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RECONSTRUCTION OF THE TROPHIC DEVELOPMENT OF LAKE KRAKOWER OBERSEE (MECKLENBURG, GERMANY) BY MEANS OF SEDIMENT- DIATOM- AND POLLEN-ANALYSIS

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Abstract

Changes in composition of diatom (Bacillariophyceae) communities and pollen content were analyzed in two cores from the lake Krakower See, Mecklenburg-Vorpommern, Northern Germany. Based on the pollen stratigraphy, a time-depth-curve was built that allowed an estimate of the rate of sedimentation. The pollen curves, especially those of settlement indicators, showed the human influence in the surrounding area. Diatom assemblages clearly indicated that human activities had influenced not only the terrestrial vegetation but also the water body of the lake and it's trophic conditions. From a natural oligo- to mesotrophic lake that had small oscillations in prehistoric times it switched relatively fast into an eutrophic one around 700 years ago. This radical change in the trophic status was an effect of both damming up for mills in the 13th century and increasing settlement activities around the lake.

Key words: paleolimnology, diatom and pollen stratigraphy, TP reconstruction

INTRODUCTION

Interest in the history of lake development is increasing, stimulated by a cumulative number of lake restorations and an associated need of a conceptual model, which are orientated towards natural or near natural conditions. Lakes and river systems of the North-German young-moraine landscape were mainly generated during late glacial time. Pre-existing structures had been destroyed by glacial activity during the Weichselian (Lorenz 2002). During alternation of warm- and frost periods connected with different water levels in the late glacial and the early Holocene, first limnic and telmatic sediments were deposited. Sedimentation was determined by climate and hydrological development until humans started to change the surrounding landscape in the Neolithic period (4000–1800 BC, Weidemann 1999). These were mostly small-scale clearings with limited regional and temporal effects (Dreßler *et al.* 2002, Selig *et al.* 2002). An irregular amount of human influence is recorded in the Krakower Obersee during prehistoric times. Conspicuous anthropogenic effects on the water balance are evident since extensive damming of the lake's outflow in medieval times (Kaiser 1996, Ruchhöft 1999).

Measures of limnological restoration need an actual classification of lakes and rivers as well as information about environmental history, both before and after significant human impact. Paleoecological reconstruction uses chemical and biological remains incorporated in the sediment in a chronological order. The fossils act as memory of the water body: the qualitative and quantitative differences in microfossil composition represent the succession of ecological conditions *e.g.* trophic conditions, pH value, salinity, productivity, sedimentation, climatic and hydrologic conditions (Fritz *et al.* 1991, Stoermer, Smol 1999). Diatoms are of great value to such investigations, because of their very stable frustules of amorphic SiO_2, and because of the broad distribution and the good indicator value of most of the taxa (Dixit *et al.* 1999, Hofmann 1994, Schmedje *et al.* 1999, Schönfelder 2000, Schönfelder *et al.* 2002).

Pollen investigations complete the picture as they allow discriminating between natural and anthropogenic effects. As well as the pollen from the lake's surrounding, water plants and some algae are also preserved in the sediment giving additional information about the lake development. Furthermore, pollen can give age estimation if no ^{14}C-dates are available.

MATERIAL AND METHODS

Coring

Three sediment cores (KOS I, II and III; Fig. 1) were taken from Lake Krakower Obersee by using a Livingstone-Usinger-corer with a diameter of 60 mm. The overlapping

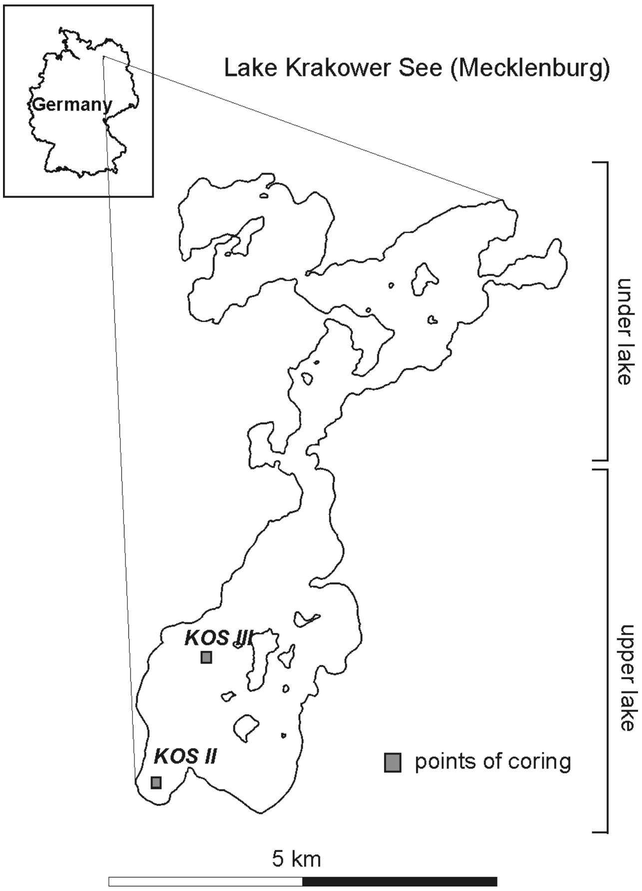

Fig. 1. Positions of KOS II and KOS III in Lake Krakower See.

