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LATE GLACIAL PALAEOENVIRONMENTAL CHANGES IN THE SOUTHERN PART OF THE HOLY CROSS MOUNTAINS BASED ON THE "BIAŁE ŁUGI" PEATLAND RECORD

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Abstract

This paper presents the Late Glacial stage of the development of the Białe Ługi peatland in the southern Holy Cross Mountains, based on a comprehensive palaeoenvironmental data. A complex analysis of palynology, Cladocera, sedimentology, geochemistry and ^{14}C dating were used. Organic deposition was initiated during the Oldest Dryas. The sedimentary record of the aquatic and terrestrial ecosystems reflects considerable difference between cooler (Oldest, Older and Younger Dryas) and warmer phases (Bølling and Allerød). Periods of intensified interaction between aeolian processes and peatland are related to stages of disappearing vegetation and changes in aquatic invertebrate communities. We therefore suggest that peatlands were created as a result of local lithological-structural, tectonic, hydrogeological and morphological conditions, and the peatland development rate was largely influenced by changing climatic conditions, which determined local vegetation development, intensity of denudation processes and water level changes. The results validate significance of selection and use of several methods, as well as value of biogenic deposits from the Białe Ługi peatland as archives of past climate change in the Małopolska Upland. Relatively stable water conditions and uninterrupted biogenic sedimentation in the Late Glacial that were provided by the geological structure and relief suggest the studied peatland is a leading one in the region.

Key words: biogenic deposits, chronostratigraphy, Małopolska Upland, multiproxy analysis, palaeoclimate

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INTRODUCTION

The Late Glacial (Late Vistulian) contains distinct periods of climate fluctuations. In paleobotanical, as well as paleopedological or palaeogeographic studies, there are the warmer Bølling/Allerød and the cooler Oldest, Older and Younger Dryas phases. Such variations of climate conditions are well recorded by the Greenland ice core NGRIP

$\delta^{18}O$ curves (Rasmussen *et al.*, 2014). The chronostratigraphy of the Late Glacial in land areas is based on various geoarchives, but the most commonly studied are biogenic accumulation reservoirs, such as lakes and peatlands (Charman, 2002). The post-glacial accumulation of biogenic formations was initiated by climatic change and local hydrogeological conditions. The reasons of development of biogenic accumulation basins in Poland include thermokarst (Goździk and Konecka-Betley, 1992; Forysiak *et al.*, 2010), aeolian processes and fluvial activity (Żurek, 1995; Forysiak, 2012) or landslides (Margielewski, 2014). Attention has been drawn many times to reconstruction of environmental changes that is afforded by the individual palaeo-ecological analyses of biogenic sediments (Dzieduszyńska and Forysiak, 2015; Pawłowski *et al.*, 2016a).

The peatlands of the Holy Cross Mountains and neighbouring areas have been studied intensively by Piwocki (1971) and Żurek (2001). According to the Polish Wetlands Geographic Information System (2006), there are 47 peat deposits within the Holy Cross Mountains, 23% of which are mesotrophic or oligotrophic peat deposits. The wetlands in this area developed in the bottoms of river valleys (floodplains and floodplain terraces, abandoned channels), in spring basins, in dry extensions, periodically drained denudational-erosional valleys, and in deflation basins accompanying dunes (Żurek, 2001). However, only a few of the peatlands in the Holy Cross Mountains began to develop at the end of the last glaciation in Poland (Szczepanek, 1961).

Here we present a case study of the Białe Ługi peatland, as an example of a detailed history of a watershed area in central Poland during the Late Glacial. The Białe Ługi peatland stands out as the largest peatland in the region. From previous studies it appears that well preserved peat deposits span the interval from the Bølling chronozone to the Middle Holocene (Żurek, 2001; Żurek *et al.*, 2014).

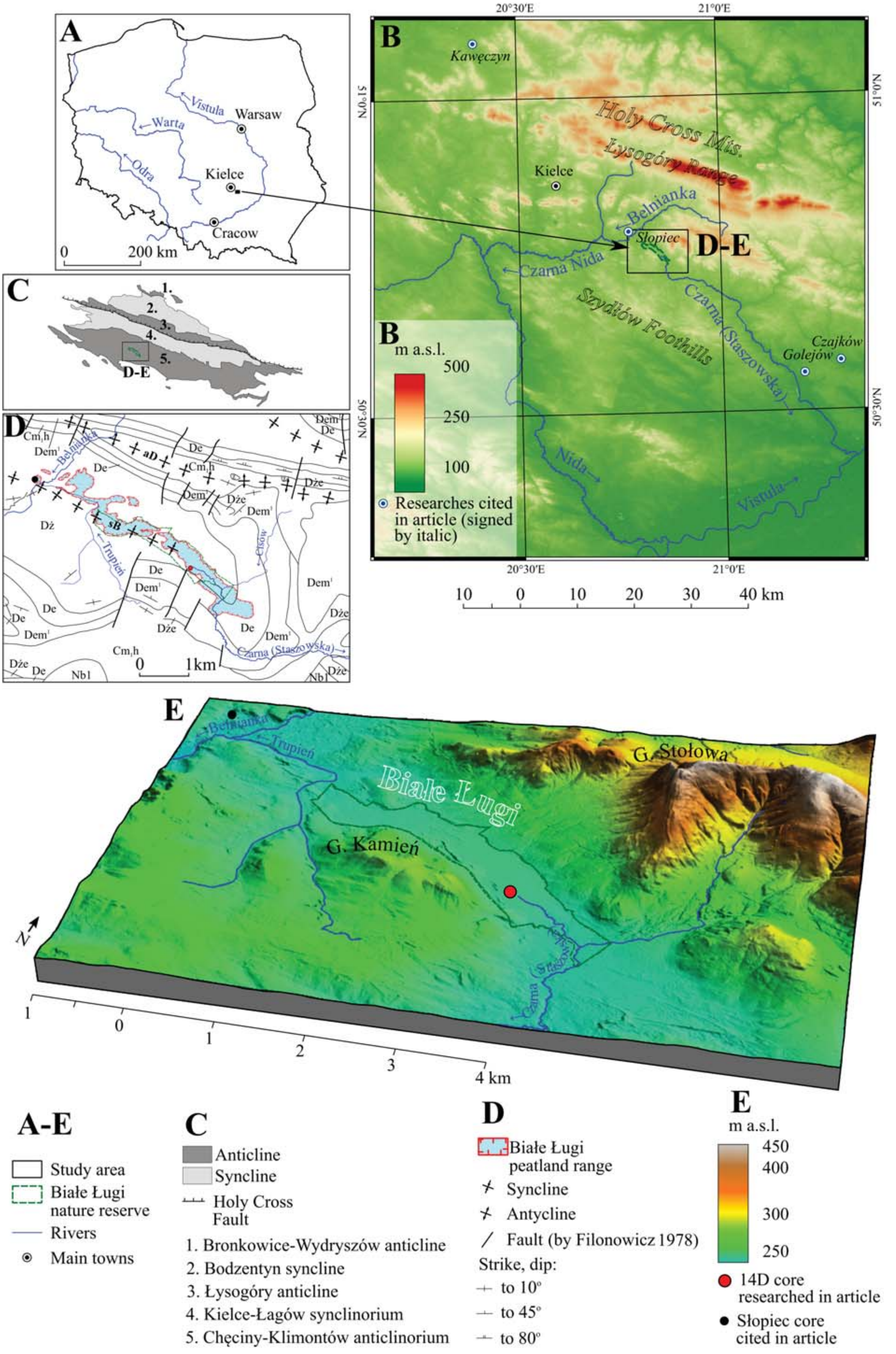
The multidisciplinary studies presented here, which incorporate palaeobiological, geochemical, and radiometric data, investigate the interrelationships between climatic and local changes of denudation processes for the purpose of reconstructing the biogenic accumulation reservoir. The main aim of this research is a palaeoenvironmental reconstruction of the stages in the Late Glacial history of the southern part of the Holy Cross Mountains based on the peat deposits taken from the Białe Ługi peatland. The specific objectives of this paper are: (1) to recognize how major hydroclimatic changes in the Late Glacial influenced paleolake and peatland development in large tectonic genesis valley; (2) show the relations of lithological, geochemical, radiocarbon, palynology and Cladocera data; (3) to estimate usefulness of palaecological research, especially tendencies to local degradation of permafrost, periods of aeolian activity, p with high water level and dry phases.

STUDY SITE

We investigated the Białe Ługi peatland, situated in southern Poland *ca.* 30 km from Kielce (Fig. 1A, B). This peatland is located in the Kielce (southern) tectono-stratigraphic unit (Czarnowski, 1919; Pożaryski, 1978) of the Palaeozoic core of the Holy Cross Mountains (Kielce Fold Zone by Konon, 2008), within the Chęciny-Klimontów anticlinorium (Czarnocki, 1975) (Fig. 1C). The peatland is located between the Daleszyckie and Cisowski Ranges and Szczecniańskie Hills. The ranges are built of the Lower Cambrian rocks (sandstones, siltstones, conglomerates) (Jurkiewicz, 2001). However, in the central part of the area, there are calcareous rocks of the Middle Devonian, i.e. limestones and dolomites, and Stromatoporoidean–Anthozoan limestones (Filonowicz, 1976; Jurkiewicz, 2001) (Fig. 1D). They build the eastern, folded part of the Bolechowice syncline (Filonowicz, 1976), which is a fragment of a larger tectonic unit – the Gałęzice-Bolechowice syncline (Konon, 2008). The axis of the Bolechowice syncline stretches from Bolechowice through Kowala to the vicinity of Cisowa (Filonowicz 1976), where it is elevated in the Strojnów-Wzdół transverse elevation zone (Gołębiówka) (Kowalczewski, 1963). According to Kowalski (2001), the Białe Ługi Valley fossil depression is a fragment of a system of grabens (Fig. 1D), a formation of which in the Miocene and Pliocene should be associated with the Carpathians' period of tectogenesis and subsidence which continues within them up to this day, with varying intensity (Jurkiewicz, 2001). Lithological and structural aspect of development of this depression, sediment compaction conditions and conditions favourable to development of peatlands in older interglacial periods (e.g. the Mazovian) (Ludwikowska-Kędzia and Nita, 2002; Nita, 2009) , is worthy of attention as a consequence, among others, of reproduction of karst features in the Quaternary formations (Ludwikowska-Kędzia, 2016).

