

The palaeolimnology of Soppensee (Central Switzerland), as evidenced by diatom, pollen, and fossil-pigment analyses

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Abstract

The development of Soppensee (Central Switzerland, 596 m a.s.l.) has been reconstructed using algal remains such as diatoms, chlorophytes and fossil pigments, as well as the pollen and spores of macrophytes. Sediment accumulation in Soppensee began at the end of the last glacial period, approximately 15,000 yrs ago. During the Oldest Dryas biozone (> 12,700 radiocarbon yrs B.P.) the lake had low primary productivity. After reforestation with birch and later pine, around 12,700 B.P., phases of summer anoxia occurred in the lake. These anoxic conditions were most probably caused by additional carbon input from the catchment, as well as longer phases of stratification due to reduced wind exposure caused by the sheltering effect of increased tree cover. From the Younger Dryas biozone (10,800 to 10,000 radiocarbon yrs B.P.) onwards, Soppensee became meromictic for several millennia.

The fossil diatom assemblages are dominated by planktonic alkaliphilous to alkalibiontic species with mainly meso- to eutrophic preferences. Diatom-inferred total phosphorus reconstructions suggest meso- to eutrophic conditions throughout the Holocene. Eutrophic conditions are also suggested by the presence of pigments of cyanobacteria, including *Oscillatoria* species. First human activity in the catchment is evidenced ca. 5000 radiocarbon yrs B.P. by the occurrence of cereal pollen. Diatom-inferred total phosphorus concentrations also increased slightly during the Neolithic period.

According to the fossil pigment record, meromictic conditions ended during the Iron Age. Deep-water anoxia, however, persisted at least during the stratification period. During the Middle Ages massive deforestation in the catchment and around the lake changed the limnological conditions drastically. The lack of forest increased the wind fetch and, therefore, also the mixing of the lake, while soil erosion and retting of hemp supplied additional nutrients. Because of intensive agriculture in its catchment, Soppensee has become hypertrophic and diatom assemblages have consequently changed completely in the last 50 yrs.

Introduction

Traditionally, lake and mire deposits have been used to reconstruct past regional vegetation and climate history but the potential of the sediment as an archive of its own genesis and development has often been neglected by palynologists. However, for a sensible reconstruction of the environmental history of the catchment of a lake, it is essential to understand the palaeolimnological processes that have affected the stratigraphy of the sediment.

Because of the relatively short life span of many aquatic organisms community composition can alter rapidly if there are environmental changes or perturbations, whereas the response of terrestrial vegetation may include a considerable time lag (e.g., Wright, 1984; Ammann, 1989a). Lake development through time may be affected by many different components. It can respond to factors originating in the atmosphere (e.g., climate), geosphere (e.g., catchment geology, soil development, erosion), and biosphere (e.g., vegetation). Superimposed on the natural long-

term development may be anthropogenic changes that influence the temperature regime (Schindler et al., 1990; Smol et al., 1991) and nutrient condition of a lake through land-use, settlements, or lake management (Schindler, 1987; Fritz, 1989; Håkansson & Regnéll, 1993). One of the major challenges of palaeolimnology is to distinguish the natural from the anthropogenic factors in lake development and to identify natural background values for important limnological variables (e.g. pH, nutrients) as well as their natural long-term variability (Anderson, 1995; Battarbee, 1997).

The aim of this study is to focus on the long-term history and development of the aquatic system of Soppensee during the Holocene with emphasis on results gained from botanical microfossils. Zoological (see Hofmann, in press) and geochemical aspects of the palaeolimnology of Soppensee are discussed separately.

Site and methods

Soppensee is a small, eutrophic hard-water lake on the central Swiss Plateau (8 °05'E, 47 °05'30"N, Figure 1; see also Gruber et al., in press). It lies at an elevation of 596 m a.s.l. in a region of intensive agriculture (see Table 1). Between 1986 and 1991 over 60 long cores were taken along two transects to study the sediment lithology in the basin (Figure 2). Cores SO86–14 and SO89–23 were taken with a Kullenberg piston corer (Lotter et al., 1997a) in the central part of the basin at a water depth of 27 m (see Figures 1 and 2).

Diatom samples were taken at 5 cm intervals and treated with 30% H₂O₂ and 10% HCl before mounting on slides with Naphrax. A total of 86 taxa in 111 samples were identified and taxonomy is based on Kramer & Lange-Bertalot (1986–1991). If possible,