KOS I and II–cores were taken at 4.35m water depth. The uppermost part was not investigated. Sampling started at a sediment-depth of 1.35 m and ended at 9.35 m below the sediment surface. The core KOS III was taken at 24.70 m water depth. From the sediment surface, the core goes down to 20 m in the sediment, 44.7 m below the water level. The 2 m segments were divided lengthwise and documented in the field, directly after coring. One of them was used for subsampling, the other one was reserved as reference material for further examination.

Subsampling preparation

For diatom analysis, subsamples (ca. 2 cm^3) were taken from KOS II and KOS III initially every 32 cm. Because of the fluid sediment at the top of KOS II, sampling ended in this core 168 cm below the sediment-water boundary. Additional subsamples were taken in KOS II between 698 and 519 cm in steps of 4 to 16 cm. Preparation followed Kalbe & Werner (1974). For 0.3 g sediment, HCl (3 ml) and H_2O_2 (8 ml) were used as the first oxidants. After washing two times with distilled water, second oxidants (H_2SO_4, 10 ml, $KMnO_4$, 1 ml) were applied for 10 minutes. For final cleaning of the organic matter, oxalic acid ($H_2C_2O_4$) was applied drop by drop. The residues were washed four times and rinsed in distilled water. Afterwards Naphrax®-mounted slides were prepared. Relative abundance was calculated for every taxon after counting nearly 500 diatom-valves under 1000-fold magnification (Zeiss-Axioplan, 1.4 plan-apochromat) in every slide. Critical taxa were confirmed using a scanning electron microscope (Zeiss DSM 960A) in the Electron Microscope Centre of the Medical Faculty at the University of Rostock. To eliminate any bias of the survey the samples were encoded beforehand. The identification of diatoms is based on Krammer & Lange-Bertalot (1986–1991), Lange-Bertalot (1993, 2001), Krammer (1997a, 1997b, 2000, 2002, 2003), Reichardt (1999) and Håkansson (2002).

For total phosphorus (TP) reconstruction the diatom-TP transfer function by Schönfelder *et al.* (2002) was used. This dataset was based on TP mean- and tolerance-values (weighted averaging, Ter Braak, Van Dam 1989) of benthic diatoms of 69 hardwater lakes and 15 riversides in the neighboring region of Brandenburg.

For pollen analytical investigations subsamples of ca. 2 cm^3 were also prepared with standard treatment according to the following procedure. Cleaning by 6-µm sieve was carried out to eliminate the clay fraction. Pollen determination followed Beug (1961), Faegri *et al.* (1989), Moor *et al.* (1991) and a reference collection of Kiel University. The pollen diagrams were calculated on the basis of dry-land plants. They show a selection of pollen types; the complete data are available from the author (W.D.) The analyses of geochemical elements (Fig. 2) were done by Sebastian Lorenz (University of Greifswald, Germany).

RESULTS AND DISCUSSION

KOS II

The vertical diatom assemblages were analyzed between 725 and 168 cm. The chemical analyses confirmed the visual impression that long phases of the core were dominated by $CaCO_3$-rich sediments, with a $CaCO_3$ component up to 85% of the dry-mass (Fig. 2, 3). Biogenic sedimentation was firstly detected at a sediment depth of 712 cm. The first diatoms were found at a depth of 698 cm. In this part, up to 679 cm diatoms were found despite the high $CaCO_3$ concentrations. In the $CaCO_3$-rich sediments the diatom frustules were nearly completely dissolved as a result of silica solution processes caused by the alkaline interstitial medium (Flower 1993, Ryves *et al.* 2001). Thus the subsequent occurrences of diatoms were strongly correlated to low $CaCO_3$ concentration (Fig. 2, 3). The section above 679 cm up to 584 cm is characterized by a decrease of $CaCO_3$. For this depth it is possible to reconstruct some early conditions of the lake. In this section of nearly 100 cm small benthic taxa like *Fragilaria construens* (Ehrenberg) Grunow (incl. the forma *construens* (Ehrenberg) Hustedt, *venter* (Ehrenberg) Hustedt and *binodis* (Ehrenberg) Hustedt), *F. pinnata* Ehrenberg, *F. brevistriata* Grunow, *Amphora pediculus* (Kützing) Grunow and *A. inariensis* Krammer dominate with overall 92–98% of the total number of frustules (Fig. 2, 3). Almost no planktonic forms were detected in this section. The interpretation of the dominance of such a small *Fragilaria-Amphora* association is in controversial discussion. On the one hand they characterize mostly late glacial to early Holocene lake conditions. Most diatomologists negate the possibility of TP-indication of these taxa. These diatoms are very eurypotent organisms

