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ORIGINAL PAPER

Eemian snails from Gorzów Wielkopolski palaeolake (NW Poland): malacological and isotopic data and their ecological implications

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Abstract The results of isotope and malacological investigations of mollusc shells from the Eemian Interglacial (MIS 5e) and Vistulian (Weichselian, MIS 5a-d - MIS 4) lake sediments in Gorzów Wielkopolski (NW Poland) are presented. The palaeolake in Gorzów Wielkoposki is the newest paleontological site with the skeleton of the Eemian rhinoceros. The analyzed sediments contained numerous mollusc shells representing 29 species. The dominant species in the malacofauna are *Valvata piscinalis* and *Bithynia tentaculata*. Two types of mollusc assemblages have been distinguished, indicating the changes in the lake environment. Carbon and oxygen isotope compositions ($\delta^{13}C$ and $\delta^{18}O$) were measured in the shells of *Valvata piscinalis* and in the opercula of *Bithynia tentaculata*. The $\delta^{18}O$ values of the Eemian snail shells changed from −6.0 to −3.8‰, and are higher than the bulk carbonate data. The $\delta^{13}C$ values oscillated between −8.6 and −1.8‰ in the Eemian shells and are lower than the bulk carbonate data. Environmental changes occurring in the immediate vicinity of the rhinoceros skeleton likely influenced the isotope composition of shells, resulting in different $\delta^{13}C$ and $\delta^{18}O$ values. The malacological and isotope data aided in distinguishing six phases of lake development. In the first phase (M-1, Early Eemian), a progressive increase in the water level was noted. Then (M-2, Middle Eemian), a significant shallowing of the lake took place. The next phase (M-3, Middle Eemian) was characterized by high water levels and stable hydrological conditions. In the M-4 phase (Late Eemian), a gradual lowering of the water level was observed, leading to the complete disappearance of the lake at the end of the Eemian. During the Vistulian, the lake reemerged. Initially (M-5), it was a permanent lake with a relatively high water level. In the highest part of the profile (M-6, Vistulian), its significant shallowing occurred, and this lake disappeared.

Keywords Lake environment · Oxygen and carbon stable isotopes · Vistulian central Europe

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Introduction

Mollusc shells occur in both terrestrial and freshwater Quaternary sediments, sometimes throughout the deposition sequence. Their assemblages are related to local habitats and may reflect the almost original composition of malacocenoses that lived during the deposition of sediments, if the state of preservation of the shells allows it. Most of the species currently living in Central Europe have been known in this area since the Eemian Interglacial. Additionally, mollusc shells appear in sediments of various origins. Therefore, assemblages of subfossil molluscs are often used for palaeogeographical, palaeoenvironmental, and stratigraphical reconstructions. Malacofauna often occurs in lake sediments, especially those containing a significant admixture of calcium carbonate (calcareous gyttja, lacustrine chalks). Many localities with such sediments have been described in Europe, and the mollusc communities present in them have been characterized. These sites are most often associated from interglacial periods of various ages, from the early Pleistocene to those associated with the end of the last glacial period and the Holocene. Localities with lake sediments containing malacofauna and representing the Eemian Interglacial have been described mainly in the Netherlands, Germany, Poland, the Baltic countries, and Belarus (Sanko and Gaigalas 2007; Meng et al. 2009a, 2009b; Strahl et al. 2010; Alexandrowicz and Alexandrowicz 2010; Sanko et al. 2011; Menzel-Harloff and Meng 2015; Hrynowiecka et al. 2018; Milano et al. 2020; Alexandrowicz et al. 2021, 2024). Mollusc communities in lake sediments are usually dominated by aquatic snails and bivalves. Sometimes they also contain an admixture of land snails, allowing for the reconstruction of the environmental conditions not only in the water body itself but also in its shore zones (Alexandrowicz et al. 2021).

Mollusc shells are the subject of palaeolimnological and ecological isotopic studies. Stable carbon and oxygen isotope records in lacustrine carbonates (bulk sediments and shells) are commonly used to reconstruct environmental and climate changes during the Quaternary. The carbon isotope record of mollusc shells is mostly controlled by $\delta^{13}C_{DIC}$ values of the ambient water, the isotope composition of the groundwater, the residence time in the lake, organic matter decay, the fractionation of carbon isotopes by molluscs, and the organic carbon composition of food (Buchardt and Fritz 1980; McConnaughey et al. 1997; Leng and Marshall 2004; McConnaughey and Gillikin 2008).

Stable oxygen isotope values in freshwater mollusc shells are important proxies for palaeoclimatic and palaeoenvironmental reconstructions, as the shells precipitate in isotopic equilibrium with the lake water and avoid contamination by allochthonous carbonate (e.g., Fritz and Poplawski 1974; Hammarlund and Buchardt 1996; Leng et al. 1999). The composition of stable oxygen isotopes in mollusc shells is mainly controlled by $\delta^{18}O$ values of the host water and the water temperature (Coletta et al. 2001; Leng and Lewis 2016). $\delta^{18}O$ values record the isotope composition of the host water, often reflecting the precipitation/evaporation ratio and/or groundwater inflow (Fritz and Poplawski 1974; Buchardt and Fritz 1980; Hammarlund and Buchardt 1996; Leng and Marshall 2004).

Many of these factors are linked to climate conditions, thus the results of investigations of oxygen and carbon isotopes enable the interpretation of past climate (Stuiver 1970). Additionally, combining the isotopic data with malacofauna allows for a more detailed palaeoecological reconstruction for the Eemian Interglacial (Milano et al. 2020; Alexandrowicz et al. 2024). Isotopic investigations of mollusc shells have most often been performed on late glacial and Holocene shell materials (Hammarlund and Buchardt 1996; Apolinarska 2009a, 2009b; Apolinarska and Hammarlund 2009; von Grafenstein et al. 2013). Records for the older Pleistocene interglacials are very rare. Preliminary data come from the Augustovian complex (MIS 21-25) (Nitychoruk 2009) and from the Eemian (Milano et al. 2020; Alexandrowicz et al. 2024), with the most comprehensive results obtained from Holsteinian molluscs in eastern Poland (Nitychoruk 2000; Szymanek et al. 2016; Szymanek 2016, 2017; Milano and Szymanek 2019).

Despite a large number of palynologically recognized Eemian sites in Poland, isotope studies of mollusc faunas are very rare and are usually limited to fragments of depositional sequences. We had the unique opportunity, for the first time in Poland, to conduct isotopic studies on mollusc shells from almost the entire Eemian Interglacial and the beginning of the Vistulian. The main goal of this work was the isotopic ($\delta^{13}C$ and $\delta^{18}O$) characterization of shells of two snails: VP and *Bithynia tentaculata* from the sediments of the interglacial period of the palaeolake in Gorzów Wielkopolski (NW Poland). These sediments were accumulated during various climatic and environmental conditions (Alexandrowicz et al. 2021; Mirosław-Grabowska et al. 2022; Stefaniak et al. 2023; Hrynowiecka et al. 2024), and therefore, we planned to reconstruct the environmental conditions based on the stable isotope data of gastropod shells. We wanted to know (1) how the isotopic composition of the shells of different snail species differed, and (2) how the changing environmental/climatic conditions of the Eemian Interglacial were reflected in the isotopic composition. Finally, our results were compared with data from the Eemian Interglacial from Piła (central Poland) and Neumark-Nord2 (Germany) sites, as well as with the results from other warm periods: Holsteinian (MIS 11) and Holocene (MIS 1). We were interested in (1) whether our results were similar to those obtained from other Eemian sites and (2) whether there were any common trends in isotope curves obtained for different interglacials. Additionally, the isotopic record and ecological preferences of snail species were used in the reconstruction of environmental conditions of the studied lake, especially changes in productivity levels and fluctuations in water level were assessed.

