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The sediment record of the past 200 years in a Swiss high-alpine lake: Hagelseewli (2339 m a.s.l.)

A.F. Lotter[1], P.G. Appleby[3], R. Bindler[4], J.A. Dearing[5], J.-A. Grytnes[6], W. Hofmann[7], C. Kamenik[8], A. Lami[9], D.M. Livingstone[2], C. Ohlendorf[2], N. Rose[10] & M. Sturm[2]
[1]*Laboratory of Palaeobotany and Palynology, University of Utrecht, Budapestlaan 4, NL-3584 CD Utrecht, The Netherlands, and Institute of Plant Sciences, University of Berne, Altenbergrain 21, CH-3013 Berne, Switzerland (E-mail: A.Lotter@bio.uu.nl)*
[2]*Swiss Federal Institute of Environmental Science and Technology (EAWAG), CH-8600 Dübendorf, Switzerland*
[3]*Department of Mathematical Sciences, University of Liverpool, P.O. Box 147, Liverpool L69 3BX, UK*
[4]*Department of Ecology and Environmental Science, Umeå University, SE-901 87 Umeå, Sweden*
[5]*Environmental Magnetism Laboratory, University of Liverpool, Liverpool L69 7ZT, UK*
[6]*Botanical Institute, University of Bergen, Allégaten 41, N-5007 Bergen, Norway*
[7]*Max-Planck-Institut für Limnologie, August-Thienemann-Strasse 2, D-24302 Plön, Germany*
[8]*Österreichische Akademie der Wissenschaft, Institut für Limnologie, Gaisberg 116, A-5310 Mondsee, Austria*
[9]*Istituto Italiano di Idrobiologia, CNR, Pallanza, Italy*
[10]*Environmental Change Research Centre, University College London, 26 Bedford Way, London WC1H 0AP, UK*

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Abstract

Sediment cores spanning the last two centuries were taken in Hagelseewli, a high-elevation lake in the Swiss Alps. Contiguous 0.5 cm samples were analysed for biological remains, including diatoms, chironomids, cladocera, chrysophyte cysts, and fossil pigments. In addition, sedimentological and geochemical variables such as loss-on-ignition, total carbon, nitrogen, sulphur, grain-size and magnetic mineralogy were determined. The results of these analyses were compared to a long instrumental air temperature record that was adapted to the elevation of Hagelseewli by applying mean monthly lapse rates.

During much of the time, the lake is in the shadow of a high cliff to the south, so that the lake is ice-covered during much of the year and thus decoupled from climatic forcing. Lake biology is therefore influenced more by the duration of ice-cover than by direct temperature effects during the short open-water season. Long periods of ice-cover result in anoxic water conditions and dissolution of authigenic calcites, leading to carbonate-free sediments.

The diversity of chironomid and cladoceran assemblages is extremely low, whereas that of diatom and chrysophyte cyst assemblages is much higher. Weak correlations were observed between the diatom and chrysophyte cyst assemblages on the one hand and summer or autumn air temperatures on the other, but the proportion of variance explained is low, so that air temperature alone cannot account for the degree of variation observed in the palæolimnological record.

Analyses of mineral magnetic parameters, spheroidal carbonaceous particles and lead suggest that atmospheric pollution has had a significant effect on the sediments of Hagelseewli, but little effect on the water quality as reflected in the lake biota.

This is the eighth of 11 papers published in this special issue on the palaeolimnology of remote mountain lakes in Europe resulting from the MOLAR project funded by the European Union. The guest editor was Richard W. Battarbee.

Introduction

In view of the likelihood that significant anthropogenically induced global warming will have a substantial effect on ecosystems at high altitudes and high latitudes, research into both terrestrial and aquatic ecosystems in such regions has become increasingly important. Furthermore, aerosols that transport acid rain, heavy metals, and nutrients may pollute even remote, uninhabited areas via atmospheric deposition. For the Alps, as a major source of water, this is of central importance, e.g., for the quality of drinking water. The study of remote mountain lakes that are not influenced directly by human activity (such as industry, agriculture or farming) can provide help in assessing the influence of atmospheric input into these aquatic systems. In addition, their sediment records allow pre-industrial background values of many pollutants to be reconstructed, as well as providing an estimate of natural climate variability and its effect on mountain ecosystems.

Over a 28-month period, we monitored the local meteorology as well as physical, chemical, and biological aspects of the limnology of Hagelseewli (Goudsmit et al., 2000; Ohlendorf et al., 2000). Five sediment cores spanning the last five to seven centuries were analysed for different biological, sedimentological, and geochemical proxies. The study we present here is aimed at assessing the extent of atmospheric pollution as well as the influence of climate variability during the last two centuries on the aquatic ecosystem of this high-altitude lake and was carried out within the framework of the EU-project MOLAR (see Battarbee et al., this issue).

Site

Hagelseewli (46° 40′N, 8° 02′E) is an 18.5 m deep lake located at 2339 m a.s.l. in a north-facing corrie in the Bernese Alps, Switzerland (Figure 1). The lake is situated about 450 m above the recent tree-line. Some important site-specific parameters are listed in Table 1. A high, north-facing cliff and steep screes dominate the southern catchment area of the lake. In contrast, the area to the north of the lake is relatively flat, with alpine meadows and snow-bed vegetation. The lake has a small outflow to the north and only one minor surficial inflow at its western shore. Geologically, Hagelseewli is situated in middle Jurassic carbonate-bearing rocks. The lake basin was formed during the last ice age by the glacial erosion of soft micaceous clay-schists from within a tectonic syncline. Its catchment consists of sandy, partly siliceous limestones of middle Jurassic age (Ohlendorf & Sturm, 2001).

Because the lake is located at a high altitude and lies in the shadow of a cliff, the meteorological conditions prevailing there are generally harsh (Table 1). Monthly mean temperatures lie below 0 °C for about 6 months of the year, and daily mean air temperatures can fall below 0 °C even in summer. Although the local topographic shading, which prevents direct solar radiation reaching the lake between October and February, has no effect on the local air temperature, it has a considerable effect on the lake surface water temperature (Livingstone et al., 1999). This results in Hagelseewli being completely or partially ice-covered during most of the year, and occasionally the lake remains frozen throughout the entire year. During the 1996–1998 observation period, there were two main periods of com-

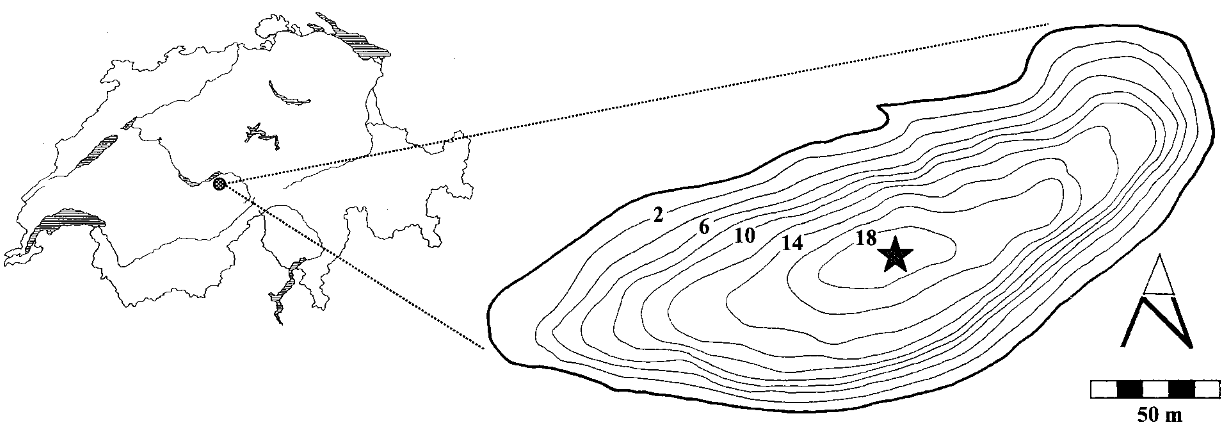

Figure 1. Location of Hagelseewli in Switzerland and bathymetric map of the lake indicating the location of the short cores.

Table 1. Important geographical, climatological and limnological data on Hagelseewli (Guthruf et al., 1999)

Latitude (N)	46° 40′26″
Longitude (E)	8° 02′11″
Elevation (m a.s.l.)	2339
Lake surface area (km²)	0.03
Volume (m³)	195800
Catchment area (km²)	0.36
Max. depth (m)	18.5
Mean depth (m)	8.3
Mean July temperature (°C)	7.4
Mean January temperature (°C)	–7.5
Mean annual temperature (°C)	–0.4
Mean annual precipitation (mm)	1658
Mean pH	8
Mean conductivity (μS/cm)	190
Mean alkalinity (meq/L)	1.8
Mean TP (μg/L)	10

The data are based on the observation period 1996-1998 (Ohlendorf et al., 2000).

plete ice cover, both of which lasted about 7.5 months, with an ice thickness of up to 2 m. The ice break-up at Hagelseewli is a complex process. Because of shading by the cliff face to the south, thawing begins along the more sun-lit northern shore. Open water there can co-exist with a thick sheet of ice (> 1 m), overlain with snow, in the centre of the lake and especially along the southern shore, for over 2 months.

