Paleoenvironmental studies on Lake Bergsee, Black Forest, Germany

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With 12 figures and 2 tables


Abstract: Bergsee is a small lake in the southern foothills of the Black Forest, Germany. The lake basin sedimentary infill consists of late Pleistocene silts and clayey silts and late Pleistocene and Holocene organic lake deposits. Radiocarbon measurements address the oldest recovered sediments an age of more than 29'000 uncal. $^{14}$C years BP. Thus, the data presented here cover the whole Late Würm and Holocene. The study of the sediments, their pollen content and late Pleistocene chironomid fauna in addition to geomagnetic and geochemical investigations facilitated the reconstruction of past changes in climate and environment as well as the deciphering of natural hazards such as distant volcanic activities as in case of the Laachersee tephra (LST).

1. Introduction

Rapid climatic and environmental changes, which are occurring at present and predicted for the near future, have increased interest in studies on the nature and timing of past changes. While records from continental ice sheets and oceanic sediments give a global picture, terrestrial archives have the advantage of recording changes in ecosystems close to human societies.

Large areas north of the Alps were covered by glaciers during the last glaciation. Thus, lake sediment records spanning more than the last 15,000 years are extremely rare. Bergsee (7°56'11"E/47°34'20"N) is a 335 m long, 250 m wide and maximal 13 m deep lake located distant from main drainage systems in the southern foothills of the Black Forest in southern Germany at an elevation of 382 m a.s.l. (Fig. 1). Its location between the centres of glaciations in the Black Forest to the north and the Alps to the south during the Würm, and its position between the high stands of the Rhine glacier during the Riss and the Würm makes this lake a unique archive that probably records palaeoenvironmental changes well beyond the last glaciation. Changes in climate and vegetation should find their expressions in the long sedimentary record of the lake. Lake Bergsee provides an ideal area to gain insight in how different methods reflect changes in environmental and anthropogenic processes in this isolated system. For this study sedimentological, geochemical, mineral magnetic and biologic parameters were taken from a set of piston cores from the deepest part of the lake basin to reconstruct the palaeoenvironmental evolution in this part of the southern Black Forest during the last approx. 30,000 years.

2. Setting and history

The lake basin of Bergsee is embedded in crystalline basement rocks of the Black Forest, which are mainly pre-Hercynian gneisses (Fig. 1). Late Hercynian granites crop out (Albtal granite) only along the eastern shore. In the surroundings patches of Permian clastics (Rotliegendes) occur, which cover larger areas NW of Bergsee. To the south and west Quaternary deposits become more widespread. Gravels and sands up to 20 m thick are common in the Rhine valley. They represent the glacifluvialite deposits of the youngest Würm glaciation in the Alps and their foreland. Loess or altered loess (loess clay) of Würm age is the most widespread Pleistocene deposit to the S and SE of Bergsee. However, some of the loess may be redeposited alluvial soil (Schwemmloess). The most recent, probably Holocene sediments outside the lake basin are alluvial deposits in the valleys, and debris talus along steep slopes. Tectonic faults in the surroundings of Bergsee (Fig. 1) do
not show any signs of young displacements. Most likely they were active for the last time during the Oligocene rifting and subsidence of the Upper Rhine Graben.

It appears that Bergsee is part of a former subglacial channel system that has formed during the Riss complex when the Rhine glacier reached the area (BECKER & ANGELSTEIN 2004, GEYER et al. 2003). The lake has no natural tributary. It is only fed by precipitation, groundwater inflow and the natural run-off from the surrounding slopes, which are covered with forest. The natural catchment area is, thus, restricted to the near vicinity of the lake and covers 0.162 km². The natural outlet of the Bergsee is the Seebachle (Fig. 1), which can be regarded as a seasonal overflow into the Rhine valley where the stream soon disappears in gravel deposits. The Schöpfbach-Heidenwuhr-System to the east of Bergsee is the most important drainage of the southern Black Forest N of Bad Säckingen. Finally, the Haselbach to the north of Bergsee follows the valley at the base of the steep slope which rises up to the high ground of the southern Black Forest with elevations between 700 and 800 m a.s.l. The main drainage of all these streams is the Rhine River about 2 km south and west of the investigation area.

