Palaeotemperature estimation in the Holsteinian Interglacial (MIS 11) based on oxygen isotopes of aquatic gastropods from eastern Poland

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ABSTRACT:


For quantitative estimation of past water temperature of four Holsteinian (MIS 11) palaeolakes from eastern Poland, the oxygen isotope palaeothermometer was applied to shells of the aquatic gastropods Viviparus diluvianus and Valvata piscinalis. The δ18O composition of their shells demonstrated the average growth-season water temperatures during the mesocratic stage of the interglacial (Ortel Królewski Lake), during its climatic optimum – the Carpinus–Abies Zone (Ossówka-Hrud, Roskosz and Szymanowo Lakes), and in the post-optimum (Szymanowo Lake). The calculation was based on δ18Oshell values and the δ18Owater assumed for the Holsteinian from the modern oxygen isotope composition of precipitation and the expected amount of evaporative enrichment. The mean oxygen isotope palaeotemperatures of Ortel Królewski lake waters were in the range of 18.1–21.9°C and were uniform for the Taxus and Pinus–Larix zones. Ossówka-Hrud and Roskosz Lakes had mean temperatures of 17.4–21.0°C during the climatic optimum, whereas the temperature of Szymanowo lake waters was estimated at 20.6–21.7°C at that time. These values are concordant with the pollen-inferred July air temperatures noted during the Holsteinian in eastern Poland. Relatively high values of ~25°C in the post optimum noted at Szymanowo were connected with the presence of a shallow and warm isolated bay indicated by pollen and mollusc records.

Key words: Oxygen Isotopes; Molluscs; Palaeotemperature; Thermometry Equation; Holsteinian Interglacial; Eastern Poland

INTRODUCTION

In the light of discussions on modern climatic changes, past temperature estimations are highly desirable being one of the principal directions in palaeoecological studies of the Quaternary period. One of the main sources of palaeoclimatic information on land areas, including palaeotemperatures, are palaeobotanical data (Aalbersberg and Litt 1998). Floristic successions indicate warm and cold phases, define subsequent interglacials and characterise environmental and climatic changes during the Pleistocene and Holocene. Essential for temperature information are both the whole phytocenoses and the marker taxa with specific thermal and habitat demands. Based on the thermal minima and maxima of their occurrence, geographical and temporal temperature ranges may be estimated (Iversen 1954; Zagwijn 1996; Aalbersberg and Litt 1998; Pidek 2003; Nita 2009).
Faunal assemblages are also prone to climatic changes, but direct absolute temperature reconstructions are restricted to selected organisms, namely coleopterans (e.g., Amman et al. 1983; Coope 1986; Atkinson et al. 1987), chironomids (e.g., Lang et al. 2010; van Asch et al. 2012), ostracods (e.g., von Grafenstein et al. 1994, 1996, 2000) and molluscs (e.g., von Grafenstein et al. 2000; Baroni et al. 2006; Candy et al. 2011; Apolinarska et al. 2015).

Basic palaeoclimatic studies based on snails and bivalves mostly use the differences in structure and composition of their assemblages. Besides characterising local habitats, they point to glacial/interglacial conditions and indicate influences of warm and cold air masses. They provide, however, qualitative rather than quantitative data (Ložek 1986; Alexandrowicz 2011). The latter may be inferred from the oxygen isotope composition of freshwater mollusc shells. This is based on the fact that shells precipitate in isotopic equilibrium with the lake water, avoid contamination by allochthonous carbonate, and that the $^{18}O/^{16}O$ shell ratios are mainly controlled by temperature and the isotope composition of ambient water (e.g., Fritz and Poplawski 1974; Buchardt and Fritz 1980; Hammarlund and Buchardt 1996; Leng and Marshall 2004; Grossman 2012). One of the approaches is an estimation of the relative air temperature changes, based on the $\delta^{18}O$/temperature coefficient which depends on the local precipitation and isotopic fractionation gradients, with the minor influence of evaporative enrichment (Dansgaard 1964; Siegenthaler and Eicher 1986; Hammarlund et al. 1999; Ahlberg et al. 1996; Ralska-Jasiewiczowa et al. 2003; Apolinarska 2009a; Apolinarska and Hammarlund 2009; Dabkowski et al. 2012). Despite some generalisations and presupposed simplifications in these reconstructions, they often appear reliable and congruent with palaeobotanical estimations (Hammarlund et al. 1999; Apolinarska and Hammarlund 2009; Szymanek 2016; Szymanek et al. 2016). Because researchers strive to be more accurate in temperature interpretations, another approach focuses on calculating the absolute past-water temperature based on several more advanced formulas applicable to biogenic carbonates, including molluscs (e.g., Epstein et al. 1953; Craig 1965; Grossman and Ku 1986; Kim and O’Neil 1997; White et al. 1999; Leng and Marshall 2004; Bugler et al. 2009; Grossman 2012). These calculations, often supported by empirical and laboratory data (White et al. 1999; Bugler et al. 2009), usually yield reliable results in the highly resolved studies of recent sediments (von Grafenstein et al. 1996; Wurster and Patterson 2001; Apolinarska et al. 2015). They are less popular but applicable to the fossil record (Dettman and Lohmann 1993; Grimes et al. 2002; Hren et al. 2013), dealing mostly with the Late Glacial-Holocene lake systems (von Grafenstein et al. 1994, 2000; Hammarlund et al. 2003), whereas data for Pleistocene interglacials are hardly available (Candy et al. 2011).

In this article, oxygen palaeothermometry has been applied and tested for shell material of Holsteinian age (MIS 11). It was based on recent isotope investigations of Viviparus diluvianus and Valvata piscinalis shells, characterising the relative air temperature changes and climate–environmental conditions of four palaeolakes of eastern Poland (Szymanek 2016; Szymanek et al. 2016). The main goal of this study is a quantitative interpretation of the oxygen isotope record of V. diluvianus and V. piscinalis shells. It is aimed at the reconstruction of past water temperatures in these palaeolakes using thermometry equations. Because the accumulation of lake deposits was not simultaneous and covered more than a single pollen zone, the temperature characteristics of different parts of the interglacial and of different lake phases were also considered. Some water temperature changes in the studied region were briefly reported by Szymanek et al. (2016), but this contribution is indeed the first experimental calculation of absolute past water temperatures for the Holsteinian Central-European lakes.

REGIONAL SETTING

The study area is located in southern Podlasie and northern Polesie (eastern Poland), c. 160 km east of Warsaw (Text-fig. 1). This area is under the influence of both oceanic and continental climates with mean annual precipitation of 527 mm and mean annual temperature of 7.4°C (Text-fig. 2). The recent mean January air temperature is -3.7°C, whereas the mean July temperature reaches 18.3°C (Woś 2010; NCDC 2015). Today, no lakes occur in the study area. The closest lakes are located in the Łęczna-Wlodawa Lake District, c. 80 km to the south, which developed during the Pleistocene/Holocene transition (Wojtanowicz 1994). However, during the Holsteinian Interglacial (c. 420–380 ka ago) a palaeolake district existed in the study area (e.g., Nitychoruk 2000; Lindner and Marciniak 1998; Nitychoruk et al. 2005). Lacustrine deposits were documented at over thirty locations in this region and were ascribed to three main types of palaeolakes based on the sedimentary environ-
ment and origin of the lake basins (Nitychoruk 2000); SW-NE or W-E oriented trough palaeolakes, corresponding to tectonic structures in the Palaeozoic substratum and characterised by long-lasting and steady calcareous sedimentation; small lakes with unstable sedimentation (mostly silts, peats, bituminous shales) located on the morainic plateau; and 1–2 km long and wide lakes of complex origin with calcareous deposits and bituminous shales (Nitychoruk 2000; Lindner and Marciniak 1998). A fourth type of lake deposition devoid of palaeontological record was connected mostly with the early Saalian Glaciation (MIS 10) and interpreted only in boreholes in the vicinity of Janów Podlaski (Lindner and Marciniak 1998).

