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Holocene sediments of Sägistalsee, a small lake at the present-day tree-line in the Swiss Alps

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Abstract

Sägistalsee is a small lake located at the modern tree-line in the Swiss Alps. A 13.5 m long core taken in the central part of the 9.5 m deep basin consists of clayey silts and sands and dates back to about 9000 cal. BP. These sediments have a low organic content that steadily increases from 4–8% loss-on-ignition at 550 °C towards the top of the core, whereas the carbonate content decreases from 20 to about 10% loss-on-ignition at 950 °C. We outline the aims of an interdisciplinary research project centred on the Holocene sediments of Sägistalsee. We also present information about the lake, its sediments, and its catchment that forms the basis for different biotic and abiotic multi-proxy studies carried out on the sediments of Sägistalsee.

Introduction

Mountainous regions such as the Alps are characterized by steep climatic gradients with prominent ecotones, thereby offering over a short geographical distance many different climate-related ecosystems. Predicted greenhouse-gas-induced climatic warming is likely to destabilize alpine permafrost slopes as well as change mountain ecosystems by inducing environmental stress (Theurillat et al., 1998). This may affect forests in the Alps, traditionally used by humans as protection against avalanches, slope instability, and soil erosion. Such changes in tree cover will also alter the hydrological regime by enhancing run-off during snow-melt or heavy precipitation, and by reducing water retention in the soils, thereby increasing the risk of landslides in the alpine valleys and river floods in lowland regions (e.g., Dapples et al., 2002). All these effects are not only ecologically important but will also have major socio-economical consequences for the inhabitants of alpine regions and for the tourism industry (Cebon et al., 1998).

In environments with a steep climatic gradient, small climatic shifts can be expected to produce large changes in the biota (see e.g., MacDonald et al., 1993). Therefore, sites at an ecotone or near an ecotonal boundary are well suited for studies of long-term climate dynamics. In addition, remote mountain lakes probably offer the only sediment archives in the Alps where continuous high-resolution records of climate variability with little or no human impact throughout the Holocene are available. Small water volumes and a long ice-cover characterize these lakes; they are therefore particularly susceptible to climatic change (see e.g., Livingstone 1993, 1997).

This is the first in a series of eight papers published in this special issue dedicated to the palaeolimnology of Sägistalsee. Drs. André F. Lotter and H. John B. Birks were the guest editors of this issue.

Palaeoecological investigations of past climatic changes in sediment archives located at sensitive altitudes are typically carried out to detect changes in the location of the tree line. Such studies have a long tradition in the Alps (e.g., Welten, 1982; Lang, 1985; Burga and Perret, 1998). However, many investigations base their tree-line reconstructions on relative pollen abundances only, without taking into account the great potential of pollen accumulation rates and especially of plant macrofossils (Wick and Tinner, 1997; Birks and Birks, 2000). Furthermore, the influence of catchment vegetation on the aquatic ecosystem has rarely been studied (MacDonald et al.,1993).

Mountain lakes have shown to be sensitive indicators of past, present, and future global change. In contrast to lowland lakes that are often heavily influenced by cultural nutrient enrichment, mountain lakes register climate change more directly (e.g., Battarbee et al., 2002a,b). Due to climate conditions prevailing at higher elevations the length of the open-water season largely determines the productivity in the water column, (e.g., Catalan et al., 2002).

In the framework of the Swiss Priority Programme Environment project AQUAREAL (Lotter et al., 1997a) and the EU project CHILL-10,000 (Korhola et al., 2000), we studied sedimentary records of mountain lakes in the Swiss Alps using a multi-proxy approach. The goals of these projects were to elaborate high-resolution, well-dated environmental reconstructions during periods of rapid environmental change in the Holocene, to explore leads and lags in reaction time between terrestrial and aquatic biota, to explore and distinguish between direct (biological) and indirect effects (sedimentological, geochemical) of climate change, and eventually to reconstruct quantitatively past climate from biological sedimentary records. In this contribution, we provide an overview of the main study site of Sägistalsee (Figs. 1 and 2), the field methods employed, and the chronology established for the Sägistalsee sediments. These data form a common basis for the studies of biotic remains such as pollen and plant macrofossils (Wick et al., 2003), chironomids (Heiri and Lotter, 2003), cladocera (Hofmann, 2003), as well as abiotic variables such as sedimentology (Ohlendorf et al., 2003), geochemistry (Koinig et al., 2003), and magnetics (Hirt et al., 2003).