Materials and methods

Materials

The studied palaeolake (52°43′51″N; 15°09′33″E) is located in Gorzów Wielkopolski city, Gorzów Plain, NW Poland (Fig. 1A).The main profile, GS-3, was exposed during the construction of the S-3 express road in 2005–2006 (Fig. 1B). An 11-m-thick sediment sequence, comprising two layers of gyttja separated by peat, fluvial sands, and silts, reflects the multi-phase development of the palaeolake. Notably,

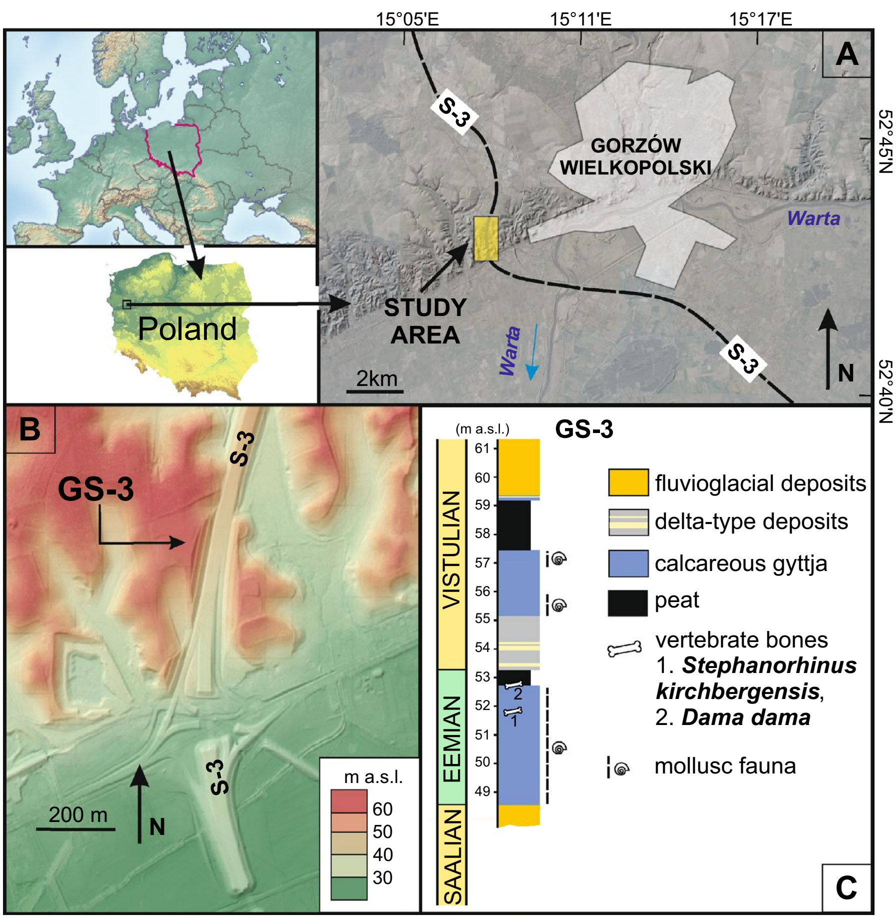

Fig. 1 Site of the Eemian and Vistulian lake deposits near Gorzów Wielkopolski. **A**. General location; **B**. Detailed location (digital map; base: www. polska.e-mapa.net); **C**. Lithological profile (after: Badura et al. 2017; Sobczyk et al. 2020; Stefaniak et al. 2023, simplified)

a nearly complete skeleton of *Stephanorhinus kirchbergensis*, including a skull with 24 well-preserved teeth, was discovered in the lower part of the palaeolake sediments. In addition to the rhinoceros skeleton, a single metacarpal bone of fallow deer (Dd) was found at the site (Badura et al. 2017). These unique sediments have been subjected to multi-proxy analyses, including geochemical, isotopic, zoological, palynological, and malacological studies (Sobczyk et al. 2020; Alexandrowicz et al. 2021; Mirosław-Grabowska et al. 2022; Stefaniak et al. 2023).

In the studied sequence, Wartanian (Saalian, MIS 6) fluvioglacial sands and gravels are present at the bottom (Fig. 1C). They are overlain by the 3.5 m yellow and greyish calcareous gyttja with increasing $CaCO_3$ content up to 80%. The lower gyttja is covered by dark brown peat, about 0.6 m thick. Silty sands, about 2 m thick, follow the organic deposits. The sequence ends with grey calcareous upper gyttja, containing interlayers of limnic chalk, with a thickness of 2.2 m. Brown peat, around 1.7 m thick, replaces the lake sediments. The profile concludes with Vistulian fluvioglacial and glacial deposits (Fig. 1C; Badura et al. 2017; Sobczyk et al. 2020; Mirosław-Grabowska et al. 2022; Stefaniak et al. 2023).

In this paper, we focus on the presentation of the results of the malacological and isotopic studies of mollusc shells from the lower gyttja (52.5–48.8 m a.s.l.) accumulated in the Early and Middle Eemian Interglacial, and only malacological results of mollusc shells from the upper gyttja (57.4–55.2 m a.s.l.), accumulated in the Vistulian (Sobczyk et al. 2020; Alexandrowicz et al. 2021; Mirosław-Grabowska et al. 2022; Stefaniak et al. 2023).

Malacological analysis

The analysis was based on material obtained from twenty-five samples derived from two layers of calcareous gyttja. The research used standard methods of sampling and laboratory processing of shell material as described by Alexandrowicz and Alexandrowicz (2011). Taxa were identified using keys (Welter-Schultes 2012; Piechocki and Wawrzyniak-Wydrowska 2016) and a comparative collection (AGH University of Krakow, Poland). Individual species were classified into ecological groups following the scheme described by Alexandrowicz and Alexandrowicz (2011). Four basic ecological groups were distinguished: T—terrestrial species, W_T—species of temporary water bodies, W_P—species of permanent water bodies, W_I—euryecological aquatic species. The percentage shares of individual specimens representing particular ecological groups were used to construct malacological spectra. The diversity of the fauna allowed for the identification of two assemblages, and their succession in the profile formed basis for palaeoenvironmental reconstructions.

