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Isotopic and Cladocera records of climate changes of Early Eemian at Besiekierz (Central Poland)

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Results of stable isotope, Cladocera and pollen analyses of lacustrine sediments from Besiekierz (Central Poland) are presented. The Besiekierz palaeolake is located about 25 km north of Łódź (Central Poland) at 130 m a.s.l. The 4 m thick deposits comprise silty sands and clayey silts, overlain by calcareous gyttja and organic silts and peat. Pollen analysis documents that these deposits accumulated during the Eemian Interglacial and the Early Vistulian. Based on the results of stable isotope analyses, nine isotopic horizons (Is) were defined and characterized, and these enabled reconstruction of both climatic and hydrological changes. A positive trend in $\delta^{18}O$ values and constant values of $\delta^{13}C$ suggest gradual climatic warming, while constant values of $\delta^{18}O$ and $\delta^{13}C$ indicate stable conditions and/or a fast rate of sedimentation. The fluctuation of isotopic values in the upper part of the succession probably points to a shallowing of the lake due to sedimentary infill. The subfossil cladoceran fauna in the Besiekierz succession is represented by 11 solely littoral species belonging to 3 families. Four zones of Cladocera development were distinguished. The Besiekierz palaeolake was a shallow reservoir. The initial period of its existence probably saw its greatest depth. The Cladocera species present indicate the initial oligotrophic status of the lake and its subsequent increase in trophic status. We compare the results of the isotopic, cladoceran and published palynological analyses, to distinguish and explain the phases of evolution of the lake.

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INTRODUCTION

Numerous localities with lacustrine succession dating from the Eemian Interglacial have been discovered in Poland (Mamakowa, 1988, 1989; Janczyk-Kopikowa, 1991, 1997; Krupiński and Morawski, 1993; Krupiński and Kucharska, 2001; Kupryjanowicz and Drzymulska, 2002; Bińka and Nitychoruk, 2003). The Besiekierz palaeolake succession, located in Central Poland, is one of the first to have been analysed as regards the isotopic composition of carbonate (Mirosław-Grabowska *et al*., 2003).

The stages of vegetation development are documented by the pollen data. The ratio of AP (pollen grains of tree and shrubs) to NAP (pollen grains of dwarf shrubs and terrestrial herbs) and the composition of plant species reflect the successive adjacent environments. The pollen sequence, the order of colonization by different tree species and proportions of these species define the stratigraphy of these deposits.

The lacustrine sediments often contain authigenic carbonates and fossil shells whose carbon and oxygen isotope composition we have measured. 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 took place (Craig, 1953; Hoefs, 1996; Schwalb, 2003). Two major processes may influence on this composition. The first is evaporation, intensification of which causes lake shallowing and enrichment in heavy isotopes (McKenzie and Hollander, 1993). The second process is an influx of fresh water into a lake, which causes its deepening and a relative depletion in heavy isotopes (Talbot, 1990). The oxygen isotope composition of the lake water is determined by the atmospheric component of the global hydrological cycle (Hoefs, 1996; Różański *et al*., 1998). The lake water reflects the mean oxygen isotopic composition of catchment precipitation, which is primarily a function of latitude, modified by orography and continentality (Schwalb, 2003).

The carbon isotope composition of authigenic carbonates is determined by the isotopic composition of bicarbonate

(HCO^{3-}), which is the main form of dissolved inorganic carbon (DIC) in the lake water (Fritz and Poplawski, 1974). The ^{13}C content in sediments is mainly influenced by exchange between CO_2 in water and the atmosphere, by the volume of incoming groundwater and the influx of dissolved carbonates, by plankton photosynthesis and by CO_2 production during the decay of organic matter (Craig, 1953; Różański *et al*., 1998). Each lake is characterized by its own specific concentration of ^{13}C, depending on the degree of biological activity of aquatic plants in the lake, which is determined by climate (Wachniew and Różański, 1998).

Many of these factors are linked to climate, thus the results of investigations of oxygen and carbon isotopes enable the interpretation of past climate (Stuiver, 1970), while combining palaeobotanical results with isotope data enables a more detailed palaeoclimate reconstruction for the Eemian Interglacial (Litt *et al*., 1996; Drescher-Schneider and Papesch, 1998).

