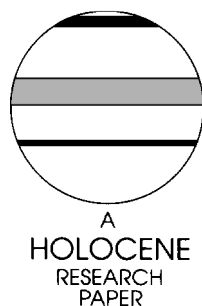


# Interactions of climate and land use documented in the varved sediments of Seebergsee in the Swiss Alps

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**Abstract:** This paper presents a multiproxy high-resolution study of the past 2600 years for Seebergsee, a small Swiss lake with varved sediments at the present tree-line ecotone. The laminae were identified as varves by a numerical analysis of diatom counts in the thin-sections. The hypothesis of two diatom blooms per year was corroborated by the <sup>210</sup>Pb and <sup>137</sup>Cs chronology. A period of intensive pasturing during the 'Little Ice Age' between AD 1346 and AD 1595 is suggested by coprophilous fungal spores, as well as by pollen indicators of grazing, by the diatom-inferred total phosphorus, by geochemistry and by documentary data. The subsequent re-oligotrophication of the lake took about 88 years, as determined by the timelag between the decline of coprophile fungal spores and the restoration of pre-eutrophic nutrient conditions. According to previous studies of latewood densities from the same region, cold summers around AD 1600 limited the pasturing at this altitude. This demonstrated the socio-economic impact of a single climatic event. However, the variance partitioning between the effects of land use and climate, which was applied for the whole core, revealed that climate independent of land use and time explained only 1.32% of the diatom data, while land use independent of climate and time explained 15.7%. Clearly land use influenced the lake, but land use was not always driven by climate. Other factors beside climate, such as politics or the introduction of fertilizers in the seventeenth and eighteenth centuries also influenced the development of Alpine pasturing.

**Key words:** Varves, climate, land use, eutrophication, baseline conditions, transfer function, multi-proxy approach, diatoms, pollen, Alps, Switzerland, 'Little Ice Age', late Holocene.

## Introduction

Palaeolimnological studies have generated wide interest in aquatic science, because they offer the opportunity to study the long-term dynamics of past climatic and trophic change. The recovery of lakes from phosphorus loads of the 1960s (Mosello *et al.*, 1986; Stoermer *et al.*, 1996) have led to a growing interest in the process

involved in re-oligotrophication. However, re-oligotrophication processes are often not yet completed and knowledge about baseline conditions, important for lake management, is often missing (Bürgi *et al.*, 1985). Palaeolimnological studies may help to define background conditions to establish lake-management goals (e.g., Anderson *et al.*, 1993; Hall and Smol, 1993) and may additionally help to predict lake dynamics.

Accurate dating of sediments constitutes an essential part of palaeolimnological studies when palaeoresults are transferred to studies of modern lakes. In the present study, a varve chronology was established and evaluated by two independent approaches: (i) the numerical analysis of diatom counts in thin-sections; (ii) caesium and lead dating. Beside the exploration of past lake dynamics, an accurate dating offers the possibility to relate external historical

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or dendrochronological studies to the palaeodata and thus aid in evaluation of diatom-inferred reconstructions. This is important because in Switzerland the tree-line ecotone was used for pasturing, and lakes at this altitude are also influenced by climatic change. On the one hand, climate has an indirect influence on the lake due to tree-line fluctuations (Wick and Tinner, 1997), thus changing the content of dissolved organic carbon (MacDonald *et al.*, 1993). It also affects chemical weathering in the catchment (Koinig *et al.*, 1998) and determines the length of ice cover (e.g., Lotter and Bigler, 2000) and the change of circulation patterns of the Lake. On the other hand, climate restricts land use and thus the nutrient input. In this paper, a palaeolimnological multiproxy approach combined with dendrochronological and historical data was used to distinguish signals of land use from natural climatic fluctuations. Long-term dynamics of changes in the trophic state are also described.

## Study site

Seebergsee (46°37'N, 7°28'E) is located at an elevation of 1830 m a.s.l., within the present-day tree-line ecotone in the northern Swiss Alps southwest of Lake Thun (Figure 1). The vegetation consists mainly of Alpine meadows, scattered stands of *Picea abies*, single trees of *Pinus cembra* and shrubs of *Alnus viridis*. The lake is surrounded by *Equisetum fluviatile* and sedges. *Potamogeton filiformis* is the dominant water plant. Since 1903 the lake has been stocked with fish, and since 1972 it has been a nature reserve (Guthruf *et al.*, 1999). The lake has a surface area of 0.06 km<sup>2</sup> and a volume of 0.38 km<sup>3</sup>. It has two basins with maximum depths of 15.5 and 9 m (Figure 1).

The hydrological catchment has an area of 0.23 km<sup>2</sup> and consists mainly of carbonate rocks. The geology and topography suggest that the lake is possibly of karstic origin and therefore naturally free of fish. No inlet is visible, and the outlet disappears 510 m beyond the lake in a doline. A steep slope 200 m high rises at the southwest shore of the water body. The catchment consists of 15% rocks, 26% screes and 45% bare ground, and 14% is used today for cattle grazing (Guthruf *et al.*, 1999). Old foundations of six Alpine farming huts exist near the lake (Zumstein, personal communication). Due to easy access, Seebergsee is economically strongly linked with the development of urban areas like Bern or Freiburg. Thus it may be sensitive to past urban developments.

In summer 1998, the water column below 7 m depth was free of oxygen and rich in sulphur bacteria. It did not circulate before

the beginning of November. In 1999, the ice cover lasted till the first week of June, followed by a mixing period of only half a week. In July, the lake reached a maximal temperature of 18°C and had a thermocline at 4 m depth.