Stable carbon and oxygen isotope analyses

A total of 41 subsamples of malacofauna shells from Gorzów Wielkopolski palaeolake were analyzed. The research included the stable carbon and oxygen analysis of shells of two common species of snails, Vp and Bt The subsamples (38) were collected from two locations of the lower (Eemian) gyttja: from the vertical profile and from the immediate vicinity of the skeleton of Sk (52.5–48.8 m a.s.l.) located approximately 15 m from the sampled vertical profile, and from the vertical profile of the upper (Vistulian) gyttja (57.4–55.2 m a.s.l.). Malacological analysis was performed for the Vistulian section (Alexandrowicz et al. 2021). Unfortunately, the crustal material from the Vistulian section that could be used for isotopic analyses due to low abundance. As a result, only preliminary isotopic analyses were performed on three samples covering this section of the profiles. The data obtained are, however, very sparse, and their interpretative value is highly uncertain. Therefore, they were not included in this study. The each analyzed subsample consisted of the several shells of V. piscinalis or opercula (analyzed separately) of B. tentaculata (Alexandrowicz et al. 2021). The multi-shell subsamples avoided the effects of internal isotopic variations within the shell related to seasonal and/or non-environmental factors and allowed obtaining an average isotopic signal for palaeoecological changes of lake sediments from different periods interpreted in the studied palaeolake (Szymanek 2016). A comparison between the mean of multiple individual analyses and the homogenized values showed consistent results for both approaches (Apolinarska 2009a). This approach has been successfully used by many authors (Nitychoruk 2000; Apolinarska 2009a, 2009b; Apolinarska and Hammarlund 2009; Szymanek 2016). The dimensions of shells of *Valvata piscinalis* are a width of a width of 4-5 mm, a height of 3-5 mm, and a thickness of 0.3 mm. Opercula of *Bithynia tentaculata* are oval with dimensions of 2–3 × 3–5 mm. The shells are formed of aragonite, but opercula are made of calcite (Apolinarska 2009a, 2009b; Szymanek 2016). Many authors examined the preservation of mollusc shell aragonite, both accumulated in younger (Holocene) and older (Holsteinian) sediments. They found "typical spectra of aragonite, implying the absence of diagenetically-induced secondary calcite" Milano and Szymanek 2019), and "were exposed to minimal diagenetic alteration and thus are likely to preserve their primary isotopic signatures" (Apolinarska 2009a; Szymanek 2016). Stable isotope analyses were performed using the classical phosphoric acid method (McCrea 1950). The mollusc shells were ground in an agate mortar, and homogenized powder from complete shells or opercula was used. For comparison, an analysis of bulk carbonate of 60 samples from the same sediment horizons of Gorzów Wielkopolski palaeolake was also conducted. The isotopic compositions were measured using a Finnigan MAT Delta + gas spectrometer in the Laboratory for Isotope Dating and Environmental Studies at the Institute of Geological Sciences in Warsaw, Poland. The carbon and oxygen isotopic compositions were presented in standard delta notation ($\delta^{13}C$, $\delta^{18}O$) relative to the V-PDB standard and are shown in the form of $\delta^{18}O$ and $\delta^{13}C$ variation curves. The analytical error was ± 0.05 ‰ for $\delta^{13}C$ values and ± 0.1 ‰ for $\delta^{18}O$ values. The data were obtained and calibrated in the same laboratory, taking into account the differences in the acid fractionation coefficient for calcite and aragonite (Kim et al. 2007).

Results

Malacological data

The malacofauna found in the two layers of calcareous gyttja at the Gorzów Wielkopolski site was relatively limited, both in terms of taxonomic composition and the number of specimens. Twenty-nine species have been identified here, consisting of seven terrestrial taxa, 16 water snails, and six bivalves. A few slug plates were also present. A comprehensive analysis of the fauna and its palaeoenvironmental interpretation is the primary focus of a separate article (Alexandrowicz et al. 2021). For the purposes of this study, we will provide a general overview of mollusc communities. Within the analyzed malacocenoses, two types of molluscan assemblages were distinguished (Fig. 2).

Assemblage A: This fauna is characterized by the presence of terrestrial species, which accounts for up to 30% of the assemblage. Among this group, moisture-loving species such as *Succinea putris* and *Pseudotrichia rubiginosa* are most common, along with less numerous mesophilic snails that prefer humid habitats like *Vertigo angustior* and *Vertigo substriata*. An essential component of this assemblage consists of aquatic molluscs typical of seasonal water bodies, including *Valvata cristata* and *Valvata macrostoma*, with their share usually exceeding 30%. The remaining components of the community are aquatic molluscs typical of permanent reservoirs and aquatic forms with high ecological tolerance, typically comprising 40–50% of the community. The most numerous representatives of these ecological groups are *Valvata piscinalis* and *Bithynia tentaculata* (Fig. 2). Assemblage A likely represents the littoral zone of the lake. It may suggest periods of lowered water levels in the lake. Faunas with similar characteristics have often been described from lake sediments representing the Eemian Interglacial, as well as the end of the Late Vistulian and the Early Holocene (e.g., Alexandrowicz 1999, 2013).

Assemblage B: This is the dominant type of malacocenosis in the discussed sequence and is present in most samples. Terrestrial species make up a marginal component, usually not exceeding 5% of the community. Species of temporary water bodies are also of limited importance, accounting for a maximum of 20% of the fauna. Molluscs typical of permanent water bodies are a significant component of this community, with their share ranging from 30 to 40%. Notably, *Valvata piscinalis* is highly abundant in some samples. The second dominant component of this assemblage is euryecological aquatic species, constituting up to 45% of the fauna. The most important and abundant representative is *Bithynia tentaculata*, found as both shells and opercula. Their proportions vary in individual samples, but usually, the shells significantly outweigh the opercula (Fig. 2). Assemblage B represents the littoral zone of the lake, likely of shallow depth. It comprises taxa of the shallow, permanently submerged, littoral zone of the lake. The fauna in question can be considered typical of

