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Isotope record of environmental changes at the Skaliska Basin during the Late Glacial and Holocene

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ABSTRACT. The results of isotopic investigations of the Skaliska Basin sediments are presented. Stable isotope analyses were done for authigenic carbonates from three profiles: W1 – Piotrowo-Ławniki, W2 – Sąkiełу Małe, and W4 – Budzewo. The profiles contain carbonate silts at the bottom, then calcareous detritus gyttja and organic silts and peat at the top. Palynological data indicate that sediment were accumulated in the Skaliska Basin from the final phase of the Younger Dryas to the Subboreal period. The values $\delta^{18}O$ change from ca –9.4 to –4.5‰, and $\delta^{13}C$ values varies from –5.1 to +0.1‰. Such a large range of isotopic data reflects changing conditions in the basin during accumulation of deposits (different water levels, water temperatures, and bioproduction). Based on the results of stable isotope analyses of the carbonates, isotopic zones (Is) were defined and characterized for each profile. The results of isotopic analysis enabled reconstruction of varying environmental conditions connected with lake deepening and/or influx of water enriched in light isotopes, climatic warming, and increase of biological activity.

The Late Glacial deposits are characterized by $\delta^{18}O$ values of ca –6.5–6‰ and $\delta^{13}C$ of ca –1‰. In the transitional time between the Late Glacial and the Holocene, $\delta^{18}O$ systematically falls below –8‰, reflecting a substantial change in the isotopic composition of the lake water, likely caused by to inflow of melt water. During the Preboreal period the $\delta^{18}O$ as well as the $\delta^{13}C$ values systematically decrease and reach minima (–8.4–9.4‰ for $\delta^{18}O$ and ca –3.5–4.7‰ for $\delta^{13}C$). At the beginning of the Boreal period, an increase of ca 2‰ in $\delta^{18}O$ is noted and is associated with climatic warming. During the Atlantic period the varying trends in the $\delta^{18}O$ record are likely connected with changing precipitation/evaporation ratios, causing changes in the isotope composition of the water. The fluctuations of the isotopic values in the upper parts of the successions probably point to shallowing of the lake due to sedimentary infill.

KEYWORDS: stable isotopes, Late Glacial, Holocene, lake environment

INTRODUCTION

The aim of this study was to reconstruct changes in the environment of the Skaliska Basin (north-eastern Poland) based on stable oxygen and carbon isotopes. The investigated sediments accumulated during the Late Pleistocene and Holocene. Several climate fluctuations in that span of time have been observed. Changes in temperature and the amount of precipitation affected the isotopic composition of lake water, recorded in the precipitated carbonates from this period. The results of isotopic study were presented on the background of the vegetation history of this area.

The stable isotope ratios of authigenic carbonates are often used in palaeolimnological studies. The oxygen isotope composition of lacustrine carbonates is controlled by the isotopic composition of the host water and the water temperature at which carbonate precipitation takes place. The oxygen isotope composition of lake water is determined in part by the atmospheric component of the global hydrological cycle (air mass source), and reflects the volume-weighted mean oxygen isotopic composition of catchment precipitation, and the precipitation/evaporation ratio (Craig 1953, Hoefs 1996, Schwalb 2003, Leng et al. 2006).

The carbon isotope composition of authigenic carbonates is determined by the isotopic composition of bicarbonate (HCO_3^-). The ^{13}C content of sediments is influenced mainly by exchange CO_2 between water and the atmosphere, by the volume of incoming groundwater and the influx of dissolved carbonates, by photosynthesis/respiration of aquatic plants and plankton within the lake, and by CO_2 production during the decay of organic matter (Craig 1953, Różański et al. 1998, Leng & Marshall 2004).

Many of these factors are connected with climatic conditions; for example, the volume of lake water is connected with the ratio of precipitation to evaporation. Thus the results of analysing oxygen and carbon isotopes can be used to interpret the past climate (Stuiver 1970) and past environment (Mirosław-Grabowska 2009).

STUDY SITE

The Skaliska Basin is located in the northern part of the Mazury Lake District, ca 10 km nort eastern of Węgorzewo (northern Poland). This basin is situated within a depression at 90–92 m a.s.l. There is a post-lacustrine plain with an area of over 90 km^2 (Fig. 1).

Several cores of the ca 3–10 m thick deposit were drilled in the studied area. The sediments were composed mainly of silts at the bottom, followed by calcareous detritus gyttja, and peat in the upper part. Deposit samples were collected at 5–10 cm intervals and subjected to numerous analyses, including pollen, macroscopic plant remains, isotope, diatom, geochemical and subfossil Cladocera analyses.

METHOD – OXYGEN AND CARBON ISOTOPE ANALYSIS

Stable isotope analyses were done for authigenic carbonates from three profiles: W1 – Piotrowo-Ławniki (68 samples from: 100–460 cm depth), W2 – Sąkiely Małe (36 samples from 91–411 cm depth) and W4 – Budzewo (94 samples from 225–975 cm depth).

