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

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ABSTRACT:

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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 $\delta^{18}O$ 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 $\delta^{18}O_{Shell}$ values and the $\delta^{18}O_{Water}$ 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).

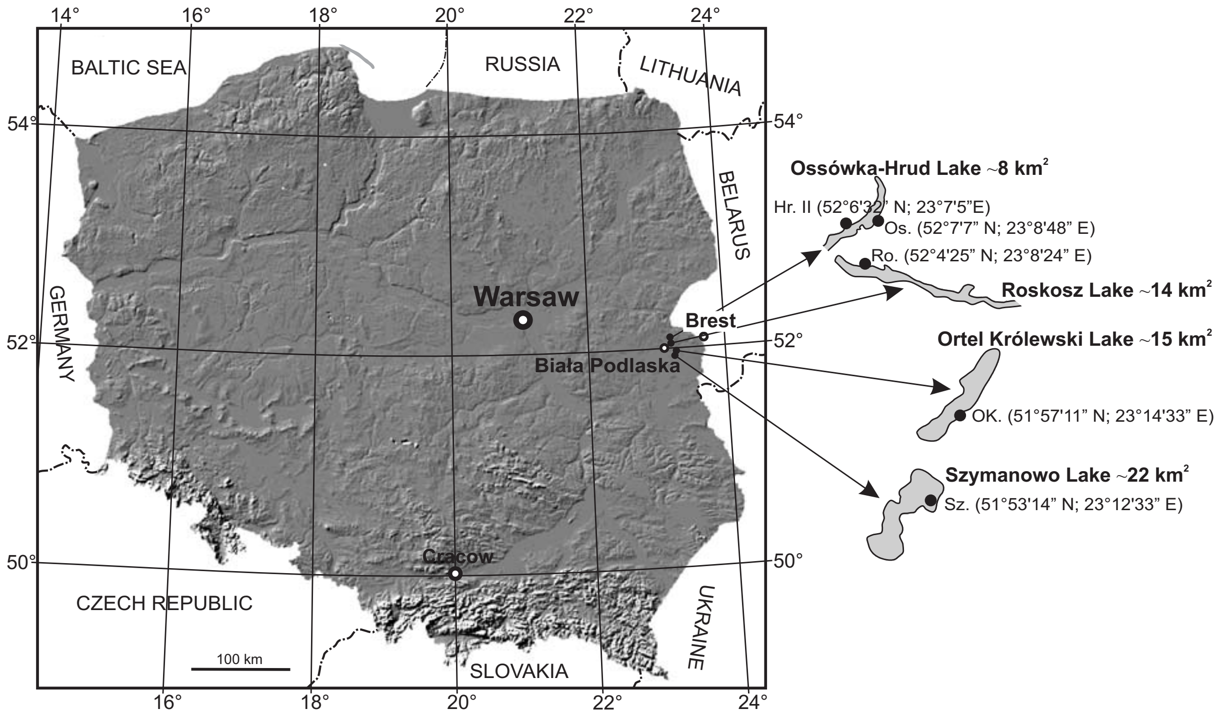
Faunal assemblages are also prone to climatic changes, but direct absolute temperature reconstructions are restricted to selected organisms, namely coleopterans (e.g., Amman *et al.* 1983; Coope 1986; Atkinson *et al.* 1987), chironomids (e.g., Lang *et al.* 2010; van Asch *et al.* 2012), ostracods (e.g., 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 and 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-Włodawa 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-



Text-fig. 1. Map of Poland and surrounding areas showing the location of the study area and Holsteinian palaeolakes. Lakes' characteristics based on Lindner and Marciniak (1998), Nitychoruk (2000) and the field work. Os. –Ossówka site, Hr. II – Hrud II site, Ro. – Roskosz site, OK. – Ortel Królewski site, Sz. – Szymanowo site

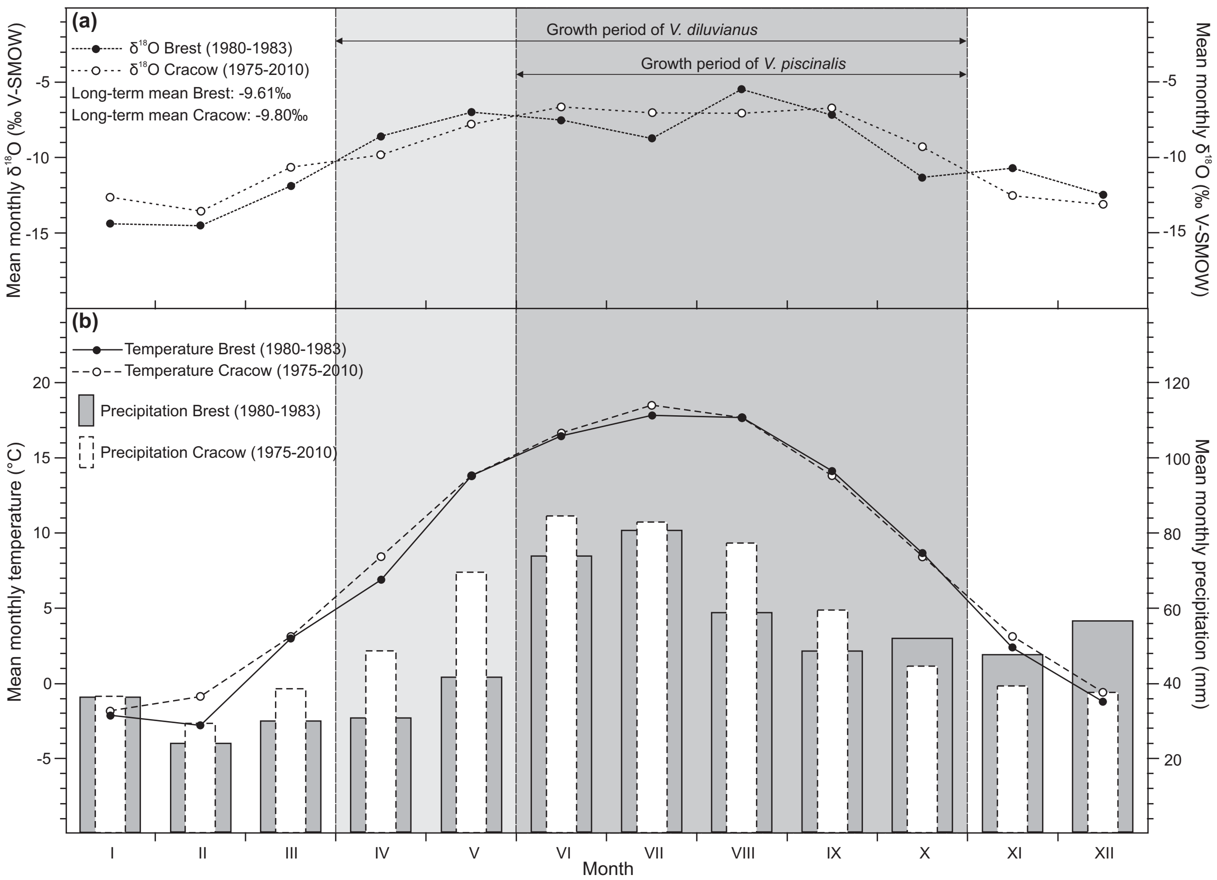
ment and origin of the lake basins (Nitychoruk 2000); SW-NE or W-E oriented trough palaeolakes, corresponding to tectonic structures in the Palaeozoic substratum and characterised by long-lasting and steady calcareous sedimentation; small lakes with unstable sedimentation (mostly silts, peats, bituminous shales) located on the morainic plateau; and 1–2 km long and wide lakes of complex origin with calacareous 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 fluvioglacial, 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; Bińka and Nitychoruk 1995, 1996; Krupiński 1995, 2000; Bińka *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.