The Białe Ługi peatland, which is 500–700 m wide and about 10 km long, formed within a longitudinal, large-radius structural palaeo-depression with NW–SE axis (Fig. 1E). It is located between the Cisowski Range, with its highest point Góra Stołowa (403.6 m a.s.l.) enclosing the peatland to the north and north-east, and the Szczecniański Range, with the Kamień mountain (302.2 m a.s.l.) limiting it to the south-west. The palaeo-depression in which the peatland lies, clearly stretches to the northwest and to the southeast, where river valleys developed in the depression sedimentary infilling – those of the Belnianka and the Czarna Staszowska rivers, respectively. The surface of the Białe Ługi peatland lies in two distinctly opposite directions that correspond to the axis of the structural depression (Fig. 1D). It is divided in the middle by a complex of dunes and aeolian sand fields (at 257.2 m a.s.l.). The sediments filling this palaeo-depression are polygenic and of various age (Kowalski, 2001).

Fig. 1. Location maps and cores. A – Location of the study area in Poland; → B – Location of the analysed peatland and other sites citied in this study in Holy Cross Mountain and surrounding areas; C – Location of the study area at the background of the tectonic-faced units in Holy Cross Mountain; D – Location of the analysed peatland in the southern part of Holy Cross Mountain; E – Location of Białe Ługi peatland at the background of the DEM model.


A
Vistula
Warta
Odra
Warsaw
Kielce
Cracow
0 200 km
B
20°30'E
21°0'E
51°0'N
50°30'N
Kawęczyn
Holy Cross Mts.
Łysogóry Range
Kielce
Belnianka
Słopiec
D-E
Czarna Nida
Szydłów Foothills
Czarna (Staszowska)
Czajków
Golejów
Nida
Vistula
m a.s.l.
500
250
100
Researches cited in article (signed by italic)
10 0 10 20 30 40 km
C
1.
2.
3.
4.
5.
D-E
D
Cm,h
Dem
De
aD
sB
Dż
Dże
Trupień
Cisów
Czarna (Staszowska)
Nb1
0 1km
E
Belnianka
Trupień
Białe Ługi
G. Stołowa
G. Kamień
Czarna Staszowska
N
1 0 1 2 3 4 km
A-E
Study area
Białe Ługi nature reserve
Rivers
Main towns
C
Anticline
Syncline
Holy Cross Fault
1. Bronkowice-Wydryszów anticline
2. Bodzentyn syncline
3. Łysogóry anticline
4. Kielce-Łagów synclinorium
5. Chęciny-Klimontów anticlinorium
D
Białe Ługi peatland range
Syncline
Antycline
Fault (by Filonowicz 1978)
Strike, dip:
to 10°
to 45°
to 80°
E
m a.s.l.
450
400
300
250
14D core researched in article
Słopiec core cited in article

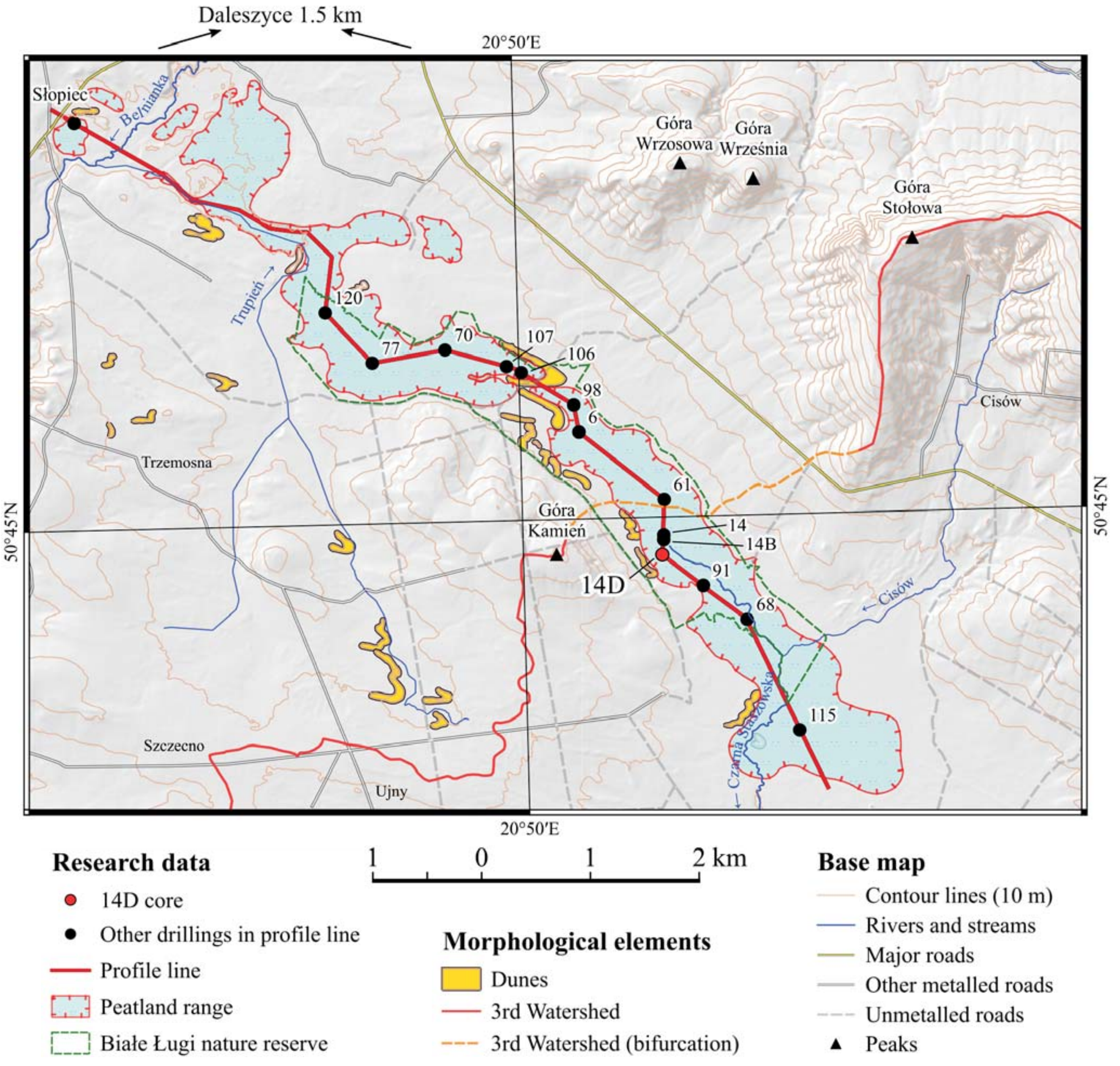


Fig. 2. Location of the Białe Ługi peatland and BŁ 14D core at the background examined site and their surroundings (after LiDAR data).

The link between Białe Ługi becoming a peatland and the activation of aeolian processes conditioned by neotectonic mobility of the substrate has been emphasised by Jaśkowski (1999). According to this author, the flow in the valley that functioned until the Late Glacial was obstructed by complex dune formations. The valley walls forced the outflow in two opposite directions. This was when shallow water basin formed (after the formation of the dunes enclosing the depression) and organic sediments began to accumulate in them. There was neither evidence of aeolian deposits interfingering with organic deposits, nor of the aeolian sands interbedding with peat. The onset of the aeolian processes was supported, according to Jaśkowski (1999), by the valley bottom being raised. This caused acceleration in permafrost degradation and relative lowering of the groundwater level, which in turn promoted drying of the sediment and development of aeolian processes. The presented hypothesis needs to be documented. From the high-resolution DEM, it appears that there is a dune complex in the vicinity of the peatland. The two largest parabolic dunes divide the peatland in two (between boreholes 106/107 and 98). The first has an area of 6 ha and is 1,500 m long (measured along the axis of its arc). The second covers 3.5 ha and is 974 m long. In the south-western part of the peatland, there is a belt of smaller dunes. Individual dunes raise 8–11 m above the peatland ground level.