Site

Sägistalsee (7°58′40″E; 46°40′50″N) is a small mountain lake located in the northern Swiss Alps of the Bernese Oberland, 8 km east of Interlaken and 7.5 km northwest of Grindelwald (Fig. 1). Tectonically, the

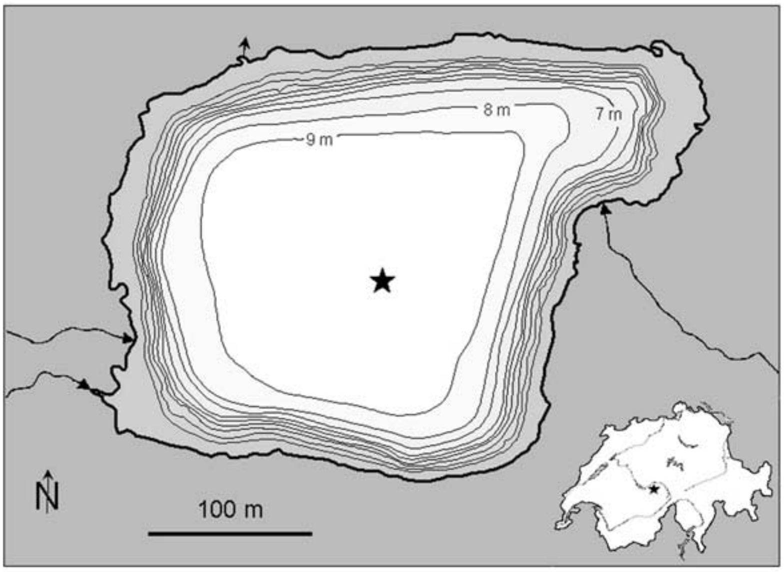

Fig. 1. Inset map of Switzerland (lower right corner) showing the location of Sägistalsee (star), and a bathymetric map of the basin with an indication of the three inflowing streams and the outflow (karstic sink hole) as well as the coring site (star). Water-depth contours are given in 1 m intervals.

Fig. 2. Oblique aerial photograph showing Sägistalsee (1935 m asl) with Schwabhorn (2373 m asl) on the northeastern horizon. The sparse stands of *Picea abies* form the present-day timberline at ca. 2000 m asl on the southern slopes.

area belongs to the Mesozoic Wildhorn nappes. The lake is situated in a SW to NE oriented valley (Figs. 2 and 3) lying within easily erodable marls and limestones (for details see Ohlendorf et al., 2003). The catchment, which consists entirely of calcareous bedrock, is characterized by karst phenomena with the lake being a doline. Sägistalsee is at an altitude of 1937 m asl, close to the transition from the subalpine to the alpine belt marked by the tree-line ecotone formed mainly by spruce (*Picea abies*, see Fig. 2), and to a lesser extent, by Swiss stone pine (*Pinus cembra*) in the northern Swiss Alps. The catchment of Sägistalsee is used as cattle pastures between July and the end of September. Its vegetation consists mainly of alpine meadows with some dwarf shrubs (*Juniperus communis*, *Rhododendron ferrugineum*, *Salix herbacea*), scattered stands of *Picea abies,* and single trees of *Pinus cembra*. Mean annual temperature of 1.7 °C, and mean January and July temperatures of –5.8 and 9.9 °C, respectively, characterize the climate at this altitude. The mean an-

