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MULTI-PROXY INFERRED HYDROCLIMATIC CONDITIONS AT BĘCZKOWICE FEN (CENTRAL POLAND); THE INFLUENCE OF FLUVIAL PROCESSES AND HUMAN ACTIVITY IN THE STONE AGE

MATEUSZ PŁÓCIENNIK[1], ALEKSANDRA JAKIEL[2], JACEK FORYSIAK[3], PIOTR KITTEL[3], DOMINIK K. PŁAZA[4], DANIEL OKUPNY[5], DOMINIK PAWŁOWSKI[6], MILENA OBREMSKA[7], STEPHEN J. BROOKS[8], BARTOSZ KOTRYS[9], TOMI P. LUOTO[10]

Abstract. Fens have been forming in the river valleys of central Poland since the Bølling and went through a transformation from fully aquatic to semiterrestrial habitats during the Younger Dryas/Holocene transition. This drove plant and invertebrate communities and left a distinct pattern in chemical sediment composition, which is why river valley peatlands are sensitive palaeo-archives of climatic, hydrological and edaphic changes. Here we reconstruct the Late Weichselian history of the Bęczkowice fen in the upper Luciąża River valley using geochemical, pollen, Cladocera and Chironomidae proxies. Pollen-based age estimation indicates that the analysed peat sequence dates from the Bølling to Early Holocene. The layers 190-170 cm and 125-105 cm of the studied core were reworked by fluvial processes. Chironomidae and Cladocera communities indicate mostly limnetic conditions during the Allerød and early Younger Dryas. Peatland pools were supplied mostly by Luciąża River floods, but also by groundwater. Since the onset of the Holocene, the water level has dropped, eliminating aquatic midges and water fleas, and supporting taxa typical of astatic waters and wet soil.

Key words: peatland, palaeoecology, climate changes, Late Weichselian, Early Holocene, central Poland

Introduction

Peatlands are ones of a major object of palaeohydrological and palaeoclimatological study. Research conducted on mires use analyses of pollen, diatoms, plant macrofossils, stable isotopes, testate amoebae, geochemical, cladocerans and chironomids as proxies (Lamentowicz *et. al.* 2010; De Vleeschouwer *et al.* 2010; Luoto *et al.* 2012; Gauthier *et al.* 2019; Łuców *et al.* 2020; Mroczkowska *et al.* 2021). Such analyses are mostly used for reconstructions of natural environmental changes, but they also reveal altered habitat states indicating human activity. The human signal is more distinct when settlement is close to the peatland or lake and influences the water supply to a biogenic accumulation basin (Enters *et al.* 2008; Słowiński *et al.* 2016; Łuców *et al.* 2020; Mroczkowska *et al.* 2021; Kittel *et al.* 2021).

Chironomidae subfossils are usually numerous in lake and mire sediments (Brooks *et al.* 2007). Since the last decades of the 20th century (Walker

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[1] University of Lodz, Faculty of Biology and Environmental Protection, Banacha St. 12/16, 90-237 Łódź, Poland; ORCID: 0000-0003-1487-6698

[2] Department of Genetics and Marine Biotechnology, IO PAN, Powstańców Warszawy 55, 81-712 Sopot, Poland; ORCID: 0000-0002-9597-8364

[3] University of Lodz, Faculty of Geographical Science, Narutowicza 88, 90-139 Łódź, Poland; e-mail: jacek.forysiak@geo.uni.lodz.pl, ORCID: 0000-0002-0084-4436; Piotr Kittel ORCID: 0000-0001-6987-7968

[4] Museum of Archaeology and Ethnography in Lodz, Palaeolithic and Mesolithic Department, Plac Wolności 14, 91-415, Łódź, Poland; ORCID: 0000-0001-6223-2307

[5] Institute of Marine and Environmental Sciences, University of Szczecin, Adama Mickiewicza St 16, 70-383 Szczecin, Poland; ORCID: 0000-0002-8836-6044

[6] Adam Mickiewicz University, Faculty of Geographical and Geological Sciences, Institute of Geology, Krygowskiego St 12, 61-680 Poznań, Poland; ORCID: 0000-0003-4616-6666

[7] Polish Academy of Sciences, Institute of Geology, Twarda 51/55, 00-818 Warszawa, Poland; ORCID: 0000-0002-3465-1894

[8] Natural History Museum, Department of Life Sciences, Cromwell Road, London SW75BD

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

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

et al. 1985; Walker, Mathewes 1989; Lotter *et al.* 1997; Brooks *et al.* 1997) they have become an important group of palaeo-indicators in peatland studies. Non-biting midges are a widespread family of flies (Nematocera, Culicomorpha). As a very diverse group, they are found in various types of water bodies, moist soil and even fully terrestrial habitats (Brooks *et al.* 2007; Saether, Speis 2013). Subfossil chironomids are good indicators of anthropogenic water acidification, past climatic conditions, water trophic state (Płóciennik 2005; Brooks 2006) and lake depth (Luoto 2009). In the last two years, new training sets (TSs) were established for mean July air temperature reconstructions in Central Europe (Luoto *et al.* 2019; Kotrys *et al.* 2020).

Cladocera are also broadly used as palaeo-indicators (Szeroczyńska, Sarmaja-Korjonen 2007). Whereas they are not so taxonomically diverse as non-biting midges, they are much more sensitive to hydrological fluctuations and maintain a high abundance during paludification processes that usually cause chironomids to disappear (Kittel *et al.* 2014; Płóciennik *et al.* 2020). Cladocera can also give more reliable palaeotemperature reconstructions compared to chironomids when oxbow sediments are analysed (Pawłowski 2017).

Whereas palaeozoological analyses give specific information on past habitat conditions, palaeobotanical data are crucial to recognising local landscape dynamics, edaphic conditions and regional plant communities (Chevalier *et al.* 2020). Pollen microfossils give a more regional signal, but plant macrofossils are indicators of vegetation *in situ* (Kowalewski 2007; Wieckowska-Lüth *et al.* 2021).

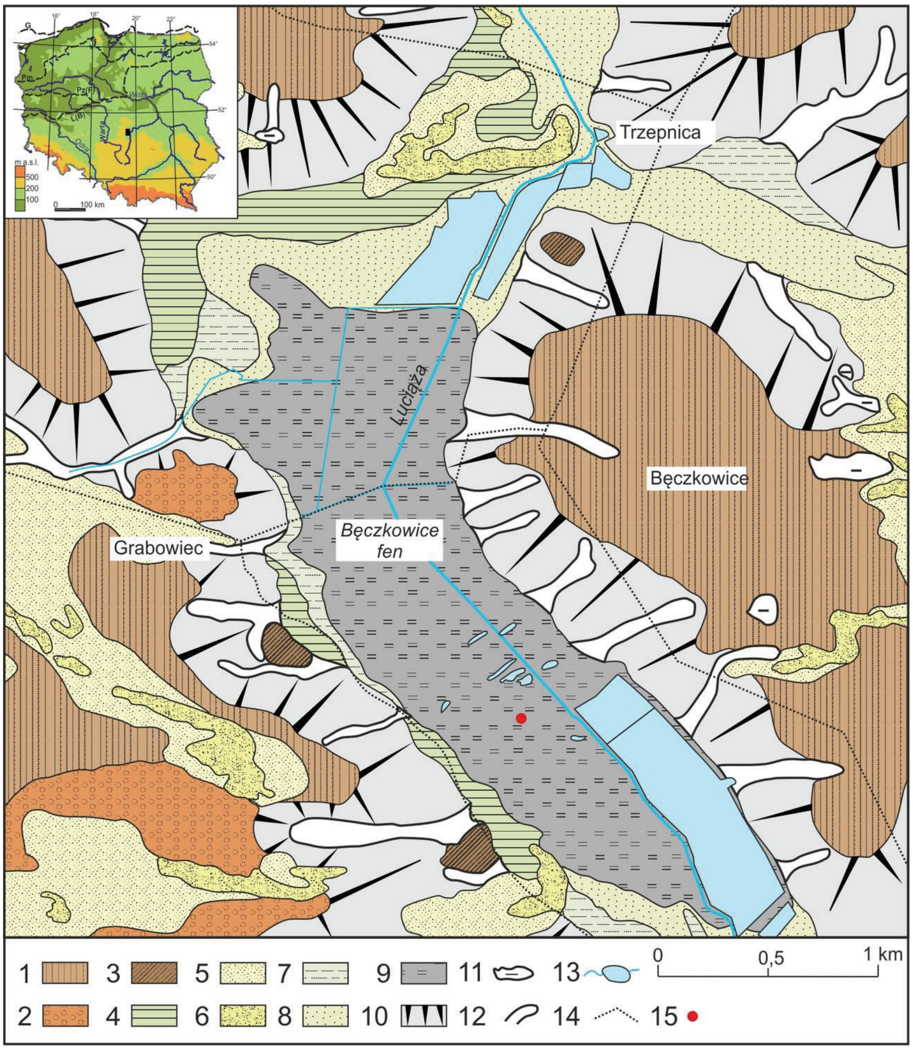
Biogenic accumulation basins are natural sediment traps and an archive of denudation processes that allow the interpretation of geochemical data. Such studies provide information about the past intensity of denudation and anthropogenic impact on water ecosystems. Among the anthropogenic activities, the most important are settlement, forest clearance and agriculture (Enters *et al.* 2010). They affect the supply of lithophilic elements and the nutritional conditions of mires or lakes, as well as sediment deposition (Borówka 1987/1988; Okupny *et al.* 2020). Those changes are faster in catchments of small rivers on account of the large differences in potential volume of the hydrologically active zone and local land use (Pawłowski *et al.* 2015a).