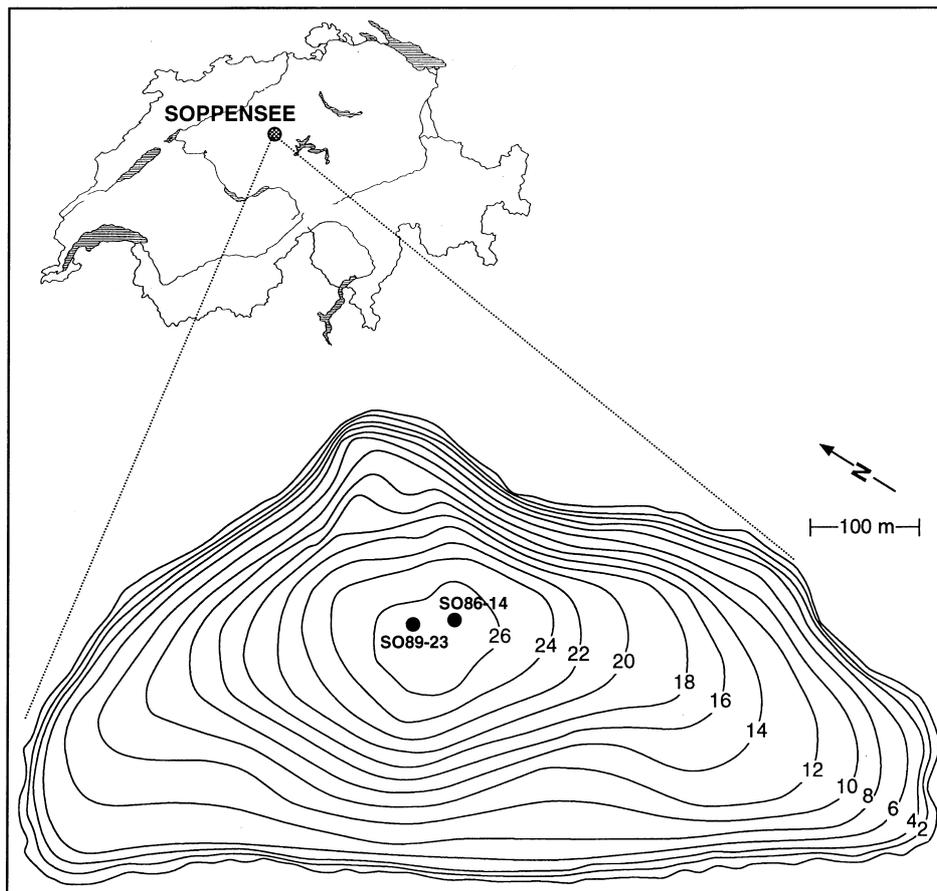


Figure 1. Map of Switzerland showing the location of Soppensee and bathymetric map of Soppensee showing the locations of the cores described in this study.

Table 1. Geographical data and present-day range of limnological variables in Soppensee (after Lotter et al., 1998; Müller et al., 1998)

elevation	596 m asl
max. depth	27 m
lake surface	0.23 km ²
catchment area	1.59 km ²
agricultural land	82%
wooded areas	12%
urban areas	6%
mean annual temperature	8.2 °C
mean January temperature	-0.7 °C
mean July temperature	17.4 °C
mean annual precipitation	1266 mm
pH	7.6 – 8.5
conductivity at 20 °C	268 – 324 µS/cm
alkalinity	2.97 – 3.46 meq/L
DOC	4.0 – 5.3 mg C/L
total N	1.83 – 2.0 mg/L
NO ₃	0.44 – 1.11 mgN/L
total P	50 – 116 µg/L
PO ₄	2 – 57 µg P/L
Si	0.2 – 0.5 mg/L
Ca	48 – 64 mg/L
Mg	4.4 – 6.7 mg/L
Na	3.7 – 4.6 mg/L
K	3.4 – 3.6 mg/L

a minimum of 500 valves was counted per slide. At some levels, however, diatom preservation was very poor (e.g. 173 cm) and below 540 cm the diatoms were very badly preserved or even totally dissolved.

The percentage sum of Figures 4 and 7 includes all diatoms, whereas in Figure 6 chrysophyte remains were also included. Zonation was carried out numerically (Birks & Gordon, 1985), and diatom assemblage-zone boundaries were placed where different zonation methods produced consistent results.

Pollen analysis was carried out on the same core as the diatoms. Standard methods were used for sample preparation (Lotter, 1988) and a minimum of 500 grains were counted per sample. The pollen zonation refers to the regional pollen assemblage zones (PAZ) defined by Ammann et al. (1996).

The absolute chronology used in Figure 5 is based on varve counts that have been connected to a calibrated radiocarbon stratigraphy, whereas the radiocarbon dates refer to AMS ¹⁴C ages on terrestrial macrofossils (for details see Hajdas et al., 1993).

Diatom zonation and chronology

Numerical zonation of the diatom data revealed six distinct diatom assemblage zones (DAZ). The lowest D-1 (*Cyclotella ocellata* - *C. comensis*, ca. 10,000 to 7700 ¹⁴C yrs B.P.) DAZ can be further subdivided into a first *Fragilaria* sub-DAZ (D-1a, ca. 10,000 to 8000 ¹⁴C yrs B.P.), and a second *Cyclotella radiososa* sub-DAZ (D-1b, 8000 to 7700 ¹⁴C yrs B.P.).

The *Cyclotella comensis* DAZ (D-2, 7700 to 700 ¹⁴C yrs B.P.) represents the first change in planktonic taxa. This zone has an initial period rich in *C. distinguenda* var. *unipunctata* and *Fragilaria ulna* (D-2₁, 7700 to 3500 ¹⁴C yrs B.P.), and a second period characterized by elevated percentages of *C. krammeri* (D-2₂, 3500 to 700 ¹⁴C yrs B.P.).

The *Fragilaria*–*C. comensis* DAZ (D-3, 700 to 50 ¹⁴C yrs B.P.) shows higher abundances of periphytic *Fragilaria* species, with still high values of *C. comensis*.

With D-4 (*C. distinguenda* var. *unipunctata* DAZ, 50 to 25 ¹⁴C yrs B.P.) a second large change in the planktonic species composition from *C. comensis* to *C. distinguenda* var. *unipunctata* assemblages takes place.

During D-5 (*Asterionella formosa* – *Fragilaria crotonensis* – *Tabellaria fenestrata* DAZ, 25 to -6 ¹⁴C yrs B.P.) the dominance of *Cyclotella* species eventually ends in Soppensee.

D-6 (*Stephanodiscus parvus* – *Asterionella formosa* DAZ, -6 to -40 ¹⁴C yrs B.P.) is characterized by the mass expansion of small *Stephanodiscus* species.

Vegetation and catchment history

In order to better understand past changes in the water column of Soppensee, it is necessary to have knowledge of past changes in the lake catchment. Detailed palynological studies at Soppensee (Lotter et al., 1992; Lotter & Kienast, 1992; Lotter, 1999) as well as at other sites in central Switzerland (Lotter, 1988) revealed the late-glacial and Holocene vegetation development of this region. Regional pollen zones as defined by Ammann et al. (1996) have been applied to the Soppensee pollen stratigraphy. A varve chronology, as well as a large number of AMS radiocarbon dates on terrestrial macrofossils helped to establish a sound chronological framework (Hajdas et al., 1993).