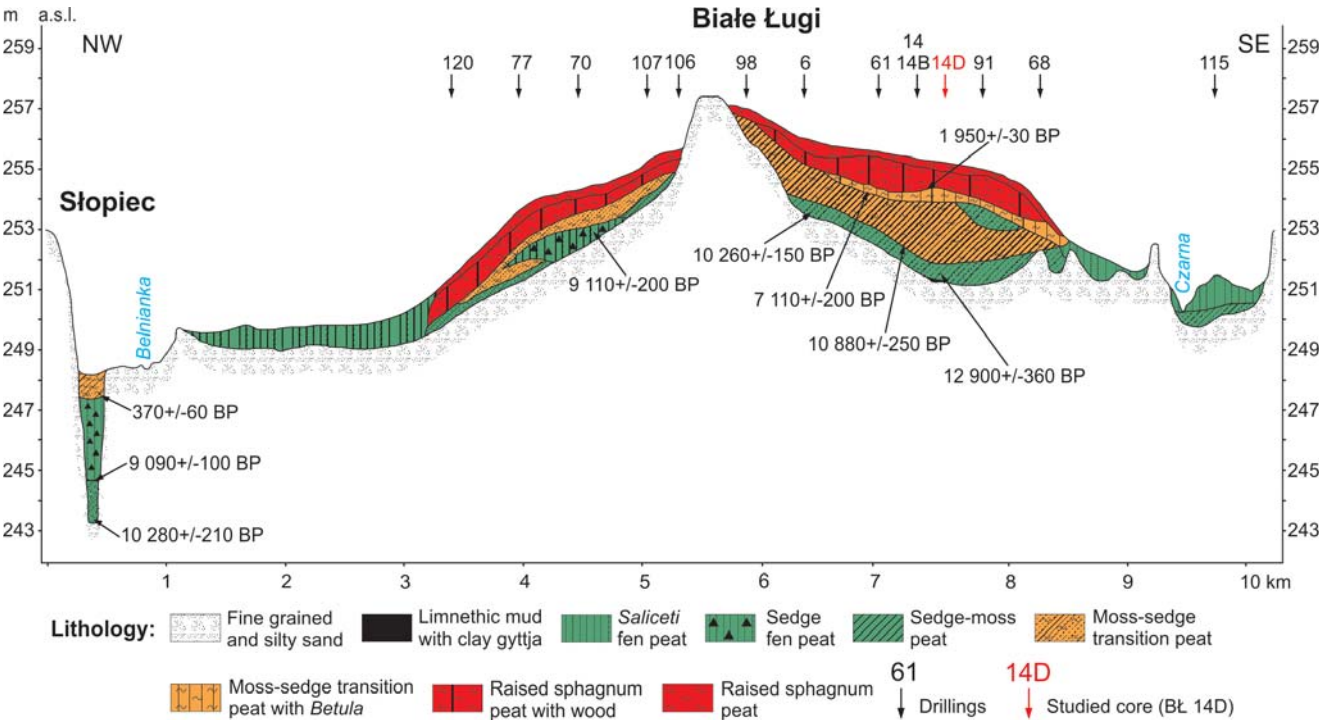


Fig. 3. Geological cross-sections by Białe Ługi and Słopiec peatlands (Szczepanek 1982; Żurek *et al.*, 2014, changed).

METHODS

A set of methods was applied for examining biogenic and mineral sediments and land relief:

(1) **Field work and GIS analysis.** Two 4-m peat monoliths were collected with a manual Instorf sampler (Russian corer) with cores of 5 cm in diameter and 0.5 m long. Furthermore, geological drillings (to depth of *ca.* 3.0–3.5 m, with a distance between drillings of *ca.* 10–20 m) were made in this part of the Białe Ługi peatland. Logs BŁ 14D (50º44’59”N, 20º51’03”E, altitude of 258.1 m a.s.l.) were collected from the south-eastern part of the peatland (Fig. 2), where the thickest biogenic deposits were found (Fig. 3). In this palaeogeographical study, we focus on the bottom part (1.57 m) of the biogenic sediments section.

Spatial data developed by the Polish geodetic and cartographic survey were used to elaborate the cartographic part of the paper. An orthophotomap of the study area was used as source data, as well as an Airborne Laser Scanner point cloud made by LiDAR (Light Detection And Ranging) technology. Based on the ALS, a high-resolution Digital Elevation Model was made. Additionally, to develop the elevation data for the wider area (Fig. 1B), an open-source DEM from SRTM (Shuttle Radar Topographic Mission) was used. The study used also data and sketches prepared during field works.

(2) **Geochemical and sedimentological analyses.** The macroscopic lithofacies analysis of organic sequences of deposits was done using the non-genetic Troels-Smith method for description of deposits (Troels-Smith, 1955). These results (Table 1) are compared with macrofossil data, previously presented by Żurek (2001).

Biogenic sediments were dried at 105ºC and homogenised in an agate mortar. The organic matter (OM) content was determined by loss on ignition (LOI) at 550ºC, following the protocol described by Heiri et *al.* (2001). The ash for 76 samples was analysed for concentrations of Na, K, Ca, Mg, Fe, Mn, Cu, Zn and Pb (Fig. 4A), using atomic absorption spectrometry (AAS). The grain size compositions of the ash samples remaining after loss on ignition analysis was determined using the Mastersizer 3000 laser

Table 1. Lithologic description of the Białe Ługi limnethic and peat sediments (core BŁ 14D).

Depth (m)	Units	Lithology description in this study	Troels-Smith formula after Żurek (2001) changed
2.18–3.58	U3	Weakly decomposed sedge-moss peat	nig.2, strf.2, sicc. 2, elas.0, lim.0, Th^{2}3, Tb^{2}1
3.58–3.60	U1	Limnethic mud	nig.2, strf.0, sicc. 2, lim.1, As1, Ag1, Dg1, Sh1
3.60–3.68	U2	Clay gyttja	nig.2+, strf.1, sicc.2, elas.0, lim.0, Ld^{3}2, As2, Lc+
3.68–3.75	U1	Limnethic mud	nig.2, strf.0, sicc. 2, lim.1, As1, Ag1, Dg1, Sh1
3.75–3.80	Bedrock	Fine-grained and silty sand	nig. 1, strf.0, sicc.3, elas.0, lim.1 Gmin4

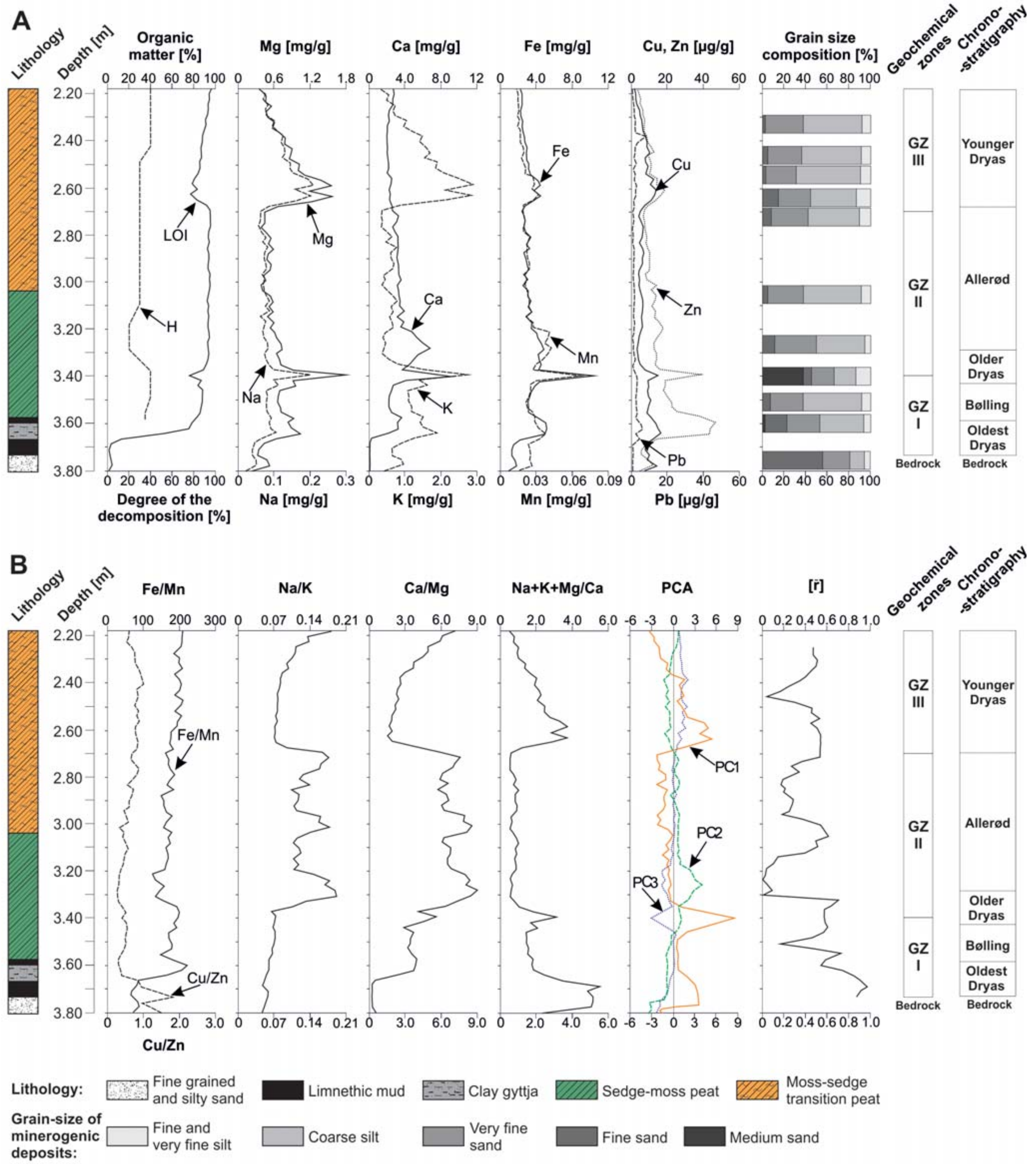


Fig. 4. Chemical characteristics of the Białe Ługi biogenic sediments. A – Geochemistry and grain size composition of the deposits from BŁ 14D core; B – Vertical differences in the selected geochemical parameters and PCA of the deposits from BŁ 14D core. GZ – geochemical zones.

particle size analyser with a Hydro MU dispersion unit (Malvern). The textural features were evaluated for 11 samples, using Folk and Word (1957) coefficients. The relationship between the mean grain size and the sorting index (the "co-ordinate system") follows Mycielska-Dowgiałło and Ludwikowska-Kędzia (2011).

(3) **Radiocarbon dating and age-depth model.** In order to construct a chronology for the investigated core, twelve bulk samples were dated using a radiocarbon method (liquid scintillation counting technique). All samples were processed according to the standard procedure (Tudyka *et al.*, 2015).