Cladocera remains (chitinous carapaces) are often found in lacustrine sediments. Cladocera are representatives of primitive crustaceans, dominant among zooplankton and inhabiting lakes with various chemical conditions. The presence and frequency of certain species reflect the climatic as well as hydrological conditions of the lake. Fluctuations in pH correlate with faunal diversity. The fauna also responds to changes in water nutrient concentrations.

Palaeolimnological studies of Cladocera have been conducted since early 1960's. In Poland, studies of subfossil Cladocera were initiated by Czeczuga, Kossacka (Czeczuga *et al*., 1970; Czeczuga and Kossacka, 1977) and Mikulski (1978). Their investigations concerned only Holocene and Late Glacial sediments. The first investigations of Cladocera from Eemian deposits were conducted by Frey (1962).

Subfossil Cladocera analyses have enabled reconstruction of changes in the water level of lakes, because the ratio of planktonic to littoral forms reflects the changes in the littoral to open water habitat area (Alhonen, 1970; Korhola *et al*., 2000; Szeroczyńska and Gąsiorowski, 2002). Cladocera analysis has been used also to estimate the trophic status and the human impact on lakes (Alhonen, 1986; Goslar *et al*., 1999; Szeroczyńska, 2002). Our comparison of the isotopic, faunal and pollen data from Besiekierz helps to reconstruct the climatic and palaeoenvironmental changes that occurred during the Early Eemian in Central Poland.

MATERIAL AND METHODS

The Besiekierz palaeolake is located about 25 km north of Łódź (Central Poland) at 130 m a.s.l. (Klatkowa, 1972; Fig. 1). The 4 m thick sediments have been investigated by Janczyk-Kopikowa (1991). The lowest part (depth: 6.20–5.80 m) is represented by silty sand and clayey silt, containing low amounts of $CaCO_3$ (below 10%). Then (depth: 5.80–3.60 m) brown and grey calcareous gyttja (25–87% of $CaCO_3$) appears (Fig. 2). The upper part (depth: 3.60–2.20 m) of this succession contains organic silts and peat.

The carbon and oxygen isotope composition was estimated for the sediments from the depth interval 3.60–6.10 m. Stable

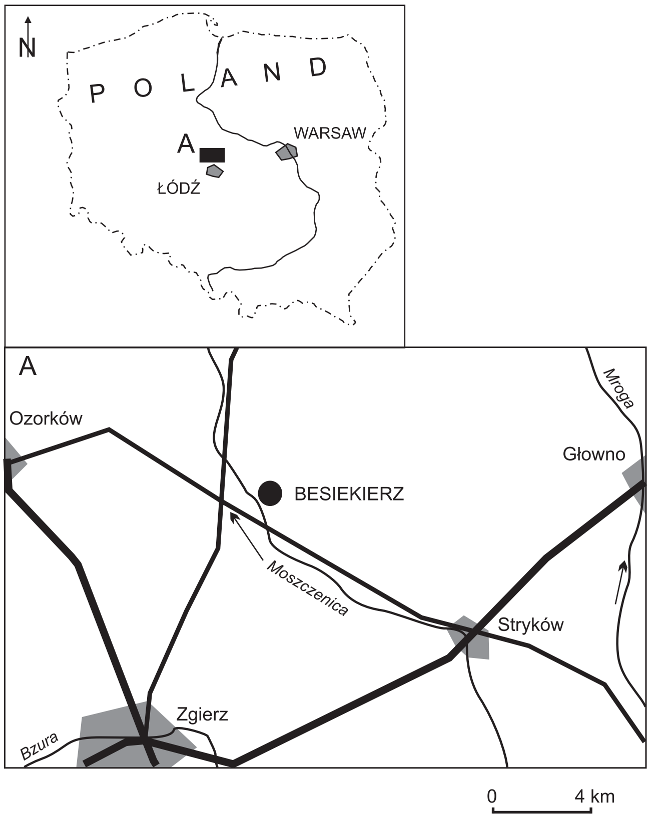

Fig. 1. Location of the Besiekierz palaeolake studied

isotope carbon and oxygen analyses were carried out on 53 sediment samples containing carbonates, using the standard phosphoric acid method (McCrea, 1950). The isotopic composition was measured with a *Finnigan MAT Delta +* gas spectrometer at the Institute of Geological Sciences, Polish Academy of Sciences, in Warsaw. The concentration of ^{13}C and ^{18}O isotopes in the samples analysed are presented as $^{13}C/^{12}C$ and $^{18}O/^{16}O$ isotope ratios *versus* the V-PDB standard (Fig. 2). The analytical error is ±0.05‰ for $\delta^{13}C$ and ±0.1‰ for $\delta^{18}O$.