The Holocene pollen stratigraphy of Soppensee (Figure 3) shows the classical succession of forest trees for the Swiss Plateau. The lowermost regional PAZ

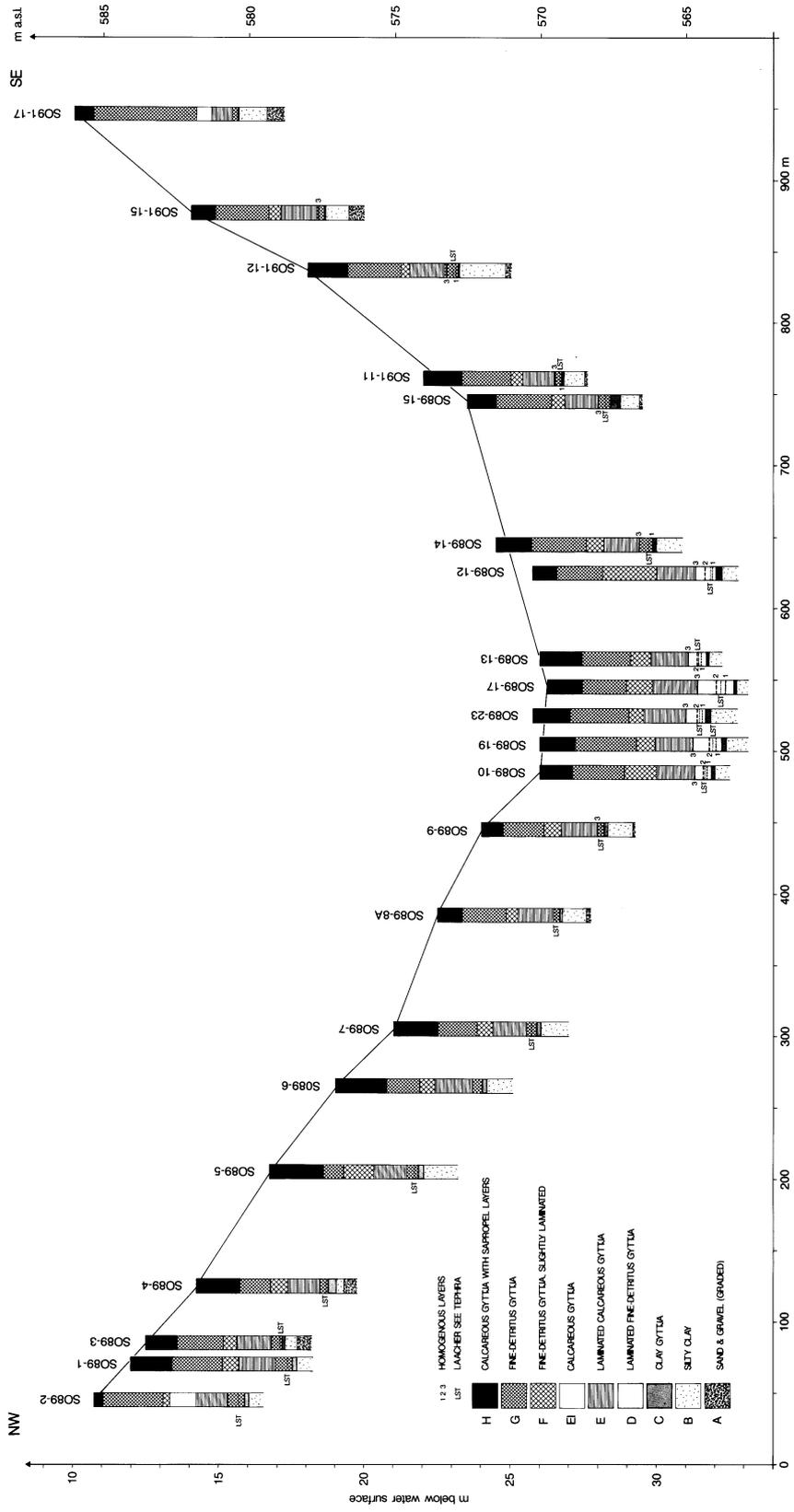


Figure 2. Longitudinal lithology transect through Soppensee.

represented in the pollen diagram (Chb-4: *Pinus* PAZ) is characterized by pine and birch pollen with many NAP taxa. The vegetation during this period has been inferred as an open *Pinus-Betula* woodland. Specifically, PAZ Chb-4b (Gramineae-NAP sub PAZ) reflects the Younger Dryas biozone (see, e.g., Ammann & Lotter, 1989), i.e. the last cooling phase of the last glacial, that ended 10,000 ¹⁴C yrs B.P., whereas Chb-4c (*Betula-Corylus* sub PAZ) represents the Preboreal biozone, i.e. the onset of the Holocene. During Chb-5 (*Corylus-Quercetum mixtum* PAZ) deciduous shrubs and trees such as hazel and mixed oak forest taxa (elm, oak, lime, maple) expanded rapidly on the Swiss Plateau. After an initial phase of hazel scrubs with oak and elm, the forests consisted of oak, lime and elm with ash on wetter soils (Chb-6: *Quercetum mixtum-Corylus* PAZ).

Around 7500 radiocarbon years B.P. the first shadow tolerant trees such as fir (*Abies alba*) migrated into the catchment of Soppensee and expanded ca. 7000 B.P. while beech (*Fagus sylvatica*) also appeared. Mixed fir and beech forest with oak dominated the vegetation around Soppensee for at least five millennia (Chb-7: *Fagus-Abies-Alnus* PAZ).

At Soppensee and at other sites on the Swiss Plateau (Haas, 1996), there are early indications of regional human activity such as single cereal pollen grains that are attributed to the transition from the Mesolithic to the Neolithic period (see e.g. Erny-Rodmann et al., 1997). According to the increased occurrence of anthropogenic indicator pollen (e.g. Cerealia, *Plantago lanceolata*) Neolithic settlements may have been established in the pollen catchment of Soppensee between 5000 and 4500 B.P., whereas forest clearances and local settlements are more evident between ca. 3800 and 3000 B.P., i.e. during the Bronze Age.