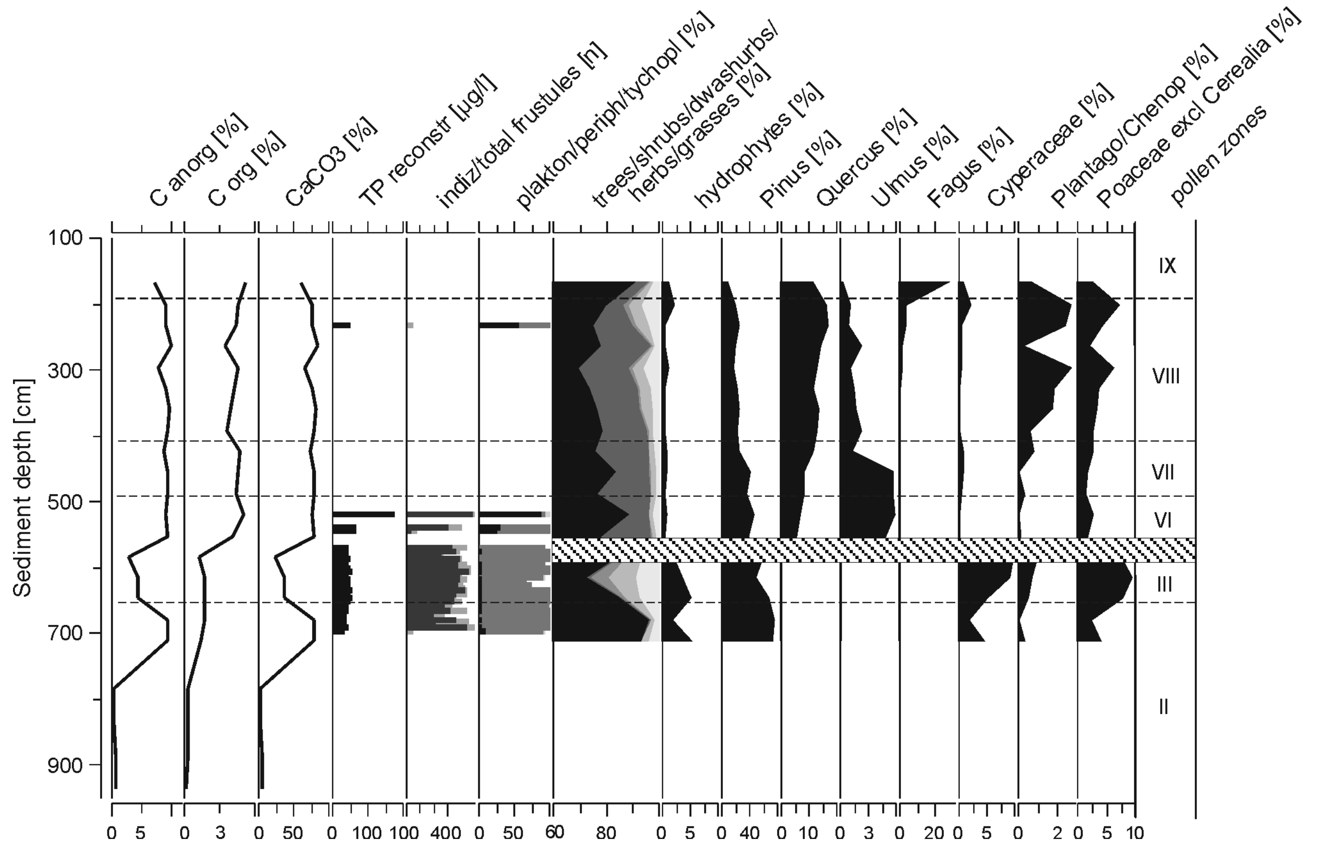

Fig. 2. Stratigraphy of KOS II: selected lithologic parameters (C_{anorg}, C_{org}, $CaCO_3$ as % dry mass), diatom based TP reconstruction (acc. Schönfelder *et al.* 2002), general diatom groups and important pollen (as % of land plants) during pollen-zones acc. Firbas. index/total frustules (n): relative abundance of frustules used for indication during TP reconstruction.