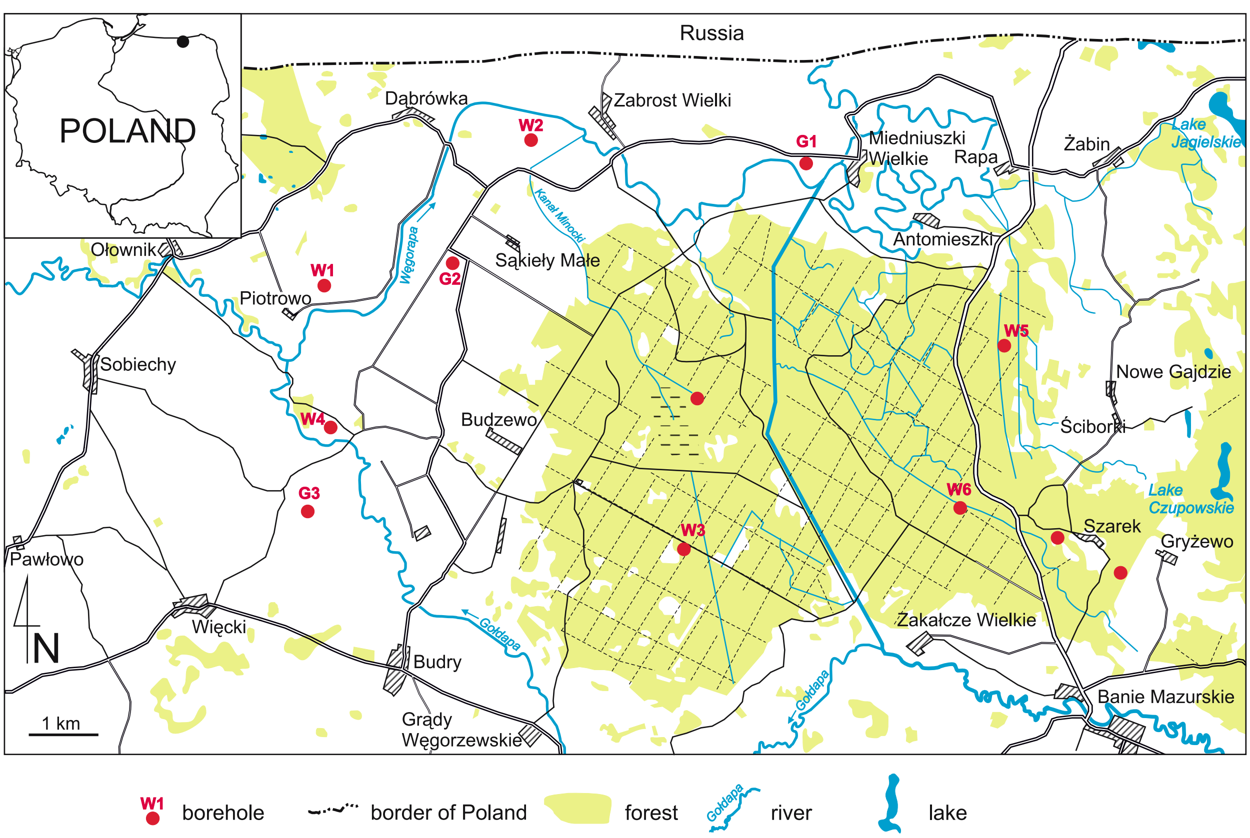


Fig. 1. Location of the studied profiles. W1, W2, W4 – analysed profiles

Stable carbon and oxygen isotope analyses followed the classical phosphoric acid method (McCrea 1950). Isotopic composition was measured with a Finnigan MAT 253 gas spectrometer at the Institute of Geological Sciences in Warsaw. Isotope ratios for carbon and oxygen are presented in standard delta notation ($\delta^{13}C$, $\delta^{18}O$) not by the V-PDB standard. Analytical error was of ±0.05‰ for $\delta^{13}C$ and ±0.1‰ for $\delta^{18}O$.

RESULTS AND INTERPRETATION

W1 PROFILE – PIOTROWO-ŁAWNIKI

Isotope data of the W1 profile

The oxygen isotope ratio varies between –8.4 and –4.5‰, while the carbon isotope ratio varies between –4.2 and +0.1‰. Based on changes in the $\delta^{18}O$ and $\delta^{13}C$ curves, seven isotope zones (Is W1/1–7) were defined and characterized (Fig. 2A).

Zone Is W1/1 (depth 370–450 cm). In this zone the $\delta^{18}O$ as well as $\delta^{13}C$ values decrease. Three subzones (Is W1/1a, Is W1/1b, W1/1c) were distinguish. In subzone Is W1/1a (depth below 450 cm), the lowest deposits are characterized by slight increase of $\delta^{18}O$ values from –6.4 to –5.8‰ and constant $\delta^{13}C$ values of ca –1‰. In subzone Is W1/1b (depth 405–450 cm), the $\delta^{18}O$ values decrease from –6.2 to –7‰ and the $\delta^{13}C$ values gradually drop to –2.2‰. In subzone Is W1/1c (depth 370–405 cm), similar to subzone Is W1/1b, the $\delta^{18}O$ values fall to –8.3‰ and the $\delta^{13}C$ values systematically decrease to –3.5‰. Only at 390–395 cm depth do the isotope values slightly increase by ca 0.5‰ for $\delta^{18}O$ and ca 0.2‰ for $\delta^{13}C$.

Zone Is W1/2 (depth 345–370 cm). In this zone, the $\delta^{18}O$ values rapidly increase to –6.5‰ and $\delta^{13}C$ values up to –2.1‰ are noted.

Zone Is W1/3 (depth 300–345 cm). This zone is characterized by an abrupt drop of $\delta^{18}O$ values and reaches its minimum of ca –8.4‰. The $\delta^{13}C$ values oscillate slightly around ca –2.3‰.