The first major forest clearances took place during the Iron Age, ca. 2500 yrs ago. It was, however, during the Medieval period, when large-scale changes in the landscape on the Swiss Plateau took place (Chb-8: *Quercus*-NAP PAZ). Hemp (*Cannabis*) cultivation and retting in lakes became an important part of local agriculture after the foundation of monasteries in the 11th and 12th century (e.g. Lotter, 1988; Ammann, 1989b). The open beech-fir and oak forest were used as wood pastures. With the opening of the forests the sediment accumulation rates increased considerably. The topmost regional PAZ (Chb-9: NAP-*Pinus*-(*Picea*) PAZ) represents the agricultural activity of the last centuries and is characterized by further deforestation

and regional plantations of pine and spruce. The first occurrence of pollen of *Zea mais* in the topmost 30 cm is dated to the 1950s when agriculture underwent an intensification.

Lake history

Diatoms

The diatom assemblages in Soppensee were stable throughout the Holocene and showed only minor long-term changes. The assemblages are characterized mainly by alkaliphilous and alkalibiontic taxa, typical for hard-water lakes. The diatom community composition was dominated by planktonic *Cyclotella* species (see Figure 4), especially by the small, taxonomically difficult *C. comensis* type (see, e.g., Wunsam et al., 1995; Hausmann and Lotter, submitted). Grouping the diatom assemblages according to their trophic requirements (e.g. van Dam et al., 1994) suggests that Soppensee has been a eutrophic lake throughout the whole Holocene. This compares well with the trophic reconstruction on the basis of chironomids and cladocera (Hofmann, in press).

Meso- to eutrophic diatoms dominated the assemblages during the Holocene until ca. 50 yrs ago (D-6), when hypertrophic taxa (mainly *Stephanodiscus parvus*) became dominant (see Figure 4). Recently, several numerical inference models using diatom assemblages for reconstructing past epilimnetic total phosphorus (TP) concentrations have been presented (e.g. Bennion, 1994; Wunsam & Schmidt, 1995). However, there have been only a few applications of these TP transfer functions to subfossil diatom assemblages (e.g. Anderson et al., 1993; Fritz et al., 1993; Bennion et al., 1995). Lotter et al. (1998) have presented a quantitative diatom-TP inference model for hard-water lakes in the Alps. Lotter (1998) successfully evaluated this model by comparing annual-resolution diatom-TP inferences with measured TP concentrations in the water column of a Swiss lake. The same TP inference model has been applied to the Soppensee diatom stratigraphy (Figure 8). The diatom-inferred TP concentrations ranged between 20–40 µg/L throughout the major part of the Holocene thus indicating meso- to eutrophic conditions (OCDE, 1982). It is only in the topmost 30–40 cm of sediment that the diatom-inferred TP concentrations increased to values comparable to the present-day TP range (see Table 1). This illustrates that the major rise in eutrophication of Soppensee took

SOPPENSEE S086-14
 Fossil Pigments
 Anl.: H. Züllig 1987

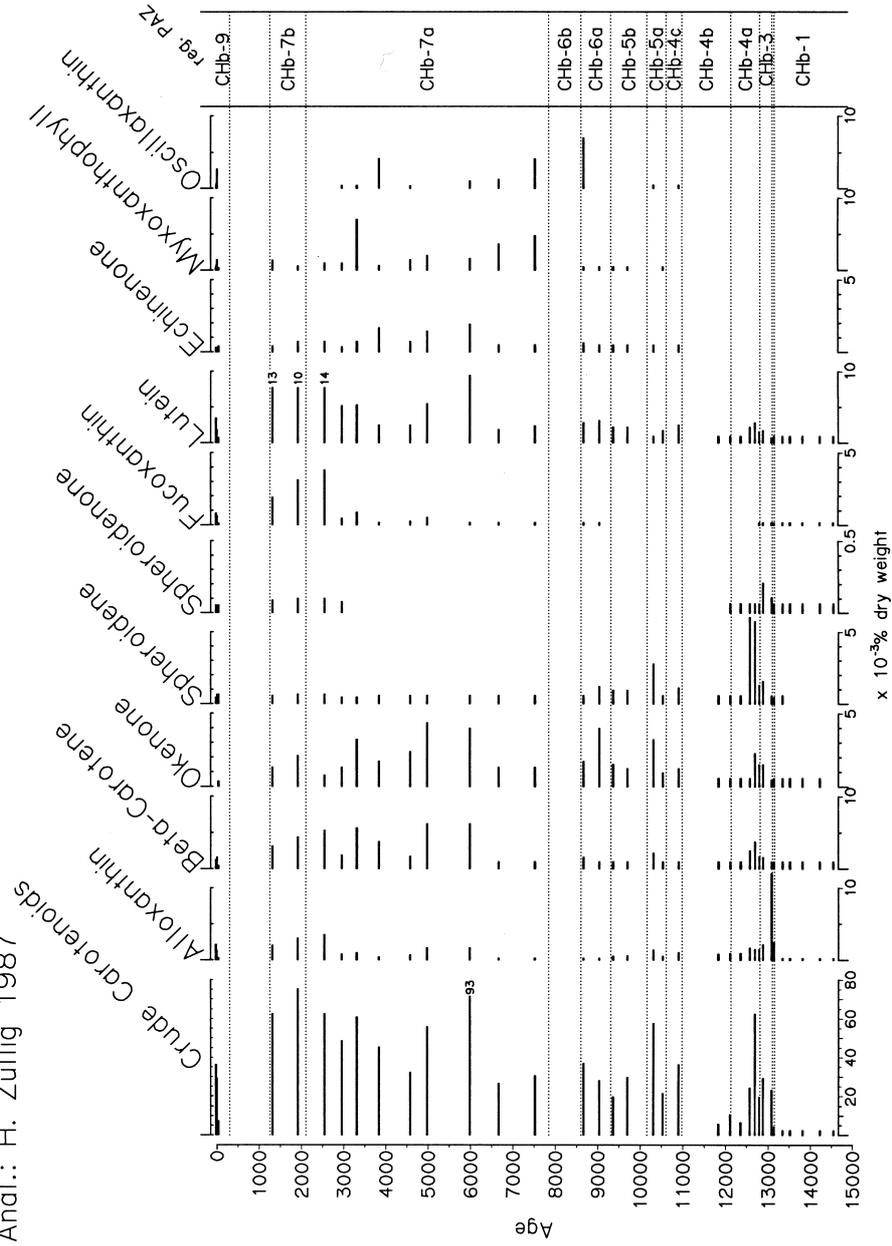


Figure 5. Fossil pigments extracted from Soppensee core Soppensee S086-14 (after Züllig, 1989). The zonation refers to the regional Pollen Assemblage Zones (see Figure 3), while the time-scale refers to calibrated years B.P. (for details see Hajdas-Skowronek, 1993 and Hajdas et al., 1993).

place as a result of the intensification of agriculture after World War II.