The Cladocera analysis was carried out on 40 samples from the depth interval 3.51–5.90 m. The samples of 1.5 g were prepared according to the standard procedure (Frey, 1986). After removal of carbonates using HCl, each sample was heated in 10% KOH for 20 minutes. After washing with distilled water, the residue was sieved through 50 μm mesh size sieve. The fine material left on the sieve was transferred into a polycarbonate test-tube. Before counting, the remains were coloured with safranine. A minimum of 200 remains of Cladocera (3–5 slides) were examined from each sample. Identification of cladoceran species was based on Frey (1962). The results of quantitative and qualitative analyses are show on the concentration diagram (Fig. 3) and the total number of Cladocera specimens for 1.5 g of sediment are given in Figure 4.

Pollen analysis was carried out on 79 samples from the 2.20–6.00 m interval of the Besiekierz core using the standard method (Janczyk-Kopikowa, 1991). From the palynological results, local pollen assemblage zones (L PAZ) were distinguished and then correlated with regional pollen assemblage zones (R PAZ). The pollen analysis results were published by Janczyk-Kopikowa (1991).

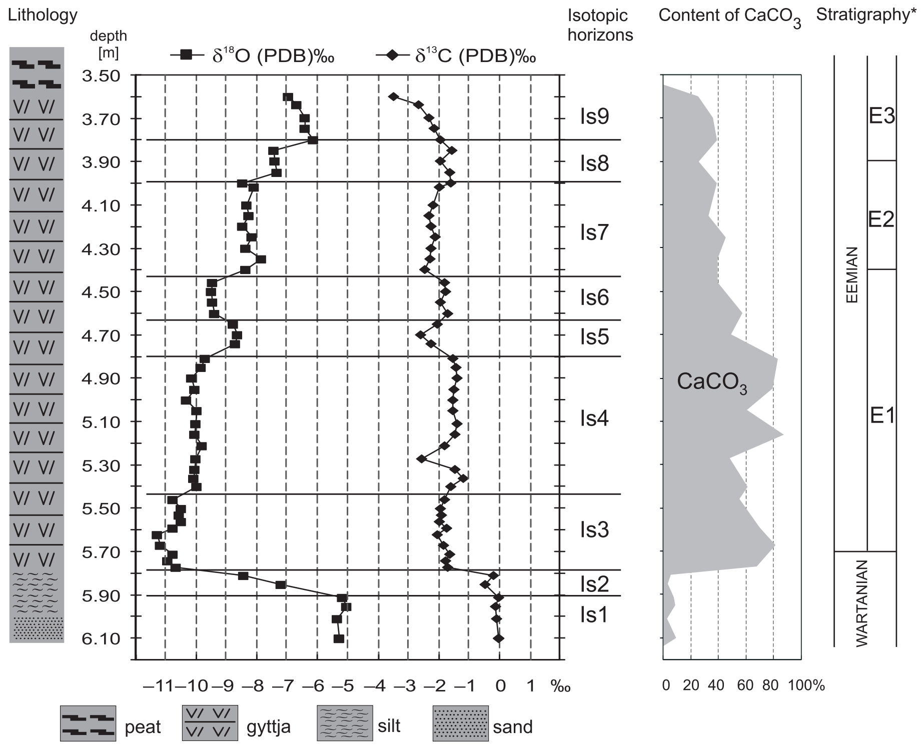

Fig. 2. Lithology, stable oxygen and carbon isotopes, $CaCO_3$ and stratigraphy of the Besiekierz section (isotope curves of $\delta^{18}O$ and $\delta^{13}C$ values and $CaCO_3$ content); * stratigraphy based on palynological data

RESULTS

ISOTOPE ANALYSIS

From the results of stable isotope analyses, nine isotope horizons (Is) were defined and characterized (Fig. 2).

Horizon Is 1: depth below 5.90 m. This isotope horizon is characterized by the highest values of $\delta^{18}O$ *ca*. –5‰ and $\delta^{13}C$ *ca*. 0‰. The highest $\delta^{18}O$ values may be associated with the presence of dispersed allochthonous carbonates from the underlying morainic till. The $CaCO_3$ content of these sediments, mainly silts, is low, below 10%.