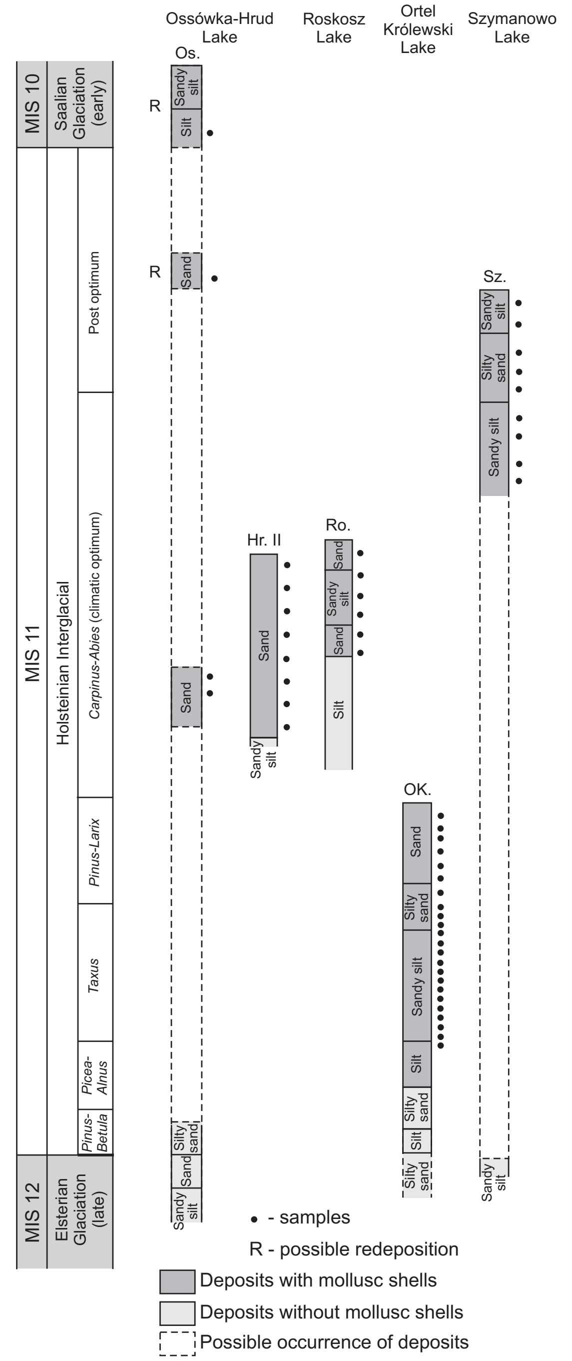
Text-fig. 2. (a) Modern oxygen isotope composition of precipitation (monthly means), and (b) modern mean monthly temperature and precipitation from Brest (April 1980 – December 1983) and Cracow-Wola Justowska (March 1975 – December 2010) stations. Data derived from Global Network of Isotopes in Precipitation (GNIP) Database (IAEA/WMO 2014)

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; Albrycht *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 km^2 (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



Text-fig. 3. Palynostratigraphy and lithology of studied palaeolake deposits from eastern Poland (based on Szymanek 2016; Szymanek *et al*. 2016). Os. – Ossówka site, Hr. II – Hrud II site, Ro. – Roskosz site, OK. – Ortel Królewski site, Sz. – Szymanowo site; MIS = marine isotope stages

2012). 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 redeposition 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 km^2, 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 $\delta^{13}C$ 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 ^{13}C 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 fluvioglacial 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 km^2 presumably was c. 11 km long and c. 2 km wide (Text-fig. 1).

The lake record encompasses the pre-optimum part of the Holsteinian Interglacial. Abundant *V. diluvianus* populations occurred in the *Taxus* and *Pinus–Larix* zones, whereas numerous *V. piscinalis* were noted in the *Picea–Alnus*, *Taxus* and *Pinus–Larix* pollen zones (Text-fig. 3; Szymanek *et al*. 2016). Shallow-water habitats are evidenced by the mollusc assemblage typical of lake margins with rich aquatic plants and possible wave action (Szymanek 2014b). However, some changes in the water conditions occur through the Ortel Królewski succession. Initially, during the *Picea–Alnus* Zone the lake was free of dense aquatic vegetation. Higher productivity and growth of aquatic plants indicated by the increased δ^{13}C values of mollusc shells and the expansion of *Valvata cristata* and *A. lacustris* were noted through the *Taxus* Zone. A shallow, overgrown littoral zone was evidenced in the *Pinus–Larix* Zone by abundant *V. cristata*, *Segmentina nitida*, *A. lacustris*, *G. albus* and *Gyraulus crista* (Szymanek 2014b, 2016; Szymanek *et al*. 2016). Moreover, some changes in the water oxygenation connected with varied productivity levels and trophic conditions occurred in this interval, being expressed in the changes of Fe and Mn concentrations in mollusc shells. After the phase of more eutrophic conditions with possible bottom-water anoxia in the middle part of *Taxus* Zone, somewhat higher oxygen concentration was noted in the transition between the *Taxus* and *Pinus–Larix* zones (Szymanek 2017).

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 km^2 (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. lacustris* and *V. cristata*, and low δ^{13}C values (Szymanek 2014a, 2016; Szymanek *et al*. 2016).

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 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 $\delta^{18}O$ 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 data-set, 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):

$$T°C = 21.36 - 4.83*(\delta^{18}O_{Carbonate(VPDB)} - \delta^{18}O_{Water(VSMOW)}),$$

formed for *Lymnaea peregra* (White *et al.* 1999) but recommended also for fossil, aragonitic *Viviparus* 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 (Bińka and Nitychoruk 1995, 1996; Krupiński 1995, 2000; Bińka *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 ($\delta^{18}O_{Water}$) corresponds with the isotope composition of meteoric precipitation ($\delta^{18}O_{Precipitation}$), 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 $\delta^{18}O_{Precipitation}$ values for the interglacial, a recent isotope record of rainfall from Brest station (Belarus; c. 40 km east of the study area; 52°5'40" 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).