All the palaeolakes studied herein appear to represent the first type of lakes. In their littoral zone 1- to 3-m-thick sands and silts with a rich and well-preserved molluscan fauna were deposited, with no signs of disturbance and redeposition (except for two samples at Ossówka; Nitychoruk 2000; Szymanek et al. 2016). They are usually covered only by topsoil or by a 2–3-m-thick layer of fluviglacial, colluvium and organic deposits which accumulated from the Saalian to the Holocene (Lindner et al. 1991; Albrycht et al. 1995; Szymanek 2012, 2013, 2014a).

### Characteristics of the studied palaeolakes

The Holsteinian Ossówka-Hrud, Roskosz, Ortel Królewski and Szymanowo lakes were investigated. Their geographical range was based on literature data (Lindner and Marciniak 1998; Nitychoruk 2000), detailed geological mapping (Albrycht 2002; Nitychoruk and Gałązka 2008) and on fieldwork conducted by the author. Their detailed bathymetry and catchment areas are difficult to assess, but both the trough-like nature of the lake basins and the several thick (up to 60 m) logs of lake deposits suggest considerable depths, especially at Ossówka-Hrud and Roskosz lakes.

The ecology of the studied palaeolakes has been based on multi-proxy palaeobotanical (Lindner et al. 1991; Bińska and Nitychoruk 1995, 1996; Krupiński 1995, 2000; Bińska et al. 1997; Marciniak 1998), malacological (Lindner et al. 1991; Albrycht et al. 1995; Skompski 1996; Szymanek 2012, 2013, 2014a, b) and geochemical analyses (Szymanek 2016; 2017; Szymanek et al. 2016), which yielded basic information about their hydrological regime (water level changes, water movements/wave action, depth conditions etc.), the aquatic vegetation, productivity and trophic conditions.
Due to the lack of absolute dating, the chronology of the lakes (Text-fig. 3) was based on numerous pollen analyses (Lindner et al. 1991; Albrecht et al. 1995; Bińka and Nitychoruk 1995, 1996; Krupiński 1995, 2000; Bińka et al. 1997; Nitychoruk 2000; Nitychoruk et al. 2005; Szymanek et al. 2016). The rich pollen data allow for the regional correlation of the studied profiles, and the correlation of lake records from eastern Poland with other European sequences of Holsteinian age (e.g., Koutsodendris et al. 2012, 2013; Candy et al. 2014).

**Ossówka-Hrud Lake**

This palaeolake occupied an elongated NE-SW-oriented depression, located 10 km north of Biała Podlaska, corresponding to the Janów Podlaski tectonic graben recognised in the Palaeozoic substratum (Nitychoruk 2000). This 9.2-km-long and up to 1-km-wide basin covered an area of c. 8 km² (Text-fig. 1) and was filled with over 55-m-thick calcareous, mostly laminated deposits. Sedimentation began in the lake in the end of the Elsterian Glaciation (MIS 12) (c. 430 ka BP; thermoluminescence dating) and lasted for nearly 40 ka until the early Saalian Glaciation (MIS 10) (Krupiński 1995; Nitychoruk 2000; Nitychoruk et al. 2005). Around the lake fluvioglacial deposits of Saalian age prevail. There also occur patches of till corresponding to the Saalian (Nitychoruk and Gałązka 2008) or the Elsterian Glaciation (Marks et al. 2016).

The lake was inhabited by abundant molluscs noted along its eastern (Ossówka, Hrud I) and western shores (Hrud II) (Lindner et al. 1991; Szymanek 2012). Molluscan assemblages with varying *V. piscinalis* and *Bithynia tentaculata* content reflect periodic depth changes. Lower water levels coincided with the expansion of bulrush and reeds, whereas higher water levels occurred together with restricted aquatic inshore vegetation and possible water movements (Szymanek et al. 2016).

Text-fig. 2. (a) Modern oxygen isotope composition of precipitation (monthly means), and (b) modern mean monthly temperature and precipitation from Brest (April 1980 – December 1983) and Cracow-Wola Justowska (March 1975 – December 2010) stations. Data derived from Global Network of Isotopes in Precipitation (GNIP) Database (IAEA/WMO 2014)
Deeper-water conditions reflected in a higher content of *V. piscinalis* were noted at Ossówka (unpublished data) and in the Hrud II profile, where they were followed by a gradual lake shallowing combined with the renewed growth of near-shore aquatic plants, evidenced by the malacological record, and increased carbon isotope values (Szymanek 2012, 2016; Szymanek et al. 2016). These changes correspond to the climatic optimum of the Holsteinian Interglacial – the *Carpinus–Abies* Zone (Szymanek 2012; Szymanek et al. 2016), whereas the Ossówka succession encompasses the *Carpinus–Abies* Zone, the post-optimum period with an undefined pollen zone, and possibly the early stage of the Saalian Glaciation (Text-fig. 3). However, the occurrence of warmth-demanding mollusc species through the entire Ossówka succession (unpublished data) may indicate some shell reposition in a post-interglacial lake (Szymanek 2016; Szymanek et al. 2016).

**Roskosz Lake**

Lake Roskosz is an elongated (c. 15 km long), narrow (maximum width of c. 1 km) palaeolake, c. 14 km², running from west to east between the villages of Roskosz and Lachówka Mała (Text-fig. 1). It is located at an altitude of c. 147.5 m a.s.l. and is surrounded by the Elsterian morainic plateau and Saalian sandur.

Calcareous sedimentation in the lake took place between the Elsterian and Saalian, covering the whole Holsteinian Interglacial (Bińka and Nitychoruk 1995, 1996; Bińka et al. 1997; Krupiński 2000; Nitychoruk 2000), whereas near-shore, minerogenic, mollusc-bearing deposits represent a part of the *Carpinus–Abies* Zone (Text-fig. 3; Szymanek 2011; Szymanek et al. 2016). Abundant rheophile species *Pisidium henslowanum*, *Pisidium nitidum* and *Pisidium subtruncatum* (Szymanek 2013) suggest a flow-through eutrophic lake, or wave action in the lowermost part of the Roskosz succession. This phase was followed by a shallow lake phase with prolonged residence time and dense bulrushes and reeds in its littoral areas evidenced by abundant pulmonate gastropods *Gyraulus albus*, *Lymnaea stagnalis* and *Acroloxus lacustris* (Szymanek 2013). Increased δ¹³C and Fe/Mn values in *V. diluvianus* and *V. piscinalis* shells point to higher productivity level and oxygen consumption due to organic matter decay at that time (Szymanek 2017). Depletion of ¹³C in the uppermost part of the succession is related to limited vegetation and deepening of the lake (Szymanek 2016; Szymanek et al. 2016).

