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Fossil akinetes of *Aphanizomenon* and *Anabaena* as indicators for medieval phosphate-eutrophication of Lake Gosciadz (Central Poland)

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Abstract

Records of fossil akinetes of *Aphanizomenon* and *Anabaena* (Cyanobacteria) in the laminated sediments of Lake Gosciadz are interpreted. Increasing human impact in the catchment area of the lake (as can be interpreted from the pollen records of human impact indicators) apparently had its effect on the trophic conditions of the lake water: from ca 1000 AD on, fossil akinetes of *Aphanizomenon* and *Anabaena* are present in enormous quantities in the sediment. The increases of the Cyanobacteria are interpreted as the effect of an intensification of farming and land fertilization in the area around Lake Gosciadz, causing eutrophication of the lake. Phosphorus enrichment from effluent and excreta in the catchment area of the lake at times will have become so high that N-limited growth conditions occurred. In such conditions Cyanobacteria capable of nitrogen fixation (namely *Aphanizomenon* and *Anabaena*) could bloom. The deposits of the last ca. two centuries are characterised by the successive appearance of *Pediastrum boryanum*, *Tetradron minimum*, *Coelastrum* cf. *reticulatum*, *Botryococcus*, *Scenedesmus*, *Spirogyra*, *Gloeotrichia* and *Staurastrum manfeldtii*, whereas Cyanobacteria show a decline. This phytoplankton succession could be interpreted in terms of competition for nutrients and light: higher eutrophication levels and higher turbidity caused a decline of available light, and as a consequence less energy was available for the energy consuming process of nitrogen fixation by *Aphanizomenon* and *Anabaena*.

1. Introduction

Palynological microscope slides, prepared in the first place for the analysis of fossil pollen, may contain a wide range of other microfossils as well. The exploration of “extra” paleoenvironmental indicators in palynology is one of the topics in the palynological research program at the Hugo de Vries-Laboratory of the University of Amsterdam. Among the “extra” fossils are, a.o., fungal and algal spores and remains of Cyanobacteria (for-

merly named Blue-green Algae) (Van Geel et al., 1983, 1984, 1989; Batten and Van Geel, 1985; Cronberg, 1986; Van Geel, 1986). The present paper deals with the fossil record and interpretation of akinetes of Cyanobacteria (*Aphanizomenon* and *Anabaena*) in the holocene deposits of Lake Gosciadz in Central Poland.

Records of recent Cyanobacteria in lakes (Livingstone and Jaworski, 1980) have shown that *Aphanizomenon* and *Anabaena* are a feature of late spring plankton. Observations by Livingstone and

Reynolds (1981) have shown that algae, having settled on deeper sediments unaffected by wave action, are protected from resuspension by a boundary layer adjacent to the sediment surface. Especially in annually laminated sediments the preconditions of an ordered stratigraphic sequence are satisfied. Akinetes of both *Aphanizomenon* and *Anabaena* from recent sediments were recorded by Livingstone and Jaworski (1980). Based on culture experiments of akinetes from these surface sediments they concluded that akinetes not only have a temporary, or overwintering function, but may also ensure long term survival. For *Aphanizomenon* and *Anabaena* the deepest layers in Rostherne Mere (England) containing viable akinetes were 18 and 64 years old, respectively. Although the hyaline walls of the akinetes (Plate I) apparently are resistant to decomposition and preserve well, these akinetes are normally not recorded in paleoecological studies of lake deposits, because palynologists do not recognize them.

The sediments of Lake Gosciaz reveal annual lamination covering the last 12,000 yr. Yearly couplets consist of a light, mostly calcitic layer, and a dark layer rich in organic detritus. In the diagram (Fig. 1) several time horizons have been indicated as horizontal lines. The (BC/AD calendar year) dates of these levels are based on the study of the lamination in the sediments by the last author. In the upper part of the core (especially after ca. 1200 BC) not all the visible traces of laminae are certain annual varves and there are also some non-laminated layers for which the duration is uncertain. As a consequence, the indicated time horizons are approximate indications. The discussion about the range of possible errors in the chronology falls beyond the scope of the present paper and will be discussed elsewhere. In the near future the strategy of wiggle-match ^{14}C AMS dating (Van Geel and Mook, 1989) will be used in order to try to pinpoint the more or less floating mid-Holocene laminae-chronology more precisely.

