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Paleolimnology of a small oligotrophic lake on Wolin Island, Baltic Sea, Poland

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Abstract

Paleolimnological studies which included analyses of diatoms, fossil pigments and physico-chemical characteristics of bottom sediments have been used to describe the limnological history of Racze Lake. The influx of terrigenous material into the lake have been determined on the basis of stratigraphy of elements associated with mineral content. The successively eroded soils as well as process of chemical erosion caused increase leaching of metals Mg, Fe, Al into the lake basin. However the concentration of these metals finally deposited in bottom sediments was also effected by the oxygen regime at the sediment-water interface. Both ratios, chlorophyll derivatives to total carotenoids (CD:TC) and Fe:Mn indicated hypolimnetic oxygen depletion in the middle part of the profile. The development of blue-green algal population, estimated by the ratio epiphasic to hypophasic carotenoids (EC:HC) was correlated with periods of redox conditions in the lake. The pH changes ranged from 6.5 to 7.7. The most important factors effecting pH changes were inflow of mineral matter from the watershed and structural changes in the littoral biocenosis.

Introduction

The framework of the International Geological Correlation Programme, subproject 158 B includes Wolin Island, on the Baltic Sea coast of Poland. Several suitable sites have been selected to demonstrate the changes that have taken place there. In this study the limnological history of Racze Lake have been reconstructed on the basis of several independent paleolimnological techniques. Geochemical analysis of selected sediments components have provided information about the impact of watershed on lake development and changes in the lake's hypolimnetic oxygen regime. The fossil pigments analysis was used to express lake productivity in the past, and blue-green algal development. The inferred pH was reconstructed using the Renberg & Hellberg (1982) equation.

Study area

Wolin Island has an area of 254 km^2. It is the biggest of 44 Polish sea islands, situated near the mouth of the Odra River. Postglacial moraine hills are present in the central part of the island whereas the west part consists of Przytorska Spit – a long sand marshy peninsula. East part of the Island is of low-land character, marshy in some places. There are 12 lakes on the island, mostly cryptodepressional, which form the Wolin Lakeland.

Lake Racze is the deepest lake on the island, with maximal depth of 12 m. Lake depression is 3.4 m below sea level. The lake is oval in shape (Fig. 1) with even slopes extending toward one deep place in the lake's center. Postglacial bottom sediments are fairly thin – their thickness does not exceed 300 cm. The lake is surrounded by small morainal hills, sloping at a degree of 8–30°. There is no known source of water other then runoff to the lake.

Fig. 1. Racze Lake.

Methods

The main core from the lake's bottom sediments was collected in the middle part of the lake (Fig. 2). The sediment core study profile was 100 cm long. Samples of sediment were taken from the core at 5 cm intervals between 797 and 897 cm. Samples for chemical and diatom analysis were collected from the same layers.

Volume weight of the sediment was determined by weighing 20 cm^3 of the natural sediment at 20 °C. Dry weight and water content were determined after drying the sample at 105 °C to constant weight. Residue after ignition was determined from 2 g samples ashed at 550 °C.

Calcium, iron, magnesium, manganese, and aluminium were determined using an atomic absorption spectrophotometer after sample mineralization with a mixture of concentrated acids: H_2SO_4, $HClO_4$, and HNO_3 (1:2:3, v/v). Total phosphorus was determined colorimetrically with the molybdate method, using $SnCl_2$ as the reducer. Total nitrogen was determined with Kjeldhal's method. Silica was determined from residue on the

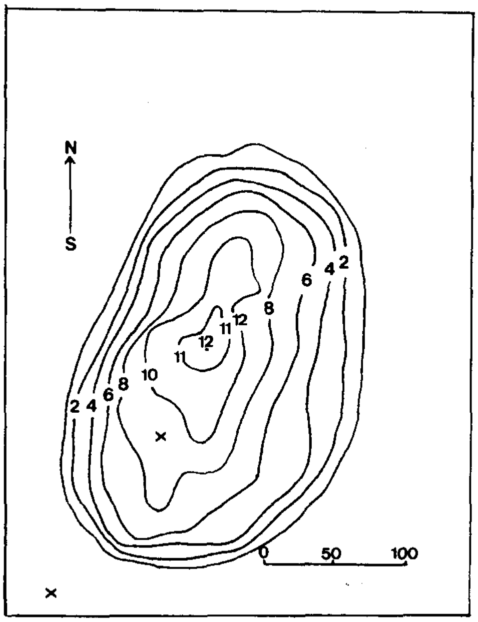

Fig. 2. A morphometric map of Racze Lake. Site where core was taken is also shown.

filter paper, after mineralization. The filter paper were ashed in 1100 °C to constant weight and the results were calculated to SiO_2.

Pigments were determined from 2 g undried samples of sediments with 90% acetone. Chlorophyll derivatives (CD) are measured at 665 nm and total carotenoids (TC) in 430 nm. Both pigments are expressed as absorbance per gram organic matter, where one unit is equal to an absorbance of 1.0 in a 10 cm cell when dissolved in 100 ml of solvent, a specific pigment unit for paleolimnological work (Sanger & Gorham, 1972).

Epiphasic and hypophasic carotenoids were analysed in another subsample by solvent sorption as described by Gorham & Sanger (1967) and Sanger & Gorham (1972).