Monthly mean air temperatures at Hagelseewli, reconstructed from 1755–1998

Because long-term time-series of air temperature in Europe are available only from lowland regions, any reconstruction of air temperatures at high-altitude sites depends not only on the availability of a reliable, homogeneous long-term series from at least one lowland station close to the site, but also on a reliable method of converting air temperature data measured at low altitudes to higher altitudes. Using two different approaches, two separate reconstructions of monthly mean air temperatures at Hagelseewli were made. The first of these is described below; the second is described by Agustí-Panareda and Thompson (this issue).

One of the longest reliable series of air temperature measurements – from 1755 to the present – is that from Basle, located 110 km NNW of Hagelseewli at 317 m a.s.l. Bider et al. (1959) and Schüepp (1961) describe the construction and homogenisation of the first 200 years of this series and tabulate the homogenised data. This series (1755–1960) will be referred to henceforth as the Schüepp series.

The latter part of the Schüepp series is based on the air temperatures measured each day at the Swiss Meteorological Institute's Basle-Binningen station; viz. three measurements at fixed observation times plus the daily minimum T_n and daily maximum T_x. On 1 January 1971, the Swiss Meteorological Institute changed both the fixed observation times and the method used to compute daily mean air temperatures, resulting in a discontinuity in the time series. To eliminate this discontinuity, for the purposes of this paper, the three daily observations at fixed times are disregarded and the daily mean is defined simply as $(T_n + T_x)/2$. This procedure, which conforms to the usual US practice, has the added advantage of removing the effect of possible errors in the times of observation. The resulting series (1901–1998) will be referred to as the SMI series.

The Schüepp and SMI series overlap from 1901–1960. For each month of the year, a linear regression was performed between the overlapping parts of the two series, yielding 12 regression equations, each based on 60 years of data. All regressions were highly significant ($p < 0.0001$), and the amount of shared variance lay between 96.6% (June) and 99.6% (January). The 12 regression equations were applied to the Schüepp series in order to extend the SMI series back to 1755.

The resulting combined series was converted to the altitude of Hagelseewli by applying appropriate lapse rates (Table 2). These lapse rates were determined by computing linear regressions of monthly mean surface air temperatures on altitude. They are based on data from 40 meteorological stations situated on the Swiss Plateau and in the northern Swiss Alps, covering an altitude range from 300–3580 m a.s.l. Because low-level temperature inversions result in a distortion of the linear relationship between air temperature and altitude, air temperature reconstructions relying on computed lapse rates are unlikely to be reliable in months in which such inversions are frequent. The standard deviations of the calculated monthly lapse rates listed in Table 2 reflect the frequency of occurrence of temperature inversions in each month. In general, inversions occur only rarely in summer, but increase in frequency during autumn to reach a maximum in winter before falling off again during spring. The lapse rates (Table 2) are therefore most reliable in summer and least reliable in winter.

Applying the mean monthly lapse rates of Table 2 to the combined homogenised Basle series, estimates of the monthly mean air temperature prevailing at the

Table 2. Information on surface air temperature lapse rates and inversions in the northern Swiss Alps, based on 25 yr (1972–1997) monthly mean air temperature data

	(a) Lapse rate ± σ (°C km^{-1})	(b) r^2 (%)
January	3.92 ± 0.98	24
February	4.70 ± 0.70	50
March	5.78 ± 0.31	81
April	6.22 ± 0.24	71
May	6.14 ± 0.13	90
June	6.11 ± 0.19	63
July	5.87 ± 0.20	80
August	5.66 ± 0.20	73
September	5.22 ± 0.41	73
October	4.53 ± 0.56	71
November	4.24 ± 0.72	17
December	3.85 ± 0.85	2

(a) Mean and standard deviation of monthly surface air temperature lapse rates based on data from 40 meteorological stations located between 300 m a.s.l. and 3580 m a.s.l. (see Livingstone et al., 1999, for station locations). (b) Percentage of variance shared between the monthly mean air temperatures at the low-altitude Basle-Binningen station (317 m a.s.l.) and at the high-altitude Jungfraujoch station (3580 m a.s.l.).

altitude of Hagelseewli from 1755–1998 were computed with no further correction. From summer 1996 to summer 1998, air temperatures were measured at an automatic weather station set up at Hagelseewli (Goudsmit et al., 2000; Ohlendorf et al., 2000), allowing the reconstructed monthly mean air temperatures to be compared with monthly mean air temperatures based on 10-min measured values from June 1996 to August 1998 (Figure 2). Livingstone et al. (1999) have already remarked that measured air temperatures at Hagelseewli in summer fall almost exactly on the calculated lapse rate line, implying that, although the steep cliff to the south undoubtedly affects the lake radiation balance, surface water temperature and duration of ice cover, it has almost no effect on the ambient air temperature at the lake. It is evident that the reconstructed and measured air temperatures agree extremely well not only during the summer proper, but also during the entire period from March to November (Figure 2, RMS error = 0.8 °C). However, in the winter months (December–January) the agreement is worse, with discrepancies sometimes exceeding 5 °C. In February 1998, for instance, unusually high air temperatures occurred at Hagelseewli (the daily mean air temperature was above 0 °C on 13 of the 28 days), but not in the lowland areas of Switzerland, implying the existence of a persistent temperature inversion during much of that month. In some winter months, however, reconstructed and measured values agree very well (e.g., February 1997, December 1997, January 1998), so that no generally valid correction can be applied. Presumably, the validity of the reconstructed air temperature in any particular winter month depends critically on the number of days on which temperature inversions occurred, and this can vary substantially both within and among winters.

The possibility of obtaining valid high-altitude air temperature reconstructions based on the Basle series was investigated further by comparing the air temperatures measured at the Basle-Binningen station with those measured at the Jungfraujoch station, located 13 km SSW of Hagelseewli at an altitude of 3580 m a.s.l., i.e., 1241 m above the surface of the lake. From March to October the proportion of shared variance lies be-

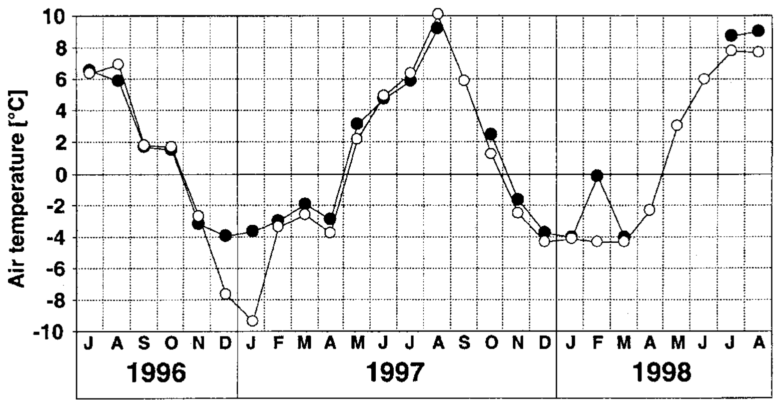

Figure 2. Comparison of reconstructed (open circles) and measured monthly mean air temperatures (solid circles) at Hagelseewli, July 1996–August 1998.

tween 60 and 90%, but during the rest of the year it does not exceed 50%. In December, the proportion of shared variance is only 2%. This confirms that high-altitude air temperature reconstructions based on low-altitude data are likely to be generally unreliable in winter and extremely unreliable in December.

Based on the monthly reconstructed values, seasonal and annual mean reconstructed air temperatures at Hagelseewli were computed and are illustrated in Figure 3. Despite their doubtful reliability, the winter reconstructions are included for the sake of completeness. Because Hagelseewli is usually completely ice-covered from November to April and sometimes longer (Goudsmit et al., 2000; Ohlendorf et al., 2000), winter air temperatures have little or no direct effect on the lake biota. An indirect influence of winter air temperatures on the lake biota is possible via the timing of the spring ice break-up. However, although winter air temperatures can influence the timing of thawing of some lakes (Livingstone, 1999), the thawing of Swiss Alpine lakes is likely to be influenced only by the air temperatures prevailing during about 1 month previous to break-up (Livingstone, 1997). Thus any unreliability in the reconstruction of winter air temperatures at Hagelseewli is unlikely to affect any calculations involving the biota of the lake.

