HELDA
HELSINGIN YLIOPISTO
HELSINGFORS UNIVERSITET
UNIVERSITY OF HELSINKI

UNIVERSITY OF HELSINKI

https://helda.helsinki.fi

Changes in habitat conditions in a Late Glacial fluviogenic lake in response to climatic fluctuations (Warta River valley, central Poland)

Forysiak, Jacek

2023-01-17

Forysiak , J , Okupny , D , Obremska , M , Antczak-Orlewska , O , Plociennik , M , Pawlowski , D , Baradyn , D , Kotrys , B , Luoto , T P , Nevalainen , L & Borowka , R K 2023 , ' Changes in habitat conditions in a Late Glacial fluviogenic lake in response to climatic fluctuations (Warta River valley, central Poland) ' , Geological Quarterly , vol. 67 , no. 1 . https://doi.org/10.7306/gq.1

http://hdl.handle.net/10138/356873
https://doi.org/10.7306/gq.1672

unspecified
publishedVersion

Downloaded from Helda, University of Helsinki institutional repository.

This is an electronic reprint of the original article.

This reprint may differ from the original in pagination and typographic detail.

Please cite the original version.

Geological Quarterly, 2023, 67: 1
DOI: http://dx.doi.org/10.7306/gq.1672

Changes in habitat conditions in a Late Glacial fluviogenic lake in response to climatic fluctuations (Warta River valley, central Poland)

Jacek FORYSIAK[1], Daniel OKUPNY[2], Milena OBREMSKA[3], Olga ANTCZAK-ORLEWSKA[4, *], Mateusz PŁÓCIENNIK[5], Dominik PAWŁOWSKI[6], Daria BARADYN[5], Bartosz KOTRYS[7], Tomi P. LUOTO[8], Liisa NEVALAINEN[8] and Ryszard K. BORÓWKA[2]

1 University of Lodz, Faculty of Geographical Sciences, Department of Geology and Geomorphology, Narutowicza 88, 90-139 Łódź, Poland; ORCID: 0000-0002-0084-4436

2 University of Szczecin, Institute of Marine and Environmental Sciences, Mickiewicza 18, 70-383 Szczecin, Poland; ORCID: 0000-0002-8836-6044, 0000-0002-6998-7638

3 Institute of Geological Sciences, Polish Academy of Sciences, Research Centre in Warsaw, Twarda 51/55, 00-818 Warszawa, Poland; ORCID: 0000-0002-3465-1894

4 University of Gdańsk, Faculty of Biology, Department of Plant Ecology, Laboratory of Palaeoecology and Archaeobotany, Wita Stwosza 59, 80-308 Gdańsk, Poland; ORCID: 0000-0001-9392-623X

5 University of Lodz, Department of Invertebrate Zoology and Hydrobiology, Banacha 12/16, 90-237 Łódź, Poland; ORCID: 0000-0003-1487-6698

6 Adam Mickiewicz University, Institute of Geology, Krygowskiego 12, 61-680 Poznań, Poland; ORCID: 0000-0003-4616-6666

7 Polish Geological Institute – National Research Institute, Pomeranian Branch in Szczecin, Wieniawskiego 20, 71-130 Szczecin, Poland; ORCID: 0000-0002-2732-6970

8 University of Helsinki, Faculty of Biological and Environmental Sciences, Ecosystems and Environment Research Programme, Niemenkatu 73, 15140 Lahti, Finland; ORCID: 0000-0001-6925-3688; 0000-0001-6837-8753

Forysiak, J., Okupny, D., Obremska, M., Antczak-Orlewska, O., Płóciennik, M., Pawłowski, D., Baradyn, D., Kotrys, B., Luoto, T.P, Nevalainen, L., Borówka, R.K., 2023. Changes in habitat conditions in a Late Glacial fluviogenic lake in response to climatic fluctuations (Warta River valley, central Poland). Geological Quarterly, 67: 1, doi: 10.7306/gq.1672

Associate Editor: Wojciech Granoszewski

The Warta River valley was greatly influenced by the ice sheet of the Last Glacial Maximum (LGM). A small peatland located in the Warta drainage system is here used as a palaeoarchive of climatic and habitat changes during the Late Glacial (Weichselian). The Ługi sediment profile was investigated using multi-proxy (pollen, Chironomidae, Cladocera and geochemistry) analyses that recorded changes in a fluviogenic sedimentary depression. After the Poznań Phase (LGM), Ługi functioned as an oxbow lake that was cut off from the active river channel as a result of fluvial erosion. Since that time, the Warta River has flowed only along the section now occupied by the Jeziorsko Reservoir. Sedimentation of lacustrine deposits started at the beginning of the Late Glacial. Summer temperature reconstructions indicate cool Oldest and Younger Dryas, but no clear cooling in the Older Dryas. During the Younger Dryas the palaeolake was completely occupied by a peatland (fen), which periodically dried out during the Holocene. Investigation of this site has tracked the reaction of the habitat to climatic, hydrological and geomorphological changes throughout the Late Weichselian.

Key words: multi-proxy analysis, Late Weichselian, denudation processes, palaeoclimate, central European river.

INTRODUCTION

Fluvial systems as means of transport of water and clastic material depend on numerous environmental factors (Schumm, 1977). Development of fluvial processes may be influenced by climatic changes, and also by regional and local tectonic stability (uplift or subsidence), which may modify the valley slope, and the position of the stream base-level (Gregory and Walling, 1973; Teisseyre, 1991; Brzezińska-Wójcik and Kociuba, 2001; Andrzejewski et al., 2018). Another important factor influencing the erosion–accumulation equilibrium state of rivers in the Middle-Polish Lowlands, especially during the Late Weichselian, was the ice sheet location, affecting the possibility of river discharge to the Baltic Sea or to the North Sea (Starkel, 1997; Toucanne et al., 2010; Kordowski et al., 2014b; Weckwerth et al., 2019). Changes of the river valley systems in central Poland during the Last Glacial Maximum (LGM) are well documented

* Corresponding author, e-mail: olga.antczak-orlewska@ug.edu.pl

Received: September 13, 2022; accepted December 8, 2022; first published online: January 17, 2023

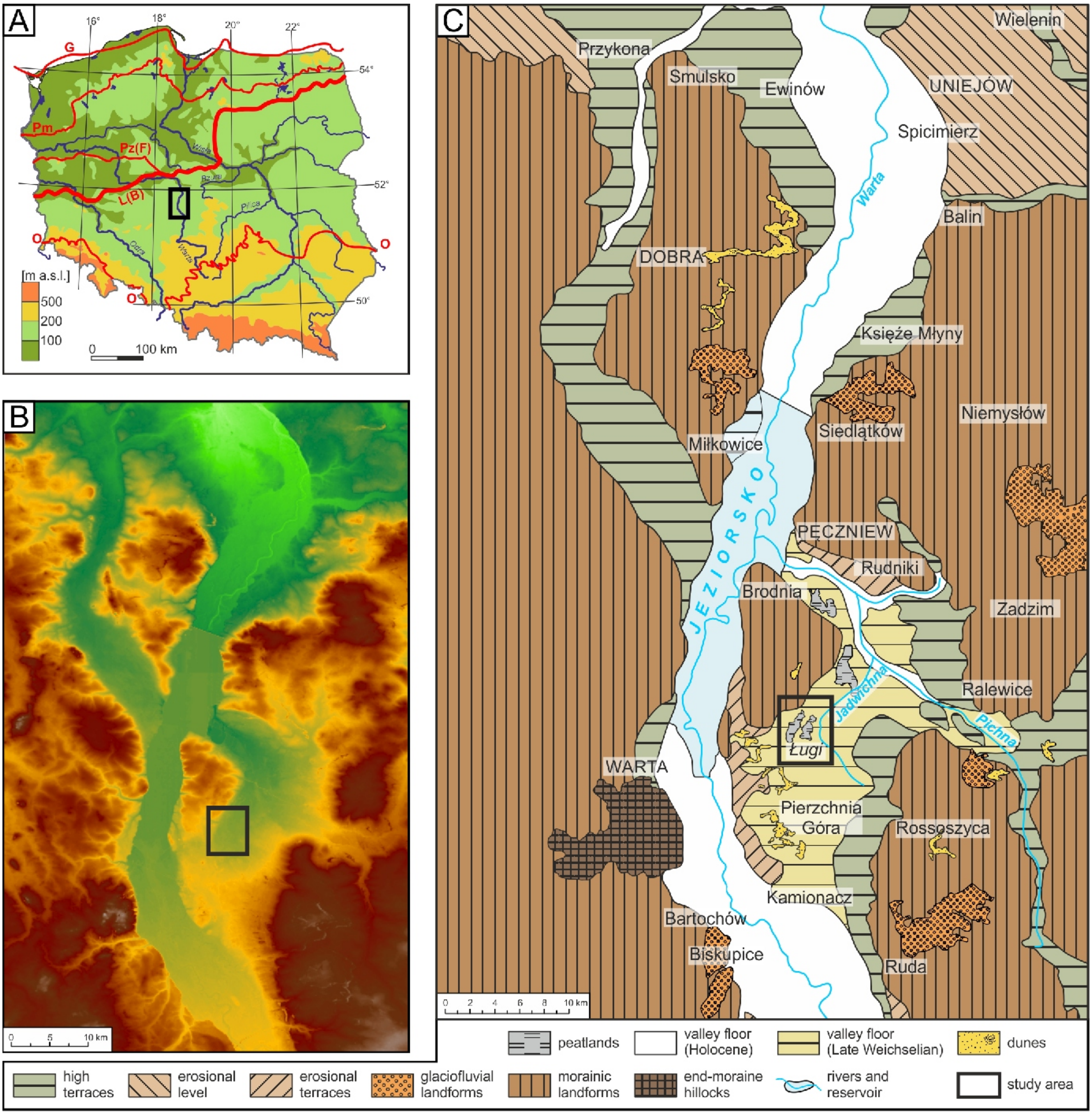

Fig. 1A – location of the study area (marked as black rectangle) and regional glacial limits (after Marks, 2012): O – Saalian Glaciation and Weichselian Glaciation: L(B) – Leszno (Brandenburg) Phase, P(F) – Poznań (Frankfurt) Phase, Pm – Pomeranian Phase, G – Gardno Phase; B – Digital Elevation Model of the middle course of the Warta River system; C – overview geomorphological map (after Forysiak, 2005)

(e.g., Rotnicki, 1987; Wiśniewski, 1987; Turkowska, 1988). The Warta River (especially its middle course) was influenced by the range of the ice sheet margin during the LGM and possibly underwent flow impediment by the ice sheet during the Leszno and Pomeranian phases (Kozarski, 1995). The study area is located ~35 km south of the axis of the Warsaw-Berlin ice-marginal valley, which was the local base-level for the then middle-course Warta River. The valley floors of the Warta River and its tributaries repeatedly changed their positions, likely due to the functioning of proglacial outflow during the glaciation phases noted above, resulting in alluvial aggradation. However, phases of increased erosion and cutting of alluvial plains during deglacial intervals may also have contributed to shifts in valley floor position (Schumm, 1977; Teisseyre, 1991; Makaske and Nap, 1995).

The Jadwichna-Pichna Valley, where the studied wetland is located (Fig. 1), was active in the Warta drainage system during the Weichselian. It was cut off from the active river channels due to erosion, induced by lowering of the base-level following the Poznań phase ice sheet recession (Rotnicki, 1987; Turkowska, 1988; Klatkowa and Załoba, 1991; Forysiak, 2005). The study site at Ługi, a highly disturbed modern peatland, occupies a fossil fluvial depression, probably a fragment of a braided river channel. The alluvial, and therefore permeable, bottom of this buried river channel, as well as its immediate surroundings, required the functioning of the lake and the fen to maintain a relatively high groundwater level.

Despite the general homogeneity of the rocks making up the drainage areas of biogenic accumulation basins within river valleys, high lithogeochemical diversity is observed in a group of Late Weichselian lacustrine deposits. Calcareous deposits, considered as indicating a hydrological regime determined by the catchment lithology, permafrost withdrawal and plant colonisation (Goździk and Konecka-Betley, 1992a; Forysiak et al., 2010; Kordowski et al., 2014a) are exceptional in this respect. In the Polish Lowland, sedimentation of calcareous gyttja was caused by the lithology and availability of calcareous material (Ca^{2+} and HCO_3 ions) in the catchment, deepening of depressions occupied by permanent water bodies, and habitat conditions such as physicochemical properties of the lake water (Mazurek, 1990; Borówka, 1992; Apolinarska et al., 2012; Okupny et al., 2016c; Makohonienko et al., 2023). Apart from calcareous sedimentation, an important group of lacustrine deposits found in the basal parts of numerous mire sections are detrital gyttja and detrital-clayey gyttja (Żurek and Okupny, 2015). Regardless of age, the chemical composition of biogenic sediments making up the mire deposits of central Poland results from the intensity of supply of allochthonous material, authigenic remains originating within the basins, and mineral components of biogenic origin (Rydelek, 2011; Okupny et al., 2013).

River valleys are among the most important landscape elements in the Central European Lowlands. Modern peatlands develop predominantly in river valleys (Succow and Joosteen, 2001), but the onset of paludification of these landforms took place in the Late Weichselian (Żurek, 1991). River valley floors are favourable for the development of peat-forming habitats, are susceptible to climate change, and offer a good record of climatic fluctuations such as those known from the Late Weichselian and the Early Holocene. Thus, research on wetlands located in river valleys of the Polish Lowland, including their fossil palaeochannels and deposits, has a long tradition (Oświt et al., 1980; Szumański, 1983; Andrzejewski, 1995; Turkowska, 1997). In central Poland, fen peatlands began to appear mostly in the Bølling or in Allerød, testifying to the stabilisation of valley bottoms and the maintenance of a relatively constant base-level position, as manifested in the activity of the meandering channel system. Several peatlands and palaeolakes that functioned in active river valleys have been already studied in the region: the Ner (Forysiak et al., 2010; Forysiak, 2012), Świętojanka (Balwierz and Goździk, 1997), Widawka (Pawłowski, 2012), Wkra (Niska et al., 2017), Grabia (Pawłowski et al., 2014), Luciąża (Płóciennik et al., 2021; Antczak-Orlewska et al., 2023) and Warta (Forysiak, 2012). However, biogenic sediments deposited in an area of active fluvial processes are often exposed to the influence of river or flood waters, which may significantly disturb the original sedimentary pattern, and contribute to the accumulation of allochthonous material (Żurek, 1993; Rydelek, 2005; Pawłowski et al., 2015; Forysiak et al., 2021). The Ługi mire was not exposed to fluvial processes during the Late Weichselian and Holocene. It was likely fed by groundwater and precipitation, thus it better reflects regional climate humidity and temperature. Climatic processes were dominant drivers of water pools and landscape formation then, hence this multi-proxy study aims at reconstruction of the varying hydroclimatic conditions.

Vegetation changes within the lake and its surroundings were tracked using pollen records. The types of vegetation cover in the catchment, along with climatic, hydrogeological and geomorphological conditions, greatly influenced the accumulation of sediment in the basin. Moreover, the biostratigraphy is based on pollen zones.

Chironomids are among the best proxies for reconstruction of past air temperature changes. Since these insects usually have short life cycles and are highly dispersive, they react much faster to environmental and climatic changes than do plant communities (Birks et al., 2000; Brooks and Birks, 2001; Walker, 2001). That feature was used in the construction of multiple training sets, including two with data from Poland: the East European Training Set (EE TS – Luoto et al., 2019) and the Swiss-Norwegian-Polish Training Set (SNP TS – Kotrys et al., 2020). Both were applied in this study.

Cladocerans, small crustaceans, are known indicators of palaeoenvironmental conditions in lakes, including trophic status, water-level fluctuations and pH (e.g., Korhola and Rautio, 2001; Zawiska et al., 2014; Pawłowski et al., 2016a). The response of cladocerans to changes in temperature is more indirect than that of other proxies (Birks and Ammann, 2000; Pawłowski, 2017).

The Ługi palaeolake is probably a rare case of a biogenic accumulation basin of fluvial origin in a region where fluvial geomorphological processes, and the impact of river waters on the functioning of the lake (which was later transformed into a wetland), have both been negligible. The lake formed in the Oldest Dryas – i.e., earlier than lakes in other valleys of the region. This enabled the recording of a history, albeit likely incomplete, of environmental changes in that phase, and again in the younger part of the Late Weichselian. The basin became entirely occupied by a mire in the Younger Dryas, by the beginning of the Holocene, due to another phase of erosion and valley floor lowering (Rotnicki, 1987; Turkowska, 1988). Then the Warta River floor, in the immediate vicinity of Ługi, lowered by several metres (Forysiak, 2005). This caused groundwater lowering in the Warta River valley and the associated Jadwichna-Pichna valley, and a marked deterioration of conditions for mire functioning. The Holocene peat section at Ługi is therefore most likely discontinuous. Its topmost part is strongly decomposed and partly mineralised, which reduces its suitability for palaeoecological analyses. For this reason, no palaeoenvironmental reconstruction is undertaken here for the Holocene. The study of the lacustrine deposits at Ługi enables a reconstruction of Late Weichselian environmental conditions in the surroundings of a basin formed within a valley excluded from the direct impact of fluvial processes. This study is an attempt to test the suggestion that the onset of biogenic accumulation at Ługi occurred as early as the end of Late Pleni-Weichselian (Klatkowa and Załoba, 1991; Forysiak, 2005, 2012). It also aims to reconstruct the wetland formation and its hydroclimatic drivers. Finally, it presents the stratigraphy of the main invertebrate and plant assemblages as a response to local habitat character.