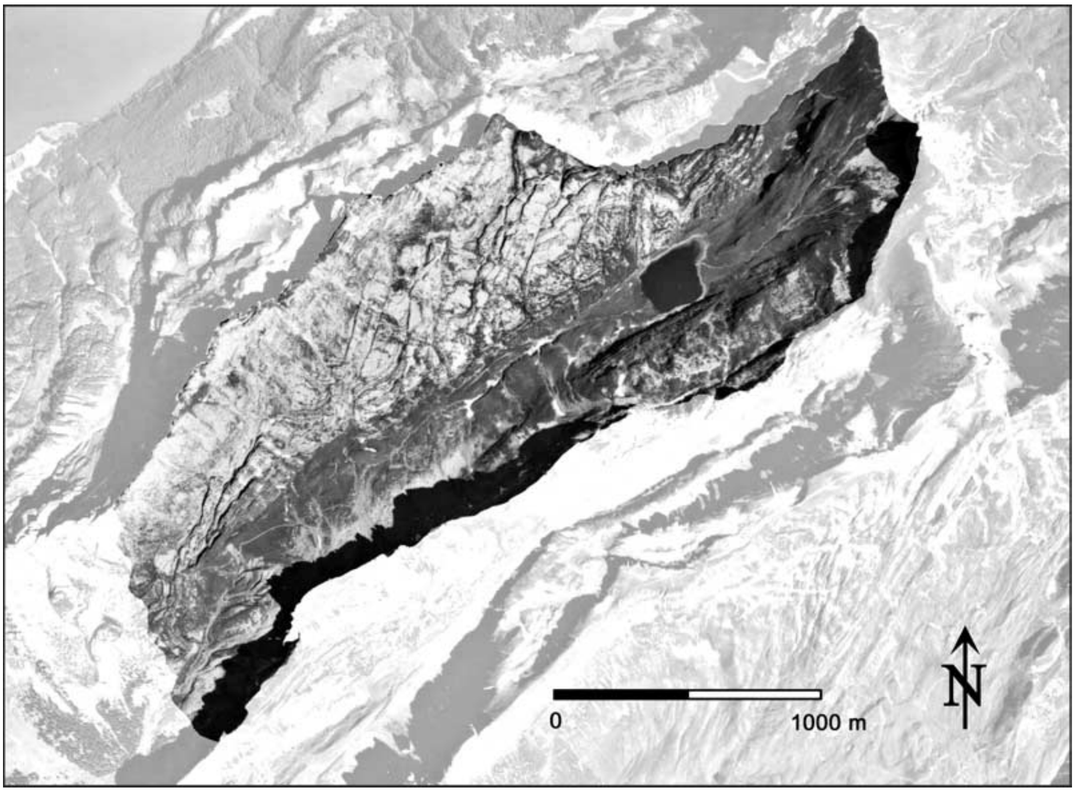

Fig. 3. Aerial photograph of Sägistalsee and its catchment.

nual precipitation, which amounts to ca. 1350 mm is about 300–400 mm lower than in adjacent valleys (Spengler, 1974).

The lake is 300 m long and 312 m wide with a surface area of 0.073 km^2 and a volume of 490600 m^3. The basin morphology is simple, with steep slopes and a large flat central part with water depths of around 9 m (Fig. 1). It has three small inflowing streams and its outflow goes through a subterranean N-S rupture in the bedrock at the north-western shore. The water level shows seasonal fluctuations with an amplitude of 1.3 m (Spengler, 1974). The maximum and the mean water depths are 9.4 and 6.7 m, respectively. The hydrological catchment area includes 4.12 km^2 but due to the karstic geology, the watershed consists only of between 20 and 25% of the topographical area. The major part of the hydrological catchment (see Figs. 2 and 3) consists of bare rock (45%), followed by alpine pastures (31%) and screes (14%).