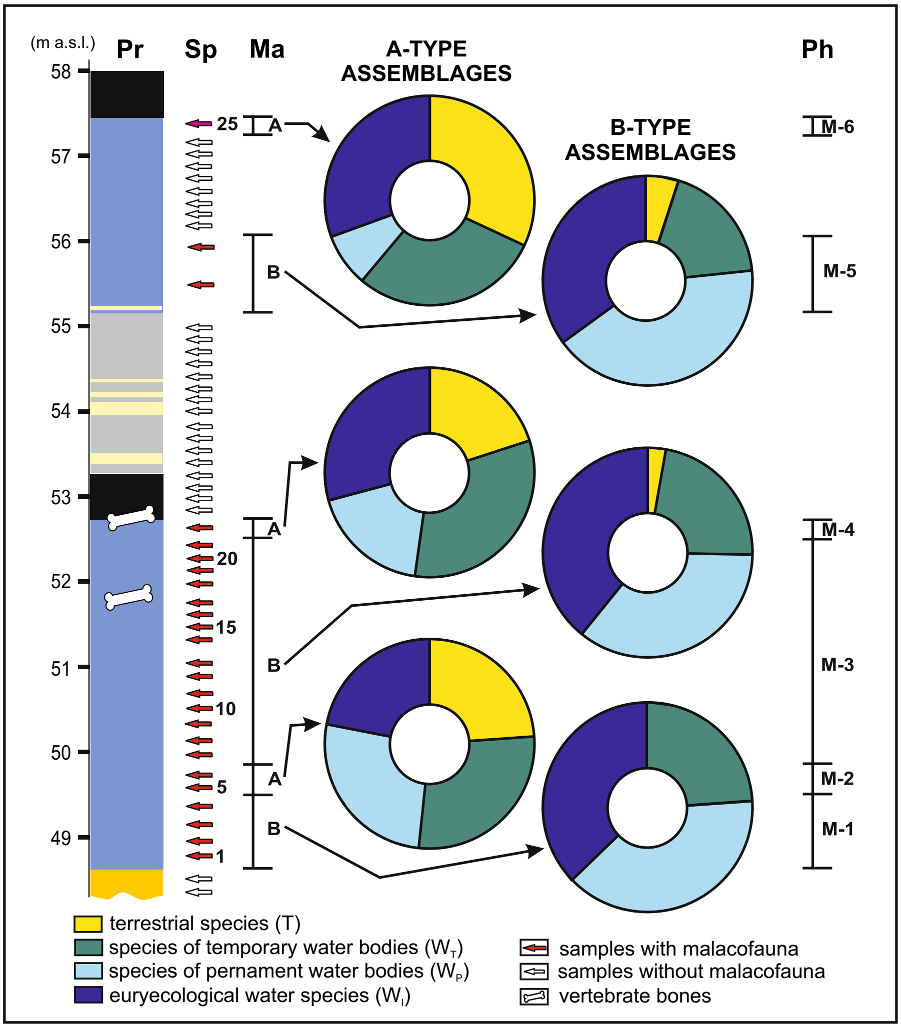

Fig. 2 Malacofauna of the Eemian and Vistulian lake deposits near Gorzów Wielkopolski. Pr—Lithological profile (after: Badura et al. 2017; Sobczyk et al. 2020; Stefaniak et al. 2023; simplified) for explanation see Fig. 1C; Sp—Samples (red arrow—with malacofauna, white arrow—without malacofauna); Ma—Molluscan assemblages (A, B) (described in text, after: Alexandrowicz et al. 2021); Ph—Phases of lake development (after: Alexandrowicz et al. 2021)

palaeolake fillings and has been described in numerous profiles of lake sediments associated with the Pleistocene interglacials: the Holsteinian, the Eemian, as well as the Late Vistulian/Early Holocene (e.g., Alexandrowicz 1999, 2013).

Isotopic data

The isotopic analysis was performed only on the malacofauna shells from the lower (Eemian) layer of calcareous gyttja at the Gorzów Wielkopolski site. The carbon isotope composition of *Bithynia tentaculata* opercula oscillates between −7.1 and −1.8‰, with a mean value of −4.8‰. The oxygen isotope composition varies between −5.4 and −3.8‰. The mean of $\delta^{18}O$ values are −4.7‰ (Fig. 3). For the opercula found in the immediate vicinity of the rhinoceros skeleton (Fig. 4), the carbon and oxygen values are slightly higher, ranging from −4.4 and −4.1‰ (mean $\delta^{13}C$ value of −4.2‰), and from −4.2 to −3.8‰ (mean $\delta^{18}O$ value of -4.0‰).

The carbon isotope composition of *Valvata piscinalis* shells ranges from −8.6 to −5.3‰, with a mean value of −6.7‰. The oxygen isotope composition varies between −6.0 and −4.3‰, with a mean of $\delta^{18}O$ value of −5.5‰. (Fig. 3). For the shells located in the immediate vicinity of the rhinoceros skeleton, the oxygen and carbon isotope values are higher, ranging from -4.5 to −3.1‰ (mean $\delta^{13}C$ value of −3.6‰), and from −5.3 to −3.9‰ (mean $\delta^{18}O$ value of -4.7‰) (Fig. 4).

The isotopic values of shells were compared with isotopic data of carbonate sediments from the same

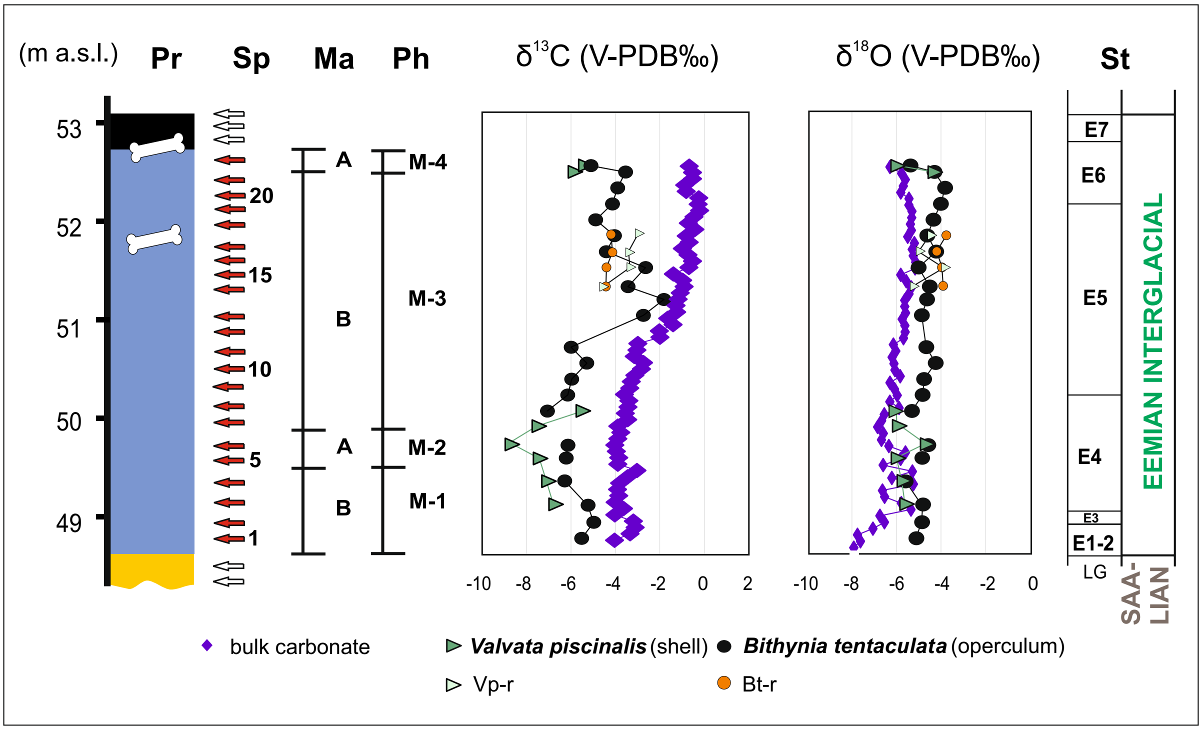

Fig. 3 Differences between $\delta^{13}C$ and $\delta^{18}O$ of *Valvata piscinalis* (shell) and *Bithynia tentaculata* (operculum) from the lake deposits near Gorzów Wielkopolski. Pr—Lithological profile, for explanation see Fig. 1C; Sp—Samples (red arrow—with malacofauna, white arrow—without malacofauna); Ma—Molluscan assemblages (A, B) (described in text, after: Alexandrowicz et al. 2021); Ph—Phases of lake development (after: Alexandrowicz et al. 2021); St –Stratigraphy (after: Mirosław-Grabowska et al. 2022): LG (SAA)—Late Saalian Glaciation; E1-E7—Eemian Regional Pollen Assemblage Zones (after: Mamakowa 1989)