STUDY AREA

The study area is located in central Poland, in the Sieradz Basin mesoregion (Kondracki, 2002), which has fewer mires than the remaining area of central Poland (Dembek et al., 2000; Lipka et al., 2008; Okupny et al., 2014b). At present, the study area is influenced by a temperate, continental maritime climate, with an annual precipitation sum of ~550–580 mm, and clear periodic rainfall shortages (Wibig and Radziun, 2019). Average annual air temperature (~8.5°C) and average air temperature for July (~18°C) both display a slowly increasing trend (Kłysik, 2001).

The Ługi fen (51°43'42"–51°44'20" N; 18°41'40"–18°43'42" E, ~124–127 m a.s.l.) is located within the vast Jadwichna-Pichna valley floor belonging to the Warta River system, but this section is not affected by fluvial processes today. From the beginning of the Late Weichselian, the Warta River has been flowing along a different, parallel section (Fig. 1), running a few km to the west and now occupied by the Jeziorsko Reservoir. This part of central Poland was last occupied by an ice sheet during the Warta Stage (Saalian; MIS-6), and the studied valley was part of the proglacial river system (Klatkowa and Załoba, 1991). Several wetlands formed within the Jadwichna-Pichna valley floor area, but in the 20th century these were drained and peat layers were exploited. The valley floor is drained by small, usually artificial, streams which drain to the Pichna river, now also flowing via an artificial channel to the Jeziorsko Reservoir. The Ługi fen is located in the western part of the valley floor, adjacent to a high alluvial terrace. The peatland is ~300 metres wide, but the buried depression, which in the Late Weichselian was a shallow lake, is ~100 m wide. The Ł-1 core studied here shows the lithology in the axial part of this fossil depression, where the greatest thickness of biogenic deposits occurs (Fig. 2).

METHODS

GEOLOGICAL FIELDWORK

The geology and geomorphology of the study area were explored using manual geological equipment (Instorf sampler and gouge auger). We also documented the lithology of biogenic deposits of the wetland. About 130 boreholes were made in the fen area, which enabled us to determine the thickness of the biogenic infill (up to 3.0 m; Forysiak, 2012) and to reconstruct the subfossil bottom of the wetland basin. Subsequent work with an Instorf sampler and a gouge auger enabled us to document a series of lake sediments in the deepest part of the wetland depression. The Ł-1 sediment core (51°43'52.8" N; 18°42'46.5" E) reached 3.0 m depth and was collected using an Instorf sampler in the form of a double core in 50 cm-long sections. In addition, a new core, Ł-2 (~10 m west of the main core of Ł-1), was taken using a Więckowski probe to complete the radiocarbon sampling.

POLLEN ANALYSIS

Pollen analysis was performed on 25 samples from the bottom part of the core. Palynological samples (1 cm^3 of sediment) were taken in 5 cm intervals. Chemical preparation followed a standard protocol with 3 min-long acetolysis (Berglund and Ralska-Jasiewiczowa, 1986). The sporomorph concentration in each sample was determined with the aid of one *Lycopodium* tablet (Stockmarr, 1971; Berglund and Ralska-Jasiewiczowa, 1986). Palynomorph identifications were based on photographic reference collections and keys (Faegri et al., 1989; Moore et al., 1991; Beug, 2004). In each sample, at least 300–500 pollen grains of terrestrial plants (according to frequency) were counted. The calculation sum contains AP+NAP (arboreal and non-arboreal pollen), except for local aquatic and telmatic plants. Green algae coenobiae were also counted, but not included in the calculation sum. The Late Glacial indicators sum curve contains: *Juniperus communis*, *Hippophaë rhamnoides*, *Helianthemum*, *Ephedra distachya* t., *Saxifraga aizoides* t., *Saxifraga* undiff., *Gypsophila repens* t., *Astrantia* t., *Rumex* sum, *Plantago media, Plantago major, Anthemis* t., *Artemisia* and Chenopodiaceae. The division of the Late Weichselian into chronostratigraphic units after Walanus and Nalepka (2010) was used in the paper.

CHIRONOMIDAE

In total 40 samples for the Chironomidae analysis were collected from the Ł-1 core. Sample volume ranged from 3 to 29 cm^3 (mean 15.1 cm^3). Mean sample resolution is 6.75 cm. The samples were passed through a 63 µm sieve and processed following Brooks et al. (2007). Subfossils were identified mainly with the Wiederholm (1983) and Brooks at al. (2007) keys. Ecological interpretation and taxon habitat preferences were taken from the publications by Brooks et al. (2007), Vallenduuk and Moller Pillot (2007), Moller Pillot (2009, 2013), and Rossaro et al. (2022). The reference collection is deposited at the Department of Invertebrate Zoology and Hydrobiology (University of Łódź).

CLADOCERA

Analysis of subfossil cladocerans was performed for 56 samples which were taken at 5 cm intervals. Each sample, representing 1 cm^3 of sediment, was processed following the standard procedure (Frey, 1986). 0.1 ml of solution was used to prepare each microscope slide (examined at 100 magnification). All cladoceran remains were counted. For each taxon, the most abundant body parts were taken to represent the number of individuals, and percentages were calculated from the sum of individuals. The taxonomy of cladoceran remains in this paper follows that given by Szeroczyńska and Sarmaja-Korjonen (2007), Van Damme and Dumont (2008), Van Damme et al. (2010) and Faustova et al. (2011). The ecological preferences of cladoceran taxa were determined following Flössner (1972, 2000) and Bjerring et al. (2009).

GEOCHEMICAL AND GRAIN-SIZE ANALYSIS

Geochemical analyses were performed for 44 samples taken from the Ł-1 core (depth range: 300–130 cm) at 2 cm intervals. Samples were processed according to the standard procedure (Borówka, 1990). Sediment samples were dried at 105°C and homogenised using an agate mortar. Calcium carbonate ($CaCO_3$) content was determined using the Scheibler volumetric method. Organic matter (OM) content was determined by loss on ignition (LOI) at 550°C in a Gallenkamp muffle furnace. The ash produced by combustion was analysed for grain size-related and detailed geochemical properties.

Grain-size analysis of the mineral part (for 25 samples) was performed using a laser particle size analyzer: a Mastersizer 3000 with a Hydro MU dispersion unit (Malvern). In order to perform geochemical assays, the ash samples were dissolved in Teflon bombs using a microwave mineraliser. Mineralisation was carried out in two microwave cycles: the first in concentrated nitric acid (HNO_3) with 2 ml of 10% hydrochloric acid (HCl) and the second in hydrogen peroxide (H_2O_2). The solution obtained was analysed for concentrations of Na, K, Ca, Mg, Fe, Mn, Cu, Zn, Cr and Ni by atomic absorption spectrometry (AAS) using a manual 969 Unicam Solaar apparatus. All the analyses were conducted at the Geochemical Laboratory at the University of Szczecin. Analytical precision (<3% for all geochemical

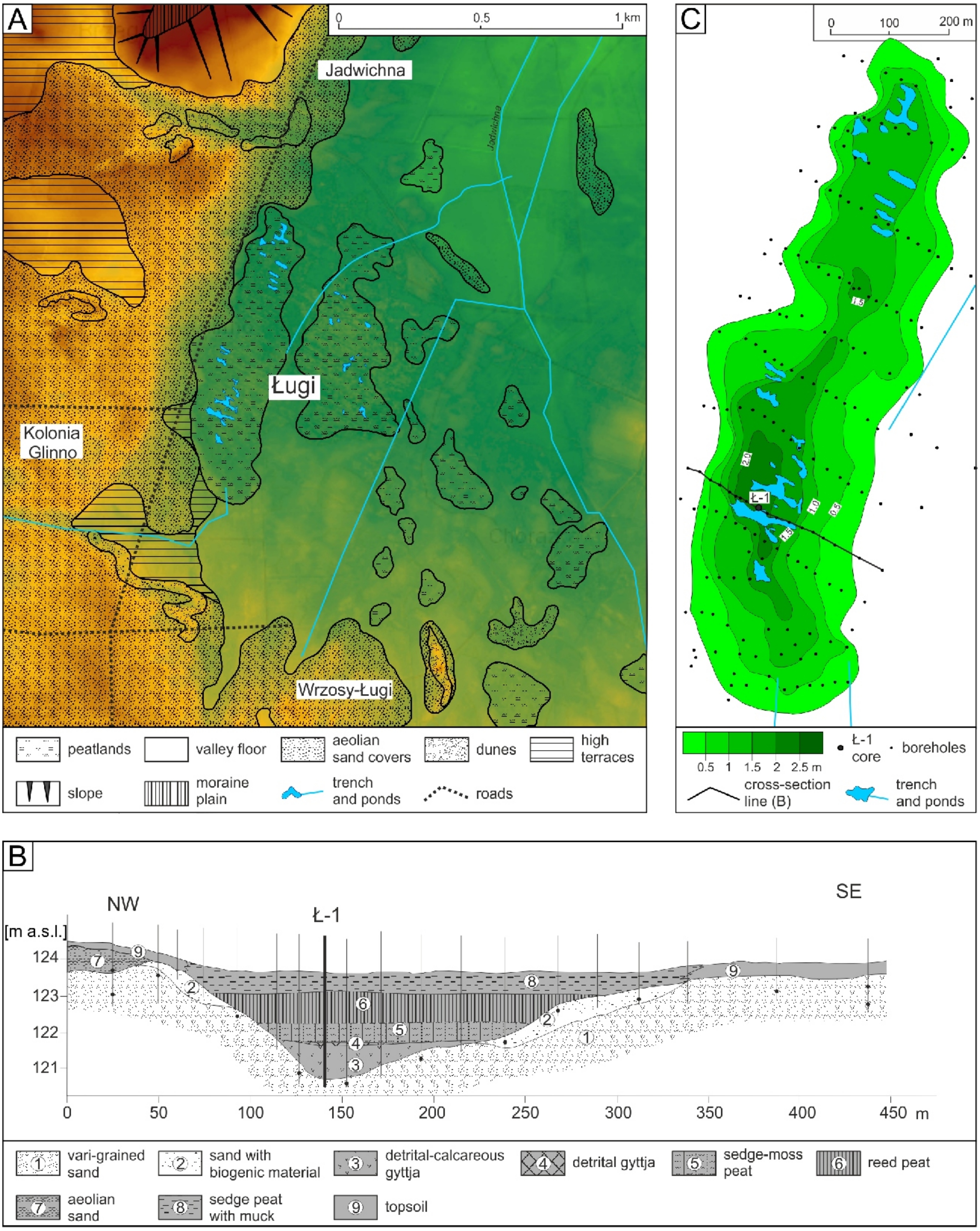

Fig. 2. The Ługi peatland (after Forysiak, 2005)

A – geomorphological map of the study area; B – geological cross-section; C – thickness of biogenic deposits in the western part of the Ługi peatland elements) was estimated in accordance with laboratory recommendations and certified reference materials, and is suitable for the analysis of biogenic deposits. This procedure is commonly used for reconstructing environmental conditions at Polish Lowland sites (Okupny et al., 2020; Okupny and Pawłowski, 2021).

NUMERICAL ANALYSES

Numerical analyses were performed in order to identify lithogeochemical facies (LGF), local palynological zones (L PAZ), local cladoceran zones (L CAZ), and Chironomidae zones.

Cluster analysis was applied to the 40-sample geochemical dataset. As grouping variables, eleven lithogeochemical properties were adopted that reflect, for example, denudation process types and dynamics, and sediment supply type. The computations employed Ward's hierarchical grouping method, which estimates distances between clusters following a variance analysis approach (Zhou et al., 2017). The resultant lithogeochemical facies form three main groups of sediments (mineral, carbonate and organic), and were named as A, B and C. We also used Principal Component Analysis (PCA) in order to determine the variability of factors controlling the chemical composition of the deposits. PCA computations were performed using PAST version 2.17c (Hammer et al., 2001). Standardised values of organic matter and nine macro- and microelement contents were used as input variables. In order to determine the intensity of migration of major and trace elements, and to reconstruct denudation processes based on the chemical composition of the infill deposits, we followed the procedure of Borówka (1992). This features the formula $K_x = AC_x/n_x$ (where: K_x – dimensionless concentration coefficient of element x; AC_x – content of element x in the ash from deposits infilling a biogenic accumulation basin – expressed as mg/g or µg/g; n_x –average content of element x in bedrock – expressed as mg/g or µg/g). As geochemical background values for individual elements, we adopted averaged concentrations from river valley mire substrates from central Poland (Borówka et al., 2014). Finally, correlation between the results of geochemical analyses [r] was calculated. This indicator has been used for palaeogeographic reconstructions at many sites in central Poland, including Lake Gościąż (Walanus, 2000), Białe Ługi peatbog (Okupny et al., 2019), kettle-holes near Wąwelnica (Okupny et al., 2020) and Żabieniec (Okupny et al., 2021), and river valley mires at the Grabia River catchment (Okupny and Pawłowski, 2021).

The robustness of palynological zones was corroborated by CONISS (Grimm, 1992); the CONISS dendrogram and diagram illustrating pollen distributions were plotted using Tilia2 and Tilia-Graph (Grimm, 1992). Similarly, stratigraphically constrained cluster analysis (CONISS) was applied to distinguish cladoceran zones. Cluster analysis was based on the constrained incremental sum of squares clustering. Only species with at least 5% abundance at each level were included in the statistical treatment. The results were plotted in a percentage diagram using *POLPAL* software (Walanus and Nalepka, 1999).

Chironomid assemblage zones were determined in *R* software (R Core Team, 2020) using detrended hierarchical clustering (with CONISS algorithm and euclidean distance) from the "rioja" package (Juggins, 2017). The zones were tested for statistical significance with the broken-stick model using the 'vegan' package (Oksanen et al., 2019).

The chironomid-inferred mean July air temperature reconstructions were based on the Swiss-Norwegian-Polish Training Set (SNP TS; Kotrys et al., 2020) and East-European TS (EE TS; Luoto et al., 2019; Table 1). WA-PLS transfer function was used both for EE TS and for SNP TS reconstructions.

In turn, the Cladocera-based mean July air temperature (TJuly) reconstruction was based on the Finnish Cladocera training set (Nevalainen et al., 2012). The Weighted Averaging-Partial Least Squares regression (WA-PLS) technique was used. The cladoceran-based July air temperature inference model parameters were the R^2_{jack} = 0.67, Root Mean Squared Error of Prediction (RMSEP) of 0.86°C, and mean and maximum biases of –0.017°C and 1.732°C, respectively (Luoto et al., 2011).

Detrended Correspondence Analysis (DCA) for the biological proxies (pollen, chironomids and cladocerans) were performed with downweighting of rare taxa, implemented in the "vegan" *R* package (Oksanen et al., 2019). Graphs were created using *C2* software (Juggins, 2007).

RESULTS

GEOLOGY AND GEOMORPHOLOGY

Wetland patches occupy parts of the Jadwichna-Pichna valley floor. The Ługi fen is the largest of them and consists of two parts. Biogenic sediments were originally identified during geological mapping. They are ~1–3 m thick, with the largest thickness found within the western patch of the wetland (Fig. 2). Subsequent radiocarbon dating of the base of the sedimentary infill indicated an accumulation in the Late Weichselian (Klatkowa and Załoba, 1992).

The immediate surroundings of the fen are flat fragments of a fluvial terrace. The western side of the terrace surface is composed of Upper Pleni-Weichselian sands of various grain sizes devoid of biogenic material (Klatkowa and Załoba, 1991; Forysiak, 2012). The terrace surface also features patches of aeolian sands and small dunes (Fig. 2). The eastern surround-

Table 1

Parameters of the chironomid-based mean July air temperature training sets used

	Swiss-Norwegian-Polish TS		East-European TS
Number of chironomid taxa	134		142
Number of lakes	357		212
Mean July air temperature range	3.5–20.1°C		11.3–20.1°C
Root mean squared error of prediction (RMSEP)	WA-PLS: 1.39°C	ANN: 1.34°C	WA-PLS: 0.88°C
Correlation coefficient (R^2_{jack})	WA-PLS: 0.91	ANN: 0.95	WA-PLS: 0.88

ings of the wetland are periodically wet. The sandy plain is composed of fine-grained sands with silt and dispersed organic matter. The base of the depression is also made up of similar sediments, but with medium-grained sands.