For diatom analysis 1 cm^3 of fresh sediment were collected. Subsamples were treated with H_2O_2 and mounted in Hyrax. Diatom taxa were determined according to Huber-Pestalozzi (1942), Cleve-Euler (1951–1955), Siemińska (1964), Patrick & Raimer (1966), Schmidt (1972), Komarienko & Wasiljewa (1975) and Kalbe (1980). In most layers 500 diatoms were counted. Only in few cases when diatoms were quite scarce this number was smaller. Specimens were identified and enumerated at 2000 X with Zeiss microscopy. In some cases the identification was studied in scanning electron microscopy Jeol JSM-1 at an accelerating voltage of 10 kV. The pH grouping of diatoms was made according to Cleve-Euler (1951–1955), Fjerdingstad (1954), Nygaard (1956), Patrick & Reimer (1966), Cholnoky (1968), Foged (1977–1979), and Beaver (1981). In controversial cases own study or the majority opinion have mostly been followed. The pH values were based on index B of Renberg & Hellberg (1982),

$$\text{Index B} = \frac{\%\ \text{ind} + 5 \times \%\ \text{acf} + 40 \times \%\ \text{acb}}{\%\ \text{ind} + 3.5 \times \%\ \text{alkf} + 108 \times \%\ \text{alkb}}$$

and equation pH = 6.40 − 0.85 log index B.

Results

Organic matter, siliceous

Organic matter and siliceous materials were the main components of the bottom sediments of Racze Lake. Organic matter was initially high (75%) but from 881 cm it decreased successively (Fig. 3). This was followed by two minor peaks at 862–852 cm and 842–832 cm. A minimum concentration occurred in layer 812–807 cm.

In opposit to these changes, is the siliceous concentration (Fig. 3). The lowest concentration was observed in two bottom layers of our core and from this it rose successively reaching a peak of 84% at 797–802 cm. The changes of these two main components suggest that most of the sediments were deposited as siliceous material and only the three first layers displayed an organic character.

Calcium, magnesium and aluminium

Calcium levels followed those of the organic matter, decreasing from initial layers of the core to the surface (Fig. 4). The concentration of calcium was very low, below 1.3% of dry matter.

Magnesium and aluminium concentration displayed a similar curve as the one described above for siliceous material. The concentration of magnesium was low ranging from 0.35 to 1.33 and aluminium from 1.03 to 6.12% of dry matter. Three minor peaks at 877–872, 852–842 and 827–817 were observed.

Iron and manganese

The lowest part of the core showed low concentration of the iron (Fig. 5). However, from 862 cm

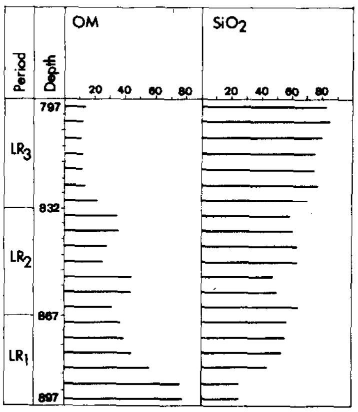

Fig. 3. Percentage of organic matter (OM) and siliceous (SiO_2) (mg g^{-1} dry matter) in bottom sediments of Racze Lake.

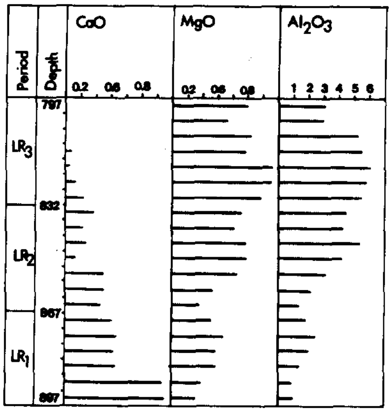

Fig. 4. The concentration of calcium (CaO), magnesium (MgO) and aluminium (Al_2O_3) (mg g^{-1} dry matter) in bottom sediments of Racze Lake.

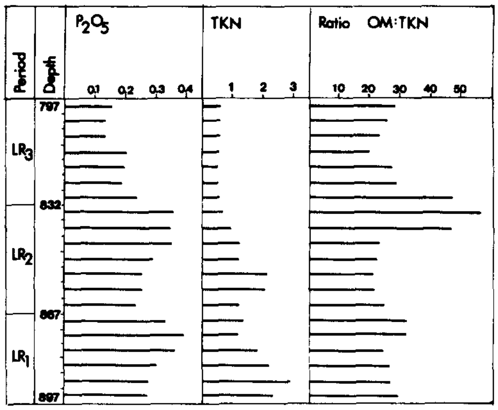

Fig. 6. The concentration of total phosphorus (P_2O_5) and total Kjeldhal nitrogen (TKN) (mg g^{-1} dry matter) and the ratio organic matter (OM) to TKN in bottom sediments of Racze Lake.

values increased regularly to 812 cm reaching this layer the maximum concentration. From here the decrease of iron concentration was observed.

Manganese levels, in contrast to iron, fluctuated little (Fig. 5). The concentration of manganese were 0.11–0.16% dry matter. The Fe:Mn ratio followed the iron profile very closely, reaching the highest concentration in 822–817 cm and the lowest between 882–877 cm.

Phosphorus and nitrogen

Phosphorus levels slowly decreased from the initial to the upper layers (Fig. 6). In this trend three

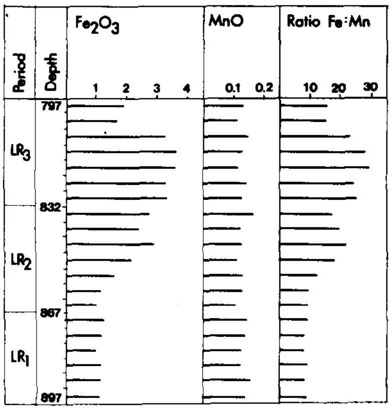

Fig. 5. The concentration of iron (Fe_2O_3), manganese (MnO) (mg g^{-1} dry matter) and the ratio Fe:Mn in bottom sediments from Racze Lake.

minor peaks at 877–822, 847–832, and 822–812 cm were observed. The curve of phosphorus concentration is similar to this observed in organic matter (Fig. 3).