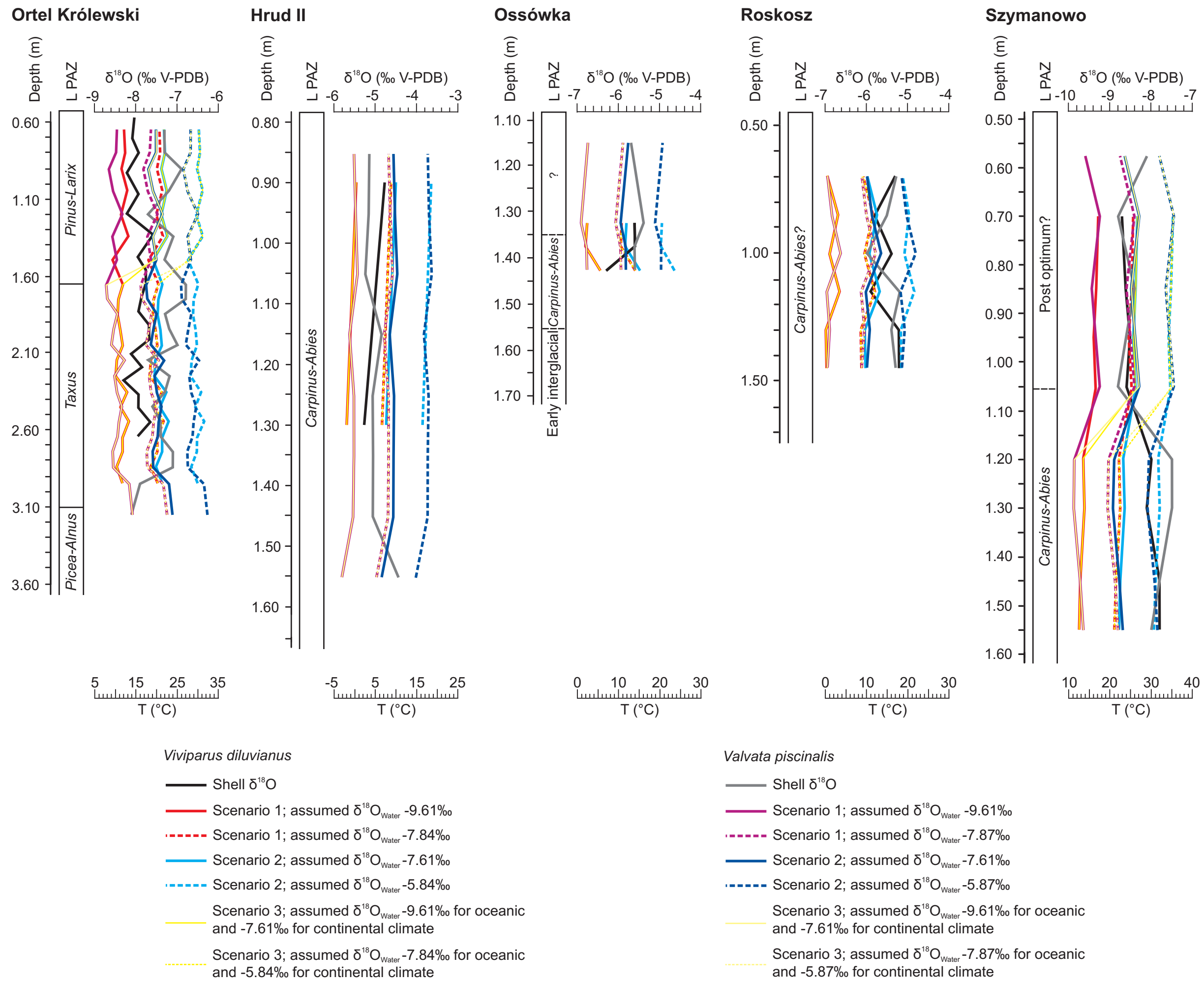
2) The $\delta^{18}O_{Water}$ values (based on $\delta^{18}O_{Precipitation}$) were corrected for the actual evaporative enrichment of approximately 2‰ (cf., von Grafenstein *et al.* 2000, 2013). This value results from the mean evaporative enrichment in several modern Central European small-medium lakes e.g., Polish Lake Gościąż (Ralska-Jasiewiczowa *et al.* 2003), German Ammersee (von Grafenstein *et al.* 2013) and Lake Steisslingen (Mayer and Schwark 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; Bińka *et al.* 1997; Nitychoruk *et al.* 2005). For periods of oceanic and continental influences the $\delta^{18}O_{Water}$ 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



Text-fig. 4. Past water temperature changes in studied Holsteinian palaeolakes based on *V. diluvianus* and *V. piscinalis* shell isotope composition, White *et al.*'s (1999) equation and assumed $\delta^{18}O$ of water. $\delta^{18}O$ of *V. diluvianus* and *V. piscinalis* after Szymanek *et al.* (2016) and Szymanek (2016), respectively

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 ($\delta^{18}O_{Precipitation}$ -9.61‰) and 20.1°C ($\delta^{18}O_{Precipitation}$ -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 $\delta^{18}O_{Water}$ values based on isotope value of the mean annual precipitation (-7.61‰) results in average tem-

Palaeolake	*Viviparus diluvianus*						*Valvata piscinalis*					
	Scenario						Scenario					
	1		2		3		1		2		3	
	Assumed δ18OWater						Assumed δ18OWater					
	-9.61‰	-7.84‰	-7.61‰	-5.84‰	-9.61 and -7.61‰	-7.84 and -5.84‰	-9.61‰	-7.87‰	-7.61‰	-5.87‰	-9.61 and -7.61‰	-7.87 and -5.87‰
	Range (Mean) °C	Range (Mean) °C	Range (Mean) °C	Range (Mean) °C	Range (Mean) °C	Range (Mean) °C	Range (Mean) °C	Range (Mean) °C	Range (Mean) °C	Range (Mean) °C	Range (Mean) °C	Range (Mean) °C
Ortel Królewski	9.6-13.3 (11.5)	18.1-21.9 (20.1)	19.2-23 (21.2)	27.8-31.6 (29.7)	10.1-22.7 (16.4)	18.6-21.9 (24.9)	7.8-14.2 (10.3)	16.2-22.6 (18.7)	17.5-23.9 (19.9)	25.9-32.3 (28.3)	7.8-13.3 (15.1)	16.2-30 (23.5)
Pinus–Larix	9.6-13.1 (11.9)	18.1-21.6 (20.4)	19.2-22.7 (21.5)	27.8-31.3 (30.1)	19.2-22.7 (21.5)	27.8-31.3 (30.1)	8.4-11.9 (10)	16.8-20.3 (18.4)	18-21.6 (19.6)	26.4-30 (28)	18-21.6 (19.6)	26.4-30 (28)
Taxus	10.1-13.3 (11.4)	18.6-21.9 (19.9)	19.7-23 (21)	28.3-31.6 (29.6)	10.1-13.3 (11.4)	18.6-21.9 (19.9)	7.8-13.3 (10.1)	16.2-21.7 (18.6)	17.5- (19.8)	25.9-31.4 (28.2)	7.8-13.3 (10.1)	16.2-21.7 (18.6)
Picea–Alnus							14.2	22.6	23.9	32.3	23.9	32.3
Ossówka-Hrud: Hrud II site*	-2-0.3 (-0.8)	6.6-8.9 (7.7)	7.7-10 (8.9)	16.3-18.5 (17.4)	-2-0.3 (-0.8)	6.6-8.9 (7.7)	-3.2-0.7 (-0.6)	5.2-9.1 (7.8)	6.4-10.3 (9.1)	14.8-18.7 (17.5)	-3.2-0.7 (-0.6)	5.2-9.1 (7.8)
Ossówka-Hrud: Ossówka site*	2-5.4 (3.2)	10.5-14 (11.8)	11.7-15.1 (12.9)	20.2-23.6 (21.4)	2-5.4 (3.2)	10.5-14 (11.8)	0.8-2.6 (1.9)	9.3-11 (10.3)	10.5-12.3 (11.6)	18.9-20.7 (20)	0.8-2.6 (1.9)	9.3-11 (10.3)
Roskosz*	0.1-3.4 (1.4)	8.6-12 (9.9)	9.7-13.1 (11)	18.3-21.6 (19.6)	0.1-3.4 (1.4)	8.6-12 (9.9)	0.3-3.8 (1.3)	8.7-12.2 (9.7)	9.9-13.5 (11)	18.3-21.9 (19.4)	0.3-3.8 (1.3)	8.7-12.2 (9.7)
Szymanowo	12.5-17.8 (14.9)	21-25.6 (23.4)	22.5-26.7 (24.5)	30.7-35.3 (33.1)	12.5-26.7 (19.7)	21-35.3 (28.2)	11.2-17.5 (14.5)	19.6-25.9 (22.9)	20.8-27.1 (24.1)	29.2-35.5 (32.5)	11.2-27.1 (19.3)	19.6-35.5 (27.7)
Post-optimum	16-17.1 (16.5)	24.6-25.6 (25.1)	25.7-26.7 (26.2)	34.2-35.3 (34.8)	25.7-26.7 (26.2)	34.2-35.3 (34.8)	14-17.5 (16.8)	22.4-25.9 (24.6)	23.6-27.1 (26.4)	32-35.5 (34.8)	23.6-27.1 (26.4)	32-35.5 (34.8)
Carpinus–Abies	12.5-13.8 (13.2)	21-22.4 (21.7)	22.2-23.5 (22.8)	30.7-32 (31.4)	12.5-13.8 (13.2)	21-22.4 (21.7)	11.2-13.5 (12.2)	19.6-21.9 (20.6)	20.8-23.1 (21.8)	29.2-31.5 (30.3)	11.2-13.5 (12.2)	19.6-21.9 (20.6)