Detailed drilling conducted within the fen allowed a recognition of a series of lake deposits under the peat cover in the deepest part of the depression. Exact lithological descriptions were made for the Ł-1 core. The lower lacustrine bed (290 to 245 cm core depth) is composed of detrital-calcareous gyttja. A detrital gyttja layer was observed between 245 and 190 cm (Fig. 2), subjacent to the peat. Lacustrine deposits are superjacent to medium-grained sands with organic matter.

BIOTIC PROXIES

Palynological analysis identified five local pollen assemblages with two subzones (L PAZ 1 to 5; Figs. 3 and 4). The stratigraphic succession of chironomid assemblages can be divided into 6 significant zones (Figs. 4 and 5). In total 897 chironomid head capsules representing 33 taxa were recorded. A clearly dominant taxon throughout the sequence was *Corynocera ambigua* (38.6% of all specimens). In turn, seven local cladoceran zones (LCAZs) have been distinguished. The Ługi core (Ł-1) deposits contain 20 cladoceran species, belonging to 4 families: Bosminidae, Daphniidae, Sididae and Chydoridae (Figs. 4 and 6). The abundance and diversity of cladocerans fluctuate between 200 and 6540 specimens, and 1 and 12 species, per 1 cm^3, respectively.

RADIOCARBON DATING

Several radiocarbon dates were obtained from the Ługi site (Table 2), but they are not sufficient to establish an age model for the Ł-1 core. A gyttja sample from the Ł-2 core, located 10 m west of Ł-1, yielded a radiocarbon age different than that from the Ł-1 core, even though the mineral substrate in the Ł-2 core rests ~30 cm deeper. A gyttja sample from the basal part of the borehole Łr6, located between cores Ł-1 and Ł-2, was also dated (Table 3). The resulting age is correlative with the Oldest Dryas (Forysiak, 2005). Calibrated BP age was used throughout the entire paper.

GEOCHEMICAL RESULTS

Based on variations in the chemical composition of the deposits, and macro- and microelement concentrations, three lithogeochemical facies (LGF) are distinguished (Table 3 and Fig. 7).

Lithogeochemical facies A – represents mineral and mineral-organic deposits with an increased content of K (between 0.25 and 1.5 mg/g), Fe (between 0.12 and 302 mg/g) and Mn (between 0.17 and 3.98 mg/g). It occurs as three thin layers in the basal and central parts of the core. In addition to the highly variable organic matter content (varying from 1 to 40%), these sediments are generally characterised by a decreasing Fe/Mn ratio (below 100) and increasing Fe/Ca ratio (from 1.79 to 30). Sand (M_z between 1.42 and 1.56 *phi*) and sandy silt (M_z between 4.6 and 4.8 *phi*), with a moderate degree of sorting (average is 1.35 *phi*) are the dominant mineral lithologies.

Lithogeochemical facies B – carbonate deposits with increased Ca (on average 212 mg/g) and $CaCO_3$ concentrations. $CaCO_3$ concentration varies between 5.6 and 67%, and peaks in an interval distinctly enriched in Cr (up to 38 µg/g), Cu (up to 28 µg/g) and Ni (up to 32 µg/g). These deposits, with a total thickness of 0.9 m, are characterised by a low average content of Na (0.08 mg/g), decreased content of sand (from 32 to 18%) and increased Ca/Mg ratio (from 1.5 to 3) and change trends of PC3 axis.

Lithogeochemical facies C – represents organic deposits with increased concentrations of lithophilic elements: K (between 0.48 and 2.18 mg/g), Na (between 0.04 and 0.31 mg/g), Zn (between 8 and 72 µg/g) and Ni (between 10.2 and 39.8 µg/g). LGF C displays a significant increase in the erosion ratio (Na+K+Mg/Ca from 0.6 to 2.8), accompanied by high organic matter content (>65%). The proportion of sand decreases from 58 to 20%, very fine sand being the dominant lithology (on average 61%). Silt dominates over clay, and very coarse and coarse silt is 7–13 times greater than the proportion of clay.

INTERPRETATION AND DISCUSSION

POLLEN AND AGE SCHEME

The radiocarbon ages obtained are not sufficient for determining the age of biogenic sediments deposited in the palaeolake basin at Ługi. Age control for the Ł-1 core is thus based on palynology. The onset of biogenic sedimentation likely took place between 15,606 and 17,072 years cal BP, correlative with the Oldest Dryas, as indicated by the radiocarbon ages obtained for the basal parts of the Ł-1 core and Łr6 profile (Table 2) and palynological data from the bottommost samples of the Ł-1 core (LPAZ 1a).

Table 2

Radiocarbon dates of the Ługi site

Nr lab.	Symbol of core, depth (cm)	Radiocarbon data	Age (cal year BP, 95.4%)	Methods; deposit type
MKL-419	Ł-1, 89–90	7430 ±90	8035–8385	LSC; peat
MKL-1548	Ł-1, 105	7500 ±90	8164–8456	LSC; peat
MKL-416	Ł-1, 139–140	10,110 ±130	11,246–12,108	LSC; peat
MKL-421	Ł-1, 279–281	13,820 ±120	16,379–17,072	LSC; gyttja
MKL-4567	Ł-2, 286	11,623 ±35	13,367–13,589	AMS; gyttja
Lod-1082	Łr6, 325	13,370 ±170	15,606–16,621	LSC; gyttja

LSC – Liquid Scintillation Counting, AMS – Accelerator Mass Spectrometry

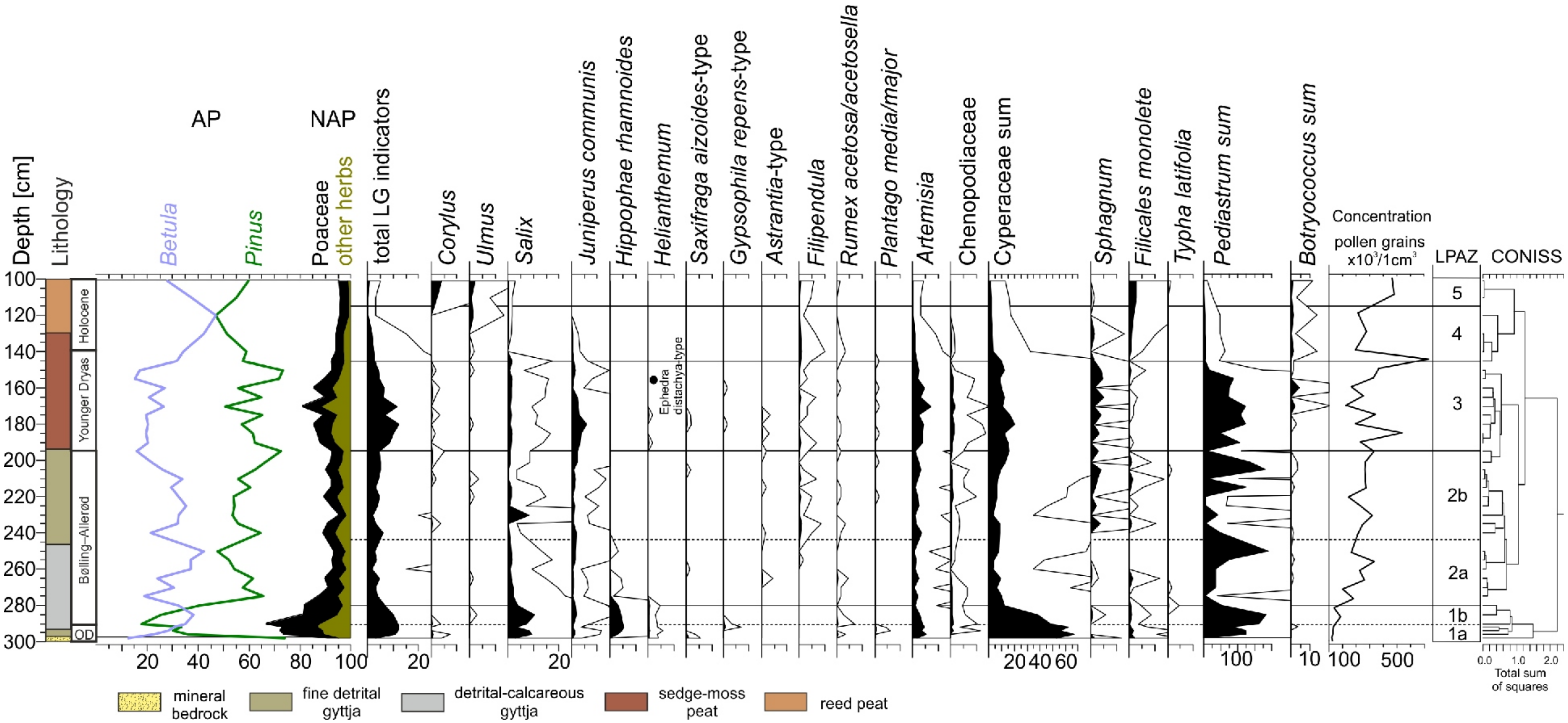

Fig. 3. Percentage pollen diagram from the Ługi peatland, Ł-1 profile

Most graphs show percentage values, except for algal (*Pediastrum* and *Botryococcus*) counts presented as an absolute sum

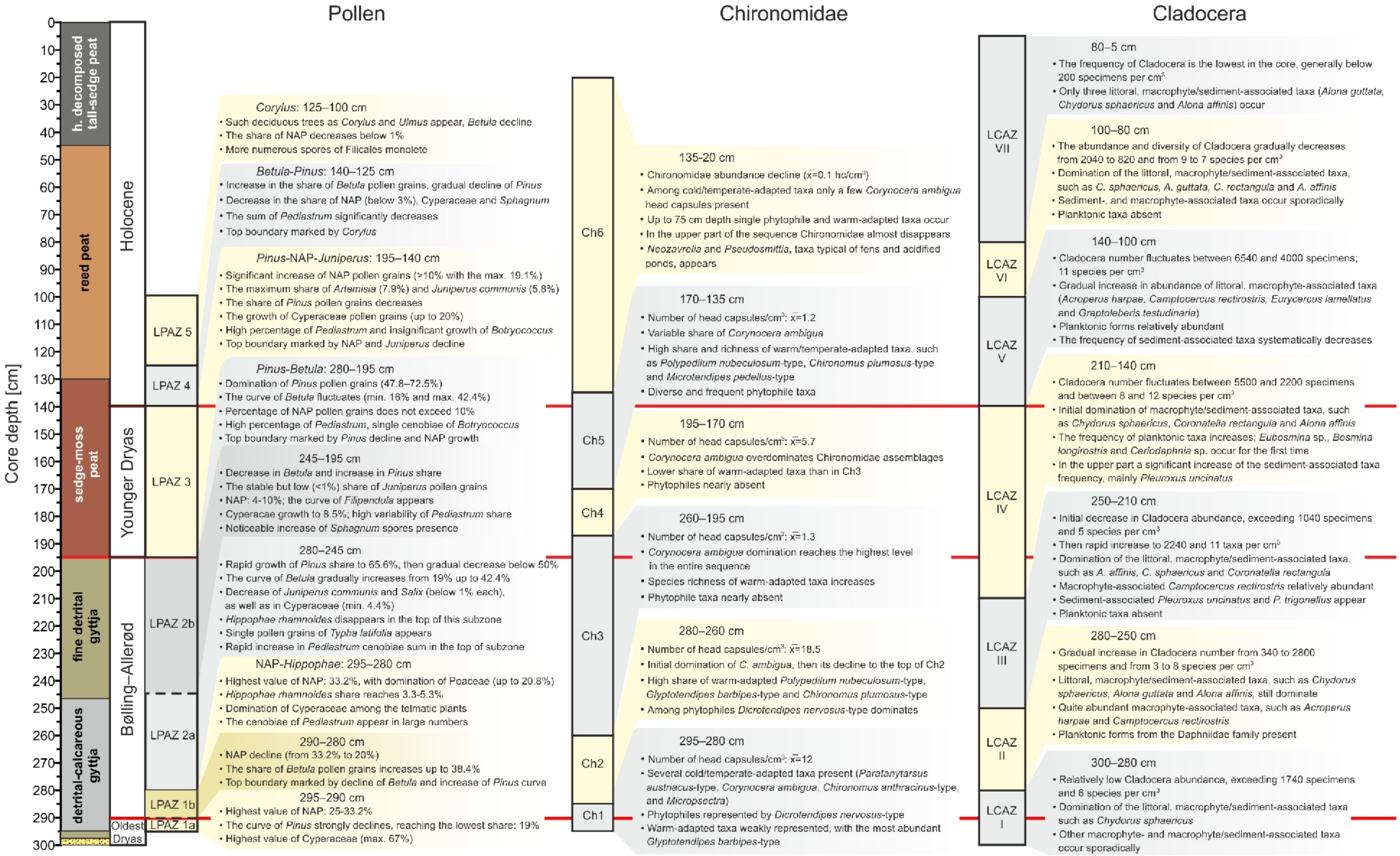

Fig. 4. Results of biotic proxy analyses

For detailed lithology see Figure 7

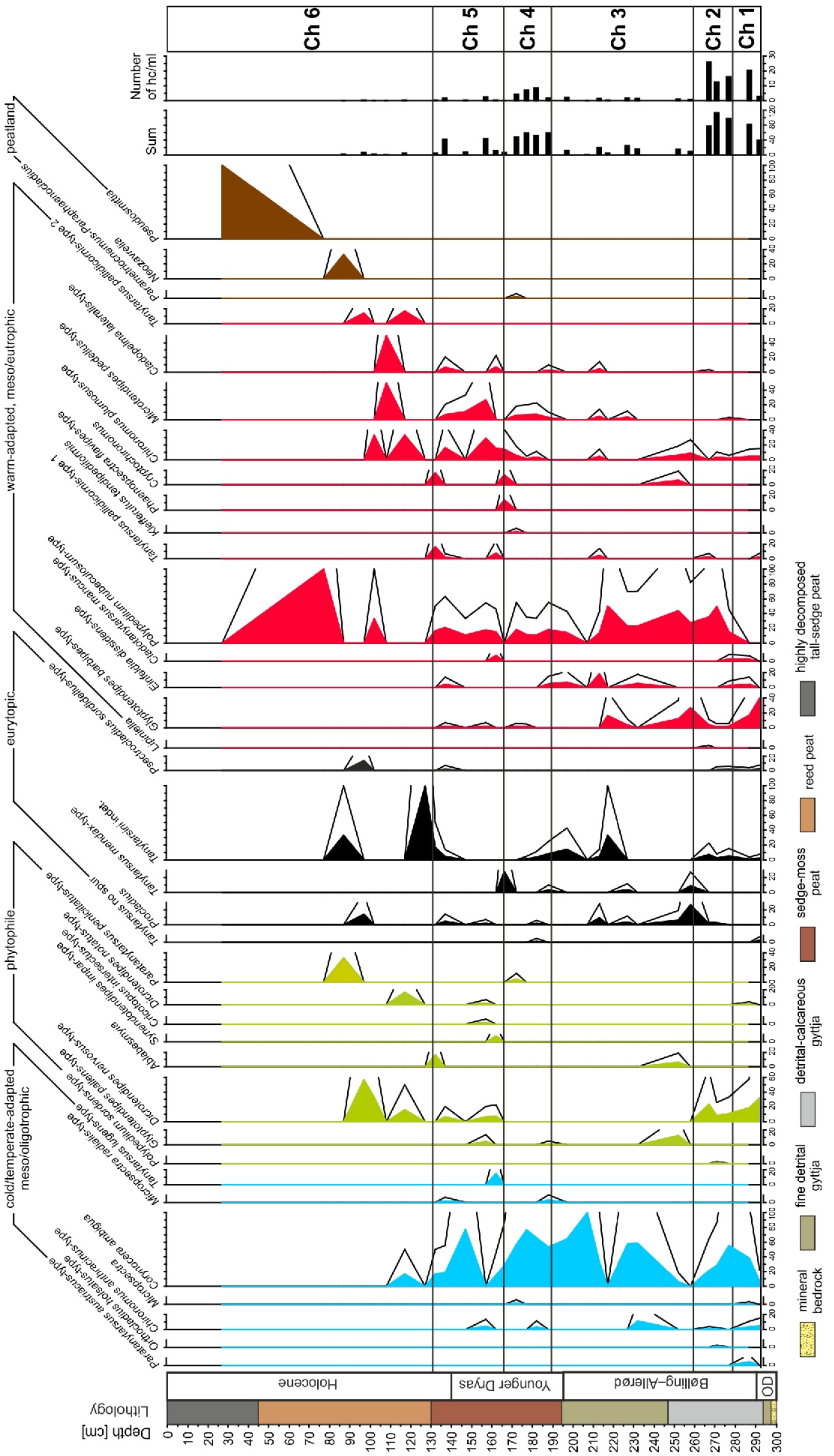

Fig. 5. Chironomidae percentage diagram from Ługi Ł-1 core (hc – head capsules)