Total Kjeldhal nitrogen (TKN) decreased upwards the core. Two noticeable maxima occurred at 892–887 and 862–852 cm respectively.

Fossil pigments

The concentration of both groups of pigments, chlorophyll derivatives (CD) and total carotenoids (TC) was very low (Fig. 7). Maximum CD and TC levels were found at 897–882 cm corresponding to the highest concentration of organic matter. Chlorophyll derivatives fluctuated very little and the concentration in most layers was 3 SPU gm^{-1} organic matter. One noticeable minima occurred at 862–857 cm. Total carotenoids showed more irregulary fluctuations (Fig. 7). Four characteristic periods of highest concentration was observed.

The curve of CD:TC ratio did not show a clear tendency, however one trend was observed, lowest values of the ratio in the middle part of the core. The values of the ratio changed from 0.27 to 0.53 showing the maximum at 817–812 cm.

Diatom stratigraphy

Diatom fossil flora was represented by 251 taxa. The most abundant genera was *Fragilaria* mainly represented by *Fragilaria pinnata* and its varieties

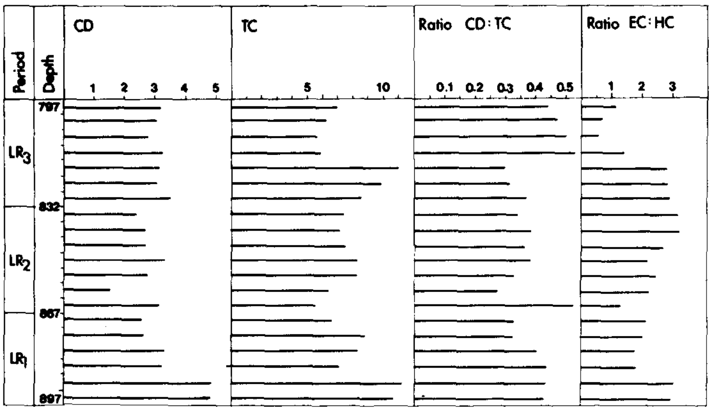

Fig. 7. Chlorophyll derivatives (CD), total carotenoids (TC) (SPU g^{-1} organic matter) and ratios CD:TC and epiphasic (EC) to hypophasic (HC) carotenoids in bottom sediments of Racze Lake.

var *subrotunda* and var *capitata*. High percentage abundance of *Fragilaria* occurred first in the initial layer of the core, however, it decreased quickly reaching a minimum at 882–877 cm. From here, they increased successively to 822–817 cm where the maximum was noticed. Additional, minor peak was also reached at 852–847 cm. From 822–817 cm upwards levels of the percentage abundance gradually declined.

The other subdominant genera such as *Pinnularia, Stauroneis, Navicula, Tabellaria* and *Cyclotella* showed general trend, reaching consequently their maxima (Fig. 8). *Pinnularia* was represented by 31 taxa from which the most abundant were: *Pinnularia interrupta, P. stauroptera* fo. *tenius* and *Pinnularia microstauron*. The genera showed the maximum at 897–892 cm. The peak of these characteristic swamp forms was correlated with initial high abundance of *Fragilaria*.

The following species which reached relatively high abundance belongs to genera *Stauroneis*, mainly represented by *Stauroneis anceps* and its varieties *Stauroneis phoenicentron* and *S. pygmea*. These taxa formed a characteristic peak at 897–877 cm.

Navicula were represented by 32 taxa from which the most abundant was the benthic form *Navicula vulpina*. The wide peak of *Navicula* occurred at the first half of the studied profile. The peak was correlated with a period of less percentage abundance of *Fragilaria*.

Next species which showed a distinct peak

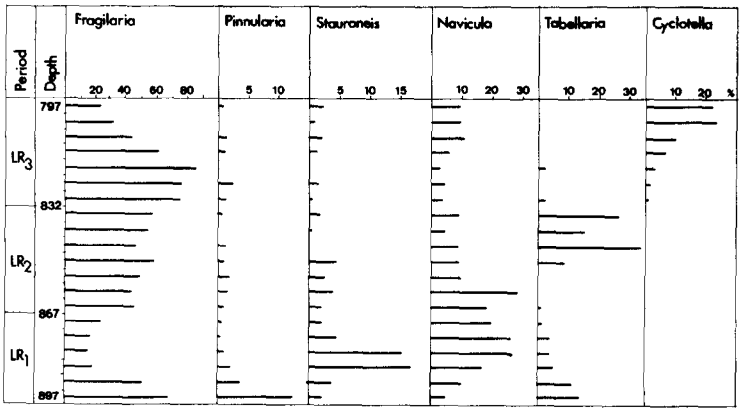

Fig. 8. The stratigraphy of most common and important diatoms genera in Racze Lake sediments.

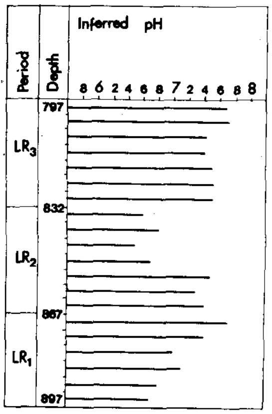

Fig. 9. The inferred water pH of Racze Lake recorded by the stratigraphy of fossil diatom flora.