Sägistalsee is a mesotrophic (TP: 20 μg L^{-1}) hardwater lake (conductivity: 225 μS cm^{-1}; pH: 8.4; alkalinity: 2.7 meq L^{-1}; Ca: 52 mg L^{-1}, see Lotter et al., 1997b, 1998; Müller et al., 1998) with a sparse vegetation of submerged aquatics such as *Potamogeton filiformis* and *Chara vulgaris*. Fish were introduced at the end of the 19th century (Guthruf et al., 1999).

Sediments

In April 1996 two parallel sediment cores were take from the central part of the frozen lake with a modified 8 cm diameter Livingstone piston corer (Merkt and Streif, 1970; Lotter et al., 1997c). A short gravity core (Kelts et al., 1986) was used to sample the topmost 70 cm of water-saturated deposits. The parallel piston cores were taken within a horizontal distance of 1 m and a vertical offset of 50 cm. After sampling 13.5 m of sediments, it was not possible to penetrate further with the coring equipment using the available manpower or an electric hammer.

The core segments had a length of 1 m and were extruded from the stainless steel tubes on site, transported to the laboratory where they were longitudinally cut into halves using an electro-osmotic guillotine (Sturm and Matter, 1972). After photographing and lithological description, the cores were correlated based on conspicuous lithological marker beds. One half-core was contiguously sampled for the different analyses, whereas the other half was stored as a back-up.

Loss-on-ignition (LOI) analyses were carried out at 5 cm sampling intervals. Figure 4 shows the results of sediment combustion for 4 h at 550 °C to estimate the organic content and during 2 h at 950 °C to estimate the carbonate content (Heiri et al., 2001). The LOI at 550 °C rises continuously from about 4% at the bottom of the core to 7–8% at the top, whereas the LOI at 950 °C decreases from over 20% at the bottom to 10–12% at the top of the core (Fig. 4). The top 600 cm of the stratigraphy is characterized by three oscillations in the organic and carbonate content. The high amount of scatter in both curves is explained by the composition of the sediment. The sediments of Sägistalsee are predominantly clastic with centimetre-scale alternations between silty-clayey layers intercalated by sandy layers (see Ohlendorf et al., 2003).

Chronology

For dating purposes, the topmost 20 cm of sediments were sampled with a short gravity corer (Renberg, 1991) and extruded on site in contiguous 0.5 cm intervals. The freeze-dried samples were then caesium dated. The 1986 peak could not be found as in other profiles from the Bernese Oberland (Lotter et al., 2000), whereas the 1963 ^{137}Cs peak is located between 4.5 and 5 cm of sediment depth.

Further downcore sediment slices of 2 cm (25 cm^3) were sieved through a 200 μm mesh and after identification of plant macrofossils, remains of terrestrial plants (Wick et al., 2003) were used for AMS radiocarbon dating. A total of 18 samples has been radiocarbon dated. The sediment depths as well as details on the dated plant material and their radiocarbon ages are given in Table 1. The radiocarbon dates were transformed into calibrated radiocarbon years before present (cal. BP) using the INTCAL98 calibration data-set (Stuiver et al., 1998) method A in the CALIB 4.1.2 program (Stuiver and Reimer 1993), and a 10-sample curve smoothing (Törnqvist and Bierkens, 1994). One sample (519–521 cm) was omitted from the age-depth modelling as its age is clearly too old in comparison to all the radiocarbon dates above and below it.

Age-depth models based on the remaining 17 AMS dates, the ^{137}Cs peak, and the water-sediment interface were developed by non-parametric weighted regression within the framework of generalised additive models.