Zone Is W1/4 (depth 230–300 cm). In this zone the $\delta^{18}O$ values fluctuate widely and the $\delta^{13}C$ decline sligtly. Two subzones (Is W1/4a, Is W1/4b) were distinguished. In subzone Is W1/4a (depth 260–300 cm), $\delta^{18}O$ rises rapidly and reaches value ca –4.5‰ (maximum value), $\delta^{13}C$ varies slightly from –2.4 to –2‰, similarly to zone Is W1/3. In subzone Is W1/4b (depth 230–260 cm) the $\delta^{18}O$ values range from –5.8 to –5.2‰, with a slight downtrend; $\delta^{13}C$ decreases again to ca –2.9‰.

Zone Is W1/5 (depth 185–230 cm). In this zone, first the $\delta^{18}O$ values drop to –7.6‰, followed by a two-stage increase to –6.7 and then –5.3‰. The $\delta^{13}C$ values gradually decrease to –4.2‰ and then rise to ca –2.9‰.

Zone Is W1/6 (depth 155–185 cm). In this zone the $\delta^{18}O$ and $\delta^{13}C$ curves differ in trend. Gradually the $\delta^{18}O$ values decrease to –6.6‰ but the $\delta^{13}C$ values rise to –0.3‰ and then slightly drop to ca –0.9‰.

Zone Is W1/7 (depth 100–155 cm). Initially the $\delta^{18}O$ values increase to –5.3 and then oscillate around ca –5.6‰. Only at 120–125 cm depth do the oxygen isotope values drop by ca 0.5–1‰. The $\delta^{13}C$ values initially rise to –0.6‰, then fall to –1.5‰, and finally rise again to +0.1‰.

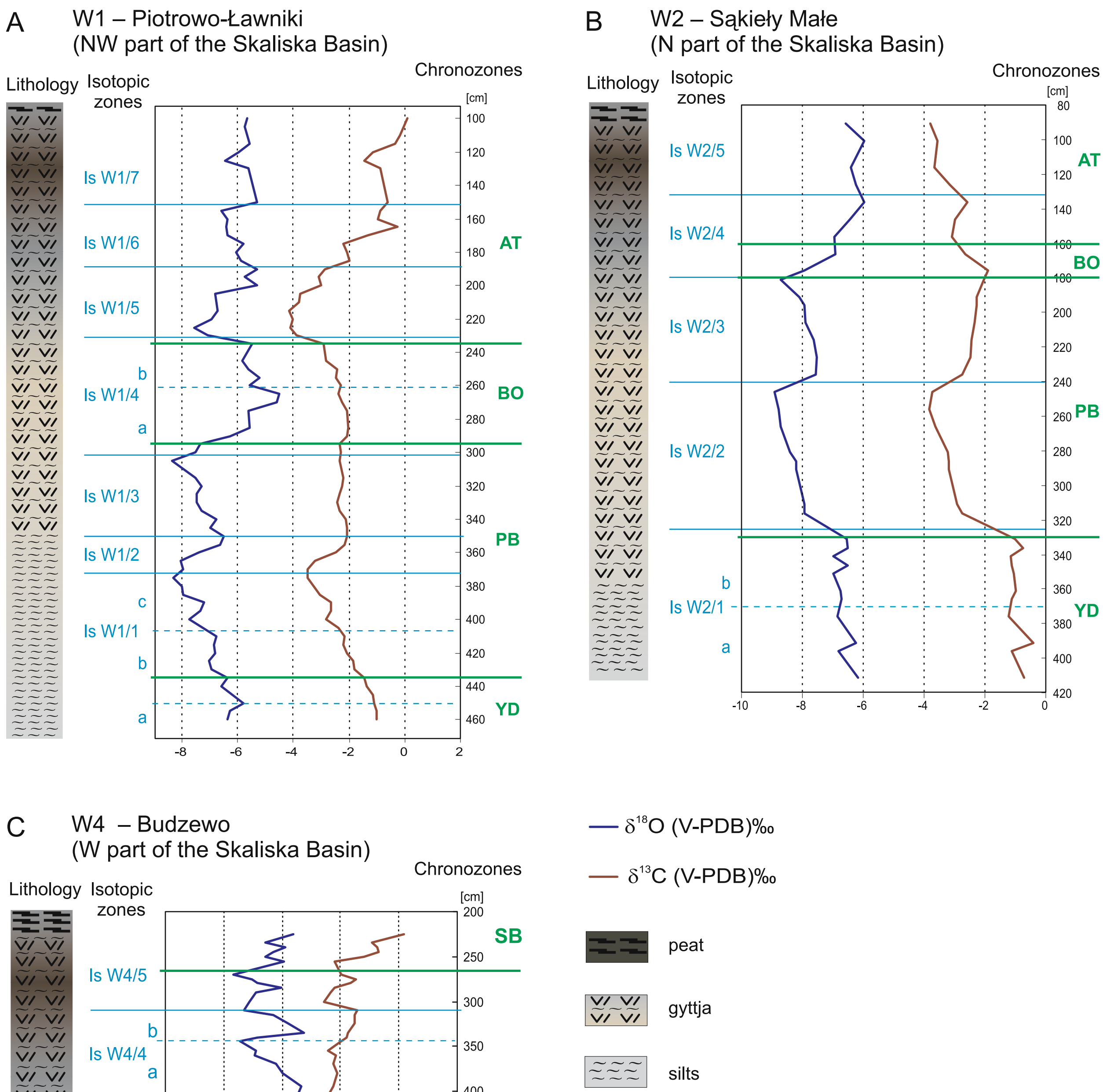
Above 100 cm the absence of carbonates made isotopic analysis impossible.