sediment layers (Fig. 3). The carbonate bulk of the lower gyttja is characterized by the carbon isotope values varying from −4.1 to −0.3‰ (mean $\delta^{13}C$ value of −2.4‰), and the oxygen isotope values oscillating between −7.7 and −5.1‰ (mean $\delta^{18}O$ value of −5.8‰, Mirosław-Grabowska et al. 2022). The upper gyttja differs from the lower layer, with $\delta^{13}C$ values ranging from −7.2 to + 12.0‰, and $\delta^{18}O$ values changing from −8.3 to −1.9‰ (Mirosław-Grabowska et al. 2022).

Discussion

Isotopic record of the environmental changes

In the studied profile, malacofauna is not continuously present. Consequently, due to the limited number of shells, the obtained isotopic results are incomplete and provide only a partial picture of the record of environmental changes. The most robust isotopic results came from shells found in the lacustrine lower gyttja, deposited during the Eemian Interglacial.

Early Eemian (pollen zones E1-E3)

In the Gorzów Wielkopolski palaeolake, the *Bithynia tentaculata* opercula (Bt) accumulated during this period exhibited an increase and relatively consistent values of both $\delta^{18}O$ and $\delta^{13}C$, with $\delta^{18}O$ values slightly higher compared to $\delta^{13}C$ values (Fig. 5). The carbonates deposited during this time were notable for their increasing $\delta^{18}O$ values (around −5.3‰) and $\delta^{13}C$ values of about −3.7‰, which are higher than the mollusc data (Fig. 5). The positive trend in $\delta^{18}O$ values likely signify an evaporative lowering of water level in the lake linked to climatic warming, leading to increased

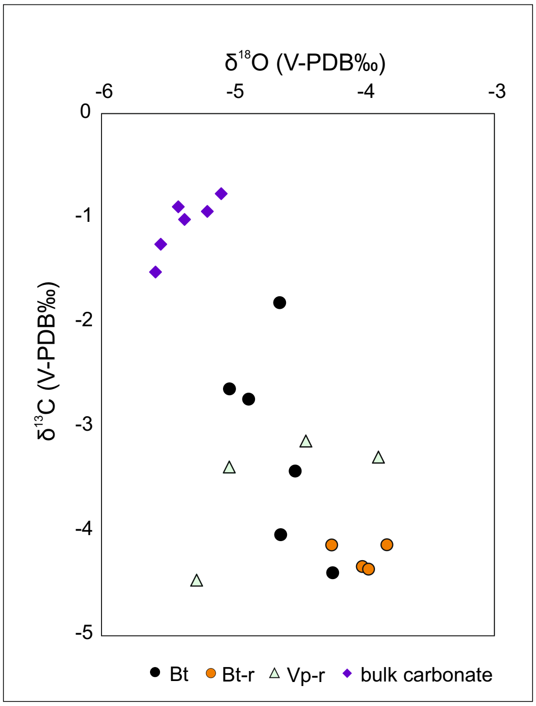

Fig. 4 Results of stable isotope composition of *Valvata piscinalis*, *Bithynia tentaculata*, and bulk carbonate from immediate vicinity of the rhinoceros skeleton. Bt—*Bithynia tentaculata* opercula from sampled vertical profile; Bt-r—*Bithynia tentaculata* shell from vicinity of the rhinoceros skeleton; Vp-r—*Valvata piscinalis* shell from vicinity of the rhinoceros skeleton

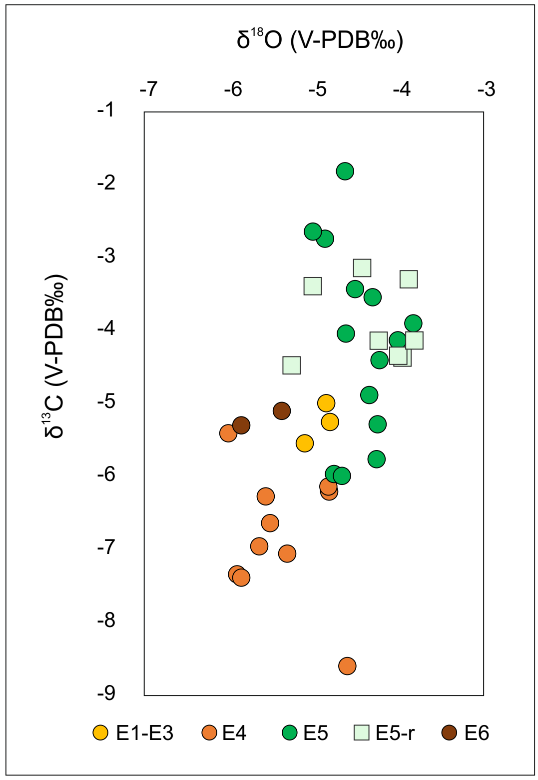

Fig. 5 Plot of $\delta^{13}C$ versus and $\delta^{18}O$ of malacofauna shells from lake deposits near Gorzów Wielkopolski. E1-E6—malacofauna shells from the Eemian Interglacial (E1-E6 Regional Pollen Zones after: Mamakowa 1989); E5-r—malacofauna shells from vicinity of the rhinoceros skeleton

winter and summer temperatures. Similar trends were observed at other sites during pollen zones E1-E3 (Litt et al. 1996; Björck et al. 2000; Boettger et al. 2000; Tzedakis et al. 2003).

Middle Eemian – climate optimum (pollen zone E4)

In the Middle Eemian, the oxygen and carbon isotope values of *Bithynia tentaculata*, *Valvata piscinalis* (vp) and bulks carbonate showed high variability up to 3‰. The initial decrease in $\delta^{18}O$ values might be attributed to a rising water level in the lake, as confirmed by malacological assemblages (the end of M-1 phase in Alexandrowicz et al. 2021). Following this decrease, the oxygen isotope values fluctuated and then stabilized. The high calcium carbonate content in the accumulated gyttja could be indicative of increased production in the lake or stronger evaporation, coinciding with climatic warming (Boettger et al. 2000; Nitychoruk 2000). The initial decrease in $\delta^{13}C$ values for Vp suggests good water oxygenation in the Gorzów Wielkopolski palaeolake, indicated by low Fe/Mn ratios (Sobczyk et al. 2020). The subsequent increase in carbon isotope values was likely linked to the development of macrophytes and phytoplankton during the warm climate, favored by the increased warmth. It may also reflect a higher trophic level (Mirosław-Grabowska et al. 2009).

