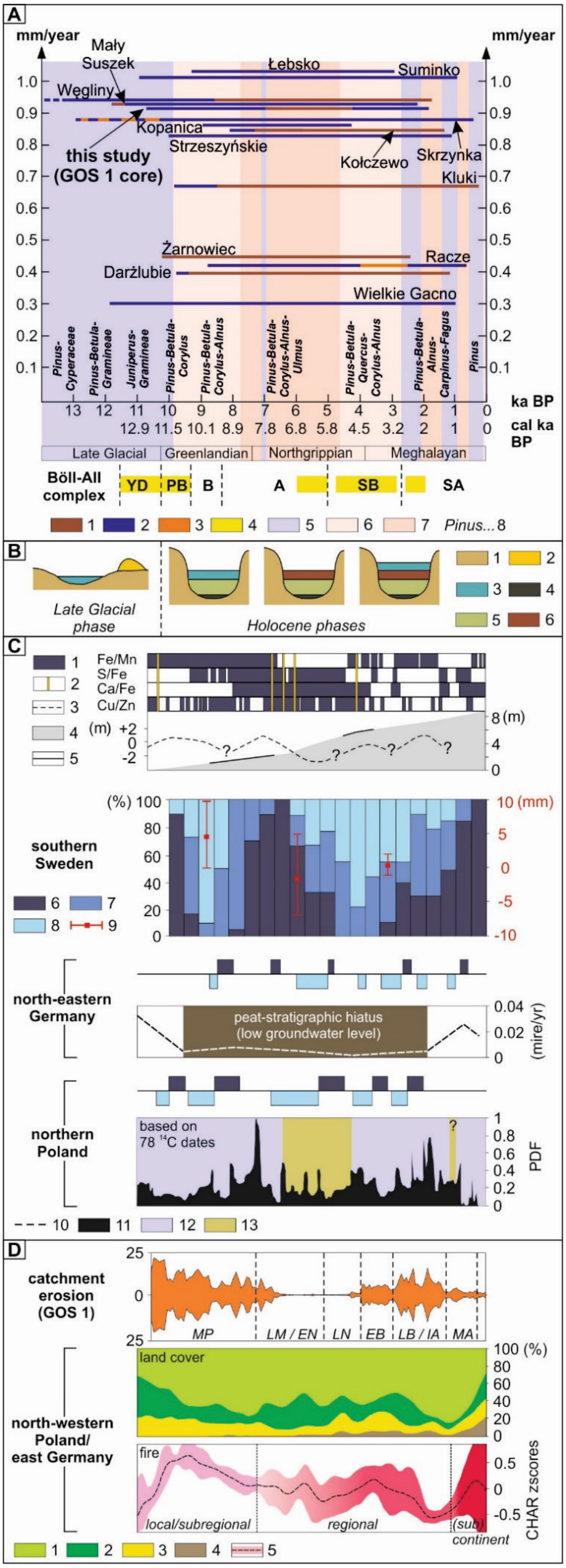

Fig. 8. Palaeo-environmental changes in Gostyń Lake reconstructed from geochemical data (core GOS 1)

A. Average rate of biogenic sediment accumulation (mm/yr) in Gostyń Lake against other lakes and peatlands in north-western Poland (based on Latałowa 1982, 1992; Żurek 1986, 1987; Miotk-Szpiganowicz 1992; Apolinarska *et al.* 2012; Jurochnik, Nalepka 2013; Pędziszewska *et al.* 2015; Staszak-Piekarska, Rzodkiewicz 2015; Pleskot *et al.* 2018; Sobkowiak-Tabaka *et al.*, 2020), the time scale of Late Glacial and Holocene after Starkel *et al.* (2013) and Walker *et al.* (2018); climate periodisation after Tolksdorf, Kaiser (2012); regional pollen assemblage zones after Miotk-Szpiganowicz (1992), Jurochnik, Nalepka (2013), Okuniewska-Nowaczyk, Sobkowiak-Tabaka (2014), Malkiewicz (2017); periods of aeolian activity resulting from climate change and anthropogenic effects after Kozarski *et al.* (1969)

1 – peat deposit; 2 – lake sediments (organic, mineral or calcareous gyttja); 3 – mineral sediment; 4 – natural and anthropogenic aeolian activity; 5 – cooling; 6 – modern temperature as reference; 7 – warming, 8 – regional pollen assemblage zones