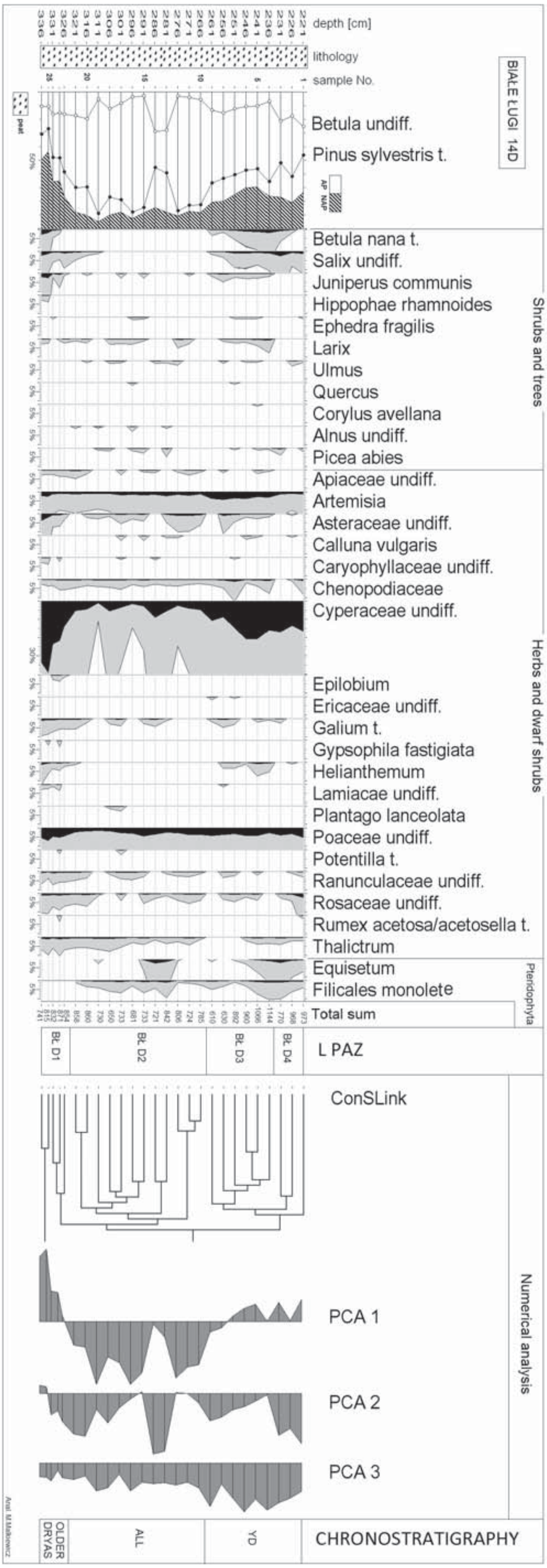


Fig. 5. Pollen percentage diagram from the Białe Ługi peatland. AP – arboreal and shrub pollen; NAP – non-arboreal pollen (herbaceous pollen). L PAZ – local pollen assemblage zones. For lithology and other explanations see Fig. 4.

(4) **Pollen and Cladocera analyzes.** 1cm^3 samples were collected for palynological and Cladocera analyses. The same number of samples (30) was counted in both analyses. For palynological analysis, chemical preparation of samples from BŁ 14D core was followed by the modified Erdtman's acetolysis method. At least 600 pollen grains of terrestrial plants were counted. The pollen percentages were calculated based on the total count of trees and shrubs, as well as of herbs. Spore plants were excluded from the total sum. The local pollen assemblage zones (L PAZ) were distinguished with a characteristic content of sporomorphs in the individual section, thus illustrating process of changes occurring in a vegetation cover (Berglund and Ralska-Jasiewiczowa, 1986).

Cladocera analysis was processed according to the standard procedure (Frey, 1986). A minimum of 200 cladoceran remains per sample was identified, except for four samples (3.60; 3.20; 2.70 and 2.30 m) in which the concentration was slightly lower. Taxonomy of cladoceran remains in this paper follows that presented by Szeroczyńska and Sarmaja-Korjonen (2007). Ecological preferences of cladoceran taxa were determined based on Bjerring *et al.* (2009). The cladoceran assemblage zones (L CAZ) were distinguished based on the composition and abundance of species.

(5) **Numerical analysis.** A stratigraphically constrained cluster analysis was applied to distinguish geochemical zones (GZ), local palynological zones (L PAZ) and local Cladocera zones (L CAZ). Proportions of lithogeochemical compounds were used to classify deposits and to reconstruct environmental changes in the biogenic accumulation reservoir and in the catchment (ratios of: Fe/Mn, Na/K, Cu/Zn, Ca/Mg and Na+K+Mg/Ca). The correlation between results of a geochemical analysis [$\hat{r}$] was also calculated. This indicator was first calculated by Walanus (2000) for a data series on chemical composition of biogenic sediments from the Gościąż Lake. For the Białe Ługi peatland, the index [$\hat{r}$] was calculated for 10 variables (geochemical characteristics) using a moving average. The averaging "window" was eight samples wide, which is about 10% of the entire total depth of the section (Fig. 4B).

We used Principal Component Analysis (PCA) in order to determine a variability of factors controlling the chemical composition of deposits. Standardised values of contents of organic matter and nine macro- and microelements were used as input variables. The calculations were run using PAST version 2.17c software (Hammer *et al.*, 2001). POLPAL software was used to make the percentage pollen and cladoceran diagram (Nalepka and Walanus, 2003). The results of pollen (Fig. 5) and Cladocera (Fig. 6) analyses are shown on a percentage diagrams and their simplified description is presented (Table 2).

Table 2. Detailed descriptions of geochemical (GZ), local pollen assemblage (L PAZ) and local cladoceran assemblages (L CAZ) zones from the Białe Ługi deposits (core BŁ 14D).

Zone	Depth (m)	Description
Geochemical		
GZ III	2.70–2.18	Represents the phase of mineral-organic deposition (organic matter range between 77.6 and 96.3%) in reducing conditions (average values of Fe/Mn ratio>200) and in the environment characterized by increased mechanical denudation (decreased Na/K and Ca/Mg ratios).
GZ II	3.75–3.40	Represents of sedentation of autochtonous rock-forming matter of autogenic origin (increase of the organic matter to 95.8%) and an associated change of type of denudation processes (decreased of lithophilic elements increased Ca/Mg ratio from 2.84 to 8.93). However, with respect to geochemical composition, the bottom part of this deposits are characterized by a distinct enrichment in mineral matter, Na, K, Mg, Ca, Fe and Mn suggest the considerable input of allochtonous matter from the catchment.
GZ I	3.40–2.70	Represents the accumulation of limnethic mud and clay gyttja with a gradual increase in organic matter from 1.47 to 88.6%. This zone is the record of a dynamic changes in the concentrations of all elements. The maximum content of lithophilic elements at the level of 3.60–3.54 m, correlated with mineral matter and an associated change of redox conditions (increase Fe/Mn ration from 79–220.6).
Palynology		
BŁ D4 NAP–*Pinus*	2.31–2.21	Decrease of NAP up to 26.6%; decrease of Cyperaceae undiff. (up to 16.9%) and *Artemisia* (up to 1.3%); disappearance of *Juniperus communis* and *Betula nana t.*; increase of *Pinus sylvestris t.* (up to 62%) and *Betula* undiff. (up to 25.3%). PCA analysis shows characteristic variability features which confirm the creation of the separate L PAZ.
BŁ D3 *Cyperaceae–Artemisia*	2.61–2.36	Increase of NAP pollen up to 30.5%; increase of Cyperaceae unidff. (up to 20.8%) and *Artemisia* (up to 4.1%);decrease of *Betula* undiff. (on average to 14.9%) and *Pinus sylvestris t.* (on average to 57.2%); a maximum for *Salix* undiff. (2.5%); and *Betula nana t.* (1.8%); low values for *Juniperus communis* (0.2–0.4%); appearance of *Helianthemum*; increase of *Equisetum* and *Filicales monolete*.
BŁ D2 *Pinus–Betula*	3.21–2.66	Increase of *Pinus sylvestris t.* – maximally to 89% and *Betula* undiff. up to 29.1%; single grains of *Juniperus communis* and *Ephedra fragilis*; increase of *Larix*; decrease of non-arboreal plants to less than 20%; decrease of *Cyperaceae* undiff., *Poaceae* undiff. and *Artemisia*; disappearance of *Hippophaë rhamnoides*, *Betula nana t., Helianthemum*, *Gypsophila fastigiata;* decrease of *Filicales monolete* and *Equisetum.* ConSLink and PCA confirm the similarity of spectra and their affiliation to the same L PAZ.
BŁ D1 NAP-*B. nana–Juniperus*	3.36–3.26	High percentages of non-arboreal plants (NAP 23.8–56.2%); increase of *Salix* undiff. (up to 2.2%), *Betula nana t.* (up to 2.7%), *Juniperus communis* (up to 2.5%); high *Pinus sylvestris t.* (up to 58.5%) and low *Betula* undiff. (up to 16.4%); very high amount a of Cyperaceae undiff. (up to 39.3%); single grains of *Larix* and *Ephedra fragilis*; presence of heliophytes: *Hippophaë rhamnoides*, *Artemisia*, *Helianthemum*, *Gypsophila fastigiata*; increase of *Filicales monolete* and *Equisetum*.
Cladocera		
L CAZ IIIb	2.60–2.30	Relatively high frequency and diversity of cladoceran fauna, which exceeds 8 taxa and 580 specimens per cm^3 of deposit. Fossils of *Alona affinis*, *Alona rectangula*, *Acroperus harpae*, *Alona guttata*, and *Chydorus sphaericus* are quite abundant. Macrophyte-associated *Eurycercus lamellatus* and macrophyte/sediment-associated taxa such as *Alonella exigua* appears for the first time At the end of subzone, oligotrophic taxa *Alonella excisa* are dominated.
L CAZ IIIa	2.90–2.60	Include only fossils such as *Ch. sphaericus, A. affinis,* and *A. guttata*. At the end only fossils of *Ch. sphaericus* appear. The frequency and diversity of cladoceran fauna not exceeding 3 taxa and 260 specimens per cm^3 of deposit.
L CAZ III	2.90–2.30	Fluctuations in both the frequency and diversity of the Cladocera. For convenience, this was divided into 2 subzones.
L CAZ II	3.20–3.10	Macrophyte/sediment-associated taxa, such as *Ch. sphaericus* and *A. affinis*, are quite abundant. Macrophyte-associated *Al. excisa*, and macrophyte/sediment-associated such as *A. guttata* var. *tuberculata* appears for the first time. The frequency and diversity of cladoceran fauna not exceeding 4 taxa and 320 specimens per cm^3 of deposit.
L CAZ Ib	3.60–3.40	An increase in frequency and diversity of cladoceran fauna, exceeding 4 taxa and over 700 specimens of cladoceran fossils per cm^3 of deposit. The most frequent were *Ch. sphaericus* and *A. affinis*. Fossils of *A. guttata* and *A. rectangula* were also significant and occur somewhat later.
L CAZ Ia	3.70–3.60	Include only fossils of macrophyte-associated taxa such as *Ac. harpae* and macrophyte/sediment-associated such as *A. affinis*, and *Ch. sphaericus*. The frequency and diversity of cladoceran fauna were very low and not exceeding 3 taxa and 200 specimens per cm^3 of deposit.
L CAZ I	3.70–3.40	The frequency and diversity of cladoceran fauna fluctuated. This zone was therefore divided into 2 subzones.