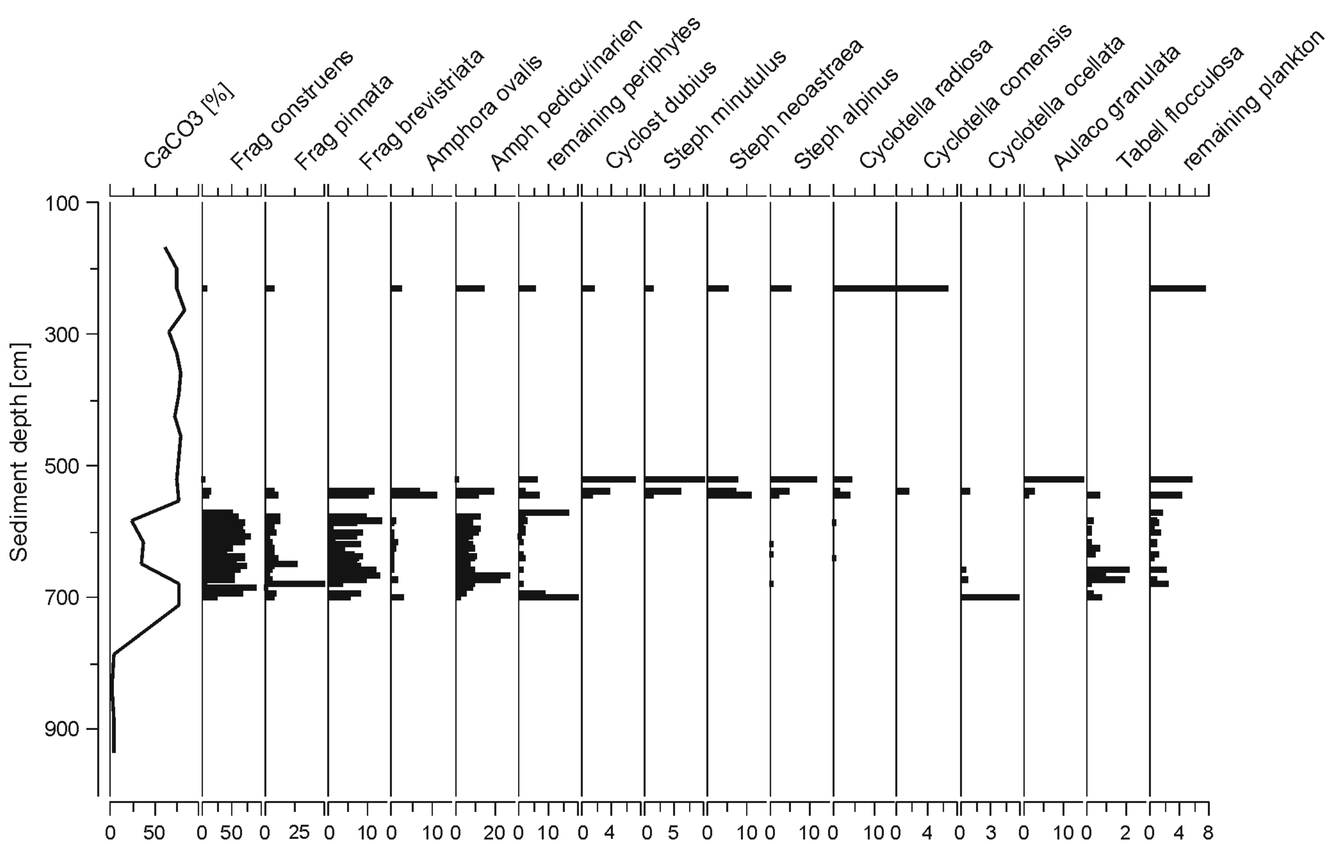

Fig. 3. Stratigraphy of KOS II: relative abundance of main diatom taxa and $CaCO_3$ stratification.

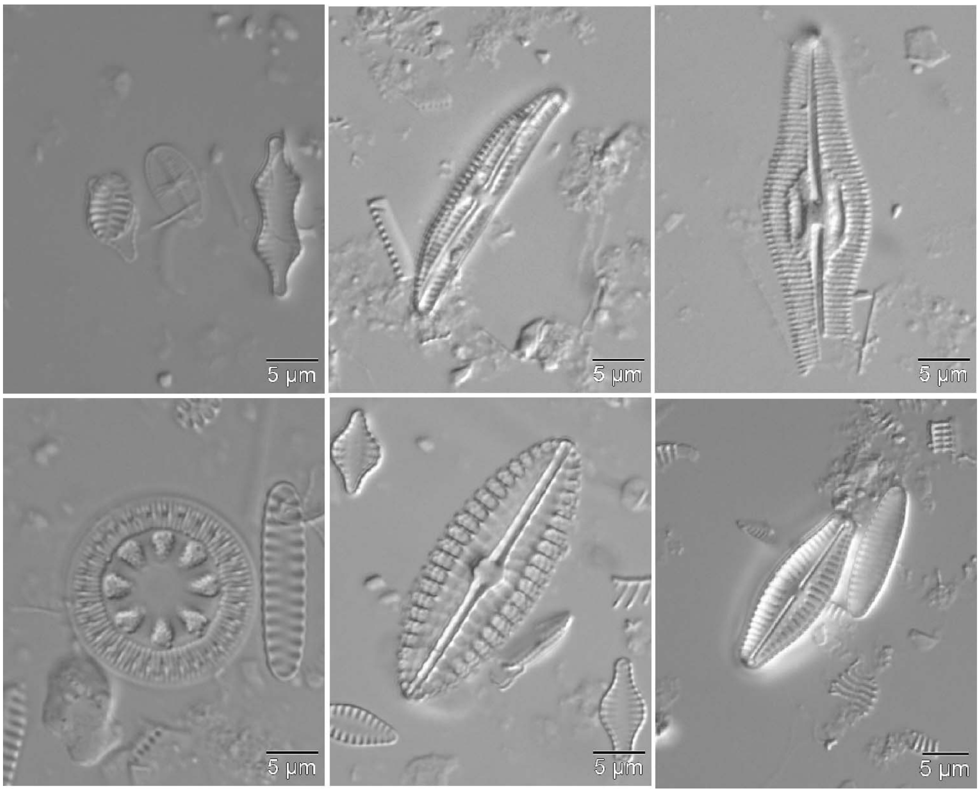

Fig. 4. Characteristic nordic-alpine taxa from the Allerřd and the Younger Dryas found in KOS II sediments. **Above**, left: *Achnanthes subatomoides* (Hustedt) Lange-Bertalot & Archibald, center: *Amphora aequalis* Krammer, right: *Caloneis schumanniana* var. *lancettula* Hustedt. **Below**, left: *Cyclotella antiqua* W. Smith, center: *Diploneis maulerii* (Brun) Cleve, right: *Navicula diluviana* Krasske.