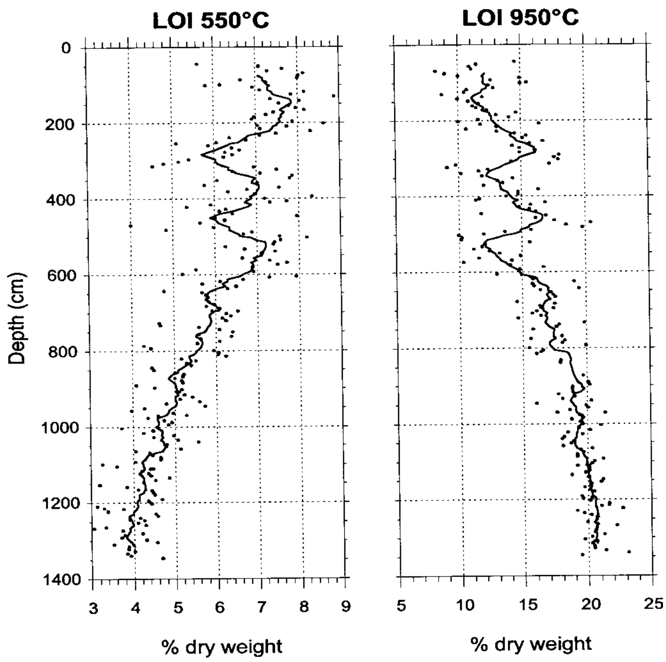

Fig. 4. Loss-on-ignition of Sägistalsee sediments showing the % dry weight loss-on-ignition at 550 and at 950 °C. The lines through the data points represent 11-sample running averages.

Table 1. Details of material used for dating the sediment from Sägistalsee and conventional radiocarbon years BP of dated material

Lab no.	Depth top cm	Depth bottom cm	Dated material	d^{13}C ‰	Radiocarbon age ^{14}C yr BP	SD
	0		Sediment surface in 1996		-46	
EAWAG	4.5	5	Bulk sediment, ^{137}Cs peak 1963		–13	
Hela-298	237	239	*Salix* wood	–28.00	1380	60
Hela-299	288	290	*Picea abies*, *Salix*	–26.30	1730	70
Ua-13636	316	318.5	*Picea abies*, *Dryas octopetala*	–27.43	2005	80
Ua-13637	495	497	*Picea abies*, *Alnus*	–27.10	3410	80
Ua-13638	519	521	*Picea abies*	–25.00	5470	120
Hela-300	541.5	543.5	*Picea abies*	–27.40	3345	65
Ua-13639	636.5	638.5	*Pinus cembra*	–28.10	4265	75
Hela-301	743	749	*Picea abies*	–24.10	4690	70
Ua-13640	792	794	*Pinus cembra*	–26.04	5770	100
Ua-13641	874.5	876.5	*Pinus cembra*	–26.47	6145	105
Ua-12934	910	912	*Alnus*, *Pinus cembra*	–26.94	6560	75
Hela-302	953.5	955.5	*Pinus cembra*, *Abies alba*	–26.60	7025	80
Hela-303	982	984	*Pinus cembra*, *Salix*	–26.40	7105	70
Ua-13343	1032	1036	*Pinus cembra*, *Abies alba*	–27.39	7125	95
Ua-12935	1128	1130	*Pinus cembra*	–26.45	7410	75
Ua-13344	1141	1143	*Pinus cembra*, *Salix*	–26.93	7755	95
Ua-13345	1241	1243	*Pinus cembra*, *Vaccinium*	–26.91	7785	95
Ua-13346	1327	1331	*Pinus cembra*, *Vaccinium*, *Betula*	–27.90	8005	90