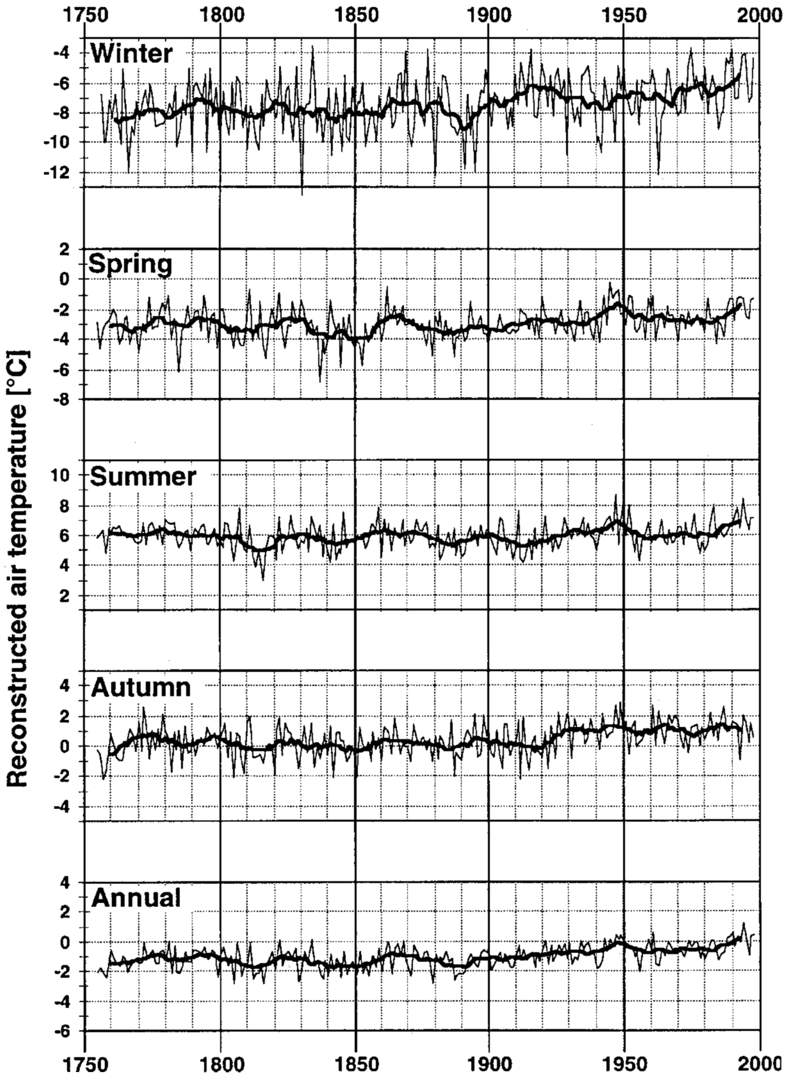

Figure 3. Reconstructed seasonal and annual mean air temperatures at Hagelseewli, 1755–1998 (thin line), and the 11-yr running mean (thick line). Note that to facilitate comparison, the vertical scales of the plots all cover the same range (10 °C).

Sediments

In May 1996 five short cores (HAG96-1 to HAG96-5) were taken in the deepest part of the basin (see Figure 1) with a Kajak corer (Renberg, 1991). The sediment was extruded on site in contiguous 0.5 cm-segments into plastic bags. Samples were stored frozen before further processing. The cores were then correlated by means of their LOI curves (Lotter et al., 2000). Using HAG96-1 as a master core, all sediment depths for cores HAG96-2 to HAG96-5 are expressed as equivalent depths in HAG96-1.

The uppermost sediment consists of black, homogenous, flocculent, slightly sandy, clayey silts with a high organic content. At about 7 cm an abrupt lithologic change is observed to irregularly laminated clayey silts, of a black, grey or brown colour, with a lower organic content. Mineralogically, the sediments are composed mainly of quartz and minor amounts of chlorite, mica, and plagioclase. In the topmost 4 cm, small amounts of gypsum were detected.

The sediments are relatively fine-grained with a median grain size varying between 5 and 15 µm. Peak values occur between 1 and 2 cm sediment depth. In these samples the sand fraction increases to values of up to 25% (Figure 6). The same feature, although less pronounced, is observed at 6–7 and 11 cm sediment depth. In an X-ray diffractogram, the intensity of the quartz-peak at 4.26 Å, normalised to the sum of all detected peaks, gives a semi-quantitative measure of the quartz concentration in the sediment. Accordingly, increased quartz concentrations occur at 5.5 cm, indicating a slightly higher input of allochthonous minerogenic detritus at that time. This input, however, has no influence on the grain size distribution, but coincides with peak values of soft IRM (χ_{low}). Consequently, the grain-size distribution of Hagelseewli sediments seems to be affected by other factors, such as the composition of the diatom community, rather than by detrital input from the catchment. The high chlorophyll derivative values coinciding with maximum sand percentages at 1 cm (Figure 6) support this interpretation.

Chronology

Radiometric dating by ^{210}Pb and ^{137}Cs was carried out on cores HAG96-1 and HAG96-3. Samples from HAG96-1 were analysed by gamma spectrometry for ^{210}Pb, ^{226}Ra and ^{137}Cs at the University of Liverpool, UK, following the methods outlined by Appleby et al. (1986). HAG96-3 was analysed at EAWAG, Switzerland, for ^{137}Cs, and separately by alpha spectrometry for ^{210}Pb.

Results of the radiometric analyses of HAG96-1 are shown in Figure 4. Equilibrium of total ^{210}Pb activity with the supporting ^{226}Ra occurred at a depth of about 10 cm. The unsupported profile of ^{210}Pb activity versus depth can be divided into three distinct zones. In the uppermost zone (0–2 cm), activity declines steeply with depth from a very high value (3290 ± 58 Bq kg^{-1}) in the surficial sample to a much lower value (684 ± 23 Bq kg^{-1}) at 1.5–2.0 cm. In the middle zone (2.0–4.5 cm), ^{210}Pb activity continues to decline more or less exponentially with depth, though at a distinctly shallower gradient. Between 4.5 and 9.5 cm, the profile becomes more irregular, with significant non-monotonic features at 6.0–7.0 and 8.5–9.0 cm. Both features coincide with layers of relatively dense inorganic sediment and may record brief episodes of rapid sediment accumulation due, for example, to slump events. The ^{137}Cs profile has a fairly well-resolved peak between 1.5 and 2.5 cm depth. The presence of traces of ^{241}Am at about the same depth suggest that this feature records the 1963 fallout maximum from the atmospheric testing of nuclear weapons (Appleby et al., 1991). Although fallout from the 1986 Chernobyl accident was widespread in Switzerland, this ^{137}Cs peak is absent in the sediments of many high-elevation lakes in the Bernese Alps because the lakes were ice-covered during the fall-out period.

Although the CRS model (Appleby & Oldfield, 1978) is generally considered to be the more reliable ^{210}Pb dating model, errors can arise due to variations in the ^{210}Pb supply rate at individual core sites due to local irregularities in sediment accumulation. Where two or more cores have been assayed for radionuclides, correlating the cores and treating them as a single record can reduce these errors. HAG96-1 and HAG96-3 were well correlated using a number of distinct common stratigraphic features. Figure 5 shows the chronology for HAG96-1 calculated using the correlated CRS ^{210}Pb-dating model (Oldfield et al., 1980) and the 1963 ^{137}Cs date as a reference level. The results indicate a relatively uniform sediment at accumulation throughout most of the past 150 years, fluctuating about a mean value of 0.011 ± 0.002 g cm^{-2} yr^{-1}, apart from a single brief episode of very rapid accumulation between 6.0 and 7.0 cm (dated 1883–1894). This event is evidenced in the sedimentological data for all five cores and in