## Methods

### Sediment sampling and dating

In 1996, three freeze cores (Lotter *et al.*, 1997) of up to 110 cm length and several Kullenberg long cores (Kelts *et al.*, 1986) were taken in the deepest part of the lake at a water depth of 15.5 m. The sediment-water interface in the longest freeze core (SEEB96-C) could not be properly sampled due to over penetration of the freeze-corer. Therefore, the topmost 10 cm of freeze core SEEB96-A were used and the two cores were correlated at a conspicuous stratigraphic marker. The resulting combined core SEEB96-A/C was sampled in contiguous 1 cm slices by cutting the frozen sediment with an electric bone-saw. Samples were freeze-dried for further analyses.

Petrographic thin-sections of the freeze cores and the first 200 cm of the Kullenberg core were prepared by impregnating the sediment with Spurr's epoxy resin (Lotter and Lemcke, 1999). Two laminae counts were carried out with low-magnification binocular microscope and crossed-nichols. The correlation between the combined freeze core and the Kullenberg core is based on distinct features in the organic carbon content of both cores. This correlation was verified by conspicuous and abrupt changes in diatom assemblages analysed in the thin-sections.

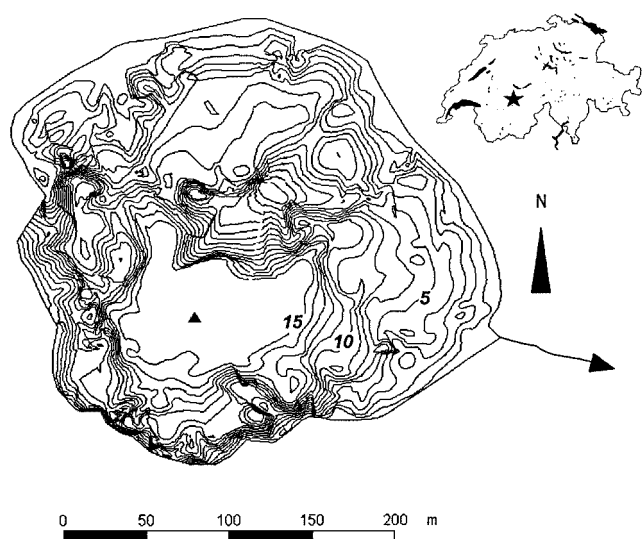
Continuous fields of view were analysed in the thin-sections by oil-immersion light microscopy at a magnification of 1000× to assess seasonal patterns of diatom abundance and thus to cross-check the laminae counts. The total amount of diatoms was enumerated in 3500 continuous rectangular fields of view for the topmost 40 cm, whereas spot-checks were carried out between 128 and 179 cm sediment depth. In order to define sections of higher diatom accumulation representing diatom blooms, a numerical zonation of  $\log(n+1)$ -transformed diatom counts, with a dummy variable as second 'taxon', was carried out by the clustering method of constrained incremental sum of squares with squared chord distance, as implemented in the software CONISS (Grimm, 1987).

### Geochemistry and mineralogy

Freeze-dried sediment was analysed for inorganic carbon ( $C_{inorg}$ ) with a coulometer (Coulometric Inc.5011 CO<sub>2</sub>-Coulometer). Total carbon ( $C_{tot}$ ) was determined with a Carlo Erba CHNS Elemental Analyzer (Model EA 1108), and organic carbon ( $C_{org}$ ) was calculated by the difference between  $C_{tot}$  and  $C_{inorg}$ .

The freeze-dried samples were measured for radionuclides in a well-type Geli detector for a minimum of 24 h. The isotopes <sup>137</sup>Cs and <sup>210</sup>Pb were used to identify the characteristic activity maximum in 1963 (atmospheric bomb fallout) and the rise of unsupported <sup>210</sup>Pb activities in 1900, respectively.

The mineral composition of sediment samples was determined by x-ray diffraction (XRD) of smear slides of 114 samples. For smear-slide preparation approximately 3 mm<sup>3</sup> of sediment were suspended with ethanol in a mortar and ground to <63 μm. The suspension was then transferred to a glass sample-holder, where it slowly dried. Diffraction patterns were recorded with a Scintag XDS 2000 at 45 kV and 40 mA with Cu Kα radiation between 2 and 70° 2θ. Peak intensities are expressed as percentage of a given peak relative to the sum of all detected peaks. In this way, peak percentages are used as semiquantitative measures for the concentration of a mineral in a given sample relative to another sample (cf. Fanning *et al.*, 1989).



**Figure 1** Study site Seebergsee (1830 m a.s.l.; contour lines 1 m) in the Swiss Alps (see inset).

## Biological analyses

The sediment was sampled in 1 cm slices covering between three and eight years. Pollen, fungal spores and diatoms were analysed at the same levels for the top 420 cm, which cover approximately the past 2600 years.

For diatom analysis, a known volume of sediment was treated with hot 10% HCl and 30% H<sub>2</sub>O<sub>2</sub>. Microspheres were added to calculate diatom-accumulation rates (Battarbee and Kneen, 1982). The diatom-microsphere suspension was mounted on slides with Naphrax<sup>®</sup>. A minimum of 300 valves was counted for each sample on a Leitz Dialux 22 microscope at a magnification of 1000× with phase contrast. The diatom nomenclature follows Krammer and Lange-Bertalot (1986–91).