B. Main Late Glacial and Holocene phases of Gostyń Lake evolution

1 – moraine bedrock; 2 – dunes near Barlinek and Gorzów Wielkopolski; 3 – lake water; 4 – silt; 5 – gyttja; 6 – sedge-moss peat

C. Gostyń Lake (core GOS 1) redox conditions against the backdrop of Holocene hydroclimatic conditions as inferred from multiproxy analyses for Central Europe (after Ralska-Jasiewiczowa 1989; Harisson *et al.* 1993; Couwenberg *et al.* 2001; Janke 2004; Michczyńska *et al.* 2013)

1 – redox ratios above the median for core GOS 1; 2 – boundary of biogenic deposits in core GOS 1; 3 – water level changes in Lake Gościąż; 4 – total biogenic sediment thickness in core GOS 1; 5 – periods of negative Fe-mineral matter correlation in core GOS 1; 6 – high level; 7 – intermediate level; 8 – low level; 9 – changes in annual precipitation and evapotranspiration anomaly for 3ka, 6ka and 9 ka BP; 10 – bog formation; 11 – probability density function (PDF) for peat samples above limnic sediments; 12 – limnic deposit (C/N ratio about 10); 13 – telmatic deposit (C/N ratio above 15)

D. Changes in catchment erosion as inferred from Na+K+Mg/Ca ratio in core GOS 1 against the backdrop of sub-regional land cover and Holocene fire activity after Dietze *et al.* (2018)

1 – arboreal; 2 – Scots pine; 3 – open land; 4 – human activity; archaeological periods: MP – Mesolithic (LM, late Mesolithic), EN/LN – early/late Neolithic, BA – Bronze Age, IA – Iron Age; MA, Medieval

2000) as well as zinc and copper sulphides (Cieśla, Marciniak 1982; Bojakowska, Sokołowska 1997; Migaszewski, Gałuszka 2007). As shown by Enters *et al*. (2010) for sediments of Sacrower See in NE Germany, incorporation of Mn into authigenic carbonates can be an important factor controlling the sediment chemical composition and, in conjunction with the removal of dissolved Fe^{2+}, leads to a reduction in the Fe/Mn ratio. In addition, the associated changes in geochemical indicators such as the Na/K and Mg/Ca ratios, interpreted as indicating the dominant type of denudation, may result from natural climate changes as well as from the presence of advantageous physical and chemical components in the parent rock making up the lake's catchment, ultimately leading to leaching and acidification of the soil cover.

The PC4 axis, which explained 7.3% of the total variance, was most strongly positively correlated with sulphur (Table 4), which may suggest the presence of strongly reducing conditions. The positive PC4 values occurred in the geochemical zones GZ I-1 and GZ II (Fig. 7). According to Rydelek (2005), the contribution of sulphur to biogenic accumulation in the basin is governed mainly by the location of the water table, which controls the accumulation conditions and organic matter decomposition. Also key for the reconstruction of redox conditions using stratigraphic variability in the S concentration is the detrital input resulting from substitution of the catchment-derived Fe and Mn in calcite (Eusterhues *et al.* 2005). As a result, pyrite precipitation in Gostyń Lake could have proceeded in two ways: syngenetically, i.e., during prolonged periods of anoxia, or diagenetically, under fairly aerobic conditions.

Gostyń Lake evolution phases against the background of major natural processes changes and human impact

The major stages in the Gostyń Lake evolution, reconstructed from geochemical data, are illustrated in Fig. 8. The uppermost panel (Fig. 8A) shows average biogenic sediment accumulation rates at selected sites (lakes and peatlands) in NW Poland. In many cases (e.g., Kołczewo, Kluki, Węgliny), Holocene peatlands developed as a result of aquatic areas becoming terrestrialised. Holocene environmental changes at other sites were reconstructed from lacustrine sediments (e.g., Wielkie Gacno, Suminko), and less frequently from such sediments intercalated by mineral deposits (e.g., Lake Racze on Wolin Island).