Text-fig. 5. Temperature range and mean temperatures calculated for studied Holsteinian palaeolakes in three considered scenarios. In scenario 1 the $\delta^{18}O_{Water}$ is based on $\delta^{18}O$ values of the mean annual and the mean growth-season precipitation; in scenario 2 those values were corrected for modern evaporative enrichment of ~2‰; scenario 3 assumes evaporative enrichment in phases of distinct continental influences, i.e. in the *Pinus–Larix* Zone (Ortel Królewski Lake) and in the post-optimum (Szymanowo Lake). Asterisk (*) indicates *Carpinus–Abies* Zone

peratures 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 $\delta^{18}O_{Water}$ 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°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 ($\delta^{18}O_{Water}$ corresponding to mean annual $\delta^{18}O_{Precipitation}$) and 9.9°C ($\delta^{18}O_{Water}$ corresponding to mean growth-season $\delta^{18}O_{Precipitation}$). 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 Szymanowo lake combined with the isotope composition of lake water derived from actual mean annual precipitation yields the past water temperature in the range of 12.5–17.8°C with the average of 14.9°C. In the final part of the *Carpinus–Abies* Zone the temperature varies between 12.5 and 13.8°C (the mean of 13.2°C), while in the post-optimum period it increases to 16–17.1°C with the mean of 16.5°C (Text-figs 4, 5). This tendency is also shown in the estimation based on oxygen isotope ratios of the April–October rainfall, yielding in the whole sequence the mean temperature of 23.4°C and the range of 21–25.6°C. The mean temperature of the *Carpinus–Abies* Zone of 21.7°C (the range of 21–22.4°C) is followed by 25.1°C (24.6–25.6°C) after the interglacial climatic optimum (Text-fig. 5).

Similar values are inferred from scenario 2 and the mean annual $\delta^{18}O_{Precipitation}$. Mean lake water temperature is estimated at 24.5°C (the range of 22.5–26.7°C) with 22.8°C (22.2–23.5°C) in the optimum and 26.2°C (25.7–26.7°C) in the post-optimum period (Text-fig. 5). After the correction of $\delta^{18}O$ values based on growth-season rainfall, the calculated temperatures increase to 33.1°C (the whole sequence; the range of 30.7–35.3°C), 31.4°C (*Carpinus–Abies*; 30.7–32.0°C) and 34.8°C (post-optimum; 34.2–35.3°C) (Text-fig. 5).

Only slight differences are noted in the temperatures estimated from oxygen isotopes of *V. piscinalis* shells. In scenario 1 the mean values of 14.5°C (the whole sequence; the range of 11.2–17.5°C), 12.2°C (*Carpinus–Abies*; 11.2–13.5°C), 16.8°C (post-optimum; 14–17.5°C) and 22.9°C (the whole sequence; 19.6–25.9°C), 20.6°C (*Carpinus–Abies*; 19.6–21.9°C), 24.6°C (post-optimum; 22.4–25.9°C) were calculated from the mean annual and the mean growth-season $\delta^{18}O_{Precipitation}$ values, respectively (Text-fig. 5). In scenario 2 those values are of: 24.1°C (mean of the whole sequence; the range of 20.8–27.1°C), 21.8°C (*Carpinus–Abies*; 20.8–23.1°C), 26.4°C (post-optimum; 23.6–27.1°C) and 32.5°C (the whole sequence; 29.2–3.5°C), 30.3°C (*Carpinus–Abies*; 29.2–31.5°C), 34.8°C (post-optimum; 32–35.5°C) (Text-fig. 5).

Statistical analysis

The differences in the estimated average past water temperatures between the studied sequences are statistically significant (one-way ANOVA: p-values < 0.0001). The results from Ortel Królewski and Szymanowo differ significantly from other palaeolakes (Tukey's test: $p < 0.05$), and both lakes differ from each other (Tukey's test: $p < 0.05$). A post-hoc Tukey's test reveals significant differences also between Ossówka and Hrud II sequences ($p < 0.05$).

The comparisons within the studied profiles indicate no significant differences between average 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 $\delta^{18}O$ 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; Albrycht *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 (Albrycht *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 – $\delta^{18}O_{Water}$ corresponds with $\delta^{18}O_{Precipitation}$

Scenario 1 assumes both the close relations of $\delta^{18}O_{Water}$ and $\delta^{18}O_{Precipitation}$ 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 km^2 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 characterised 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 $\delta^{18}O_{Shell}$ 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 equation 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 then 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 $\delta^{18}O_{Water}$ 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

Królewski and Szymanowo. Moreover, the oxygen isotope palaeotemperatures based on the mean annual precipitation vary significantly from those inferred from the vegetation succession (Krupiński 1995; 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 $\delta^{18}O_{Water}$ related to the mean growth-season $\delta^{18}O_{Precipitation}$. The mean temperatures of 19.9 (*V. diluvianus*) and 18.6°C (*V. 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 (Szymanek 2016; Szymanek *et al.* 2016) and palynology (Krupiński 1995; Nita 2009). The temperatures of 21.7 and 20.6°C indicated by *V. diluvianus* and *V. 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. cristata*, *A. lacustris* and *B. tentaculata* (Szymanek 2014a). These conditions appear suitable also for the water fern *Salvinia natans* abundant in these warm and well-vegetated waters of Szymanowo Lake (cf., Krupiński 1995; Pidek 2003).