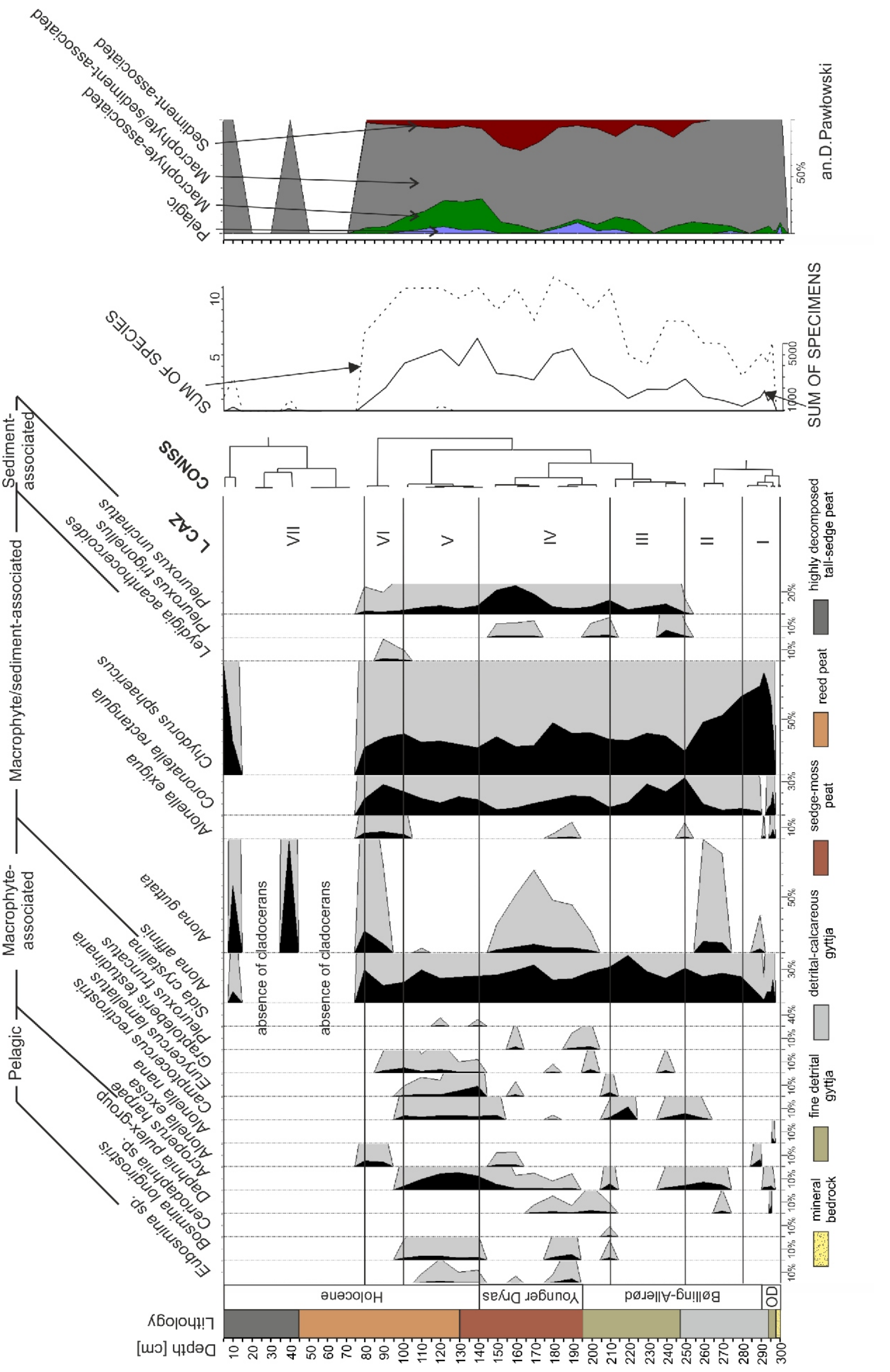

Fig. 6. Cladocera percentage diagram, main Cladocera ecological groups, total sum of species and specimens from Ł-1 core

LCAZ – Local Cladocera Assemblage Zones

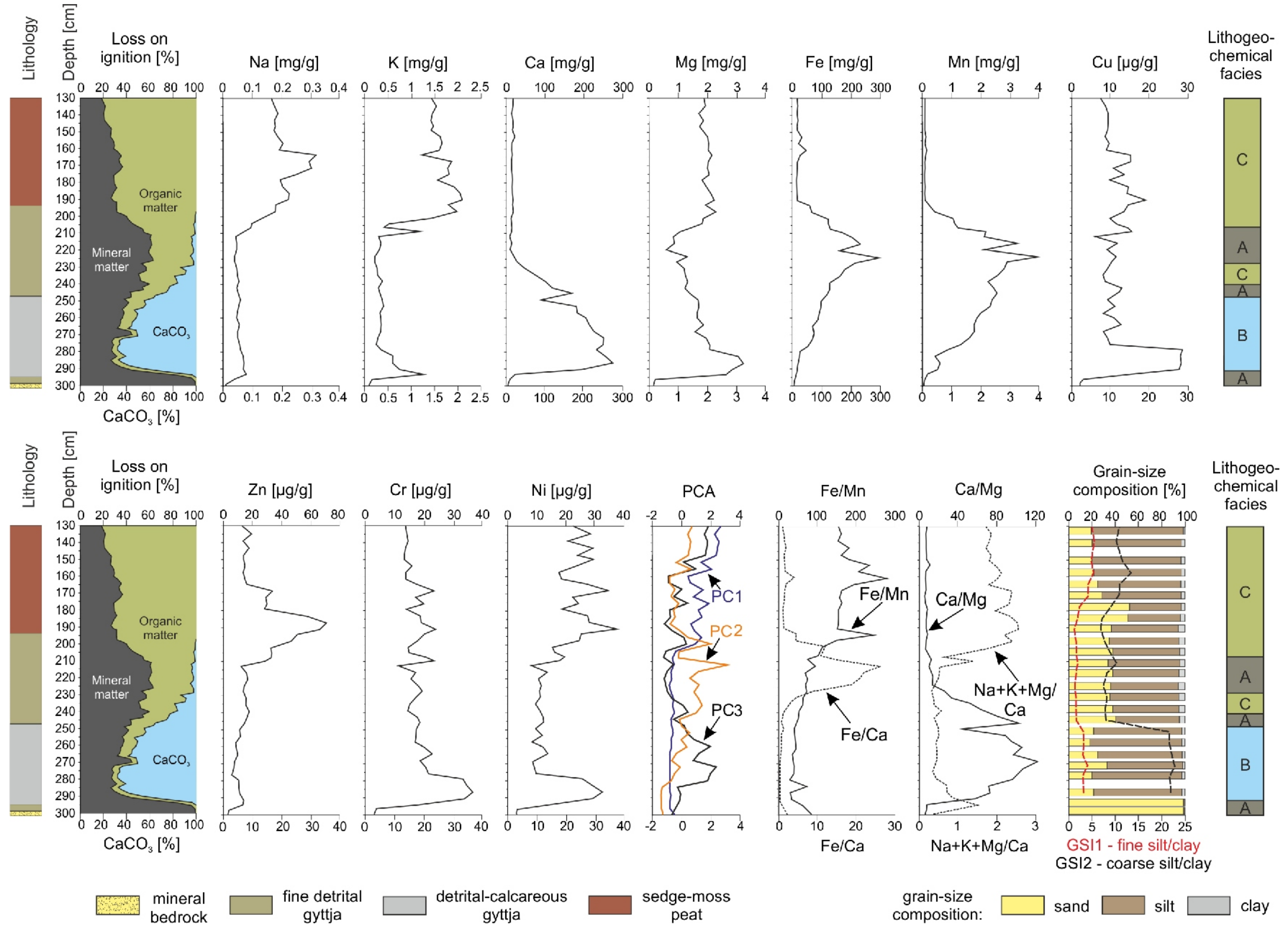

Fig. 7. Geochemical (content of organic matter, mineral matter and $CaCO_3$; concentrations of metals and selected geochemical ratios) and sedimentological (content of sand, silt and clay fractions; grain-size indicators: GSI1 and GSI2) results for the Ł-1 core, together with lithology and lithogeochemical facies

Table 3

Lithogeochemical facies for biogenic deposits from the Ł-1 core

Lithogeochemical facies symbol*	Lithology	Facies/lithofacies**	Depositional environment	Total thickness of analysed core [m] (% of sum)
A	fine detrital gyttja with sandy admixture	limnic/C, FS	lake, river	0.50 (29.6)
B	detrital-calcareous gyttja	limnic/C, FS	lake	0.40 (23.7)
C	fine detrital gyttja, sedge-moss peat	limnic, telmatic/C, S, FS	lake, mire	0.79 (46.7)

* symbols as in Figure 7; ** lithofacial-textural symbols of clastic sediments after Zieliński and Pisarska-Jamroży (2012)

L PAZ 1a (NAP -HIPPOPHAË) – OLDEST DRYAS

This L PAZ spans the core depth from 295 to 290 cm (Figs. 3 and 4) and includes a range of species representing this cold period. It displays the highest NAP value in the entire core, with a maximum proportion of Poaceae. There is the highest percentage of *Pinus* pollen grains, but these come from long-distance transport, and their share declines rapidly upsection. The largest share of *Hippophaë rhamnoides* and *Helianthemum* in the entire core is also very important, as this results in a high LG indicators sum. A very similar percentage of these species was reported from the nearby Witów site (Wasylikowa, 1964), unambiguously placing it within the Oldest Dryas.

A high abundance of pollen from plants typical of a warmer climate was noted from 295 cm upsection, and was also reported from Żabieniec (Balwierz, 2010). These pollen grains are certainly redeposited, consistent with the observations of Wasylikowa (1964), who regarded reworking as characteristic of the earliest Late Weichselian. The peak proportion of Cyperaceae pollen, and the presence of telmatic plants (*Sphagnum,* Filicales) both point to the existence of large areas of swampy habitats in the vicinity of the palaeolake during the Oldest Dryas. The upper boundary of LPAZ 1 is marked by a decline in *Betula*, *Salix* and other LG indicators.Ø

L PAZ 1b AND L PAZ 2 (*PINUS-BETULA*) – BØLLING-ALLERØD

L PAZ 1b still shows open landscape vegetation (a very high proportion of light-demanding species as *Hippophaë rhamnoides*, *Helianthemum*, *Artemisia*) but also reflects a change in plant cover. The share of birch increases significantly. This record is very similar to that of the Witów site (Wasylikowa, 1964) and other palaeolakes in Central Poland (Forysiak et al., 2010; Pawłowski et al., 2016b).

L PAZ 2 is divided into two subzones. At the beginning of the older one (L PAZ 2a) there is a clear decline in the proportion of LG indicators, and a rapid rise in the proportion of *Pinus* pollen, which indicates climate warming. The proportion of Cyperaceae pollen rapidly decreases, likely signifying a reduction in their habitat area in the vicinity. Importantly, single pollen grains of *Typha latifolia* appear, also indicative of warming (Ralska-Jasiewiczowa, 2004).

At the beginning of the 2b subzone within the *Pinus-Betula* L PAZ, there is a slight increase in NAP, with a higher proportion of Cyperaceae and *Artemisia*, with increased LG indicators, and a significant share of *Juniperus* pollen. In this core interval (245–230 cm; Fig. 3), such species composition may be indicative of the Older Dryas event. This, however, is ambiguous in the absence of radiocarbon ages. The constant presence of *Sphagnum* spores since the beginning of this subzone suggests the spread of peatland habitats featuring peat moss. In the younger part of the 2b subzone, the *Betula* percentage decreases, but the proportion of *Juniperus* pollen remains constant, as does NAP. This indicates that the climatic conditions and humidity had stabilized by that time. At the end of this phase, the proportion of birch begins to decrease, and the share of pine increases, and again there was a development of wet communities with Cyperaceae. All this most likely points to a deterioration of climatic conditions. Similar trends are documented at Witów (Wasylikowa, 1964) in an interval assigned to Allerød.

L PAZ 3 (*PINUS*-NAP-*JUNIPERUS*) – YOUNGER DRYAS

From the base of the L PAZ 3 at 195 cm, most palynological indicators point to distinct changes. The increase in the proportion of pollen grains, including LG indicators, reflects the dominance of open plant communities associated with a considerable cooling correlated with the Younger Dryas. The increase in *Juniperus, Artemisia* and Cyperaceae within this zone is similar to that reported from Witów (Wasylikowa, 1964). A distinct share of Cyperaceae and *Sphagnum* suggests favourable conditions for fen development. The dating of the material from the top of L PAZ 3, at 140–139 cm core depth, is generally consistent with the palynology, suggesting a change towards Holocene warming.

L PAZ 4 (*BETULA-PINUS*), L PAZ 5 (*CORYLUS*) – HOLOCENE

A clear drop in NAP and the sum of LG indicators, including *Juniperus* and *Salix* (L PAZ 4) indicates an amelioration of thermal conditions in the early Holocene (Wasylikowa, 1964). The subsequent rapid appearance of *Corylu*s and *Ulmus* (L PAZ 5) documents a progressive warming. L PAZ 4 may be linked with the Preboreal period, while L PAZ 5 suggests the Boreal. This record, however, is most likely discontinuous, as indicated by the dating results. A radiometric date obtained from the core depth of 105 cm suggests this interval falls within the Atlantic period.

TEMPERATURE RECONSTRUCTIONS

The Chironomidae-inferred (CH-I) mean July air temperatures are based on two models – EE TS and SNP TS. EE TS reconstruction values vary from 15.9 °C (172 cm) to 19.6 °C (157 cm; Fig. 8). SNP TS reconstruction values range from 13.0°C (188 cm) to 19.8°C (157 cm). Both reconstructions reveal similar trends, but the SNP TS reconstruction generally gives lower temperature estimates than EE TS, and the SNP TS-derived temperature amplitude is higher than that derived from EE TS. The reconstructions indicate high temperatures for

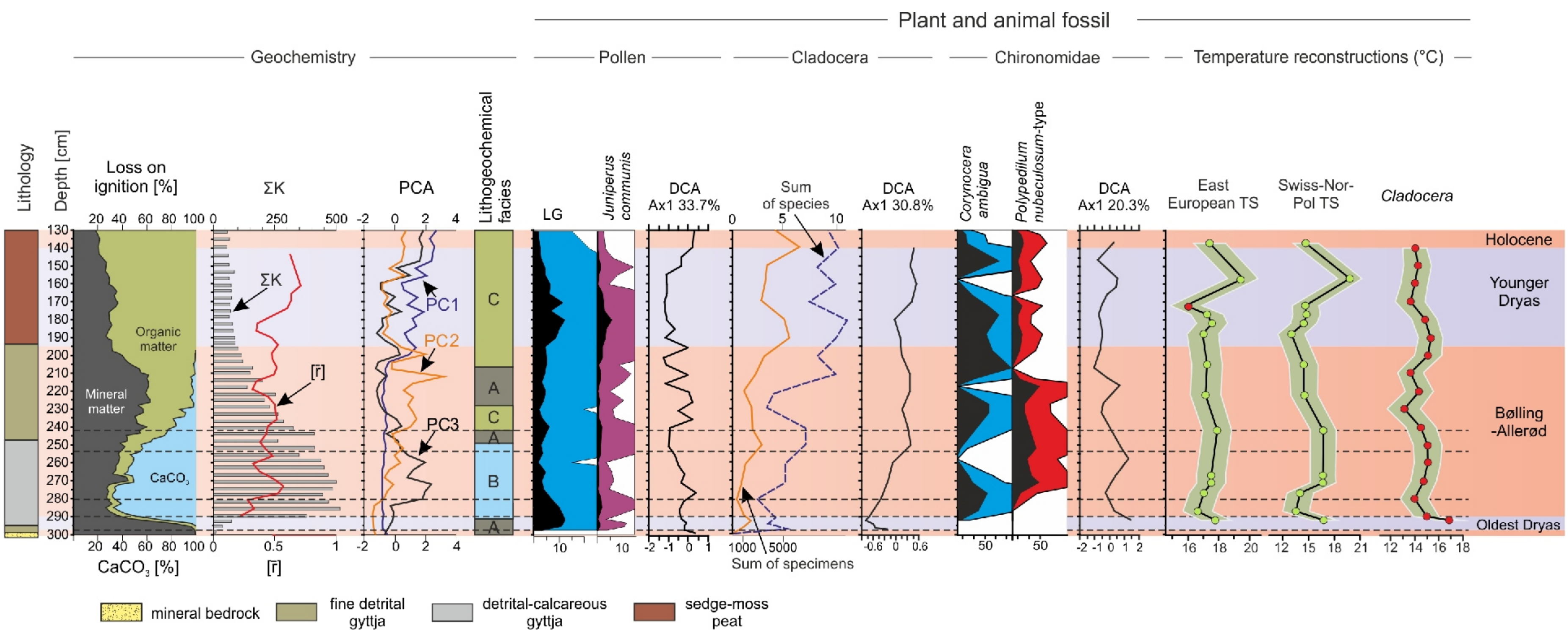

Fig. 8. Selected results of the multi-proxy analysis along with the interpretation of the temperature and chronostratigraphy of the Late Glacial

K calculated as K_x for each element ($K_x = AC_x/n_x$) after the procedure of Borówka (1992) and the [r] marker was calculated for 12 variables following the protocol described by Walanus (2000). Temperature reconstructions: red dots – poor modern analogues, green dots – good modern analogues the bottommost sample, i.e., 17.8°C (EE TS) and 16.8°C (SNP TS). A subsequent remarkable drop to 16.6°C–13.5°C (EE TS vs SNP TS, respectively) corresponds to the Oldest Dryas. During the Bølling-Allerød Interstadial, mean summer air temperature ranged between 17.0 and 17.9 °C (EE TS) and 14.0 and 16.7°C (SNP TS). The cool oscillation in the Older Dryas is not resolved due to coarse sample spacing. There is a remarkable transition from higher temperatures at the Bølling-Allerød transition to lower temperatures in the second phase of Allerød. During the first phase of the Younger Dryas CH-I mean summer air temperatures were lower: 15.9–17.6 °C (EE TS) or 13.0–14.8°C (SNP TS). The last but one sample (157 cm) yields the highest temperature value in the entire core – 19.6°C (EE TS) up to 19.8°C (SNP TS), suggesting warmer climatic conditions at the end of Younger Dryas, but it should be regarded as an outlier. Both EE TS and SNP TS reconstructions have moderate to good modern analogues. Only one sample in the EE TS reconstruction represents a poor modern analogue [minDC >10 percentiles (9.75318)]. According to SNP TS, all samples represent good to moderate modern analogues [minDC <10 percentiles (10.05639)]. Both reconstruction trends correspond generally with Chironomidae DCA Ax1 (from higher values during Bølling-Allerød to lower during Younger Dryas) but DCA SD values reveal oscillations in the Interstadial that do not follow temperature reconstructions (Fig. 8).