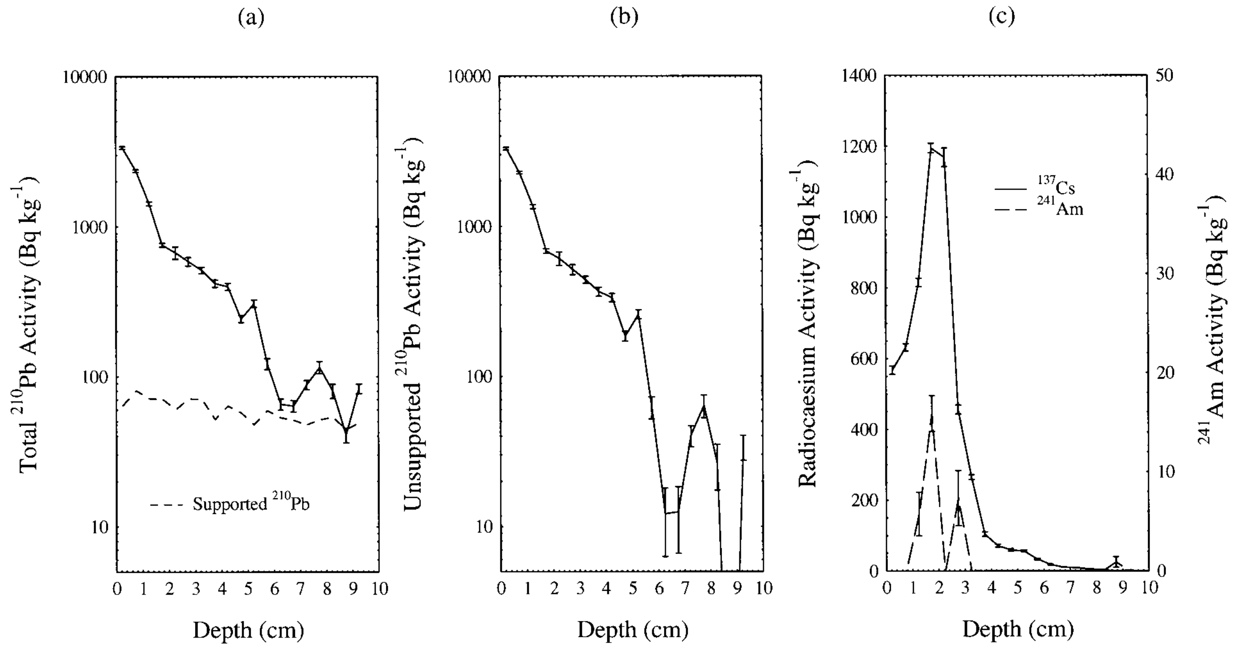

Figure 4. Fallout radionuclides in Hagelseewli core HAG96-1 showing (a) total and supported ^{210}Pb, (b) unsupported ^{210}Pb, (c) ^{137}Cs and ^{241}Am concentrations vs. depth.

the ^{210}Pb profiles by dilution features at 6.0–7.0 cm in HAG96-1 and 7.0–8.0 cm in HAG96-3. During the past few decades a significant decline in accumulation rates has occurred. The mean post-1963 rate in HAG96-1 is 0.0061 ± 0.0010 g cm^{-2} yr^{-1}.

Spheroidal carbonaceous particles

The spheroidal carbonaceous particle (SCP) analysis followed the method described by Rose et al. (1994) with a detection limit for the technique of 100 g^{-1} dry

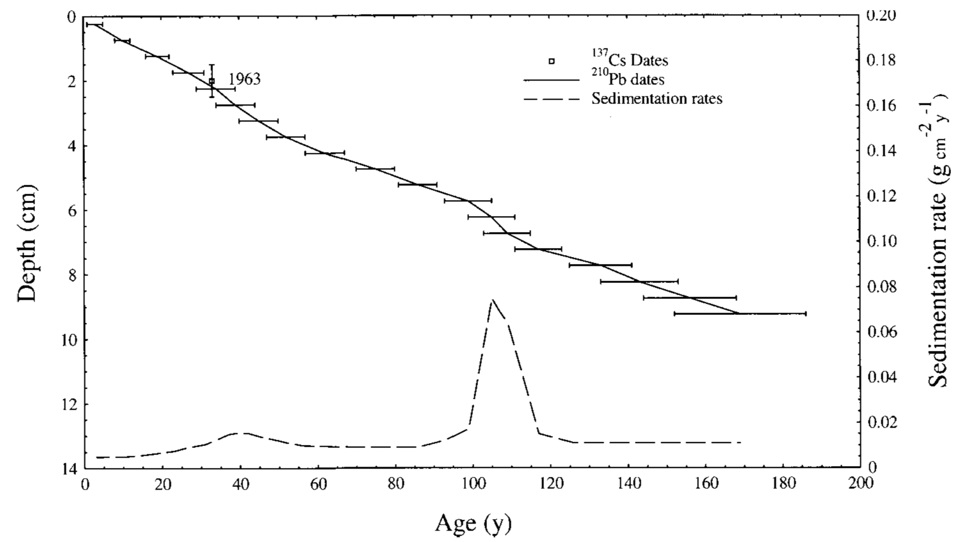

Figure 5. Radiometric chronology of Hagelsee core HAG96-1 showing ^{210}Pb dates and sedimentation rates together with the 1963 date determined from the ^{137}Cs stratigraphy. The ^{137}Cs date has been used as a reference point in calculating the ^{210}Pb dates.

matter and accuracy for the concentrations of ± 45 g^{-1} dry matter.

The SCP sediment profile (Figure 6) predominantly reflects the typical features found in sediment cores throughout Europe. The start of the record (at the end of the 19th century) is quite late compared with other areas of Europe but this may be due to the detection limit of the technique. The rapid increase is dated to the early 1950's and the SCP concentration peak dates to 1977 ± 4 yr, which is similar to other European areas.

The SCP accumulation rate within the surface sediments of Hagelseewli (84 SCPs $cm^{-2} yr^{-1}$) is similar to that of Jörisee III (87 SCPs $cm^{-2} yr^{-1}$), the only other site in the Swiss Alps where SCPs were analysed within the framework of the MOLAR program. The full SCP inventory for Hagelseewli suggests that deposition in Hagelseewli as similar to Jörisee III over the post-industrial period. Converting this inventory to an SCP/^{210}Pb ratio, reasonable agreement is obtained with the latitudinal pattern of SCP contamination suggested for Europe (Rose et al., 1999).

Lead analyses

Lead concentrations and stable isotopes (^{204}Pb, ^{206}Pb, ^{207}Pb and ^{208}Pb) were analyzed using inductively-coupled plasma mass spectrometry (ICP-MS) following a strong acid digestion (conc. HNO_3:$HClO_4$, 10:1 v/v). Isotope correction factors were made using certified standard reference material, SRM 981 (NIST), and concentrations verified against certified standards. Relative analytical error is < ±10% for Pb concentrations and < ±0.5% for the ^{206}Pb/^{207}Pb isotope ratio.

Lead analyses were made to a depth of 37 cm into the sediment. Lead concentrations increase gradually from 14 µg g^{-1} at the base of the core (36.5–37 cm) to 21 µg g^{-1} at 15.5 cm (not shown in Figure 6). Above 7 cm, lead concentrations increase more rapidly up to the maximum concentration, 100 µg g^{-1}, in the surface sediments (Figure 6). The increase in lead concentrations in the core is generally mirrored by a decline in the ^{206}Pb/^{207}Pb isotope ratio, which varies between 1.20 and 1.21 in deeper sediments and declines to 1.15 in the surface sediments. The declining trend for ^{206}Pb/^{207}Pb is correlated with declines in other isotope ratios, e.g., ^{208}Pb/^{204}Pb (r = 0.74).

Magnetic measurements

Room-temperature magnetic hysteresis measurements were made on weighed freeze-dried 0.5 cm contiguous samples of core HAG96-1 in the depth range 0–9 cm in plastic film, using a vibrating sample magnetometer. This procedure provided continuous measurements of magnetisation in fields 0–1 T (cf. Thompson & Oldfield, 1986; Dearing et al., 1998; Dearing et al., 2001).

Profiles of selected hysteresis parameters (Figure 6) show that concentrations of ferrimagnetic (specific susceptibility [χ_{low}]), and low coercivity ferrimagnetic (mass specific soft remanence [soft IRM]) minerals covary, with a minor peak at ~ 8 cm, a rise at ~ 6 cm and three distinctive peaks at 5, 4 and 2.5 cm. The uppermost 2 cm show a declining trend in concentration of both parameters. Paramagnetic Fe-bearing mineral concentrations [χ_{high}] show a similar curve with less variability overall but with a relatively stronger peak at 5 cm (Figure 6).

The rise in M_{rs}/χ_{low} in the surface sediment (0–1 cm) is reasonably strong evidence for greigite or magnetosomes, especially as rising values of Mo, Mn and Fe in the upper 4.5 cm of core HAG93-1 (Sturm & Lotter, unpublished data), as well as the presence of pigments of purple and green sulphur bacteria and the occurrence of S in the sediment (Figure 6) indicate increased bottom water anoxia since the 1950's (Ohlendorf et al., 2000).

Biostratigraphies

All biological remains analysed in the different Hagelseewli cores were zoned with the optimal sum of squares partitioning method (Birks & Gordon, 1985) implemented in the computer program ZONE (Lotter & Juggins, 1991). The significant number of biozones was assessed for each biostratigraphy separately by a broken-stick model (Bennett, 1996).