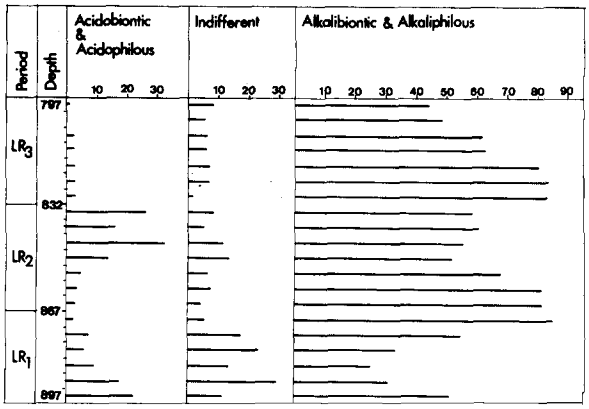

Fig. 10. Diatom composition of Racze Lake according to the water pH requirements.

(Fig. 8) was a planktonic form *Tabellaria flocculosa* var *flocculosa.* The peak occurred at 852–832 cm. From here the successively development of *Cyclotella comta* was observed. This trend was correlated with a decline in *Fragilaria.*

The pH history based on diatom pH spectrum showed that the core can be divided into three characteristic zones (Fig. 9). The first one (897–867) was characterized by increase of inferred pH, resulting in the significant decrease of acidobiontic and acidophilous forms (Fig. 10). The decline was caused by a significant decrease of *Eunotia praerupta* var *minor* fo. *intermedia* and *Tabellaria flocculosa* var *flocculosa* (Fig. 11). The alkaliphilous and alkalibiontic forms were represented mainly by *Navicula vulpina* which attained its maximum abundance. Also *Achnanthes exigua* var *heterovolvata, Melosira italica* and *M. italica* var *subarctica* reached the maximum in this zone.

The second period occurred from 867 to 832 cm. The acidobiontic and acidophilous species were dominant forms in this zone. This group of diatoms was dominated by *Tabellaria flocculosa* var *flocculosa* which attained the maximum abundance. The subdominant form was *Hantzschia am-*

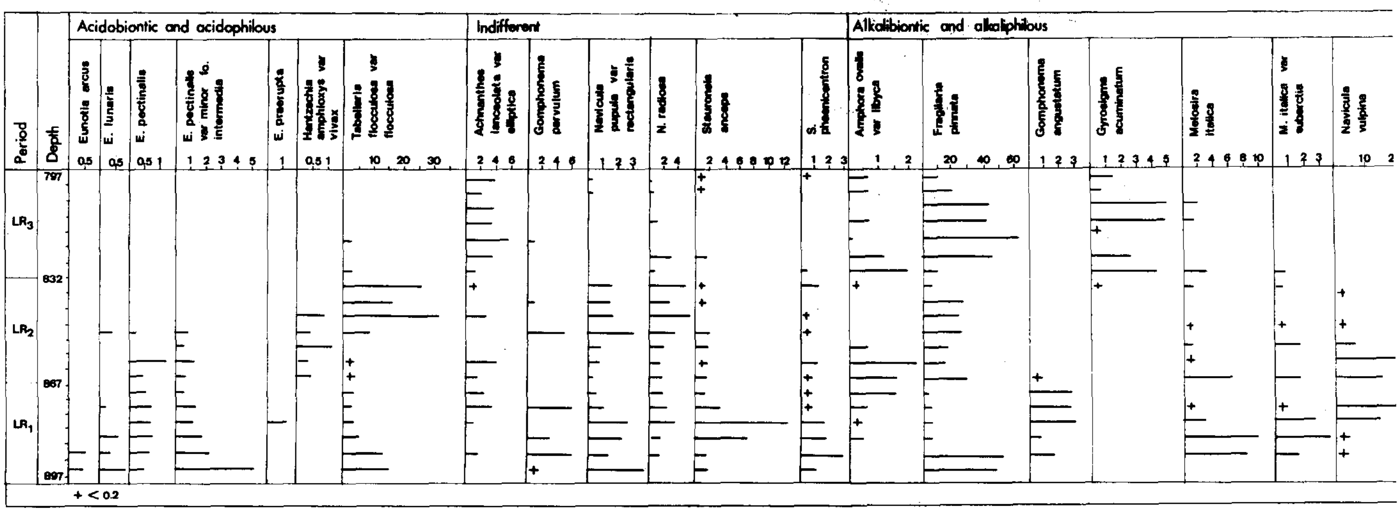

Fig. 11. Most common and important diatoms in Racze Lake illustrated with respect to their pH requirements.

phioxys var *vivax*. The alkaliphilous and alkalibiontic forms during the initial stage of this period decreased and then a slight increase was observed. As a result of these trends the inferred water pH decreased to 6.5 in the middle part of the period.

The third zone was characterized by a decrease in alkaliphilous and alkalibiontic forms corresponding to a low percentage abundance of acidobiontic and acidophilous forms. The alkaliphilous forms were characterized by a successive increase in *Cyclotella comta*. The inferred pH estimated for this zone ranged from 7.4 to 7.7.

Discussion

Erosional indicators

The influx of terrigenous material into the lake can be determined on the basis of stratigraphy of elements associated with mineral matter (Mackareth, 1966; Huttunen & Tolonen, 1977; Starmach *et al.*, 1978). We confirmed that mineral content and Mg, Al, Fe are typically indicators of erosion in the catchment area of the Racze Lake. Mineral content of the sediment mainly represented by siliceous material have been successively increasing reaching a maximum in the upper layer of sediments. This trend appears to be associated with the increase in eroded soils from the watershed. The successive erosion process was a result of the intensity and type of transformation in the catchment area. As was estimated by Latałowa (1984) sediments layer 887 cm corresponds with the fourth settlement phase which was observed in this area. The sharp increase of siliceous content in this layer support this statement.