The ratio of diatoms to chrysophyte cysts has often been used as a tool to assess past trophic conditions in lakes (Smol, 1985). In the case of Soppensee, this ratio (Figure 6) is high throughout the whole lake history thus suggesting nutrient-rich conditions. Single peaks of chrysophyte cysts in core SO89-23 may rather be related to the better preservation of these more heavily silicified microfossils than to trophic changes.

The lowermost sediments analysed for diatoms date back to the transition from the Younger Dryas to the Preboreal biozone (i.e. 10,000 ^{14}C yrs B.P.). The Preboreal biozone (Chb-4c) reflects the rapid change from pioneer pine-birch woodland to a thermophilous mixed deciduous forest. Regional PAZ CHb-5b represents the consolidation phase of this mixed deciduous forest. The changing abundance of *Fragilaria* species in DAZ D-1a occurs parallel to changes in the terrestrial vegetation and changes in the lithology. The

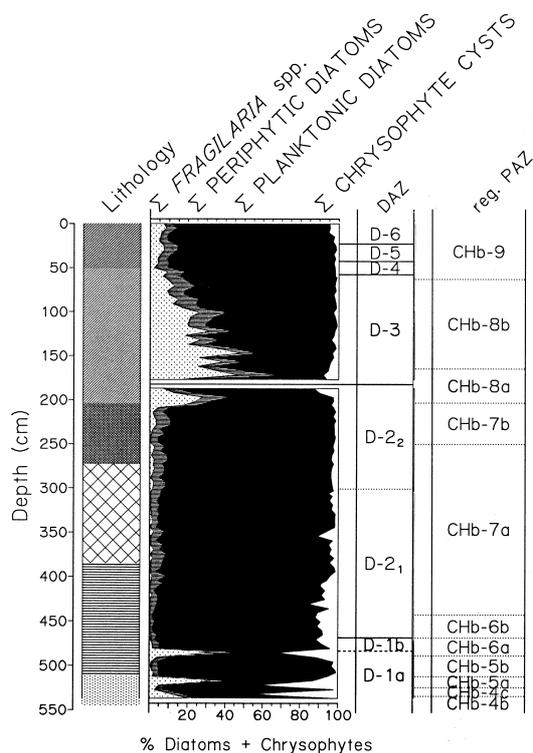


Figure 6. Summary diagram of diatoms versus Chrysophyte cysts in core Soppensee SO89-23. The zonations refer to Diatom Assemblage Zones (DAZ, see Figure 4) and to regional Pollen Assemblage Zones (reg. PAZ, see Figure 3).

occurrence of periphytic *Fragilaria* species is a characteristic feature of late-glacial sediments at many sites. This phenomenon is commonly interpreted as being either the effect of a longer ice-cover reducing the growth of planktonic diatoms (Smol, 1983, 1988) or as the effect of higher nutrient availability, e.g. through soil erosion in the catchment. The short increase at 485 cm in *Fragilaria* species before the transition to D-1b is synchronous with the deposition of the Vasset-Killian tephra, dated to 8230 ± 40 radiocarbon years B.P. (Hajdas-Skowronek, 1993). High-resolution diatom analyses combined with constrained ordination techniques may provide a tool for testing the hypothesis that the actual tephra deposition or the volcanic eruption may have had an impact on aquatic and terrestrial ecosystems. Investigations of pollen and diatom assemblages from different sites in Central Europe in relation to volcanic eruptions suggest that catchment geology as well as the distance from the eruption have an influence on whether there is an impact on aquatic and/or terrestrial ecosystems (see, e.g., Lotter & Birks, 1993; Birks & Lotter, 1994; Lotter et al., 1995).

The transition from D-1 to D-2 is synchronous with the boundary between PAZ CHb-6a to CHb-6b, i.e. the decrease in hazel and the fir migration into the catchment of Soppensee ca. 7500 radiocarbon yrs ago. Although there was a large change in forest composition in the catchment of Soppensee during D-2, the diatom assemblages reflect more stable conditions. However, some minor fluctuations in the species composition correspond to the development of terrestrial vegetation as revealed by the pollen stratigraphy. The onset of the *Fragilaria crotonensis* occurrence during D-2₁ in Soppensee (ca. 5000 B.P.) is correlated with the occurrence of anthropogenic indicator pollen such as *Cerealia* and *Plantago lanceolata* (see Figure 3). The changes in the diatom assemblages in D-2₂ (i.e. the occurrence of *Cyclotella stelligera* and *C. meneghiniana*) are closely correlated with increases in herb pollen and anthropogenic indicator pollen reflecting increased human impact in the catchment of Soppensee during the Bronze Age. With the establishment of local Neolithic (ca. 4700 B.P.) and especially Bronze Age settlements (ca. 3800 B.P.) at Soppensee the TP reconstructions (Figure 8) increased from around 30 to 30–40 $\mu\text{g/L}$. This trend continues into the Iron Age (ca. 2200 B.P.), when the diatom-inferred TP concentrations started to decrease to ca 20 $\mu\text{g/L}$.