The $\delta^{18}O_{Water}$ of approximately -7.8‰ (reflecting the mean growth-season $\delta^{18}O_{Precipitation}$) 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 to 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 (Albrycht *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 – $\delta^{18}O_{Water}$ corrected for evaporative enrichment

Reliable mean water temperatures of the Ossówka-Hrud and Roskosz Lakes were calculated in scenario 2 (Text-fig. 5). For $\delta^{18}O_{Water}$ of -5.84‰ (-5.87‰ for *V. 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 $\delta^{18}O_{Water}$ based on the mean annual precipitation to -7.61‰ provides similar temperatures to those received in scenario 1 for $\delta^{18}O_{Water}$ 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

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

Text-fig. 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, $\delta^{18}O_{Water}$ of approximately -7.8‰ should be accepted for reliable results ($\delta^{18}O_{Water}$ equals $\delta^{18}O_{Precipitation}$ of the growth season or mean annual $\delta^{18}O_{Precipitation}$ 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* zo 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 *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 $\delta^{18}O_{Precipitation}$ 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 *Taxus* and *Carpinus–Abies* zones could result in rainfall enriched in the heavier oxygen isotope and thus higher $\delta^{18}O_{Water}$ of the studied lakes (Rozanski *et al.* 1993; Nitychoruk 2000; Nitychoruk *et al.* 2005). The increased values of $\delta^{18}O_{Water}$ of Ossówka-Hrud and Roskosz Lakes postulated in scenario 1 also should be a consequence of higher $\delta^{18}O_{Precipitation}$ 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 Höfle 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 $\delta^{18}O$ 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 Grafenstein *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 $\delta^{18}O$ 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 *Taxus* 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 palaeoecological 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 *Taxus* 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; Bińka *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 $\delta^{18}O$ 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 $\delta^{18}O$ 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 $\delta^{18}O$ values of *V. diluvianus* and *V. piscinalis* shells may be converted for the absolute growth-season past water temperature.
- Former $\delta^{18}O_{Water}$ values corresponding with the present-day mean annual $\delta^{18}O_{Precipitation}$ of approximately -9.6‰ yield temperatures which are too low, and which diverge from other proxies such as regional pollen and mollusc records.
- The $\delta^{18}O_{Water}$ 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 $\delta^{18}O$ 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

Aalbersberg, G. and Litt, T. 1998. Multiproxy climate reconstructions for the Eemian and Early Weichselian. *Journal of Quaternary Science*, **13**, 367–390.

Ahlberg, K., Almgren, E., Wright, H.E., Jr., Ito, E. and Hobbie, S. 1996. Oxygen-isotope record of Late-Glacial climatic change in western Ireland. *Boreas*, **25**, 257–267.

Albrycht, A. 2002. Szczegółowa mapa geologiczna Polski 1:50 000, arkusz Łomazy (605). Centralne Archiwum Geologiczne PIG-PIB; Warszawa.

Albrycht, A., Skompski, S. and Pidek, I.A. 1995. Significance of mollusk fauna from Ortel Królewski and Rossosz sites for the Quaternary stratigraphy of Podlasie (East Poland). *Przegląd Geologiczny*, **43**, 321–330.

Alexandrowicz, S.W. and Alexandrowicz, W.P. 2011. Analiza malakologiczna. Metody badań i interpretacji. *Rozprawy Wydziału IV Przyrodniczego PAU*, **3**, 1–302.

Ammann, B., Chaix, L., Eicher, U., Elias, S.A., Gaillard, M.-J., Hofmann, W., Siegenthaler, U., Tobolski, K. and Wilkinson, B. 1983. Vegetation, insects, molluscs and stable isotopes from Late Würm deposits at Lobsigensee (Swiss Plateau). *Revue de Paléobiologie*, **2**, 221–227.

Apolinarska, K. 2009a. Reconstructions of the early and middle Holocene climate and environment based on $\delta^{13}C$ and $\delta^{18}O$ records in biogenic carbonates; Lake Niepruszewskie, western Poland. *Acta Geologica Polonica*, **59**, 359–370.

Apolinarska, K. 2009b. $\delta^{18}O$ and $\delta^{13}C$ isotope investigation of the Late Glacial and early Holocene biogenic carbonates from the Lake Lednica sediments, western Poland. *Acta Geologica Polonica*, **59**, 111–121.

Apolinarska, K. 2013. Stable isotope compositions of recent Dreissena polymorpha (Pallas) shells: palaeoenvironmental implications. *Journal of Paleolimnology*, **50**, 353–364.

Apolinarska, K. and Hammarlund, D. 2009. Multi-component stable isotope records from Late Weichselian and early Holocene lake sediments at Imiołki, Poland: palaeoclimatic and methodological implications. *Journal of Quaternary Science*, **24**, 948–959.

Apolinarska, K., Pełechaty, M. and Kossler, A. 2015. Within-sample variability of $\delta^{13}C$ and $\delta^{18}O$ values of freshwater gastropod shells and the optimum number of shells to measure per sediment layer in the Paddenluch palaeolacustrine sequence, Germany. *Journal of Paleolimnology*, **54**, 305–323.

Atkinson, T.C., Briffa, K.R. and Coope, G.R. 1987. Seasonal temperatures in Britain during the past 22,000 years, reconstructed using beetle remains. *Nature*, **325**, 587–592.

Baroni, C., Zanchetta, G., Fallick, A.E. and Longinelli, A. 2006. Mollusca stable isotope record of a core from Lake Frassino, northern Italy: hydrological and climatic changes during the last 14 ka. *The Holocene*, **16**, 827–837.

Beaulieu, J.-L., Eicher, U. and Monjuvent, G. 1994. Reconstruction of Middle Pleistocene palaeoenvironments based on pollen and stable isotope investigations at Val-de-Lans, Isère, France. *Vegetation History and Archaeobotany*, **3**, 127–142.

Bińka, K., Lindner, L. and Nitychoruk, J. 1997. Geologic-floristic 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. *Geological Quarterly*, **39**, 109–120.

Bińka, K. and Nitychoruk, J. 1996. Geological and palaeobotanical setting of interglacial sediments at the Kaliłów site in southern Podlasie. *Geological Quarterly*, **40**, 269–282.

Buchardt, B. and Fritz, P. 1980. Environmental isotopes as environmental and climatological indicators. In: P. Fritz and J.C. Fontes (Eds), Handbook of Environmental Isotope Geochemistry, Vol. 1A, The Terrestrial Environment, 473–504. Elsevier; Amsterdam.

Bugler, M.J., Grimes, S.T., Leng, M.J., Rundle, S.D., Price, G.D., Hooker, J.J. and Collinson, M.E. 2009. Experimental determination of a *Viviparus contectus* thermometry equation. *Rapid Communications in Mass Spectrometry*, **23**, 2939–2951.

Candy, I., Abrook, A., Elliot, F., Lincoln, P., Matthews, I.P. and Palmer, A. 2016. Oxygen isotopic evidence for high-magnitude, abrupt climatic events during the Lateglacial Interstadial in north-west Europe: analysis of a lacustrine sequence from the site of Tirinie, Scottish Highlands. *Journal Of Quaternary Science*, **31**, 607–621.