Middle Eemian – climate optimum (pollen zone E5)

During this period, $\delta^{18}O$ values of Bt remained fairly constant (around −4.5‰), while $\delta^{13}C$ values varied between −4.4 and −1.8‰. Additionally, *Bithynia tentaculata* opercula (Bt-r) and shells of *Valvata piscinalis* (Vp-r) collected from the immediate vicinity of the rhinoceros skeleton were analyzed (Fig. 4). The oxygen and carbon isotope values of Bt-r remained relatively constant, with the $\delta^{18}O$ values approximately 1‰ higher than those of Bt from the studied profile (at a distance of 15 m). Oxygen and carbon isotope values of Vp-r showed greater variability than those of Bt-r, with $\delta^{13}C$ values approximately 1‰ higher than those of Bt-r. The $\delta^{13}C$ data of bulk carbonate are higher than the mollusc compositions in the entire period (up to 3‰), and the $\delta^{18}O$ of bulk carbonate is generally lower than the mollusc $\delta^{18}O$ data in the Eemian gyttja. The constant values of $\delta^{18}O$ in mollusc shells and carbonates suggest stable climatic and hydrological conditions (Mirosław-Grabowska and Niska 2007; Mirosław-Grabowska et al. 2009). The rapid increase and maximum $\delta^{13}C$ values could be associated with an increase in biological activity in the lake, potentially indicating a rise in trophic status. These isotopic data could also suggest a prolonged water retention time or the presence of aquatic plant cover on the water surface, inhibiting water mixing and oxygenation (Mirosław-Grabowska et al. 2009).

Late Eemian (pollen zone E6)

In the Late Eemian, there was an initial trend in Bt opercula showing a slight increase in both isotope values, followed by a decrease of approximately 1.5‰ (Fig. 5). The $\delta^{18}O$ values of Vp shells followed a similar pattern to Bt opercula, but the $\delta^{13}C$ values exhibited a slight increase of about 0.5‰. Meanwhile, the isotopic values of the carbonates accumulated during this period showed lower $\delta^{18}O$ values but significantly higher $\delta^{13}C$ values than the mollusc record (Fig. 5). The decrease of the $\delta^{18}O$ values by about 1–2‰, as well as the drop of the $\delta^{13}C$ values, are evident in both sediment and mollusc fauna of the Gorzów Wielkopolski palaeolake. This shift was likely caused by increased effective precipitation, resulting in the deepening of the lake due to rising water levels, as suggested by other proxies (Mirosław-Grabowska et al. 2022), and possibly accompanied by a period of progressive cooling (Mirosław-Grabowska et al. 2022). The drop in $\delta^{13}C$ values is attributed to a reduction likely in the density of aquatic plants associated with the later cooling of the water (Mirosław-Grabowska 2009; Mirosław-Grabowska et al. 2022).

Vistulian (Weichselian)

From this period, only three samples of *Bithynia tentaculata* shells from the upper gyttja were analysed. The isotopic data obtained are insufficient and their interpretative value is highly uncertain.

Differences in the isotopic record of shells and carbonate sediments

In the Gorzów Wielkopolski palaeolake, we have the opportunity to calculate the differences between the stable isotopic values of the two snail species, and also between the species and bulk carbonates (Fig. 3). The $\delta^{18}O$ values are very similar for both species, which may prove the preservation of the primary isotopic composition of water recorded in the shells. In the $\delta^{13}C$ record, the data range of *Bithynia tentaculata* is larger than that of *Valvata piscinalis*. This difference can be related to the habitat conditions (environmental preferences) of *Bithynia tentaculata*. This taxon is more resistant to changing hydrological conditions, such as drying, compared to the less resistant *Valvata piscinalis*. Generally, the $\delta^{18}O$ values of mollusc shells from the GS-3 profile are higher than those for the bulk carbonate, probably connected with "vital offsets" (von Grafenstein et al. 2000; Leng and Marshall 2004). The lower $\delta^{13}C$ values of mollusc shells than bulk carbonate likely reflect the presence of more CO_2 (with a higher portion of the ^{12}C isotope) associated with the snail respiration process (Fig. 3).

The $\delta^{13}C$ and $\delta^{18}O$ values of the studied shells show a moderate positive correlation with $R = 0.72$ for Vp and $R = 0.68$ for Bt (R—Pearson Correlation Coefficient). Only in the immediate vicinity of rhinoceros skeleton, we observe higher $\delta^{18}O$ values and lower $\delta^{13}C$ values for Bt-r relative to Bt, and lower or comparable $\delta^{18}O$ values and higher $\delta^{13}C$ values for Vp-r relative to Bt-r (Fig. 4). 'The higher $\delta^{18}O$ values of shells occurring in vicinity of rhinoceros skeleton may have resulted from a lower water level, causing lower water exchange/inflow in this part of the lake. The differences in $\delta^{13}C$ are likely due to the presence of decaying organic matter. The decomposition of organic matter may result in the enrichment of water with the ^{12}C isotope due to the release of ^{12}C-enriched carbon (Apolinarska et al. 2015).

We compared the data obtained from the Gorzów Wielkopolski palaeolake with isotope data from other sites of interglacial sediments and malacofauna to determine whether the difference in isotope composition between the two analyzed snail species was also observed in other sequences. It should be noted that each lake basin constitutes a local microenvironment with a separate history. Nevertheless, we sought to identify common trends in the isotopic values. The data obtained from the Gorzów Wielkopolski palaeolake were compared to the Eemian succession in Piła, located about 120 km to the northeast. The isotopic records ($\delta^{13}C$ and $\delta^{18}O$ values) of snail shells from the Gorzów Wielkopolski palaeolake are significantly higher in analogous periods from the end of the E4 to the end of the E6 pollen zones (Alexandrowicz et al. 2024). This difference is evident in the results of both species. It is likely that this phenomenon reflects differences in the depths or water exchange of the two palaeolakes; perhaps the Piła palaeolake was deeper (or experienced faster water change) than the Gorzów Wielkopolski one (based on oxygen data) and had more oxygenated water (based on carbon data). In the Piła palaeolake, we observe significant differences between *Bithynia tentaculata* shells and opercula, and *Valvata piscinalis* in the same samples (Alexandrowicz et al. 2024). The $\delta^{13}C$ and $\delta^{18}O$ values of Bt opercula are higher than the data of shells. The larger differences between *Bithynia tentaculata* shells and opercula are larger for the $\delta^{13}C$ values (up to 4‰) than for the $\delta^{18}O$ values (up to 0.9‰), and the oxygen isotope data are more constant than the carbon isotope data.

Bt from the entire Eemian Interglacial sediments were also analyzed in Germany at the Neumark-Nord 2 site (Milano et al. 2020). There, the $\delta^{18}O$ values range from approximately −3 to 3‰, and $\delta^{13}C$ values between −8 and −3‰ are significantly higher by approximately 2–4‰ than the isotopic data from the Gorzów Wielkopolski palaeolake (Milano et al. 2020). These differences may be due to the location of the studied lake, specifically the distance from the sea ($\delta^{18}O$ values) and different lake conditions such as water retention, trophic state, and the presence of aquatic plants ($\delta^{13}C$ values).