**Ortel Królewski Lake**

Palaeolake Ortel Królewski is situated 12 km southeast of Biała Podlaska, at an altitude of c.
142.5 m a.s.l., in the area covered mostly by fluvio-glacial deposits of the Saalian Glaciation. Holsteinian lake deposits, up to 7 m thick, are preserved only in the eastern part of the Zielawa river valley. They have been eroded from the central part of the basin. The lake with a surface area of c. 15 km² presumably was the eastern part of the Zielawa river valley. They have cial deposits of the Saalian Glaciation. Holsteinian
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Characteristics of the Holsteinian vegetation in eastern Poland

Most of the palynological analyses in the studied area were conducted by Krupiński (e.g., 1995, 2000) and Bińka (e.g., Bińka and Nitychoruk 1995, 1996; Bińka et al. 1997, Nitychoruk et al. 2005), who differ in their descriptions of the pollen zones and interpretation of the climatic optimum of the Holsteinian Interglacial. Bińka limits its range only to the Carpinus–Abies Zone (Bińka and Nitychoruk 1995, 1996; Bińka et al. 1997), whereas Krupiński treats it in a broader framework starting with the Taxus expansion (Taxus–Picea–Alnus Zone; Krupiński 1995, 2000). However, despite these discrepancies the vegetation succession and climatic conditions during the interglacial are usually described in a similar way by both palynologists (cf., Krupiński 1995, 2000; Bińka and Nitychoruk 1995, 1996; Bińka et al. 1997). Because palynological interpretations in the studied sites were undertaken by Bińka (Szymanek et al. 2016), the pollen zones of the Holsteinian Interglacial are presented in this paper according to this author (Text-fig. 3).

Beginning of the Holsteinian Interglacial

The interglacial succession started with predominance of birch and birch-pine forests (Betula–Pinus Zone) typical of a boreal climate with average July temperature of c. 12–14°C and average January temperature of c. -5°C (Krupiński 1995, 2000; Bińka and Nitychoruk 1996; Bińka et al. 1997). Progressive amelioration of the climate coincided with the appearance of oak and hazel in plant communities as well as with the gradual rise of alder and spruce noted in the following Picea–Alnus Zone. The predominant climate still had a continental character, but in the final part of this zone a rapid expansion of yew took place, due to a gradual increase of humidity. The average temperature ranged from 16 to 19°C in July and from -3 to -5°C in January (Krupiński 1995, 2000; Bińka and Nitychoruk 1996; Bińka et al. 1997).

During the Taxus Zone, distinct oceanic influences were evidenced in eastern Poland by the predominance of yew and spruce-yew communities. A mild, warm and humid climate predominated at that time, with the average July temperature between 19 and 21°C and average January temperature c. -1°C (Krupiński 1995, 2000; Bińka and Nitychoruk 1996; Bińka et al. 1997).

In the following Pinus–Larix Zone, continental influences and lower humidity notably reduced the occurrence of yew. Pine-birch forests with larch

Szymanowo Lake

Palaeolake Szymanowo is situated 18 km SE of Biała Podlaska. The lake was probably 9 km long and over 3 km wide, with a total area of c. 22 km² (Text-fig. 1). At Szymanowo site, the Holsteinian deposits occur near the surface, c. 146 m a.s.l. The occurrence of Salvinia natans, the abundant plant-associated snails A. lacustris and V. cristata indicate rather shallow and densely overgrown waters in the upper part of the Carpinus–Abies Zone. The littoral zone of the post-optimum lake was characterised by less vegetated conditions evidenced by decrease in A. lacus-

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dominated in the vegetation cover in the region. The average January temperature probably dropped by a few Celsius degrees, whereas the average July temperature could be close to that of the Taxus Zone (Krupiński 1995).

Climatic optimum of the Holsteinian Interglacial

In the climatic optimum of the Holsteinian Interglacial (Carpinus–Abies Zone) the greatest area in eastern Poland was occupied by mixed temperate forests with fir, hornbeam, oak and hazel. Birch pine and spruce occurred less abundantly. A mild, humid climate with a long vegetation season and high average summer (20–22°C) and winter (between 0 and -1°C) temperatures predominated at that time. A distinct increase of climate continentality and drop of average temperatures to 19°C in July and to -2°C in January were noted at the final part of Carpinus–Abies Zone (Krupiński 1995; Nitychoruk 2000).

Late Holsteinian Interglacial

Increasing continentality of the climate continued in eastern Poland after the interglacial climatic optimum (Picea–Pinus–Pterocarya and Pinus–Juniperus pollen zones). Arboreal taxa which prevailed in the Carpinus–Abies Zone became less significant in plant communities, and an expansion of pine and birch took place. Spruce, wingnut, juniper and herbaceous plants were more common in the vegetation cover as well (Krupiński 1995, 2000; Bińka and Nitychoruk 1996; Bińka et al. 1997). Average July and average January temperatures varied between 17 and 19°C, and between -2 and -3°C, respectively, and dropped to 15–17°C and -4 to -5°C at the end of the interglacial (Krupiński 1995).

Characteristics of molluscan species

Viviparus diluvianus

Viviparus diluvianus is an extinct, gilled freshwater gastropod, widely distributed in European stagnant and slowly moving waters of the Holsteinian and older interglacials (Gittenberger et al. 2004). The shells of adult V. diluvianus are up to 36 mm high and 25 mm wide. They are composed of aragonite precipitated mostly between April and October (Hren et al. 2013). As other recent European Viviparus snails, it was viviparous and dioecious, reproduced probably during the entire vegetation period and lived approximately 5 years (Jakubik and Lewandowski 2007; Jakubik 2012). Between spring and early autumn it inhabited the shallow littoral zone (0.1–2.0 m) and it overwintered buried in the mud in its deeper parts (< 4 m), where probably stayed inactive (Jakubik 2012; Welter-Schultes 2012; Hren et al. 2013).

Valvata piscinalis

Valvata piscinalis is a gill-breathing aquatic gastropod of wide climatic tolerance noted across Europe through the whole Quaternary period. It usually occurs in water depths of 3–10 m (Welter-Schultes 2012). Mature aragonitic shells of this oviparous and monoecious species reach a height and width of 5 and 7 mm, respectively. V. piscinalis lives approximately for one year (under various food conditions its lifespan may range from 5 to 21 months), hatches and secretes shells from June to October, and reproduces from April to September (Myzyk 2007; Welter-Schultes 2012).

METHODS

Isotope analysis

Isotope studies of aragonitic shells of V. diluvianus and V. piscinalis from the Holsteinian lake deposit of eastern Poland were carried out in years 2012–2014, and these results have been already published (Szymanek 2016; Szymanek et al. 2016). Because the same data set is used in the present paper, and the methods have been described and widely discussed in previous works (Szymanek 2016; Szymanek et al. 2016), only short summary of isotope procedures is presented here.

Oxygen isotope measurements were conducted in the Stable Isotope Laboratory at the University of Erlangen-Nuremberg in Germany, using a Thermo-Finnigan Five Plus mass spectrometer. The standard procedures were applied to sample preparation (McCrea 1950) and the results were reported in per mil in relation to V-PDB by assigning δ18O values of -2.20 and -26.7‰ to NBS19 and LSVEC, respectively. Repeated measurements of V. diluvianus shells gave reproducibility better than ±0.2‰, whereas the reproducibility for V. piscinalis was monitored by replicate analysis of laboratory standards and was better than ±0.07‰ (1σ) (Szymanek 2016; Szymanek et al. 2016).

The pulverised multi-shell samples from 5- to 10-cm-thick intervals were used for both species – 40 for V. diluvianus and 49 for V. piscinalis (3–5 and 5–10 adult individuals, respectively). This
method (cf., Hammarlund et al. 1999; Nitychoruk 2000; Shanahan et al. 2005; Apolinarska 2009a, b; Apolinarska and Hammarlund 2009; Apolinarska et al. 2015) produced some generalization of the dataset, but also reduced the effects of internal seasonal and/or non-environmental isotopic variations within shell material. These allowed the mean isotope signal to be obtained for average palaeoecological changes during the few-decades-long sedimentary periods interpreted in the palaeolakes studied (Szymanek 2016; Szymanek et al. 2016) and gave the opportunity of following through the general trends in their past water temperature changes.