The successively eroded soils as well as process of chemical erosion caused increase leaching of metals into the lake basin. The curves of Mg, Al and Fe concentration followed the siliceous profile being the second evidence of successive erosion. However, in surface layers of sediments the concentration of Al, Fe and Mg excluding the upper layer decreased (Figs 4 & 5). Nevertheless, changes in the metal concentration in the bottom sediments cannot be simply interpretated as an effect of water erosion. Both transport from watershed and the final accumulation in sediments depends on several factors from which the most important are redox conditions. Under oxidizing conditions in soils, metals highly unsolubled in water are transported to the water in small amount. However, in infiltration and saturation zone in soils, where the redox conditions occur, metals can be mobilized from soils. On the other hand, a similar process can be observed in the bottom sediments. Mackareth (1966) proposed a scheme to reconstruct the profundal oxygen concentration from the stratigraphy of ratio iron to manganese concentrations. As was shown in his model the resuspension and transport of Fe and Mn may be enhanced by redox cycling at the sediment-water interface. Mortimer (1940) observed that Fe and Mn are highly insoluble in oxidazed forms, while reduced forms can be mobilized from sediments. This indicated that changes in the oxygen hypolimnetic concentration may caused the dissolution, precipitation and redeposition processes. These processes can modify the concentration of metals finally deposited in bottom sediments. However, as was shown before these observed changes may also occurred in the soils of the basin as in the lake itself and a difficulty is to establish where the observed processes occurred. Mackareth (1966) suggested also that increase of ratio Fe:Mn during periods of hypolimnetic anoxia is a result of the greater mobility of Mn in the mildly reducing conditions. However, Engstrom *et al.* (1985) and Engstrom & Wright (1984) do not agree with this observation.

Our results from Racze Lake also showed that the high value of Fe:Mn ratio was probably correlated with anoxic conditions at the sediment-water interface. This statement is supported by other independent evidence of sediment redox conditions i.e. fossil pigment analysis. However, Engstrom *et al.* (1985) suggested an alternative explanation to the Mackareth model of Fe:Mn ratio. As was observed in Harvey's Lake (Engstrom *et al.*, 1985) an increased flux of Fe and particulate Mn from reduced sediments during summer stratification caused increases in the physical transport and redeposition of Fe and Mn at autumnal turnover. The author contend that direction of this redeposition should be downsloped as long as profundal environments are sufficiently oxygenated to prevent dissolution. As a result the maxima in Fe and Mn accumulation indicate periods of greater oxygen depletion in surficial sediments, whereas minima correspond to periods of higher sedimentary redox potential.

It appears that changes in the oxygen regime in sediment-water interface in Racze Lake were also the most important factors effecting the concentration of Mg and Al in sediments.

Ratio of Fe:Mn in the fourth surface layers decreased suggesting improvement of hypolimnetic oxygen conditions in the lake. As a result of this process the concentration of Al and Mg decreased too.

Lake productivity indicators

The basic information about lake productivity in the past can be derived from fossil pigment analysis. There is a direct correlation between the primary production and the pigment concentration in the surface and deeper sediments layers (Sanger & Gorham, 1970; Sanger & Crowl, 1979; Guilizzioni *et al.*, 1983). High primary production results in an increase in the pigment content of the organic matter deposited in the sediments.

Low levels of chlorophyll derivatives (CD) (Fig. 7) found in the sediments profile from Racze Lake, comparing to other results (Sanger & Crowl, 1979; Rybak & Rybak, 1985a, b; Rybak, 1986a) reflect low primary productivity characteristic for oligotrophic lakes.

However, it should be noted that amount of fossil pigments finally deposited in lakes is determined by the conditions of sedimentation and sediment formation, mainly by redox processes. As was noticed by Gorham & Sanger (1972) and Sanger & Crowl (1979) and Sanger & Gorham (1970) carotenoids preservation in the sediments depends more on the redox conditions than did chlorophyll preservation. The phenomenon is chemically conditioned by the fact that enzymic destruction of carotenoids depends most of all on the oxygen conditions whereas chlorophyll decomposition is less dependent on this factor (Fogg & Belcher, 1961).

The ratio of chlorophyll derivatives to total carotenoids is a good index of oxygen condition in the hypolimnetic waters. Our results from Racze Lake showed that during all periods represented by the sediments core the ratio varied from 0.27 to 0.54. These results are in accordance with values for other dimictic lakes studied by Sanger & Gorham (1970), Sanger & Crowl (1979), Rybak & Rybak (1985b), and Rybak (1986a). The low values of the ratio suggest periods of high anoxic conditions occurred between sediment layers 862 to 817 cm. This period was also characterized by increase of Fe, Al, Mg concentration and high values of Fe:Mn ratio.

Both ratios CD:TC and Fe:Mn indicate hypolimnetic oxygen depletion which is usually correlated with eutrophic condition in lake or high stability of water body.

The bradymictic conditions were probably one of the most important factor effecting preservation of pigments in sediments. Shape of the lake basin as well as forested hills surrounding the lake basin could prevent hypolimnetic water from mixing during spring and fall.