Horizon Is 2: depth 5.90–5.80 m. In this horizon the $\delta^{13}C$ values are similar to the $\delta^{13}C$ values of horizon Is1 (*ca*. 0‰). The $\delta^{18}O$ values systematically decrease to –10.5‰, caused by a change in the isotopic composition of the lake water, associated with inflow of water enriched in the lighter isotope ^{16}O.

Horizon Is 3: depth 5.80–5.45 m. In this horizon small fluctuations in $\delta^{18}O$ values from –10.5 to –11.3‰ were noted. It includes a minimum in $\delta^{18}O$ values for the entire succession. The $\delta^{13}C$ values decrease to –2‰. There is a change in lithology, the low-carbonate silts being replaced by authigenic calcareous gyttja (*ca*. 70% $CaCO_3$).

Horizon Is 4: depth 5.45–4.80 m. This horizon is characterized by constant values of $\delta^{18}O$ *ca*. –10‰ and $\delta^{13}C$ *ca*. –1.5‰. Only at a depth of 5.27 m, $\delta^{13}C$ values decrease to –2.5‰. These generally constant isotopic values indicate stable climatic and hydrological conditions and/or a fast rate of sedimentation.

Horizon Is 5: depth 4.80–4.62 m. In this horizon the $\delta^{18}O$ values increase up to –8.5‰ and a drop in $\delta^{13}C$ values to –2.5‰ takes place. Such a trend is associated with climatic warming or/and lake shallowing and a supply of organic matter into the lake. The content of $CaCO_3$ decreases to *ca*. 40% (Fig. 2).

Horizon Is 6: depth 4.62–4.43 m. This horizon is characterized by a 1‰ decrease in $\delta^{18}O$ values (–9.5‰) and a rise of *ca*. 0.5‰ in $\delta^{13}C$ values. The deflection of in $\delta^{18}O$ values and rise in $\delta^{13}C$ values may have coincided with a small rise in lake level.

Horizon Is 7: depth 4.43–3.98 m. In this horizon the $\delta^{18}O$ values remain between –8.0 and –8.5‰ and the $\delta^{13}C$ values oscillate between –2.0 and –2.5‰. The isotope values reflect stable climatic and hydrological conditions and a slight warming.

Horizon Is 8: depth 3.98–3.60 m. The features of this horizon are an increase in $\delta^{18}O$ values to –7.4‰ while the $\delta^{13}C$ values change from –1.5 to –2.0‰. The higher isotope values may have been associated with climate warming and/or lake shallowing.

Horizon Is 9: depth above 3.60 m. At the beginning of this horizon the $\delta^{18}O$ values reach a maximum of –6.1‰ and then they systematically decrease to –7.0‰. The $\delta^{13}C$ values decrease from –2.0 to –3.5‰. The isotope compositions initially reflect lake shallowing and then a deepening or an influx of water enriched in light isotopes.

From depth of 3.60 m onwards there is a lithologicaly change, the calcareous gyttja being replaced by organic silts and peat.