**Oxygen isotope palaeothermometry**

Reconstruction of past water temperature was based on the carbonate thermometry equation of White et al. (1999):

\[ T^\circ C = 21.36–4.83 \times (\delta^{18}O_{\text{Carbonate(VPDB)}} − \delta^{18}O_{\text{Water(VSMOW)}}), \]

formed for *Lymnaea peregra* (White et al. 1999) but recommended also for fossil, aragonitic *Viviparusb)* shells (Bugler et al. 1999). The unknown and hardly measurable former water isotope composition was substituted by modern isotope data including the modern lake records and the precipitation/evaporation ratios (Leng and Marshall 2004), assuming a similar distribution of air mass sources (Dabkowski et al. 2012) and the close palaeoclimatic patterns of MIS 11 and MIS 1 (Koutsodendris et al. 2012, 2013; Candy et al. 2014).

Due to various climatic influences through the interglacial noted in the region (Bińska and Nitychoruk 1995, 1996; Krupiński 1995, 2000; Bińska et al. 1997; Nitychoruk 2000) and possible local differences between the lakes three scenarios have been considered in this study:

1) The isotope composition of lake water (\( \delta^{18}O_{\text{Water}} \)) corresponds with the isotope composition of meteoric precipitation (\( \delta^{18}O_{\text{Precipitation}} \)), which is characteristic of small-medium open lakes (von Grafenstein et al. 1994; Leng and Marshall 2004; Prendergast and Stevens 2014). Regarding a lack of \( \delta^{18}O_{\text{Precipitation}} \) values for the interglacial, a recent isotope record of rainfall from Brest station (Belarus; c. 40 km east of the study area; 52°54'00" N; 23°42'21" E), obtained from GNIP – Global Network of Isotopes in Precipitation (IAEA/WMO 2014), was applied (Text-fig. 2). Oxygen isotope measurements were gathered between April 1980 and December 1983, recording monthly and annual fluctuations. Because this record is relatively short and compatible with the snails’ lifespan, it was also compared to the 35-year-long observations from Cracow-Wola Justowska (50°3'42" N; 19°50'55" E) (Text-fig. 2). No significant differences were noted between both stations (Student’s t-test: \( t = -0.31, p = 0.75 \)). Both the mean annual and the mean growth-period isotope compositions of rainfall (Leng and Marshall 2004; Navarro et al. 2004; Hren et al. 2013) were applied in the calculation, providing the values of -9.61, -7.84 (April–October; *V. diluvianus*) and -7.87‰ (June–October; *V. piscinalis*; IAEA/WMO 2014).

2) The \( \delta^{18}O_{\text{Water}} \) values (based on \( \delta^{18}O_{\text{Precipitation}} \)) were corrected for the actual evaporative enrichment of approximately 2‰ (cf., von Grafenstein et al. 2000, 2013). This value results from the mean evaporative enrichment in several modern Central European small-medium lakes e.g., Polish Lake Gościaż (Ralska-Jasiwieczowa et al. 2003), German Ammelsee (von Grafenstein et al. 2013) and Lake Steisslingen (Mayer and Schwarcz 1999), and Swiss Gerzensee (von Grafenstein et al. 2000, 2013).

3) Scenarios 1 and 2 were further modified according to possible differences in the evaporation ratio in the Holsteinian succession based on palaeoclimatic data (e.g., Krupiński 1995, 2000; Bińska et al. 1997; Nitychoruk et al. 2005). For periods of oceanic and continental influences the \( \delta^{18}O_{\text{Water}} \) values corresponding to the mean \( \delta^{18}O \) values of precipitation and those corrected for actual evaporative enrichment were accepted, respectively. This scenario joins scenario 1 and 2, thus its results are only summarised in Text-figs 4 and 5 and further discussed in the Discussion section.

Differences in estimated palaeotemperatures were tested between the lakes by analysis of variance (one-way ANOVA) followed by a post-hoc Tukey’s test in the case of significant results. The temperature changes between the pollen zones distinguished at Ortel Królewski and Szymanowo, and the differences in *V. diluvianus* and *V. piscinalis* records were compared using the Student’s t-test in the PAST program with a significance level of 0.05 (Hammer et al. 2001).

**RESULTS**

Past water temperatures of the studied palaeolakes derived from isotope records of *V. diluvianus* and *V. piscinalis* shells and based on White et al.'s (1999) carbonate thermometer are presented in Text-figs 4 and 5. Because fluctuations in the \( \delta^{18}O \) values of both species, being a background for the general thermal characteristics of palaeolakes, has already
been discussed in detail (Szymanek 2016; Szymanek et al. 2016), they are not further commented here. The minimum, maximum and mean values of estimated temperature will be presented for each lake and the pollen zone if applicable (Text-fig. 5).

**Ortel Królewski Lake**

The estimated temperature range based on the mean rainfall isotope values (scenario 1) and *V. diluvianus* shell carbonate is 9.6–13.3°C and 18.1–21.9°C for the mean annual and the mean growth-season precipitation, respectively (Text-figs 4, 5). The average water temperatures are 11.5 (δ¹⁸O<sub>Precipitation</sub> -9.61‰) and 20.1°C (δ¹⁸O<sub>Precipitation</sub> -7.84‰) during the lake existence, 11.4 and 19.9°C during the *Taxus* and 11.9 and 20.4°C during the *Pinus–Larix* Zone (Text-fig. 5).

*V. piscinalis* shells provide the average temperatures of 10.3°C (the temperature range of 7.8–14.2°C) and 18.7°C (the range of 16.2–22.6°C) for the full sequence (Text-fig. 5). One sample from *Picea–Alnus* Zone yields the values of 14.2 and 22.6°C for the mean annual and the growth-season rainfall, respectively. The ranges of temperature for the *Taxus* and *Pinus–Larix* zones overlap (Text-figs 4, 5). The mean past water temperatures are almost equal in these periods being 10.1 and 10°C (the mean annual precipitation) and 18.6 and 18.4°C (the mean growth-season precipitation) (Text-fig. 5).

Water isotope values corrected for evaporative enrichment (scenario 2) give considerably higher temperatures in both cases (Text-fig. 4 and 5). Corrected δ¹⁸O<sub>Water</sub> values based on isotope value of the mean annual precipitation (-7.61‰) results in average tem-
temperatures of 21.2°C (the whole sequence), 21.0°C (Taxus) and 21.5°C (Pinus–Larix) for V. diluvianus and 19.9, 19.8 and 19.6°C for V. piscinalis, respectively (Text-fig. 5). Correction of isotope water composition during the shell growth period provides average temperatures of 29.7, 29.6, 30.1°C (the whole sequence; Taxus; Pinus–Larix; V. diluvianus) and 28.3, 28.2, 28.0°C (the whole sequence; Taxus; Pinus–Larix; V. piscinalis) (Text-fig. 5).

Ossówka-Hrud Lake

Two sections from the lake show slight differences in the estimated past water temperatures (Text-figs 4, 5). At Ossówka the δ¹⁸Owater based on the oxygen composition of mean annual precipitation produces very low average temperatures of 3.2°C (V. diluvianus) and 1.9°C (V. piscinalis), with the ranges of 2–5.4°C and 0.8–2.6°C, respectively. During the snail growth periods the temperature is estimated at 11.8°C (10.5–14°C) and 10.3°C (9.3–11°C) (Text-fig. 5).