For pollen and fungal-spore analysis, a known volume of sediment was treated with hot 10% KOH and 40% HF. *Lycopodium* tablets were added to calculate pollen- and spore-accumulation rates (PAR, SAR; Stockmarr, 1971). Pollen samples were analysed at 400× magnification. For identification of pollen types, the *Northwest European pollen flora* (Punt, 1976; Punt and Blackmore, 1991; Punt *et al.*, 1988; 1995; Punt and Clarke, 1980; 1981; 1984), Reille (1992; 1995; 1998), Moore *et al.* (1991), and the reference collection of the Institute of Plant Sciences in Bern were consulted. Fungal spores were determined following van Geel (1986) and van Geel *et al.* (1995).

## Numerical methods

Zonation of biological stratigraphical data was carried out on percentage data by optimal partitioning (Birks and Gordon, 1985), which is a non-hierarchical method implemented in the program ZONE (Lotter and Juggins, 1991). The number of statistically significant zones was assessed by a broken-stick model according to Bennett (1996). Spores, aquatics and chrysophyte remains were excluded from the zonation, but are shown in the diagrams.

A diatom-inference model for total phosphorus (TP), consisting of 68 surface samples and 9 well-dated fossil samples of small, hardwater lakes in Switzerland (Lotter *et al.*, 1998), was extended by 21 surface samples and 7 well-dated fossil samples (Hausmann, unpublished data) and applied to the diatom biostratigraphy by the method of weighted averaging partial least squares (WA-PLS; ter Braak and Juggins, 1993).

The varve chronology allowed the calculation of accumulation rates of the biological data as well as comparison of the total phosphorus reconstruction with documentary data and latewood densities from trees of the Bernese Oberland (Schweingruber *et al.*, 1988). In order to compare equivalent time intervals, averages of latewood density were calculated for those years covered by each sediment sample.

The variance of the diatom data was partitioned between climate and land use. Climate was represented by latewood density, whereas land use was modelled by the sum of grazing-indicator pollen and diatom-inferred TP and their interaction, because we assume that total phosphorus of the water column might be influenced by grazing. The temperature index of Pfister (1985) with a seasonal resolution was not used because it does not encompass the beginning of the '*Stephanodiscus parvus* period'. Unimodal methods were used for direct gradient analysis, because the gradient length of the diatom data is 2.86 SD, as recommended by ter Braak and Prentice (1988). For the variance-partitioning analysis of the diatom data, a series of partial Canonical Correspondence Analyses (CCA) were carried out on square-root-transformed percentage data (Table 1). To test the climatic hypothesis, latewood density was the explanatory variable, and the sum of grazing-indicator pollen, diatom-inferred TP and age were used as covariables, thus statistically partialling out their effect. In order to test the land-use hypothesis, the sum of grazing-indicator pollen and diatom-inferred TP were the explanatory variables, and latewood density and age were used as covariables. The significance of the

predictor-response relationship was tested by a Monte Carlo permutation test (999 permutations). In order to investigate the dynamic changes of the diatom assemblages, a detrended correspondence analysis (DCA) was applied to the square-root-transformed diatom data. The results are shown in a trajectory plot (Figure 7). All ordinations were performed with the program CANOCO version 4.0 (ter Braak and Smlauer, 1998).

## Results

### Chronology

According to the <sup>137</sup>Cs profile, the 1963 peak from nuclear bomb tests is in the sample at 5–6 cm sediment depth (Figure 3). The nuclear accident at Chernobyl in April 1986 is not documented in the sediment, as at the time of the radioactive fallout the mountain lakes in the Bernese Oberland were still ice-covered. The <sup>210</sup>Pb concentrations reach background levels at a sediment depth of about 20 cm (Figure 3). This level is therefore dated to c. AD 1900. This is in agreement with palynological results showing a decline in *Cannabis* pollen, commonly dated to the end of the nineteenth century (van der Knaap *et al.*, 2000), between 19 and 16 cm.

The first 4 m of the sedimentary record in the deepest part of Seebeggsee show distinct couplets of light and dark laminae. However, no apparent laminations can be observed in the topmost 15 cm by naked eye. The laminae couplets consist of dark layers of homogenous organic matter and light carbonate (dolomite) layers with occasional fine quartz grains.

The cumulative number of diatom blooms/2 is linearly related with a slope of 0.98 ( $r = 1.00$ ) to the cumulative number of laminae before 1900 (below 20 cm; Figure 2). The two diatom abundance maxima in each lamina were considered to be the late spring/early summer and autumn diatom blooms (e.g., Tippett, 1964; Simola, 1979; Sommer *et al.*, 1986). The hypothesis of two diatom blooms per year was corroborated by the <sup>137</sup>Cs (5–6 cm = AD 1963) and the <sup>210</sup>Pb (20 cm c. AD 1900) chronology which are in good agreement with the diatom dating (6.7 cm = AD 1963 and 19.5 cm = AD 1900). Consequently, the couplets are formed seasonally (varves). However, every third year one layer is missing in the top 100 years ( $m = 0.66$ ,  $r = 1.00$ ). Therefore, the chronology of the Seebeggsee sediment is based on diatom counts for the topmost 40 cm and on varve counts between 40 and 213 cm of sediment depth. The chronology was extrapolated for the section between 214 and 400 cm by the mean accumulation rates of 0.128 cm yr<sup>-1</sup> as assessed for the sediments between 183 and 213 cm, which was before the eutrophication.