The first substantial decrease in *C. comensis* at the transition from D-2 to D-3 occurs within PAZ CHb-8a

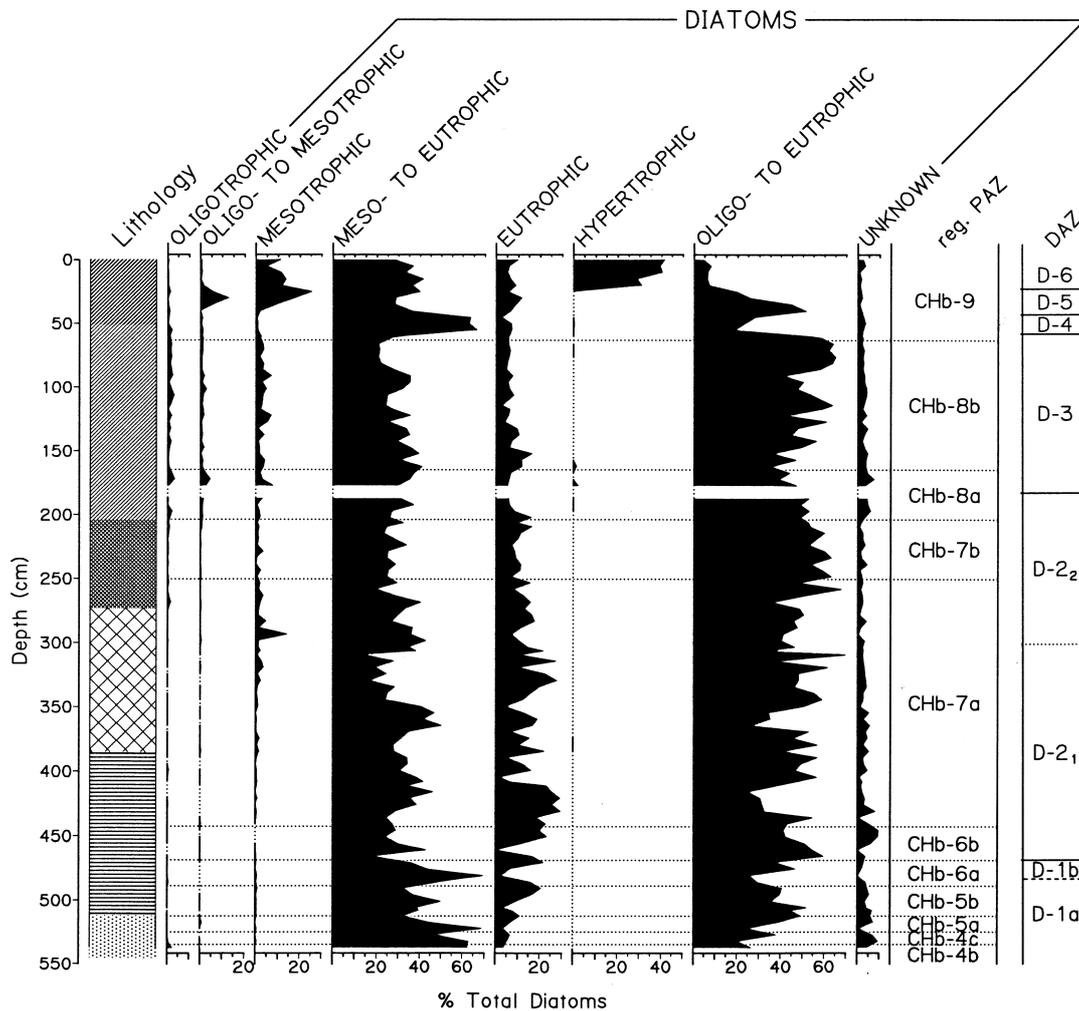


Figure 7. Diatoms in core Soppensee SO89–23 grouped according to their trophic preferences (grouping according to van Dam et al., 1994). The zonations refer to Diatom Assemblage Zones (DAZ, see Figure 4) and to regional Pollen Assemblage Zones (reg. PAZ, see Figure 3).

(i.e. during the Middle Ages). Its onset, however, occurs at the beginning of CHb-8a, i.e. at a time when agriculture and pasturing were intensified and hemp retting in Soppensee started. Increased herb pollen values indicate an increased and massive clearing of the forests, including the riparian *Alnus* woodlands at the border of the lake (Figure 3). The soil erosion due to forest clearance is also likely to have led to an increase in nutrients (Bormann et al., 1974). Moreover, hemp retting in the littoral parts of the lake may have provided additional habitats for periphytic algae as well as additional nutrients such as carbon, phosphorus, and nitrogen. It is likely that the lack of tree cover around the lake led to higher wind exposure of the open-water area, thus inducing a better mixing of the water column

and a better mineralization of nutrients at the water-sediment interface. Such an increase in the mixing rate may also favour focusing of diatoms from the littoral part to the centre of the basin.

The end of the *Cyclotella* dominance (i.e. the transition from D-3 to D-4) is preceded by only a few centimetres by the transition from PAZ CHb-8b to CHb-9, with a renewed increase in herb pollen, especially grasses (Figure 3). The highest dynamics in the subfossil diatom flora occur in the topmost 50 cm and include DAZ D-4 to D-6. Similar diatom successions have been observed in Diss Mere (Fritz, 1989) as well as in the topmost sediments of the hypertrophic Rotsee (419 m a.s.l.), located only 15 km to the SE of Soppensee (Lotter, 1988; Lotter, 1989), where the succession has

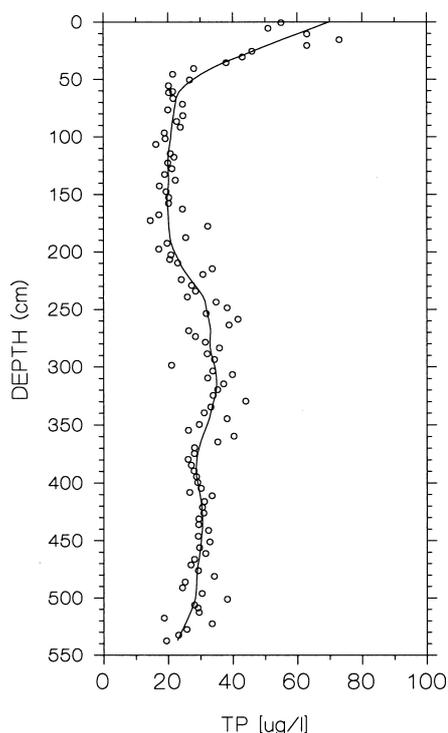


Figure 8. Diatom-inferred total phosphorus (TP) concentrations for Soppensee core SO89-23. The reconstruction applied the weighted averaging partial least squares (WA-PLS) model by Lotter et al. (1998).

been interpreted as the result of steadily increasing nutrients leading to a change in the Si:P ratio. High-resolution diatom analyses in annual sediment layers of Baldeggersee (Lotter et al., 1997b) show similar dynamic changes from *C. comensis* to *F. crotonensis* and eventually to *S. parvus* dominated assemblages that are the result of increasing eutrophication (Lotter, 1998).