River valleys underwent significant geological, geomorphological and hydrological transformation in the Late Weichselian and Holocene (Starkel 2002; Turkowska, Dzieduszyńska 2011). This had a strong influence on local ecosystems and aquatic invertebrate fauna. There are still many places in central Poland where valley fen mires are preserved in good condition. The Prosna River valley (Rotnicki 1988; Gałka *et al.* 2020), the Świętojanka River valley (Balwierz, Goździk 1997), the Koźmin Las site (Dzieduszyńska *et al.* 2014), the Wilczków fen (Płóciennik *et al.* 2015), wetlands in the Grabia River valley (Pawłowski *et al.* 2016; Okupny, Pawłowski 2021), the Ner River valley (Płóciennik *et al.* 2016; Kittel *et al.* 2016), the Widawka River valley (Pawłowski 2012) and the Luciąża River valley (Antczak-Orlewska *et al.* in press) were studied to reconstruct the main factors influencing midge communities on peatlands from the Older or Younger Dryas to Middle Holocene. The Bęczkowice fen in the Luciąża River valley stands out from the other peat deposits in the region for its relatively thick Late Weichselian accumulation over a large area. Sediments were only partly decomposed in the Holocene here. The relatively continuous Late Weichselian sequence makes this site suitable for palaeohydrological and palaeoclimatic reconstructions. The local human activity during the Late Palaeolithic and Mesolithic is also well recognised, revealing the potential local human impact of hunter–gatherer communities on the wetland in the past (Niesiołowska-Śreniowska *et al.* 2011). Several traces of human activity close to the Bęczkowice fen were registered during the Polish Archaeological Record Project (hereinafter, the PAR project). They are connected with the Late Palaeolithic Świderian Culture, Mesolithic Komornica Culture and middle Neolithic Funnel Beaker Culture.

Climate changes are the main drivers of wetland ecology. In the Luciąża River valley, they have influenced hydrological conditions, depositional processes and biota communities since the Bølling (Antczak-Orlewska *et al.* in press). Regional factors like mean summer air temperature, local landscape character and hydrological regime in river valleys have controlled human activity since the Palaeolithic in Europe. Here we present a multi-proxy reconstruction of the Bęczkowice fen habitat changes and chironomid-inferred local palaeoclimatic conditions from the Late Weichselian to the Early Holocene as a background for Palaeolithic and Mesolithic settlement in the region. According to the previous studies of Antczak-Orlewska *et al.* (in press) in middle Luciążą River valley, we hypothesise that: 1) there was no substantial drop in mean summer air temperature in the region during Younger Dryas and 2) during the Late Weichselian, the water level was higher than in the Early Holocene when Bęczkowice fen transformed to more terrestrial conditions. This peatland is a river valley where the active channel and flood waters could interfere with peat sedentation process. According to the palaeoecological investigation and current state of archaeological studies we discuss human–environment relations in the Late Palaeolithic and Early Mesolithic in that region.

Study area

The Bęczkowice fen is located in the Radomsko Hills mesoregion (Kondracki 2000) in the middle section of the Luciąża River valley (Fig. 1). This region has more mires than other parts of central Poland (Okupny *et al.* 2014). Peatland covers the valley floor on a 3.5-km-long and about 400–800-m-wide stretch. It has a polygenic complex genesis (Wachecka-Kotkowska 2004; Forysiak 2012). The valley was formed during the Saalian Glaciation as part of a proglacial outflow system, and then transformed into a river valley with a few basin extensions and narrowings (Wachecka-Kotkowska 2004). Quaternary substrates cover Miocene deposits and Cretaceous bedrock (Kurkowski, Popielski 1991).



1 – undulating morainic plain; 2 – fluvioglacial plain; 3 – fluvioglacial hillocks; 4 – high terrace; 5 – aeolian sand sheets; 6 – dunes; 7 – low terrace; 8 – valley bottoms; 9 – peatland; 10 – slopes; 11 – closed depressions; 12 – major denudational valleys; 13 – waters; 14 – roads; 15 – Be-1 core

The studied peatland area covers about 200 ha. The mire was developed mostly on fine sand deposits. Peatland takes up almost all of the valley floor width. Its altitude decreases from the south (210 m a.s.l.) to the north (208 m a.s.l.). The Luciąża's riverbed is regulated in that area. The Bęczkowice fen is degraded by local agricultural activity and divided into small plots. Until the middle

1980s the area was used as meadows and pasture. There was also extensive peat exploration up to the 1950s, after which there remained peat pools.

Peat layers do not exceed 1.5 m thickness (Forysiak 2012). In the south part of the fen, reed peat – and in some places reed-moss peat – accumulated. In the central and northern peatland part, reed peat dominates. In the southern part of the peatland, the peat layer thickness increases to 2.9 m, but it decreases to the north to only about 1 m.

Materials and methods

Core sampling and laboratory techniques

The analysed core BE-1 has a length of 290 cm. The core was taken by a 50-cm-long Instorf sampler. The lowest core section contains gyttjas (275–290 cm b.g.l.), above which (215–275 cm) there are herbaceous peat and sedge peat with reed remains. At 215–150 cm there is a sedge-moss peat layer, above which, at 150–100 cm there is reed peat, and at 100–75 cm herbaceous peat appears. The uppermost core section (75–30 cm) contains sedge peat deposits, which are decomposed in subsurface layers (Forysiak 2012). Pollen, plant macrofossil, Chironomidae, Cladocera and geochemical analyses were carried out.

For pollen analysis, 46 samples were taken at 3-to-10-cm resolution. At least 300–500 pollen grains of terrestrial plants (in accordance with frequency) were counted for each sample. The calculation sum contained AP + NAP (arboreal pollen and non-arboreal pollen), except for the local aquatic and telmatic plants. To estimate palynomorph concentrations in each sample, one tablet of Lycopodium was added (Berglund, Ralska-Jasiewiczowa 1986).

For Chironomidae analysis, 29 samples were taken at 10-cm resolution. Sample volume ranged between 10 and 19 ml. Because of the low concentration of head capsules, kerosene flotation was used following the methods of Rolland, Larocque (2007). The solution was sieved through a 63-µm sieve. To remove kerosene residue, detergent was added during washing on the sieve. Preparation methods followed Brooks *et al.* (2007). Sieved sediment was poured with a little water into a Bogorov counting tray. Subfossils were picked with fine forceps and placed in 95% ethanol, then slide-mounted in Euparal. Identification of Chironomidae head capsules follows Wiederholm (1983) and Brooks *et al.* (2007). Ecological interpretation of the data follows information on species habitat preferences described in Brooks *et al.* (2007), Wiederholm (1983), Vallenduuk, Moller Pillot (2007), and Moller Pillot (2009). The reference collection is deposited in the Department of Invertebrate Zoology and Hydrobiology (University of Lodz).

For Cladocera analysis, 1 cm^3 of fresh sediment samples were taken at 10-cm resolution and processed according to standard procedures (Frey 1986). The taxonomy of cladoceran remains in this paper follows that presented by Szeroczyńska, Sarmaja-Korjonen (2007). The ecological preferences of cladoceran taxa were determined based on the published key after Bjerring *et al.* (2009).

Lithogeochemical analyses of 40 dried samples and pH deposits (in distilled water) were performed according to procedures following Borówka (1992) and Domińczak, Okupny (2010). The organic matter content (OM) was determined from loss-on-ignition (combustion at 550°C for 4 hours) and calcium carbonate content ($CaCO_3$) was assayed using the Scheibler apparatus. Concentrations of Na, K, Ca, Mg, Fe, Mn, Cu, Zn and Pb in the deposits were measured using atomic absorption spectrometry (AAS Solar 969 Unicam). Prior to the instrumental analysis, dried samples of known weight were reconstituted in a mixture of concentrated nitric acid (HNO_3), hydrochloric acid (10% HCl) and perhydrol (H_2O_2) using a Berghof microwave mineraliser. The results expressed in g/l were converted to mg/g or µg/g dry weight (d.w.).

Chronology

The chronology of the core is based on pollen analysis and two radiocarbon dates (MKL-893, MKL-895; Table 1). Palynological analysis showed the sediment decay at depths of 107–120 and 170–190 cm b.g.l., but also numerous redeposited pollen grains in the range 190–250 cm, which indicates the possibility of the deposits collected in the core having been contaminated with allochthonous macroremains. The dating results obtained from such material cannot be the basis for the chronology of the core, except for the extreme samples. Radiocarbon dates were carried out by Marek Krąpiec from AGH University of Science and Technology and β-Analytics (Miami, USA).

Table 1

Radiocarbon dates for Bęczkowice BE-1 core

Lab. Code	Depth of core (cm b.g.l.)	Material	^{14}C conv BP	^{14}C cal. BP (95%)
MKL-893	104–106	bulk	8,480±80	9,280–9,600
Beta-416378	200	pollen AMS	11,070±40	13,055–12,810
MKL-894	212–215	bulk	12,340±110	13,950–14,900
Beta-415120	220	pollen AMS	11,090±40	13,065–12,825
Beta-417912	240	pollen AMS	10,090±30	11,810–11,600
MKL-617	250	bulk	12,450±140	14,025–15,020
MKL-895	282–285	bulk	12,430±110	14,050–15,000

Statistical analyses

Statistically significant Chironomidae zones (Ch1 and Ch2) were determined using optimal sum-of-squares partitioning (Birks, Gordon 1985; Birks 1986; Bennett 1996) and statistical significance was tested with the broken-stick model (MacArthur 1957). ZONE (Lotter, Juggins 1991) and BSTICK (J.M. Line and H.J.B. Birks, unpublished program) software was used for Chironomidae and Cladocera analyses. Additionally, zone Ch2 was divided into two not-statistically-significant subzones (Ch2a and Ch2b) based on stratification suggested by optimal sum-of-squares partitioning. Based on results of the palynological analysis, seven local pollen assemblage zones (L PAZ Be-1 – Be-7) were distinguished, reflecting the stages of vegetation history. The zonation was confirmed by CONISS cluster analysis (Grimm 1992). The pollen percentages diagram and dendrogram were plotted using Tilia2 and Tilia-Graph (Grimm 1992). During the palynological analysis, green algae coenobia were also counted; these were not included in the calculated sum of Chlorophyta, which contains: *Pediastrum boryanum*, *Ped. Integrum*, *P. boryanum v. longicorne*, *Ped. duplex* and *Botryococcus*.