with great competition potential, thus such assemblages are indicating at most alternating environmental conditions (Haworth 1976, Carrick *et al.* 1988, Hickmann, Reasoner 1998, Lotter, Bigler 2000). In recent studies we find them as dominating epiphytes in macrophyte-rich shallow lakes (Adler 2003). It can be assumed that the southwestern bay of the lake was dominated by submerged macrophytes. The reconstructed mesotrophic to weakly eutrophic TP levels (37–51 µg/l, Fig. 2) may have allowed a sufficient lightening for submerged macrophytes. Sporadic occurrences of oligotrophic nordic alpine taxa (*Achnanthes pusilla* (Grunow) De Toni; *A. subatomoides* (Hustedt) Lange-Bertalot et Archibald , Fig. 4; *Amphora aequalis* Krammer, Fig. 4; *Cymbella helvetica* Kützing; *Diploneis oblongella* (Naegeli) Cleve-Euler; *D. maulerii* (Brun) Cleve, Fig. 4; *Cyclotella antiqua* W. Smith, Fig. 4; *Sellaphora laevissima* (Kützing) D.G. Mann var. *laevis*sima; *Navicula diluviana* Krasske; Fig. 4) support the assumption of cold and nutrient limited conditions during this time.

These early diatom associations up to the sample in 584 cm represent two different pollen zones during the late glacial oscillation. The Allerød (Zone IX) is represented in the lowermost three samples where dominate of tree pollen and low values of non-arboreal pollen is followed by an increase of light-demanding dwarf-shrubs and herbs like *Empetrum*, *Helianthemum* and *Artemisia* representing the climatic setback of the Younger Dryas (Zone VIII, Fig. 2). These two pollen zones from the beginning of organic sedimentation in the lake up to 584 cm represent nearly 1800 years from around 13,500 to ca. 11,700 years cal. BP.

At sediment depth of 569 cm there is a distinct change in sediment color and character. Based on the characteristic Younger Dryas pollen-assemblage below and an early Atlantic pollen flora above, this remarkable change represents a hiatus of nearly 2000 years (Fig. 2, 6). The subsequent dominance of thermophilic trees accompanied by *Hedera* and *Viscum* belong to the mid-Holocene climate optimum. In between there was no sedimentation or even erosion in this bay of lake Krakower See. An explanation for this phenomenon could be a lowering of the lake's water level. The bay might have become so shallow that the waves eroded sediments or at least prevented new sediment accumulation. Even a drying up of this part of the lake cannot be excluded. These questions cannot be answered without further investigations. The following sediments up to 545 cm characterized a period of changing water level in the lake and a massive increase of $CaCO_3$ values, so that diatoms were dissolved again.

The sea level rose again in the early Atlantic period. The calcium carbonate sediments from 545 cm upwards cannot be interpreted as littoral calcium, as we have a mass development of eutrophic planktonic diatoms (*Stephanodiscus minutulus* (Kützing) Cleve et Möller, *S. neoastraea* Håkansson et Hickel, *Aulacoseira granulata* (Ehrenberg) Simonsen, *Cyclostephanos dubius* (Fricke) Round) between 545 and 519 cm. Epiphytic diatoms, which may indicate submerged macrophytes were not detectable. In parts of the lake that had dried up before, nutrients were remobilized as illustrated by the high TP concentration (60.8–172.2 µg/l) after the remarkable rising of the sea level in the early Atlantic. Due to the