Interpretation of isotope data from the W1 profile

The W1 profile (Piotrowo-Ławniki) is located in the north-western part of the Skaliska Basin. The lowest sediments were deposited near the end of the Younger Dryas (Kołaczek et al. 2013). Light grey carbonate gyttja accumulated during this period. Those sediments are characterized by $\delta^{18}O$ values of ca –6.4–5.8‰ and $\delta^{13}C$ values of ca –1‰ (isotopic zone Is W1/1a). These isotopic values might be associated with input of dispersed detrital carbonates from the adjacent areas. The presence of Dinoflagellata cysts and Tertiary spores (Kołaczek et al. 2013) suggests intensive erosion of the lake catchment.

Next, in the Preboreal chronozone (Kołaczek et al. 2013), there is a systematic decrease of ca 1–2‰ in $\delta^{18}O$ as well in $\delta^{13}C$ values (isotope zone Is W1/1b-c). The lowering of the $\delta^{18}O$ values reflects a substantial change in the isotopic composition of the lake water caused by inflow water enriched in light oxygen isotopes. This could be connected with an increase in precipitation and/or inflow of melt water. The low isotopic values and plant composition (Kołaczek et al. 2013) suggest cold climatic conditions.

Following this an increase of ca 2‰ in $\delta^{18}O$ and ca 1.5‰ in $\delta^{13}C$ values (isotope zone Is W1/2). Such a trend may be associated with climate warming (oxygen isotope) and linked



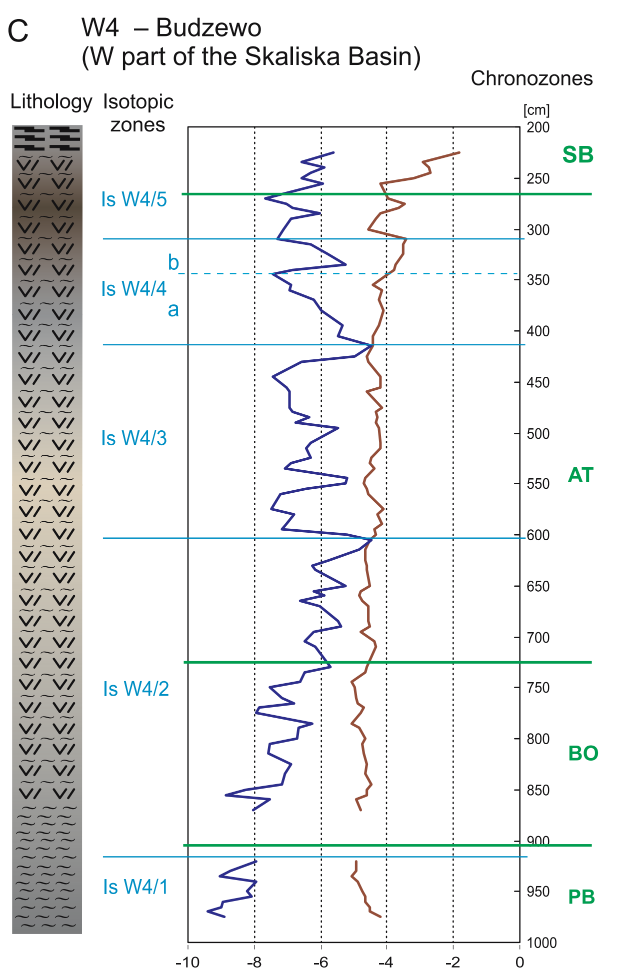


Fig. 2. Isotope curves of $\delta^{18}O$ and $\delta^{13}C$ and isotopic zones from: **A** – the W1 profile (Piotrowo-Ławniki); **B** – the W2 profile (Sąkieły Małe); **C** – the W4 profile (Budzewo)

Chronozones: **SB** – Subboreal period **AT** – Atlantic period, **BO** – Boreal period, **PB** – Preboreal period, **YD** – Younger Dryas (based on Kołaczek et al. 2013) increase in bioproduction (carbon isotope). The improvement of climatic conditions is reflected in the decline of juniper community, the expansion of pioneer birch-pine forest, and a steady increase of pollen concentration (Kołaczek et al. 2013).

In overlying sediments the $\delta^{18}O$ values gradually fall reaching minimum at –8.4‰ (Is W1/3). Palynological data suggests the occurrence of climatic deterioration called Preboreal oscillation (Kołaczek et al. 2013).

From 300 cm depth, $\delta^{18}O$ shifts ca 4‰ to reach the highest values. Such a trend could be due to further climate warming (isotope zone Is W1/4). At that time (Boreal) the occurrence of *Betula* in pine-birch forests is restricted, *Coryllus avellana* rapidly increases, and *Tilia cordata*-type pollen appears, indicating the start of a warmer period (Kołaczek et al. 2013). In these sediments the values of $\delta^{13}C$ (ca –2.3‰) steady, reflecting constant bioproduction (isotope zones Is W1/3-4).