Lake Gosciaz (latitude $52^{\circ}30'$, longitude $20^{\circ}10'$, altitude 64.4 m above sea level) is one of about 60 lakes forming the Na Jazach lake district in the depression of the Toruń–Eberswalde ice-marginal valley which currently is occupied by the middle

course of the Vistula River. The lakes are generally of glacial origin, as the area was reached by the southern marginal ice-sheet lobe during the maximum extent of the Vistulian glaciation. The lake is 45 ha in area, and its maximum water depth today is 22.5 m. The deepest point is situated in the central part of the lake, with another depression of about 12.1 m in its western part. The most shallow part in between has a water depth of ca. 6 m. A shallow bay in the north is drained by the small stream Ruda, which connects four lakes and flows into the Vistula River 5 km northeast of Lake Gosciaz. The catchment of the lake is ca. 588 ha and belongs to the Vistula valley. During the summer season the thermic stratification typical for dimictic lakes develops in the deepest part with a temperature gradient of $3^{\circ}\text{C}/\text{m}$ in the metalimnion layer, and a strong oxygen deficit (Churski et al., 1993).

Systematic archeological investigations in the vicinity of the lake were carried out by Pelisiak and Rybicka (1993). During the period represented by the records in the diagram, the following numbers of sites were discovered in the area around Gosciaz: 17 Bronze Age sites, 57 settlements and cemeteries of the Lusatian Culture (Late Bronze Age and Hallstatt Periods); 19 sites of the Late Roman Period (Przeworska Culture) were found; the Middle Ages are represented by 47 sites, and 67 sites are dated in the last 500 years.

Descriptions of Lake Gosciaz and its surroundings, including geological, geomorphological and vegetational characteristics, have been presented earlier (Ralska-Jasiewiczowa et al., 1987; Goslar et al., 1988). Since 1987 the lake has been the subject of multidisciplinary studies by an international group of scientists, with the aim of reconstructing the rates and processes of changes in the terrestrial and limnological environments on an absolute time-scale, and building up a reference model for central Europe (Ralska-Jasiewiczowa et al., 1987, 1992; Ralska-Jasiewiczowa and Van Geel, 1992).

2. Methods

The palynological samples were treated with $\text{Na}_4\text{P}_2\text{O}_7$ and acetolysed. Organic material was

separated from inorganic material using a bromoform–alcohol mixture (specific gravity 2.0) and embedded in glycerine. The percentages of all taxa are based on the pollen sum (Σ -pollen) of trees, shrubs and herbs, excluding aquatics, telmatophytes and spores. Records of non-pollen palynomorphs were made during the analysis of 350–600 Σ -pollen per sample. In case of extremely high frequencies of fossils (e.g. aknetes of Cyanobacteria) the percentage calculations are based on lower pollen totals.

3. Results

In Fig. 1, a selection of pollen curves for the upper 8.90 m of core G1/87 were included, namely curves of the taxa mainly being indicative for human impact in the past in the vicinity of Lake Gosciz from the Early Bronze Age till recent times. Next to these pollen curves, the records of *Aphanizomenon*, *Anabaena*, *Pediastrum boryanum*, *Tetradion minimum*, *Coelastrum* cf. *reticulatum*, *Scenedesmus*, *Spirogyra*, *Gloeotrichia*, *Botryococcus* and *Staurastrum manfeldtii* are shown.

3.1 Human impact on the landscape around Lake Gosciz as reflected in the pollen diagram

Two sites of the Bronze Age Trzciniecka and pre-Lusatian cultures have been found in the closest neighbourhood of the ‘‘Na Jazach’’ lake complex, besides several others recognized within a few kilometers area to the east of the lake (A. Pelisiak and M. Rybicka, pers. commun., 1993). The presence of those cultural groups is first expressed around 1950 BC by rising frequencies of ruderal and weed pollen (*Artemisia*, *Chenopodiaceae*, *Urtica*, *Rumex acetosella* type) and later also of meadow indicators (*Plantago lanceolata*, *Gramineae* and *Cichorioideae*). Their economy was mostly based on animal husbandry. During this phase, and especially during its younger part, an expansion of *Betula* and *Carpinus* (not included in the diagram) coincident with the reduction of *Quercus* and *Corylus* took place, but it is difficult to say how far those changes in the forest structure were stimulated by human activity.