Scenario 2 considering evaporative enrichment of lake water reveals the average temperatures of 12.9°C (11.7–15.1°C) and 21.4°C (20.2–23.6°C), and 11.6°C (10.5–12.3°C) and 20°C (18.9–20.7°C) for V. diluvianus and V. piscinalis, respectively (Text-fig. 5). At Hrud II, unrealistic negative values are received for both species and the mean annual precipitation: -0.8°C (-2.0–3.0°C) for V. diluvianus and -0.6°C (-3.2–0.7°C) for V. piscinalis (Text-figs 4, 5). Temperatures estimated from the rainfall isotope composition of April (June)–October interval are: 7.7°C (6.6–8.9°C; V. diluvianus) and 7.8°C (5.2–9.1°C; V. piscinalis) (Text-fig. 5). The temperature in scenario 2 equals 8.9°C (7.7–10°C) and 17.4°C (16.3–18.5°C), and 9.1°C (6.4–10.3°C) and 17.5°C (14.8–18.7°C) for V. diluvianus and V. piscinalis, respectively (Text-fig. 5).
Roskosz Lake

According to scenario 1 and *V. diluvianus* shells, the Roskosz Lake water is characterised by low average temperature of 1.4°C (δ¹⁸O<sub>water</sub> corresponding to mean annual δ¹⁸O<sub>Precipitation</sub>), and 9.9°C (δ¹⁸O<sub>water</sub> corresponding to mean growth-season δ¹⁸O<sub>Precipitation</sub>). The overall temperature ranges from 0.1 to 3.4°C and from 8.6 to 12°C (Text-figs 4, 5).

Scenario 2 demonstrates both the higher temperature ranges (9.7–13.1 and 18.3–21.6°C) and the higher means calculated for the lake water (11 and 19.6°C) (Text-figs 4, 5).

Similar temperatures are received from *V. piscinalis* shells. In scenario 1: 1.3°C (0.3–3.8°C) and 9.7°C (8.7–12.2°C), in scenario 2: 11°C (9.9–13.5°C) and 19.4°C (18.3–21.9°C) (Text-fig. 5).

Szymanowo Lake

The isotope record of *V. diluvianus* from Szyma-

The differences in the estimated average past water temperatures estimated for the Taxus and Pinus–Larix zones in Ortel Królewski lake (Student’s t test: p < 0.82), whereas at Szymanowo the temperatures of the optimum and post-optimum periods differ significantly (Student’s t test: p < 0.003).

The temperature records inferred from *V. diluvianus* and *V. piscinalis* shell carbonates are congruent, but significant differences between both species occur at Ortel Królewski (Student’s t test: p < 0.004), being already connected to specific subhabitats, diet, or even the different lifetimes of both species (Szymanek 2016).

DISCUSSION

An application of thermometry equations to the fossil record may encounter some problems due to difficulties in estimation of past δ¹⁸O of local water (Bugler et al. 2009; Grossman 2012). If proper material is available, it may be calculated from rodent tooth enamel (Grimes et al. 2002; Navarro et al. 2004). If not, then some assumptions based on other available proxies must be made to estimate absolute palaeotemperatures (Leng and Marshall 2004). A vast background based on multi-disciplinary studies is crucial here, as such studies provide important palaeoclimatic data, characterise well the depositional conditions and allow the reduction of the degree of uncertainty of the interpretation.
In this study, the past water temperature reconstruction based on oxygen isotopes of freshwater snail shells is verified by pollen (Bińka and Nitychoruk 1995, 1996; Krupiński 1995, 2000; Bińka et al. 1997), molluscs (Lindner et al. 1991; Albricht et al. 1995; Skompski 1996; Szymanek 2012, 2013, 2014a, b) and geochemistry (Nitychoruk 2000; Nitychoruk et al. 2005; Szymanek 2016, 2017; Szymanek et al. 2016). The occurrence of characteristic plants combined with the characteristic regional floristic succession reveal air temperature changes through the Holsteinian Interglacial (Krupiński 1995; Nitychoruk 2000), whereas the mollusc assemblages (Albricht et al. 1995; Szymanek 2012, 2013, 2014a, b), oxygen and carbon isotopes (Szymanek 2016; Szymanek et al. 2016) and shell elemental composition of V. diluvianus and V. piscinalis (Szymanek 2017) allow the definition of environmental conditions in the studied water bodies. Because this study deals with lakes which no longer exist there still remain some doubts in their catchment characteristics (cf., Candy et al. 2016), and the discussion may appear somewhat subjective at some points, but it is still significant for the interglacial record, which in general is devoid of oxygen isotope temperature reconstructions. Correlation with other proxies makes these assumptions more reliable (cf., von Grafenstein et al. 2013).

**Palaeotemperature reconstruction**

Scenario 1 assumes both the close relations of δ¹⁸Owater and δ¹⁸Oprecipitation and the limited influence of evaporation. This approach refers, among others, to palaeotemperature reconstruction of the Late Vistulian lacustrine sequences from northwest England (Marshall et al. 2002) and western Ireland (van Asch et al. 2012). According to Leng and Marshall (2004), this should work mainly in small-medium open lakes, whereas other types of water bodies may be affected by both evaporitic and catchment processes. The surface area of the studied palaeolakes is in the range of 8–22 km² and the relatively stable oxygen isotope record within the studied sequences (changes of 0.3–1.3‰; Text-fig. 4; Szymanek 2016; Szymanek et al. 2016) appears typical of the lakes described by Leng and Marshall (2004). As mentioned earlier, their hydrology is characterized by molluscs, which, in general, point to rather shallow, overgrown littoral zones with possible changes in the water-level and the near-shore aquatic vegetation during the lakes’ existence. These intra-basin changes are discounted in scenario 1, based on the narrow range of δ¹⁸Oshell values suggesting stable isotope conditions (cf., Candy et al. 2016), but will further be considered in scenario 3. The river supply is not unequivocal in the studied lakes, but the admixture of rheophile species indicates possible water movements connected with the currents and/or the wave action (Szymanek 2012, 2013, 2014a, b).