At 230 cm depth (Atlantic period) the $\delta^{18}O$ values decrease by ca 2‰ and $\delta^{13}C$ by ca 1.2‰, perhaps coinciding with an increase of precipitation leading to lake deepening by a rise water level, and/or with an influx of water enriched in light isotopes. The presence of typical limnophytes such as *Nuphar* and *Nymphaea alba* corroborates the expansion of the open water environment as compared to the previous period. High frequency of *Alnus* and the presence of taxa connected with oceanic climate (Kołaczek et al. 2013) support the possibility of increased precipitation. The drop in $\delta^{18}O$ values is followed by an increase up to –5.3‰ and a rise in $\delta^{13}C$ values (isotopic zone Is W1/5). The upward trend of $\delta^{13}C$ suggests an increase of biological activity.

From 185 cm depth the oxygen and carbon curves differ in trend. The $\delta^{18}O$ values fall but the $\delta^{13}C$ values irregularly rise up to –0.3‰ (isotopic zone W1/6). The higher $\delta^{13}C$ values could be due to overgrowing of this lake. This process is confirmed by the increasing frequency of rush vegetation (e.g. *Typha latifolia*, *T. angustifolia* – Kołaczek et al. 2013).

The uppermost carbonate sediments of the W1 profile were accumulated as more detritus and calcareous gyttja. The $\delta^{18}O$ values oscillate between –6.5 and –5.3‰, and the $\delta^{13}C$ values rise from –1.5 to +0.5‰ (isotope zone Is W1/7). They are likely connected with changing water level. At that time the proportion between rush, shoreline and aquatic vegetation fluctuates.

W2 PROFILE – SĄKIEŁY MAŁE

Isotope data of the W2 profile

The oxygen isotope ratio varies between –8.9 and –6‰, while the carbon isotope ratio oscillates between –3.8 and –0.4‰. Based on changes in the $\delta^{18}O$ and $\delta^{13}C$ curves, five isotope zones (Is W2/1–5) were defined and characterized (Fig. 2B).

Zone Is W2/1 (depth below 325 cm). These lowest deposits are characterized by mean values both of $\delta^{18}O$ about –6.7‰ and $\delta^{13}C$, ca –1‰. Two subzones (Is W2/1a, Is W2/1b) were distinguished. In subzone Is W2/1a (depth below 370 cm), $\delta^{18}O$ values decrease from –6.2 to –6.9‰ and $\delta^{13}C$ values gradually drop to –1.2‰. Only at depth of 391 cm the isotope values slightly increase of ca 0.7‰ for $\delta^{18}O$ and ca 0.6‰ for $\delta^{13}C$. In subzone Is W2/1b (depth: 325–370 cm), $\delta^{18}O$ values oscillate around ca –6.7‰ and $\delta^{13}C$ values – around ca –1‰.

Zone Is W2/2 (depth 240–325 cm). In this zone both $\delta^{18}O$ and $\delta^{13}C$ reach their minima of values. $\delta^{18}O$ values drop to –8.9‰. $\delta^{13}C$ values systematically decrease to –3.8‰.

Zone Is W2/3 (depth 180–240 cm). In this zone the $\delta^{18}O$ and $\delta^{13}C$ curves differ from each other in their trends. Both values suddenly increase: $\delta^{18}O$ to –7.5‰ and $\delta^{13}C$ to –2.7‰. Then the $\delta^{18}O$ values systematically fall to ca –8.7‰ but the $\delta^{13}C$ values rise to ca –2‰.

Zone Is W2/4 (depth 130–180 cm). This zone shows a two-stage increase of $\delta^{18}O$ values to –6.9 and then –6‰ (maximum $\delta^{18}O$ values). $\delta^{13}C$ initially drops to ca –3‰ and then slightly increases to ca 0.5‰.

Zone Is W2/5 (depth 91–130 cm). $\delta^{18}O$ values oscillate between –6 and –6.6‰, the $\delta^{13}C$ decreases again to ca –3.8‰.

Above 91 cm the absence of carbonates made isotopic analysis impossible.

Interpretation of isotope data from the W2 profile

The W2 profile (Sąkiełý Małe) is located in the northern part of the Skaliska Basin. The lowest sediments were deposited near the end of the Younger Dryas (Kołaczek et al. 2013). Light grey carbonate silts accumulated during this period. They are characterized by $\delta^{18}O$

values of ca –6.7‰ and $\delta^{13}C$ of ca –1‰ (isotopic zone Is W2/1). These isotopic values might be associated with input of dispersed detrital carbonates from the adjacent areas. Intensification of surface run-off, a consequence of decreased vegetation cover, is indicated by a visible increase in the frequency of Tertiary spores, Dinoflagellata cysts, and degraded sporomorphs in the Sąkieły Małe profile (Kołaczek et al. 2013).

During the Preboreal chronozone (Kołaczek et al. 2013), $\delta^{18}O$ rapidly drops to ca 1.5‰ and then systematically decreases, reaching its minimum at –8.9‰ (isotope zone Is W2/2). The lowering of $\delta^{18}O$ values reflects a substantial change in the isotopic composition of the lake water caused by addition of water enriched in light oxygen isotopes, due to increased precipitation and/or inflow of melt water. This process is confirmed by the absence of rush vegetation and the presence of *Nuphar*, *Myriophyllum spicatum*, and *M. verticillatum*, suggesting extension of the aquatic vegetation environment (Kołaczek et al. 2013). The low isotopic values suggest cold climatic conditions. At that time the trend is similar for $\delta^{13}C$. Initially the $\delta^{13}C$ values fall to –2.7‰ and then decrease further to the minimum of ca –3.8‰. This same event is noted in the W1 profile.