Fossil pigments can also provide information on development of photosynthetic organisms in the past (Zullig, 1961; Brown & Colman, 1963; Griffiths *et al.*, 1968; Rybak, 1979; Rybak & Rybak, 1982; Rybak & Rybak, 1985b; Rybak, 1986b). In this study we propose to use the ratio between epiphasic to hypophasic carotenoids as indicator of blue-green algal development (Rybak, 1986a). Epiphasic carotenoids (EC) are an extract of β-carotene and monohydroxy derivatives, while the hypophasic carotenoids are those with two or more hydroxyl groups and lutein. β-carotene which is separated to EC is especially, abundant in blue-green algae constituting more than 50% of all carotenoids (Goodwin, 1965). Hence, it can be assumed that mass development of these algae would result in an increase in epiphasic carotenoids deposited in sediments, and thus also in an increase in the EC:HC ratio. As was noticed by Gorham *et al.* (1974) during blue-green algal blooms the EC:HC ratio of live algae was very high, from 1.1 to 5.3.

In our profile from Racze Lake ratio EC:HC ranged from 0.53 to 3.09 (Fig. 7). The highest values were observed in the lowest and middle part of the profile. These suggest that development of blue-green algal population was mainly correlated with redox conditions in the lake (layers 862 to 817). Detailed studies of fossil non-siliceous algae supported these analysis, indicating that at that time the high development of *Gloeotrichia echinulata* occurred (Rybak, unpublished materials). The values of EC:HC ratio were moderately correlated with phosphorus concentration in sediments ($r = 0.58$; $N = 20$; $\alpha = 0.01$).

Nitrogen and phosphorus are the most important nutrients in lake productivity. Bartleson & Lee (1972) stated that total Kjeldhal nitrogen is the dominant form of nitrogen in lake sediments, about 95 to 98% of total nitrogen. In our profile, deposition of total nitrogen is associated with organic matter. However, comparing organic matter and nitrogen content as a ratio of OM:TKN, the wide, characteristic peak between 842 and 822 can be observed. The peak was probably correlated with the high portion of aquatic macrophytes production in the lake. As was stated by Wetzel (1975) the nitrogen content of algal remains deposited in sediments is higher then from material derived from macrophytes and terrestrial sources. So, proportionally greater aquatic macrophytes production can be observed as a higher value of OM:TKN ratio. The greater portion of macrophytes production was also determined by diatom analysis (discussed below).

Phosphorus can also be used as an indicator of paleoproductivity (Shapiro *et al.*, 1971; Williams *et al.*, 1976). However, other papers are opposed to that statement (Engstrom & Wright, 1984; Engstrom *et al.*, 1985) because phosphorus is mobile in sediment under different conditions. The phosphorus profile in Racze Lake also did not show any positive correlation with other productivity indicators. We observed continuously decrease of phosphorus concentration what proves that we do not have evidence of eutrophication process in the lake.

Concentration of calcium in bottom sediments of Racze Lake was very low. Such small values of calcium in sediments, in the northern part of Poland were also noticed by Solski (1964) and Januszkiewicz (1970). Calcium as CO_2 donor is one of the most important factor controlling the eutrophication process. General trend in calcium profile, is the successive decrease upwards the core. This supports our first statement that the eutrophication process could not be observed in the lake.

pH history and diatom succession

History of pH changes in a freshwater ecosystem is a result of complex processes taking place both within water body and its catchment area. It seems that in the case of Racze Lake the most important factors were: inflow of mineral matter from the watershed and structural changes in the littoral biocenosis.

pH changes in Racze Lake ranged from 6.5 to 7.7 and core was divided on three different zones (Fig. 9). In zone 1 pH value of water tended to increase. This process was probably connected with increasing portion of allochtonic matter deposited in the sediments. The alkalification process was concordant with defforestation of the lake's catchment area in this period (Latałowa, 1984). Soil which so far was bounded by plant cover, mostly by forest, become more open to erosion. Several mineral components migrated to the lake during this period, such as siliceous (Fig. 3), magnesium, aluminium (Fig. 4) so that pH value of water increased. However, as was stated before, the decrease of calcium concentration also occurred.

Trends of the pH changes observed in this zone can also be viewed from another point. It seems that results obtained on the basis of diatom analyses could be affected by changes taking place in the structure of the littoral biocenosis. An increase of alkaliphilous and alkalibiontic form was connected with the development of benthic forms mainly by *Navicula vulpina* and planktonic *Melosira italica* and *M. italica* var *subarctica* (Fig. 11). This process can suggest a decrease of the littoral zone. We have also other evidence which suggests decline of littoral zone, such as decreased values of ratio OM:TKN (organic matter:total Kjeldhal nitrogen) (discussed above) and also decrease of genus *Fragilaria* (Fig. 8). *Fragilaria* in our profile was dominated by *Fragilaria pinnata* and *F. pinnata* var *subrotunda*. Both, these taxons are characteristic epiphitic forms. However, it should be said that acidophilic species were also found in this zone, such as *Eunotia pectinalis, E. pectinalis* var *minor* fo. *intermedia*. This may suggest that these diatoms, usually observed in acidic waters, are also able to adopt to more alkaline conditions. The fact could have constituted modyfying factor as regards pH values calculated on the basis of diatom analysis.

Changes of inferred pH values of water from second zone were more complicated. In this zone inferred pH decreased. Diatom flora was predominated by acidobiontic planktonic form *Tabellaria flocculosa* var *flocculosa*, which reached a maximum percentage abundance. Development of this species was a decisive importance as regards pH value of water calculated on the basis of diatom analysis. Many authors (Knudsen, 1954; Florin, 1957; Stoermer & Yang, 1969; Stoermer & Ledowski, 1976) stated that *Tabellaria flocculosa* var *flocculosa* should be classified as an indifferent form. If this was the case, pH values calculated for this zone would change considerably, pointing to circumnatural or slightly alkaline waters, and no changes to the next zone would be observed. It is very difficult to explain changes taking place in this zone. Chemical analysis showed continuously increase of mineral matter, siliceous, magnesium, aluminium and iron. However, at the same zone calcium concentration decreased too. Assuming this, our explanation is, that probably the changes were not so distinct as it was shown by inferred pH. It seems also that development of *Tabellaria flocculosa* var *flocculosa* was connected with formation of the pelagic zone rather than with the pH value of water.