As mentioned above, scenario 1 adapts the actual isotope values of precipitation to thermometry assuming no significant variations in the dominant source of air masses (cf., Dabkowski et al. 2012) and the close analogues between the Holsteinian Interglacial and the Holocene, observed especially in their insolation pattern and the orbital forcing (Koutsodendris et al. 2012, 2013 and references contained therein; Candy et al. 2014). To separate more and less probable estimations, no distinct changes in the distribution and composition of precipitation have been also considered at this stage. Because V. diluvianus and V. piscinalis shells are secreted mostly between the late spring and the early autumn, they are best suited to the estimation of palaeotemperatures during their growth season. In that time, the isotope composition of the surface lake water in the near-shore zone inhabited by molluscs should reflect the summer rainfall rather than mean annual precipitation (Leng and Marshall 2004). It may be suggested by the results, that these are more reliable for the growth period than for the actual annual precipitation. The latter shows improbably low temperatures in Ossówka-Hrud and Roskosz palaeolakes with negative values noted in the Hrud II sequence (Text-figs 4, 5). Summer temperatures below 3.5°C are hardly acceptable for the littoral zone indicated by the mollusc assemblage (Szymanek 2012). Past water temperatures based on the δ¹⁸Owater corresponding to the mean annual precipitation, calculated for Ortel Królewski and Szymanowo Lakes also appear too low. Their range between 9.6 and 17.8°C (Text-figs 4, 5) is probable for greater habitat depths than that preferred by the molluscs of both lakes. In Lake Lednica (west-central Poland) the water temperature in August reaches 20.1 and 18.6°C at the depths of 6 and 7 m (Apolinarska 2013), respectively, whereas in Gerzensee 12°C is noted below 8 m (von Grafenstein et al. 2000). The aggregations of V. diluvianus shell, high contents of B. tentaculata and pulmonate gastropods associated with the shallow-water macrophytes suggest a water depth of < 2 m (Szymanek 2014a, b; Piechocki and Wawrzyniak-Wydrowska 2016) and thus higher temperatures would be expected at Ortel.
of pollen analyses (Krupiński and Patterson 2001; Dabrowski and Nitychoruk 2000). If we consider that the summer water temperature of the uppermost 5 m of the water column is close to air temperature (Siegenthaler and Eicher 1986; Livingstone and Lotter 1998; Wurster and Patterson 2001; Dabrowski et al. 2004), the results of pollen analyses (Krupiński 1995) appear to support the temperatures estimated for Ortel Królewski and Szymanowo Lakes with $\delta^{18}O_{\text{Water}}$ related to the mean growth-season $\delta^{18}O_{\text{Precipitation}}$. The mean temperatures of 19.9 ($V. \text{diluvianus}$) and 18.6°C ($V. \text{piscinalis}$) calculated for the Taxus Zone at Ortel Królewski Lake are consistent with the mean pollen-inferred July temperature of 19–21°C (Text-fig. 6; Krupiński 1995), whereas only slight, insignificant temperature changes noted between the Taxus and Pinus–Larix zones would already have been expected based on the oxygen isotopes (Szymaneck 2016; Szymanek et al. 2016) and palynology (Krupiński 1995; Nita 2009). The temperatures of 21.7 and 20.6°C indicated by $V. \text{diluvianus}$ and $V. \text{piscinalis}$ for the Carpinus–Abies Zone at Szymanowo, are also in the range derived from the vegetation (20–22°C; Text-fig. 6; Krupiński 1995). Some discrepancies occur in the post-optimum phase of Szymanowo Lake, where the calculated oxygen isotope palaeotemperatures of 25.1 and 24.6°C exceed that suggested by the changes in the plant cover (17–18°C; Text-fig. 6; Krupiński 1995). Similar temperatures occur in some modern Polish lakes during summer, usually being typical of shallow isolated bays (Apolinarska 2013; Pukacz et al. 2014), which at Szymanowo was indicated by considerable amounts of $V. \text{crisata}$, $A. \text{lacustris}$ and $B. \text{tentaculata}$ (Szymanek 2014a). These conditions appear suitable also for the water fern $\text{Salvinia natans}$ abundant in these warm and well-vegetated waters of Szymanowo Lake (cf., Krupiński 1995; Pidek 2003).

The $\delta^{18}O_{\text{Water}}$ of approximately -7.8‰ (reflecting the mean growth-season $\delta^{18}O_{\text{Precipitation}}$) at Ossówka-Hrud and Roskosz Lakes provided the mean past water temperature in the range of 7.7–11.8°C (Text-fig. 5), which again is low for the shallow-water reed zones (Szymanek 2012, 2013) and optimal climatic conditions recorded in both lakes (air temperature up to 22°C; Krupiński 1995; Nitychoruk 2000). This lower temperature could correspond to greater water depths (Baroni et al. 2006; von Grafenstein et al. 2013) compared to Ortel Królewski and Szymanowo Lakes, but this was not evidenced by mollusc records (Szymanek 2012, 2013, 2014a, b). Alternatively a different isotope water composition rather than considerable environmental differences between the studied palaeolakes should be expected. This is probable if we consider the different time of the lakes’ existence covering the pre-optimum of the Holsteinian Interglacial at Ortel Królewski, the climatic optimum at Ossówka-Hrud, Roskosz and Szymanowo Lakes and the post-optimum at Szymanowo (Text-fig. 2), each with somewhat different climate characteristics (Albrecht et al. 1995; Szymanek 2011; Szymanek et al. 2016). What’s more, this situation is observed today at many regions, where the lake systems lying even in close proximity can be characterised by different isotope concentrations at the same time, which may result from different lake processes (Eicher and Siegenthaler 1976; von Grafenstein et al. 2000; Apolinarska 2009b; Apolinarska and Hammarlund 2009; van Asch et al. 2012).

**Scenario 2 – $\delta^{18}O_{\text{Water}}$ corrected for evaporative enrichment**

Reliable mean water temperatures of the Ossówka-Hrud and Roskosz Lakes were calculated in scenario 2 (Text-fig. 5). For $\delta^{18}O_{\text{Water}}$ of -5.84‰ (-5.87‰ for $V. \text{piscinalis}$), enriched by 2‰ in relation to $\delta^{18}O$ values of the actual mean April (June)–October rainfall (cf., von Grafenstein et al. 2000, 2013; Ralska-Jasiewiczowa et al. 2003), they go well together with the pollen evidence (Krupiński 1995; Nitychoruk 2000) being in the range of 17.4–21.4°C (Text-fig. 6). However, it is worth noting that the slightly lower temperature calculated at Hrud II may suggest some various local conditions in Ossówka-Hrud Lake (cf., Szymanek 2016, 2017). The palaeotemperatures of 29.6 and 33.1°C, calculated with these assumptions for Ortel Królewski and Szymanowo Lakes (Text-figs 4, 5), respectively, appears to be overestimated. The correction of $\delta^{18}O_{\text{Water}}$ based on the mean annual precipitation to -7.61‰ provides similar temperatures to those received in scenario 1 for $\delta^{18}O_{\text{Water}}$, based on the growth-period rainfall and needs no further comments (Text-figs 4, 5).

**Scenario 3 – assumed differences in evaporation ratio**

Both scenario 1 and 2 allow for preliminary verification of basic assumptions. If we discount a significant impact of evaporation, the oxygen isotope water composition of the studied Holsteinian palaeolakes should be higher than the $\delta^{18}O$ values of actual mean annual precipitation. For Ortel Królewski
Table 6. Estimates of mean past water temperature in Holsteinian palaeolakes from eastern Poland compared to the pollen-inferred mean July air temperature (Krupiński 1995; Nitychoruk 2000)

<table>
<thead>
<tr>
<th>Palaeolake</th>
<th>Local Pollen Zones</th>
<th>Mean July Temperature (Krupiński 1995; Nitychoruk 2000)</th>
<th>Mean Water Temperature based on V. diluvianus</th>
<th>Mean Water Temperature based on V. piscinalis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Szymanowo</td>
<td>Post-optimum</td>
<td>17-18°C (~17.5°C)</td>
<td>25.1°C</td>
<td>24.6°C</td>
</tr>
<tr>
<td></td>
<td>Carpinus–Abies (final part)</td>
<td>19-20°C (~19.5°C)</td>
<td>21.7°C</td>
<td>20.6°C</td>
</tr>
<tr>
<td>Roskosz</td>
<td>Carpinus–Abies</td>
<td>20-22°C (~21°C)</td>
<td>19.6°C</td>
<td>19.4°C</td>
</tr>
<tr>
<td>Ossówka-Hrud</td>
<td>Carpinus–Abies</td>
<td>20-22°C (~21°C)</td>
<td>21.4°C</td>
<td>20°C</td>
</tr>
<tr>
<td></td>
<td>Carpinus–Abies</td>
<td>20-22°C (~21°C)</td>
<td>17.4°C</td>
<td>17.5°C</td>
</tr>
<tr>
<td>Ortel Królewski</td>
<td>Pinus–Larix</td>
<td>19-21°C (~20°C)</td>
<td>20.4°C</td>
<td>18.4°C</td>
</tr>
<tr>
<td></td>
<td>Taxus</td>
<td>18-21°C (~20°C)</td>
<td>19.9°C</td>
<td>18.6°C</td>
</tr>
</tbody>
</table>

Text-figure 6. Estimates of mean past water temperature in Holsteinian palaeolakes from eastern Poland compared to the pollen-inferred mean July air temperature (Krupiński 1995; Nitychoruk 2000)

and Szymanowo Lakes, $\delta^{18}O_{\text{water}}$ of approximately -7.8‰ should be accepted for reliable results ($\delta^{18}O_{\text{water}}$ equals $\delta^{18}O_{\text{precipitation}}$ of the growth season or mean annual $\delta^{18}O_{\text{precipitation}}$, and is enriched by evaporation), whereas for Ossówka-Hrud and Roskosz Lakes the values of approximately -5.8‰ should be expected (Text-fig. 5). However, it must be highlighted that those scenarios are based on stable and similar conditions in the lakes throughout the entire period of deposition, which, admittedly, is some simplification. To be sure, the small fluctuations in the oxygen isotope curves in the studied sections suggest the stability of lake conditions, but we should further consider some changes in the climate features (scenario 3) noted in eastern Poland during the Holsteinian Interglacial (Bińka and Nitychoruk 1995, 1996; Krupiński 1995, 2000; Bińka et al. 1997; Nitychoruk 2000; Nitychoruk et al. 2005). As being observed today (Woś 2010), they were connected with various influences of maritime and continental air masses providing changes in the precipitation/evaporation ratio in the region. Some differences in the rate of evaporation might have also occurred between the lakes due to their varied surface areas and depth conditions, but these are not easy to assess based on the available material.