Table 3. Results of radiocarbon dating of Białe Ługi peatland (BŁ 14D core, all bulk samples).

Sample	Lab code	Radiocarbon age (BP)	Modelled age 68.2% intervals (cal BP)	Modelled age 95.4% intervals (cal BP)
BŁ 1.26 m	GdS-3890	6,590 ± 90	7,750 – 7,610 (68.2%)	7,830 – 7,570 (95.4%)
BŁ 1.55–1.60 m	GdS-3854	7,250 ± 75	8,330 – 8,250 (41.9%) 8,190 – 8,120 (26.3%)	8,360 – 8,080 (95.4%)
BŁ 1.82–1.87 m	GdS-3857	8,820 ± 105	9,880 – 9,550 (68.2%)	10,110– 9,540 (95.4%)
BŁ 2.05–2.10 m	GdS-3858	9,390 ± 120	10,720–10,400 (68.2%)	10,870–10,840 (0.5%) 10,830–10,240 (94.9%)
BŁ 2.40–2.45 m	GdS-3868	9,170 ± 110	10,490–10,450 (8.1%) 10,440–10,230 (60.1%)	10,670–10,160 (95.4%)
BŁ 2.70–2.75 m	GdS-3863	10,880 ± 170	12,990–12,690 (68.2%)	13,120–12,540 (95.4%)
BŁ 3.10–3.15 m	GdS-3859	11,820 ± 130	13,760–13,530 (68.2%)	13,290–13,430 (95.4%)
BŁ 3.38–3.43 m	GdS-3862	12,300 ± 120	14,440–14,040 (68.2%)	14730–13890 (95.4%)
BŁ 3.48–3.52 m	GdS-3873	11,160 ± 110	13,130–12,870 (68.2%)	13,240–12,760 (95.4%)
BŁ 3.52–3.56 m	GdS-3892	11,115 ± 85	13,080–12,870 (68.2%)	13,130–12,760 (95.4%)

RESULTS

All applied proxies allowed regional vegetation change, along with local palaeohydrology and denudation processes, to be reconstructed to reflect climatic and environmental changes (Szczepanek, 1961, 1971, 1982; Latałowa, 2004). Based on the variability of particular proxies, such as geochemistry (Fig. 4), palynology (Fig. 5), Cladocera (Fig. 6) and radiocarbon age (Table 3 and Fig. 7), a few main stages of the development and features of the natural environment in the southern Holy Cross Mountains during the Late Glacial were determined (Fig. 8).

Lithology

The sequence of mineral and biogenic sediments includes three main lithostratigraphic units, coded chronologically 1–3 (Table 1). The bottom section of the BŁ 14D core (from 3.75 to 3.58 m) was dominated by mineral-organic sediments, mainly limnethic mud (U1), interrupted by an 8-cm-thick intercalation of clay gyttja (U2) between 3.68 and 3.60 m. The remaining Late Glacial part of the section (3.60–2.18 m) was represented by weakly decomposed (H 30%) sedge-moss peat (U3). Two layers of biogenic sediments with an admixture of mineral matter (above 25%) were observed at depths of 3.40–3.34 m and 2.70–2.54 m. They are overlain by a weakly decomposed Holocene series of raised Sphagnum peat with wood and raised Sphagnum peat (Żurek, 2001; Żurek *et al.*, 2014).

Geochemical and sedimentological data

Three geochemical zones were distinguished (Fig. 4) and are described (Table 2). Bottom sediments are dominated by organic matter, with admixture of mineral matter <47%. A significant enrichment of mineral matter was accompanied by increased contents of lithophilic elements (Na, K and Mg) and Fe, Mn and Cu. By contrast, the organic-rich layer (LOI above 93%) was deposited in reduced supply of almost all elements, except Zn. The first component (PC1) explains ~49% of the total variation and is connected to denudation processes, because it is positively correlated with concentration of K, Na and Mg, and negatively with organic matter. The second component (PC2) explains 26% of the total variance. It is positively correlated with Ca and organic matter content. The third component (PC3), which explains only <13% of the total variance, is negatively correlated with concentrations of Mn and Fe. This component reaches its maximum within the zone GZ3, along with the highest mineral matter content.

Pollen and Cladocera data

In the pollen diagram that was obtained, four Local Pollen Assemblage Zones (L PAZ) were distinguished, which were given the designation BŁ D and numbered from the bottom to the top (Fig. 5). The local pollen assemblage zones (L PAZ) were correlated with stratigraphic units of the Late Glacial (Mangerud *et al.*, 1974; Litt *et al.*, 2001). The most ancient local pollen assemblage zones, BŁ D1 NAP-*Betula nana–Juniperus*, correspond to a cooler period of the Older Dryas. The second, BŁ D2 *Pinus–Betula* represents a warming of the Allerød and the next (BŁ D3 Cyperaceae–*Artemisia* and BŁ D4 NAP-*Pinus*) – the Younger Dryas. The first component (PC1), which explains 61% of the total variance, is positively correlated with the *Pinus sylvestris* only. The second component (PC2) explains 18% of the total variance. It is positively correlated with *Betula undiff.* and negatively correlated mainly with the *Juniperus communis*, *Betula nana t.* and *Asteraceae undiff.* The third component (PC3) explains 6% only of the total variation and is connected to a cold and dry climate, because it is positively correlated with the concentration of *Betula nana t.* and *Salix undiff.*

The study sediments contain nine, only littoral, macrophyte- and macrophyte/sediment-associated Cladocera species, belonging to a single family of Chydoridae (Fig. 6).

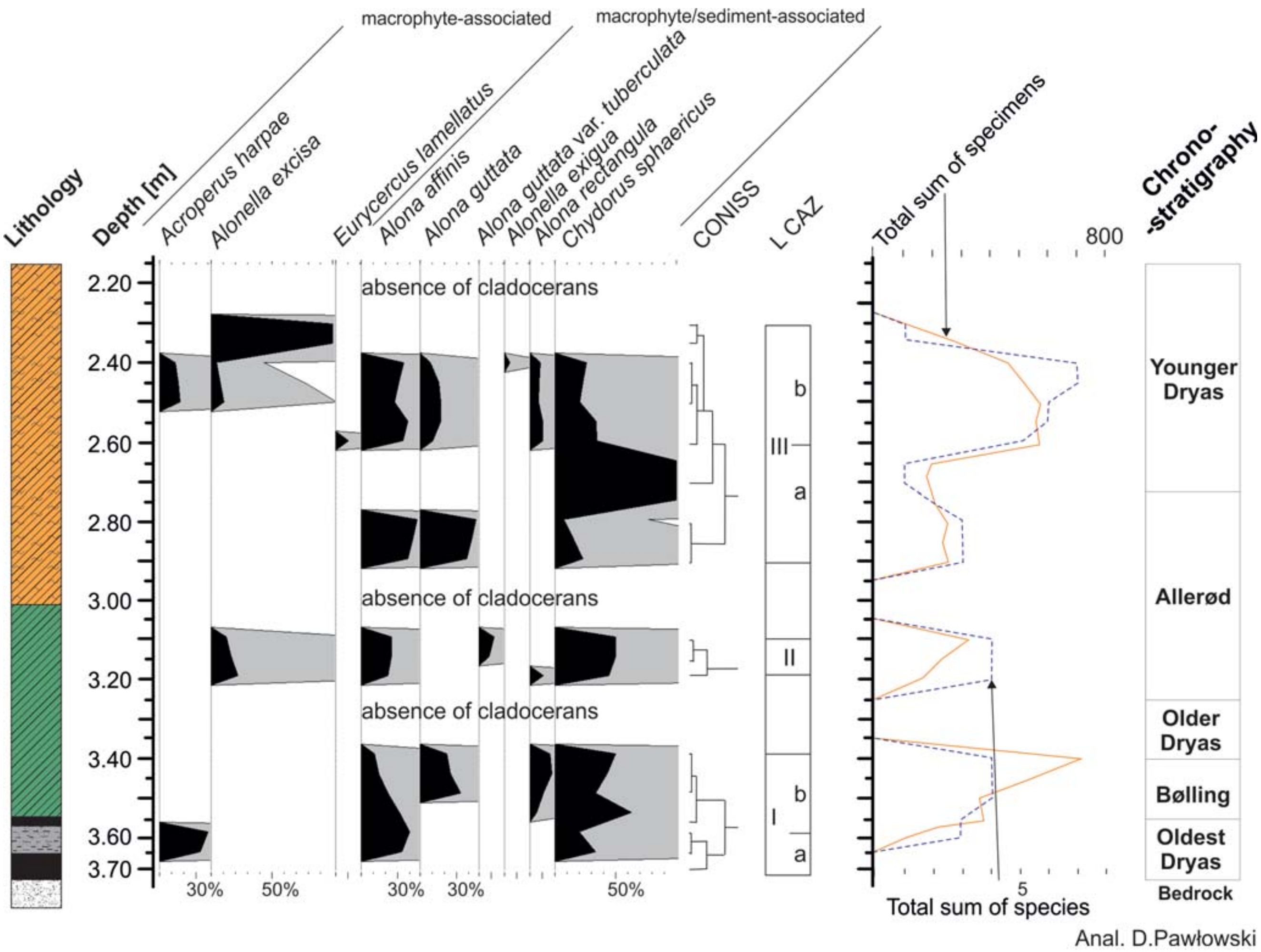


Fig. 6. Cladocera percentage diagram from the Białe Ługi peatland. L CAZ – local Cladocera assemblage zones. For lithology and other explanations see Fig. 4.