In the first phase of Gostyń Lake's evolution, during the Late Glacial and the onset of the Holocene, the water level began to rise (Fig. 8B). The lacustrine sediment accumulation rate, estimated at 0.41 mm/yr (Fig. 4) occurred during distinctly elevated values of redox indicators (Fig. 8C). The sediment chemical composition data evidence a close relationship between the iron concentration and the concentration of mineral matter or the catchment erosion index along most of the GOS 1 profile. As a result, the stratigraphic variability of the Fe/Mn ratio could have resulted, in part, from the intensity of denudation processes in the catchment, and to a lesser extent from the redox conditions, as pointed out earlier by, *inter alia*, Tribovillard *et al.* (2006), Borówka (2007) and Żarczyński *et al.* (2019). In the Gostyń sediments, two Holocene sections (the entire Greenlandian and the end of the Northgrippian) constitute exceptions in this regard and correspond to a generally high water level in Gościąż Lake (Fig. 8C). The high values of the catchment erosion index recorded at the initial phase of the Gostyń Lake evolution are a regional characteristic that has been reported for numerous sites in the Polish Lowland, for example from the lakes Woryty (Pawlikowski *et al.* 1982), Gościąż (Łącka *et al.* 1998), Ostrowite (Kowalewski *et al.* 2006) and Skrzynka (Apolinarska *et al.* 2012).

Analysis of geochemical data of the Gostyń sediments being deposited during the middle (Northgrippian) and final (Meghalayan) stages of the Holocene, i.e., since about 8,000 b2k, allows it to be contended that the onset of the Northgrippian was accompanied by a distinct change in the sediment lithology, testifying to a gradual shallowing of the lake and it becoming a peat bog. The termination of the lacustrine phase coincided, however, with an increase in the sediment accumulation rate to 1.68 mm/yr at the initial stage of the peat bog formation (Fig. 4). A sediment accumulation rate of a similar order of magnitude was documented by Kowalewski (2014) for heavily hydrated peat in the central part of the fossil Bór Bagienny Lake basin in the Tuchola Forest. The change was primarily climate-driven. At that time, after the 8,200-BP event, the air temperature was gradually increasing to peak about 7,000 b2k (Heikkila, Seppa 2010; Edvardsson *et al.* 2016). At the same time, Western Pomerania was experiencing maturation of forest ecosystems, the photophilous trees being replaced by much more environmentally demanding deciduous ones (Madeja 2012; Bloom 2015), which must have resulted in increasing evapotranspiration and ultimately in the groundwater level being lowered. The evapotranspiration-regime-controlled Gostyń Lake, situated on a morainic upland and filling a drainless depression, was no longer fed by subsurface water, which led to its gradual drying out; eventually, about 7,650 b2k, it changed into a peat bog. The most legible record of the biogenic accumulation basin changing from aquatic to terrestrial is found in the C/N ratio. During a period from about 7,300 to 5,100 b2k, the C/N ratio is observed to have increased from 14 to 26. Subsequently, within 5,100–4,600 b2k, the ratio dropped to 10–12. According to Meyers (1994), these are values typical of terrestrial plants, the autochthonous lacustrine organic matter typically showing relatively low C/N ratios (usually below 10).

The period discussed was characterised by a distinct increase in the number of lakes with a low water level in southern Sweden (Harisson *et al.* 1993), a low groundwater level in north-eastern Germany (Couwenberg *et al.* 2001; Janke 2004), and the longest-lasting Holocene low water level phase in lakes of northern Poland (Ralska-Jasiewiczowa 1989), with a concurrent increase in the number of sites showing a change in biogenic sedimentation from limnic to peatland (Michczyńska *et al.* 2013) (Fig. 8C). The profile reflected in core GOS 1 showed it initially to be a low, sedge-type, peat bog, grading – as of about 6,850 b2k – into a transitional, moss-type bog (Table 3) fed mainly by precipitation and periodically by the supply of surface or subsurface hydrocarbon-rich water. Such conditions were amenable to calcium carbonate precipitation in warm and CO_2-depleted peat bog water. An average Ca content in moss peat (GZ III-1 and GZ III-2) of about 8–13 mg/g d.w. (Fig. 5) shows that without palaeobotanical data it is difficult to conclude whether the peat bog was ombrogenic or transient. Ombrogenic peat bogs usually show a much lower average Ca content, up to as little as 2 mg/g (Borówka 1992; Słowiński *et al.* 2016). However, the small sedimentary basin of Gostyń Lake, situated at the time within a multi-species deciduous or mixed woodland, suggests that some of the calcium present may have been derived from decomposition of leaves, usually Ca-rich – particularly in the *Quercetum mixtum* associations – blown into the peat bog by the wind (Rodin, Bazylević 1965; Fortescue 1980).