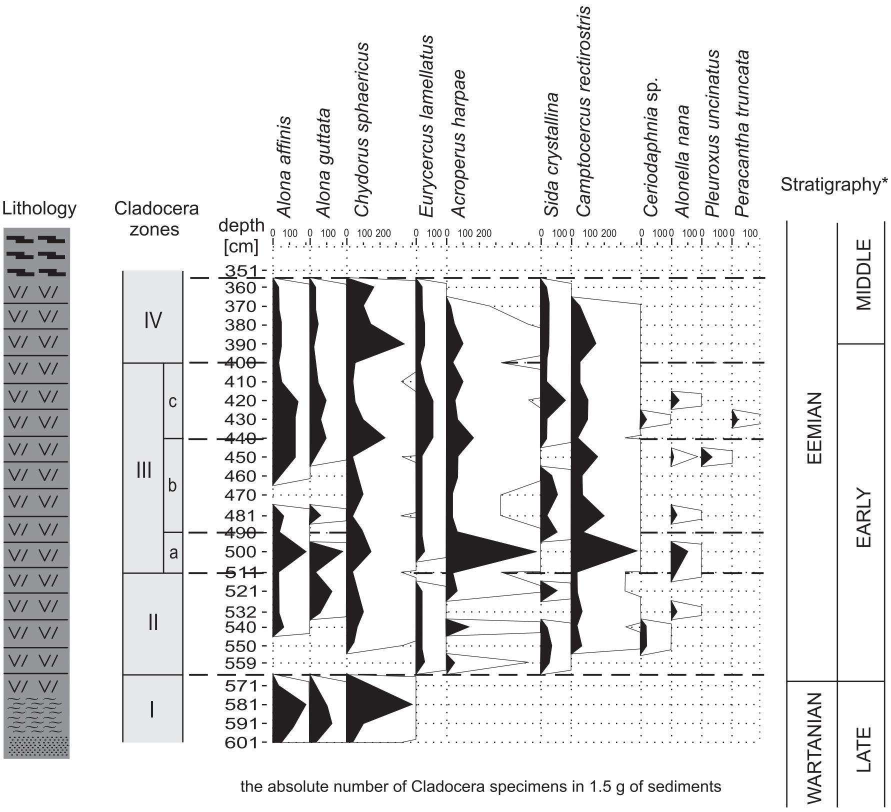

Fig. 3. Concentration diagram of Cladocera in the Besiekierz section

Other explanations as on Figure 2

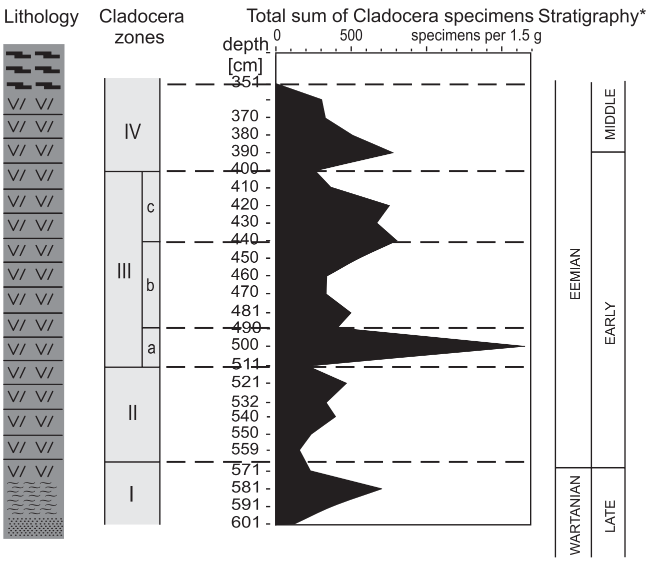

Fig. 4. Diagram of total number of Cladocera specimens in the Besiekierz section

Other explanations as on Figure 2

CLADOCERA ANALYSIS

The subfossil cladoceran fauna of the deposits from Besiekierz is represented by 11 species belonging to 3 families. All are littoral species. Four zones of Cladocera development were distinguished (Figs. 3 and 4):

Zone I: depth 5.90–5.65 m. In this zone a low diversity of Cladocera species was noted, comprising only three initial species: *Alona affinis*, *Chydorus sphaericus* and *A. guttata*. *Ch. sphaericus* is characterized by broad ecological tolerance to major environmental factors (water temperature, amount of nutrients). The presence of *A. guttata* indicates the low trophic status of the lake. *A. affinis* suggests cold water in the lake.

Zone II: depth 5.65–5.11 m. In this zone the diversity of Cladocera species increases. A decrease in the frequency of species of Cladocera tolerating cooler water was noted, while the presence of *Camptocercus rectirostris* indicates warmer water in the lake.

Zone III: depth 5.11–4.00 m. This zone is the period of maximum development of zooplankton. 11 species of Cladocera have been found, and three subzones have been distinguished. Subzone IIIa (5.11–4.90 m) is characterized by the highest frequency and diversity of Cladocera remains and species. Among the Chydoridae, *Acroperus harpae* is dominant. The maximum of *Camptocercus rectirostris* suggests warm climatic conditions. The overall species composition suggests optimal conditions for this group. In subzone IIIb (4.90–4.40 m) a lower frequency of Cladocera remains was observed. The presence of *C. rectirostris* and *Pleuroxus uncinatus* suggests the continuing warm climatic conditions. In subzone IIIc (4.40–4.00 m) an improvement of the hydrological conditions in the lake took place, with most Cladocera species being continuously present.