The Cladocera-inferred (CL-I) mean summer air temperature is based on Fn TS. The CL-I temperature reconstruction reveals a consistent trend with CH-I reconstructions, except for the Younger Dryas. The values are slightly lower and range from 13.1°C (230 cm) to 16.9°C (292 cm). The amplitude is also generally lower than in CH-I reconstructions. Subsequently, in concert with CH-I, temperature drops to 13.9°C at the Oldest Dryas-Bølling transition. During the Bølling-Allerød Interstadial mean summer air temperature ranges from 13.1 to 15.1°C. During the Younger Dryas CL-I summer temperature remains similar to the range reconstructed for the Bølling-Allerød Interstadial (13.6–15.3°C). All the Cladocera communities represent poor modern analogues to Fn TS [minDC >3.48 (10 percentile)].

PALAEOLAKE FORMATION (INITIAL STAGE)

The Ługi fen is one of many peatlands formed within the middle course of the Warta River system. Its fluvial origin is indicated by lithological features of the deposits in the basal part of the fen section, and in the surroundings (Figs. 1 and 2). The palaeolake, whose deposits are buried under the peat series, was formed within a fluvial depression, probably as part of a braided river channel of the Warta River, which used this valley in the Late Pleni-Weichselian (Klatkowa and Załoba, 1991; Forysiak, 2005, 2012). Following an episode of efficient fluvial aggradation, which accumulated high terrace alluvia (synchronously with glacier advance phases), a rapid base-level lowering occurred in the Warta River system, which led to channel downcutting by ~10–15 m (Turkowska, 1988, 2006; Klatkowa and Załoba, 1991; Petera, 2002; Forysiak, 2005). Part of the valley including the Ługi site was cut off from the Warta River at that time, and water flowed via a different course, between Brodnia and Jeziorsko (Fig. 1). The depressions of the braided river bed became shallow basins. Some of them became filled with water, likely derived from rainfall and surface runoff from the immediate surrounding. Groundwater supply was likely hampered by permafrost, as this stage of the fen development is correlated with the Oldest Dryas, a period for which continuous or discontinuous permafrost presence is inferred for central Poland (Goździk, 1995). Ground-ice lenses may have occurred in fluvial deposits and in sediments infilling floodplain-lacustrine depressions in the Late Pleni-Weichselian (Goździk and Konecka-Betley, 1992a; Turkowska, 1997). Biogenous sedimentation within such depressions took place in shallow-water conditions, as recorded in the layer of fine detritus gyttja with an admixture of mineral matter, mostly sand.

The events recorded at the Ługi site took place in the Late Weichselian, i.e., a period characterized by alternating phases of cooling and warming (Brooks and Langdon, 2014). These changes were of global extent and are recorded in a variety of depositional environments (Dzieduszyńska and Forysiak, 2013; Müller et al., 2021). In the case of the Jadwichna-Pichna Valley, individual climatic changes of the Late Weichselian determined water circulation, and both the type and efficiency of hydrochemical processes. The chemical composition of biogenic sediments laid down during this time is an archive of meteoric water circulation in oxidising conditions, and of leaching of elements from the acidic to weakly acidic soil cover within the catchment. As a result, the concentrations of K, Mg, Fe, Ni and Ca are closely linked to sedimentary lithology in the studied basin, and the highest concentrations of these metals were documented in mineral-organic and carbonate deposits.

The fine detritus gyttja documented in the basal part of the section shows the highest proportion of mineral matter, with a negligible percentage of organic matter and a total absence of calcium carbonate. The sum of lithophile elements is nearly twice as high as Ca concentration (Fig. 7). Intense denudation of the basin catchment (a stage correlated with the Oldest Dryas) took place while the plant cover was poorly developed, and the soil cover was not yet stabilized. This is corroborated also by elevated concentrations of Fe, Cr and Ni. The lack of correlation between the Fe/Mn and Cu/Zn ratios in the deposits, however, precludes an interpretation of their changes in the context of redox conditions, as previously performed for other sections representing small river valleys, and offering an archive of the Late Weichselian in central Poland (Niska et al., 2017; Okupny and Pawłowski, 2021; Płóciennik et al., 2021).

The chironomid stratigraphy is consistent with geochemical patterns. In the Ługi lacustrine sediments chironomids (and algae) that are indicative of permanent water conditions dominate, which is why at least a shallow water body existed throughout the Late Weichselian. In the initial stage of the palaeolake development, the dominant chironomid species were those preferring slightly alkaline conditions (*Polypedilum sordens*-type, *Chironomus anthracinus*-type, *Dicrotendipes nervosus*-type, *Glyptotendipes barbipes*-type, *Micropsectra radialis*-type, *Orthocladius holsatus*-type, *Lipiniella*, *Einfeldia dissidens*-type). During the mire formation stage, the pH declined, as indicated by acidophilic taxa such as *Pseudosmittia* and *Neozavrelia*.

The Oldest Dryas is characterised by a low frequency of cladocerans. *Chydorus sphaericus,* which is the dominant species, is known to occur over a wide range of conditions, and is tolerant of environmental stress, including cold climate (Whiteside, 1970).

The basin-forming stage ends with a distinct change in the pollen record upsection from 280 cm core depth. At this level, a distinct increase is observed in the sum of tree pollen grains, and a reduction in the proportion of pollen grains from cold-adapted plants.

INTERPHASE LAKE STAGE (BØLLING-ALLERØD)

Due to climate warming and local permafrost thawing, surface denudation was initiated, as documented for many regions of Central Europe (Goździk and Konecka-Betley, 1992a; Forysiak et al., 2010; Kulesza and Bałaga, 2015). Depending on the local geological and geomorphological conditions, distinct changes were taking place in the quantity and origin of mineral sediments supplied to lakes existing at that time (Dobrowolski et al., 2001; Bałaga, 2007; Błaszkiewicz, 2007).

The progressive warming caused the development of plant cover in the basin catchment, but also changes in the lake ecosystem. A change in water supply to the lake may have also contributed to these transformations, as early in this stage there was a clear increase of groundwater supply, caused most likely by the unlocking of deeper circulation and thermal gradient, for the dissolved calcareous ions to able to be precipitated (Goździk and Konecka-Betley, 1992b; Dobrowolski, 2011). Such conditions were favourable for the accumulation of detrital calcareous gyttja (280–190 cm). $CaCO_3$ precipitation was accomplished via biological processes, owing to plant uptake of CO_2, and via physico-chemical processes, e.g., water temperature changes. Previous research on sites hosting calcareous deposits of Late Weichselian age (Głowacki, 2006; Strzelecka and Wróbel, 2021) suggests that their accumulation was mostly attributable to $CaCO_3$ incrustations by plants, and less frequently to molluscan skeletons. The main source of carbonates were the tills and fluvioglacial sands surrounding the basin, and composing extensive terraces in the vicinity of the villages of Glinno and Brodnia. Notably, local hydrogeological conditions and the character of depositional basins were commonly the most important factor in interpreting the conditions of lacustrine carbonate sediment deposition (Stasiak, 1971; Żurek and Dzięczkowski, 1971; Gerlach, 1990; Harasimiuk et al., 2010; Okupny et al., 2016b). This is corroborated by a comparison of calcareous gyttja sedimentation rates compiled for selected limnogenous fens of central Poland (Fig. 9). Groundwater levels and lake levels fluctuated during the Late Weichselian, but the most optimal conditions for calcareous gyttja deposition occurred in the Bølling-Allerød.

This comparison corroborates previous studies in that the assessment of biogenic accumulation basins as natural geological barriers requires a detailed recognition of the catchment geology, but also depends on the type of water supply, which in turn determines the physical and chemical parameters of water supplying a given lake basin or mire (Oświt et al., 1980; Okupny et al., 2014a; Ścibior et al., 2015). As a consequence, river valley deposits are among the most non-homogeneous as regards biogenic composition (Pawłowski et al., 2014; Okupny et al., 2016a; Rydelek, 2021).

Moreover, this geochemical stratification of the profile (280–190 cm) reflects the three-stage evolution of the Ługi lake. In general, the changes in sediment chemical composition are gradual, which – in conjunction with the increasing organic matter content – testified to a slow infilling of a small lake basin with deposits.

In the first stage (280–250 cm), decarbonization and endogenous $CaCO_3$ precipitation are reflected by a rapid increase in Ca concentrations (reaching >250 mg/g) with a concomitant decrease in the concentrations of all the remaining elements. The proportion of Ca in the total sum of concentration coefficients reaches 54%, while in a Younger Dryas-aged sedge-moss peat, the analogous value is <40%.

Another significant event is documented between 250 and 240 cm, where detrital-calcareous gyttja is gradually replaced by deposits with an admixture of non-carbonate mineral matter (from 40 to 52%), with a concomitant decrease in the sum of the concentration coefficient (K) and PC1 axis (Fig. 7), which are interpreted as measures of intensity of carbonate leaching in the studied basin catchment. Clear oscillations are also displayed by the PC2 and PC3 axes (Fig. 7), whose increases are correlated with the changes in other geochemical proxies (mostly Ca/Mg and Fe/Mn), and are restricted to individual sediment types (e.g., detrital calcareous gyttja and fine-detrital gyttja; Fig. 10). In this case, the key factors controlling transformation of organic matter were the depth of the groundwater table and the associated redox conditions. These factors acted in conjunction with an increase in passive allochthonous matter supply, consistent with the models documented at other Polish Lowland sites, both lacustrine and telmatic (Damicz, 1995; Cedro, 2007; Forysiak et al., 2012).

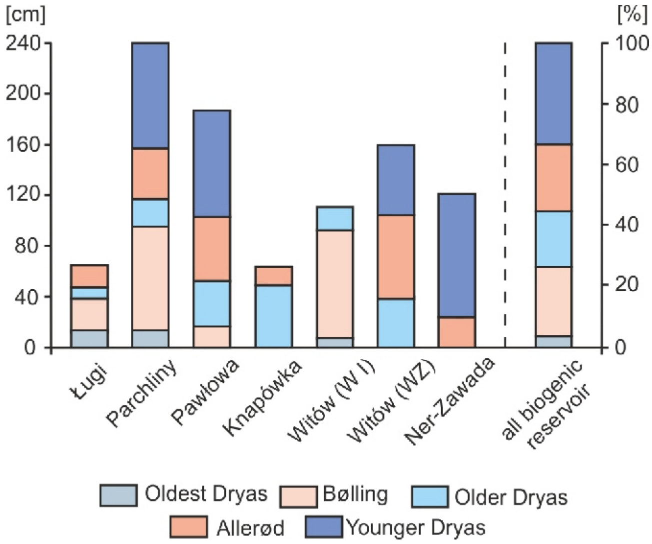

Fig. 9. Rate of calcareous gyttja sedimentation in the Late Weichselian at Ługi (this study); other sites in central Poland according to Wasylikowa (1964, 2011), Kaczmarska (1973), Goździk and Konecka-Betley (1992), Forysiak et al. (2010), Pawłowski et al. (2016b), and all biogenic accumulation sites

Between 240 and 190 cm core depth, the chemical composition of the deposits is an archive of a gradual restriction of carbonate sediment accumulation ($CaCO_3$ content decreases from 40 to 1%, and Ca concentration drops from 180 mg/g to 7.6 mg/g). A reduction in Ca/Mg ratio to as little as 5.53 points to a distinctly weaker intensity of carbonate leaching from the catchment. The average proportion of mineral matter does not exceed 56%, with a concomitant increase in organic matter from 21 to 74%. Furthermore, a clear increase in the eutrophication proxy (i.e., Fe/Ca ratio even >25), coupled with an increase in Fe/Mn value and Zn concentration (>30 μg/g), points to a deterioration of redox conditions during the Allerřd. This may have been caused by the decomposition of large volumes of birch leaves supplied to the basin, as birch is noted for its unusually intense absorption of Zn (Fortescue, 1980). An increase in Fe concentration from 100 to 294 mg/g indicates a positive correlation with mineral matter proportion, and Fe/Mn ratio values in excess of 100 may indicate a change in soil reaction in the immediate vicinity of the basin. As a consequence, the selective mobility of certain metals in the terrestrial environment became diminished, as reported previously for the Late Weichselian period (Borówka et al., 1999; Konecka-Betley and Manikowska, 2005).

The distinct increase in the number of Cladocera species and specimens suggests warmer waters, and perhaps, a longer open-water season in the lake, as indicated by the presence of planktonic taxa from the Daphniidae family. Additionally, a gradual increase in the frequency of more phytophilous Cladocera

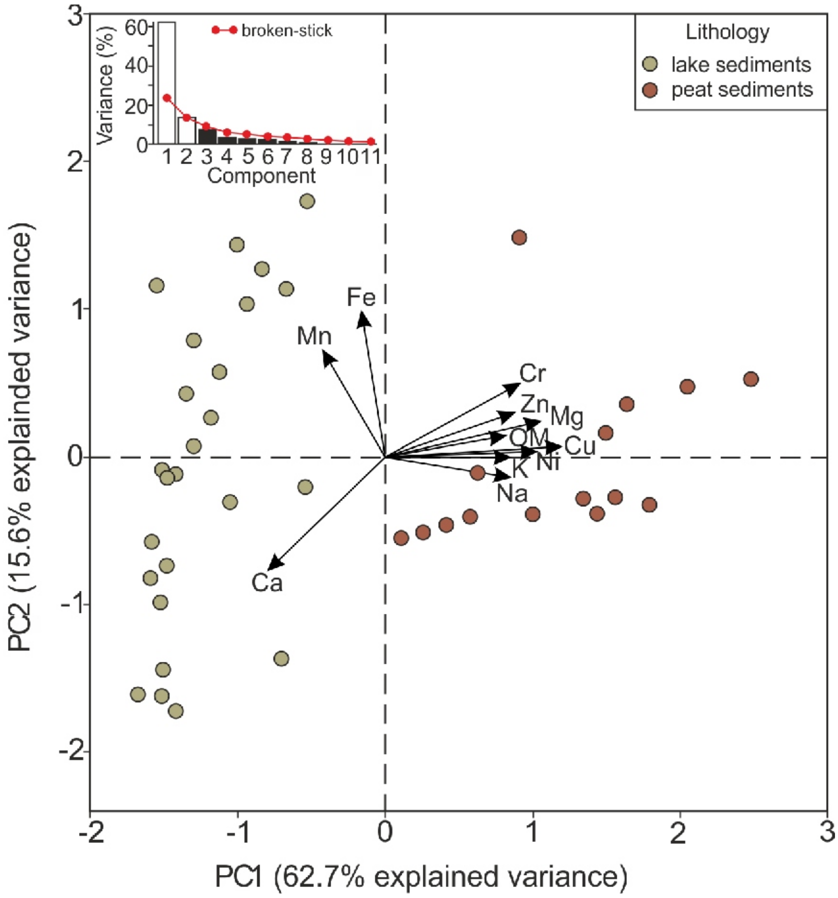

Fig. 10. PCA biplot of geochemical data for the Ł-1 core

species such as *Alona affinis*, *Camptocercus rectirostris, Alona guttata,* and *Acroperus harpae* implies an increasing macrovegetation cover in this part of the lake. These changes in the cladoceran record may be a response to conditions of the Bølling. At a depth of 245–225 cm further noticeable changes in the cladoceran assemblages are noted. The warm-water preferring taxa (*Camptocercus rectirostris*, *Graptoleberis testudinaria*) disappear. Additionally, a decrease in cladoceran abundance, and domination of macrophyte/sediment taxa such as *Alona affinis* and *Chydorus sphaericus*, which are tolerant of environmental stress, including cold climate, are observed. These are accompanied by a sediment-associated taxon, *Pleuroxus uncinatu*s, whose presence can be linked to enhanced soil erosion from the catchment. All this could indicate a cold period, possibly the Older Dryas, and a transition to the Allerřd. From 220 cm upsection, an increase in cladoceran abundance is observed, and warm-water preferring taxa appear. This suggests milder conditions in the lake.