The two major dynamic changes in the diatom assemblages are characterized by variations in the abundance of periphytic *Fragilaria* species (Figure 6), which may be used as an indicator for periods of perturbation, such as lake-level lowering, climatic cooling, or forest clearance. Although the origin and dynamics of these disturbances are different, their effect on the diatom assemblages may be similar, with periphytic *Fragilaria* taxa rapidly occupying new niches.

Fossil pigments

The analysis of sedimentary fossil algal pigments may help in interpreting past changes in lake productivity

and trophic state. Züllig (1982) investigated several Swiss lakes with respect to fossil carotenoids, thus allowing a reconstruction of the trophic history of these lakes on the basis of their fossil sedimentary pigments. Optical density analysis of crude carotenoids, i.e. the sum of carotenes and carotenoids, was used as a measure for past algal bioproduction (Züllig, 1985). Single carotenoids can be separated by means of thin-layer chromatography. Several pigments are characteristic of specific groups of algae, such as myxoxanthophyll for Cyanophyta (oscillaxanthin for *Oscillatoria* taxa), lutein for Chlorophyta but also for higher plants, fucoxanthin for Chrysophyta (including diatoms), alloxanthin for Cryptophyta. Other pigments originate from specific taxa, such as okenone from *Chromatium* and a few other phototrophic purple sulphur bacteria of the family Chromatiaceae that live in anoxic conditions. *Rhodospseudomonas* and a few other Rhodospirillaceae taxa produce the yellow pigment spheroidene under anoxic conditions, but as soon as even small amounts of oxygen are available they produce the red spheroidenone pigment (Züllig, 1985). Therefore, the presence of spheroidene as well as okenone in sediments may be used as an indicator for past meromictic lake conditions.

Core SO86-14 from the deepest part of Soppensee includes the late-glacial and Holocene sedimentary record. It has been analysed for fossil pigments by Züllig (1989). The chronological time-control of the original diagram has been improved by refined pollen analysis and varve counts. It has, therefore, become possible to plot the pigment results on an age scale (Figure 5). Owing to an equipment malfunction a substantial portion of sediment between the trip-weight gravity core and the main Kullenberg core has not been recovered. Therefore, no sediment was available for the time between ca. 1300 to 50 cal. yrs B.P.

In the lowest samples of regional PAZ CHb-1 (*Artemisia* PAZ, corresponding to the Oldest Dryas biozone), low algal productivity can be inferred on the basis of the low concentration of carotenoids. Alloxanthin was the dominant pigment, suggesting that Soppensee was mainly colonized by Cryptophyta, an algal group usually characteristic for cold environments. With the onset of PAZ CHb-2 (*Juniperus-Hippophaë* PAZ, corresponding to the Bølling biozone) the productivity increased and spheroidene started to occur. Traces of lutein and fucoxanthin as well as of okenone and spheroidenone indicate that during the late-glacial period (i.e. regional PAZ CHb-1 to CHb-4b) Soppensee was holomictic with periods of hypolimnetic anoxia. The occurrence of trees in the catchment and around

the lake may have had a twofold influence on lake development. Firstly, pedogenesis may have accelerated, and the organic compounds washed in brought additional carbon into the lake to augment the oxygen-consumption rate. And secondly, the tree cover around the lake protected the lake surface from wind, thus changing the mixing rate and prolonging the time of stratification. During CHb-4b (Younger Dryas biozone) spheroidenone disappeared, marking the onset of meromixis. However, as there is only one sample analysed for the whole of this zone, the exact timing of this event cannot be determined with certainty. Nevertheless, judging from the occurrences of both okenone and spheroidene as well as the absence of spheroidenone, Soppensee had a long Holocene phase characterized by meromictic conditions. This phase ended during the third part of PAZ CHb-7a approx. 3000 cal. yr B.P. During this part of the Holocene the high values of raw carotenoid as well as the presence of myxoxanthophyll and especially of oscillaxanthin indicate a nutrient rich phase with cyanobacteria and *Oscillatoria* species. After the break-down of meromixis lutein, fucoxanthin, and alloxanthin increased and may be considered as indicators for a change in algal composition. Comparison of the amount of all pigments as well as the crude carotenoids in the uppermost sediment with the values further down the core, would imply a decrease in the trophic state of Soppensee. This is in contrast to the diatom assemblages in the topmost sediment, which indicate hypertrophic conditions. However, the effect of dilution by higher accumulation rates and less sediment compaction of the topmost sediment may explain this phenomenon.

Pollen of aquatic plants

As core SO89-23 was taken in the deepest part of the basin, little pollen of macrophytes was found (Figure 9). Today, only at the NW and SE end of the lake a small littoral zone allows the formation of floating-leaved and reed vegetation, whereas the major part of the basin has a steep morphometry (see Figure 1). Pollen of *Myriophyllum* and *Potamogeton* species are present throughout the entire Holocene, whereas vegetative parts of *Ceratophyllum* and *Nuphar* as well as *Nymphaea* pollen have their first occurrences in PAZ CHb-6 and 7, respectively. Remains of planktonic green algae such as *Pediastrum* and *Coelastrum* are also preserved in the pollen samples.