Only in the Ch2a Chironomidae zone was sufficient head capsule concentration found (at least 50/sample) for palaeotemperature reconstruction (Quinlan, Smol 2001). The Norwegian TS (No TS), East-European TS (EE TS) and Swiss–Norwegian–Polish TS (SNP TS) chironomid-based mean July air temperature inference models were used for palaeotemperature reconstruction (Brooks, Birks 2001; unpubl.; Luoto *et al*. 2019; Kotrys *et al*. 2020). The No TS uses a Weighted Averaging–Partial Least Squares transfer function (WA-PLS); it is based on a 153-lake set covering a temperature range of 3.5–16.0°C and has a root mean square error of prediction (RMSEP) of 1.01°C and an R^2 of 0.91 (Brooks, Birks 2001; unpubl.). SNP TS includes 357 lakes, 134 taxa and a 3.5–20.1°C temperature range. It includes Norwegian lakes (including Svalbard), Alpine lakes and 102 lakes from Poland. The SNP TS RMSEP and R^2jack for the WA-PLS component 3 are 1.39°C and 0.91, respectively. The SNP TS RMSEP and R^2jack for the Artificial Neural Network (ANN) are 1.34°C and 0.95, respectively (Kotrys *et al.* 2020). The EE TS includes 212 lakes and 142 taxa, and it covers the 11.3–20.1°C temperature range. The EE TS uses the WA-PLS transfer function. The EE TS RMSEP and R^2jack for the WA-PLS component 2 are 0.88 and 0.88, respectively (Luoto *et al.* 2019).

Detrended Correspondence Analyses (DCA) for Chironomidae and Cladocera were calculated on percentage data with downweighting rare species using Canoco 4.5 (ter Braak, Šmilauer 2002). Rarefaction (ES(2)) was calculated using Primer 6 software (Clark, Gorley 2001). Principal Component Analysis (PCA) for the Chironomidae dataset on percentage data, the temperature reconstructions, and for the stratigraphic diagrams of Chironomidae and Cladocera were all carried out with C2 software (Juggins 2007).

Geochemical zonation was constructed based on a constrained cluster analysis with PAST version 2.17c software (Hammer *et al.* 2001). The variability in conditions of sedimentation was estimated based on the correlations of results of different measurements |r| as was done by Walanus (2000) and selected geochemical ratios, such as Fe/Mn, Cu/Zn, Ca/Mg, Ca/Fe, Na/K, Na+K+Mg/Ca and ΣK following the protocol described by Borówka (1992) and Kittel *et al.* (2018). In the case of the BE-1 core, the |r| marker was calculated for ten variables (geochemical properties) as a moving mean. Principal Component Analysis (PCA) was used to determine the variability of factors controlling the chemical composition of lake and peat deposits.

Results

Pollen analysis

LPAZ Be-1 *Pinus-NAP* (290–245 cm). Percentage of pollen grains of *Pinus* fluctuated between 70 and 80% before reaching max. 93.2%, and NAP reached *ca* 5% (Fig. 2). The curve of *Juniperus* was present but at a low value. The highest share of pollen grains was for Cyperaceae, with max. 65%. Presence of *Typha latifolia* pollen grains and *Menyanthes trifoliata*. The curve of green algae reached 20%. The top border is marked by an increase in the NAP curve.

LPAZ Be-2 *Juniperus-NAP* (245–190 cm). The percentages of NAP increased significantly up to 10.4% with the domination of *Artemisia* pollen grains. The curve of *Pinus* declined. The share of *Juniperus* increased and reached 3.4%. Percentages of Cyperaceae were still high (*ca* 30%) The curve of *Typha latifolia* disappeared. There was low presence of green algae cenobiae. The top border is marked by a decline in NAP (Fig. 2). Sediments decay (190–170 cm) – the record is distorted – only *Pinus* pollen grains and Filicales monolete spores are present.

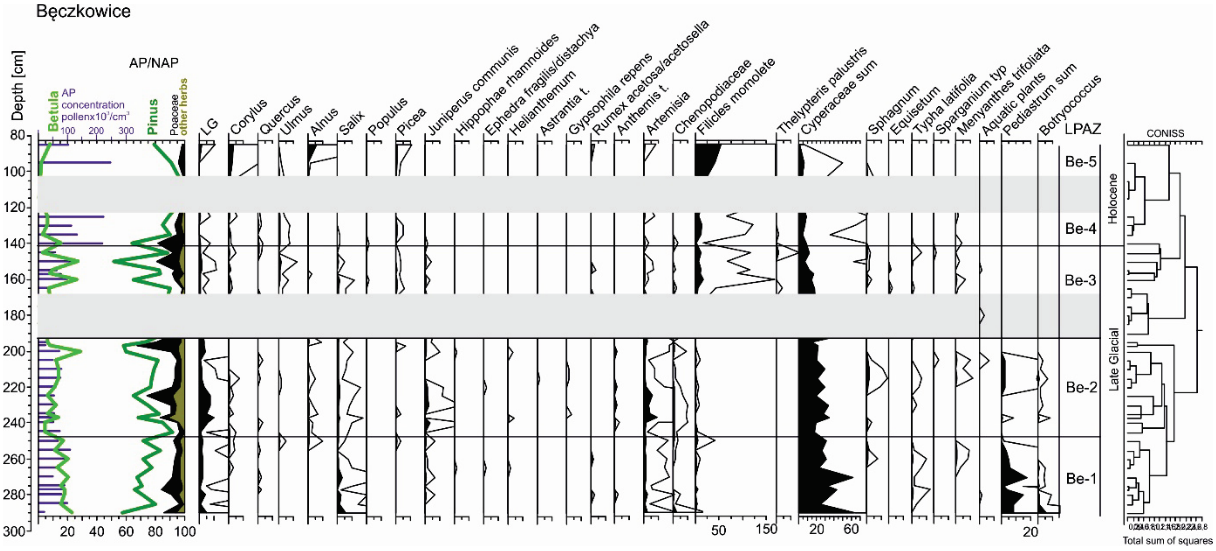


Fig. 2. Stratigraphic diagram of pollen assemblages

LPAZ Be-3 *Pinus-Betula* (170–145 cm). The share of pollen grains of *Pinus* decreased (to 60.5%). The curve of *Betula* increased and reached max. 31.2%. The curves of NAP increased (mostly the share of Poaceae). Presence of a discontinuous curve of *Juniperus.* Spores of Filicales (*ca* 10%). The share of Cyperaceae reached 17.7% and gradually declined to the top of PAZ. The curve of Filicales monolete appeared, and the top border is marked by the growth of *Pinus.*

LPAZ Be-4 *Pinus* (145–120 cm). The share of NAP significantly decreased. The curve of *Pinus* inclined rapidly. The pollen grains of *Juniperus* disappeared. The share of spores of Filicales increase up to 42.4%. The top border was marked by *Pinus* increasing to *ca* 100%. Sediments decay (120–105 cm) – the record is distorted – only *Pinus* pollen grains and Filicales monolete spores are present.

LPAZ Be-5 *Pinus-Corylus* (105–80 cm). A high percentage of *Pinus.* The curves of *Corylus* and *Alnus* continue throughout the profile. Significantly increased share of Filicales spores (Fig. 2).

Chironomidae

Three zones can be distinguished that correspond to three main succession phases of the community (Fig. 3).

Zone Ch1 (290–280 cm). There are nine morphotypes. Morphotypes characteristic for Ch1 are *Cryptochironomus* and *Parakiefieriella bathophila*-type.

Subzone Ch2a (280–130 cm). In the Ch2a subzone the chironomid subfossils concentration is at its highest for the whole core BE-1 sequences. A total of 749 head capsules representing 51 morphotypes were collected from this core section. It is clearly distinctive that the number of morphotypes relates to the abundance of individuals. The lowest chironomid subfossil abundance

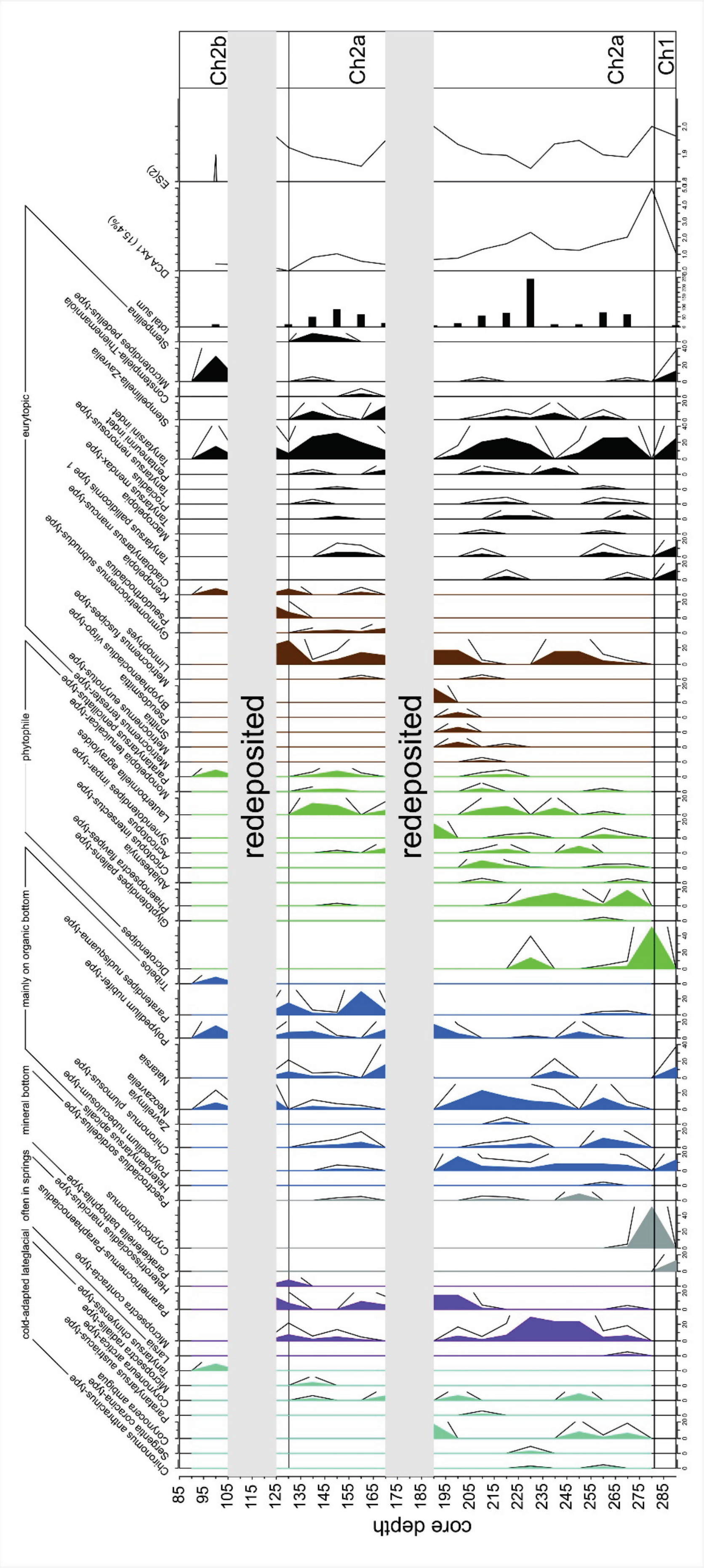


Fig. 3. Percentage stratigraphic diagram of Chironomidae assemblages

was found at the 190 and 120 cm core depths (six and five head capsules, respectively). The most abundant species in that subzone were *Limnophyes*, *Lauterborniella agrayloides*, *Natarsia*, *Paratendipses nudisquama*-type, *Parametriocnemus-Paraphaenocladius*, *Polypedilum nubifer*-type, and *Zavrelia-Stempellinella*. DCA keeps the highest values at the beginning of Ch2a and then subsequently decrease, ES(2) variates from 1 to 2. Material from 190–170 cm is redeposited.