Calibrated ages were used as the response variable and sediment depths were used as the predictor variable. Three different variance functions (constant variance, variance proportional to the mean, variance proportional to squared mean) and an identity link function were used in conjunction with a cubic smoothing spline incorporating different approximate degrees of freedom or 'roughness' as an estimator (Hastie and Tibshirani, 1990). Five levels of smoothing (degrees of freedom = 1, 2, 3, 4, and 5) were allowed, corresponding to a range from linear to very flexible models. The weights used in the modelling were inversely related to the range of the calibrated ages. The simplest parsimonious age-depth model was selected on the basis of the model being statistically significant, having the fewest degrees of freedom in the spline smoother, and showing no serious deviations or patterns in the resulting regression diagnostic plots. The final age-depth model selected is based on a variance function proportional to the mean and with a four degrees of freedom equivalent smoother parameter. Ages were estimated by interpolation for every cm along with 95% confidence intervals for each estimate. The resulting age-depth model is plotted in Fig. 5 with calibrated ^{14}C years on the x-axis and sediment depth on the y-axis. Note that in the age-depth modelling, depth was the predictor variable and calibrated ages were the response variable. The sedimentation rate (mm yr^{-1}) is also plotted on Fig. 5.

The age-depth relationship (Fig. 5) is slightly sigmoidal with two phases of high sediment accumulation. The highest accumulation rates of over 3 mm yr^{-1} occurred in the lowermost part of the core (sediments older than 8000 cal. BP). Between 1200 and 800 cm of sediment depth (i.e., ca. 8500–6500 cal. BP) the accumulation rates decreased to about 1 mm yr^{-1} where they remained before gradually increasing to ca. 1.8 mm yr^{-1} between 600 and 100 cm of sediment depth (i.e., ca. 4000–500 cal. BP). This age-depth model is used in all contributions (Heiri and Lotter, 2003; Hirt et al., 2003; Hofmann, 2003; Koinig et al., 2003 Ohlendorf et al., 2003; Wick et al., 2003; Lotter and Birks, 2003).

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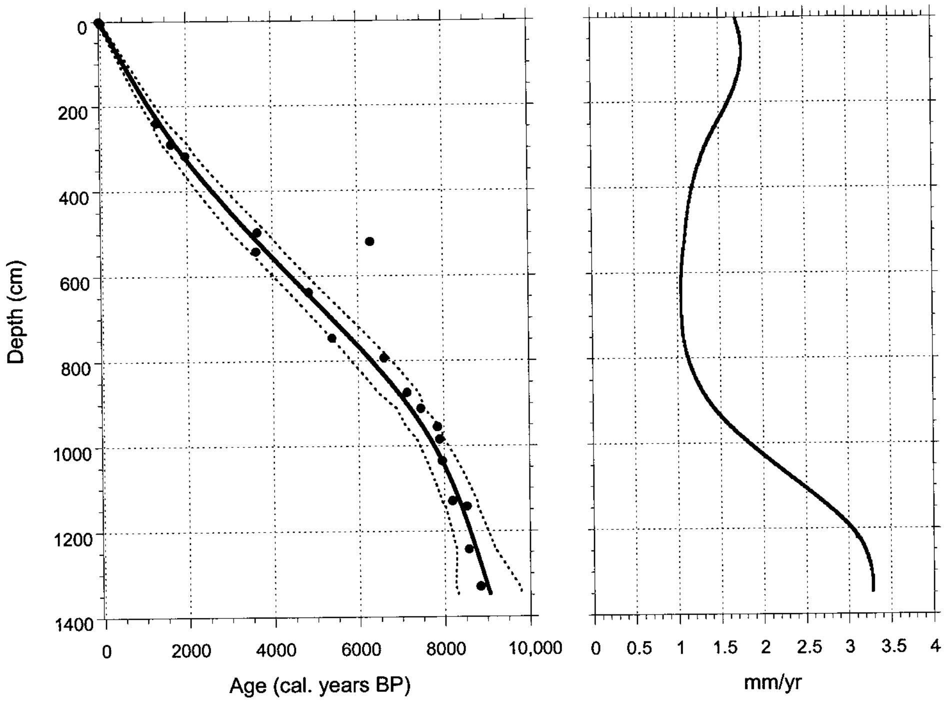

Fig. 5. Depth-age relationship (left) and sedimentation rates for the Sägistalsee sediment. Ages are given in calibrated radiocarbon years before present (BP). Dashed lines indicate the 95% confidence intervals of the depth-age model.

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