Diatoms

Contiguous 0.5 cm sediment samples of core HAG96-1 were treated with 10% HCl, 30% H_2O_2, for diatom analyses. A minimum of 300 valves was counted in each slide. Zonation of the stratigraphy revealed three significant diatom assemblage zones (Figure 7). Changes between the zones are characterized mainly by shifts between *Cyclotella comensis* in zones DIA-1 and

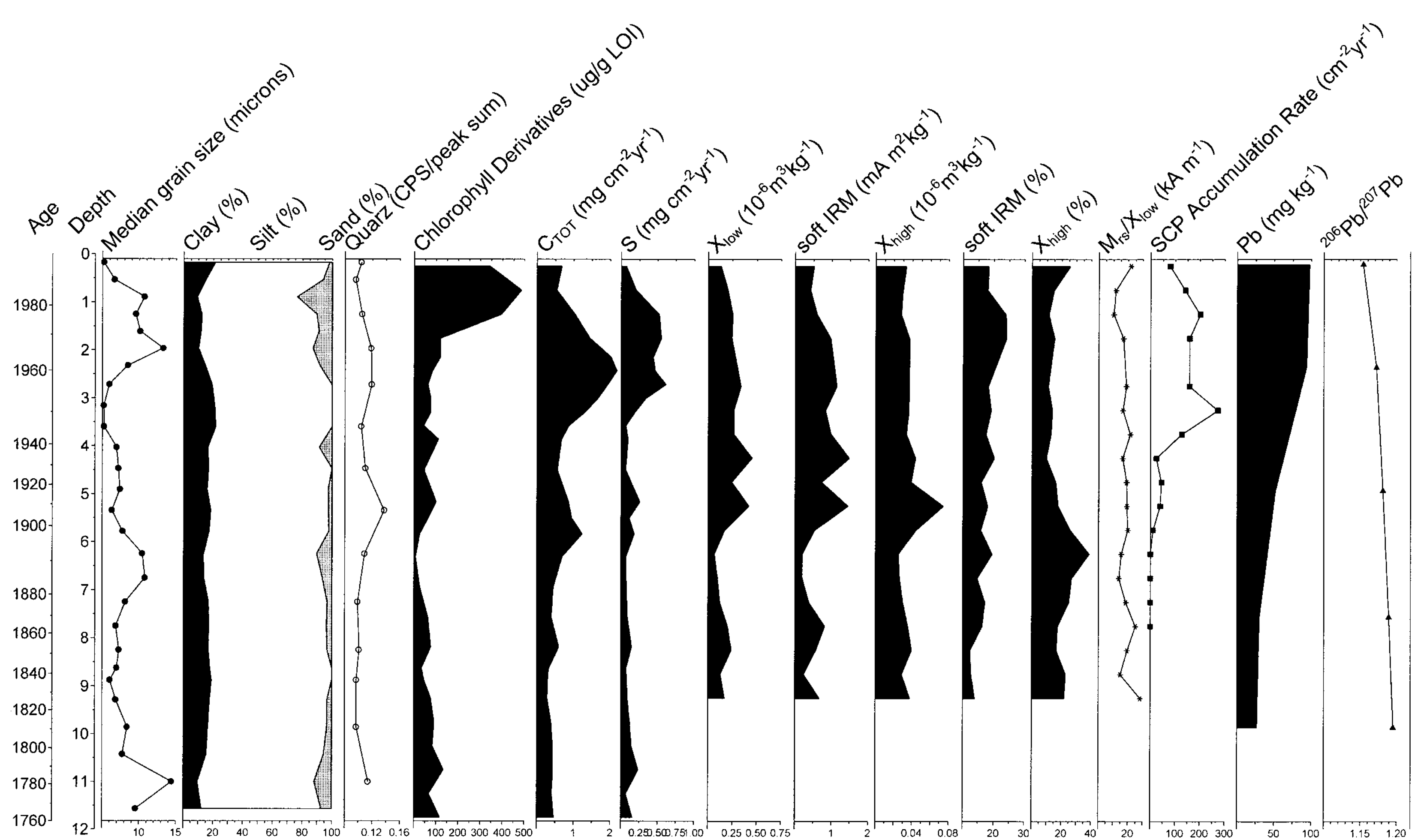

Figure 6. Selected sedimentological, geochemical and geomagnetic parameters: median grain size, grain-size composition; quartz content; Chlorophyll derivative concentration; total carbon and sulphur accumulation rates; mass specific suceptibility (χ_{low}); mass specific soft IRM (soft IRM); mass specific paramagnetic susceptibility (χ_{high}); percent soft IRM; percent paramagnetic susceptibility (χ_{high}); ratio saturation remanence: susceptibility (M_{rs}/χ_{low}); spheroidal carbonaceous particle accumulation rate (SCP), lead concentrations and ratios.

DIA-3 and *Fragilaria pinnata* in zone DIA-2. Until the onset of the 20th century (DIA-1), the assemblages were dominated by planktonic life-forms, mainly *C. comensis* and *Thalassiosira pseudonana*, but scales of *Mallomonas striata* were also abundant (Figure 7). A period of higher abundances of periphytic *Fragilaria* species then followed (DIA-2), before planktonic diatom assemblages again began to dominate the sediment in Hagelseewli in the early 1960s (DIA-3).

Chrysophyte cysts

The relative stomatocyst abundance in the samples prepared for diatom analysis was investigated using a scanning electron microscope. In each sample a minimum of 200 cysts was counted. A total of eleven stomatocyst types were identified in Hagelseewli (Figure 8). The different cysts are characterized in Table 3.

Optimal zonation revealed three significant chrysophyte cyst assemblage zones that are characterized by the dominance of cyst 1 (CHRY-1 and CHRY-3) and higher values of cysts 2 and 15 (CHRY-2; Figure 8).

Cladocera

A standard procedure following Frey (1986) was used for the preparation of chironomid and cladoceran remains from core HAG96-4.

Although subsamples were rather large (0.5–6.0 g, median: 1.04 g wet weight), the cladoceran numbers counted were extremely low. In total, 1539.5 cladoceran remains were counted, 98.6% of which belonged to only two taxa, i.e., carapaces of *Chydorus sphaericus* (83.1%) and post-abdominal claws of *Daphnia pulex* group (15.6%). In the chydorids, 99.7% of the specimens belonged to *Chydorus sphaericus*. The *Daphnia pulex* group accounted for 93.6% of the planktonic cladocerans. Because of the scarcity of the remains and the dominance of few taxa, accumulation rates for the dominant taxa were calculated instead of percentage values (Figure 9).

Chironomids

For chironomid analysis, the > 200 μm and 100–200 μm sediment fractions in contiguous 0.5 cm samples from core HAG96-4 were examined. Due to low concentrations, in several cases adjacent 0.5 cm samples had to be pooled to reach at least 50 specimens, resulting in unequal sample sizes (Figure 10).

Chironomid densities varied from 0.2–28.0 specimens g^{-1} wet sediment. The values were higher in the 0–4.5 cm section (mean density: 11.8 specimens g^{-1}) than in the sediment below 5 cm (mean density: 2.7 specimens g^{-1}). The two most frequent taxa, *Micropsectra* (64.3%) and *Pseudodiamesa* (24.0%), accounted for 88.3% of the chironomid assemblages.

The development of the chironomid fauna is characterized by shifts in the relative abundance of these two dominant taxa, which divide the profile into three chironomid assemblage zones (Figure 10). Zone CHI-1 is characterized by higher values of *Pseudodiamesa*, whereas CHI-2 forms a transitional zone with increasing percentages of *Micropsectra*. In the top 5.5 cm, these dominant taxa have almost equal numbers (zone CHIR-3), while the other taxa are particularly badly represented, so that *Pseudodiamesa* and *Micropsectra* together accounted for 94.5% of the chironomids.

Numerical analyses

Based on the combined Schüepp temperature time-series adapted to the elevation of Hagelseewli as described above, the reconstructed monthly and seasonal air temperatures at Hagelseewli were averaged over the number of years contained in each biostratigraphical sample. Then, a set of (partial) redundancy analyses (RDA) of the square-root transformed percentages of diatoms, chrysophyte cysts and chironomids using the averaged air temperature data as predictors and covariables (Table 4) was carried out to estimate the importance of the different mean temperatures on the biological data. Diatoms, chironomids and chrysophyte cysts show statistically significant marginal effects in relation to September temperatures (Table 4). When sample age was partialled out as a covariable, September temperature still explained a significant amount of variance in the case of the diatom data, but not in the case of the other two biota. Mean spring temperatures and mean summer temperatures were found to have a statistically significant unique effect (i.e., the amount of variance explained when the effects of all other seasonal climate data, as well as age, are partialled out) on the diatoms and chrysophyte cyst assemblages, respectively (Table 4), whereas none of the mean temperatures have significant unique effects on the chironomids.