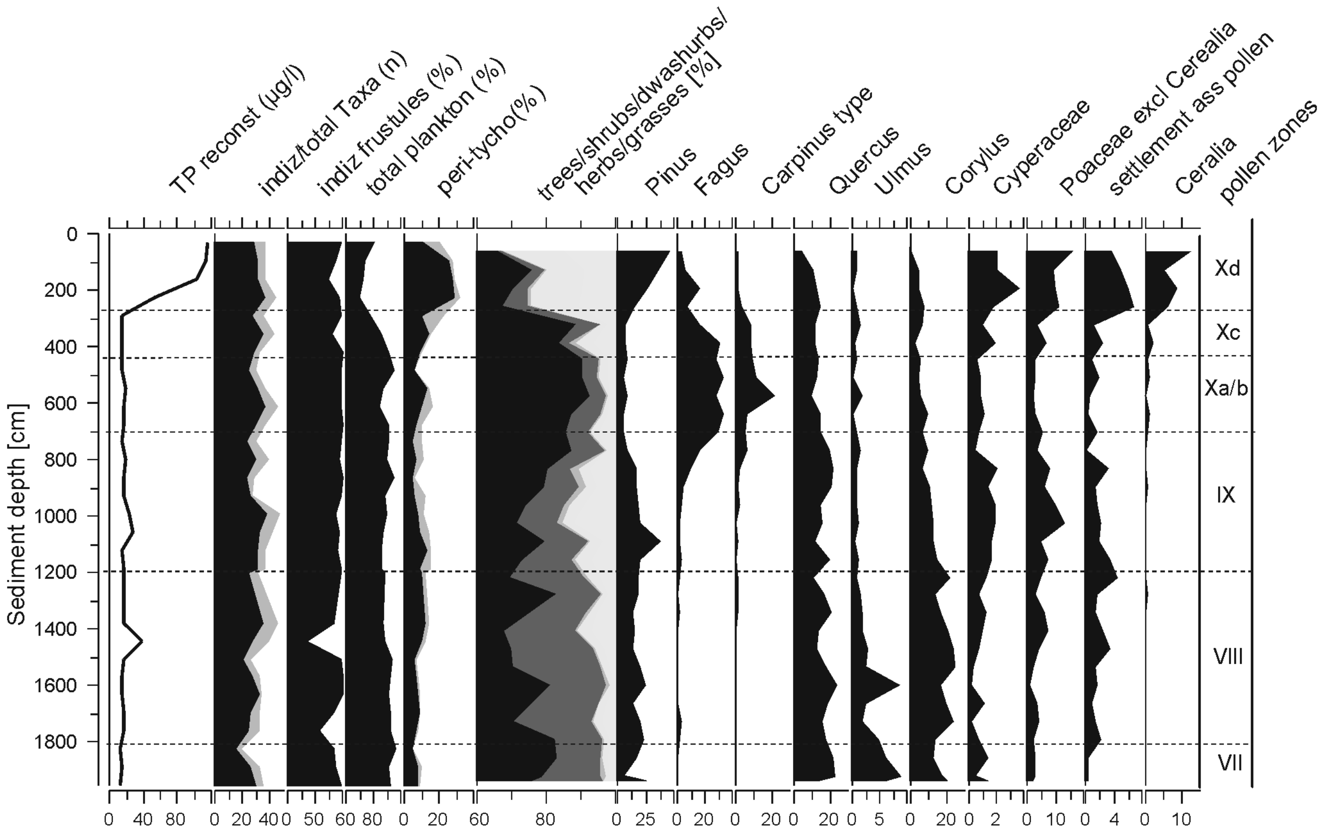

Fig. 5. Stratigraphy of KOS III: general diatom groups, diatom based TP reconstruction (acc. Schönfelder *et al.* 2002) and important pollen (as % of land plants) during pollen-zones according Firbas. index/total taxa (n): relative abundance of taxa used for indication during TP reconstruction. index frustules (%): relative abundance of frustules used for indication during TP reconstruction.

high $CaCO_3$ concentration, diatoms were dissolved in all samples above 519 cm with the exception of one sample at 231 cm.

KOS III

The deepest sediments of the core KOS III represent a mid to late Atlantic phase characterized by increasing values of *Fraxinus* in a woodland dominated by deciduous trees (Fig. 5). Thus there is no overlapping and no correspondence between diatom assemblages of the early Atlantic in KOS II and the oldest drilled sediments of KOS III. The continuously deposited sediments of KOS III contain rich diatom assemblages at all vertical subsamples. A total of 189 diatom taxa were determined in this core. The average number of taxa per slide was 34.3. A mean of 27.3 taxa was used for the TP-reconstruction, so that on average 98% of the counted frustules were used for this calculation (Fig. 5). For the discussion of local biodiversity it is important to note that only 500 frustules per slide were identified; the total number of identified taxa for this study (KOS II and KOS III) was 210.

The vertical succession of diatom communities from the bottom of the core at 1954 cm up to 290 cm was dominated by the planktonic *Cyclotella comensis* Grunow (interim *C. pseudocomensis* (Grunow) Scheffler see Scheffler & Morabito 2003). This species indicates oligo- to mesotrophic conditions of the lake. Up to sediment depth of 418 cm planktonic diatoms made up more than 90% of the total. This number decreased slowly from a sediment depth of 418 cm upwards. However, the fraction of periphytic diatoms (incl. tychoplanktonic ones) never reached more than 30% of the total number of diatoms (Fig. 5).

Due to the absolute dominance of *C. comensis*, the reconstructed TP level was very stable at 15 µg/l in the whole sediment core up to 290 cm (Fig. 5, 6). This level characterizes the borderline between oligo- and mesotrophic conditions in deep and stratified lakes (Vollenweider 1979, OECD 1982). There are just some episodic fluctuations from this continuous trophic level.

The whole sediment core of KOS III can be divided into three distinct diatom zones (Fig. 6). Zone I comprised the basal sediments up to nearly 1200 cm; zone II included the subsamples above this layer and ended at a sediment depth of 290 cm. The last diatom zone started at 226 cm and continued to the recent top layer sediments.

Diatom phase I (1954 cm–ca. 1200 cm sediment depth)

According to the pollen stratigraphic results this phase includes the late Atlantic and the whole Subboreal. The Atlantic-Subboreal transition was marked by the elm-decline between the samples 1856 and 1792 cm. From this time onwards the development of the landscape, but also the internal development of the lake, is influenced by human activities.