The most contemporary sediments are represented by zone 3. During the initial period of the zone a noticeable development of *Fragilaria pinnata* and *F. pinnata* var *subrotunda* was noticed, probably associated with development of aquatic macrophytes. However, at the end of the zone characteristic increase of planktonic forms, mainly *Cyclotella comta* was observed. The curve of inferred pH showed that there were no drastic changes in this zone which could be estimated on the basis of fossil diatom flora.

Concluding remarks

The analysed core represents three characteristic periods of the lake development. The first period (897 – 867 cm) is characterized by gradual increase of inferred pH. The chemical analysis of sediments indicate small inflow of allochthonous material into the lake. At this time the lake was probably well oxygenated and the hypolimnetic oxygen depletion was not observed. The lake primary production was relatively high the highest concentration of chlorophyll derivatives and total carotenoids in the profile and it seems that portion of blue-green algal in the phytoplankton was moderately high.

The next zone, represented by the middle part of the core (867 – 832 cm) showed significant changes in the lake's environment. The most important were anoxic conditions at the sediment-water interface indicated by Fe:Mn and CD:TC ratios. It appears that changes in the oxygen regime effected the concentration of Al and Mg deposited in sediments. However, productivity indicators showed a low level of primary production. The blue-green algae was one of the main components of phytoplankton. Diatom flora was dominated by planktonic, acidobiontic form *Tabellaria flocculosa* var *flocculosa*. At this time, pH reached 6.5 which was the minimum level in our core. At the end of the period the highest portion of aquatic macrophytes production was estimated. These phenomena may suggest bradymictic conditions in the lake. Shape of the lake basin as well as forested hills surrounding the lake basin could prevent hypolimnetic water from mixing during spring and fall.

The most recent sediments in the core (832 – 797 cm) showed development of pelagic zone in the lake. The planktonic forms, represented mainly by *Cylotella comta* showed gradual increase upwards the core. Both ratios CD:TC and Fe:Mn indicated improvement of hypolimnetic oxygen condition in the lake. As a result of the process the concentration of Al and Mg decreased too. The primary production in the lake was still low and there was no evidence of eutrophication process in the lake.

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References

Adams, M. S., P. Guilizzioni & S. Adams, 1978. Sedimentary pigments and recent primary production in northern Italian lakes. Mem. Ist. Ital. Idrobiol. 36: 267 – 285.

Bartleson, G. C. & G. F. Lee, 1972. Recent sedimentary history of Lake Mendota. Environ. Sci. Tech. 6: 794 – 808.

Beaver, I., 1981. Apparent ecological characteristics of some common freshwater diatoms. Minist. Envir. Ontario, Can.: 513 pp.

Brown, S. R. & B. Colman, 1963. Oscillaxanthin in lake sediments. Limnol. Oceanogr. 8: 233 – 241.

Cholnoky, F. J., 1968. The ecology of diatoms in inland waters. I. Cramer, Lehre, 699 pp.