Subzone Ch2b (110–85 cm). The chironomid subfossils abundance and species richness are the lowest of any (sub)zone. There are only a few head capsules of mostly limnetic taxa, material from 125–105 cm core depth is redeposited.

The Chironomidae-inferred mean July air temperature (CH-I T Jul) No TS reconstruction values vary from less than 12.0°C (210 cm) to 13.8°C (260 cm) (Fig. 4). The SNP TS CH-I Jul T reconstruction values vary from *ca* 16.0°C (220 cm) to 18.3°C (150 cm). The EE TS CH-I Jul T reconstruction values vary from *ca* 14.0°C (160 cm) to *ca* 17.0°C (220, 140 cm). The TS SNP and No TS have similar decreasing trends for the early to late Bølling, whereas EE TS gives stable temperature conditions for that period. The SNP TS and No TS give a cooling in the Older Dryas. This trend is not supported by EE TS, but SNP TS has better modern analogues for this core section. The reconstructions are not consistent for the Younger Dryas. No TS gives the lowest temperature ranging from *ca* 12.5°C to 13.5°C, SNP TS gives *ca* 17–18°C, and EE TS high variation from below 14°C to 17°C. The SNP TS gives mostly good modern analogues for the lower core section (270–210 cm). The EE TS reconstruction shows good modern analogues for only the bottommost sample at 270 cm. All the other samples reveal poor modern analogues. The modern analogues were not computed for No TS reconstruction, whereas No TS is located far from the study site (southern Norway, northern Norway, Svalbard) and it is considered to have obviously poor modern analogues. The first PCA Axis does not fit any temperature reconstructions. The other environmental variables than temperature were correlated with Chironomidae communities on PC Ax 1. The pattern of the second PC Axis correlates with EE TS temperatures, validating this reconstruction reliability as fitting best to midge community trends contrary to poor modern analogues. PCA Ax 1 has 0.306487 and Ax 2 has 0.249362 eigenvalues, respectively.

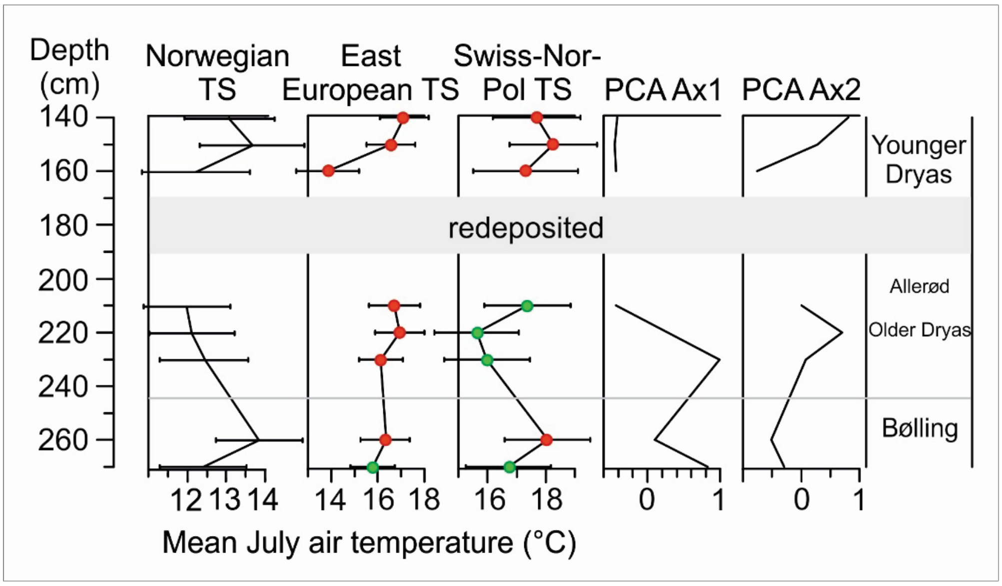


Fig. 4. Chironomidae-inferred mean July air temperature

green points - good modern analogues, red points - poor mondern analogues

Cladocera analysis

The sediments contain 11, only littoral **Cladocera** species. Four Cladocera zones can be distinguished (Fig. 5).

Zone CL 1 (295–285 cm) is characterised by relatively low finds of cladocerans, with the dominance of *Chydorus sphaericus*.

Zone CL 2 (285–195 cm) is characterised by fluctuating but systematic increase in species and is composed mainly of macrophyte/sediment-associated taxa such as *Ch. sphaericus*, *Alona guttata* and macrophyte-associated *Acroperus harpae*, as well as sediment-associated *Pleuroxus uncinatus*.

Zone CL 3 (195–115 cm) is characterised by a systematic drop in the number of Cladocera. *Alona affinis* and *Ch. sphearicus* dominated.

Zone CL 4 (115–85 cm) is characterised by only two macrophyte/sediment-associated taxa such as *A. affinis* and *Ch. sphaericus*.

Geochemical analysis

Based on the varying contents of the two main components of deposits (organic and mineral matter) and macro- and microelement concentrations, four main geochemical zones are distinguished, coded: GZ I–IV (Fig. 6).

GZ I (290–200 cm) represents gyttja and peat sediments with average content of mineral matter at 37.7%. The deposits of this zone are characterised by high contents of Na (average is 0.1 mg/g), Fe (average is 14 mg/g), K (average is 0.98 mg/g) and Zn (average is 12 μg/g). The Fe/Mn ratio is maximum throughout the whole profile (average is 419), but the Na/K ratio is lowest (<1) of all the zones in the core. The sediment reaction is acidic (pH 4.3–5.2).

GZ II (200–90 cm) comprises peat with average content of organic matter at 91.4%. This zone is distinguished by the lowest and stable concentrations of K (about 0.05 mg/g), Mg (about 1 mg/g), Fe (about 1.5 mg/g), Mn (about 0.025 mg/g) and Cu (about 4 μg/g). This fact results in very low Na+K+Mg/Ca and Fe/Mn ratios. The sediment reaction is still acidic (pH often does not exceed 5.0).

GZ III (90–20 cm) is distinguished by a rapid decrease in organic matter (from 88 to 69%) and increase in lithophilic element contents (Na, K and Mg). Only Fe content shows no clear changes, and it fluctuates around the average values calculated for the whole of core BE-1 (i.e., 3.21 mg/g). The three periods of increased |r| values correspond with the periods of increased Fe/Mn ratio only. The sediment reaction is neutral (pH 5.5–5.9).