Candy, I., Schreve, D.C., Sherriff, J. and Tye, G.J. 2014. Marine Isotope Stage 11: Palaeoclimates, palaeoenvironments and its role as an analogue for the current interglacial. *Earth-Science Reviews*, **128**, 18–51.

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

Coope, G.R. 1986. Coleoptera analysis. In: B.E. Berglund (Ed.), Handbook of Holocene Palaeoecology and Palaeohydrology, 703–713. John Wiley and Sons Ltd; Chichester.

Craig, H. 1965. The measurement of oxygen isotope palaeotemperatures. In: E. Tongiorgi (Ed.), Stable Isotopes in Oceanographic Studies and Palaeotemperatures, 161–182. Spoleto: Consiglio Nazionale delle Ricerche, Laboratorio di Geologica Nucleare; Pisa.

Dabkowski, J., Limondin-Lozouet, N., Antoine, P., Andrews, J., Marca-Bell, A. and Robert, V. 2012. Climatic variations in MIS 11 recorded by stable isotopes and trace elements in a French tufa (La Celle, Seine Valley). *Journal of Quaternary Science*, **27**, 790–799.

Dabrowski, M., Marszelewski, W. and Skowron, R. 2004. The trends and dependencies between air and water temperatures in lakes in northern Poland from 1961–2000. *Hydrology and Earth System Sciences*, **8**, 79–87.

Dansgaard, W. 1964. Stable isotopes in precipitation. *Tellus*, **16**, 436–468.

Dettman, D.L. and Lohmann, K.C. 1993. Seasonal change in Paleogene surface water $\delta^{18}O$: Fresh-water bivalves of western North America. In: P. Swart, K.C Lohmann, J. McKenzie and S. Savin (Eds), Continental Climate Change from Isotopic Records. *AGU Geophysical Monograph Series*, **78**, 153–163.

Eicher, U. and Siegenthaler, U. 1976. Palynological and oxygen isotope investigations on Late-Glacial sediment cores from Swiss lakes. *Boreas*, **5**, 109–117.

EPICA community members, 2004. Eight glacial cycles from an Antarctic ice core. *Nature*, **429**, 623–628.

Epstein, S., Buchsbaum, R., Lowenstam, H.A. and Urey, H.C. 1953. Revised carbonate water isotopic temperature scale. *Geological Society American Bulletin*, **64**, 1315–1326.

Fritz, P. and Poplawski, S. 1974. ^{18}O and ^{13}C in the shells of freshwater molluscs and their environments. *Earth and Planetary Science Letters*, **24**, 91–98.

Gittenberger, E., Janssen, A.W., Kuijper, W.J., Kuiper, J.G.J., Meijer, T., Van Der Velde, G. and De Vries, J.N. 2004. De Nederlandse Zoetwatermollusken: Recente en fossiele weekdieren uit zoet en brak water. Nederlandse Fauna 2, pp.1–292. Nationaal Natuurhistorisch Museum Naturalis, KNNV Uitgeverij and EIS-Nederland; Leiden.

Grimes, S.T., Matteyet, D.P., Hooker, J.J. and Collinson, M.E. 2002. Paleogene paleoclimate reconstruction using oxygen isotopes from land and freshwater organisms: the use of multiple paleoproxies. *Geochimica et Cosmochimica Acta*, **67**, 4033–4047.

Grossman, E.L. 2012. Applying oxygen isotope paleothermometry in deep time. In: L.C. Ivany and B.T. Huber (Eds), Reconstructing Earth's Deep-Time Climate – The State of the Art in 2012. *The Paleontological Society Papers*, **18**, 39–67.

Grossman, E.L. and Ku, T.L. 1986. Oxygen and carbon isotope fractionation in biogenic aragonite – temperature effects. *Chemical Geology*, **59**, 59–74.

Hammarlund, D., Björck, S., Buchardt, B., Israelson, C. and Thomsen, Ch.T. 2003. Rapid hydrological changes during the Holocene revealed by stable isotope records of lacustrine carbonates from Lake Igelsjön, southern Sweden. *Quaternary Science Reviews*, **22**, 353–370.

Hammarlund, D. and Buchardt, B. 1996. Composite stable isotope records from a Late Weichselian lacustrine sequence at Graenge, Lolland, Denmark: evidence of Allerød and Younger Dryas environments. *Boreas*, **25**, 8–22.

Hammarlund, D., Edwards, T.W.D., Björck, S., Buchardt, B. and Wohlfarth, B. 1999. Climate and environment during the Younger Dryas (GS-1) reflected by composite stable isotope records of lacustrine carbonates at Torreberga, southern Sweden. *Journal of Quaternary Science*, **14**, 17–28.

Hammer, Ø., Harper, D.A.T. and Ryan, P.D. 2001. PAST: paleontological statistics soft ware package for education and data analysis. *Palaeontologia Electronica*, **4**, 1–9.

Hinsch, W. 1993. Marine Molluskenfaunen in Typusprofilen des Elster-Saale-Interglazials und des Elster-Spätglazials. *Geologisches Jahrbuch*, **A 138**, 9–34.

Hren M.T., Sheldon N.D., Grimes S.T., Collinson M.E., Hooker, J.J., Bugler, M. and Lohmann, K.C. 2013. Terrestrial cooling in Northern Europe during the Eocene–Oligocene transition. *Proceedings of the National Academy of Sciences of the United States of America,* **110**, 7562–7567.

IAEA/WMO. 2014. Global Network of Isotopes in Precipitation. The GNIP Database. http://www.iaea.org/water, accessed on 9 June 2015.

Imbrie, J., Shackleton, N.J., Pisias, N.G., Morley, J.J., Prell, W.L., Martinson, D.G., Hays, J.D., MacIntyre, A. and Mix, A.C. 1984. The orbital theory of Pleistocene climate: support from a revised chronology of the marine $\delta^{18}O$ record. In: A. Berger (Ed.), Milankovitch and Climate. Part 1. pp. 269–305. Reidel, Hingham; Massachusetts.

Iversen, J. 1954. The Late-Glacial flora of Denmark and its relation to climate and soil. *Danmarks Geologiske Undersøgelse Række II*, **80**, 87–119.

Jakubik, B. 2012. Life strategies of Viviparidae (Gastropoda: Caenogastropoda: Architaenioglossa) in various aquatic habitats: *Viviparus viviparus* (Linnaeus, 1758) and *V. contectus* (Millet, 1813). *Folia Malacologica*, **20**, 145–179.

Jakubik, B. and Lewandowski, K. 2007. Size structure, age, mortality and fecundity in *Viviparus viviparus* (Linnaeus, 1758) (Gastropoda: Architaenioglossa: Viviparidae). *Folia Malacologica*, **15**, 109–117.

Jouzel, J., Masson-Delmotte, V., Cattani, O., Dreyfus, G., Falourd, S., Hoffmann, G., Minster, B., Nouet, J., Barnola, J.M., Chappellaz, J., Fischer, H., Gallet, J.C., Johnsen, S., Leuenberger, M., Loulergue, L., Luethi, D., Oerter, H., Parrenin, F., Raisbeck, G., Raynaud, D., Schilt, A., Schwander, J., Selmo, E., Souchez, R., Spahni, R., Stauffer, B., Steffensen, J.P., Stenni, B., Stocker, T.F., Tison, J.L., Werner, M. and Wolff, E.W. 2007. Orbital and millennial Antarctic climate variability over the past 800,000 years. *Science*, **317**, 793–796.