In AD 1361 Bergsee was mentioned for the first time in a written document (METZ 1980). For most of its recent history the lake was used as a fish pond, always in danger to become overgrown and gradually changed into a mire. Also the historical name "Schwarzsee" or black lake, points to a dystrophic lake. A canal and a gallery were built in 1802/1803 to link Bergsee with the catchment area of the Schöpfbach-Heidenwuhr-System (Fig. 1), which enlarged the catchment area by 10 km². The lake level was artificially raised successively in 1837, 1880 and 1907 (MÜLLER 1993) to enlarge the water reservoir. Today the maximum water depth is 13 m, which is about 6 m above the natural water level before 1802. By the additional inflow of suspended matter by stream water the former dystrophic gradually changed into a mesotrophic lake (WÜTHRICH 2003, WÜTHRICH & LIESER 1999). The discharge of untreated sewage into the Schöpfbach-Heidenwuhr-System in the 1960s and 1970s severely polluted Bergsee and changed the mesotrophic into an eutrophic lake. In 1987 the lake was equipped with a deep water aeration system, and together with the installation of a sewage system in the catchment area, the ecological situation of Bergsee improved.

3. Methods and results

3.1. Geophysical investigations and lake basin geometry

In order to study the sub-surface geology of the lake basin and its geometry a 3.5 kHz high resolution seismic reflection survey was carried out in May

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Fig. 2. Contour lines of the present lake basin given in metre a.s.l., recent and historical lake levels, the positions of the reflection seismic lines and of the core sites (BS: short corer, BL: Livingstone probe). The broken line indicates the approximate extent of a layer which can be seen in all reflection seismic lines which pass the deepest lake basin (for example see line A in Fig. 3) and which tapers out at a depth of about 376 m a.s.l. Present maximum water depth of the lake is about 13 m.
1998. For this purpose, a 3.5 kHz source (Geoacoustic pinger) was mounted on an inflatable boat so that eight seismic lines were recorded in an E-W and N-S direction (Fig. 2). Navigation was obtained from a series of way-points marked along the shore. The shot interval was 300 ms with a cruising speed of approx. 3 km/h. Data were digitally recorded, gained (automatic gain control of 50 ms), band-pass filtered (1400-6500 Hz) and water bottom-muted. In some marginal areas of the lake, seismic penetration into the lake’s subsurface reaches up to 10 m displaying the sediment geometry at a vertical resolution of 10-20 cm. In the deeper areas closer to the lake center, occurrence of free gas in the lacustrine deposits prevented significant penetration of the seismic signal, so that the bedrock depth could not be determined.

Fig. 3A displays the 3.5 kHz seismic profile A, imaging the southern area of the lake (Fig. 2). This profile shows that the seismic signal only penetrates a few decimeters into the deeper areas. A detailed look at the shallow seismic stratigraphy (Fig. 3B) nevertheless images one onlapping reflector (marked by arrows) indicating a sediment package that wedges out on both sides at a depth of approximately 8 m from the lake surface. The unit can be traced around the entire lake and consistently wedges out at the same water depth. This onlapping unit is overlain by a draping sedimentary succession of approx. 60 cm thickness that continues into shallower water depths. This geometry probably is explained by the lower lake level in the pre-19th century period. After the lake level increased in the 19th century, sedimentation extended to higher elevations, thus burying the previously deposited onlapping sediment layers.

Fig. 3. 3.5 kHz seismic section ‘A’ from the southern area of the lake (for position see Fig. 2). A: Overview of entire profile, displaying the different seismic penetration in the central areas (free gas, no penetration) and the flanks (good penetration, weak to absent multiple reflection). B: Detail of above displayed profile, as indicated in A: The arrow-marked reflection laps out on both sides, whereas the next shallower reflection laps out on the western side. The onlap surface likely marks an increase of lake level that occurred at the end of the 19th century, after which sedimentation extended to shallower areas consequently burying the onlapping unit. C: Uninterpreted and interpreted detail of profile ‘A’, as indicated in Fig. 3A. Slope section with approx. 10 m of seismic penetration displaying sequences separated by unconformities characterized by high-amplitude reflections. The sediment geometry indicates some dynamic downslope processes such as sediment slumping.