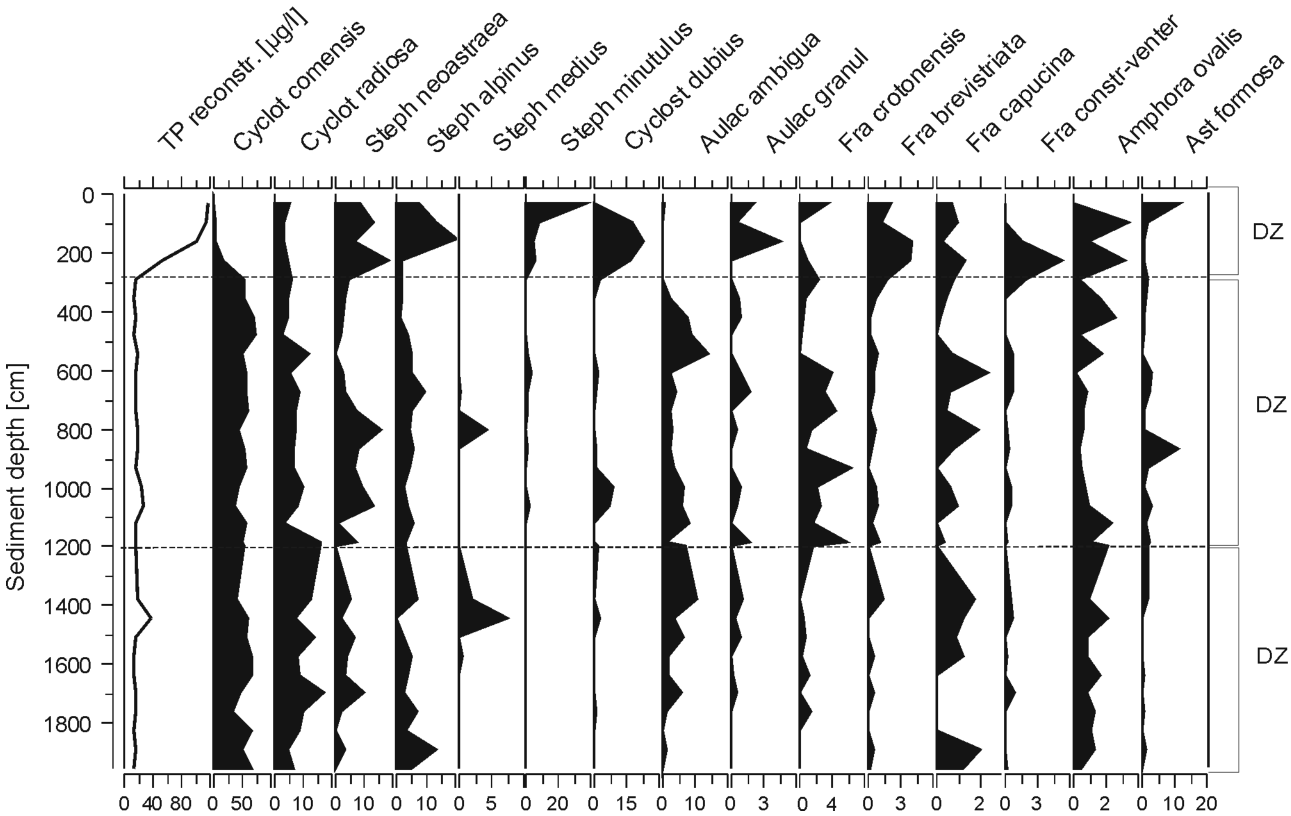

Fig. 6. Stratigraphy of KOS III: relative abundance of main diatom taxa and diatom based TP reconstruction (acc. Schönfelder *et al.* 2002). DZ I, II, III: different diatom zones.

Proof of agrarian activities increased continuously but stayed on a low level. Herbs and grasses never exceeded 10% of the total pollen sum of dry land plants, showing that the wood was dominating the landscape even when it was influenced by several utilizations (Dörfler 2001). The reconstructed TP level was constant at 15 µg/l. The diatom assemblages were dominated by *Cyclotella comensis* and an important codominant species was *C. radiosa* (Grunow) Lemmermann. A remarkable change occurred at 1442 cm, where a TP value of 37.8 µg/l was calculated, relating to the occurrence of *Stephanodiscus medius* Håkansson. Possibly this could just be an artifact of identification problems between *S. alpinus* Hustedt and *S. medius*; the first one was not found in this subsample, but very consistently below and above. High values of *S. alpinus* would indicate a lower TP value as the reconstructed one. The deflection at 800 cm (next diatom zone) is assessed in the same way (Fig. 6).

Diatom phase II (above 1200 cm–290 cm sediment depth)

Settlement indicators and especially the low values of *Calluna* in the first half of this phase show the continuous opening of the landscape in the following Subatlantic. Woodland still dominated but wide areas also must have been covered by heather, and in the woods beech and hornbeen started to expand. At sediment depth of 1058 and 994 cm there were distinct increases in TP values from the background level of around 15 µg/l up to 28.0 and 23.3 µg/l TP. They derived from a significant occurrence of *Cyclostephanos dubius* (6.7%; 9.2%, Fig 6). Usually this taxon is typical for high eutrophic conditions. These early *C. dubius* layers had a prehistory already at 1200 cm. By further high relative dominance of *Cyclotella comensis*, the composition of associated taxa changed conspicuously. For example, significant amounts of moderate eutrophic species (*Stephanodiscus neoastraea, Fragilaria crotonensis* Kitton) were found as well as high eutrophic ones (*Aulacoseira granulata*, *Fragilaria ulna* (Nitzsch) Lange-Bertalot). At this level, this did not influence the reconstructed TP level because of a parallel decline of the TP-upraising *Cyclotella radiosa*.

The mentioned *Cyclostephanos dubius* subdominance at 1058 and 994 cm (besides the dominant *Cyclotella comensis*) ended with subdominant occurrence of moderately eutrophic species such as *Asterionella formosa* Hassall and *Stephanodiscus neoastraea* up to 738 cm. The whole 'early *Cyclostephanos dubius* layer' from 1200 up to 738 cm comprised a total of 462 cm (Fig. 6). According to the pollen based age-depth calculation (Fig. 7) this is equivalent to nearly 1100 years between 2800 years and 1700 years cal BP. Subsequently a continuous decline of the reconstructed TP concentrations back to the natural background level of approximately 15 µg/l TP occurs parallel to a decrease of settlement-associated pollen. This is also connected with a renewed dominance of *C. comensis* up to the end of this diatom zone in the sample of 290 cm. The transition to the next zone is dated at about 700 BP.