Most of them (i.e. *Alona affinis*, *Chydorus sphaericus* and *Acroperus harpae*) could exist in a cold climate. Three Local Cladoceran Assemblage Zones (L CAZ) were distinguished (Table 2). Frequency of Cladocera is relatively low and ranges from 100 to 720 individuals per cm^3. No cladoceran remains occur at 3.35–3.25 m, 3.05–2.95 m or 2.25–2.18 m.

Core chronology

In order to obtain a chronology of the core we constructed an age-depth model based on radiocarbon ages using the OxCal v4.2.4. (Bronk Ramsey and Lee, 2013) calibration program (Fig. 7). It was constructed using the *PSequence* command with the k parameter value equal to 0.5. Moreover, in the model, using the *Interval* command, we included additional information (mainly geochemical) about possible changes in accumulation rate or possible hiatuses. One important problem in the construction of the age-depth model was caused by an inversion of the age of the two lowermost samples (depths: 3.48–3.52 m and 3.52–3.56 m), in comparison with those located above them. These two samples came from adjacent layers and are statistically identical, so we may assume that they in fact refer to the same object (point on a time scale), which may be some kind of intrusion. We therefore decided to reject these dates from the model and estimate the age of the sediment for depths below 3.43 m based on the model calculated for depths above 3.43 m. Because of the aim of our research the age-depth model was limited to the Late Glacial and the beginning of Holocene only (depth in the core below 1.2 m).

The total agreement index of the model constructed as described above amounts to 57%, which is a little below the suggested critical value of 60%, but may be accepted. If we remove from the model one date only – for the sample at depth 2.40–2.45 m – the total agreement index exceeds 60% and reaches 78%. This shows that the dates and assumptions accepted during construction of the model are correct. The obtained chronology of the core is presented (Fig. 7). According to our chronology, there is a period when an increase in mineral fraction and hiatus or considerable slowing of accumulation rate, are noted in the

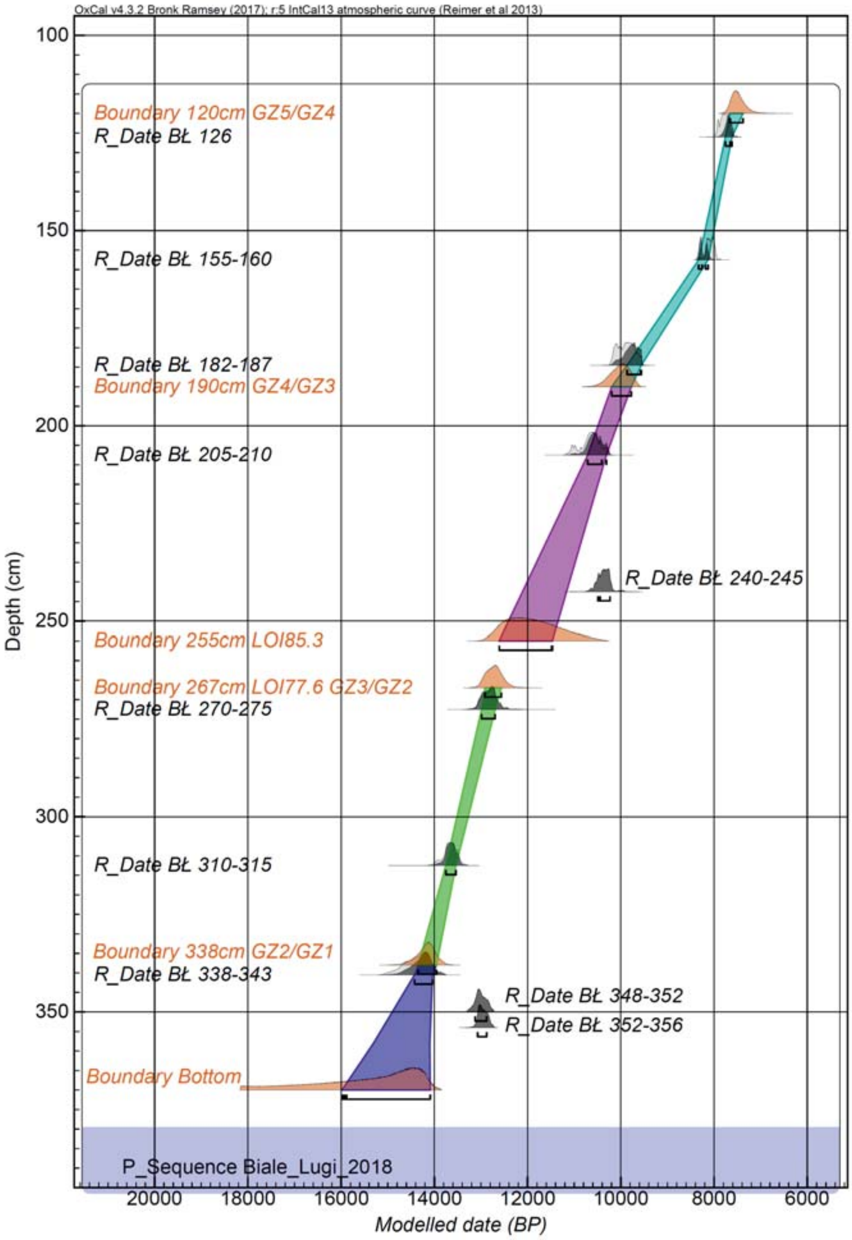


Fig. 7. Chronology of the BŁ 14D core from Białe Ługi peatland.

sediments. This period can be assigned to the onset of the Younger Dryas (depth: 2.67–2.54 m). A significant – but very short in depth (and in time) – increase in mineral fraction at depth of *ca.* 3.35 m is dated to about 14,000 cal BP, so must indicate the Older Dryas.

DISCUSSION

The phase of shaping of the peatland basin (age: >14,300 ± 700 cal BP)

A lack of pollen material in this part of the section makes it impossible to compare the vegetation history of the Białe Ługi peatland in the southern Holy Cross Mountains with neighbouring regions. The bottom of the deposits in the BŁ 14D section, which had a high but variable mineral matter content and was correlated with the Oldest Dryas, was probably the stage when the oldest aeolian sediment series formed in a dune zone to the west, adjacent to the peatland (see Fig. 2). It may be associated with a period of aeolian processes distinguished by Jaśkowski (1996) for dunes in the Czaplów region, in the upper Belnianka valley.

The sedimentation of limnethic mud (U1), which basically forms in conditions of permanent flooding at a bottom of a shallow water basin or in periodically flooded and fairly well oxygenated areas (cf. Okruszko, 1969), and clay gyttja (U2) were accompanied with a distinctly increased supply of Na, K and Mg (Fig. 4). These components are considered to be indicators of the intensity of denudation processes in a basin (Engstrom and Wright, 1984). On the one hand, these metals are products of chemical weathering of aluminosilicates, but their supply may also be passive, accompanying mineral matter. Maximum values of the catchment erosion rate (Na+K+Mg/Ca about 6) are accompanied by a high Fe/Mn ratio (above 220) that indicates redox conditions in the basin. Inorganic admixtures of these deposits represent very coarse, poorly sorted silt. The grain size index according to Folk and Ward (1957) has a median (Mz) of 4.9 phi, and sorting (σ) is 1.4 phi. High dynamics of environmental changes are also confirmed by the course of PCA curves and the highest values of the [r̂] indicator. These changes were probably connected with deepening of a local basin due to onset of thermokarstic processes and slow subsidence of bedrock (Goździk and Konecka-Betley, 1992). Under such conditions the mobilisation of dissolved organic matter is possible (Zawiska *et al.*, 2015). These processes may be partly responsible for probable disturbances that caused age inversion of the two lowermost samples in the examined core.

This time was characterised by a low frequency of cladocerans (L CAZ Ia; Fig. 6). Only 3 taxa (*Chydorus sphaericus*, *Alona affinis*, *Acroperus harpae*) exist that can tolerate a broad range of ecological conditions. These species are tolerant to cold water, but can also indicate supply of fine-grained sediments to a shallow pond, as was also noted in sediments of palaeo-oxbow lakes and peatlands in central Poland (Pawłowski, 2017). Therefore, it is also possible that a hydrological regime during the cooling of the Oldest Dryas, together with a decrease in landscape openness and an increase in mechanical denudation in the catchment of the Białe Ługi basin, could have favoured floods. The suggestion regarding flooding is confirmed in accumulation of non-cation facies (silt, sandy and organic silt, and peat) in the bottom of the Napęków-Smyków section of the Belnianka river valley, which persists throughout the Late Glacial (Ludwikowska-Kędzia, 2000).