Fig. 3 (Legend see p. 410)
In some areas, mostly on the flanks of the lake slopes, the 3.5 kHz signal penetrates much deeper into the lake sediments (Fig. 3C). These zones are easily recognized by a much weaker amplitude of the first multiple reflection, since most of the seismic energy indeed reaches the subsurface. A series of high-amplitude reflections can be recognized (Fig. 3C) that defines major sedimentary packages separated by unconformities. These windows allow a seismic view into the sediment architecture of the slope, documenting dynamic downslope processes such as sediment slumping. Because this geometrical information is restricted to the lake slopes, a complete 3D reconstruction of the sedimentary architecture of the lake basin is not possible.

3.2. Core sampling and preparation

Coring in the lake basin was carried out from an inflatable boat with a gravity driven short-corer and from a fixed pontoon with a modified Livingstone piston-corer (MERKLE & STRIEF 1970). The six short-cores that were taken had a diameter of 58 mm and a length of about 1 m (Fig. 2). Cores from sites BS1 to BS3 were split, described lithologically, photographed and sampled for geochemistry. Short-cores BS4 to BS6 were kept for 137Cs- and 210Pb investigations.

The Livingstone coring sites were located close to the centre of the lake at a water depth of c. 10 m (Fig. 2). For the sites BL1 and BL2 two twin cores 2-3 m apart were taken with overlapping core sections in order to have undisturbed sediment throughout the entire length; for site BL3 only one core was taken. The Livingstone cores have a diameter of 80 mm in the upper sections, changing to 50 mm at depth as indicated in Fig. 4. The longest sediment core was recovered from site BL3 reaching a total length of 20.60 m. After careful splitting of the cores parallel to the long core axes

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**Fig. 4.** Lithological core logs, radiocarbon ages (uncal. 14C ages BP) and ‘Multi-scanner’ susceptibility data (AU: arbitrary unit) for the lower core sections of BL 1.2 and BL 3.1. LST is Laacher See tephra. W and M refers to enrichments of wood fragments and moss lumps. The description of the sediments is based on the Treos-JM classification scheme (BIRKS AND BIRKS, 1980), where Ag and As refer to silt and clay, respectively, LD to fine grained lake mud (LD4 is gyttja), Dg to coarser grained detritus mud in general, Dh to detritus mud with herbs and DI such with wood fragments.

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**Fig. 4 (Legend see p. 412)**
using a plate or a string wire, the cores were described lithologically and photographed. One half was used for sampling, and the other was kept for documentation and nondestructive investigations.

3.3. Lake sediments

3.3.1. Methods

The description of the lacustrine sediments in Fig. 4 is based on the Troels-Smith classification scheme (BIRKS & BIRKS 1980), which is favourably applied to organic sediments, but can be used for clastic deposits as well. However, for clastic deposits a classification based on the three-component system clay-silt-sand following TREFETHEN (1950) has been applied in addition. The description of the organic sediments is made purely by eye. Samples from BL1.2 were taken to determine the density of organic sediments for which details are given in BECKER et al. (2004), and some noticeable mineral aggregates were investigated by x-ray diffractometry on powder samples. In addition scanning electron microscope (SEM) images were taken at depths of 3.24 m, 7.25 m and 10.25 m (BECKER et al. 2004). Core specimens were taken from BL1.1 and BL2.2 to analyze the total carbon content (TC) (BECKER 2003) and, finally, some samples from the clastic section of BL3.1 were taken for particle size analyses. The samples were wet sieved for grain sizes ≥ 32 μm. The finer particles were analysed with a ‘SediGraph’ using X-rays to measure directly the relative mass concentration of particles in a liquid medium. Particle size was determined from Stokes law.