Enhanced evaporation is expected under continental influences noted during the Picea–Alnus and Pinus–Larix zones (Ortel Królewski), and in the post-optimum (Szymanowo), whereas higher humidity and rather constrained evaporative loss is referred to oceanic influences in the Taxus and Carpinus–Abies zone ne (Bińka and Nitychoruk 1995, 1996; Krupiński 1995, 2000; Bińka et al. 1997; Nitychoruk 2000; Nitychoruk et al. 2005). The climate of the latter was not uniform, but the general oceanic trends and higher precipitation rates were connected mainly with the Atlantic air masses and the marine transgression in northern Germany, northern Poland, Latvia and Lithuania (Kondratiene and Gudelis 1983; Hinsch 1993; Bińka et al. 1997; Koutsodendris et al. 2013).

During the Picea–Alnus Zone a climate with continental features prevailed, although some oceanic events could occur in this level (Bińka and Nitychoruk 1996; Bińka et al. 1997; Pidek 2003; Nita 2009). However, at Ortel Królewski this zone was documented only in one sample, rather unrepresentative for further estimations. The more arid conditions of the Pinus–Larix Zone and the post-optimum (Krupiński 1995; Pidek 2003, Szymanek et al. 2016) were associated with the rearrangement of plant communities in the study area, reflected by the expansion of pine forest with larch and birch in the cost of oak, fir and hornbeam (Bińka and Nitychoruk 1995, 1996; Krupiński 1995, 2000; Bińka et al. 1997; Nitychoruk 2000; Nitychoruk et al. 2005), and the episodes of low water stands indicated by abundant V. cristata, A. lacustris, G. crista and other species typical of macrophyte-covered bottom in shallow waters (Szymanek 2014a, b). To be sure, the lake systems might become more susceptible to evaporation under these conditions (Candy et al. 2016; Szymanek 2016; Szymanek et al. 2016), but the assumption of 2‰ difference in evaporative enrichment between the phases of oceanic and continental influences, reveals a highly unlikely, approximately 10°C rise in water temperatures of Ortel Królewski and Szymanowo Lakes in the Pinus–Larix Zone and the post-optimum, respectively (Text-figs 4, 5). The narrow range of oxygen isotope shell values in...
both lakes and no significant increase in the air temperature postulated from pollen records (Krupiński 1995; Pidek 2003; Szymanek 2016; Szymanek et al. 2016) may indicate, that the changes in evaporation were compensated by more negative values of δ\(^{18}\)O\(_{\text{Precipitation}}\), connected with the so-called continental effect (Rozanski et al. 1993). In contrast, the wider extent of oceanic air masses and proximity of the Holsteinian Sea during the Taxis and Carpinus–Abies zones could result in rainfall enriched in the heavier oxygen isotope and thus higher δ\(^{18}\)O\(_{\text{Water}}\) of the studied lakes (Rozanski et al. 1993; Nitychoruk 2000; Nitychoruk et al. 2005). The increased values of δ\(^{18}\)O\(_{\text{Water}}\) of Ossówka-Hrud and Roskosz Lakes postulated in scenario I also should be a consequence of higher δ\(^{18}\)O\(_{\text{Precipitation}}\) rather than evaporative loss related to lake morphometry, as Ossówka-Hrud Lake appears to be the smallest and the deepest among the studied palaeolakes.

**Comparison to other records**

Although isotope records are widely applied to palaeoecological reconstructions, it is still hard to find comparable quantitative interpretations of absolute temperatures for Pleistocene sequences. Most of the Holsteinian isotope records are based on sediments rather than on mollusc shells (Beaulieu et al. 1994; Müller and Höflé 1994; Nitychoruk et al. 2005; Dabkowski et al. 2012), and even if the isotope shell composition is considered, no absolute temperature reconstructions are conducted (Nitychoruk 2000). Some oxygen isotope data of *V. diluvianus* and *V. piscinalis* shells are available for Ossówka-Hrud and Roskosz Lakes (OS 1/96, HR 1/89, WL 1/97 cores; Nitychoruk 2000), but further comparisons are hampered by the shortcomings in pollen stratigraphy of the malacological samples. Similar ranges of δ\(^{18}\)O shell values from WL 1/97 profile (Nitychoruk 2000) and Roskosz site (Szymanek 2016; Szymanek et al. 2016) suggest rather uniform temperature conditions, whereas slight differences in isotope records between OS 1/96 and Ossówka site and between HR 1/89 and Hrud II profiles (Nitychoruk 2000; Szymanek 2016; Szymanek et al. 2016) may result from different times of deposition and/or different habitats.

Although not fully comparable with the Holsteinian sequences due to great variability of lake systems, site-specific variations and various ages, the oxygen isotope palaeothermometry based on Late Glacial and Holocene biogenic carbonates (von Grafenstien et al. 2000, 2013; Baroni et al. 2006; Apolinarska et al. 2015) may be the key avenue towards temperature reconstruction in fossil records. This provides general guides for methodology, checks the relevance of results by comparisons with existing lakes and indicates the role of bioindicator data in past climate estimations. The combination of modern and past data at West Runton in eastern England demonstrated no distinguishable differences between actual summer temperatures and those of the Cromerian Complex inferred from δ\(^{18}\)O of *V. piscinalis* shells, and was considered in the context of early human occupation (Candy et al. 2011). Although being in contrast with the Antarctic ice core data (EPICA 2004; Jouzel et al. 2007) and SPECMAP project (Imbrie et al. 1984) indicating temperatures for the interglacials of the Cromerian Complex lower than those noted in the Holocene, they were supported by coleopterans providing the warmest month temperature range of 16–19°C fully comparable with the present-day July temperature of 16–17°C (Candy et al. 2011). It is worth noting, that these values are nearly in the range estimated for the Taxis Zone in eastern Poland and lower than the temperatures estimated for the climatic optimum of the Holsteinian Interglacial (Text-fig. 6), which may suggest that the latter was warmer than the early Middle Pleistocene interglacials (MIS 19, 17, 15, 13) and the Holocene (cf., Jouzel et al. 2007; Candy et al. 2011, 2014). This has also been indicated by pollen-inferred temperatures (Krupiński 1995) and shows that, despite being relatively underutilised, the palaeotemperature estimations based on oxygen isotopes of mollusc shells and thermometry equations appear promising for interglacial episodes (cf., Candy et al. 2011). They require further comparisons and high resolution studies, but the palaeolake records from eastern Poland appears of crucial importance for MIS 11 sharing many similarities with other European sequences of that age (Turner 1970; Müller 1974; Meyer 1974; Bińka and Nitychoruk 1995, 1996; Dabkowski et al. 2012; Koutsodendris et al. 2012). They show the main palaeocological trends through the Holsteinian in the central and northwestern part of the continent (Koutsodendris et al. 2012, 2013; Candy et al. 2014) providing valuable reference data for supra-regional correlations (e.g., Bińka and Nitychoruk 1995, 1996; Nitychoruk et al. 2005; Koutsodendris et al. 2012, 2014).