The Lusatian culture of the Late Bronze/Early Iron Age, with its heavy population was one of the most potent and transforming prehistorical cultures on Polish areas. There are only very scarce traces of that culture found close to the lake, one of them being probably the remnant of a settlement. There is, however, a big concentration of Lusatian sites found at 3–5 km west of the lake (Pelisiak and Rybicka, unpubl. data). The activities of Lusatian people must have affected the direct surroundings of the lake, as the first rise of the whole group of human indicators in the pollen diagram from ca. 1200 BC is synchronous with the first disturbance of laminae formation in the lake sediments. The pollen of meadow plants together with ruderals and plants of wood openings on sandy soils are typical indicators of an economy dominated by animal husbandry. However, the regular appearance of cereal pollen of *Hordeum* and *Triticum* types evidences the accompanying agricultural activities. The rising pollen curves of pioneer shrubs and trees are coincident with the declines of *Carpinus*, *Quercus* and other deciduous trees.

The following forest regeneration phase of ca. 420 yr duration, connected with the decline of Lusatian settlements around 150 BC is followed by a short but very distinct land occupation phase (ca. 270 AD–ca. 500 AD) resulting from the expansion of the Przeworska Culture tribes. The changes in the pollen diagram point to a strong human impact on the natural environment caused by the rising importance of agriculture including the introduction of *Secale* and *Cannabis* into cultivation. However, the archaeological evidence from that time in the close vicinity of the lake is still unclear.

The Migration Period (starting relatively late in the present chronology which is based on the study of laminae) is indicated in the pollen diagram by a drastic decline in all human indicators and high maxima of *Betula* and *Carpinus* pollen evidencing the tree succession on abandoned land.

The development of the Early Medieval settlement recorded in the pollen diagram from ca. 1000 AD corresponds with the official foundation of the Polish state in 966 AD. The area in question was then colonized by tribes of Masovians and the

adjacent region of fertile Kujavian czernozems was still more densely inhabited. However, during the 12th and 13th centuries both provinces were invaded and devastated by Baltic tribes, and in the 13th century the Polish state disintegrated into a group of autonomic duchies fighting against each other. Around the mid-13th century the Gosciaz region was situated at the confluence of three provinces, which may explain the phase of forest regeneration and corresponding decline of anthropogenous indicators.

A new intensification of colonization in the Masovia region progressed during the 14th century (with Plock as one of the most important towns), and lasted till the 16th century (as the area was not reached by the black death!). Since that time the deciduous forests disappeared practically from the discussed area (some *Quercus* and *Corylus* being components of mixed pine forest). From around the mid-16th century at least three of the villages existing until today are mentioned in historical sources: Dab (= oak), Dobiegniew and Ruda, the latter called “an industrial settlement”, connected with the local smelting of ore (Ruda means ore). The dates for the beginning and end of those industrial activities which undoubtedly heavily affected not only the vegetation of the area, but also the limnological regime of the lakes by producing severe air pollution, are being searched for in the archives.

A strong German colonization started in the area in the second half of the 18th century and became more intense particularly after the Polish insurrection in 1863, which resulted in setting up many small villages and a rising level of agriculture, in spite of the prevailing poor sandy soils.

The economic degradation and depopulation of the area was the consequence of the last World War. In 1954–1956 the abandoned lands were re-afforested, and today Lake Gosciaz is closely surrounded by pine and mixed pine woods.

3.2 Recorded changes in the lake environment

After ca. 1000 AD considerable numbers of akinetes of the Cyanobacteria *Aphanizomenon* and *Anabaena* have been found, followed after ca. 1800 AD by the green algae *Pediastrum boryanum*,

Tetradron minimum, *Coelastrum* cf. *reticulatum*, *Botryococcus*, *Scenedesmus*, *Spirogyra* and *Staurostrum manfeldtii*.

Cyanobacteria and Chlorophyceae are known to be dominant in more eutrophied systems (Hutchinson, 1957). The sharp increase of Cyanobacteria around 1000 AD can be considered as an indication for increased nutrient loading, related with the above-mentioned contemporaneous increase of human impact in the catchment area (as is reflected in the pollen records and in archeological data).