### Diatom stratigraphy and reconstruction of diatom-inferred total phosphorus

The zonation by optimal partitioning based on relative abundances revealed that the diatom diagram can be divided into four statistically significant diatom-assemblage zones (DAZ). Percentage and corresponding accumulation rates of diatoms with a minimum abundance of 5% are shown in Figure 4.

During DAZ 1 (644 BC to AD 1377; 417–146 cm) the lake was dominated by small *Cyclotella* species like *Cyclotella gordonensis* Kling & Håkansson, *Cyclotella comensis* Grunow and *Cyclotella distinguenda* var. *unipunctata* Hustedt. *Stephanodiscus parvus* Stoermer & Håkansson occurs with a peak of 90%, followed by a peak of periphytic diatoms and *Fragilaria ulna* var. *acus* (Kützing) Lange-Bertalot in the subzones DAZ 1b (AD 1346 to 1377; 155–146 cm).

DAZ 2 (AD 1379 to 1693; 145–70 cm) is characterized by dominance of *Stephanodiscus parvus*.

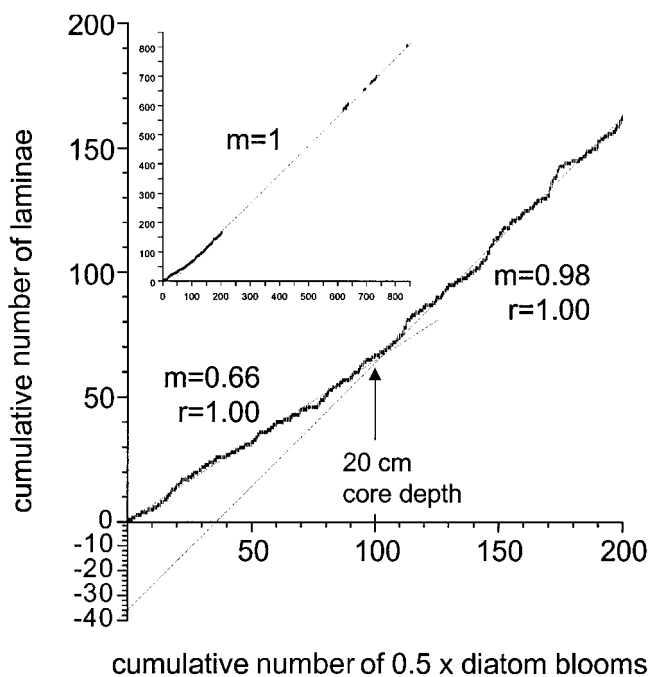
During DAZ 3 (AD 1699 to 1866; 69–29 cm) the small *Cyclotella* species, which were replaced by *S. parvus* in DAZ 2,

**Table 1** Partitioning of the variance for the diatom assemblages of the varved Seebergsee sediments

Response variable	Covariable(s)	Explanatory variable(s)	p-value <sup>1</sup>	Total inertia	Sum of canonical eigenvalues	% Variance explained	Eigenvalue 1. Axis	Eigenvalue 2. Axis
Diatoms	Age	latewood density + sum of grazing indicator pollen + diatom-inferred TP + sum of grazing indicator pollen* diatom-inferred TP	0.001* 0.001* 0.001* 0.001* 0.001*					
<b>Explained variance independent of age</b>				2.572	0.472	<b>20.27</b>	0.403	0.033
Diatoms	Age + latewood density	sum of grazing indicator pollen + diatom-inferred TP + sum of grazing indicator pollen* diatom-inferred TP	0.002* 0.001* 0.001* 0.001*					
<b>Effects of trophic state independent of climate</b>				2.572	0.404	<b>15.70</b>	0.367	0.025
Diatoms	age + sum of grazing indicator pollen + diatom-inferred TP + sum of grazing indicator pollen* diatom-inferred TP	latewood density	0.001*					
<b>Effects of climate independent of trophic state</b>				2.572	0.034	<b>1.32</b>	0.034	0.159
<b>Interaction due to covariation of trophic state and climate with age</b>						<b>3.25</b>		
<b>Unexplained variance</b>						<b>79.73</b>		

<sup>1</sup>Exact Monte Carlo probability (999 permutations).

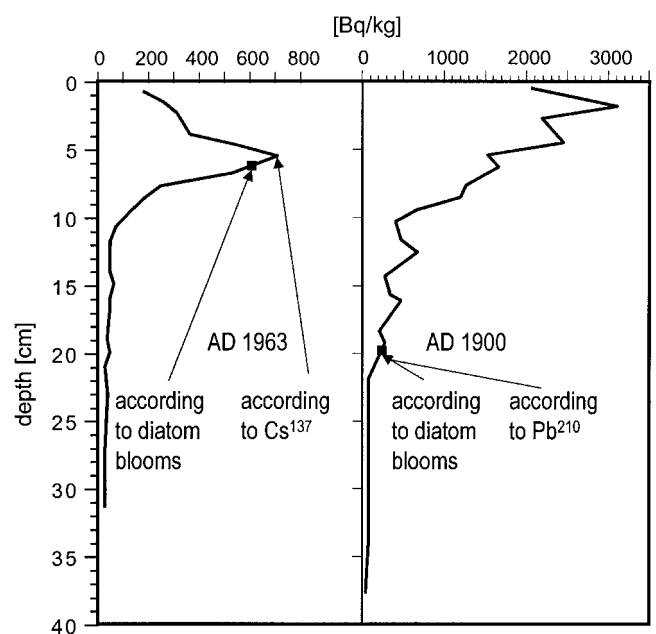
\*Significant at 5% level.