PEATLAND/MIRE STAGES (YOUNGER DRYAS AND HOLOCENE)

The onset of peat accumulation, with organic matter content exceeding 70% (Fig. 7), is observed at 190 cm depth in the Ł-1 core. The studied core was taken from the part of the basin where the thickness of gyttja was the largest, but also at a point within a depression where the contact between the lacustrine series and the peat is located at the deepest level. What follows is that deposits from this core interval record a total terrestrialisation of the palaeolake surface. The studied core displays a many-fold increase in lithophile element concentrations (Na, K and Mg), up to levels typical of sediments laid down in lacustrine and telmatic environments, consistent with numerous sites located in central Poland (Forysiak, 2012; Pawłowski et al., 2015; Petera-Zganiacz et al., 2022; Antczak-Orlewska et al., 2023). This is associated with a deterioration of climatic conditions during the Younger Dryas, and a resultant withdrawal of forest assemblages, which led to intensified erosion within the catchment. More intense slope processes and aeolian processes are consistent with the highest values (reaching >0.6) of the environmental condition dynamics index [*r*], in the absence of $CaCO_3$, and a rapid decrease in Ca concentrations in the lake deposits from >200 mg/g to ~12–14 mg/g. A clear change in the conditions of sediment accumulation, and a distinct reduction in the significance of groundwaters in the water balance of the Ługi basin, caused a tenfold drop in the metal concentration sum coefficient *K* (Fig. 11).

The beginning of the Younger Dryas in the cladoceran record displays a relatively high number of species and specimens, especially of the species associated with the littoral zone of eutrophic lakes such as *Chydorus sphaericus*, *Coronatella rectangula* and pelagic taxa such as *Bosmina longirostris*, which are also considered trophic indicators. In the second part of the Younger Dryas, from 180 cm core depth upsection, cladoceran abundance decreases, and conditions become less favourable, suggesting gradual terrestrialisation of the lake.

In the Younger Dryas and the early Preboreal Period, *Tanytarsus lugens*-type and *Micropsectra radialis*-type – oligotrophs associated with higher pH and low air temperature –

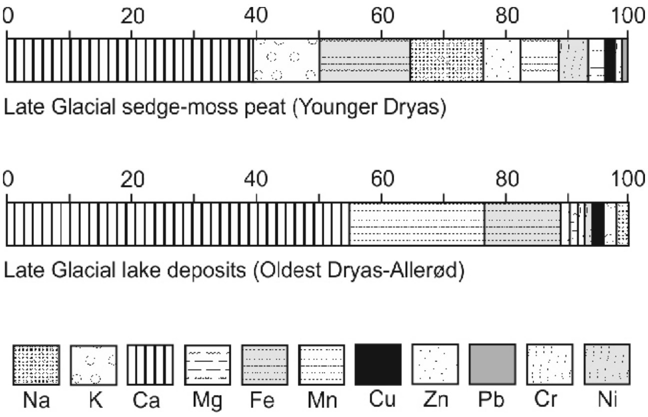

Fig. 11. Differences in concentration coefficients for particular metals, presented as percent of the sum of these coefficients in two deposit groups of the Ł-1 core

appeared. Although their occurrence may reflect climate cooling, *Corynocera ambigua* remains a dominant species.

Corynocera ambigua was the dominant species in the lake through the whole Late Weichselian sequence. Its ecological preferences are still a matter of debate. In many publications, it is treated as a typically oligotrophic and cold-adapted species (Brooks et al., 2007), or even as an indicator of water temperature decrease. Luoto et al. (2008) recorded *Corynocera ambigua* in even colder conditions than the typically cold-adapted *Tanytarsus lugens*-type. Similar results were obtained by van Asch et al. (2012), who classified this species among other cold condition indicators such as *Micropsectra radialis*, *Paracladius* or *Corynocera olivieri*.

On the other hand, the temperature preferences of *Corynocera ambigua* are unclear (Brodersen and Lindegaard, 1999). Despite abundant occurrences in cold Arctic and subarctic lakes, it has also been found in warmer lakes characterised by high productivity (e.g., Halkiewicz, 2008, Kotrys et al., 2020). There are also suggestions that while *Corynocera olivieri* is indicative of cold conditions, *Corynocera ambigua* is more typical of warmer climate conditions (Porinchu et al., 2002). Luoto and Sarmaja-Korjonen (2011) argued that this species adapts to the existing climate conditions. In Finland, *Corynocera ambigua* prefers cold lakes, but its large adaptability to local conditions allows for equally frequent occurrences in warmer Danish lakes (Brodersen and Lindegaard, 1999). In the Ługi deposits studied, *C. ambigua* was abundant in the Late Weichselian (Ch1-5) and after the Holocene onset it disappeared, as elsewhere in the region (Pawłowski et al., 2015; Płóciennik et al., 2015). The marked domination of *C. ambigua* might interfere with the results of temperature reconstructions, but EE TS and SNP TS, which include the warmer part of its range (Polish sites), do not cause underestimation of temperatures when this species is abundant. In SNP TS *C. ambigua* is an intermediate temperate species. When only SN TS is included in the reconstruction, temperatures are considerably lower because the species is represented only in its cold range of Norwegian lakes (Heiri et al., 2011). CH-I EE TS and SNP TS reconstructions from the Ługi Interstadial section are at similar level to Bęczkowice records (16–18°C; Płóciennik et al., 2021). The CL-I summer temperature reconstruction from the Ługi Interstadial section is lower than those inferred from chironomids and oscillates at ~14 °C, which is similar to the Pawłowa palaeolake CL-I record (Pawłowski et al., 2016b). The CL-I temperatures are lower than CH-I ones because of ecological characteristics of the cladocerans and chironomids. Cladocerans are more sensitive to water temperature than Chironomidae (Płóciennik et al., 2020).

The CH-I SNP TS reconstruction suggests that the onset of the Younger Dryas could be marked by substantial cooling as it was 100 km north, at Lake Gościąż (Płóciennik et al., 2022) and, excluding outlier sample at 157 cm, seems to fit the general trend in Greenland ice cores (Rasmussen et al., 2006). However, other reconstructions from the Łódź region contradict this trend, suggesting locally warmer climatic conditions. The CH-I reconstruction from Rozprza (Antczak-Orlewska et al., 2023) and CL-I reconstructions from Świerczyna and Pawłowa (Pawłowski et al., 2015, 2016b) show a bit warmer first stage of the Younger Dryas, which is more consistent with the CL-I than CH-I reconstruction from Ługi.

Species that may exist in waters with low pH (e.g., *A. excisa*, *A. guttata*) and with a high density of macrophytes are frequent (Pawłowski et al., 2015). This likely resulted from the Younger Dryas cooling, as species tolerant of environmental stress, including of cold climate (*Alona affinis* and *Chydorus sphaericus*), are dominant.

The peat layer extending from 140 cm core depth to the terrain surface displays progressive signs of strong decomposition toward the top. There are also layers with an increased mineral matter content, likely accumulated due to a break in peat sedentation, perhaps also due to desiccation and partial mineralization of the deposits. The entire surface of the mire bears signs of peat exploitation, these being partly obscured by a secondary succession of peat-forming vegetation during the past several decades. For this reason, the part of the succession correlated with the Holocene offers a discontinuous record of mire evolution, likely even disturbed due to human activity in the uppermost part. Therefore, only palaeoecological interpretation of the older part of this record was justified.

The Holocene deposits from the Ługi site are characterised by increasing organic matter content (~90%), paralleled by low values of all of the calculated geochemical ratios established for the peat series (Okupny, 2013). Such biogenic deposits accumulated in the Holocene in numerous river valley mires, but the sedimentation rate varied greatly, and is not easily constrained due to periods of low water level and the introduction of hydrotechnical treatments favouring organic matter decomposition (Forysiak, 2012).

At the beginning of the Holocene, cladoceran abundance was still relatively high, especially that of macrophyte-associated taxa, which implies increasing macrovegetation, continued terrestrialisation, and mire formation. Starting from 100 cm core depth, conditions become unfavourable for cladocerans – only taxa that may exist in waters with low pH and with a high density of macrophytes are present (Pawłowski et al., 2015). At the end of the Holocene, the occurrence of few, sporadic fossils of macrophyte/sediment-associated taxa such as *A. affinis*, *A. guttata* and *Ch. sphaericus* indicates a temporary increase in the water table level in the mire. However, acidophiles are represented by individual head capsules and the number of midges preferring alkaline and circum-neutral conditions was definitely higher at the beginning of the Holocene. This raises a question whether the decline in midge abundance since the Holocene onset was associated with a gradual acidification, or with terrestrialisation and disappearance of a permanent water table (Pawłowski et al., 2015; Płóciennik et al., 2016)?

CONCLUSIONS

A palaeogeographic study of a lacustrine sedimentary section retrieved close to the western slope of the Jadwichna-Pichna valley indicates that the development of the lake basin was associated with waters that filled an abandoned depression in a braided river channel. No traces of fluvial processes were detected after that part of the valley was cut off from the Warta River system before the Oldest Dryas.

Fine-detrital gyttja, detrital-calcareous gyttja and peat deposits accumulated in the palaeobasin. Depending on their chemical composition, these were classified into three lithogeochemical facies. In comparison to other sites from central Poland bearing Late Weichselian carbonate deposits, the studied section shows a remarkably slow accumulation rate, likely resulting from a small portion of the catchment being composed of tills and fluvioglacial sands. As a consequence, the chemical composition of waters supplying the palaeolake at Ługi was shaped by the groundwaters reaching the alluvial deposits from the post-glacial plateau in the vicinity of Brodno and Glinne, initially also river waters, periodically infiltrating the alluvia, and rainwaters that did not undergo evapotranspiration.

The reconstructed changes in sediment chemical composition and lithology indicate a variable intensity of denudational processes that developed during the Late Weichselian. The basic factor modifying the conditions of sedimentation within the lake and the mire were the air-water conditions, associated with the terrain relief and hydrogeology and partly changes in vegetation cover. In the studied section of the river valley, geology and morphology determined the considerable spatial and temporal variability in surface run-off, and the rate of catchment leaching depended on the amount of the circulating water, and the variable depth of the first aquifer. The high concentrations of elements such as Ca, Mg and Cu testify to the increasing contribution of groundwater supply to the river discharge of the Jadwichna-Pichna system, mainly in the Bølling-Allerød. The intense weathering of morainic and fluvioglacial sediments making up the catchment of the basin was most clearly linked to increased deforestation during the Younger Dryas and, in turn, is indicated by the increasing passive supply of allochthonous elements such as K, Na and Ni. Hence, the local geochemical patterns of the Younger Dryas were generally parallel to the regional changes of vegetation cover in the middle part of the Warta River system.

Palynology served as a basis to distinguish pollen zones indicating three cool episodes, including the more pronounced Oldest Dryas and Younger Dryas, and a less well-defined cooling within the Bølling-Allerød complex, which is correlated with the Older Dryas. While the radiocarbon ages are dubious and inconsistent with palynological dating, age control for the studied profile is based on palynology. The pollen record is likely continuous through the Late Weichselian. In the mire development phase, however, the record is likely discontinuous.

Changes in cladoceran and chironomid assemblages at the Ługi site demonstrate a correlation with climate change. In cold periods such as the Oldest Dryas and Older Dryas, low cladoceran abundance and diversity reflect unfavourable conditions for zooplankton development. Conversely, in the Bølling and Allerød, a clear increase in the number of cladoceran species and specimens, especially of planktonic and more phytophilous taxa living in the warm water littoral zone, suggests warmer waters, and a longer open-water season in the lake. These trends are generally consistent with CH-I temperature reconstructions, except for the Younger Dryas, when the lake transformed into a mire, which influenced the benthic and zooplankton populations. A high domination of *C. ambigua* at the Ługi site does not obscure CH-I temperature reconstructions which reveal a common trend to DCA and have good to moderate modern analogues. The temperature values are consistent with other CH-I EE TS and SNP TS reconstructions from central Poland for the Bølling and Allerød (Kotrys et al., 2020). The latest reconstruction from Lake Gościąż (Płóciennik et al., 2022) indicates clear summer air temperature cooling at the beginning of the Younger Dryas. This would support the SNP TS reconstruction from Ł-1 which indicates some drop of temperature at the beginning of the Younger Dryas and then a gradual increase. The Fn TS CL-I temperature reconstruction is more common to regional trends for the Younger Dryas (CH-I from Rozprza, CL-I from Świerczyna and Pawłowa) with higher temperatures at the onset and cooling in its mid-stage. The chironomid sample resolution of Ł-1 is too low for precise palaeoclimatic interpretation.

Acknowledgements. This work was made possible by financial support from the government (grant no. NN 306 276735). We are grateful to J. Tomkowiak, who participated in laboratory work, and thanks to J. Petera-Zganiacz for sharing the result of a radiocarbon date from Ł-2 core. We would like to thank the reviewers, whose comments greatly improved the manuscript.

REFERENCES

Andrzejewski, L., 1995. Genesis of the fluvial system of the Lower Vistula River based in the selected side valleys. Geographical Studies PAN, Special Issue "Evolution of the Vistula river valley", **8**: 139–156.

Andrzejewski, L., Krzemień, K., Zwoliński, Z., 2018. Outline of natural and anthropogenic determinants for the evolution of valley and river channel system in Poland (in Polish with English summary). Landform Analysis, **37**: 17–51.

Antczak-Orlewska, O., Okupny, D., Pawłowski, D., Kotrys, B., Krąpiec, M., Luoto, T.P., Peyron, O., Płóciennik, M., Stachowicz-Rybka, R., Wacnik, A., Szmańda, J.B., Szychowska-Krąpiec, E., Kittel, P., 2023. The environmental history of the oxbow in the Luciąża River valley – study on the specific microclimatic during Allerød and Younger Dryas in central Poland. Quaternary International, **644–645**: 178–195.

Apolinarska, K., Woszczyk, M., Obremska, M., 2012. Late Weichselian and Holocene palaeoenvironmental changes in northern Poland used on the Lake Skrzynka record. Boreas, **41**: 292–307.

van Asch, N., Lutz, A.F., Duijkers, M.C.H., Heiri, O., Brooks, S.J., Hoek, W.Z., 2012. Rapid climate change during the Weichselian Lateglacial in Ireland: Chironomid-inferred summer temperatures from Fiddaun, Co. Galway. Palaeogeography, Palaeoclimatology, Palaeoecology, **315–316**: 1–11.

Balwierz, Z., 2010. Analiza pyłkowa osadów torfowiska Żabieniec (in Polish). In: Torfowisko Żabieniec. Warunki naturalne, rozwój i zapis zmian paleoekologicznych w jego osadach (eds. J.

Twardy, S. Żurek, J. Forysiak): 179–188. Bogucki Wyd. Naukowe, Poznań.

Balwierz, Z., Goździk, J., 1997. Palaeoenvironmental changes established through pollen analysis of Latevistulian calcareous deposits in closed depressions in Bełchatów. Acta Universitatis Lodziensis, Folia Geographica Physica, **1**: 7–21.

Bałaga, K., 2007. Changes in the natural environment recorded in the sediments of the Karaśne lake-mire complex (Lublin Polesie, E Poland). Geochronometria, **29**: 1–21.

Berglund, B.E., Ralska-Jasiewiczowa, M., 1986. Pollen analysis and pollen diagrams. In: Handbook of Holocene Palaeoecology and Palaeohydrology (ed. B.E. Berglund): 455–484. Wiley and Sons Ltd., Chichester.

Beug, H.-J., 2004. Leitfaden der Pollenbestimmung für Mitteleuropa und angrenzende Gebiete. Verlag Dr. Friedrich Pfeil, München.

Birks, H.H., Ammann, B., 2000. Two terrestrial records of rapid climatic change during the glacial-Holocene transition (14,000–9000 calendar years B.P.) from Europe. Proceedings of the National Academy of Sciences of the United States of America, **97**: 1390–1394.