Towards the termination of the moss peat sedentation (GZ III-2), i.e., since about 5,450 b2k (3450 BC), the deposit's geochemical properties underwent a distinct change expressed primarily as increasing contents of lithophile (Na, K, Mg, Fe) and trace elements (Cu, Zn, Pb), with a concurrent decline in the concentration of organic matter and contents of biogenic elements (Figs 5, 6). The sediment lithology changed as well, the change evidencing the peat bog inundation and the sedimentation basin turning limnic. The higher contents of lithophile elements attest to mobilisation of mechanical denudation processes, as confirmed also by the erosion indicator (Na+K+Mg/Ca) and the Mg/Ca ratio (Fig. 6). These data allow it to be presumed that the Gostyń Lake catchment experienced a substantial change in the type of vegetation, enhancing mechanical denudation. Most likely, the upland area in the immediate vicinity of the lake became partly deforested, which led to reduced evapotranspiration, a renewal of subsurface water resources and an increased water level in the lake. The cause of those environmental changes should most likely be sought in intensified human impact, as documented – on the regional scale – by Dietze *et al.* (2018). The archaeological and palaeo-ecological data collected from Racze Lake (Bloom 2015), not particularly far from Gostyń, showed the environmental changes discussed to have coincided with the expanding of the FBC communities. However, results of surveys carried out within the framework of the AZP showed the closest settlements to be present and fairly abundant in Dziedzice village only, about 5 km to the NW of Gostyń, a single settlement being identified near Osina village, 2.5 km ENE of the lake (Fig. 2). Nevertheless, the timing of a distinct increase in the mechanical denudation in both Racze Lake (Bloom 2015) and Gostyń Lake was similar, i.e., about 5,500 b2k. An increased supply of allochthonous geochemical components at that time was observed also by Tobolski (1987) in the Kluki peat bog deposits and Sobkowiak-Tabaka *et al.* (2020) in the Kopanica peat bog.

The geochemical data show a more distinct intensification of mechanical denudation in the Gostyń Lake catchment to have begun at about 4,650 b2k (2650 BC), i.e., still during the FBC prevalence in Pomerania (Jankowska 1980, 1990, 2005), and to continue until 3,250 b2k (1250 BC), i.e., until the middle Bronze Age. The biogenic deposits from that period showed a three-fold increase in the contents of Cu, Zn and Pb. An accelerated circulation of elements in numerous lakes was explained by developing settlements and catchment deforestation coupled with the use of copper products and mineral dyes (Cieśla, Stupnicka 1980; Hildebrandt-Radke *et al.* 2011; Owsianny *et al.* 2011; Forysiak *et al.* 2012). However, Woszczyk and Spychalski (2013) demonstrated that the metals mentioned occur in the sediments in various forms (exchangeable, acid-extractable, reducible, oxidisable, and residual) which, in addition, could have been altered quantitatively during the Holocene. The authors mentioned are of the opinion that the three distinct shifts in the total content of trace elements and their total content in chemical fractions of the Lake Sarbsko sediment were caused by, *inter alia*, changes in sediment lithology and human impact.

The next, rapid increase in mechanical denudation intensity is typical of the geochemical zone GZ IV-2 spanning the period of 3,250–1,450 b2k (1250 BC–550 AD). This is the time when the Lusatian Culture developed, expanded and dwindled, followed by the occupation of the Pre-Roman Period and the Roman Period as well as the Migration Period peoples. Although no archaeological site that could be dated to that period was identified in the direct Gostyń Lake catchment, there are many such sites in the environs (Fig. 2), although most of them lack a detailed chronology and have not been excavated. Much better archaeological evidence pertains to the Bronze Age settlements in the neighbouring, western part of the Myślibórz Lakeland (Wesołowski 1996; Kot 2013). The municipalities of Myślibórz and Nowogródek Pomorski alone feature, based on the AZP data and results of excavations, 14 Lusatian Culture settlements dated to the Late Bronze and the Early Iron Ages (Kot 2013). As shown by Kot (2013), numerous (more than 200) Lusatian Culture sites, dated both to the Bronze Age and the Early Iron Age (the Hallstatt Period) are located primarily on slopes and margins of small valleys, while settlements outside valleys, particularly on upland plateaus, are much rarer. Such settlements were usually located on exposed areas in the vicinity of lakes, streams and current wetlands, but very seldom on the bottom of a valley (Kot 2013). It follows then that the recently glaciated area of the Myślibórz Lakeland was fairly attractive to the Lusatian Culture settlers, and the low number of well-documented archaeological sites in its eastern part (the environs of Barlinek) may result from the dearth of studies in the area. Results of geochemical research on Gostyń Lake indicate a substantial effect of Bronze Age and Iron Age settlers on the catchment ecosystem and are firmly embedded in the picture of the human signature and effects of man's economic activities in western Poland (Fig. 8D).