3.3.2. Clastic sediments

The sediments of Bergsee can be subdivided into a lower section that is dominated by bright yellowish and greenish brown clastic sediments and an upper section dominated by mainly very dark brown to almost black organic sediments (Fig. 4). The clastic sediments are mainly clayey silts (Fig. 5). The lower- and uppermost samples become more clayey, whereas the samples from the middle section are clearly dominated by a coarse silt fraction (Fig. 5). The lowermost sediments in core BL3.1 show a weak grey stain, which indicates a slightly higher organic content compared to the clastic deposits further up the core. The same is found in the uppermost section of the clastic dominated sediments where the gradual transition into the organic dominated lake deposits is indicated by a continuous increase of grey scale values. Hardly any bedding can be seen in the clastic dominated sequences, with the exception of the deepest part of BL3.1, and some vague occasional

Fig. 5. Particle size distribution of clastic deposits from core BL 3.1 with depth.
occurrences in the other elatic sections of BL1.2 and BL3.1. In several sections of these elatic deposits dark blue mineral patches can be seen (indicated with 'v' in Fig. 4), which are similar to mineral patches further up the profile; these have been identified as vivianite. The boundary between the elatic and the organic sediments is at a depth of about 13 m.

3.3.3. Tephra layer

Close to this boundary several whitish and greenish silt layers and disrupted silt patches are included in the dark grey organic deposits, which partly contain a considerable amount of relatively large pumice shards, feldspar, amphibole and pyroxene, mixed with rock fragments, many diatoms and other lake deposits. These pumice enrichments are of volcanic origin; this may also hold for the pyroxenes and amphiboles (Schmincke, pers. comm.), which indicate a volcanic tephra layer. This tephra layer can be seen in three sites in depths between 12.60 m in BL3.1 and 13.20 m in BL1.2 (LST in Fig. 4) (Becker 2003).

3.3.4. Organic sediments

The organic deposits can be sub-divided into three sections (I-III).

I. The lower part consists of gyttja, a highly elatic, jelly-like, non-greasy, non-sticky, homogeneous dark grey organic lake mud with almost no large plant remains. Freshly cut cores frequently show light brownish and reddish colours which darken within minutes. In some lower sections greenish colours can be seen, as for instance in BL 1.1, that may be indicative of algae gyttja (Aaby & Berglund 1986). The SEM images from gyttja in core BL1.2 show mats, fibres and spherical remains of organic material that are generally related to algae and in particular to diatoms (Becker et al. 2004). Clastic remains in the gyttja are extremely rare and are more frequent at the base than at the top of the sequence. They are mainly restricted to the occurrence of pinkish and white single angular grains, (feldspar, quartz) of sand size. These grains appear to be concentrated in fractures, whereas other grains are in small aggregates. Some of these aggregates are related to large fruits of terrestrial plants, for instance beech nuts. Blue patches of vivianite, sometimes up to more than 2 cm in diameter, can be seen in the gyttja sections of boreholes BL1.1, BL1.2, BL2.1 and BL3.1. Most occurrences are in the lower sections, whereas the top sections are mainly free of vivianite (Fig. 4). In addition to blue vivianite whitish soft mineral patches of an undetermined mineral can be seen. The density of gyttja is very low (Becker et al. 2004). In BL1.2 the density at a depth of 6.5 m is at 1.03 g/cm³ and increases to 1.11 g/cm³ at a depth of 11.5 m. The low density is caused by the extremely high water content between 85 and more than 90 vol. %. The transition to the coarser detritus gyttja and detritus at the top is gradual and can be placed between 5 and 7 m depth in the different core sites. The more detritus dominated deposits (II) have a total carbon content (TC) between 35 and 45 %, as opposed to 25 to 35 % C which is found generally in the gyttja deposits (I) (Becker 2003). A transition between both lithologies occurs at a depth of 6 m in core BL2.2.