Peatland development during the Bølling and Allerød complex
(age: 14,300 ± 700 cal BP – 12,700 ± 200 cal BP)

Pollen spectra from a depth of 3.36–3.26 m (zone BŁ D1 NAP-*B. nana*–*Juniperus* L PAZ) present a time when the area around the study site was dominated by shrub communities with *Betula nana*, *Salix*, *Hippophaë rhamnoides*, *Juniperus* and herbaceous plants, mainly Cyperaceae and Poaceae (Fig. 5). Regular occurrence of heliophytes *Artemisia*, *Gypsophila fastigiata* and *Helianthemum* confirms presence of open areas. Low percentage values of pine and birch indicate their presence at some distance from the study site. Pre-Allerød cool sediments were also recorded in the nearby sections 6A (Szczepanek, 2001) and 14B (Żurek *et al.*, 2014). In the first, the local pollen zone distinguished at the bottom of the section is not sufficiently reliable to reconstruct vegetation, and no age interpretation was undertaken. Bottom sediments of the 14B section (Żurek *et al.*, 2014) and the one being analysed (BŁ 14D) can be considered as contemporary to one another and correlated with a cool part of the Older Dryas. A development of open communities with willow, juniper *Salix, Juniperus communis* and sea-buckthorn *Hippophaë rhamnoides* in the post-glacial stratigraphic scheme has been recorded by many researchers (Wasylikowa, 1964; Jurochnik and Nalepka, 2013; Żurek *et al.*, 2014), but it has been interpreted as correlating to a diverse range of periods, from the Oldest Dryas, through the Bølling and the interstadial Bølling/Allerød complex to the Older Dryas.

A composition of flora in the pollen spectra from a depth of 3.26–2.66 m (zone BŁ D2 *Pinus–Betula* L PAZ) is typical of the younger section of the Allerød, which is referred to as the pine phase (Wasylikowa, 1964; Ralska-Jasiewiczowa *et al.*, 1998). It indicates development of forest communities – mainly pine forests, with a greater or lesser share of birch and admixture of juniper and larch spruce (Fig. 5). The presence of heliophytes such as *Artemisia*, Chenopodiaceae, Poaceae or Cyperaceae indicates also a significant role of open areas. It can be assumed that forest communities prevailing at that time were not very dense, as also confirmed by presence of juniper and larch. Birch forest, which is typical of the older phase of the Allerød (Wasylikowa, 1964; Ralska-Jasiewiczowa *et al.*, 1998), does not seem to be of much significance in the studied area. The short birch phase was captured in one among the Staszów karst sections only (Szczepanek, 1971) and in section 14B (Żurek *et al.*, 2014).

Forest development and reduction of open areas limited gradually aeolian processes and supply of mineral material and lithophilic elements to the peatland (Fig. 4A). Fe/Mn and Cu/Zn ratios, which indicate redox conditions, were constant (Fig. 4B). During this period, a number of biogenic accumulation basin formed and the accumulation rate increased in basins of various environments (Żurek, 1995). Progressive permafrost degradation caused groundwater circulation and possibility of soligenic feeding of biogenic accumulation in a basin. In the studied section BŁ 14D, beginning in the Bølling-Allerød complex, several-fold increase in Ca concentration (about 8 mg/g) and several changes in course of the PC2 curve were observed. In many sites in central and southern Poland, a decalcification of the sediments in palaeolake basins was more intensive, as reflected in lithology of sediments, i.e. clay-calcareous gyttja (Okupny *et al.*, 2013) or lacustrine chalk (Goździk and Konecka-Betley, 1992; Okupny *et al.*, 2016). However, when interpreting changes in Ca concentration in biogenic sediments, it should be borne in mind that these values depend on average $CaCO_3$ content of the rocks that form the catchment. In the case of the Białe Ługi peatland, the main source of carbonates was the Devonian carbonate complex, which sometimes occurs at the surface.

This complex is characterised by the repetitive occurrence of cladocerans (Ib, II, IIIa L CAZs; Fig. 6). Rapid increase in Cladocera frequency at the turn of L CAZ Ia

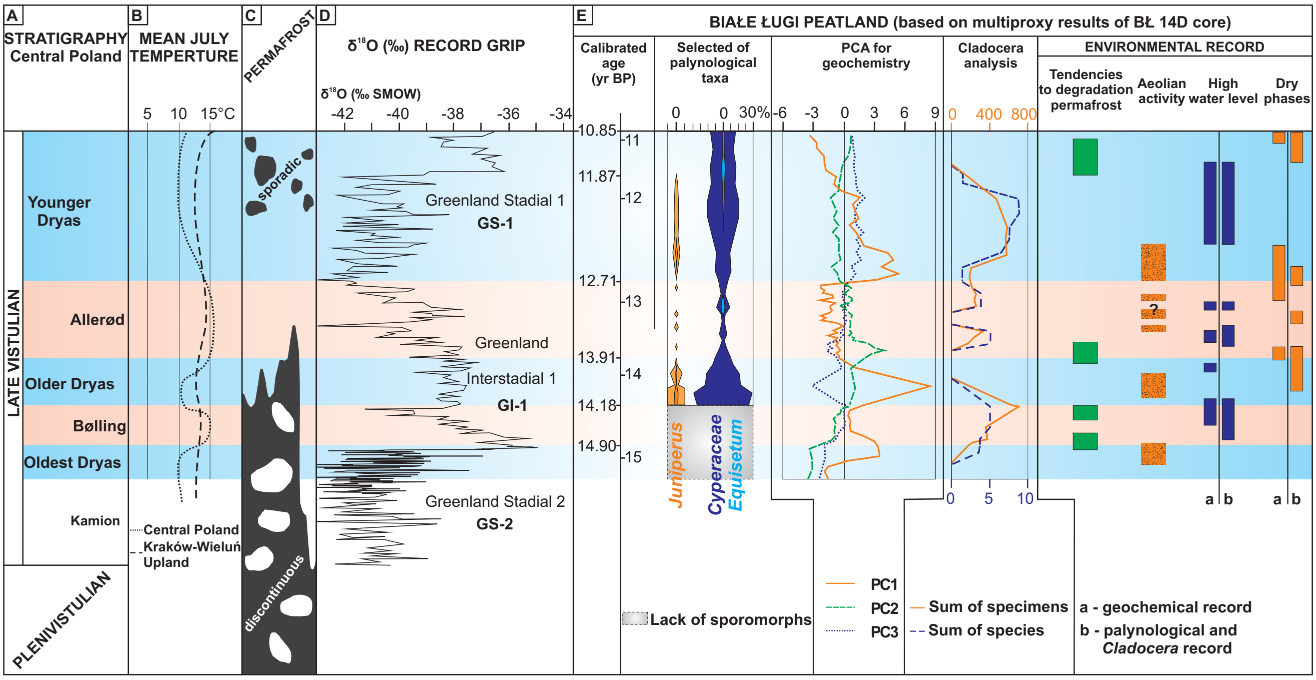


Fig. 8. Multi-proxy environmental record from Białe Ługi peatland deposits at the background features of natural environment in central and southern Poland during the Late Glacial. A – stratigraphy of Central Poland list according Dzieduszyńska (2013); B – changes of July temperature for Central Poland list according Dzieduszyńska (2013) and Kraków-Wieluń Upland (after Lorenc 2008); C – occurrence of the permafrost in the Central Poland list according Dzieduszyńska (2013); D – stratigraphy based on the Greenland ice-core record (Björck *et al.*, 1998); E – environmental record at Białe Ługi peatland (tendencies to degradation permafrost, aeolian phases, higher water level and dry phases) were recognized based on PCA for geochemistry results (a column), palynological and Cladocera data (b column).

and LCAZ Ib, especially of macrophyte-associated taxa, suggests better habitat conditions in the peatland and may indicate relatively warm and more trophic conditions. Alternatively, these changes in cladoceran frequency may reflect increase in summer water temperature, as the temperature reconstructions (July temperature estimations) from central Poland for the Bølling and Allerød varied between 12°C and 15°C (Pawłowski *et al.*, 2016b). However, at depths of 3.35–3.25 m and 3.05–2.95 m no cladoceran remains occurred. Such a situation is connected with a drop in water level, low pH of water during peatland development or an increase in delivery of mineral matter (from 5.8 to 23.8%) and lithophilic elements to the peat bog – Na (from 0.07 to 0.1 mg/g), K (from 0.38 to 2.74 mg/g) and Mg (from 0.63 to 1.8 mg/g) – as a reaction to cooling. The short-term increasing trend in PC1 indicates catchment erosion and aeolian activity (Fig. 8). Late Glacial aeolian processes have been recorded to have developed alongside lowering water levels in peatlands by geochemical research on several sites in central Poland (Forysiak *et al.*, 2013; Okupny *et al.*, 2013). For the same reason, it is possible that periods without Cladocera, or even distinct drop of sum of Cladocera species and specimens at Białe Ługi (which represent dry phases), could be also related to aeolian phases Fig. 8).

The appearance of Cladocera at depths of 3.2–3.1 m (L CAZ II), and from 2.9 m (L CAZ IIIa) suggests an increase in the water table in the peatland and a short-term improvement in habitat conditions. In this periodic, small and shallow water pool on the peatland, Cladocera are mainly represented by *Alona affinis*, *Chydorus sphaericus* and *Alona guttata* var. *tuberculata*. These taxa are abundant in temperate lakes and peatlands, and their relatively high frequency in such a shallow pool is presumably related to macrophyte density and low pH (Słowiński *et al.*, 2016); however, these changes may also result from climate-related variables such as an increase in summer temperature (Pawłowski, 2017). At the end of this period, at depth of 2.75–2.66 m, only one species of Cladocera, *Chydorus sphaericus* was noted that possesses broad ecological tolerance. Therefore, it is possible that its occurrence was associated with a drop in water level or low pH of water in a shallow pool, or an increase in aeolian processes and cooling around Białe Ługi.