Vp and Bt opercula were also investigated in the Holocene lake sediments, for example, in western Poland (Apolinarska 2009a, 2009b). There, the data obtained for *Valvata piscinalis* ranged from approximately −3.5 to −0.5‰ for $\delta^{18}O$ values, and from −4 to 6‰ for $\delta^{13}C$ values, and were significantly higher than the values for the Eemian shells from Gorzów Wielkopolski. The same was observed for *Bithynia tentaculata*, where the values ranged from approximately −2.5 to 0‰ for $\delta^{18}O$, and from −1 to 6‰ for $\delta^{13}C$ (Apolinarska 2009a, 2009b). In the case of *Bithynia tentaculata*, it must also be taken into account that opercula were examined from the Holocene sediments, and shells from the Eemian sediments. Based on the study of the Piła site, there appears to be a shift between the shell and operculum data). There, the differences between isotope composition determined in *Bithynia tentaculata* shells and opercula are up to 4‰ for $\delta^{13}C$ values, and up to 0.9‰ for $\delta^{18}O$ values (Alexandrowicz et al. 2024). This is due to the mineralogy of these remains: the shells are formed of aragonite, and opercula are made of calcite. The relationship between water temperature and the oxygen isotope composition ($\delta^{18}O$) in water and in calcium carbonate is different for calcite and for aragonite (Craig 1965; Kim and O'Neil 1997; Grossman and Ku 1986).

The obtained isotope data for the Eemian malacofauna were compared with records for older sediments from the Holsteinian Interglacial (Szymanek 2016, 2017; Milano and Szymanek 2019). The isotope analyses of Holsteinian malacofauna included shells of, among others, *Valvata piscinalis* from several sites in eastern Poland (Szymanek 2016). Depending on the site and the palynological zone, $\delta^{18}O$ values ranged from approximately −8.8 to −4.5‰, and $\delta^{13}C$ values were between approximately −12.1 and −5.9‰ (Szymanek 2016), which are comparable to the data from the Eemian deposits.

Lake development in the light of isotopic and malacological data

The malacological data, as described by Alexandrowicz et al. (2021), in conjunction with isotopic data, allowed for distinguishing six phases of lake history (M-1 to M-6) during the Eemian Interglacial and the Vistulian period (Fig. 6). The deposits containing the mollusc shells correspond to two different cycles of lake accumulation, each culminating with peat deposition. The lake's history began during the final phase of the Late Wartanian (Saalian, MIS 6) Glaciation, as

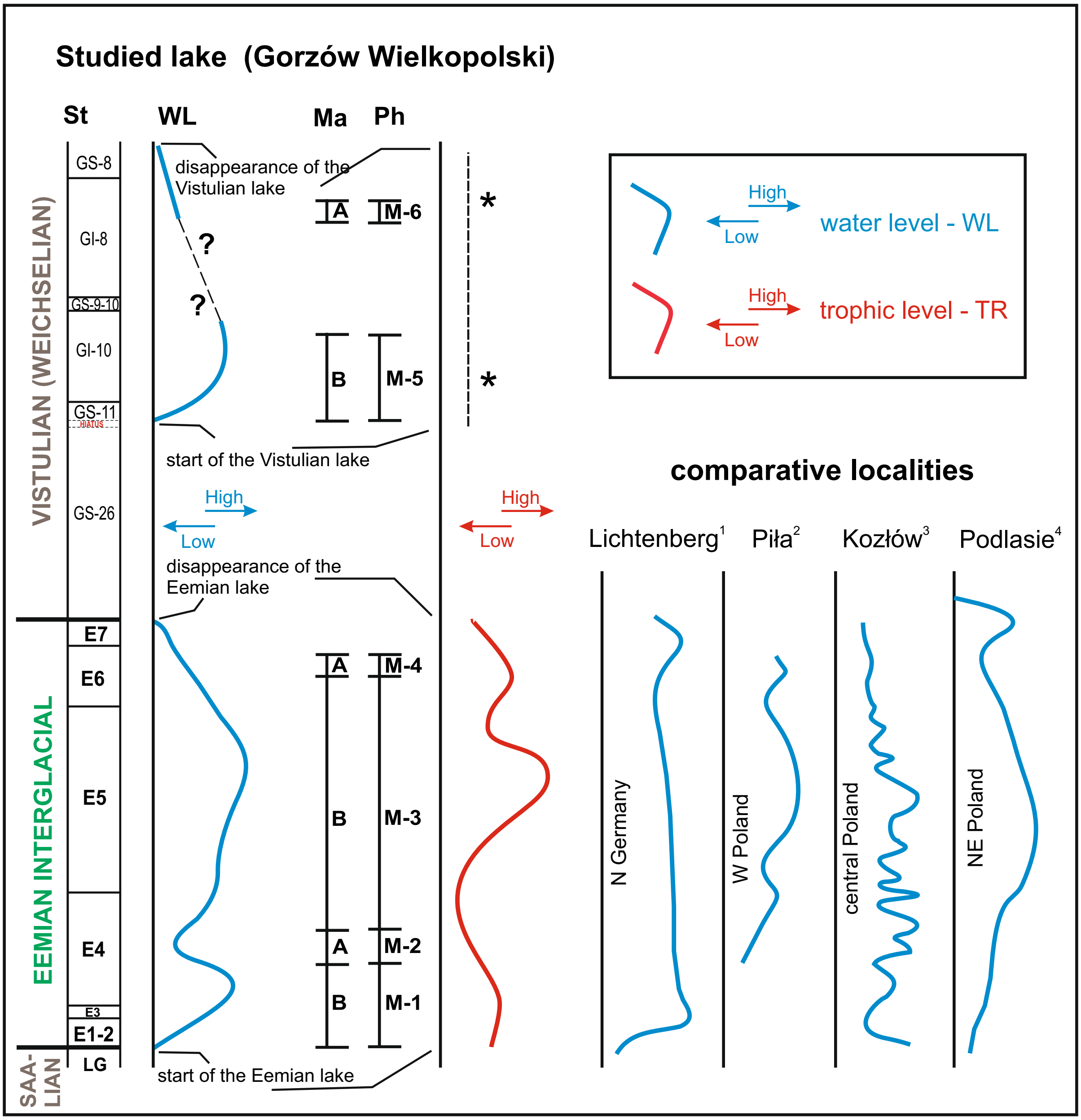

Fig. 6 History of Eemian and Vistulian palaeolakes near Gorzów Wielkopolski. St—Stratigraphy (for explanation see Fig. 3); WL—Water level fluctuations (according to malacological and isotopic data); Ma—Molluscan assemblages (assemblages A and B described in text, after: Alexandrowicz et al. 2021); Ph—Phases of lake development (after: Alexandrowicz et al. 2021); TR—Trophic fluctuations (according to isotopic data); *—only on the malacological data; Comparative localities: 1—Lichtenberg (after: Hein et al. 2021); 2—Piła (after: Alexandrowicz et al. 2024); 3—Kozłów (after: Suchora et al. 2022); 4—Podlasie (after: Kupryjanowicz 2008)

documented by Sobczyk et al. (2020) and Mirosław-Grabowska et al. (2022).