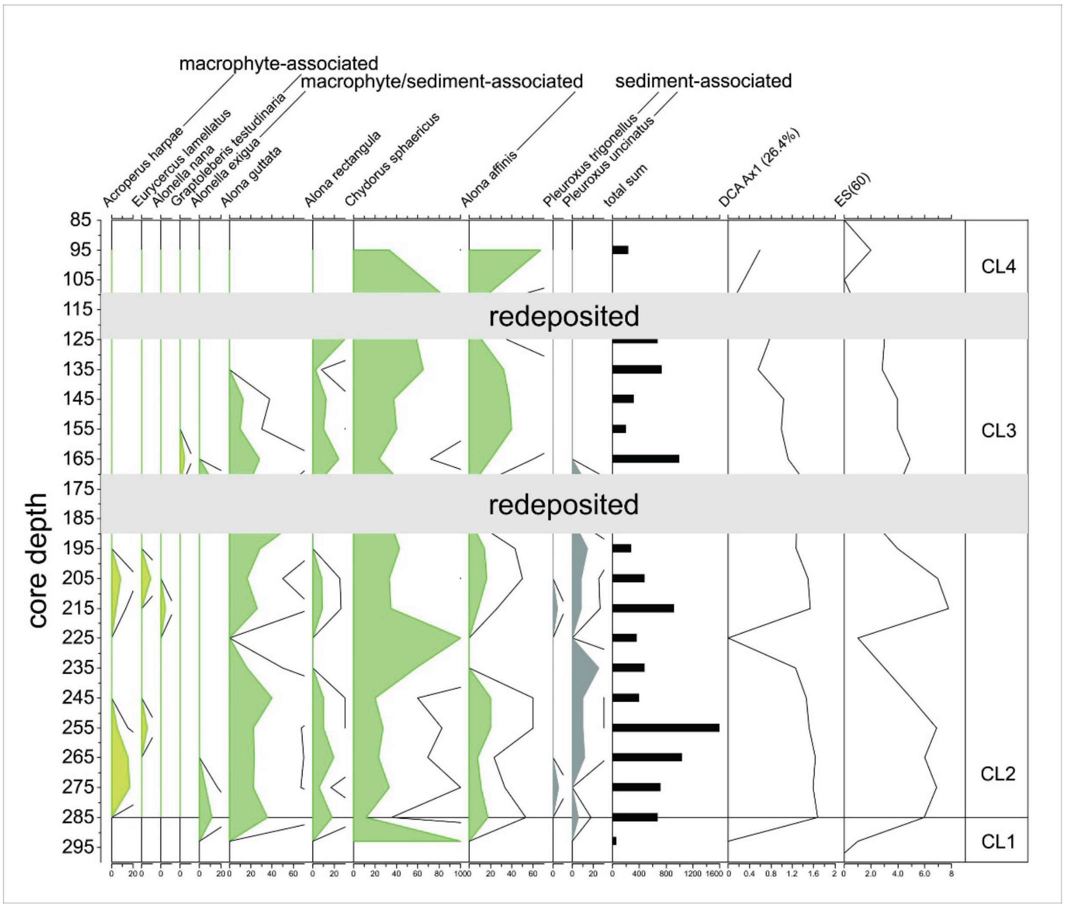


Fig. 5. Percentage stratigraphic diagram of Cladocera assemblages

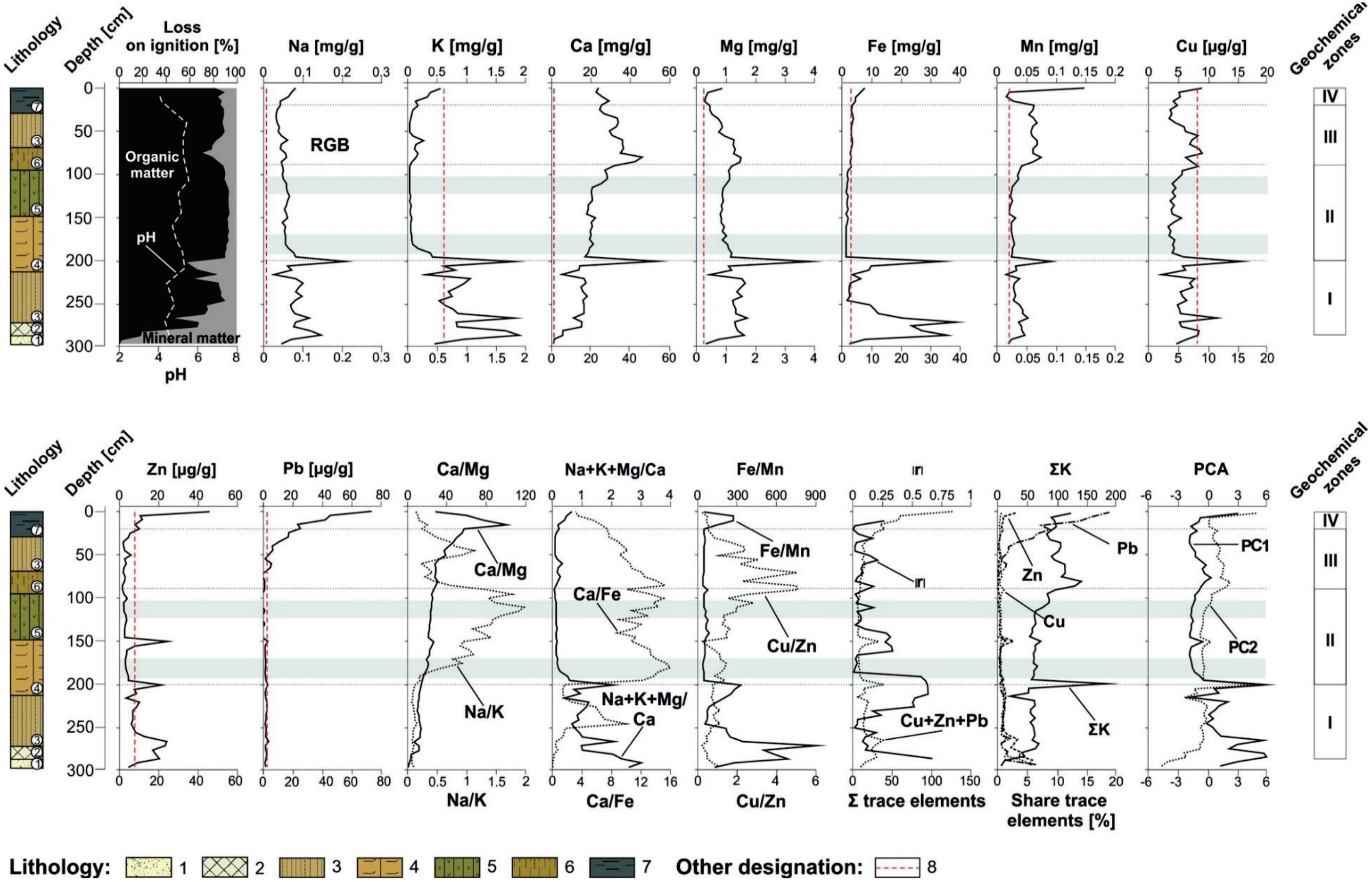


Fig. 6. Results of geochemical analysis

lithology: 1 – sand with organic matter, 2 – gyttja, 3 – herbaceous peat and sedge peat with reed remains, 4 – sedge-moss peat, 5 – reed peat, 6 – herbaceous peat, 7 – strongly decomposed peat; 8 – RGB: regional geochemical background

GZ IV (20–0 cm) records the sedentation of autochthonous rock-forming matter (increase in OM content to 90%) and is associated mainly with changes in Ca/Mg and Fe/Mn ratios. The concentrations of Na, Ca and Fe are also low, while the contents of other elements fluctuate a few times above regional geochemical background. The peat-forming community was characterised by acidification (pH range 4.3–4.0).

The first two principal components are significant (PC1 and PC2), explaining a total of 68% of the variance. The first component (PC1), which explains 47% of the total variation, is directly proportional to the concentrations of lithophilic elements (Na, K, Mg) and Fe, and inversely proportional to the organic matter content. The second component (PC2) is less important (it explains 21% of the geochemical variability of the deposits). This eigenvector is positively correlated mainly with Ca and Mn content, and is inversely proportional only to the content of K, Fe and Na.

Archaeological background

Analysis of archaeological data from the Bęczkowice fen was based on the results of field walking studies in the 1970s and 1980s as a part of PAR project. In the study area, there are more than 170 archaeological sites with at least 286 individual human activity factors (Fig. 7). Generally, for the Stone Age from around 11,000 to 2000 BC, almost 80 archaeological sites were attributed. However, only one site was qualified to the Late Palaeolithic. It should be linked to the Sviderian Culture most popular in Central Poland in that period (Chmielewska 1978; Sobkowiak-Tabaka 2011; Płaza *et al.* 2013/2015). More than 20 sites were dated to the Mesolithic and the Neolithic. Only eight of them could be precisely designated to the Early or Middle Mesolithic Komornica Culture, and six other sites are connected with the Middle Neolithic Funnel Beaker Culture. The rest is generally defined as Mesolithic and could be linked with the Komornica, Chojnice-Pieński or Janisławice Cultures (Kozłowski 1989). The Funnel Beaker Culture groups were the earliest farming society in the sandy area of Central Poland (Kukawka 2015). The other 60 sites were dated during the PAR project to the younger phase of the Stone Age.

Ecological interpretation

Pollen

The pollen record from the bottom part of the core (LPAZ Be-1) suggest that the sediments were accumulated during the Late Weichselian in the Bølling/Allerød (Fig. 2). During this period, low-density pine–birch forest dominated. The moist habitats were overgrown by willow shrubs and telmatic plant communities with Cyperaceae, *Typha latifolia* and *Menyanthes trifoliata*. Colonies of Chlorophyta developed in the lake.

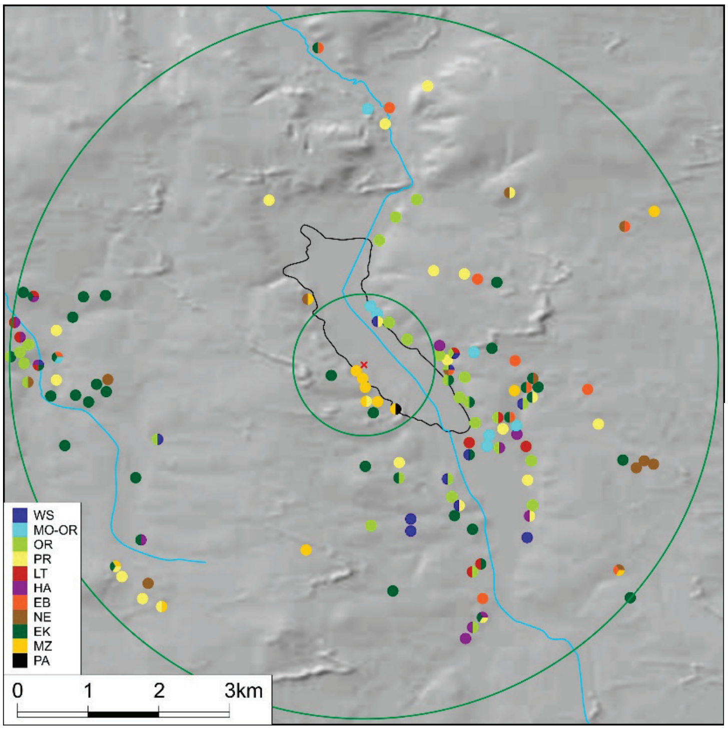


Fig. 7. Location of archaeological sites surrounding the Bęczkowice fen

chronology of archaeological sites: WS – Early Middle Ages, MO-OR – OR – Roman Period, PR – Pre-Roman Period, LT – La Tene Period, HA – Hallstatt Period, EB – Bronze Age, NE – Neolithic, EK – Stone Age, MZ – Mesolithic, PA – Late Palaeolithic; circles located in radius of 1 km and 5 km from the Be-1 profile, which is marked with a red sign

In the second phase (LPAZ Be-2), the vegetation changed. These changes were probably caused by a deterioration of climatic conditions (Older Dryas). The open landscape area extended, and herb communities spread. Light-demanding plants such as *Helianthemum*, *Gypsophila*, *Artemisia* and Chenopodiaceae had favourable conditions. In this open landscape, scattered juniper shrubs appeared. Communities of sedges still developed. At the end of this PAZ, the share of Late Weichselian indicators declines and this may suggest that the temperature grew and perhaps represents some part of the Allerød. In the lake, the population of Chlorophyta decreased, and broadleaf cattail disappeared from the rush components.