The period from the Early Middle Ages until present is reflected in the geochemical zone GZ V (1450–0 b2k; 550–2000 AD). The two first components providing information on growing human impact after a periodic decline during the Migration Period demonstrate its increasing importance. This is evident primarily in increased contents of trace metals (Cu, Zn and Pb), and periodically – particularly since the 14th century AD – also of lithophile elements (K, Mg and Fe) as well as Ca. The elevated content of calcium, as well as the Ca/Mg and Na/K ratios, may be indicative of a periodic increase in the importance of soil leaching in the Gostyń Lake catchment. On the other hand, the passive supply of calcium together with the lithophile elements that result from intensive soil erosion associated with the prevailing agricultural practices cannot be ruled out. This may be suggested by the escarpments resulting from ploughing that occur around the western, southern and eastern shores of the lake. The archaeological evidence shows early-medieval settlements to be present in the direct vicinity of the north-eastern shores (Fig. 3).

According to the site catchment analysis (*cf* Kobyliński 1986) assumptions, the zone of intensively used areas near Gostyń Lake could extend to a maximum of 1 km from the settlements. In this case, the mires related to small lake basins (near Barlinek) and the river (near Dziedzice) favoured the development of hydrogenic soils and could potentially provide higher yields in garden cultivation. The small distances between prehistoric settlements found in other regions of the Polish Lowland are associated with areas of high geodiversity (Pelisiak 1991; Kittel 2012).

An important role in shaping the intensity of Late Glacial and Holocene evolution of the slopes of the Gostyń Lake was played by the geological surface structure, relative height not exceeding 10 m and average slopes not exceeding 1°. However, the spatial differentiation of the surface runoff on till need not have translated into higher erosion intensity, which results from their greater erosion resistance. This is evidenced by the stratigraphic variability of the erosion rate calculated for the GOS 1 core. This problem requires further research, especially in the context of the morphodynamics of the young-glacial relief dependent not only on the lithology of the sediments that build the catchment area but also on the transformations of the soil cover (Stach 2003). These changes are highly related to human activity, which is reflected in the physicochemical properties of deposits filling biogenic accumulation basins (Borówka 1992; Karasiewicz *et al.* 2014b). An exceptional role in the lithological and geochemical record of palaeo-environmental changes can be played by evaporation basins, the functioning of which is related to surface retention possibilities, climatic conditions and the drainage deficit of the river network.

Conclusions

The results of the geochemical analyses for biogenic deposits in Gostyń Lake point to highly dynamic environmental changes in the area from the end of the Late Glacial until today. Principal Components Analysis (PCA) identified four major geochemical variable groupings. The changes concerned the water level, as recorded by the Fe/Mn, Ca/Fe, S/Fe and Cu/Zn ratios; organic matter accumulation milieu (limnic and telmatic); and catchment erosion intensity, reflected by the Na+K+Mg/Ca ratio. In the first two cases, the processes and sedimentation conditions recorded resulted from natural Holocene hydroclimatic conditions and are in agreement with evidence reported from other Central European lakes. It must be emphasised, however, that geochemical indicators of changes in redox conditions in the near-bottom water layers of the lakes should be interpreted with due consideration of local geochemical background as well as the geological and lithological set-up of the catchment. Analyses of lithophile element contents evidence highly dynamic denudation processes in the Gostyń Lake catchment during the Late Glacial, at the onset of the Holocene, and since the Northgrippian/Meghalayan. The causes should be sought in changes in the vegetation cover and land-use practices in Western Pomerania, which have been documented palynologically at numerous sites elsewhere in the western part of Poland and the eastern part of Germany. The chemical data collected reflect a close association between climate change and terrain relief types preferred by early settlers.

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