Zone IV: depth 4.00–3.51 m. In this zone a decrease of the number of Cladocera species and a low frequency of faunal remains was noted. *Camptocercus rectirostris* and *Chydorus sphaericus* dominate. The presence of *C. rectirostris* suggests warm climatic conditions. The sediments of zone IV above 3.60 m are very poor in Cladocera remains. *Ch. sphaericus*, widely tolerant of temperature and trophic status, eventually declines. Above 3.51 m no Cladocera remains were found.

POLLEN ANALYSIS ACCORDING TO JANCZYK-KOPIKOWA (1991)

Results of pollen analysis indicate that the sediments accumulated during the Eemian Interglacial and the Early Vistulian (Janczyk-Kopikowa, 1991).

The lowest part of the succession (below 5.70 m) is characterized by the high values of NAP (above 30%). The spectrum of non-arboreal vegetation may be differentiated into three late-glacial local pollen zones: B1–B3 L PAZ (Janczyk-Kopikowa, 1991).

The sediments above 5.70 m are characterized by forest spectra and represent local pollen zones of the succeeding interglacial: B4–B9 L PAZ (Janczyk-Kopikowa, 1991):

B4 — *Pinus-Betula* (depth: 5.70–4.40 m). *Pinus* and *Betula* are both represented and reach their maxima here. The proportion of NAP changes from 4.4 to 15.0%.

B5 — *Pinus-Betula-Ulmus* (depth: 4.40–3.90 m). *Pinus* and *Betula* pollen are most abundant here, the occurrence of *Ulmus* being constant (up to 3%). NAP values remain below 10%.

B6 — *Quercus-Fraxinus-Ulmus* (depth: 3.90–3.40 m). In this period *Quercus* dominates (max. 56.2%). *Fraxinus* reaches a maximum of 3.2%. *Ulmus* oscillates between 1 to 3.2%. NAP values remain below 5%.

B7 — *Corylus-Quercus-Tilia* (depth: 3.40–3.04 m). A characteristic feature of this zone is the dominance of *Corylus* (max. 36.2%). *Tilia* appears for the first time and reaches a maximum of 25.6% after the culmination of *Corylus*.

B8 — *Picea-Abies-Alnus* (depth: 3.04–3.00 m). In this zone, the absolute maximum of *Picea* occurs (36.2%). The value of *Abies* is 5.8% and of *Alnus* is 13.8%. NAP values reach 2.6%

B9 — *Pinus* (depth: 3.00–2.20 m). This zone is characterized by dominance of *Pinus* (max. 64.8%). The *Betula* pollen value increases gradually from 8.6 to 33.6%. NAP values increase to about 40%.

RECONSTRUCTION OF LAKE EVOLUTION

The comparison of the results of isotopic and Cladocera analyses with the pollen data enables reconstruction of the climatic and environmental changes in the Besiekierz palaeolake (Fig. 5).

The Besiekierz palaeolake was shallow, and its greates depth likely occurred at the beginning of its existence.

The lowest part of the succession was deposited in the final part of the Middle Polish Glaciation (Wartanian). The pollen spectrum from deposits below 5.70 m is typically glacial (B1–B3 L PAZ). High values of Gramineae, Chenopodiaceae and *Artemisia* show the dominance of steppe-tundra type vegetation. The presence of light-demanding dwarf shrubs and shrubs reflects the existence of tundra-type vegetation locally (Janczyk-Kopikowa, 1991).

During this period low-carbonate silts accumulated. They are characterized by highest values of $\delta^{18}O$ (*ca*. –5‰) and $\delta^{13}C$ (*ca*. 0‰), caused by the presence of dispersed allochthonous carbonates (isotopic horizon Is 1).

At that time only three pioneer species of Cladocera, tolerating cool, oligotrophic water, existed in the lake (Cladocera zone I).

According to the pollen studies, the succession above 5.70 m accumulated during an interglacial period. Characteristic features such as the order of expansion of trees including hazel (i.e. *Pinus-Betula, Ulmus*, *Quercus-Fraxinus*, *Corylus*, *Alnus*, *Tilia*) suggests that the pollen succession from Besiekierz correlates with the Eemian Interglacial succession recognized in Poland (Janczyk-Kopikowa, 1991). The local