The LPAZ Be-3 can be correlated with the Younger Dryas. In the initial part, the share of tree pollen decreases, and herbaceous vegetation increases.

LPAZ Be-4 probably shows the transition to the Early Holocene. The sharp increase in tree pollen concentration in the sediment suggests a significant change in the landscape, as open landscapes begin to give way to trees.

The pollen record of LPAZ Be-5 definitely exhibits the pattern of Holocene plant communities (Fig. 2). In the vegetation cover, forest development is visible; the record is probably incomplete and more consistent with the Boreal period, because hazel and alder are already present. So, a hiatus in the Preboreal period is possible.

Chironomidae

Environmental conditions in the Ch1 zone were not favourable for non-biting midges. Each morphotype is represented by only a few individuals. The unstable assemblage composition and low head capsule concentration suggest that it was the first stage of wetland ecosystem appearance, and midges were just colonising the studied basin. Between 290 and 280 cm of the core, gyttja deposits accumulated and correspond with a limnetic taxa occurrence in that zone. The small number of subfossils suggests that they may have been eluted.

Environmental conditions were more stable in the Ch2a subzone than the Ch1 zone. Limnetic taxa were the main dominants. Also present were the semiterrestrial taxa: *Gymnometriocnemus subnudus*-type, *Krenopelopia*, *Limnophyes*, *Metriocnemus eurynastus*-type, *Metriocnemus fuscipes*-type, *Metriocnemus terrester*-type, *Parametriocnemus–Paraphaenocladius*, *Psedosmittia* and *Smittia* and the fully terrestrial *Bryophaenocladius virgo*-type. Chironomid diversity increased rapidly compared with zone Ch1 and is the highest of the whole BE-1 sequence. While the number of species increased, phytophile morphotypes started to appear (*Ablabesmyia*, *Cricotopus intersectus*-type, *Lauterborniella agralyoides*, *Glyptotendipes pallens*-type, *Monopelopia tenuicalcar*-type, *Paratanytarsus austriacus*-type, *Paratanytarsus penicillatus*-type). This proves the presence of water pools providing favourable conditions for limnetic species and aquatic vegetation.

The presence of semiterrestrial species suggests that, in the first stages of the fen succession, small pools underwent phases of drying or at least had a partially telmatic character. One of the dominant semiterrestrial taxa was *Limnophyes*, which occurred in nearly every sample in the Ch2a subzone. It often appeared in large numbers especially in the upper part of the subzone. From 190 cm to 170 cm core depth, species richness increased. This is a reworked sediment layer. There were crenophile and rheophile taxa in this subzone. Morphotypes that are often found in brooks and spring habitats are: *Heterotanytarsus apicalis*-type, *Heterotrissocladius marcidus*-type, *Metriocnemus terrester*-type and *Micropsectra contracta*-type. The appearance of species potentially associated with spring habitats suggests that the pools were fed by groundwater. Other potentially rheophile taxa (*Zavrelimyia*) are often found in small lowland streams. Morphospecies associated with meso/eutrophic habitats are frequent in the Ch2a subzone. Only in Ch2a was the number of head capsules high enough for mean July air palaeotemperature reconstruction (Fig. 4).

In subzone Ch2b, the head capsule concentration decreased. The main reason could be a water level decrease and redeposition of sediment. The number of subfossils is too small for any certain conclusions. Drying out of the fen and a hiatus in peat accumulation might have caused chitinous subfossils decomposition or some break in chironomid head capsule accumulation. Only taxa associated with limnetic conditions occurred. Phytophilous *Paratanytarsus penicillatus*-type subfossils were sometimes found.

Cladocera

Environmental conditions in the zone CL1 were not favourable for cladoceran, which are represented by a cosmopolitan taxon, *Chydorus sphaericus* (Pawłowski *et al.* 2013).

An increase in the number of benthic and phytophilous littoral Cladocera species suggests that this situation in the zone CL2 and CL3 (Fig. 5) resulted from the rich macrovegetation allowing an increase in the number of macrophyte-associated species. However, periodic increases in the proportion of sediment-associated Cladocera accompanied with a drop in diversity could be correlated with a decrease in water level and phases of sediment supply to the fen (Pawłowski *et al.* 2015a, b, 2016).

The low diversity and frequency of Cladocera in CL4 indicates unfavourable conditions for their development, probably due to periodic drying of the fen. Only cosmopolithic taxa, *A. affinis* and *Ch. sphaericus* could survive such water conditions (Pawłowski 2011).

Geochemical analysis

Variability of content elements and geochemical ratios in the GZ I were caused by environmental conditions in the Late Weichselian (Fig. 6). Gyttja deposits accumulated under a highly changeable water level in the Luciąża River valley and increased erosion of the catchment area. The disappearance of dense vegetation cover is reflected in increased contents of lithophilic elements and high content of allochthonous mineral matter.

The factors responsible for the strong acidification of the depositional environment at the Luciąża River valley floor are: the predominance of quartz in the mineral matter that builds the Bęczkowice fen catchment area and the short time of water circulation below the surface. The chemical composition of the deposits included in GZ II is typical for fen peatlands in central Poland (cf. Pawłowski *et al.* 2014; Antczak-Orlewska *et al.* in press), but here they are characterised by a slightly reduced concentration of alkaline components. Changes in the river network and an increase in the cover of vegetation in the Early Holocene caused a change in the type of accumulated sediments (from limnic to telmatic) and a several-fold increase in the proportion of organic matter, with a simultaneous decrease in the concentration of lithophilic metals.

In the case of GZ III, changes in the chemical composition of the deposits prove that the stable environmental conditions in the catchment were interrupted. The greater role of groundwater in the water balance of the fen is reflected in the change in the material reaction towards more neutral and slightly alkaline and an increased supply of minerals. Under the influence of mobile groundwater and surface waters, sedge communities developed, to which admixtures of sand were supplied.

The palaeo-environmental interpretation for the GZ IV level is difficult because the organic matter is undergoing secondary decomposition as a result of meliorative activities. The maximum concentrations were found for trace elements; the share of organic matter also increases, with a simultaneous decrease in the reaction and acidification of the accumulation environment.

Discussion

Fen community development in palaeovalleys

The main palaeoecological studies in Central Poland are mostly concerned with peatbogs, fens and palaeochannel habitats (e.g. Forysiak 2012; Pawłowski *et al.* 2016). The Wilczków fen located in the Balin-Chropy palaeovalley and the Luciąża palaeochannel close to Rozprza (Antczak-Orlewska *et al.* in press) reveal similar conditions to the Bęczkowice site in their initial phase. Both fens (Wilczków and Bęczkowice) had similar aquatic conditions and passed through parallel dry and moist phases in the Holocene (Płóciennik *et al.* 2015, unpublished data on the Bęczkowice fen Holocene sequence). Similarly the Luciąża palaeochannel and Brzęczkowice fen formed during the Bølling. A comparison between the Wilczków and Bęczkowice fens reveals an analogy in the Chironomidae abundance found in the parallel ecological phases. In zone X_1, which falls on the Early Holocene (Płóciennik *et al.* 2015), and zone Ch2a, which falls on Bølling/Allerød and Younger Dryas, there is the same high species richness and abundance of Chironomidae. This reflects optimal conditions for midge development at both sites. At both fens and in the Luciąża palaeochannel, *Micropsectra contracta*-type was one of the dominant taxa. Many *Micropsectra* species are associated with cold, oligotrophic conditions and are often found in small brooks and spring habitats. They may indicate groundwater supply and the presence of springs in the lower Ch2a zone (in Bęczkowice) as it was at the Wilczków fen. The species composition of upper Ch2a corresponds to the early Y zone at the Wilczków fen that falls on the Early to Mid-Holocene (Płóciennik *et al.* 2015). At both sites – Wilczków and Bęczkowice – the prevailing species are associated with semiterrestrial habitats like *Parametriocnemus-Paraphaeonocladius*-type and *Limnophyes*. In Wilczków, *Krenopelopia* dominated (Płóciennik *et al.* 2015), being associated with spring margins and wet meadows. At Bęczkowice, *Limnophyes* is an indicator of semiterrestrial conditions. During the Younger Dryas/Holocene transition, the palaeochannel in the lower Luciąża River valley also passed through a dry phase and a decline in aquatic midge share in biocenoses. However, the water level was still higher in the Bęczkowice fen than in Wilczków and in the RW-4 Rozprza fens in their terminal stages, and this is reflected in a higher concentration of subfossils and higher species diversity. The subsequent dry Holocene phases (later Y phase at Wilczków fen, Rozprza Early Holocene phase, Ch2b zone at Bęczkowice) show a similar trend – a decrease in head capsule concentration and poor diversity. The frequency and diversity of Cladocera in the X_1 zone in Wilczków and the Ch2a zone in Bęczkowice were the highest in the studied core sequences. Species living among plants are characteristic for the compared zones.

These results are also confirmed by the chemical composition of the sediments (Fig. 6, 8), despite the local differences in the geochemical background for individual metals (elements). The initial phase of the development of the wetlands in Bęczkowice and Wilczków in a cool climate is reflected in changes in the concentration of mainly K and Fe and, to a lesser extent, the share of organic matter and Zn. The maximum concentrations of lithophilic elements in the BE-1 profile show a high correlation with the participation of mineral matter, with maximum values of 2 mg/g for K, 4 mg/g for Mg and 0.22 mg/g for Na (Fig. 6).

In the core sediments from the Wilczków fen, there were also several periods of increased metal supply as a result of mechanical denudation, with the maximum concentrations of K (1.8 mg/g), Mg (2.7 mg/g), Na (0.18 mg/g) being typical for the section with the average share of mineral matter above 80% (see Borówka *et al.* 2014). The supply of mineral matter and lithophilic elements in both wetlands was related to the deterioration of climatic conditions, less stable and diverse accumulation conditions and the activation of slope processes in the catchment area. This is also confirmed by the physical and geographical features of the peatlands themselves, as well as the geological structure and relief of the catchment area.