II. The middle section of the organic sequence is still homogeneous in most parts, showing dark brown to almost black colour. The organic particles are larger than those in the gyttja section deeper down. The density of the sediments is between 1.02 to 1.05 g/cm³ at depths from 1.5 to 5.5 m in core BL1.2. No increase of density is found with depth (Becker et al. 2004). The basal section consists of fine to coarse detritus gyttja, containing larger fibrous plant remains, occasional wood fragments, seeds of trees and reed plants (Cyperaceae). The organic material becomes increasingly coarser to the top of the middle section, and the uppermost parts of the detritus mud largely consist of leaves of Cyperaceae, seeds, roots and wood fragments. A layer of large wood fragments, some of them small stems of birches that can be identified by their barks, can be found in all cores (W in Fig. 4). An enrichment of moss lumps about 2 m deeper in the profiles (M in Fig. 4) can be seen in three cores. A SEM image at a depth of 3.24 m in BL1.2 shows numerous diatoms, which point to a lacustrine origin of the sediments (Becker et al. 2004). A sample taken from BL3.1 at 1.85 m depth to be investigated under a binocular showed moss remains, wood fragments, plant fibres, including Carex (sedge) in addition to aquatic organisms. Therefore, the organic layers at the top of the sequence can be considered to be of aquatic and not of subaerologic origin as in the case of peat.

III. The most recent change in the sedimentation is seen in the uppermost, top 1 m of the sedimentary record, which is best documented in the short-cores BS1 to BS3 and in the Livingstone core BL1.1. A sudden change from dark grey to black coarse detritus to a fine grained, red brown mud with some clastic input and occasional faint layering of black and red brown sediments can be seen. Macroscopically the sediments have been described as clayey gyttja and weakly silty clayey gyttja. However, this gyttja differs significantly from the gyttja deposits at greater depth: it is soft, greasy, sticky and only weakly elastic, giving the impression of a higher degree of decomposition of the organic material.
3.4. Age model and sedimentation rates

The $^{14}$C method was used for age determinations on 15 samples from the long cores by the accelerator mass spectrometry (AMS). For two samples, plant fibres from the coarse grained detritus and detritus gyttja were picked by hand, however, in most cases dispersed organic material was sampled from the fine grained organic core sections. After a standard acid-alkali-acid pretreatment (AAA), the samples were dried and combusted in quartz tubes for further processing. Samples containing dispersed carbon material also required AAA-pre-treatment where after each step material was centrifuged. After pre-treatment, the CO$_2$ obtained was cracked to graphite. The preparation and pre-treatment of the samples for radiocarbon dating was carried out at the $^{14}$C-laboratory of the Department of Geography at the University of Zurich. The AMS with the tandem accelerator of the Institute of Particle Physics at the ETH-Hönggerberg was used for dating.

The results of $^{14}$C-dating on the organic matter are given in Table 1. The positions of the sample sites in the cores and the $^{14}$C-dates are given in Fig. 4. The calibration program OxCal v.3.9 (Bronk Ramsey 1995) was used for the calibration of the radiocarbon dates. The 1σ and 2σ ranges from dendo-calibrated dates from cumulative probability are given in Table 1. A graphical illustration of the radiocarbon dates and their ages in calibrated calendar years AD/BC of the gyttja and detritus sections of the cores is given in Fig. 6 a, b. The error bars are too small to be indicated in case of radiocarbon ages (Fig. 6a), whereas the 2σ ranges of the probability distribution for the dendo-calibrated age curves using Bayesian statistics are indicated in Fig. 6b. The data can be fit very well with a linear regression line; only two radiocarbon dates do not fit the regression line (Fig. 6a, b). Using this average sedimentation rate in Bergsee is 1.0 mm/a for the last 14,000 years.

There is only one radiocarbon date for the lowermost part of the section at a depth of 20.46 m, which suggests that the sedimentation rate is lower and could be in the range of 0.5 mm/a. In addition to the estimate of the rate of average sedimentation the radiocarbon dates show three major features: (1) the lower clastic section of the cores ends in the second to the last Interstadial of the Late Pleistocene (Bolling), covers the entire Würm maximum and reaches the Denkamp Interstadial; (2) it is most likely that the tephra layer seen in three cores is the Laacher See Tephra (LST) (Bogaard & Schmincke 1985, Haars et al. 1995, Schmincke et al. 1999); (3) the onset of deposition of organic-rich lake deposits already started in the last Late Pleistocene Interstadial (Allerød).