**Figure 2** Linear relationship between diatom blooms as assessed by CONISS and cumulative number of laminae ( $m$  = slope;  $r$  = Pearson's correlation coefficient).

became established again after a peak of *Asterionella formosa* Hassall and a peak of *Cyclotella radiosia* (Grunow) Lemmermann.

During DAZ 4 (AD 1866 to 1996; 28–1 cm) the small *Cyclotella* species declined and *Cyclotella distinguenda* var. *unipunctata*



**Figure 3** Validation of dating by diatom blooms: activities of <sup>137</sup>Cs and <sup>210</sup>Pb of the Seebergsee sediment. Quadrates in the graph are independently dated by the numerical analysis of diatom counts.

increased together with periphytic taxa such as *Achnanthes minutissima* Kützing and *Fragilaria brevistriata* Grunow. Towards the top a peak of Chrysophyte statospores occurred.

The application of the WA-PLS diatom-TP transfer function revealed oligo- to mesotrophic conditions during DAZ 1a, 3 and

4 but hypertrophy during DAZ 1b and DAZ 2, with diatom-inferred TP values around  $150 \mu\text{gL}^{-1}$  (Figure 6).

### Pollen and coprophilous fungal spore biostratigraphy

Percentages and accumulation rates of pollen taxa with a minimum abundance of 5% are shown in Figure 5. The pollen stratigraphy can be divided into eight statistically significant pollen assemblage zones (PAZ).

PAZ 1 and 2 (643 BC to AD 1328; 417–158 cm) consist of up to 80% arboreal pollen, mainly *Alnus viridis*, *Picea*, and *Pinus cembra*.

PAZ 3 to 6 (AD 1339 to 1655; 156–78 cm) reveal an increase of grazing-indicator pollen up to 70%, such as *Trollius europaeus* (Hegi, 1931), *Ranunculus acris*-type and *Plantago alpina*-type. The sum of grazing-indicator pollen (accumulation rate) showed a peak at AD 1390 (141 cm) and increased steadily up till AD 1594 (92 cm). The coprophilous fungal spores *Podospora* and *Sporormiella* occur since c. AD 800. Their abundance is three times higher between AD 1372 and 1594 than before AD 800 till 1371 or after AD 1595 up to the present.

In PAZ 6 (AD 1603 to 1655; 91–78 cm) *Picea*, *Alnus viridis* and *Castanea sativa* show an increase, whereas upland herb pollen decreases.

PAZ 7 (AD 1661 to 1838; 77–37 cm) reveals a return of *Juglans* and *Picea*, and PAZ 8 (AD 1839 to 1996; 36–1 cm) shows a decrease of *Potentilla*, *Cannabis*, *Plantago media* and *P. alpina*-type.

The sum of grazing-indicator pollen (accumulation rate) (Figure 6) consists mainly of *Trollius europaeus* (Hegi, 1931), *Ranunculus acris*-type *Rumex acetosa*-type, *Potentilla*-type and *Plantago alpina*-type.

### Geochemistry

$C_{\text{org}}$  concentrations (Figure 6) are high in the Seebergsee sediments, ranging between 10% and 28%. Highest values were detected at the top of the core and between AD 1555 and 1685 (70 and 100 cm). The lowest values occur between AD 1820 and 1900 (20–45 cm). C/N values (Figure 6) show only small fluctuations around a mean of about 10, indicating that the organic matter is autochthonous and almost entirely originated from internal lake production. In contrast,  $C_{\text{inorg}}$  concentrations (Figure 6) are generally low (<2%). A narrow peak with the highest values was observed at AD 1346 (155 cm).

Mineralogically, Seebergsee sediments consist of quartz, dolomite (Figure 6) and chlorite (not shown), which were detected in most of the samples. In addition, significant amounts of mica, calcite, feldspars (plagioclase), gypsum and small amounts of amphibole (all not shown) were detected in some samples. Quartz, dolomite and chlorite appear regularly in the sediments back to AD 1000 (200 cm). Below this level they are only found sporadically. Whereas quartz and chlorite intensities are relatively stable in the upper 200 cm of the core, dolomite intensities exhibit a pronounced minimum between AD 1360 and 1600 (90–150 cm).

### Ordination

The DCA ordination (Figure 7) shows the dynamic changes in the diatom assemblages. The change towards eutrophication took only eight years, while the recovery, which is defined as the time from the first sample free of coprophilous fungi AD 1595 to TP values of times of pre-eutrophication (i.e., AD 1683), took 88 years.

The 20.3% of the variance of the diatom data could be explained by the trophic state and by climate independently of time, and 79.7% remained unexplained (Table 1). The significant effects of trophic state (sum of grazing-indicator pollen and diatom-inferred TP) independent of time and climate are 15.7%, whereas climate (latewood density) independent of the trophic state and time explained only 1.32% of the total variance of the diatom data.