Although *Aphanizomenon* and *Anabaena* are both nitrogen-fixing and flake-forming taxa, their physiology and ecology are different. In deeper lakes both organisms can be present in large quantities and can form surface scums during summertime. *Aphanizomenon* is not only found under nitrogen-limiting conditions but can also compete with other species under phosphorus- or light-limiting conditions (Zevenboom, 1980). The niche of *Anabaena* is much more restricted to nitrogen-limiting conditions and it is never found in large quantities under other limitations (Schreurs, 1992).

From these data we can conclude that the intensification of human impact around 1000 AD started with an increase of the phosphorus loading, causing a larger biomass of phytoplankton which consumed a large part of the available nitrogen (NH_4^+ and NO_3^-), causing a nitrogen limitation (which initially will not have been very strict and not constant during the growing season). After ca. 1600 AD the imbalance of phosphorus and nitrogen in the lake increased, causing a more severe nitrogen limitation over longer periods of time, resulting in a decline of *Aphanizomenon* whereas *Anabaena* remained relatively important.

Nitrogen fixation is a very energy-consuming process, so at higher eutrophication levels, and under higher turbidity, there is no longer enough energy (light) available for nitrogen fixation by Cyanobacteria (Zevenboom and Mur, 1980). It is likely that the recent sharp decline of both Cyanobacteria in Lake Gosciaz is related to increased nitrogen and phosphorus loading, causing a succession to other (not preserved) Cyanobacteria and green algae, a combination which is known from highly eutrophied or hyper-

trophic systems. *Staurastrum manfeldtii*, coming very late in the succession of algae in Lake Gosciąz (present in the upper samples only, see Fig 1), indicates a decrease in eutrophication (Coesel, 1992; pers. comm., 1994) which apparently is related to the relatively low human population density during the last fifty years. For N-limited conditions in the present Eifel lakes, Scharf (1985) mentioned a positive correlation between *Anabaena* and *Staurastrum pingue* and *S. planctonicum* (both belonging to the *Staurastrum manfeldtii* complex; Coesel, 1992). This may indicate that the upper samples of Lake Gosciąz still represent N-limited conditions.

4. Discussion

The analysis of fossil remains of Cyanobacteria has shown to be worthwhile because it allows a better understanding of the changing local environments in lakes and pools during the past. Van Geel et al. (1984, 1989) recorded *Gloeotrichia* as a pioneer during the early part of the Late glacial period. These records from the type section at Usselo were of crucial importance for the understanding of the vegetation development during the early part of the Late glacial period: Cyanobacteria of the *Gloeotrichia*-type apparently played a pioneer role in nutrient-(nitrogen)poor situations thanks to their ability to fix nitrogen and thus making conditions suitable for other aquatic plants.

In Bronze Age and Late Holocene lake and pool deposits, studied by Van Geel et al. (1983) and Odgaard (1989), human impact in the surroundings of these lakes caused eutrophication of the lake water and remains of *Gloeotrichia* (in combination with large quantities of Chlorophyceae) were recorded at corresponding levels. In the Danish lake Skånsø (Odgaard, 1994) eutrophication was triggered by increased nutrient loading connected with heathland expansion and retting of *Cannabis* and *Linum* in the lake.

Cronberg (1986) studied subfossil algae (Cyanophyceae, Chlorophyceae and Chrysophyceae) from the lake Våxjösjön in Sweden, but unfortunately she did not combine her study with

pollen analysis of the same sample series. In Våxjösjön *Anabaena* spores were considered as indicators for oligotrophic conditions (in the period 1300–1600 AD) and no attention was paid to the possibility that the balance between phosphorous and nitrogen components might have played an important role in the competition between algae and Cyanobacteria.

In the Italian Lake Monterosi, Goulden (1970) recorded that Cyanobacteria became very abundant during a period of cultural disturbance (2300–2500 yr ago) and were replaced by *Pediastrum*. Also during a medieval settlement phase Cyanobacteria became dominant immediately before a rise of *Pediastrum*. Goulden realised that eutrophication of the lake was the immediate effect of cultural disturbances in the area, with associated Cyanophyceae blooms and a following change to a green algal flora, but he did not fully understand the ecological background (competition for nutrients and light, see our interpretation of the succession of Cyanobacteria and Chlorophyceae in Lake Gosciąz) for the observed phenomena.