The major changes in the aquatic pollen assemblages and *Pediastrum* percentages take place at the transition

from PAZ CHb-7 to CHb-8. The coincidence of the massive forest clearing and hemp retting with the higher amounts of *Pediastrum* found (Figure 9) may be caused by additional nutrient input through soil erosion and/or retting.

The topmost 30 cm of the record is characterized by a mass occurrence of remains of the planktonic coccal green algae *Coelastrum* cf. *cambricum*.

Conclusions

The development of terrestrial vegetation in the catchment of Soppensee was reconstructed by pollen analysis, whereas analyses of diatoms and fossil pigments allowed the lake's history to be inferred. Several regional, natural and man-made changes in forest composition took place throughout the Holocene. The major natural changes in terrestrial vegetation first occurred around 9500 B.P. with the change from a pine-birch woodland to a deciduous mixed oak forest. Meromixis was already established towards the end of the late-glacial period in Soppensee. Total phosphorus levels increased in the early Holocene and the lake was meso- to eutrophic throughout its Holocene history.

Another important change in terrestrial vegetation occurred around 7000 B.P. when the mixed oak forest was successively replaced by a shadow-tolerant fir-beech forest. The first traces of human activity around Soppensee are present for the last 5000 years and consequently the total phosphorus concentrations are slightly increased. The first significant forest clearances took place during the Bronze Age and especially during the Iron Age. This more exposed situation led to a better wind-induced mixing of the lake and meromixis subsequently broke down during the Iron Age.

Major anthropogenic deforestation occurred during the Middle Ages and changed the terrestrial ecosystem drastically leading to today's open landscape. Soil erosion and hemp retting brought more organic matter and nutrients into the lake. After World War II agriculture intensified leading to a massive anthropogenic eutrophication of the lake resulting in a complete change in diatom assemblages within the last 50 years.

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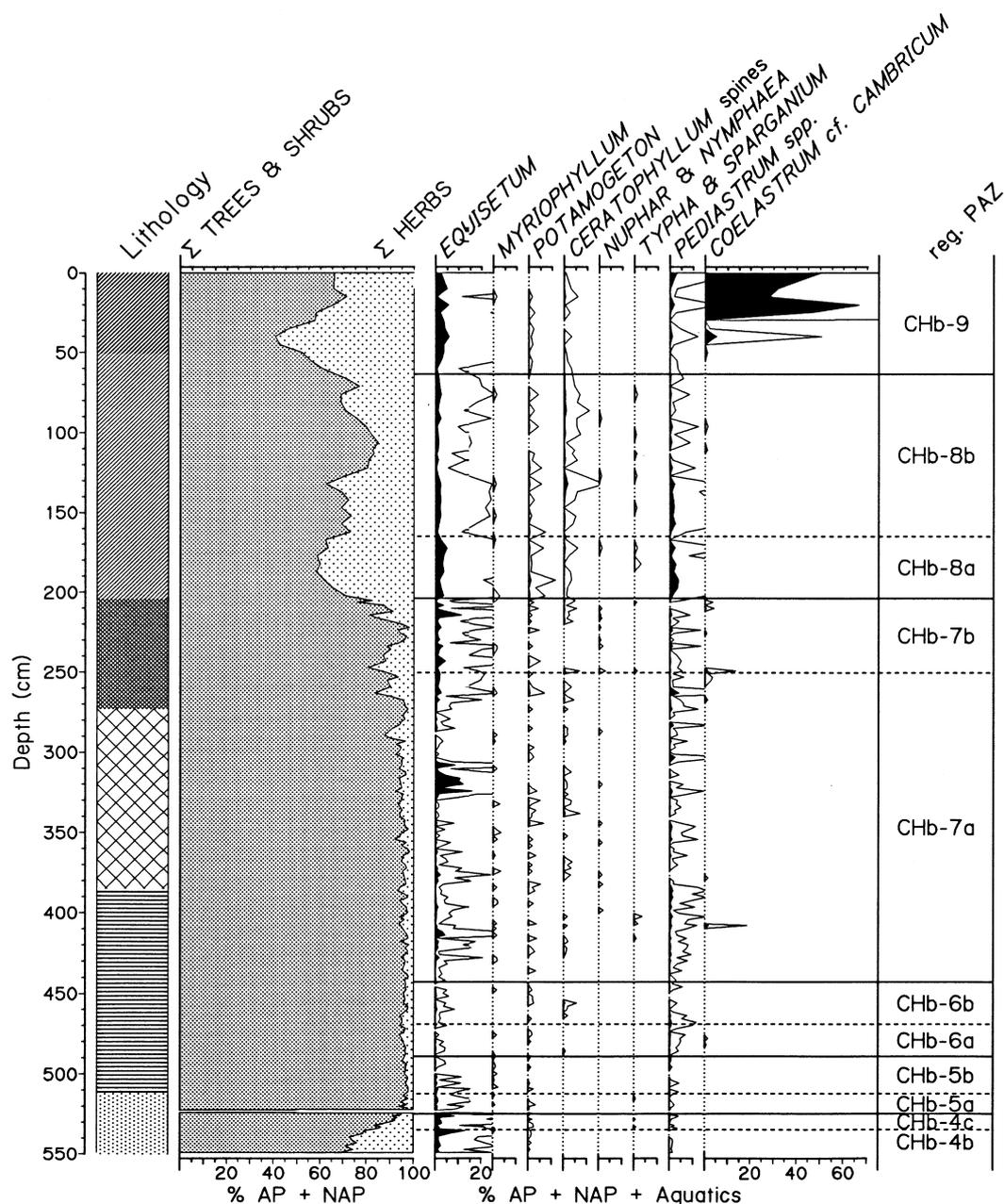


Figure 9. Holocene summary pollen diagram of upland vegetation and percentage curves of aquatic taxa and palynomorphs in Soppensee core SO89-23. AP: arboreal pollen; NAP: non-arboreal pollen. The zonation refers to regional Pollen Assemblage Zones (reg. PAZ, see Figure 3) defined on the basis of the upland vegetation.

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