During phase M-1 (Early Eemian, covering pollen zones E1, E2, E3, and the early part of E4), the lake formed, and carbonate gyttja began to accumulate. The malacological fauna suggests the presence of a shallow, nearshore part of the littoral zone with relatively abundant vegetation (assemblage type B). The dominance of taxa intolerant to drying periods indicates the permanence of the water body. An increase in the presence of *Valvata piscinalis* and a decrease in δ^{18}O values may indicate a slight deepening of the lake. This corresponds to a period of climatic amelioration, leading to increased precipitation, suggested by pollen data (Sobczyk et al. 2020; Hrynowiecka et al. 2024). The rise of water level in the lake during the Early Eemian is also supported by analyses conducted in many lake-sediment sites in Poland, Germany, and other European countries, indicating that this trend is likely regional, if not continental (Fig. 6).

In phase M-2 (Middle Eemian, the middle part of pollen zone E4), the lake became shallower. Terrestrial and temporary water body species (assemblage type A) became the dominant malacofauna component. Higher δ^{18}O values suggest a decrease in lake water levels associated with higher temperatures and/or reduced precipitation. However, it is important to note that such fluctuations are not evident in many localities, suggesting that this phenomenon was possibly more local and limited to some areas (Mirosław-Grabowska and Niska 2005; Mirosław-Grabowska and Gąsiorowski 2010; Kultys et al. 2023).

Phase M-3 (Middle Eemian, encompassing the late parts of pollen zones E4, E5, and the early part of E6) represents a period of a permanent water body. At that time malacofauna consisted of aquatic species (assemblage type B) characterizing the littoral zone of the lake. This period saw more diverse mollusc taxa in the lake, with numerous species intolerant to drying, indicating a permanent water body. Constant δ^{18}O values in shells and bulk carbonate suggest stable hydrological conditions. A significant increase in δ^{13}C values is likely a result of the enhanced activity of macrophytes and phytoplankton (Fig. 6). The stability of hydrological and climatic conditions in the middle part of the Eemian Interglacial has been confirmed at numerous sites, with any fluctuations or lowering of water levels likely due to local factors and processes (Fig. 6).

Phase M-4 (Late Eemian, late part of pollen zone E6) is characterized by the termination of lacustrine sedimentation. During this phase, a mollusc community with a significant proportion of species living in temporary water bodies and hygrophilous terrestrial taxa (assemblage type A) appeared. Simultaneously, gyttja was replaced by peat. This phenomenon was recorded in many other lake profiles of the Eemian Interglacial and marks the period of progressive disappearance of Eemian lakelands (Mirosław-Grabowska and Niska 2007; Mirosław-Grabowska 2009; Roman et al. 2021; Kultys et al. 2023).

Following phase M-4, the water level increased, and the lake reappeared, initially as a flow-through lake (Mirosław-Grabowska et al. 2022). During this time, fine-grained sediments such as silty sands and silts without fauna accumulated (as documented by Sobczyk et al. 2020; Alexandrowicz et al. 2021; Stefaniak et al. 2023).

Phase M-5 (Vistulian) indicates a relatively shallow, littoral zone of the lake (assemblage type B).

Phase M-6 (Vistulian) represents an important environmental change. The proportion of terrestrial taxa increased significantly (assemblage type A), clearly indicating the filling of the lake basin with sediments (Fig. 6).

Conclusions

The malacofauna at the Gorzów Wielkopolski site was discovered in two layers of calcareous gyttja, where twenty-nine species were identified, with species, *Valvata piscinalis* and *Bithynia tentaculata* being the most abundant.

Two distinct molluscan assemblages were distinguished: Assemblage A, characterized by a mix of terrestrial and aquatic species, and Assemblage B, dominated by species from permanent water bodies.

The oxygen and carbon isotope compositions of snail shells and opercula were compared with isotopic composition of bulk carbonate from the Eemian gyttja. The increase in δ^{18}O values of shells likely indicates climatic warming, when a rising temperatures and/or a decrease in rainfall resulted in higher evaporation and the relative enrichment of water in the ^{18}O isotope (Milano and Szymanek 2019). The subsequent increase in δ^{13}C values suggests the development of macrophytes and phytoplankton, supported by warm climatic conditions, with the highest values reflecting a higher trophic level.

Significant differences of up to 2‰ in the mean δ^{13}C and 0.8‰ in the δ^{18}O values were observed in the isotope records of *Bithynia tentaculata* aup tond *Valvata piscinalis*. They are partly due to the different mineralogy, i.e. aragonite shells of *Valvata piscinalis* and calcite opercula of *Bithynia tentaculata* (0.95‰ for $\delta^{13}C$ and 0.37‰ for $\delta^{18}O$: values; Lécuyer et al. 2012), and partly are the result of species differences of snails. The $\delta^{18}O$ values of Vp shells were similar to or lower than Bt opercula. In terms of the $\delta^{13}C$ record, *Bithynia tentaculata* exhibited a broader range and often higher values compared to *Valvata piscinalis*. Additionally, the oxygen isotope record of the Eemian molluscs displayed higher values than the carbonates from profile GS-3, with the carbon isotope record showing the opposite trend.

The combined results of malacological and isotopic analyses provide valuable insights into the environmental and hydrological conditions of the Eemian palaeolake in Gorzów Wielkopolski. It is likely that the lake basin formed at the end of the Saalian Glaciation or the beginning of the Eemian Interglacial. During the initial development phase (covering pollen zones E1, E2, E3, and the early part of E4), there was a progressive increase in water level. However, in the middle of the pollen zone E4, a significant shallowing of the lake occurred. The subsequent period, spanning the late parts of pollen zones E4, E5, and the early part of E6, was characterized by high water level and stable hydrological conditions. In the Late Eemian (late part of pollen zone E6), a gradual lowering of water level was observed, ultimately leading to the complete disappearance of the lake at the end of the interglacial period. These patterns of hydrological and environmental changes have been identified in many lake-sediment sites, indicating regional environmental trends and similar lake-development conditions across extensive areas of the European lowlands. The decrease in water level observed in the middle part of pollen zone E4, while rare in other lakes, suggests that it was possibly influenced by local factors. The Vistulian section of the profile has insufficient isotopic data The results of malacological analysis of the Vistulian palaeolake sediments in Gorzów Wielkopolski suggest that initially, it was a permanent lake with a relatively high water level. However, in the uppermost part of the profile, significant shallowing occurred, and the presence of peat overlying the lake sediments indicates the complete disappearance of the lake.

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Data availability The stable isotope data were generated and analysed in the current study. The authors do not have permission to share data.

Declarations

Conflict of interest The authors declare no competing interests.

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