Following this, an increase of more than 2‰ in $\delta^{18}O$ and ca 1‰ in $\delta^{13}C$ values is noted. Such a trend may be associated with climate warming, reflected in, for example, an increase in the frequency of *Corylus avellana* (Kołaczek et al. 2013).

From 236 cm depth, the oxygen and carbon curves differ from their previous trends. The $\delta^{18}O$ values fall to –8.7‰ but the $\delta^{13}C$ values systematically rise to ca –2‰ (isotopic zone W2/3). This record can be linked with the shift from pine-dominated forests in the older part of the Preboreal chronozone to birch-dominated forest in its younger part, suggesting the possibility of Preboreal oscillation (Kołaczek et al. 2013).

A two-stage increase in $\delta^{18}O$ values, reaching maximum (–6‰) occurs in overlying sediments. Such a trend may be due to further climate warming, documented by the development of multispecies deciduous forest with lime, oak and alder (Boreal and early Atlantic – Kołaczek et al. 2013). In these sediments the $\delta^{13}C$ values decrease, followed by a slight increase to ca –2.6‰ (isotope zone Is W2/4). This record may reflect an increase of bioproduction and/or decomposition of organic matter.

Above 136 cm depth (Atlantic and Subboreal – Kołaczek et al. 2013) the $\delta^{18}O$ values fluctuate around the value of ca 0.5‰. $\delta^{13}C$ decreases again to ca –3.8‰ and remains at that level (isotopic zone W2/5). Probably those values are connected with changing water level.

W4 PROFILE – BUDZEWO

Isotope data of the W4 proflie

The oxygen isotope ratio varies between –9.4 and –4.5‰, while the carbon isotope ratio oscillates between –5.1 and –1.8‰, mainly from –4.7 to –4.3‰. Based on changes in the $\delta^{18}O$ and $\delta^{13}C$ curves, five isotope zones (Is W4/1–5) were defined and characterized (Fig. 2C).

Zone Is W4/1 (depth below 920 cm). The lowest deposits (below 955 cm) are characterized by the lowest values of $\delta^{18}O$ from –9.4 to –8.9‰ and slight decrease of $\delta^{13}C$ values, –4.2 to –4.6‰. Then (depth 920–955 cm) the fluctuation of $\delta^{18}O$ values from ca –9–8‰ and a slight drop in $\delta^{13}C$ values to ca –5‰ are still noted.

At depth of 870–920 cm the lack of materials made isotopic analysis impossible.

Zone Is W4/2 (depth 605–860 cm). This zone is characterized by the irregular, multi-stage increases followed by drops in $\delta^{18}O$ values. Generally $\delta^{18}O$ values vary from –8.8 to –4.5‰ (maximum of values). $\delta^{13}C$ values oscillate from –5.1 (minimum of $\delta^{13}C$ values) to –4.4‰ and their slightly upward trend is observed.

Zone Is W4/3 (depth 410–605 cm). $\delta^{18}O$ values rapidly fall and then mainly oscillate from ca –7.4‰ to –6.3‰. At the depths of 545–550 cm, 495 cm and 415–425 cm the strong upward shifts of ca 1–3‰ in $\delta^{18}O$ values occur. The $\delta^{18}O$ values reach a maximum of –4.5‰, the $\delta^{13}C$ values slightly vary from –4.6 to –4.1‰.

Zone Is W4/4 (depth 310–410 cm). Two subzones (Is W4/4a, Is W4/4b) were distinguish. In subzone Is W4/4a (depth 340–410 cm), $\delta^{18}O$ values gradually decrease to –7.4‰, $\delta^{13}C$ shows the opposite trend. These values rise from –4.4 to –4‰. In subzone Is W4/4b (depth 310–340 cm): firstly a significant increase in $\delta^{18}O$ values to –5.2‰, followed by a systematically fall to –7.3‰ is noted, $\delta^{13}C$ values further increase to –3.5‰.

Zone Is W4/5 (depth 225–310 cm). This zone is characterized by irregular increase as well in $\delta^{18}O$ and $\delta^{13}C$. $\delta^{18}O$ values rise to –5.6‰ and $\delta^{13}C$ values go up to –1.8‰. Only at the depth of 270–280 cm the oxygen isotope values drop of ca 1–1.5‰. At depth of 270–255 cm $\delta^{13}C$ values fall ca 0.5–0.7‰.

Above 225 cm the lack of carbonates made isotopic analysis impossible.

Interpretation of isotope data from the W4 profile

The W4 profile (Budzewo) is located in the western part of the Skaliska Basin. There the sediments are thickest, more than 10 m thick. The feature of the W4 profile distinguishing it from the W1 and W2 profiles is the absence of a positive correlation between the $\delta^{18}O$ and $\delta^{13}C$ curves for most of this profile. The $\delta^{18}O$ values vary in a wide range from –9.4 to –4.5‰, while the $\delta^{13}C$ values mainly oscillate between –5 and –4.3‰; only in the uppermost carbonate sediments do they rise from –5.4 to –1.8‰.

The bottom sediments were deposited during the Preboreal chronozone (Kołaczek et al. 2013) as grey carbonate gyttja. They are characterized by minimal $\delta^{18}O$ values of ca –9.4–8‰ and $\delta^{13}C$ values of ca –5‰ (isotopic zone Is W4/1). Such low oxygen isotope values, similar to those of the W1 and W2 profiles, are likely associated with inflow of melt water. The low isotopic values probably also reflect the cool climatic conditions suggested by the palynological record. Pine-dominated forest was replaced by birch-dominated forest (Preboreal oscillation? – Kołaczek et al. 2013) and a domination of small *Fragilaria* spp., pioneer diatom species (Sienkiewicz 2013).