## Discussion

The dominant diatom during the inferred hypertrophic period was *Stephanodiscus parvus*. This taxon seems to be not only an indicator of eutrophic conditions but also sensitive to climatic change (Hausmann, unpublished data). Its modern distribution indicates that *S. parvus* has a July air-temperature optimum of  $13^{\circ}\text{C}$  and a TP optimum of  $230 \mu\text{gL}^{-1}$  (Hausmann, unpublished data). Additionally, the duration of the mixing period of the water column has an impact on the blooming of *S. parvus* (Bradbury, 1988). Thus the present conditions at Seebergsee may be suboptimal for *S. parvus*: the July air temperature at Seebergsee is only  $10^{\circ}\text{C}$ , and the present nutrient status of the lake is around  $30 \mu\text{gL}^{-1}$ . This raises the question whether in the past the dominance of *S. parvus* was induced by climate or by land use change. Our approach to differentiate between these two factors was to investigate pollen and fungal spore occurrences as indicators for past land use. Additionally, the varve chronology enabled the comparison with climate proxies from Schweingruber *et al.* (1988) and documentary data (Aerni, 1991). Because the grazing-indicator pollen and the diatom-inferred TP explain ten times more of variance in the diatom data than the latewood density, we assume that climate had only an indirect effect, as it allowed pasturing at an elevation of 1830 m a.s.l. between two cooler phases with glacier advances described as 'Little Ice Age' Events 3 (AD 1300–1380) and 2 (AD 1570–1640) by Wanner *et al.* (2000). A pasturing hypothesis is also corroborated by the increased occurrence of the coprophilous fungal spores.

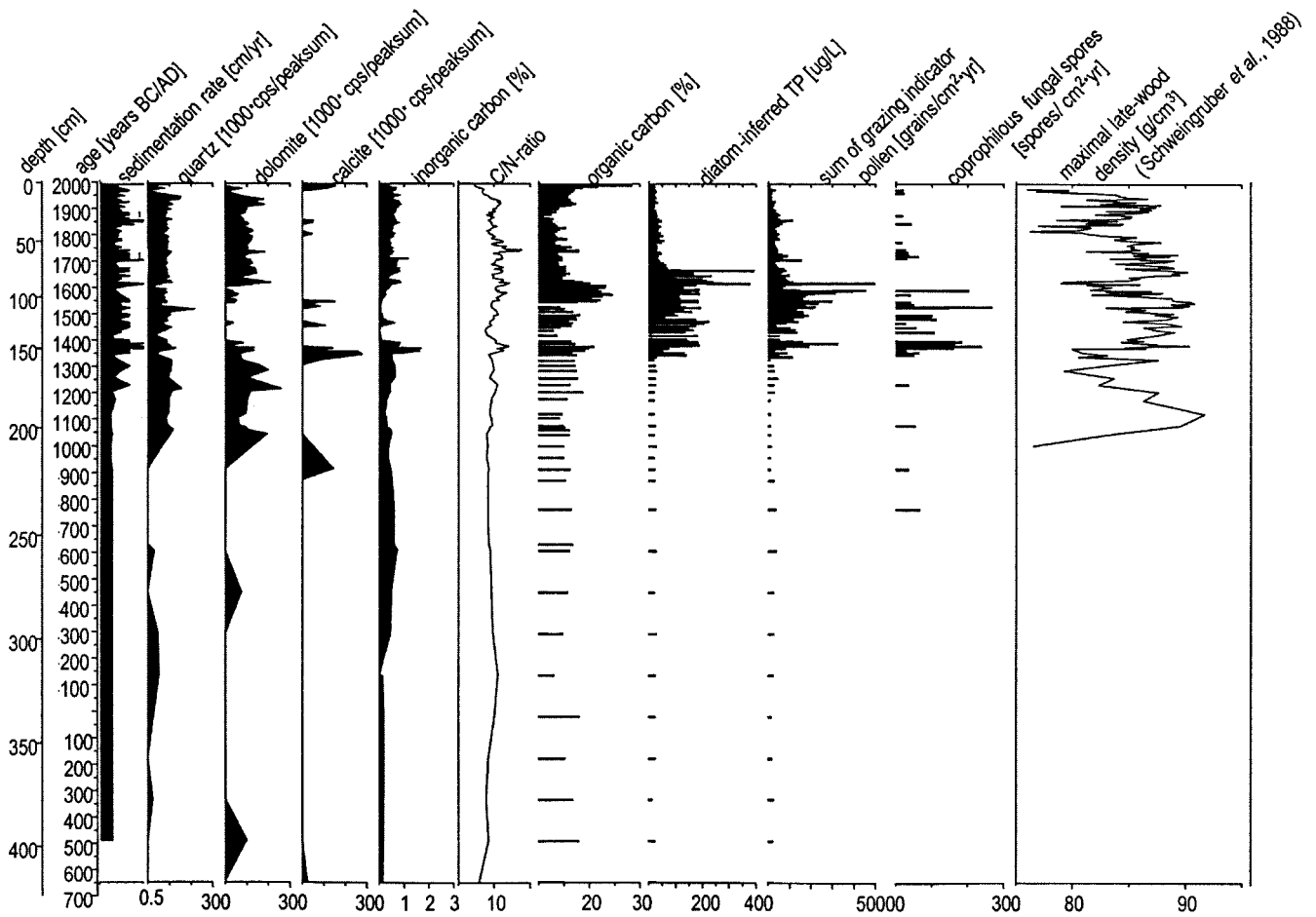
We defined as time of **baseline conditions** the period from c. 650 BC till c. AD 607, when the coprophilous fungal spores as indicators of local pasturing (van Geel *et al.*, 1995) were absent, with an exception of a single sample (AD 294). The aquatic and the terrestrial systems were stable. The *Cyclotella*-dominated assemblages are typical for this altitude and geology and can be considered to represent a background situation (Hausmann, 1999; Hausmann and Lotter, 2001). The diatom-inferred TP concentrations between 20 and  $50 \mu\text{gL}^{-1}$  would refer to a mesotrophic status of the lake.