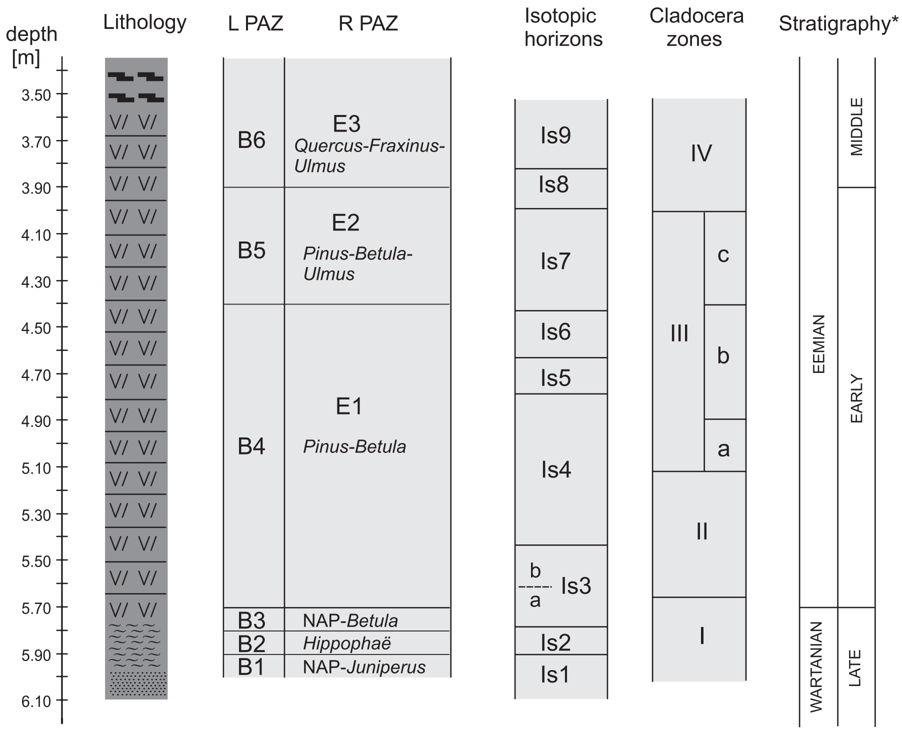

Fig. 5. Correlation of the results of palynological, isotopic and Cladocera analyses in the Besiekierz section

L PAZ — local pollen assemblage zones; R PAZ — regional pollen assemblage zones; other explanations as on Figure 2 pollen assemblage zones (B4–B6 L PAZ) from Besiekierz correspond well to the regional pollen zones of the Eemian (E1–E3 R PAZ), established by Mamakowa (1989; Fig. 5). The beginning of the interglacial period is expressed by a predominance of AP, as the forest communities replaced the vegetation of steppe-tundra type (B4 L PAZ).

The boundary between the glaciation and the interglacial is very clearly reflected in the oxygen isotope curve and expressed by a decrease in δ^{18}O values to –10.5‰ (isotopic horizons Is 2–Is 3). This event appears already at a depth 5.80 m, therefore earlier than the pollen data suggest. It may be that the isotope curves show an earlier and more spontaneous response to climatic fluctuations than do the pollen diagrams (Nitychoruk, 2000). This drop in the δ^{18}O values reflects a substantial change in the isotopic composition of the lake water caused by inflow of water enriched in light oxygen isotopes and/or lake deepening. In addition the low-carbonate silts were replaced by calcareous gyttja. An increased content of $CaCO_3$ can be interpreted as an effect of higher bioproduction in the lake (Nitychoruk, 2000). At the transitional period the increase of precipitation of *ca*. 200 mm/yr has been inferred (Cheddadi *et al*., 1998).

The beginning of the interglacial was expressed by a greater diversity of Cladocera and the occurrence of species indicating warmer water and the increased trophic status of the lake e.g. *Camptocercus rectirostris*, *Chydorus sphaericus* (Cladocera zone II).

In the interval 5.40–4.80 m, the values of δ^{18}O and δ^{13}C are constant (isotopic horizons Is 4). The isotopic data show the stable climatic and hydrological conditions in the lake prevailing at that time and/or a rapid rate of sedimentation. From 5.40 m depth a gradual warming expressed by a positive trend in δ^{18}O values was observed.

The maximum development of cladoceran fauna is recorded at a depth of 5.10 m. The composition of the Cladocera fauna suggests optimal conditions of water level, temperature and nutrient contents. The maximum frequency of *Camptocercus rectirostris* suggests warm climatic conditions (Cladocera subzone IIIa).