Birks, H.H., Battarbee, R.W., Birks, H.J.B., 2000. The development of the aquatic ecosystem at KrÍkenes Lake, western Norway, during the late-glacial and early-Holocene – a synthesis. Journal of Paleolimnology, **23**: 91–114.

Bjerring, R., Becares, E., Declerck, S., Gross, E.M., Hansson, L.A., Kairesalo, T., Nykanen, M., Halkiewicz, A., Kornijów, R., Conde-Porcuna, J.M., Seferlis, M., Noges, T., Moss, B., Amsinck, S.L., Vad Odgaard, B., Jeppesen, E., 2009. Subfossil Cladocera in relation to contemporary environmental variables in 54 Pan-European lakes. Freshwater Biology, **54**: 2401–2417.

Borówka, R.K., 1990. Late Vistulian and Holocene denudation magnitude in morainic plateaux: case studies in the zone of maximum extend of the last ice sheet. Quaternary Studies in Poland, **9**: 5–31.

Borówka, R.K., 1992. The pattern and magnitude of denudation in intraplateau sedimentary basins during the Vistulian and Holocene (in Polish with English summary). Adam Mickiewicz University Press, Seria Geografia, **54**.

Borówka, R.K., Belczyńska, A., Tomkowiak, J., 1999. Morphological features and some chemical properties of fossil soils developed within the aeolian sands in the vicinity of Świętoujście and Grodno (in Polish with English summary). In: Ewolucja geosystemów nadmorskich południowego Bałtyku (eds. R.K. Borówka, Z. Młynarczyk and A. Wojciechowski): 37–42. Bogucki Wyd. Naukowe, Poznań-Szczecin.

Borówka, R.K., Tomkowiak, J., Okupny, D., Forysiak, J., 2014. Chemical composition of biogenic sediments from the Ner River Valley (Mianów peatland, Łask Elevation). Folia Quaternaria, **82**: 51–69.

Błaszkiewicz, M., 2007. Geneza i ewolucja mis jeziornych na młodoglacjalnym obszarze Polski – wybrane problemy (in Polish). Studia Limnologica et Telmatologica, **1**: 5–16.

Brodersen, K.P., Lindegaard, C., 1999. Classification, assessment and trophic reconstruction of Danish lakes using chironomids. Freshwater Biology, **42**: 143–157.

Brooks, S.J., Birks, H.J.B., 2001. Chironomid-inferred air temperatures from Lateglacial and Holocene sites in north-west Europe: progress and problems. Quaternary Science Reviews, **20**: 1723–1741.

Brooks, S.J., Langdon, P.G., 2014. Summer temperature gradients in northwest Europe during the Lateglacial to early Holocene transition (15–8 ka BP) inferred from chironomid assemblages. Quaternary International, **341**: 80–90.

Brooks, S.J., Langdon, P.G., Heiri, O., 2007. The Identification and Use of Palaearctic Chironomidae Larvae in Palaeoecology. QRA Technical Guide No. 10. Quaternary Research Association, London.

Brzezińska-Wójcik, T., Kociuba, W., 2001. Transformation of the Roztocze segment of the Wieprz River Valley (SE Poland) in the Pleistocene (in Polish with English summary). Przegląd Geologiczny, **49**: 257–266.

Cedro, B., 2007. Evolution of the River Rega valley near Łobez in Late Pleistocene and Early Holocene. Geochronometria, **28**: 55–59.

Damicz, J., 1995. Związek wieku osadów pojeziornych z ich typem litologicznym na Warmii i Mazurach (in Polish). Przegląd Geologiczny, **43**: 35–38.

Dembek, W., Piórkowski, H., Rycharski, M., 2000. Wetlands against the background of physico-geographical regionalization of Poland (in Polish with English summary). Biblioteczka Wiadomości IMUZ, **97**.

Dobrowolski, R., 2011. Problems with classification of deposits of spring-fed fens (in Polish ith English summary). Studia Limnologica et Telmatologica, **5**: 3 -12.

Dobrowolski, R., Bałaga, K., Bogucki, A., Fedorowicz, S., Melke, J., Pazdur, A., Zubovic, S., 2001. Chronostratigraphy of the Okunin and Czerepacha lake-mire geosystems (Volhynia Polesiye, NW Ukraine) during the Late Glacial and Holocene. Geochronometria, **20**: 107–115.

Dzieduszyńska, D., Forysiak, J., 2013. Signals of environmental changes of the Late Vistulian (Weichselian late glacial) in biogerasmussnic sediments of the Łódź Region. Acta Geographica Lodziensia, **101**: 37-48.

Faegri, K., Kaland, P.E., Krzywinski, K., 1989. Textbook of Pollen Analysis. John Wiley & Sons, London.

Faustova, M., Sacherová, V., Svensson, J.E., Taylor, D.J., 2011. Radiation of European *Eubosmina* (Cladocera) from *Bosmina* (*E.*) *longispina* – concordance of multipopulation molecular data with paleolimnology. Limnology and Oceanography, **56**: 440–450.

Flössner, D., 1972. Krebstiere, Crustacea (Kiemen- und Blattfüßer, Branchiopoda, Fischläuse, Branchiura). Die Tierwelt Deutschlands 60. VEB Gustav Fischer Verlag, Jena.

Flössner, D., 2000. Die Haplopoda und Cladocera (ohne Bosminidae) Mitteleuropas. Backhuys Publishers, Leiden.

Fortescue, J.A.C., 1980. Environmental Geochemistry. A Holistic Approach. Springer, New York.

Forysiak, J., 2005. The development of the Warta river valley between Burzenin and Dobrów in the Late Quaternary Period (in Polish with English summary). Acta Geographica Lodziensia, **90**: 1–116.

Forysiak, J., 2012. Record of changes in the natural environment of the Late Weichselian and Holocene preserved in the sediments of peatlands of the Łódź region (in Polish with English summary). Acta Geographica Lodziensia, **99**: 1–164.

Forysiak, J., Obremska, M., Pawłowski, D., Kittel, P., 2010. Late Vistulian and Holocene changes in the Ner River valley in light of geological and palaeocological data from the Ner-Zawada peatland. Geologija, **52**: 25–33.

Forysiak, J., Borówka, R.K. Kloss, M., Obremska, M., Okupny, D., Żurek, S., 2012. Geological and geomorphological features of the Rąbień peatland and preliminary results of investigations of biogenic sediments (in Polish with English summary). Acta Geographica Lodziensia, **100**: 65–76.

Forysiak, J., Kadrow, S., Noryśkiewicz, A.M., Okupny, D., Saile, T., Twardy, J., Zawiska, I., 2021. The environmental context of Early Neolithic Cultural transformation in the Targowisko settlement region (Southern Poland). Sprawozdania Archeologiczne, **73**: 177–201.

Frey, D. G., 1986. Cladocera analysis. In: Handbook of Holocene Paleoecology and Paleohydrology (ed. B.E. Berglund): 667–692. John Wiley and Sons, Chichester.

Gerlach, T., 1990. Ewolucja młodoczwartorzędowych zbiorników jeziornych centralnej części Dołów Jasielsko-Sanockich (in Polish). Studia Geomorphologica Caraptho-Balcanica, **24**: 119–160.

Goździk, J., 1995. A permafrost evolution and its impact on some depositional conditions between 20 and 10 ka in Poland. Biuletyn Peryglacjalny, **34**: 53–72.

Goździk, J., Konecka-Betley, K., 1992a. Late-Vistulian carbonateous formations in outflow-closed depressions of the

Bełchatów Brown Coal strip mine. Part I. Genesis and stratigraphy (in Polish with English summary). Roczniki Gleboznawcze, **43**: 103–112.

Goździk, J., Konecka-Betley, K., 1992b. Late-Vistulian carbonateus formations in outflow-closed depressions of the Bełchatów Brown Coal strip mine. Part II. Chemical and mineral compositions (in Polish with English summary). Roczniki Gleboznawcze, **43**: 113–124.

Głowacki, M., 2006. Genesis of biogenic accumulation reservoirs near Brody in the Lubska Highland in light of morphological and lithological investigations (in Polish with English summary). Badania Fizjograficzne nad Polską Zachodnią. Seria A – Geografia Fizyczna, **57**: 21–34.

Gregory, K.J., Walling, D.E., 1973. Drainage Basin Form and Process. Arnold, London.

Grimm, E.C., 1992. TILIA/TILIA graph. Version 1.2. Illinois State Museum.

Halkiewicz, A. 2008. *Corynocera ambigua* (Insecta, Diptera) subfossils occurrence in recent sediments of four shallow Polesie lakes. Annales Universitatis Mariae Curie-Sklodowska: Biologia, Sectio C, **63**: 31.

Hammer, Ø., Harper, D.A.T., Ryan, P.D., 2001. PAST: Paleontological Statistics software package for education and data analysis. Palaeontologia Electronica, **4**: 1–9.

Harasimiuk, A., Wicik, B., Grabowski, T., 2010. The lake deposits in Płocki Basin (case studies of Lakes Rakutowskie and Żłoby). Limnological Review, **10**: 23–28.

Heiri, O., Brooks, S. J., Birks, H. J. B., Lotter, A. F., 2011. A 274-lake calibration data-set and inference model for chironomid-based summer air temperature reconstruction in Europe. Quaternary Science Reviews, **30**: 3445–3456.

Juggins, S., 2007. C2 Version 1.5 User Guide. Software for Ecological and Palaeoecological Data Analysis and Visualisation. Newcastle University, Newcastle upon Tyne.

Juggins, S., 2017. Rioja: Analysis of Quaternary Science Data. R package version 0.9-21. http://cran.r-project.org/package=rioja

Kaczmarska, I., 1973. Late-Glacial diatom flora at Knapówka near Włoszczowa (South Poland). Acta Palaeobotanica, **14**: 179–193.

Klatkowa, H., Załoba, M., 1991. Kształtowanie budowy geologicznej i rzeźby południowego obrzeżenia Basenu Uniejowskiego (in Polish). In: Przemiany środowiska geograficznego obszaru Konin-Turek (ed. W. Stankowski): 33–44. Wyd. Nauk UAM, Poznań.

Klatkowa, H., Załoba, M., 1992. Objaśnienia do Szczegółowej mapy geologicznej Polski 1:50 000, ark. Warta (in Polish). Państwowy Instytut Geologiczny, Warszawa.

Kłysik, K., 2001. Warunki klimatyczne. In: Funkcja regionalna Łodzi i jej rola w kształtowaniu województwa (in Polish). Zarys monografii województwa łódzkiego (ed. S. Liszewski): 68–81. Łódzkie Towarzystwo Naukowe, Łódź.

Kondracki, J., 2002. Geografia regionalna Polski (in Polish). Wyd. Naukowe PWN, Warszawa.

Konecka-Betley, K., Manikowska, B., 2005. Late Glacial and Holocene stratotype profile of palaeosols in the Warsaw Basin. Studia Quaternaria, **22**: 3–16.

Kordowski, J., Błaszkiewicz, M., Kramkowski, M., Słowiński, M., Tyszkowski, S., Brauer, A., Brykała, D., Gierszewski, P., Lamparski, P., Lutyńska, M., Mirosław-Grabowska, J., Noryśkiewicz, A.M., Obremska, M., Ott, F., Wulf, S., Zawiska, I., 2014a. Characteristics of depositional environments of Czechowskie Lake basin and its vicinity (in Polish with English summary). Landform Analysis, **25**: 55–75.

Kordowski, J., Gamrat, W., Gierszewski, P., Kubiak-Wójcicka, K., Szmańda, J.B., Tyszkowski, S., Solarczyk, A., 2014b. Record of fluvial and biogenic sedimentation processes in sediments of the Lower Vistula Valley floor (in Polish with English summary). Landform Analysis, **25**: 77–93.

Korhola, A., Rautio, M., 2001. Cladocera and other branchiopod crustaceans. In: Tracking environmental change using lake sediments, **4**: Zoological Indicators (eds. J.P. Smol, H.J.B. Birks and W.M. Last): 5–41. Kluwer Academic Publishers, Dordrecht.

Kotrys, B., Płóciennik, M., Sydor, P., Brooks, S.J., 2020. Expanding the Swiss-Norwegian chironomid training set with Polish data. Boreas, **49**: 89–107.

Kozarski, S., 1995. The periglacial impact on the deglaciated area of Northern Poland after 20 kyr BP. Biuletyn Peryglacjalny, **34**: 73–102.

Kulesza, P., Bałaga, K., 2015. Reconstruction of palaeoenvironmental changes in the area of Lake Syczyńskie on the basis of palaeoecological analyses. Annales Universitatis Mariae Curie-Skłodowska, sectio B, **70**: 39–57.

Lipka, K., Stabryła, J., Zając, E., 2008. Peat cover and water resources of peat deposits in the upper Warta basin (in Polish with English summary). Infrastruktura i Ekologia Terenów Wiejskich, **5**: 63–70.

Luoto, T.P., Sarmaja-Korjonen, K. 2011. Midge-inferred Holocene effective moisture fluctuations in a subarctic lake, northern Lapland. Boreas, **40**: 650–659.

Luoto, T.P., Nevalainen, L., Sarmaja-Korjonen, K., 2008. Multiproxy evidence for the 'Little Ice Age' from Lake Hampträsk, Southern Finland. Journal of Paleolimnology, **40**: 1097–1113.

Luoto, T.P., Nevalainen, L., Kultti, S., Sarmaja-Korjonen, K., 2011. An evaluation of the influence of water depth and river inflow on quantitative Cladocera-based temperature and lake level inferences in a shallow boreal lake. Hydrobiologia, **676**: 143–154.

Luoto, T.P., Kotrys, B., Płóciennik, M., 2019. East European chironomid-based calibration model for past summer temperature reconstructions. Climate Research, **77**: 63–76.

Makaske, B., Nap, R.L., 1995. A transition from a braided to a meandering channel facies, showing inclined heterolithic stratification (Late Weichselian, central Netherlands). Geologie en Mijnbouw, **74**: 13–20.

Makohonienko, M., Płóciennik, M., Papiernik, P., Kittel, P., Gałka, P., Mroczkowska, A., Apolinarska, K., Okupny, D., Panfil, M., Kotrys, B., Luoto, T.P., Krąpiec, M., Tyszkowski, M., 2023. Environmental changes during Mesolithic-Neolithic transition in Kuyavia Lakeland, Central Poland. Quaternary International, **644–645**: 196–221.

Marks, L., 2012. Timing of the Late Vistulian (Weichselian) glacial phases in Poland. Quaternary Science Reviews, **44**: 81–88.

Mazurek, M., 1990. Fluctuations of water level in Lake Lednickie, the Gniezno Plateau, on the basis of study of terrace sediments (in Polish with English summary). Badania Fizjograficzne nad Polską Zachodnią. Seria A – Geografia Fizyczna, **41**: 63–74.

Moller Pillot, H.K.M., 2009. Chironomidae Larvae. Biology and Ecology of the Chironomini. KNNV Publishing, Zeist.

Moller Pillot, H.K.M., 2013. Chironomidae Larvae of the Netherlands and Adjacent Lowlands, Biology and Ecology of the Aquatic Orthocladiinae, Prodiamesinae, Diamesinae, Buchonomyiinae, Podonominae, Telmatogetoninae. KNNV Publishing, Zeist.

Moore, P., Webb, J., Collinson, M., 1991. Pollen Analysis. Blackwell Sci. Publ., Oxford.

Müller, D., Tjallingii, R., Płóciennik, M., Luoto, T.P., Kotrys, B., Plessen, B., Ramisch, A., Schwab, M.J., Błaszkiewicz, M., Słowiński, M., Brauer, A., 2021. New insights into lake responses to rapid climate change: the Younger Dryas in Lake Gościąż, central Poland. Boreas, **50**: 535–555.

Nevalainen, L., Luoto, T.P., Kultti, S., Sarmaja-Korjonen, K., 2012. Do subfossil Cladocera and chydorid ephippia disentangle Holocene climate trends? The Holocene, **22**: 291–299.

Niska, M., Joncza, J., Gadziszewska, J., 2017. Late Pleistocene and Holocene environmental evolution of the Wkra River Valley near Bielawy Gołuskie (central Poland) recorded in palaeo-oxbow lake deposits. Geological Quarterly, **61**: 305–318.

Oksanen, J., Blanchet, F.G., Kindt, R., Legendre, P., Michin, P.R., O'Hara, R.B.; Simpson, G.L., Solymos, P., Henry, M., Stevens, H., Szoecs, E., Wagner H., 2019. "Vegan" 2.3.3. Community Ecology Package. Available online: https://cran.r-project.org/package=vegan (accessed on 20 April 2020)

Okupny, D., 2013. Zmiany środowiska geograficznego w regionie łódzkim w świetle cech geochemicznych osadów wybranych torfowisk (in Polish). Ph.D. thesis, Department of Geomorphology and Paleogeography, University of Lodz. Łódź.