Following this (during the Boreal and early Atlantic chronozone – Kołaczek et al. 2013) there is a systematic but irregular increase of ca 3–4‰ in $\delta^{18}O$, reaching a maximum of ca –4.5‰ (isotope zone Is W4/2). The upward trend in $\delta^{18}O$ values may be associated with climate warming, reflected in the spread of *Tilia cordata* and a gradual increase of *Quercus* (Kołaczek et al. 2013). At that time the planktonic/littoral ratio for Cladocera species reaches maximum and planktonic diatoms increase, reflecting higher water level (Gąsiorowski 2013, Sienkiewicz 2013). In these sediments the $\delta^{13}C$ values slightly oscillate around ca –4.6‰. This record may reflect constant bioproduction.

During the Atlantic chronozone (depth 410–600 cm) the $\delta^{18}O$ values falls irregularly by ca 3‰ (isotope zone Is W4/3). At that time the water level often fluctuated. At depths of 545–550 cm, 495 cm, and 425–415 cm there are three increases in $\delta^{18}O$ (by ca 1.5–2.5‰). At that time benthic cladocerans and diatom taxa increase, suggesting a drop of water level (Gąsiorowski 2013, Sienkiewicz 2013).

Next is a significant drop in $\delta^{18}O$ by ca 3‰, followed by an increase to –5.2‰. The $\delta^{13}C$ values rise systematically to ca 1‰. Such an upward trend may be connected with an increase in bioproduction (isotopic zone Is W4/4).

From 300 cm depth (Subboreal periodthe oxygen and carbon curves continue the previous trends. Initially both $\delta^{18}O$ and $\delta^{13}C$ fall, then irregularly increase (isotopic zone W4/5). The higher $\delta^{18}O$ and $\delta^{13}C$ values may be due to sedimentary infilling and overgrowing of this lake. This scenario is documented by the composition of Cladocera (e.g. *Bosmina longirostris*, *Chydorus sphaericus* – Gąsiorowski 2013) and diatoms (e.g. *Fragilaria* taxa – Sienkiewicz 2013) as well as the increasing frequency of telmatophytes such as *Typha latifolia* and *T. angustifolia* (Kołaczek et al. 2013).

INTERPRETATION OF ISOTOPE DATA ON THE BACKGROUND OF VEGETATION HISTORY

The isotopic data from the three profiles (W1, W2, and W4) enabled to reconstruct the evolution of the Skaliska Basin. The oxygen and carbon isotope records of the W1 and W2 profiles (from the north and north-western parts of this area) are similar. The W4 profile is different and more complicated than the other profiles. The three successions (Fig. 2). contain carbonate sediments accumulated from the late Younger Dryas to the early Subboreal chronozen (Kołaczek et al. 2013).

Sedimentation in this basin began with grey carbonate silts. Then the deposits were replaced by calcareous detritus gyttja and at the top of profiles by peat. The Late Glacial deposits are characterized by $\delta^{18}O$ values of ca –6.5‰ and $\delta^{13}C$ values of ca –1‰ (W1 and W2 profiles). These isotopic values might be associated with input of dispersed detrital carbonates from the adjacent areas. Intensification of surface erosion is also documented by pollen data, as a visible increase in the frequency of Tertiary spores, Dinoflagellata cysts, and degraded sporomorphs (Kołaczek et al. 2013). In the final stage of the Younger Dryas there is a rise or fluctuation in $\delta^{18}O$ values in the north and north-western parts of this basin, likely due rapid shallowing (ice-cover, blocked inflow?). At that time *Sphagnum* dominates and the reservoir is overgrown by macrophytes from *Eupotamogeton* subgenus and *Myriophyllum verticillatum* (Kołaczek et al. 2013).

At the transitional period between the Late Glacial and the Holocene, $\delta^{18}O$ shows a trend towards more negative values (systematic decrease below –8‰ in the W1 and W2 profiles). The lowering of the $\delta^{18}O$ values reflects a substantial change in the isotopic composition of the lake water caused by addition of water enriched in light oxygen isotopes, possibly due to change of precipitation and/or inflow of melt water. The absence of plant having higher thermal requirements suggests cool climatic conditions.

At many European sites the isotopic records show an opposite trend of $\delta^{18}O$ curves, that is, an increase of $\delta^{18}O$ at the beginning of the Holocene, mainly interpreted as the effect of temperature increase (e.g. Różański 1987, Mayer & Schwark 1999, Schwander et al. 2000, Magny et al. 2006, Apolinarska & Hammarlund 2009). In north-eastern Poland, located ca 600 km from the Scandinavian Ice Sheet, this temperature increase had to cause melting and then final decline of stagnant ice, in this way delivering light oxygen isotopes into the reservoirs (rapid decrease in $\delta^{18}O$ values noted in the studied profiles). Additionally, an influx of cold melt water from disintegrating stagnant ice and rapid sedimentation, may have kept lake's organic productivity low and delayed the response of the limnic environment to temperature increase (Wohlfarth et al. 2007).