In a second approach, the biological and geochemical data were reduced to their principal component sample scores by applying principal components analy-

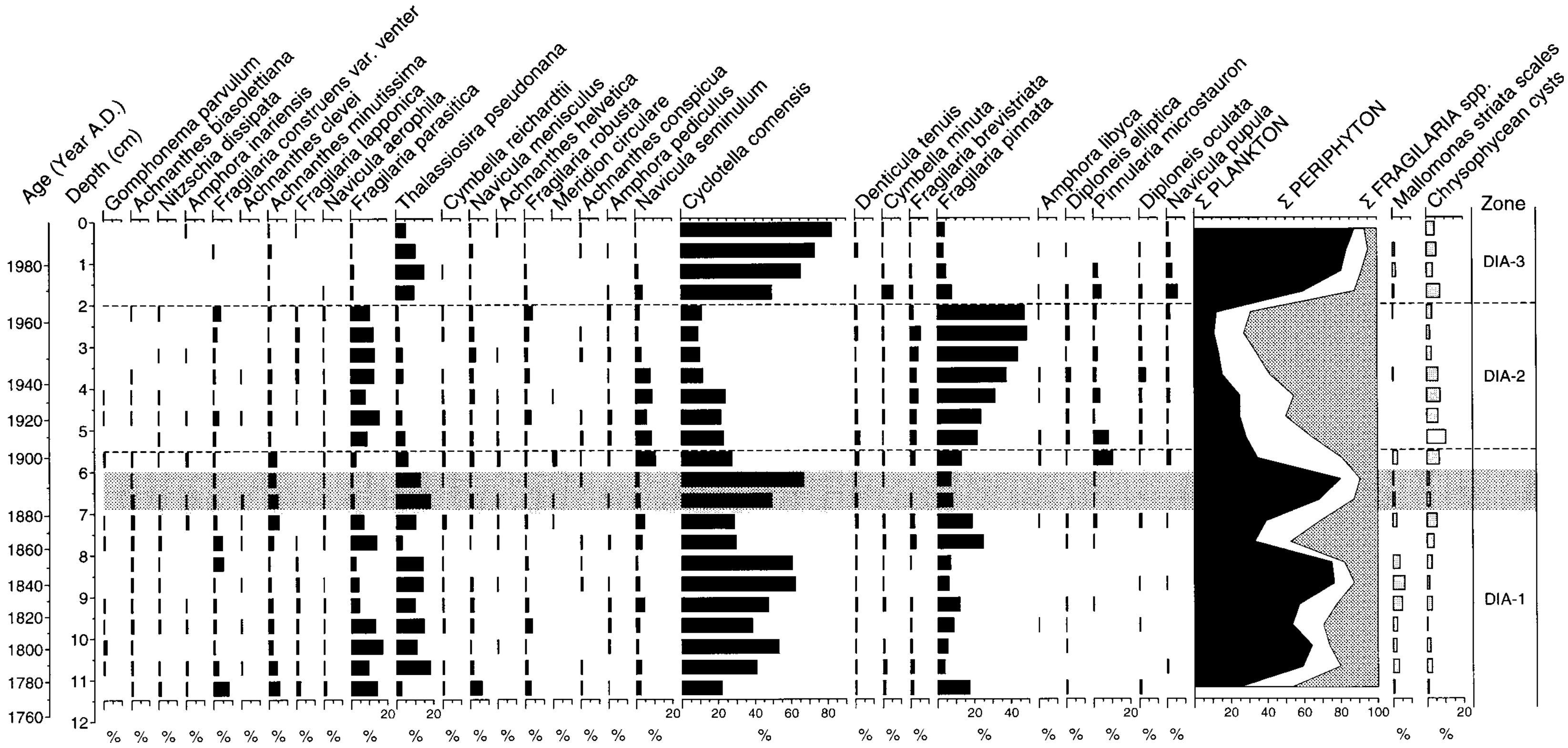

Figure 7. Diatom diagram from core HAG96-1. Only selected taxa are shown. The percentages of *Mallomonas* and the sum of chrysopyte cysts were calculated relative to the diatom percentages. The hatched area between 6 and 7 cm indicates a single, short enhanced sedimentation event.

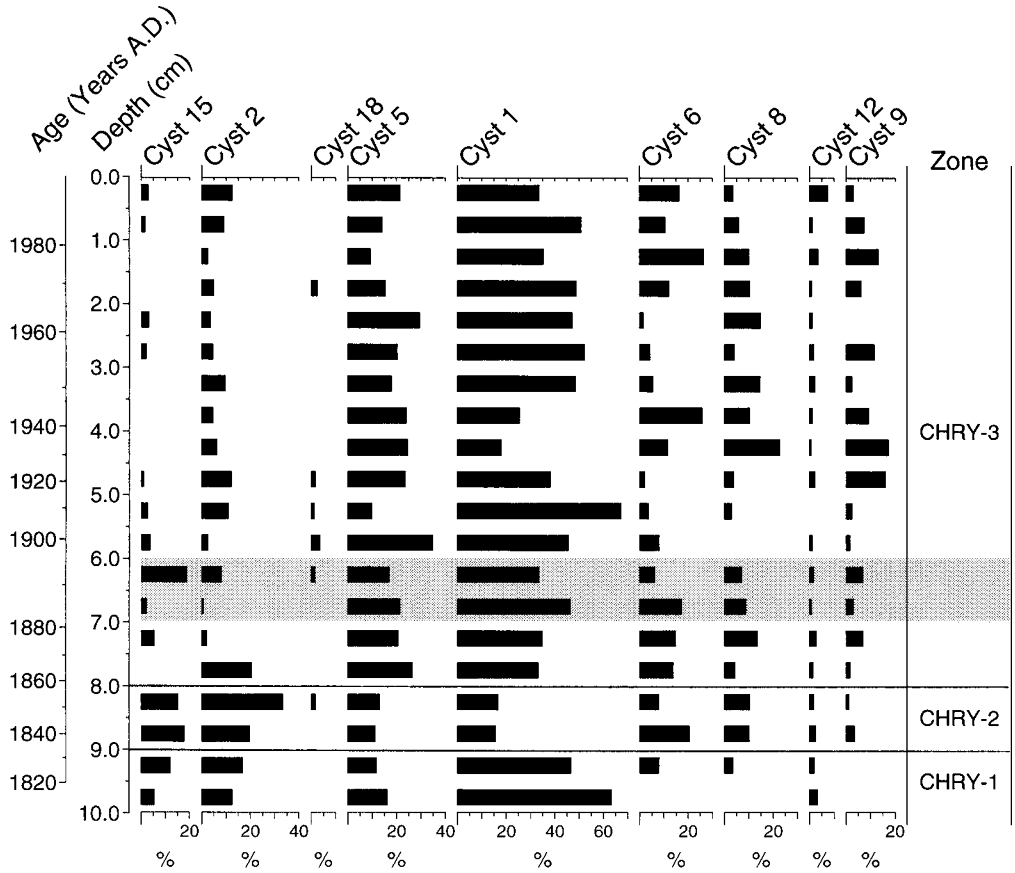

Figure 8. Chrysophyte cyst diagram from core HAG96-1. Only selected taxa are shown. The hatched area between 6 and 7 cm indicates a single, short enhanced sedimentation event.

sis (PCA) as implemented in the software CANOCO 4 (ter Braak & Smilauer, 1998). The second reconstructed air temperature time-series at Hagelseewli (Agustí-Panareda & Thompson, this issue), was smoothed using three different LOESS smoothers (spans used: 0.5; 0.1; 0.05), and the following 3-monthly means were calculated: JJA (June–August); JAS (July–September); SON (September–November); DJF (December–February). In addition, the annual mean (ANN) and a measure of continentality (CON: the absolute difference between DJF and JJA) were calculated. Linear regressions were carried out between the PCA axes and each of these sets of mean smoothed air temperature data. All these linear regressions showed that the highest statistically significant proportion of shared variance was obtained with the highest degree of smoothing (i.e., span = 0.5). We therefore concentrate solely on these results. The general temperature increase during the last century, in combination with the increase in organic matter towards the top of the cores, results in high coefficients of determination (see LOI in Table 5). This is unlikely to be a direct causal climatic effect, however, but is probably due rather to the lack of minerali-

Table 3. Stomatocyst types found in Hagelseewli compared with those found by other authors

Stomatocyst number	Author
1	cf. #167, Duff et al. (1995)
2	Stomatocyst of *Mallomonas striata* (Asmund & Kristiansen, 1986)
5	Unpublished
6	No. 81, Facher & Schmidt (1996) cf. immature stage of #223, Duff et al. (1995)
8	Unpublished
9	#33, Duff et al. (1995)
12	cf. #205, Duff et al. (1995)
15	No. 2, Facher & Schmidt (1996) #9, Duff et al. (1995)
18	No. 5, Facher & Schmidt (1996) #120, Duff et al. (1995)