Okupny, D., Pawłowski, D., 2021. Elemental composition of biogenic sediments reveals palaeoclimatic changes during the Late Weichselian in a Central European river valley: a statistical approach. Catena, **200**: 105188.

Okupny, D., Fortuniak, A., Tomkowiak, J., 2013. Denudation features of the Late Vistulian (Weichselian late glacial) preserved in the geochemical analysis of the biogenic deposits of the Łódź Region (in Polish with English summary). Acta Geographica Lodziensia, **101**: 89–99.

Okupny, D., Borówka, R.K., Fortuniak, A., Tomkowiak, J., 2014a. Chemical composition of organic sediments from the Koźmin Las site (in Polish with English summary). Acta Geographica Lodziensia, **102**: 71–86.

Okupny, D., Żurek, S., Forysiak, J., 2014b. Spatial pattern of mire distribution of the Lodz region (in Polish with English summary). Studia Limnologica et Telmatologica, **8**: 81–91.

Okupny, D., Fortuniak, K., Kloss, M., Ziułkiewicz, M., Forysiak, J., Fortuniak, A., Bednorz, L., Pawlak, W., 2016a. Preliminary geological and palaeobotanical description of the Kopytkowo swamp in relations to the analysis of contemporary water conditions and vegetations (Biebrza River valley, NE Poland) (in Polish with English summary). Acta Geographica Lodziensia, **105**: 149–162.

Okupny, D., Nita, M., Kloss, M., Alexandrowicz, W.P., Fortuniak, A., Żurek, S., 2016b. The tentative reconstruction of evolution of the biogenic accumulation reservoir in Bydlin (Silesian-Cracovian Upland) (in Polish with English summary). Acta Geographica Lodziensia, **105**: 55–68.

Okupny, D., Rzepecki, S., Borówka, R.K., Forysiak, J., Twardy, J., Fortuniak A., Tomkowiak, J., 2016c. Factors influencing temporal changes in chemical composition of biogenic deposits in the middle Tążyna River Valley (Kuyavian Lakeland, central Poland). Geologos, **22**: 121–136.

Okupny, D., Malkiewicz, M., Pawłowski, D., Ludwikowska-Kędzia, M., Borówka, R.K., Forysiak, J., Michczyński, A., Jucha, W., Cybul, P., Żurek, S., 2019. Late Glacial palaeoenvironmental changes in the southern part of the Holy Cross Mountains based on the “Białe Ługi” peatland record. Studia Quaternaria, **36**: 119–135.

Okupny, D., Borówka, R.K., Cedro, B., Sławińska, J., Tomkowiak, J., Michczyński, A., Kozłowska, D., Kowalski, K., Siedlik, K., 2020. Geochemistry of a sedimentary at the Wąwelnica archeological site, Szczecin Hills (Western Pomerania). Acta Geographica Lodziensia, **110**: 169–186.

Okupny, D., Borówka, R.K., Forysiak, J., Twardy, J., Kloss, M., Żurek, S., 2021. The relationship between the chemical composition and lithology of Late Glacial and Holocene biogenic deposits of the Żabieniec mire (Central Poland). Geological Quarterly, **65**: 11.

Oświt, J., Żurek S., Liwski, S., 1980. Soil conditions in the Ślina river valley against the background of water conditions (in Polish with English summary). Zeszyty Problemowe Postępów Nauk Rolniczych, **234**: 159–194.

Pawłowski, D., 2012. Younger Dryas Cladocera assemblages from two valley mires in central Poland and their potential significance for climate reconstructions. Geologos, **18**: 237–249.

Pawłowski, D., 2017. The usefulness of subfossil Cladocera remains in Younger Dryas climatic reconstructions in central Poland. Acta Geologica Polonica, **67**: 567–584.

Pawłowski, D., Okupny, D., Włodarski, W., Zieliński, T., 2014. Spatial variability of selected physicochemical parameters within peat deposits in small valley mire: a geostatistical approach. Geologos, **20**: 269–288.

Pawłowski, D., Milecka, K., Kittel, P., Woszczyk, M., Spychalski, W., 2015. Palaeoecological record of natural changes and human impact in a small river valley in Central Poland. Quaternary International, **370**: 12–28.

Pawłowski, D., Borówka, R.K., Kowalewski, G., Luoto, T.P., Milecka, K., Nevalainen, L., Okupny, D., Płóciennik, M., Woszczyk, M., Tomkowiak, J., Zieliński, T., 2016a. The response of flood-plain ecosystems to the Late Glacial and Early Holocene hydrological changes: A case study from a small Central European river valley. Catena, **14**: 411–428

Pawłowski, D., Borówka, R.K., Kowalewski, G., Luoto, T.P., Milecka, K., Nevalainen, L., Okupny, D., Tomkowiak, J., Zieliński, T., 2016b. Late Weichselian and Holocene record of the paleoenvironmental changes in a small river valley in Central Poland. Quaternary Science Reviews, **135**: 24–40.

Petera, J., 2002. Vistulian valley deposits in the Uniejów Basin and their palaeogeographical significance (in Polish with English summary). Acta Geographica Lodziensia, **83**: 1–164.

Petera-Zganiacz, J., Dzieduszuńska, D., Milecka, K., Okupny, D., Słowiński, M., Michczyńska, D.J., Forysiak, J., Twardy, J., 2022. Climate and abiotic landscape controls of Younger Dryas environmental variability based on a terrestrial archive (the Żabieniec mire, Central Poland). Catena, **219**: 106611.

Płóciennik, M., Kruk, A., Michczyńska, D.J., Birks, H.J.B., 2015. Kohonen artificial neural networks and the IndVal index as supplementary tools for the quantitative analysis of palaeoecological data. Geochronometria, **42**: 189–201.

Płóciennik, M., Kittel, P., Borówka, R.K., Cywa, K., Okupny, D., Obremska, M., Pawłowski, D., Stachowicz-Rybka, R., Szperna, R., Witkowski, A., 2016. Palaeoecological and palaeohydrological patterns of the Kolonia Bechcice subfossil oxbow in the mid-Ner River valley. Acta Geographica Lodziensia, **105**: 107–124.

Płóciennik, M., Pawłowski, D., Vilizzi, L., Antczak-Orlewska, O., 2020. From oxbow to mire: Chironomidae and Cladocera as habitat palaeoindicators. Hydrobiologia, **847**: 3257–3275.

Płóciennik, M., Jakiel, A., Forysiak, J., Płaza, D., Kittel, P., Okupny, D., Pawłowski, D., Obremska, M., Brooks, S.J., Kotrys, B., Luoto, T.P., 2021. Multi-proxy inferred hydroclimatic conditions at Bęczkowice fen (Central Poland); the influence of fluvial processes and human activity in the Stone Age. Acta Geographica Lodziensia, **111**: 135–157.

Płóciennik, M., Zawiska, I., Rzodkiewicz, M., Noryśkiewicz, A.M., Słowiński, M., Müller, D., Brauer, A., Antczak-Orlewska, O., Kramkowski, M., Peyron, O., Nevalainen, L., Luoto, T.P., Kotrys, B., Seppä, H., Camuera Bidaurreta, J., Rudna, M., Mielczarek, M., Zawisza, E., Janowska, E., Błaszkiewicz, M., 2022. Climatic and hydrological variability as a driver of the Lake Gościąż biota during the Younger Dryas. Catena, **212**: 106049.

Porinchu D. F., Macdonald G. M., Bloom A. M., Moser K. A. 2002. The modern distribution of chironomid sub-fossils (Insecta: Diptera) in the Sierra Nevada, California: potential for paleoclimatic reconstructions. Journal of Paleolimnology, **28**: 355–375.

R Core Team, 2020. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. Available online: https://www.r-project.org/

Ralska-Jasiewiczowa, M. 2004. Late Glacial and Holocene history of vegetation in Poland based on isopollen maps. W. Szafer Institute of Botany, PAS, Kraków.

Rasmussen, S. O., Andersen, K. K., Svensson, A. M., Steffensen, J. P., Vinther, B. M., Clausen, H. B., Siggaard-Andersen, M.-L., Johnsen, S. J., Larsen, L. B., Dahl-Jensen, D., Bigler, M., Röthlisberger, R., Fischer, H., Goto-Azuma, K., Hansson, M. E., Ruth, U., 2006. A new Greenland ice core chronology for the last glacial termination. Journal of Geophysical Research, **111**: D06102.

Rossaro, B., Marziali, L., Montagna, M., Magoga, G., Zaupa, S., Boggero, A., 2022. Factors controlling morphotaxa distributions of Diptera Chironomidae in freshwaters. Water, **14**: 1014.

Rotnicki, K., 1987. Main phases of erosion and accumulation in the middle and lower Prosna valley in the last glacial-interglacial cycle. Geographia Polonica, **53**: 53–65.

Rydelek, P., 2005. Genetic conditions of spatial variability of Total Organic Carbon (TOC) and sulphur concentration in the peat bog area of Kurówka River Valley (in Polish with English summary). Przegląd Geologiczny, **53**: 673–676.

Rydelek, P., 2011. Origin and composition of mineral particles of selected peat deposits in Lubartowska Upland (in Polish with English summary). Woda-Środowisko-Obszary Wiejskie, **11**: 135–149.

Rydelek, P., 2021. Variability of physicochemical parameters pf peats in the subsurface zone of the fen in the Struga Wodna valley (Lubartów Plateau) (in Polish with English summary). Przegląd Geologiczny, **69**: 867–872.

Schumm, S.A., 1977. The Fluvial System. John Wiley and Sons, New York.

Starkel, L., 1997. The evolution of fluvial in the Upper Vistulian and Holocene in the territory of Poland. Landform Analysis, **1**: 7–18.

Stasiak, J., 1971. Sedimentation rate of calcareous gyttja deposits (in Polish with English summary). Zeszyty Problemowe Postępów Nauk Rolniczych, **107**: 113–119.

Stockmarr, J., 1971. Tablets with spores used in absolute pollen analysis. Pollen Spores, **13**: 615–621.

Strzelecka, A., Wróbel, R., 2021. Differences in the development of the Szczecin Lagoon area in the Late Glacial and Holocene based on the geochemical analysis of carbonate sediments from Lake Nowowarpieńskie (NW Poland). Acta Geographica Lodziensia. **111**: 47–57.

Succow, M., Joosten, H., 2001. Landschaftsökologische Moorkunde. E. Schweizerbart'sche Verlagsbuchhandlung (Nägele u. Obermiller), Science Publishers, Stuttgart.

Szeroczyńska, K., Sarmaja-Korjonen, K., 2007. Atlas of Subfossil Cladocera from Central and Northern Europe. Friends of Lower Vistula Society, Świecie, Poland.

Szumański, A., 1983. Paleochannels of large meanders in the river valleys of the Polish Lowland. Quaternary Studies in Poland, **4**: 207–216.

Ścibior, K., Rydelek, P., Stępień, M., 2015. Influence of selected peat bogs Drawa National Park on the formation of the chemical composition of shallow groundwater (in Polish with English summary). Przegląd Geologiczny, **63**: 1099–1104.

Teisseyre, A.K., 1991. Klasyfikacja rzek w świetle analizy systemu fluwialnego i geometrii hydraulicznej (in Polish). Acta Universitatis Wratislaviensis, 1287, Prace Geologiczno-Mineralogiczne, **12**.

Toucanne, S., Zaragosi, S., Bourillet, J-F., Marieu, V., Cremer, M., Kageyama, M., Van Vliet-Lanoë, B., Frédérique, E., Turon, J-L., Gibbard, P.L., 2010. The first estimation of Fleuve Manche palaeoriver discharge during the last deglaciation: Evidence for Fennoscandian ice sheet meltwater flow in the English Channel ca 20–18 ka ago. Earth and Planetary Science Letters, **290**: 459–473.

Turkowska, K., 1988. Evolution of river valleys in the Łódź Plateau at the Quaternary decline (in Polish with English summary). Acta Geographica Lodziensia, **57**: 1–157.

Turkowska, K., 1997. The state of knowledge of valley evolution in non-glaciated regions of the Polish Plain during the transitions period from Pleistocene to Holocene (in Polish with English summary). Acta Universitatis Lodziensis. Folia Geographica Physica, **1**: 67–87.

Turkowska, K., 2006. Geomorfologia regionu łódzkiego (in Polish). Wyd. UŁ, Łódź.

Vallenduuk, H.J., Moller Pillot, H.K.M., 2007. Chironomidae Larvae of The Netherlands and Adjacent lowlands. General ecology and Tanypodinae. KNNV Publishing, Zeist.

Van Damme, K., Dumont, H.J., 2008. Further division of *Alona* Baird, 1843: separation and position of *Coronatella* Dybowski & Grochowski and *Ovalona* gen. n. (Crustacea: Cladocera). Zootaxa, **1960**: 1–44.

Van Damme, K., Kotov, A.A., Dumont, H.J., 2010. A checklist of names in *Alona* Baird 1843 (Crustacea: Cladocera: Chydoridae) and their current status: an analysis of the taxonomy of a lump genus. Zootaxa, **2330**: 1–63.

Walanus, A., 2000. Statistical significance of inferences from quantitative analysis as applied to the Upper Quaternary. Geologia, Kwartalnik AGH, **26**: 1–59.

Walanus, A., Nalepka, D, 1999. Polpal program for counting pollen grains, diagrams plotting and numerical analysis. Acta Palaeobotanica, Supplementum, **2**: 659–661.

Walanus, A., Nalepka, D, 2010. Calibration of Mangerud's boundaries. Radiocarbon, **52**: 1639–1644.

Walker, I.R., 2001. Midges: Chironomidae and related Diptera. In: Tracking environmental change using lake sediments, Vol. 4: Zoological Indicators (eds. J.P. Smol, H.J.B. Birks and W.M. Last): 43–66. Kluwer Academic Press, Dordrecht.

Wasylikowa, K., 1964. Roślinność i klimat późnego glacjału w środkowej Polsce na podstawie na podstawie badań w Witowie koło Łęczycy (in Polish). Biuletyn Peryglacjalny, **13**: 261–417.

Wasylikowa, K., 2011. Wiek osadów spągowych torfowiska Silne Bagno koło Witowa w świetle analizy pyłkowej (in Polish). Warsztaty Naukowe "Torfowiska w krajobrazie przekształconym – funkcjonowanie i ochrona". Wawrzkowizna, 1–3 czerwca 2011: 93–94.

Weckwerth, P., Wysota, W., Piotrowski, J.A., Adamczyk, A., Krawiec, A., Dąbrowski, M., 2019. Late Weichselian glacier outburst floods in North-Eastern Poland: Landform evidence and palaeohydraulic significance. Earth-Science Reviews, **194**: 216–233.

Whiteside, M.C., 1970. Danish chydorid Cladocera: modern ecology and core studies. Ecological Monographs, **40**: 79–118.

Wibig, J., Radziun, W., 2019. Precipitation in the Łódź Voivodeship in the period 1961–2015. Acta Geographica Lodziensia, **109**: 29–47.

Wiederholm, T. (ed.), 1983. Chironomidae of the Holarctic region: keys and diagnoses. Part 1. Larvae. Entomol. Scand. Suppl. **19**: 1–457.

Wiśniewski, E., 1987. The evolution of the Vistula river valley between Warsaw and Płock Basins during the last 15 000 years. In: Evolution of the Vistula river valley during the last 15 000 years, part II (ed. L. Starkel): 171–187. Geographical Studies, Special Issue **4**, IGiPZ PAN.

Zawiska, I., Słowiński, M., Correa-Metrio, A., Obremska, M., Luoto, T., Nevalainen, L., Woszczyk, M., Milecka, K., 2014. The response of a shallow lake and its catchment to Late Glacial climate changes – a case study from eastern Poland. Catena, **126**: 1–10.

Zieliński, T., Pisarska-Jamroży, M., 2012. Which features of deposits should be included in a code and which not (in Polish with English summary)? Przegląd Geologiczny, **60**: 387–397.

Zhou, S., Zhou, K., Wang, J., Yang, G., Wang, S., 2017. Application of cluster analysis to geochemical compositional data for identifying ore-related geochemical anomalies. Frontiers of Earth Science, **12**: 491–505.

Żurek, S., 1991. The development of the peat forming processes versus the lowland relief of Poland and hydrological change in the postglacial period. Quaestiones Geographicae, **17/18**: 95–100.

Żurek, S., 1993. Palaeohydrological changes in the wetlands (in Polish with English summary). Przegląd Geograficzny, **64**: 75–95.

Żurek, S., Dzięczkowski, A., 1971. Tentative reconstruction of evolution of fossil lakes in „Biebrza" peat bog (in Polish with English summary). Przegląd Geograficzny, **43**: 403–424.

Żurek, S., Okupny, D., 2015. Peatlands of the Łódź region (in Polish with English summary). Studia Limnologica et Telmatologica, **9**: 59–69.