At 4.80 m depth an increase in δ^{18}O and a decrease in δ^{13}C values was observed (isotopic horizons Is 5). Climatic warming and/or lake shallowing and the decay of organic matter in the lake may have caused such a trend, which is also reflected in the Cladocera analysis data. A lower frequency of Cladocera remains was noted (Cladocera subzone IIIb). The Cladocera species composition suggests an increased trophic status caused by a short-term shallowing of the lake. The presence of *Camptocercus rectirostris* and *Pleuroxus uncinatus* point to the continued warm climatic conditions.

A small rise in water level reflected a decrease in δ^{18}O values by *ca*. 1‰ and a rise of *ca*. 0.5 ‰ in δ^{13}C values in the interval 4.60–4.40 m (isotopic horizons Is 6). The rise in lake level is documented also by the occurrence of aquatic plants such *Nymphaea* and *Nuphar*.

From 4.40 m depth the pollen spectrum indicates the spread of forest communities (AP values above 90%) with domination by pine and birch (B5 L PAZ). The δ^{18}O and the δ^{13}C values oscillate a little, which reflects stable climatic and hydrological conditions at that time (isotopic horizon Is 7). A continuing presence of most Cladocera species was recorded (Cladocera subzone IIIc). The presence of aquatic plants such *Nymphaea* and *Nuphar* suggest a yet higher water level.

At 4.00 m depth fluctuations of the isotopic curves reaching 2‰ were noted (isotopic horizon Is 8). They may have been caused by shallowing of the lake through infill with sediments, as is also suggested by the presence of rush plants (*Alisma*). Simultaneously a climate warming took place.

In this period a reduction of Cladocera species numbers and diversity took place. The domination by *Camptocercus rectirostris* and *Chydorus sphaericus* confirms the warm climate (Cladocera zone IV).

In the upper part of the succession (above 3.90 m) a development of thermophilous deciduous forest with oak, elm and hazel was noted (B6 L PAZ). The warming of climate is expressed by the appearance of *Hedera helix* and *Viscum album*.

From 3.80 m depth a decrease of *ca*. 1‰ in δ^{18}O and δ^{13}C values is recorded (isotopic horizon Is 9). In this period precipitation probably increased leading to lake deepening by raised water level and/or by influx of groundwater enriched in light isotopes.

A very quick sedimentological change followed: above 3.60 m depth organic silts and peat replaced the calcareous gyttja. The water lever was so low that Cladocera could no longer exist. At that time the shallow lake was completely transformed into a peat bog.

In the deposits above 3.50 m (organic silts, sand, peat) only palynological data are documented. At 3.40 m depth the pollen spectrum (*Corylus*, *Quercus*, *Tilia*) indicates the climatic optimum of the interglacial (B7 L PAZ).

From 3.30 m depth the pollen sequence contains hiatuses, which provide an incomplete history of the vegetation (B8 L PAZ).

Above 3.00 m depth expansion of the pine forest with an admixture of birch was observed, with simultaneous regression of other forest communities. This change in vegetation was a result of climate cooling (B9 L PAZ).

CONCLUSIONS

1. Detailed isotopic, Cladocera and palynological analyses of the lacustrine sediments enable distinction of several phases of lake evolution.

2. According to the palynological data the succession studied comprises carbonate sediments accumulated during the final part of the Middle Polish Glaciation (Wartanian) through to the Middle Eemian intervals.

3. The palynological record initially documents the existence the steppe-tundra type vegetation and then the development of forest communities.

4. The species composition of the cladoceran fauna enabled the reconstruction of the lacustrine environment during the accumulation of these deposits:

— the Besiekierz palaeolake was shallow, containing only littoral species of Cladocera. Probably the greatest depth of this lake occurred during the initial phases of lake history;

— Cladocera species indicate the oligotrophic status of the lake initially and then an increase of trophic status.

5. Results of isotopic analysis enabled the reconstruction both of the climate and of hydrological changes:

— the constant values of $\delta^{18}O$ and $\delta^{13}C$ show stable climatic and hydrological conditions and/or a rapid rate of sedimentation (e.g. in the interval 5.40–4.80 m);

— a positive trend in $\delta^{18}O$ values and constant values of $\delta^{13}C$ in the interval 5.80–3.80 m suggest the gradual warming of climate;

— the fluctuations of the isotopic curves in the upper part of the succession point to a shallowing of the lake through the infilling with sediments.

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