The coprophilous fungal spores, as evidence for grazing, occurred more frequently since AD 764. The appearance of quartz, dolomite and chlorite 200 years later, around AD 1000, probably represents increased catchment erosion due to pasturing. According to documentary data (Aerni, 1991), the subsequent 325-year-long diatom-inferred hypertrophy (AD 1347–1670) encompasses three developing steps in Swiss dairy production, which resulted in an increase of cattle pasturing in the Swiss Alps: (1) at the end of the thirteenth century, sheep-herding was replaced by cattle pasturing; (2) the demand for butter, which was traded even as far as The Netherlands, rose in urban areas during the fifteenth century; (3) during the sixteenth and seventeenth centuries, Swiss hard cheese was invented as an effective way to conserve milk. This allowed the production and processing of higher quantities of milk.

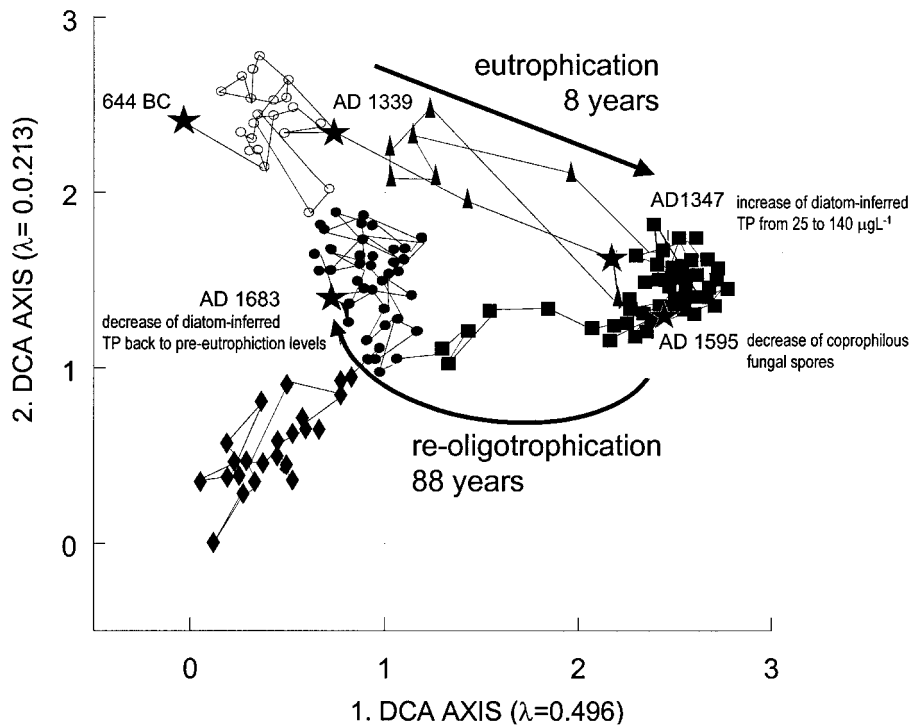
The **eutrophication** of the lake around AD 1350 occurred remarkably fast. The diatom-inferred TP increased between 1339 and 1347 in only eight years (one sample) from 25 to  $136 \mu\text{gL}^{-1}$ . The typical diatom succession recorded in many eutrophication studies was absent in Seebergsee (e.g., Alefs, 1997; Lotter, 2001). During the eutrophication phase, the diatom diversity decreased considerably, and *Stephanodiscus parvus*, as a low Si:P specialist and thus an indicator of eutrophic conditions (Interlandi *et al.*, 1999; Mechling and Kilham, 1982), gained dominance of 90%. The beginning of the '*S. parvus* period' coincided with a threefold increase of the grazing-indicator pollen (accumulation rates), which could be due to wind (direction, velocity; Markgraf, 1980) and precipitation, and thus be a reflection of a regional rather than a local signal. However, the coprophilous fungal spores, less







**Figure 6** Sedimentation rates ( $\text{cm yr}^{-1}$ ), mineralogy (cps per peak sum), inorganic and organic carbon (%), diatom-inferred TP ( $\mu\text{g L}^{-1}$ ), accumulation rates of grazing-indicator pollen and coprophilus fungal spores (numbers  $\text{cm}^{-2} \text{yr}^{-1}$ ) compared to local latewood densities ( $\text{g cm}^{-3}$ ).



**Figure 7** Detrended correspondence analysis of the diatom-percentage data. Symbols were selected according the diatom assemblage zones (DAZ). Hollow circles: DAZ 1a. Triangles: DAZ 1b. Rectangles: DAZ 2. Solid circles: DAZ 3. Diamonds: DAZ 4.

affected by long-distance transport and therefore a valuable proxy for local pasturing (van Geel *et al.*, 1995), also increased threefold at the same time. All biological proxies suggest increased pasturing since AD 1347, which might have been by cattle, as Aerni (1991) suggested, who described a shift from sheep to increased cattle pasturing at the end of the thirteenth century. The beginning of intensive pasturing might have led to the initial erosion of travertine ('meadow-chalk'), which may have formed earlier, as indicated by the high calcite peak at the beginning of the eutrophication. Therefore the shift back to earlier diatom assemblages might have been a result of reworking of the sediment, maybe due to cattle trampling in the shore regions instead of a real oscillation back to prior communities. During the second half of the fifteenth century the coprophilous fungal spores, grazing-indicator pollen and  $C_{org}$  show peaks, whereas the diatom-inferred TP maintained a high level. According to the varve chronology this increase of pasturing may reflect the second step in dairy production (the increased butter production) and coincided with a warming after the cold period from AD 1250 to 1320 as assessed by latewood density by Schweingruber *et al.* (1988).