The best example here are the simultaneous climatically driven water level fluctuations during the Taxis and Pinus–Larix zones. Based on biostratigraphical data they have been described from Poland across to Britain, with high stands induced
by enhanced regional precipitation and oceanic influences, and low stands resulted from stronger climate continentality (e.g., Turner 1970; Müller 1974; Meyer 1974; Biłaka et al. 1997; Nitychoruk et al. 2005; Koutsodendris et al. 2011, 2012, 2013; Candy et al. 2014). The latter corresponds with the regression in vegetation cover noted in German and Polish sequences approximately 6 kyr after the expansion of interglacial forests and is connected with perturbations in the North Atlantic circulation and the solar activity (Krupiński 2000; Dabkowski et al. 2012; Koutsodendris et al. 2010, 2012, 2013). At Ortel Królewski this regressive phase is expressed by an increase in Pinus, Larix and then Betula at the expense of yew and, in part, may represent the so-called Older Holsteinian Oscillation (OHO) (cf., Koutsodendris et al. 2012; Candy et al. 2014). This vegetation shift was affected by increasing aridity with no significant rise in summer temperatures, indicated by the isotope record of freshwater gastropods (Szymanek 2016; Szymanek et al. 2016), pollen (Krupiński 1995) and oxygen palaeothermometry (this study), which is in agreement with Dethlingen palaeolake data indicating stable July temperatures and a significant decrease of the temperature of the coldest month at that time (Koutsodendris et al. 2012). The general consistency of Polish and German palaeodata (Nitychoruk et al. 2005; Koutsodendris et al. 2012, 2013; Szymanek 2016) makes the Ortel Królewski palaeolake record prospective for highly resolved studies of the OHO. The Ossówka-Hrud, Roskosz and Szymanowo records offer comparative material for the oligocratic forest phase with Carpinus and Abies predominance, widely recognised in the European Holsteinian sequences (Müller 1974; Meyer 1974; Koutsodendris et al. 2010, 2013; Candy et al. 2014), with the enhancement of continental influences after the interglacial thermal maximum documented, among others, at Szymanowo (Szymanek 2016; Szymanek et al. 2016), Dethlingen (Koutsodendris et al. 2013) and well marked in δ18O values of calcareous tufa of La Celle in France (Dabkowski et al. 2012).

CONCLUSIONS

The oxygen isotope signatures of two gilled freshwater snails V. diluvianus and V. piscinalis from eastern Poland for the first time were used for quantitative climatic assessment of palaeolake records of the Holsteinian (MIS 11) age. Based on the oxygen-isotope composition of their shells, with the assumed δ18O values of former lake waters, White et al.’s (1999) thermometry equation and with significant support of bioindicator data, the past water temperature was estimated for four Holsteinian lakes. The results may be summarised as follows:

- The δ18O values of V. diluvianus and V. piscinalis shells may be converted for the absolute growth-season past water temperature.
- Former δ18O_water values corresponding with the present-day mean annual δ18O_prelimate of approximately -9.6‰ yield temperatures which are too low, and which diverge from other proxies such as regional pollen and mollusc records.
- The δ18O_water values of approximately -7.8 and -5.8 ‰ provide reliable temperature estimations for Ortel Królewski and Szymanowo, and Ossówka-Hrud and Roskosz Lakes, respectively. These estimations are congruent with the pollen-inferred air temperatures in the region.
- During the Taxus Zone the average temperature of Ortel Królewski lake water ranged from 18.6 to 19.9°C. Comparable growth-season temperatures estimated for the following Pinus–Larix Zone suggest uniform thermal conditions in the warm seasons of both stages being in agreement with mid-European pollen data.
- In the Holsteinian climatic optimum (Carpinus–Abies Zone) the waters of Ossówka-Hrud and Roskosz Lakes reached mean temperature of 17.4–21°C.
- At Szymanowo Lake V. diluvianus and V. piscinalis shells indicate temperatures of 21.7 and 20.6°C at that time, being in the range derived from the vegetation (20–22°C; Krupiński, 1995). The increased values of 24.6–25.1°C in the post-optimum lake may be connected with the water depth rather then with significant climate change indicating shallow, warm waters of an isolated bay.
- Despite some speculation about past water δ18O composition, the high integrity of estimated palaeotemperatures with other proxy records makes the isotope signature of aquatic mollusc shells prospective for quantitative climatic interpretations of Pleistocene interglacials.

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REFERENCES


Apolinarska, K. 2009a. Reconstructions of the early and mid-Holocene climate and environment based on δ13C and δ18O values of freshwa-
ter gastropod shells and the optimum number of shells to measure per sediment layer in the Paddenluch palaeolacus-


Apolinarska, K., Pelechaty, M. and Kossler, A. 2015. Within-sample variability of δ13C and δ18O values of freshwater gastropod shells and the optimum number of shells to measure per sediment layer in the Paddenluch palaeolacus-

Atkinson, T.C., Briffa, K.R. and Coope, G.R. 1987. Seasonal temperatures in Britain during the past 22,000 years, reconstruc-


struction of Middle Pleistocene palaeoenvironments based on pollen and stable isotope investigations at Val-de-Lans, Isère, France. Vegetation History and Archaeobotany, 3, 127–142.


istic setting of the Mazovian Interglacial sites in Wilczyn and Lipnica in southern Podlasie (eastern Poland) and their palaeogeographic connections. Geological Quarterly, 41, 381–394.

Bińka, K. and Nitychoruk, J. 1995. Mazovian (Holsteinian) lake sediments at Woskrzenice near Biała Podlaska. Geo-
logical Quarterly, 39, 109–120.

Bińka, K. and Nitychoruk, J. 1996. Geological and palaeo-

Buchardt, B. and Fritz, P. 1980. Environmental isotopes as envi-

Candy, I., Abrook, A., Elliot, F., Lincoln, P., Matthews, I.P. and Palmer, A. 2016. Oxygen isotopic evidence for high-magni-
itude, abrupt climatic events during the Lateglacial Inter-
stadial in north-west Europe: analysis of a lacustrine se-


Candy, I., Stephens, M., Hancock, J. and Waghorne, R. 2011. The application of oxygen and carbon isotopes to the re-
construction of Pleistocene environments. In: N. Ashton, S. Lewis and Ch. Stringer (Eds), The Ancient Human Occu-
pation of Britain, 23–37. Elsevier; Amsterdam.

logy, 703–713. John Wiley and Sons Ltd; Chichester.

Craig, H. 1965. The measurement of oxygen isotope palaeo-

nary Science, 27, 790–799.


Welter-Schultes F. 2012. European non-marine molluscs, a
guide for species identification, pp. 1–679. Planet Poster Editions; Goettingen.
calibration and field investigation of the oxygen isotopic
Wojtanowicz, J. 1994. On thermokarst genesis of the Łęczna-
Woś, A. 2010. Climate of Poland in the second half of the
20th century, pp. 1–489. Wydawnictwo Naukowe UAM; Poznań.
Wurster, Ch.M. and Patterson, W.P. 2001. Seasonal variation
in stable oxygen and carbon isotope values recovered from
modern lacustrine freshwater molluscs: Paleoclimatologici
Zagwijn, W.H. 1996. An analysis of Eemian climate in Western and Central Europe. Quaternary Science Reviews, 15,
451–469.

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