The present records of Cyanobacteria from Lake Gosciąz are important for the understanding of environmental change in, and around the lake. From ca. 1000 AD on, phosphorus enrichment from effluent and excreta in the catchment areas of the lake will have become so high that the supply of nitrogen was exhausted. Under nutrient-limited growth conditions, the competitive ability of phytoplankton populations is primarily determined by their uptake characteristics for the limiting nutrient. The N₂-fixing capability of *Aphanizomenon* and *Anabaena* are a clear advantage in the N-limited situation. The decline of both taxa around 1900 AD was probably caused by a further increase of nitrogen and phosphorus loading at higher eutrophication levels; light became a limiting factor (increased turbidity as a consequence of dense algal populations) for the energy-consuming process of nitrogen fixation.

We realize that only a selection of algal and cyanobacterial taxa will be recognizable as fossils. It is probable that, apart from the recorded Cyanobacteria and green algae from which the cell walls were preserved, large quantities of an other

PLATE I

1–8 Fossil akinetes of *Aphanizomenon* $\times 1000$.

1, 2 Akinetes broken off at one end

3–8 Cup-shaped appendages at the rounded ends of the spores. 8a and 8b showing the same aknete at high and low focus in order to show both ends

9–17 Fossil akinetes of *Anabaena*. $\times 1000$ 9–12, 14, 16–18 showing a suture (broken, but still attached) at one end, and 13 and 14 showing sutures at both ends 14 and 17b showing pores visible at both ends of the spores 17a and 17b showing the same aknete at high and low focus

18, 19 Overview of parts of microfossil slides, showing akinetes of *Anabaena* and *Aphanizomenon*

scum-forming Cyanobacteria, namely *Microcystis*, will have been present in the lake. However, *Microcystis* does not form spores and cannot be detected as a recognizable fossil in sediments.

Pelagic Cyanobacteria are slowly growing organisms. From (actuo-)hydrobiological studies it is known that Cyanobacteria can disappear after changes of the hydrological situation of a site (decrease of residence time of the water). However, in case of Lake Gosciadz it is unlikely that the

recent decline of Cyanobacteria and the related increase of green algae were related to a shortened residence time of the lake water, so our above-mentioned interpretation in terms of changing trophic conditions and turbidity is most probable.

Also in pre-Quaternary deposits remains of Cyanobacteria can be recognized: Batten and Van Geel (1985) identified the Early Cretaceous form-taxon *Celyphus rallus* as a relative of extant Cyanophyceae (family Rivulariaceae). Among the

“miscellaneous algal-derived” palynomorphs illustrated by Traverse (1988, p. 287, fig. 13.20 m) is a *Navifusa* species, which in our opinion most probably is a (Palaeocene) *Anabaena* spore

5. Description and illustrations of akinetes of *Aphanizomenon* and *Anabaena* (Plate I)

The Type number system of the Hugo de Vries-Laboratory is followed here (cf. Van Geel et al., 1989). The complete record of “extra” fossils of Lake Gosciarz will be published later, and will also be included in the *Atlas of “extra” Palynomorphs* which is in preparation by the first author.

Type 600 *Aphanizomenon* cf. *gracile*, **akinetes** (Plate I, 1–8)

Akinetes (spores) hyaline, tube-shaped, (15.5–)19–33(–58) × 4–7 µm, excl. the (not always preserved) 2.7–3.1 µm broad and 1.9–4.9 µm deep, cup-shaped appendages at the rounded ends of the spores (see Plate I, 4, 5, 7 and 8). Spores often broken off at one end (see Plate I, 1, 2).

Type 601 *Anabaena* sp., **akinetes** (Plate I, 9–17)

Akinetes (spores) hyaline, tube-shaped, with rounded ends, (14–)21–26(–39) × 9–12 (–18.0) µm. Most spores showing a suture (broken, but still attached) at one end (see Plate I, 9–12, 14, 16–18) or both ends (Plate I, 13, 14). Often pores visible at both ends of the spores (Plate I, 14, 17b).

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