It is unlikely that the absence of dolomite during the hypertrophic phase is due to the cessation of its detrital input, because the amounts of other detrital minerals are not affected. An explanation internal to the lake seems to be more likely. We therefore propose the following hypothesis. With the beginning of intensive grazing, hypertrophic conditions led to severe bottom-water anoxia. During this anoxia, the bottom-water pH was persistently below 7 and the lake may have been meromictic. Under such conditions, detrital dolomite that entered the lake through diffuse erosion from the catchment was dissolved in the monimolimnion. As soon as grazing stopped, external nutrient input decreased, meromixis was reverted, bottom-water pH increased again, and dolomite was preserved consequently. Nevertheless, epilimnic productivity remained high for several decades because phosphorus was released from the sediments during winter stagnation and mixed into the productive zone during spring and autumn overturn.

A further increase of grazing proxies around AD 1550 might be a consequence of the invention of hard cheese. Latewood density, as proxy for late-summer temperature, indicated a warm phase between AD 1460 and 1570 (Schweingruber *et al.*, 1988). It seems that a warm climate enabled pasturing at this altitude. The diatom-inferred TP values were above  $200 \mu\text{gL}^{-1}$ . The accumulation rates of the grazing-indicator pollen display an increasing trend, and the abundance of coprophilous fungal spores is elevated. The diatom-inferred hypertrophy coincides with high values of fungal spores and grazing-indicator pollen, whereas the diatom-accumulation rates decreased. A possible explanation for the decreasing diatom-accumulation rate is that enhanced diatom growth during phosphate enrichment can lead to Si-depletion, so non-silica-demanding primary producers would be more competitive (Schelske and Stoermer, 1972).

The Great Aletsch and lower Grindelwald Glaciers were advancing between AD 1570 and 1640, a period of cold, dry, continental winters and wet, cold summers with summer snowfall down to 1560 m a.s.l. (Pfister, 1985; Wanner *et al.*, 2000). This cold period was also recorded in latewood density (Schweingruber *et al.*, 1988). A series of volcanic eruptions and solar forcing is discussed as driving forces for this globally recorded cooling about AD 1600 (Schimmelmann *et al.*, 1998; van Geel *et al.*, 1999). Historical records show inhibited Alpine pasturing by the cold climate at this time (Aerni, 1991). According to the coprophilous fungal-spore data, grazing at this altitude tentatively ended c. AD 1595 at Seebergsee. A lag of 35 years is apparent before the grazing-indicator pollen reached background levels around AD 1630 and of almost 90 years before the diatom-inferred TP reached background levels at AD 1683. Therefore we assume that

it took about a century for the lake to recover from its phosphorus load. Lakes often suffer from internal phosphorus loading after the external nutrient source was eliminated (e.g., Liukkonen *et al.*, 1993; Mosello *et al.*, 1986). The delayed drop of diatom-inferred TP at the end of the seventeenth century took place very rapidly at the same time as latewood density indicates a warming (Schweingruber *et al.*, 1988) and summer temperatures were warm (Pfister, 1992) at the beginning of the eighteenth century. The onset of meromixis can result in a reduced productivity of a lake (Jellison *et al.*, 1998; Ramon *et al.*, 1998). Therefore this coincidence raises the possibility that a warming resulted in a strong stratification of the water column and that nutrients of the monimolimnion were therefore eventually separated from the trophogenic zone. According to the species succession, the observed re-oligotrophication process at the end of the seventeenth century represents a typical inversion of the eutrophication process (e.g., Lotter, 1998, 2001; Bennion *et al.*, 1996). *Asterionella formosa* as a good competitor for P and a high Si:P specialist (Interlandi *et al.*, 1999) and pre-eutrophication *Cyclotella* assemblages could develop. This process could be taken as an example of a natural re-oligotrophication and the high temporal resolution makes the study comparable with modern long-term monitoring studies. The agricultural revolution of the seventeenth and eighteenth centuries made cattle pasturing relatively independent of climate, because the introduction of fertilizers made crop rotation redundant, subsequently providing more space for cattle pastures in the lowland. Cattle were increasingly kept over the whole year in barns, which was very space-saving, so the increasing demand for dairy products could be satisfied. Second, it was discovered that lowland cheese was as good as mountain-cheese and could be produced at lower cost. Therefore, mountain-cheese production decreased drastically. Thus the climatic warming after the 'Little Ice Age' did not result in a revival of Alpine pasturing.

The diatom assemblage did not revert to pre-eutrophication conditions, as can be seen in the DCA plot (Figure 7). The increase of *Cyclotella radiososa* and Chrysophyte cysts in the nineteenth and twentieth centuries coincide with the beginning of fish stocking (Guthruf *et al.*, 1999). Fish stocking can result in an elimination of large zooplankton and replacement by smaller copepods and rotifers (McNaught *et al.*, 1999). These would restrict their diet to smaller phytoplankton, so the relatively big centric *Cyclotella radiososa* could dominate.

We conclude that our study of several independent palaeoproxies together with the varve chronology makes it possible to disentangle the effects of human and climatic impact on the aquatic system. This might help to understand the dynamic of lakes at this altitude. Due to our high temporal resolution, a comparison with modern re-oligotrophication processes is possible and interesting with respect to the delayed nutrient decrease.

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