Cleve-Euler, A., 1951–1955. Die diatomeen von Schweded und Finnland. Vetenskapsakad. Handl. 4. 2: 1 (1951), 3: 3 (1952), 2: 1 (1953a), 4: 5 (1953b), 5: 4 (1955).
Engstrom, D. R. & H. E. J. Wright, 1984. Chemical stratigraphy of lake sediments as a record of environmental change. Lake Sediments and Environmental History. ed. E. Y. Howarth & J. W. G. Lund, pp. 11–67. Leicester University Press.
Engstrom, D. R., E. B. Swain & J. C. Kingston, 1985. A paleolimnological record of human disturbance from Harvey's Lake, Vermont: geochemistry, pigments and diatoms. Fresh. Biol. 15: 261–288.
Foged, N., 1977. Freshwater diatoms in Ireland. Bibltca. Phycol. B. 34.
Foged, N., 1978. Diatoms in Eastern Australia. Bibltca. Phycol. B. 41.
Foged, N., 1979. Diatoms in New Zealand, the North Island. Bibltca. Phycol. B. 47: 244 pp.
Fjerdingstad, E., 1954. The subfossil algal flora of the lake Bølling Sø and its interpretation. Kgl. Danske Vidensk. Selsk. Biol. Skr. 7: 7–81.
Fogg, G. E. & J. H. Belcher, 1961. Pigments from the bottom deposits of an English Lake. New Phytologist 60: 129–142.
Goodwin, E., 1965. Distribution of carotenoids. p. 143–173. In T. W. Goodwin (ed.), Chemistry and biochemistry of plant pigments. Academic Press.
Gorham, E. & J. E. Sanger, 1972. Fossil pigments in the surface sediments of a meromictic lake. Limnol. Oceanogr. 17: 618–622.
Gorham, E. & J. E. Sanger, 1976. Fossilized pigments as stratigraphic indicators of cultural eutrophication in Shagawa Lake, northeastern Minnesota. Geol. Soc. America Bull. 87: 1638–1642.
Gorham, E., J. W. G. Lund, J. E. Sanger & W. E. Dean, 1974. Some relationship between algal standing crop, water chemistry, and sediment chemistry in the English Lakes. Limnol. Oceanogr. 19: 601–617.
Griffiths, M., P. S. Perrot & W. T. Edmondson, 1968. Oscillaxanthin in the sediments of Lake Washington. Limnol. Oceanogr. 20: 945–952.
Guilizzioni, P., G. Bonomi, G. Galanti & D. Ruggiu, 1983. Relationship between sedimentary pigments and primary production: evidence from core analyses of twelve Italian Lakes. Hydrobiologia 103: 103–106.
Huber Pestalozzi, G., 1942. Das Phytoplankton des Süsswassers, 2. Die Binnengewasser. E. schweizerbarksche Verlagsbuchhandburg, Stuttgart, 16: 3–19.
Huttunen, P. & K. Tolonen, 1977. Human influence in the history of Lake Lovojärvi, S. Finland. Finsk. Mus. 1975: 68–105.
Januszkiewicz, T., 1970. Skład osadów głebinowych grupy jezior na Pojezierzu Kaszubskim. Rocz. Nauk. Roln., H 92: 67–84.
Kalbe, L., 1980. Kieselalgen in Binnengewässern. A Zimsen Verlag, Wittenberg Lutherstad, 206 pp.
Knudsen, B. M., 1954. The ecology of the diatom genus Tabellaria in the English Lake District. J. Ecol. 42: 345–358.
Komarienko, L. & I. Wasiljewa, 1975. Priesnovodnyje diatomovyje i siniesielienyje wodorosli wodojemow Jakutii. Nauka, Moskwa, 1–422.
Latałowa, M., 1984. Analiza palynologiczna osadów dennych Jeziora Raczego, Wolin. Symposium of the Polish Group of International Geological Correlation Programme, Poznań, 5 pp.
Mackareth, F. J. H., 1966. Some chemical observations on post glacial lake sediments. Phil. Trans. Royal Soc. London 250: 165–213.
Nygaard, G., 1956. Ancient and recent flora of diatoms and Chrysophyceae in Lake Gribsø. In: K. Berg, I. C. Petersen (eds), Studies on the Humic Acid Lake Gribsø. Folia Limnol. scand. 8: 32–93.
Patrick, R. & C. W. Reimer, 1966. The diatoms of the United States, exclusive Alaska and Hawaii. Philad. Acad. Sci. Monogr. 13: 1–689.
Renberg, I. & T. Helberg, 1982. The pH history of lakes in Southwestern Sweden, as calculated from the subfossil diatom flora of the sediments. Ambio 11: 30–33.
Rybak, I. & M. Rybak, 1985a. Development of Lake Kortowskie in relation to the climatic changes in three Holocene periods. Hydrobiologia 124: 151–166.
Rybak, I. & M. Rybak, 1985b. Stratigraphy of fossil pigments as a guide to the environmental changes of Kortowskie Lake. Acta Hydrochim. Hydrobiol. 13: 297–305.
Rybak, M., 1979. Barwniki osadów dennych Jeziora Mutek. Zesz. nauk. ART Olszt. 9: 85–92.
Rybak, M., 1986a. The effect of agriculture on the primary production in the lake recorded by the stratigraphy of fossil pigments. Hydrobiologia, in press.
Rybak, M., 1986b. Chlorobium chlorophyll as an indicator of organic pollution in paleolimnological investigation. Acta Hydrochim. Hydrobiol. 14: 255–261.
Rybak, M. & I. Rybak, 1982. Plant pigments in contemporary bottom sediments of Lake Długie in Olsztyn. Acta Hydrobiol. 24: 21–28.
Sanger, J. E. & G. H. Crowl, 1979. Fossil pigments as a guide to the paleolimnology of Browns Lake, Ohio. Quat. Res. 11: 342–352.
Sanger, J. E. & E. Gorham, 1970. The diversity of pigments in lake sediments and its ecological significance. Limnol. Oceanogr. 15: 59–69.
Schmidt, A., 1972. Atlas der Diatomaceen Kunde 1874–1959, 1–4 Zentralantiquariat DDR Leipzig.
Shapiro, J., W. T. Edmondson & D. E. Allison, 1975. Changes in the chemical composition of sediments of Lake Washington, 1958–1970. Limnol. Oceanogr. 16: 437–452.
Siemińska, J., 1964. Chrysophyta, 2. Bacillariophyceae. Flora słodkowodna Polski. PWN Warszawa-Kraków: 519 pp.
Solski, A., 1964. Szkic limnologiczy jezior Charzykowskich i Jeziora Wdzydze. Pol. Arch. Hydrobiol. 12: 189–231.
Stoermer, E. F. & T. B. Ladewski, 1976. Apparent optimal temperatures for the occurrence of some common phytoplankton species in southern Lake Michigan. Gt. Lakes Res. Div. Publ. 18: 1–49.
Stoermer, E. F. & J. J. Yang, 1969. Plankton diatom assemblages in Lake Michigan. Special Report 47. Gt. Lakes Res. Div., University of Michigan, Ann Arbor.
Starmach, K., S. Wróbel & K. Pasternak, 1978. Hydrobiologia-Limnologia. PWN Warszawa, 621 pp.
Wetzel, R. G., 1975. Limnology. W. B. Saunders Co., Philadelphia, 793 pp.
Williams, J. D. H., T. P. Murphy & T. Mayer, 1976. Rates of accumulation of phosphorus forms in Lake Erie sediments. J. Fish. Res. Bd. Can. 33: 430–439.
Zullig, H., 1981. Die Bestimmung von Myxoxanthophyll in Bohrprofilen zum Nachweis vergangener Blaualgenentfaltung. Verh. Int. Ver. Limnol. 14: 263–270.

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