Diatom phase III (from 226 cm sediment depth)

Beginning with the sample at the depth of 226 cm, we found a clear and irreversible change in diatom communities up to recent sediments (Fig. 6). During the time of sedimentation of only 1m, *C. comensis*, which has dominated for thousands of years, decreased from 55% to only 5% of the analyzed diatom assemblages. In recent days this taxon has been totally absent. The diatom associations in the sediment core were dominated by moderate eutrophic taxa (*Stephanodiscus neoastraea, S. alpinus, Fragilaria ulna* div. var.) as well as heavy eutrophic ones (*Cyclostephanos dubius*, *Aulacoseira granulata*, *Stephanodiscus minutulus*). This resulted in an increase of the reconstructed TP concentrations of finally 116 µg/l, which is in accordance with recent measurements. The beginning of this strong increase at 226 cm can be dated to around 700 years cal. BP. Lorenz (2002) has proved increases of the lake's water level of nearly 1 m, caused by extensive damming up for mills in the 13th century. The trophic reaction of the lake's water body was caused by two processes: flooding of the former shores and surrounding areas which initiated an input of nutrients and secondly by increasing settlement activities around the lake.

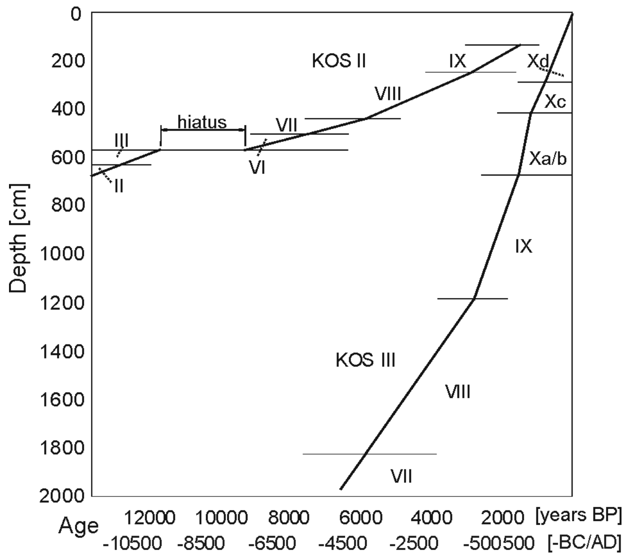

Fig. 7. Sedimentary time depth development of KOS II and KOS III based on pollen-stratigraphy during pollen-zones according Firbas.

CONCLUSIONS

The earliest limnic sediments of the core KOS II from 700 cm up to 584 cm represent the Allerød and at least parts of the Younger Dryas. This includes a time-span of nearly 1800 years from 13,500 to 11,700 years cal BP. Digestion of diatoms in the alkaline interstitial-water of the $CaCO_3$-rich sediments of this bay caused the nearly complete dissolution of silica frustules. Only between 698 cm and 519 cm there were good preserved diatom assemblages. A significant decline of $CaCO_3$ values allowed a small insight into this early period of the lake. The dominating small epiphytic *Fragilaria-Amphora* association, combined with continual evidence of nordic alpine oligotrophic diatoms, confirmed the assumption of submerged littoral macrophytes and an oligo- to mesotrophic situation. At the sediment depth of 569 cm a disruption in the pollen-record and in sedimentation was detected. Characteristic pollen of the Atlantic succeeded directly on that from the Younger Dryas. For nearly 2000 years limnetic sedimentation was interrupted or destroyed. The subsequent sediments up to 545 cm characterized a period of changing water level and massive increases in $CaCO_3$ values, so that diatoms were dissolved again.

The sea level must have risen again in the early Atlantic period. Planktonic diatoms indicated eutrophication. Reconstructed TP values of 60.8–172.2 µg/l at the beginning of this refilling of the bay documented the high degree of nutrient re-mobilization. With exception of the depth of 231 cm no diatoms were preserved up to the top of KOS II.

In KOS III the trophic development of lake Krakower See was recorded from the end of the Atlantic up to recent days. This deep part of the lake is characterized by an obviously higher sedimentation rate than KOS II (Fig. 7). The earliest analyzed diatoms characterized the lake as oligo- to mesotrophic, with a natural background of total phosphorus of approximately 15 µg/l. This situation was stable for several thousand years. Just temporary peaks in this curve indicated TP inputs but the level of approximately 15 µg/l TP was reached again. Starting from the sediment depth of 226 cm there was the beginning of an irreversible change in diatom communities. The oligo- to mesotrophic planktonic association that was dominated by *Cyclotella comensis* was transformed by the occurrence of eutrophic species. Thus we consider eutrophic conditions with early spring TP levels of approximately 100 to 120 µg/l for the uppermost part. This is in accordance with recent measurements of the TP values by the Office for Environmental Affairs, which confirms the methodical design of TP determination by using individual mean and tolerance values of diatoms found in sediment assemblages.

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