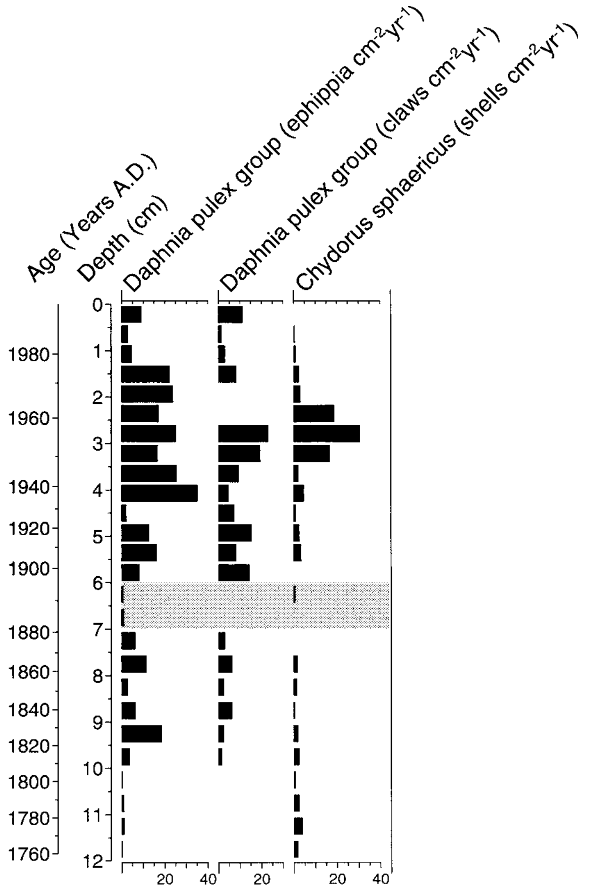

Figure 9. Cladoceran accumulation rates for core HAG96-4. The hatched area between 6 and 7 cm indicates a single, short enhanced sedimentation event.

sation of organic matter observed in many surficial sediments. In the linear regression, the climate parameters also explain a large amount of variance in core depth (i.e., in sediment age).

Linear regressions between the PCA axes of diatom, chrysophyte cyst, and chironomid data and the climate parameters show a somewhat different picture. SON and ANN explain the highest amount of variance of the third diatom PCA axis, whereas CON and DJF explain the highest amount of variance of the second diatom PCA axis (Table 5). The highest statistically significant variance of the sample scores on the first PCA axis of the chrysophyte cyst data is explained by JJA and JAS. JAS also explains most of the variance of the *Mallomonas* scale percentages. For the first chironomid PCA axis, ANN, followed by SON and DJF, explain the highest proportion of the variance but a significant proportion is also explained by JAS and CON (Table 5). These results suggest that the composition of diatom assemblages is not directly related to seasonal temperatures in Hagelseewli, whereas the chrysophyte data are strongly related to summer temperatures and the chironomid assemblages are strongly related to annual temperatures. These biota seem to react more to the temperatures prevailing during the open-water period.

Discussion

The sedimentological investigations of the Hagelseewli deposits indicate an astonishingly high amount of organic matter (10–35% LOI) for a high-elevation lake (Lotter et al., 2000). This is mainly the result firstly of the lack of any glacial influence, and secondly of the dissolution of precipitated calcite at the sediment/water interface (Ohlendorf & Sturm, 2001). Based on the C:N ratios, which were found to remain around or below 10, the organic sediment can be presumed to be of autochthonous origin, whereas the minerogenic component is chiefly washed in from the catchment. Apart from one obvious layer between 6 and 7 cm sediment depth, originating from a brief single event that is well marked by an increase in grain-size as well as by a dilution effect in the pigment and ferrimagnetic mineral data (Figure 6), there is no other evidence for an increased allochthonous input of minerals.

The main peaks in soft IRM concentrations at 6.5 cm and between 1–2 cm (Figure 6) do not coincide with peaks in sediment accumulation rates. This suggests that the amount of eroded material was relatively small and represented a shift in sediment source or in grain-size rather than an increase in erosional intensity. The ferrimagnetic concentrations (soft IRM, Figure 6) may be linked indirectly to temperature and as observed in other lakes, they are probably related to silt-sized particles (cf. Dearing, 1999).

The peaks in magnetic concentrations may represent phases of enhanced wet and dry deposition of magnetite (with hæmatite) in atmospheric aerosols, a finding supported by the evidence for gradually increasing proportions of multidomain magnetite upcore. The soft IRM % curve suggests that 'magnetite' pollution from fossil fuel burning started around 1860 and increased gradually during the 19th century and the first half of the 20th century, with possibly a stronger rise around 1900 and peak deposition between 1910 and 1970. Soft IRM % values decline after 1977 and the ferrimagnetic concentration parameters decline after about 1970 indicates magnetite.

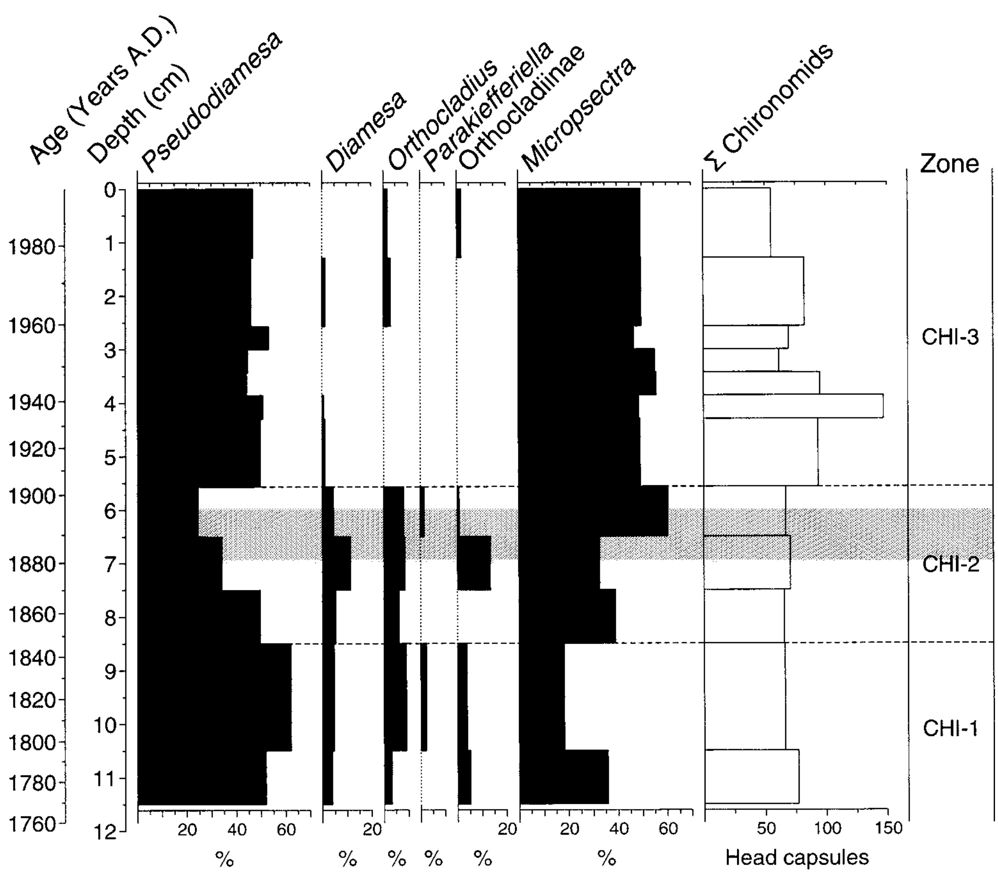

Figure 10. Chironomid diagram for core HAG96-4. The hatched area between 6 and 7 cm indicates a single, short enhanced sedimentation event.

Analyses of the long-term record in a peat bog in the Swiss Jura Mountains (Shotyk et al., 1998) and lake sediments and peat in Sweden (Brännvall et al., 1997; Renberg et al., 2000) indicate an onset of atmospheric lead pollution at least 3000 years ago. The oldest analysed sediment in the core from Hagelseewli (37 cm) may therefore not represent true background conditions. Above 15 cm (late 17th century), i.e., for the whole two hundred year long period shown in Figure 6, there is a clear impact of airborne pollution. The concentration increase and isotope ratio decline can be explained in terms of an addition of lead with a lower $^{206}Pb/^{207}Pb$ isotopic composition, i.e., pollution lead. Atmospheric pollution lead in Europe had an isotope ratio typically about 1.17 before ca. 1900 (see references in Brännvall et al., 1997; Shotyk et al., 1998; Renberg et al., 2000), decreasing in Switzerland to 1.12–1.14 at the end of the 20th century (Weiss et al., 1999).

Accumulation rates of SCPs rise only at the end of the 19th century and show a double peak within the upper 3 cm during the period 1955–1980. Magnetic records of pollution from the USA and UK (Dearing, 1999) also show initial rises from 1850–1900 and peak values from 1950–1980, with declines in recent decades demonstrating the effects of pollution controls.