Hydrology, trophic state and pH

After climatic factors, hydrological factors (mostly water level fluctuations) are the next most important factor that influences the distribution of Chironomidae and Cladocera assemblages on peatlands (Płóciennik *et al.* 2020). Spitzer and Danks (2006) distinguished fens from other peatlands by considering two parameters: water table fluctuation and pH. Generally, water level fluctuations are lower in fens than in bogs (Rydin, Jeglum 2006). The supply regime of the fens comprises inflow from precipitation and surface water and outflow as groundwater (Płóciennik *et al.* 2015). Nevertheless, in dry periods, like the relatively cool Early Holocene, lower discharge and precipitation caused the desiccation of valley fens, the elimination of freshwater invertebrates and even caused the decomposition of peat, as was observed at the Bęczkowice sites and another site in the region (Kittel *et al.* 2016; Płóciennik *et al.* 2016; Pawłowski *et al.* 2016). That implied changes in abundance and species composition of Chironomidae and Cladocera. In this period, there is also a clear decrease in Fe/Mn ratio (from 358 to 45) and a gradual increase in Ca/Mg ratio (from 0.11 to 0.13), which may mean sedentation of autochthonous organic matter. It is possible to indicate the conditions of periodic good oxygenation with a simultaneous slow increase in the role of groundwater in the water balance of the fen. Calcium in peat deposits can be present as a component of both organic matter or in the form of carbonates as a result of the sedimentation of molluscs or as a mineral component. Its vertical variability of concentration in Late Weichselian sediments was treated as an indicator of the unblocking of the underground water supply (Goździk, Konecka-Betley 1992; Okupny *et al.* 2019).

The Chironomidae DCA Ax1 clearly indicates a water level decrease from early Ch2a to Ch2b (Fig. 3, 4, 8). This process is visible in the upper Ch2a and Ch2b, where the number of Chironomidae species decreased significantly, and species previously present were replaced by semiterrestrial ones. The habitat desiccation in Ch2b is confirmed by the results of sedimentological analysis (Forysiak 2012). At 280–230 cm, the fen was supplied by fluvial waters that caused a reworking of the sediment, and later (230–130 cm core depth) also by groundwater. This allowed sedge-moss plant communities to develop. In the upper Ch2, the Luciąża's floods regularly influenced the water table of the Bęczkowice fen, but the peat from the Early Holocene section dried out for some time and was strongly decomposed (60–70% decomposition), especially at 90–85 cm. This was a period of willow-sedge rush communities, also with *Sphagnum* in modern times. This means that chironomid subfossils were partly decomposed and reworked, so reconstruction of the Chironomidae assemblages in Ch2b should be treated with caution. This is also why the Holocene sequence of the sediment is not complete and could not be dated, and why their stratigraphic importance is weak.

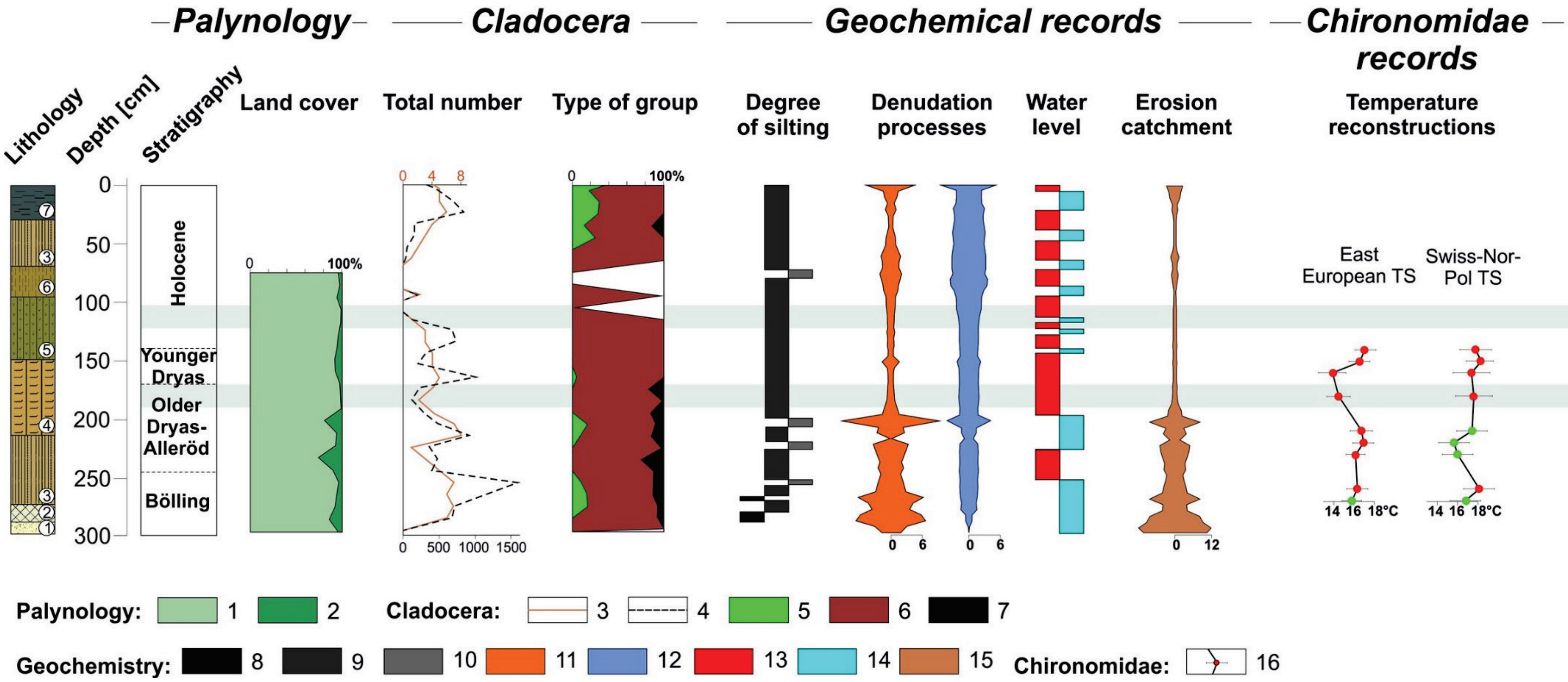


Fig. 8. Main results of palaeo-ecological analyses

lithology: 1 – sand with organic matter, 2 – gyttja, 3 – herbaceous peat and sedge peat with reed remains, 4 – sedge-moss peat, 5 – reed peat, 6 – herbaceous peat, 7 – strongly decomposed peat
palynology: 1 – AP, 2 – NAP
Cladocera: 3 – number of species, 4 – number of specimens, 5 – macrophyte-associated, 6 – macrophyte/sediment-associated, 7 – sediment-associated
geochemistry: 8 – heavily silted deposits, 9 – moderately silted deposits, 10 – unsilted deposits, 11 – mechanical denudation (based on Na/K ratio), 12 – chemical denudation (based on Ca/Mg ratio), 13 – low water level (based on Fe/Mn ratio), 14 – high water level (based on Fe/Mn ratio), 15 – catchment erosion (based on Na+K+Mg/Ca ratio)
Chironomidae: 16 – summer air temperature reconstructions

A similar phenomenon was observed in the DCA trend in the Cladocera assemblages – a systematic decline in DCA Axis 1 values from the bottom to the top of the sequence reveals a decrease in water level. However, periodic floods and higher water levels may be indicated by the increase in the abundance of sediment-associated Cladocera taxa, as was also noted in other sites in the region (Pawłowski 2012; Pawłowski *et al.* 2015a,b, 2016). Moreover, the development of vegetation caused, on the one hand, the limitation of physical denudation processes in the catchment (decrease in Na + K + Mg/Ca ratio from 2 to 0.14) and, on the other hand, their supply with groundwater and chemical denudation (increase in the values of Ca/Mg, Na/K indicators and the course of the PC2 curve).

As was mentioned above, pH and water trophic state are subsequent factors that influence species richness and assemblage diversity in wetland habitats. Rich fens are characterised by circumneutral pH conditions (5–7), while poor fens are more acidified (pH: 4–5.5) (Rydin *et al.* 2006). The pH is one of the main factors influencing wetland chemical conditions and indirectly affects the flora and fauna (van der Valk 2006). Chironomidae diversity usually decreases when pH drops below 5 (Henrikson *et al.* 1982). Acidification changes the predator–prey system by favouring dragonflies (Brooks *et al.* 2007). Low pH can negatively influence the emergence of certain taxa. For instance, *Chironomus* and *Dicrotendipes* emerge when pH is highest in the season (Henrikson *et al.* 1982). In acid conditions, toxic metal ions (i.e. Al^{3+}) dissolve into the water (Brooks *et al.* 2007). At the Bęczkowce fen, acid-tolerant taxa (*Heterotantarsus apicalis*, *Pseudorthocladius*, *Psectrocladius sordidellus*-type) are rare. This indicates rather circumneutral or at most weakly acidified conditions and is confirmed by slight fluctuations in the pH of the sediments (pH in the 4–6 range) and a relatively uniform concentration of some elements (e.g. Ca and Mn). Walker *et al.* (1985) noted that pH value strongly correlates with other environmental factors; for example, quite high pH (>6) occurs in lakes enriched by groundwater. Some species that are often found at low pH are semiterrestrial (i.e. *Limnophyes*). Habitat acidity influences water trophic state.

The chironomid assemblage composition suggests that the Bęczkowice fen was initially a meso/eutrophic habitat. The dominant taxa include: *Cryptochironomus* in Ch1 and *Polypedilum nubeculosum*-type in Ch2. *Micropsectra contracta*-type is the only oligo-stenotopic abundant morphotype from Ch2a. The species diversity of Cladocera in Bęczkowice is generally similar to other valley mire sites in the region (Pawłowski *et al.* 2016). The assemblages were composed mainly of macrophyte/sediment-associated taxa but later, during low water and low pH conditions, was rather cosmopolitan.