Peatland during the Younger Dryas (age: 12,700 ± 200 cal BP – 11,500 ± 200 cal BP)

Pollen spectra from the depth 2.66–2.21 m (zones BŁ D3 Cyperaceae – *Artemisia* L PAZ and BŁ D4 NAP-*Pinus* L PAZ) indicate a thinning of a forest cover, accompanied by spreading of shrub and herbaceous communities typical of the Younger Dryas (Fig. 5). The percentages of *Pinus* and *Betula* are less important. *Juniperus communis*, *Salix* and *Betula nana* appear again. NAP is dominated by Cyperaceae, *Poaceae* and *Artemisia*. *Helianthemum*, *Thalictrum*, *Rosaceae* and Chenopodiaceae also occur frequently. This indicates significant insolation of plant communities. In the studied area, alongside the thinning pine forests with birch, and larch, there were also shrub communities with juniper, willows and shrubby birches, as well as open communities with a significant share of photophilous vegetation. The spruce wasn't a significant component of tree stands at this time. Its sporadic presence may result from a small distance from the Carpathians, where spruce appeared in a local forests (Latałowa*,* 2004). A similar floristic record was recorded in the 6A and 14B cores (Szczepanek, 2001; Żurek *et al*., 2014), in Słopiec (Szczepanek, 1982) and Napęków (Ludwikowska-Kędzia, 2000). In all these sites, the plant communities are distinguished by a greater share of herbaceous plants (especially heliophytes, i.e. *Artemisia*, *Helianthemum* and Chenopodiaceae) and presence of willow juniper, dwarf birch and larch.

It is assumed that the climate of the Younger Dryas period was not stable, but oscillated significantly (Lotter, 1991). Strong environmental dynamism has been recorded in, for example, Retna (the Brodnickie Lakeland), where the juniper curve has several fluctuations, with maxima above 10% separated by minima below 4.0% (Karasiewicz *et al*., 2014). In the analysed profile, such strong environmental dynamism was not observed. However, the division of the Younger Dryas into two was clearly visible. The older part was decidedly cooler, as confirmed by presence of *Betula nana*, *Juniperus communis*, *Helianthemum* and Chenopodiaceae and the greater participation of *Artemisia* and Cyperaceae. This stage surely corresponds to the period of cold and dry climate and considerable input of mineral matter from the catchment (Fig. 4). The milder climate of the upper part of Younger Dryas contributed to the partial withdrawal of heliophytes, and of dwarf birch and juniper. The development of dense vegetation cover hampered the effectiveness of surface erosion, which is reflected in reduced contents of lithophilic elements and increase in organic matter (Fig. 4A). Similar dichotomy of Younger Dryas period is observed by two remaining sections (6A and 14B) of the Białe Ługi peatland (Szczepanek, 2001; Żurek *et al*., 2014) and in nearby Słopiec (Szczepanek, 1982). Milder thermal conditions in the upper part of Younger Dryas also manifest in increased participation of pine and birch. However, in diagrams from the Czajków and Golejów sites in the Staszów karst (Szczepanek, 1971) and at Kawęczyn in the northern Holy Cross Mountains (Szczepanek, 1961) these two parts of the Younger Dryas are so short as to be indistinguishable.

The delivery of allochthonous (aeolian) mineral matter to the peatland is marked on the loss on ignition curve and in the content of elements such as K, Na and Mg. The change in the dynamics of environmental conditions, including increased aeolian activity, is confirmed by increased correlations between results of the geochemical analysis [$\hat{r}$] and the rapid increase in the PC1 curve (Fig. 4B). Positive values of the first eigenvector reflect the occurrence of products of weathering in the catchment, and document an enhanced accumulation of coarse silt with admixture of fine sand clastic material. In this period, Jaśkowski (1996) records an onset of aeolian processes in the Czaplowa area (Belnianka valley) in the Holy Cross Mountains and around Gnieździska (Czarna Mieczyńska valley). However, in the neighbouring Belnianka valley, the Younger Dryas was marked by an erosive episode (Ludwikowska-Kędzia, 2000). A Fe/Mn ratio slightly higher than in the underlying sediments, and a maximum of 207, was located at *ca*. 12,300–12,100 cal BP, which is the upper part of peat. Such situation indicates reducing conditions in biogenic accumulation reservoirs and can be explained by a high groundwater level (Fig. 8).

The onset of the Younger Dryas Cladocera is represented by taxa that can exist in waters with a high density of macrophytes: *Alona affinis*, *Chydorus sphaericus*, *Alona guttata* and *Acroperus harpae* (Fig. 6). Most of them may be tolerant of cold waters. However, the frequency of Cladocera increased, and species requiring a better habitat appeared (*Alona rectangula*). This could be related to local environmental forces such as habitat modification, increase in water level (the influence of the river or a rising groundwater table in the valley), macrophyte abundance, which also leads to cascading effects, such as changes in trophic status in the system (Pawłowski *et al*., 2016b). This could also be a reaction to summers when the water was warmer – in the Younger Dryas in central and southern Poland the summer temperature decreased but ranged between 12.5°C and 17.1°C (central Poland; Pawłowski *et al*., 2015), and 13.5°C and 16°C (Kraków-Wieluń Upland, southern Poland; Lorenc, 2008). However, at the end of the L CAZ IIIb there is a distinct drop in Cladocera frequency and only one species exists – *Alonella excisa*, which is mostly tolerant of low pH. We must also mention that during the Younger Dryas, a high content of Mn (increase content from 0.01 to 0.03 mg/g), mineral matter (average content exceeds 12%) and presence of some cladocerans that tolerate flowing water and temporarily inhabit rivers and streams (e.g. *Acroperus harpae* and *Chydorus sphaericus* (*sensu lato*) may also confirm influence of floods at the Białe Ługi peatland. This interpretation is consistent with an increased water level during the Younger Dryas as postulated by Forysiak *et al*., (2013) for the Rąbień peatland and many flood-plain ecosystems in the Grabia river valley (Pawłowski *et al*., 2016a, b).

CONCLUSION

Based on analyses of chemical composition, vegetation succession and subfossil Cladocera remains from the lake and peat sediments, a diagram of the Late Glacial evolution of the Białe Ługi peatland is presented (Fig. 8).

Bottom sediments of the section BŁ 14D document development of a shallow basin with periodic water level fluctuations. Under such conditions silt sedimentation occurred, separated by a series of clayey gyttja. Age-wise, the sediments are associated with the Oldest Dryas stage. In addition, no pollen material was found in these sediments, which made it impossible to reconstruct the development of vegetation in the peatland and surrounding area. The results of the geochemical analysis of the mineral fraction indicate that deflation eroded probably local depressions, to which moderately sorted fine-grained sand was delivered. The pioneer Cladocera community could indicate a cold climate, which caused a variable supply of mineral matter to this shallow pond.

The next stage of peatland development, which is clearly recorded in chemical composition of the sedge-moss peat, is correlated with the Bølling/Allerød chronozone, an onset of which was marked by increased share of organic matter and simultaneous decrease in concentration of lithophilic elements. This is confirmed by the oldest radiocarbon date in the tested profile (GdS-3862: 12,300 ± 120 BP). During this time, communities developed in the research area: from non-forest communities with a significant share of herbaceous vegetation before the Allerød warming, to forest communities – mainly pine forests with a greater or lesser share of birch and an admixture of juniper in the Allerød. At the beginning of the Bølling/Allerød, relatively warm and more trophic conditions in a shallow peat pool were conducive to the development of macrophyte-associated Cladocera taxa. Later, these conditions changed and the cladocerans disappeared. The short-term appearance of cladocerans might be related to an episodic increase in groundwater table in the peatland and an increase in summer temperature. However, chemical composition of sediments indicates inhomogeneity of this warming, which allowed an approximately 200-year cool fluctuation to be distinguished, correlated with the 14,200–14,000 cal BP interval, i.e. the cooler period of the Older Dryas. As a result of less dense vegetation and the onset of aeolian processes, dunes were probably created in the area between the villages of Ujny and Trzemosna.

A record of the Younger Dryas cooling correlated with a very sharp drop in organic matter and a simultaneous increase in concentrations of lithophilic elements. By contrast, the organic-rich layer was a result of sedentation and a decrease in denudation processes in the vicinity of the peatland. Apart from short-term variations, the general increase in organic matter and decrease in lithophilic elements in the upper part of the profile indicates gradually decreasing intensification of aeolian activity. The flora of the discussed section indicates a thinner forest cover and spreading of shrub and herbaceous communities. It also indicates a distinct division of the Younger Dryas into two. It is supposed that the vegetation of the older part (local zone BŁ D3) was park tundra. The younger part of the Younger Dryas (local zone BŁ D4) shows a milder climate, as manifested by decreased participation of shrub and herbaceous communities. The relatively high frequency of the Cladocera community from the Younger Dryas could be related to local environmental forces or a reaction to summers when the water was warmer. However, at the end of this period there is a distinct drop in Cladocera frequency, which could be reaction to the cooling of the Younger Dryas. Nevertheless, it is possible that this cold phase was slightly warmer and wetter at the Białe Ługi peatland than in other part of Poland.

Finally, we must mention that in the Oldest Dryas and Younger Dryas the influence of swamping at the Białe Ługi peatland was also significant. The age-depth model performed for the Holocene indicates the date 11,500 cal BP and is reflected in the palaeoenvironmental results. The Białe Ługi peatland is undoubtedly unique in the region, not only because of its full record of climatic and environmental conditions for the Late Glacial, but also as an excellent record of the local morphostructural and tectonic conditions of morpho- and lithogenetic processes in the southern part Holy Cross Mountains.

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