Kim, S.T. and O'Neil, J.R. 1997. Equilibrium and nonequilibrium oxygen isotope effects in synthetic carbonates. *Geochimica et Cosmochimica Acta*, **61**, 3461–3475.

Kondratiene, O. and Gudelis, W. 1983. Pleistocene marine sediments in the Pribaltica area. *Przegląd Geologiczny*, **31**, 497–502.

Koutsodendris, A., Brauer, A., Pälike, H., Müller, U.C., Dulski, P., Lotter, A.F. and Pross, J. 2011. Sub-decadal to decadal-scale climate cyclicity during the Holsteinian interglacial

(MIS 11) evidenced in annually laminated sediments. *Climate of the Past*, **7**, 987–999.

Koutsodendris, A., Lotter, A.F., Kirilova, E., Verhagen, F.T.M., Brauer, A. and Pross, J. 2013. Evolution of a Holsteinian (MIS 11c) palaeolake based on a 12-kyr-long diatom record from Dethlingen (northern Germany). *Boreas*, **42**, 714–728.

Koutsodendris, A., Müller, U.C., Pross, J., Brauer, A., Kotthoff, U. and Lotter, A.F. 2010. Vegetation dynamics and climate variability during the Holsteinian interglacial based on a pollen record from Dethlingen (northern Germany). *Quaternary Science Reviews*, **29**, 3298–3307.

Koutsodendris, A., Pross, J., Müller, U.C., Brauer, A., Fletcher, W.J., Kühl, N., Kirilova, E., Verhagen, F.T.M, Lücke, A. and Lotter, A.F. 2012. A short-term climate oscillation during the Holsteinian interglacial (MIS 11c): an analogy to the 8.2 ka climatic event? *Global and Planetary Change*, **92**–**93**, 224–235.

Koutsodendris, A., Pross, J., Zahn, R. 2014. Exceptional Agulhas leakage prolonged interglacial warmth during MIS 11c in Europe. *Paleoceanography*, **29**, 1062–1071.

Krupiński, K.M. 1995. Stratygrafia pyłkowa i sukcesja roślinności interglacjału mazowieckiego. *Acta Geographica Lodziensia*, **70**, 8–189.

Krupiński, K.M. 2000. Palynostratigraphic correlation of deposits of the Mazovian Interglacial of Poland. *Prace Państwowego Instytutu Geologicznego*, **169**, 1–61.

Lang, B., Brooks, S.J., Bedford, A., Jones, R.T., Birks, H.J.B. and Marshall, J.D. 2010. Regional consistency in Late-glacial chironomid-inferred temperatures from five sites in north-west England. *Quaternary Science Reviews*, **29**, 1528–1538.

Leng, M.J. and Marshall, J.D. 2004. Palaeoclimate interpretation of stable isotope data from lake sediment archives. *Quaternary Science Reviews*, **23**, 811–831.

Lindner, L., Krupiński, K.M., Marciniak, B., Nitychoruk, J. and Skompski, S. 1991. Pleistocene lake sediments of the site Hrud I near Biała Podlaska. *Geological Quarterly*, **35**, 337–362.

Lindner, L. and Marciniak, B. 1998. Middle Pleistocene lake deposits in southern Podlasie (eastern Poland). *Studia Geologica Polonica*, **113**, 65–83.

Livingstone, D.M. and Lotter, A.F. 1998. The relationship between air and water temperatures in lakes of the Swiss Plateau: A case study with palaeolimnological implications. *Journal of Paleolimnology*, **19**, 181–198.

Ložek, V. 1986. Mollusca Analysis. In: B.E. Berglund (Ed.), Handbook of Holocene Palaeoecology and Palaeohydrology, 729–740. John Wiley and Sons Ltd; Chichester.

Marciniak, B. 1998. Diatom stratigraphy of the Mazovian Interglacial lacustrine sediments in southeastern Poland. *Studia Geologica Polonica*, **113**, 7–64.

Marks, L., Karabanov, A., Nitychoruk, J., Bahdasarau, M., Krzywicki, T., Majecka, A., Pochocka-Szwarc, K., Rychel, J., Woronko, B., Zbucki, Ł., Hradunova, A., Hrychanik, M., Mamchyk, S., Rylova, T., Nowacki, Ł. and Pielach, M. Revised limit of the Saalian ice sheet in central Europe, *Quaternary International* (2016), http://dx.doi.org/10.1016/j.quaint.2016.07.043

Marshall, J.D., Jones, R.T., Crowley, S.F., Oldfield, F., Nash, S. and Bedford, A. 2002. A high resolution Late-Glacial isotopic record from Hawes Water, Northwest England Climatic oscillations: calibration and comparison of palaeotemperature proxies. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **185**, 25–40.

Mayer, B. and Schwark, L. 1999. A 15,000-year stable isotope record from sediments of Lake Steisslingen, Southwest Germany. *Chemical Geology*, **161**, 315–337.

McCrea, J.M. 1950. The isotopic chemistry of carbonates and a palaeotemperatures scale. *Journal of Chemical Physics*, **18**, 849–857.

Meyer, K.-J. 1974. Pollenanalytische Untersuchungen und Jahresschichtenzählungen an der holstein-zeitlichen Kieselgur von Hetendorf. *Geologisches Jahrbuch*, **A 21**, 87–105.

Müller, H. 1974. Pollenanalytische Untersuchungen und JahresschichtenzaKhlungen an der Eemzeitlichen Kieselgur von Bispingen/Luhe. *Geologisches Jahrbuch*, **A 21**, 149–169.

Müller, H. and Höfle, H.Ch. 1994. Die Holstein-Interglazial vorkommen bei Bossel westlich von Stade und Wanhöden nördlich Bremerhaven. *Geologisches Jahrbuch*, **A 134**, 71–116.

Myzyk, S. 2007. Life cycle of *Valvata piscinalis* (O. F. Müller, 1774) (Gastropoda: Heterobranchia) in the laboratory. *Folia Malacologica*, **15**, 145–174.

Navarro, N., Lécuyer Ch., Montuire, S., Langlois, C. and Martineau, F. 2004. Oxygen isotope compositions of phosphate from arvicoline teeth and Quaternary climatic changes, Gigny, French Jura. *Quaternary Research*, **62**, 172–182.

NCDC. 2015. National Climatic Data Center. NOAA Satellite and Information Service. http://www7.ncdc.noaa.gov/CDO/cdodata.cmd, accessed on 3 August 2014.

Nita, M. 2009. Pollen stratigraphy and vegetation history during the Mazovian Interglacial and the older part of Liviecian Glaciation in the western and central parts of Polish Uplands. pp. 1–158. University of Silesia Press; Katowice.

Nitychoruk, J. 2000. Climate reconstruction from stable-isotope composition of the Mazovian Interglacial (Holsteinian) lake sediments in eastern Poland. *Acta Geologica Polonica*, **50**, 247–294.

Nitychoruk, J., Bińka, J., Hoefs, J., Ruppert, H. and Schneider, J. 2005. Climate reconstruction for the Holsteinian Interglacial in eastern Poland and its comparison with isotopic data from Marine Isotope Stage 11. *Quaternary Science Reviews*, **24**, 631–644.