The extremely low cladoceran diversity manifested in the almost exclusive occurrence of one benthic element (*Chydorus sphaericus*) and one planktonic element (*Daphnia pulex* group) reflects not only the high altitude of the lake, but also the particular local situation (shading and low summer water temperature as well as a long period of ice cover). Cladoceran accumulation rates (Figure 9) generally higher accumulation rates during warmer periods (e.g., the 1820's, 1860's, and especially since the 1940's) and lower accumulation rates during cooler periods.

A statistically significant but rather small amount of the variance in the diatom data is explained by spring temperature (Table 5). Observations in the water column,

Table 4. Marginal and unique effects of different monthly and seasonal mean temperatures based on the altitude-corrected (see Table 2) combined Schüepp series (see text and Figure 3) on biotic assemblages in the Hagelseewli sediments

	Diatoms						Chironomids						Chrysophyte cysts					
Covariable	Marginal effects		Marginal effects Age		Unique effects All		Marginal effects		Marginal effects Age		Unique effects All		Marginal effects		Marginal effects Age		Unique effects All	
Variable	%	p	%	p	%	p	%	p	%	p	%	p	%	p	%	p	%	p
Age	12.1	0.27					40.9	**0.00**					15.7	**0.00**				
JAN	5.7	0.55	2.8	0.80			26.8	0.09	2.6	0.92			10.0	0.11	3.2	0.71		
FEB	3.9	0.51	5.2	0.37			1.9	0.87	5.7	0.65			6.3	0.37	3.2	0.79		
MAR	12.5	0.20	6.1	0.28			46.7	**0.00**	17.6	0.19			9.4	0.16	3.6	0.82		
APR	5.1	0.29	4.5	0.32			9.1	0.47	3.0	0.88			4.9	0.32	4.9	0.51		
MAY	5.2	0.44	5.7	0.40			22.5	0.14	19.4	0.09			4.4	0.49	4.7	0.28		
JUN	4.7	0.46	2.9	0.74			16.0	0.19	5.3	0.77			15.9	**0.00**	18.2	**0.00**		
JUL	3.9	0.63	3.1	0.69			16.7	0.37	4.9	0.85			6.7	0.27	5.7	0.38		
AUG	3.8	0.76	4.6	0.51			13.6	0.34	3.5	0.78			6.9	0.32	8.5	0.18		
SEP	17.3	**0.02**	16.0	**0.02**			38.8	**0.00**	15.1	0.14			15.3	**0.00**	6.0	0.31		
OCT	7.6	0.48	3.0	0.77			37.1	**0.04**	11.1	0.22			4.8	0.62	6.9	0.16		
NOV	7.3	0.43	2.8	0.70			16.4	0.23	3.4	0.81			11.0	0.11	4.3	0.55		
DEC	7.3	0.54	2.9	0.81			35.1	**0.05**	17.1	0.17			7.0	0.36	9.3	0.28		
ANN	9.6	0.42	3.9	0.86			41.5	**0.00**	12.3	0.21			11.2	**0.05**	7.0	0.18		
SPR	10.6	0.30	6.8	0.39	12.3	**0.05**	32.9	**0.00**	10.9	0.41	13.6	0.41	7.5	0.23	4.7	0.63	6.9	0.49
SUM	4.0	0.64	3.1	0.72	10.3	0.11	18.0	0.25	1.7	0.96	13.4	0.56	10.2	0.09	12.1	0.07	17.1	**0.04**
AUT	11.1	0.43	4.3	0.60	4.1	0.54	39.7	**0.00**	9.4	0.32	6.7	0.96	12.3	**0.00**	3.9	0.71	1.9	0.89
WIN	7.6	0.50	3.7	0.76	6.9	0.40	29.4	0.17	9.9	0.61	10.8	0.72	4.9	0.59	12.6	**0.04**	14.2	0.07

Significance levels were assessed by 999 restricted Monte Carlo permutations; bold numbers indicate statistically significant values ($p < 0.01$).

coupled with sediment trap data from Hagelseewli (Lotter & Bigler, 2000), suggest that the ratio of planktonic diatoms to the sum of periphytic *Fragilaria* taxa may be used as an indicator for the duration of the period of ice-cover. The latter, however, may not only be dependent on the seasonal temperatures, but also on the amount of precipitation falling in winter and spring, as snow-cover on the ice may substantially prolong the duration of ice-cover on Hagelseewli. Following Smol's (1988) and Douglas and Smol's (1999) theory, *Fragilaria* taxa may develop in the marginal 2–3 m broad ice-free moat at the northern shore of Hagelseewli, whereas the thick ice and snow cover at the centre of the lake will inhibit light penetration and mixing, and thus also inhibit the development of planktonic diatoms. Through focusing enhanced by water currents (Goudsmit et al., 2000), *Fragilaria* species will be transported to the centre of the lake, where they have the effect of diluting the planktonic signal in the surficial diatom assemblages (Lotter & Bigler, 2000). Plank-

Table 5. The percentage of the total variance in the response variables accounted for by each of the temperature predictor variables (data according to Agustí-Panareda & Thompson, this issue) by linear regression

Temperatures	Depth in core HAG96-1	Diatoms PCA 1	Diatoms PCA 2	Diatoms PCA 3	Mallomonas Scales	Chrysophyte cysts PCA 1	Chironomids PCA 1	LOI 550° % DW	Geochemistry & Pigments PCA 1	Geochemistry & Pigments PCA 2	Geochemistry & Pigments PCA 3
Eigenvalues		0.53	0.122	0.082		0.356	0.528		0.519	0.12	0.08
JJA (%)	**38.8**	0.2	4.1	**26.8**	**27.1**	**45.2**	14.5	**42.2**	**29.3**	0.3	12.2
JAS (%)	**54.8**	9.3	17.0	13.3	**57.4**	**43.7**	42.7	**31.7**	11.0	1.7	**23.1**
DJF (%)	**86.5**	0.6	**32.3**	**34.1**	**33.6**	21.3	**51.1**	**78.0**	**38.6**	0.0	**38.3**
CON (%)	**84.1**	0.6	**37.3**	**29.2**	**28.5**	13.2	40.6	**73.0**	**33.6**	0.1	**40.5**
ANN (%)	**77.3**	1.5	19.3	**50.2**	**28.3**	24.8	**64.6**	**76.4**	**36.4**	0.5	**32.8**
SON (%)	**61.1**	0.2	10.7	**62.5**	12.2	13.7	**52.3**	**72.6**	**37.9**	1.4	**25.7**

The temperature variables were smoothed using a LOESS smoother (span = 0.5). Bold numbers indicate statistically significant values ($p < 0.01$). JJA: mean of June, July, August; JAS: mean of July, August, September; DJF: mean of December, January, February; CON: continentality (i.e., absolute difference between DJF and JJA); ANN: mean annual temperature; SON: mean of September, October, November.

tonic cladocerans, however, are mobile and may live and feed in the marginal open water of the moat.

The chironomid fauna is also characterized by low species diversity, by the total absence of taxa from the subfamily Tanypodinae and the tribus Chironomini, and by the dominance of Diamesinae and Orthocladiinae. These assemblages reflect extreme ecological conditions, such as the extreme temperature regime of this site. This view is in accordance with the occurrence of *Micropsectra borealis*, which was first observed in Novaya Zemlya and has so far only been known to occur in alpine regions of northern Europe (Säwedal & Willassen, 1980).

Although chironomids, diatoms, and chrysophytes have been shown to be indicators of direct or indirect temperature change (e.g., Walker et al., 1991; Pienitz et al., 1995; Lotter et al., 1997), the relationships of these biota to air temperatures at Hagelseewli are only weak or not statistically significant. This is not surprising for the following reasons: (i) sample amalgamation will essentially reduce any climate signal to a linearly increasing trend; (ii) the amplitude of changes in monthly and seasonal air temperatures during the open-water season over the last two centuries are on the order of about 2 °C, which might still be within the range of biological tolerance for the cold-adapted organisms investigated; and (iii) Hagelseewli may, therefore, be located too far away from ecotonal boundaries, so that small changes in environmental conditions are not able to trigger large biological changes. Furthermore, the duration of the period of complete or partial ice cover suggests that climatic influence on this lake is more likely to be indirect, i.e., mediated by ice cover, than direct. Livingstone et al. (1999) have shown that surface water temperatures in Hagelseewli tend to be decoupled from air temperatures for much of the summer, which is in contrast to other neighbouring lakes that are not subject to local topographic shading. This has implications for the palæolimnological study of Hagelseewli: aquatic biota are subjected to a more severe environment and shorter open-water periods in Hagelseewli than would be expected for lakes at this altitude. The timing and duration of the open-water period is likely to be governed to a large extent by the air temperatures prevailing during thawing and by those prevailing immediately previous to freeze-up. Therefore, air temperatures prevailing in May–July (thawing) and in September-October (freezing) may play a greater role for the aquatic biota than those prevailing during the open water period in August.

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