Palaeoclimatic conditions during the Late Weichselian

The CH-I No TS and SNP TS reconstructions seem to support pollen records of the Older Dryas cooling at the LPAZ Be-2 zone, but there are only three temperature records falling on the Older Dryas layers, and the EE TS reconstruction results reveal a different, even increasing trend at the 220 cm core depth. Recently, Antczak-Orlewska *et al.* (in press) presented a Chironomidae-inferred summer temperature reconstruction from the lower section of the Luciąża valley revealing a colder late Allerød than early Younger Dryas. The new reconstruction from Żabieniec (Kotrys *et al.* 2020) also seems to give a lower temperature at the Allerød termination than the Younger Dryas, but the Z-2 chironomid sequence presented by Płóciennik *et al.* (2011) and Kotrys *et al.* (2020) has a very low resolution that does not allow for such detailed palaeoclimatic analysis. It must be stated that BE-1 Chironomidae subfossils were redeposited at the Allerød/Younger Dryas transition and can't be compared in this case with the Rozprza RW-4 sequence presented by Antczak-Orlewska *et al.* (in press). The values of EE TS and SNP TS are consistent with reconstructions presented by Kotrys *et al.* (2020) and No TS values are consistent with Płóciennik *et al.*'s (2011) estimations of Late Glacial summer temperatures in central Poland from the Żabieniec palaeolake. The decadal-level-resolution reconstruction from the laminated Gościąż lake (Müller *et al.* 2021) gives similar values for the Younger Dryas to estimate from midge communities of the Bęczkowice fen. Results of the CH-I temperature reconstructions from the Bęczkowice fen must be interpreted with caution due to the low resolution of the temperature records and the approximate modelling of age.

All the environmental changes discussed above are confirmed by significant fluctuations in the chemical composition of the sediments of the studied profile and other fens from Central Poland. In the context of regional differentiation of biogenic accumulation conditions, these fluctuations are mainly related to changes in plant cover, which directly determined the intensity of the supply of terrestrial material to peatlands (Forysiak *et al.* 2013; Okupny *et al.* 2013). In the case of the concentration of biophilic components, the interpretation may concern changes in the productivity of aquatic and terrestrial vegetation as well as oxidation–reduction conditions (Borówka *et al.* 2015; Pawłowski *et al.* 2016).

Implications of human settlement in the Palaeolithic and Mesolithic

The territory of Central Poland was seasonally or periodically occupied at the end of the Late Weichselian by various small human groups that left remains of camps quite poor in artefacts. For the Late Pleistocene in the Allerød, the remains of activity of hunter–gatherers of the Arch-Backed Pieces or Federmesser Culture are discovered (Sobkowiak-Tabaka 2011, 2017). Federmesser Culture groups are correlated with the period from the Bølling to the beginning of the Younger Dryas – between 12,240 and 10,630 BC (Wiśniewski 2020). For the Younger Dryas, the domination of reindeer hunters of the Sviderian Culture is defined. These groups mostly use landscapes similar to that in the vicinity of the Bęczkowice fen. They occupied mainly valleys of large rivers like the Warta (Cyrek 1996; Sobkowiak-Tabaka 2011; Płaza *et al.* 2014) or Bzura (Chmielewska 1978), and inland dunes close to lakes that are now peatlands (Niesiołowska-Śreniowska *et al*. 2011). The Bęczkowice fen, with its sandy surroundings in the southern and northern part (Fig. 7), fits very well that idea of the occupation of inland, sandy, dry land close to freshwater reservoirs. In which season Sviderian hunters visited and used Bęczkowice area offering probably good water quality and food availability, it is hard to decide. The end of the short warm summer, when large mammals were roving in Central Poland, seems to be more favourable for hunter–gatherer activity.

From the beginning of the Holocene, there were quite abrupt changes in the ecosystem, and also in social aspects. Those situations brought the need for a different type of weapon and hunting strategy (Chmielewska 1978; Schild 1975; Sulgostowska 1997). A different, smaller kind of point was required. These points were made from much smaller blades with precisely fixed parameters of arrowheads, in contrary to the large-tanged points of the Sviderian Culture. Smaller blades could have been obtained from bad quality, local raw material, which did not involve the long and hard journeys to southern Poland in search of chocolate or Jurassic flint that had been required in the Late Palaeolithic. From that time, Kolonia Bartodzieje campsites are known, proving that humans explored that area in the first part of the Holocene. Later, at the end of the Boreal and in the early and middle Atlantic, during the Holocene Climatic Optimum, there is a luxuriant growth of forests and aquatic and wetland fauna. The process particularly intensifies in lowland areas with well-developed hydrographic networks.

In these places, there is a visible increase in the number of Mesolithic sites, frequently very rich in artefacts, revealing features of the Komornica Culture. In the early Atlantic, there is a clear change in the method of flint processing. Erratic, poor-quality raw material was used to perfection, and chocolate flint began to be extracted again, as it had during the existence of the Sviderian Culture (Sulgostowska 1997).

In the analysed sediment profile, it is difficult to identify the stages related to the geochemical indicators of human economic activity. It follows that, during the Late Weichselian, the human influence may have been weak, and the variability of environmental conditions implied by climate change was certainly large. On the other hand, both these factors are manifested by an increase in the share of allochthonous mineral matter, lithophilic elements (Na, K, Mg) and trace elements (Cu, Zn and Pb) and the index of dynamics of sedimentation conditions |r|.

The first distinct period of increased supply of lithophilic elements was in the Bølling (GZ I, 267–260 cm). This is accompanied by slight changes in the oxidation–reduction conditions (equal values of Ca/Fe and Fe/Mn) with a low concentration of Pb (below 3 μg/g) and a slightly increased concentration of Cu (above 11 μg/g) and Zn (above 24 μg/g). In the case of Zn, however, the possibility of strong bioaccumulation in a tundra environment by some plants, especially birch and dwarf (Arctic) willow, should be taken into account (see Reimann *et al.* 2007).

The geochemical record of the next period of high values of the catchment erosion index is in the Older Dryas–Allerød (GZ I, 230–200 cm). Initially, a gradual increase in the concentration of lithophilic elements (mainly K from 0.31 mg/g to 1.8 mg/g) was found here, with the sum of heavy metals poorly marked in the geochemical diagram (below 50 μg/g). However, the concentrations of these elements are typical for biogenic sediments filling the basins of valley fens in Central Poland (Rydelek 2011; Borówka *et al.* 2014; Pawłowski *et al.* 2014; Antczak-Orlewska *et al.* in press).

The core section correlated with the Boreal/Atlantic transition (GZ III, 0.8–0.5 m) is interesting. There is a two-fold increase in the catchment erosion index (Na + K + Mg/Ca from 0.11 to 0.35), an increase in the share of mineral matter (from 10 to 30%) with equal values of the oxidation–reduction conditions indices (i.e. Fe/Mn and Ca/Fe). However, these changes occur due to an increase in the intensity of chemical denudation processes in the catchment (Na/K is slightly above 1), which may be related to the rise in the water table in the catchment area. The highest fluctuations are shown by the Cu/Zn ratio, with a relatively low concentration of the sum of trace elements (maximum 15 μg/g). However, the mutual relation of Cu, Zn and Pb concentration is broken according to Weng *et al.* (2003), suggesting the influence of human activity in the fen environment. After Hildebrandt-Radke *et al.* (2011) and Płaza *et al.* (2013/2015), when indicating the record of human activity in sediments, we should remember about the local hydrogeological conditions shaping the geochemical background levels and the genesis of biogenic sediments and their possible enrichment in selected metals (Fig. 6, 8).

Due to the high degree of decomposition of organic matter and the lack of radiocarbon dating for sediments from the top Be-1 profile, it is impossible to establish the chronostratigraphy of palaeo-environmental changes and the record of the impact of human activity in the Early Holocene.

Conclusions

The Bęczkowice fen is one of the largest wetlands in Central Poland. It developed within the Luciąża River valley floor. The peat-lacustrine deposits in the studied BE-1 core began to accumulate in the Bølling, and then the wetland expanded to cover the entire width of the valley floor. Although it is the upper course of the river, the stream probably occupied various positions when it flowed through the fen, creating a multi-channel river system and interfering with the peat deposition process, which could have resulted in incomplete fossilisation of the biogenic sediments of the studied core. However, only by obtaining a wide range of palaeoecological data and radiocarbon dating was it possible to conclude the existence of breaks in the accumulation of the peat layers and a possible redeposition of allochthonous material included in the peat series.

The record of changes in vegetation is presented in the pollen diagram, despite the identified sections with poorly preserved material and the increased presence of redeposited pollen grains, this analysis is the basis for the presented stratigraphic scheme, which includes the warm phases of the Late Weichselian (Bølling and Allerød) and the cold phases (Older Dryas and Younger Dryas). The beginning of the Holocene warming is also clearly noticeable, although the core is incomplete in this section as well. Radiocarbon dating of the material gave mostly erroneous results, and therefore they are not suitable for building a chronological axis.

The high dynamics of changes in depositional conditions in the Bęczkowice fen basin is confirmed by the palaeo-environmental pronunciation of individual metals and geochemical indices. The lack of stabilisation of the soil cover in the Older Dryas and Younger Dryas was a result of climate change. During the Holocene, soil instability and denudation were related to the activity of Late Palaeolithic and Mesolithic tribes. The catchment erosion was also conditioned by the geological structure (the presence of clay sands in the substrate with an admixture of carbonate crumbs and the high water-permeability of fluvioglacial and fluvial sands).

The results of the Chironomidae and Cladocera remains analyses support the conclusions about unstable hydrological conditions. The high species richness of Chironomidae indicates that the fen was at least seasonally inundated. Permanent aquatic conditions may also be considered, but there is a high share of semiterrestrial midges, and the concentration of subfossils is also low. This suggests high energy states in the valley (floods) or a partly unfavourable environment for aquatic taxa. The taxonomic composition of chironomid assemblages of the Bęczkowice fen corresponds well with subfossil communities of the Rozprza RW-4 palaeo-oxbow terminal phase, and the Wilczków fen initial phase. Results of previous research and the present study give a general picture of a peatland ecosystem functioning during the Late Weichselian and the Early Holocene.

The studied section of the Luciąża River valley and its vicinity were intensively explored and inhabited by Palaeolithic and Mesolithic communities. However, the incomplete record in the studied deposits of the Bęczkowice fen and the possible overlapping of the effects of environmental changes with human influences make it difficult to properly identify the scale of the human impact of hunter–gatherer communities.

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