Nitychoruk, J. and Gałązka, D. 2008. Szczegółowa mapa geologiczna Polski 1:50 000, arkusz Biała Podlaska (568). Centralne Archiwum Geologiczne PIG-PIB; Warszawa.

Pidek, I.A. 2003. Mesopleistocene vegetation history in the northern foreland of the Lublin Upland based on palaeobotanical studies of the profiles from Zdany and Brus sites, pp. 1–96. Maria Curie-Skłodowska University Press; Lublin.

Piechocki, A. and Wawrzyniak-Wydrowska, B. 2016. Guide to Freshwater and Marine Mollusca of Poland, pp. 1–279. Bogucki Wydawnictwo Naukowe; Poznań.

Prendergast, A.L. and Stevens, R.E. 2014. Molluscs (Isotopes) – Analyses in environmental archaeology. In: C. Smith (Ed.), The Encyclopedia of Global Archaeology, pp. 510–514. Springer-Verlag; New York.

Pukacz, A., Pełechaty, M., Frankowski, M., Kowalski, A. and Zwijacz-Koszałka, K. 2014. Seasonality of water chemistry, carbonate production, and biometric features of two species of *Chara* in a shallow clear water lake. *The Scientific World Journal*, **vol. 2014**, 1–11.

Ralska-Jasiewiczowa, M., Goslar, T., Różański, K., Wacnik, A., Czernik, J. and Chróst, L. 2003. Very fast environmental changes at the Pleistocene/Holocene boundary, recorded in laminated sediments of Lake Gościąż, Poland. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **193**, 225–247.

Rozanski, K., Araguás-Araguás, L. and Gonfiantini, R. 1993. Isotopic patterns in Modern Global Precipitation. In: P.K. Swart, K.C. Lohmann, J. McKenzie and S. Savin (Eds), Climate Change in Continental Isotope Records. *Geophysical Monographs*, **78**, 1–36.

Shanahan, T. M., Pigati, J.S., Dettman, D.L. and Quade, J. 2005. Isotopic variability in the aragonite shells of freshwater gastropods living in springs with nearly constant temperature and isotopic composition. *Geochimica et Cosmochimica Acta*, **69**, 3949–3966.

Siegenthaler, U. and Eicher, U. 1986. Stable oxygen and carbon isotope analyses. In: B.E. Berglund (Ed.), Handbook of Holocene Palaeoecology and Palaeohydrology, 407–422. John Wiley and Sons Ltd; Chichester..

Skompski, S. 1996. Standard assemblages of malacofauna in different Quaternary stratigraphic units. *Prace Państwowego Instytutu Geologicznego*, **151**, 1–47.

Szymanek, M. 2011. Climate oscillations of the Holsteinian (Mazovian) Interglacial recorded in shell morphometry of *Viviparus diluvianus* (Kunth, 1865) from eastern Poland. *Quaternary International*, **241**, 143–159.

Szymanek, M. 2012. Malacofauna of the Holsteinian lake deposits at Hrud II (eastern Poland) and its ecological significance. *Geological Quarterly*, **56**, 117–126.

Szymanek, M. 2013. Palaeoecology of the Holsteinian lake in vicinity of Wilczyn (Eastern Poland) based on molluscan studies. *Geological Quarterly*, **57**, 637–648.

Szymanek, M. 2014a. Environmental changes of the Mazovian (Holsteinian /~MIS 11) palaeolake near Szymanowo (Eastern Poland) in the light of malacological analysis. *Acta Geologica Polonica*, **64**, 249–260.

Szymanek, M. 2014b. Geochemical studies of *Viviparus diluvianus* (Kunth) from Ortel Królewski (eastern Poland) and their climatic and environmental significance. In: W.N. Gubin, W.I. Zui, O.W. Lukaszew, N.S. Pietrowa, A.F. Sanko and D.L. Tworonowycz-Sewruk (Eds), Geology and Mineral Sources of Quaternary Deposits: Proceedings of VIII University's Geological Readings, pp. 42–44. Minsk.

Szymanek, M. 2016. Stable isotope composition of the Holsteinian (MIS 11) freshwater snail *Valvata piscinalis* (O. F. Müller, 1774) from eastern Poland and its palaeoenvironmental implications. *Journal of Quaternary Science*, **31**, 622–630.

Szymanek, M. 2017. Elemental geochemistry of freshwater snail shells: palaeolimnology of a Holsteinian (MIS 11) deposit from eastern Poland. *Boreas* 10.1111/bor.12283, in press.

Szymanek, M., Bińka, K. and Nitychoruk, J. 2016. Stable ^{18}O and ^{13}C isotope records of *Viviparus diluvianus* (Kunth, 1865) shells from Holsteinian (MIS 11) lakes of eastern Poland as palaeoenvironmental and palaeoclimatic proxies. *Boreas*, **45**, 109–121.

Turner, C. 1970. The Middle Pleistocene deposits at Marks Tey, Essex. *Philosophical Transactions of the Royal Society B*, **257**, 373–440.

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

Von Grafenstein, U., Belmecheri, S., Eicher, U., van Raden, U.J., Erlenkeuser, H., Andersen, N. and Ammann, B. 2013. The oxygen and carbon isotopic signatures of biogenic carbonates in Gerzensee, Switzerland, during the rapid warming around 14,685 years BP and the following interstadial. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **391**, 25–32.

Von Grafenstein, U., Eicher, U., Erlenkeuser, H., Ruch, P., Schwander, J. and Ammann, B. 2000. Isotope signature of the Younger Dryas and two minor oscillations at Gerzensee (Switzerland): palaeoclimatic and palaeolimnologic interpretation based on bulk and biogenic carbonates. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **159**, 215–229.

Von Grafenstein, U., Erlenkeuser, H., Kleinmann, A., Müller, J. and Trimborn, P. 1994. High-frequency climatic oscillations as revealed by oxygen isotope records of benthic organisms (Ammersee, southern Germany). *Journal of Paleolimnology*, **11**, 349–357.

Von Grafenstein, U., Erlenkeuser, H., Müller, J., Trimborn, P. and Alefs, J. 1996. A 200 year mid-European air temperature record preserved in lake sediments: An extension of the $\delta^{18}O_p$-air temperature relation into the past. *Geochimica et Cosmochimica Acta*, **60**, 4025–4036.

Welter-Schultes F. 2012. European non-marine molluscs, a guide for species identification, pp. 1–679. Planet Poster Editions; Goettingen.

White, R.M., Dennis, P.F. and Atkinson, T.C. 1999. Experimental calibration and field investigation of the oxygen isotopic between biogenic aragonite and water. *Rapid Communications in Mass Spectrometry*, **13**, 1242–1247.

Wojtanowicz, J. 1994. On thermokarst genesis of the Łęczna-Włodawa lakes. *Annales UMCS Sectio B*, **49**, 1–18.

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: Paleoclimatological implications for sub-weekly temperature records. *Journal of Paleolimnology*, **26**, 205–218.

Zagwijn, W.H. 1996. An analysis of Eemian climate in Western and Central Europe. *Quaternary Science Reviews*, **15**, 451–469.

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