During the early Holocene (Preboreal chronozone), with the retreat and then decline of the Scandinavian Ice Sheet the anticyclone over the Baltic Sea was blocked and the influence of warm and moist air masses from the North Atlantic increases (Wohlfarth et al. 2007, Yu & Harrison 1995). In northern Poland the influence of Westerlies was expressed in increased temperature and humidity. The istopic record of the Preboreal chronozone is characterized by a further two-step decline, reaching minimum $\delta^{18}O$ values (Fig. 2). First the $\delta^{13}C$ values systematically decrease to a minimum of ca –3–4‰. Following this is an increase in $\delta^{18}O$ to more than 2‰ and to ca 1‰ $\delta^{13}C$. Such a trend could be associated with the climate warming noted in pollen data (oxygen isotope record) and a linked increase in bioproduction (carbon isotope record).

A characteristic feature of the ending of the Preboreal period is a significant drop in $\delta^{18}O$ values (Fig. 2), probably connected with an increase of precipitation and/or a rise of water level (influence of Westerlies?). A larger amount of meteoric water could have caused an increase of water level and relative depletion of heavy isotopes. The low isotopic values probably also reflect the cool climatic conditions suggested by palynological record; pine-dominated was replaced by a birch-prevailing forest (Preboreal oscillation? – Kołaczek et al. 2013) and a domination of small *Fragilaria* spp., pioneer diatom species (Sienkiewicz 2013).

A significant increase in $\delta^{18}O$ values occurred only in the Boreal chronozone as a result of progressive climate warming and a rise of the precipitation/evaporation ratio (Fig. 2). The improvement of edaphic conditions is documented by restriction of the occurrence of *Betula* in pine-birch forests, a rapid rise of hazel, and the appearance of lime and alder (Kołaczek et al. 2013).

The Atlantic period starts with a drop in $\delta^{18}O$ values, possibly indicating higher water level (Fig. 2). Then the frequency of diatoms living in open water increased. The development of planktonic *Cyclotella ocellata*, *C. radiosa*, *Stephanodiscus hantzschii*, *S. minutulus*, and *Cyclostephanos dubius* and the simultaneous decrease of benthic *Fragilaria* spp. indicate higher water level (Sienkiewicz 2013).

During the Atlantic period there are multiple fluctuations in $\delta^{18}O$ values, by ca 2–3‰, possibly coinciding with changes in the precipitation/evaporation ratio leading to changed water levels. $\delta^{18}O$ also reaches its maximal values (Fig. 2). Such a trend could be caused by further climate warming, as reflected in the development of climax woodlands with *Tilia cordata*, *Ulmus*, *Quercus*, *Corylus avellana*, and *Alnus* in damp places (Kołaczek et al. 2013).

During Atlantic period this basin was shallowing. The fall in the water level was also demonstrated in the expansion of *Typha angustifolia* and *T. latifolia* (telmatophytes) as well as in the smaller frequency or lack of *Nyphaea alba* (limnophyte) within the lake (Kołaczek et al. 2013). Sedimentation was a gradual change and carbonate sediments were replaced by more organic gyttja and then by peat. This process occurred earliest in the W1 profile, in the north-western part of the Skaliska Basin.

During early Subboreal chronozone the oxygen and carbon curves followed similar trends. Initially the values of both $\delta^{18}O$ and $\delta^{13}C$ irregularly increase (W2 and W4 profiles) and then fell slightly (W2 profile). The higher values of $\delta^{18}O$ and $\delta^{13}C$ could be due to sedimentary infilling and overgrowing of this basin. This process is documented by incerasing frequency of rush vegetation, the absence of typical aquatic plants (Kołaczek et al. 2013), and the composition of Cladocera (Gąsiorowski 2013), and diatom species (Sienkiewicz 2013).

The oxygen and carbon curves can also be compared for the purpose of examining hydrological relations in the Skaliska Basin. Generally the positive correlation of $\delta^{18}O$ and $\delta^{13}C$ curves suggests that the reservoir is a closed system. Such a system occurred several times in the history of the Skaliska Basin and was recorded in the W1, W2 and W4 profiles (only upper part). During the second half of Preboreal chronozone and in most of the Boreal chronozone the different trends of these curves are observed in the W1 and W2 profiles. This may suggest the opening of hydrolocigal system and/or existing small isolated reservoirs. At that time there may have been changes in inflow and outflow of water. Additionally, the constant (especially in the W4 profile) and still low values of $\delta^{13}C$ throw the most of profiles suggest good oxidation and mixing of the lake water.

CONCLUSIONS

This study analysed the oxygen and carbon isotopes in the carbonate sediments that accumulated from the final phase of the Younger Dryas to the early Subboreal chronozone in the Skaliska Basin.

The boundary between the glaciation and the interglacial period was expressed in a significant decrease in $\delta^{18}O$. This drop reflects a substantial change in the oxygen isotope composition of the lake water, caused by inflow of water enriched in light oxygen isotopes. Probably the lake was deepest at the end of the Boreal chronozone.

The positive trend in $\delta^{18}O$ values confirms gradual warming of the climate, especially at the transition from the Preboreal to Boreal chronozones.

The usually low and constant values of $\delta^{13}C$ suggest good oxidation and mixing of lake water.

The fluctuations of the isotopic curves in the upper part of the profiles point to shallowing of this basin through infilling with sediments.

The negative correlations between the $\delta^{18}O$ and δ13C curves during the second half of the Preboreal chronozone and in most of the Boreal chronozone suggest the opening of this lake system and/or changes in water flow.

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