<table>
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<th>Lab. code</th>
<th>Core code</th>
<th>Cores</th>
<th>Depth (m)</th>
<th>$^{14}$C age BP</th>
<th>Cumulative probability [B/CAD]</th>
<th>1σ-range</th>
<th>2σ-range</th>
<th>Material</th>
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<td>1370 BC - 1120 BC</td>
<td>1850 ± 560</td>
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<tr>
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<td>740 BC - 1550 BC</td>
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<tr>
<td>BL2.1</td>
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<td>5.30</td>
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<td>4220 BC - 3850 BC</td>
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Table 1. Summary of radiocarbon dating (Disp. material: disperse organic material).
3.5. Magnetic susceptibility and drill core correlation

Magnetic susceptibility was used as a means to correlate events among the different cores. Magnetic susceptibility was measured on the whole cores with a Bartington Loop Sensor MS2E (sensitivity: $5 \times 10^{-6}$ (arbitrary unit, AU)). Although the susceptibility was below the detection level in the gyttja sections of the cores, a measurable signal was detected in the more clastic sections in cores 1.2 and 3.1 (Fig. 4). The clayey silts in cores BL1.2 and BL3.1 are virtually homogeneous with occasional faint layering. The susceptibility measurements on the other hand show variations due to differences in iron mineralogy and these can be correlated between the two cores. This correlation indicates that the two sedimentation rates were similar. The only difference is seen in the interval between 14.50 m and 17 m, where the sedimentation rate in BL1.2 is slightly higher (Fig. 4). The decrease in susceptibility seen around 14 m correlates with the increase in organic content in the sediments. The end of clastic sedimentation correlates with very low susceptibility values, typical for organic sediments. A pronounced peak is seen, however, towards the end of the gyttja section over a narrow interval in both cores (around 13.10 m in core 1.2 and 12.72 m in core 3.1, Fig. 7a, b). This corresponds to the Laachersee Tephra.

In order to evaluate whether the susceptibility data can also be used as a paleoclimatic proxy, cores BL1.2 and 3.1 were subsampled over several intervals, so that the sediment magnetic properties could be characterised. Samples were taken by pushing a 2 cm cube into the split core. Mass susceptibility ($\chi$) was measured on an AGICO KLY-2 susceptibility bridge with a sensitivity level of $2 \times 10^{-6}$ (SI). The general trend features found in the whole core measurements are also found in the specimen measurements. Susceptibility is low, but positive in the gyttja. The pronounced peak towards the end of the gyttja section is also seen in both cores (around 13.10 m in core BL1.2 and 12.72 m in core BL3.1, Fig. 7a, b). There is a gradual increase in the susceptibility with the transition to more clastic sediments. Two predominant peaks are found toward the base of core BL1.2 between 17.00 and 18.00 m depth; these are also identified in core BL3.1 between 16.00 and 17.00 m depth, where they are less pronounced.

An anhysteretic remanent magnetization (ARM) was imparted to all specimens from core BL1.2 in a 150 mT alternating field superimposed with a 0.1 mT DC bias field. The ARM intensity is low in the gyttja but increases in the tephra layer (Fig. 7c). It is higher in the clastic section but only shows slight variations as a function of depth, including the specimens taken between 17.00 and 18.00 m. An isothermal remanent magnetization (IRM) was imparted in three fields, at 150, 300 and 1000 mT. The IRM intensity is also low in the gyttja (Fig. 7d), but increases in the tephra layer. There is a
gradual increase in intensity between 13.50 and 14.00 m with increased clastic content. Below 14.00 m depth the IRM intensity shows some high frequency variation with the trend to slightly higher intensities with depth.

The ratio of the IRM acquired at 300 mT and 1000 mT (IRM_{300}/IRM_{1000}) is relatively constant through the entire sampled section, except immediately above the tephra layer (Fig. 7b). The ratio is between 0.85 and 1.00 for most of the section, which suggests that a low coercivity phase, most likely magnetite or maghaemite, is present in all samples. A high coercivity phase, haematite, of variable concentration is also present. IRM_{300}/IRM_{1000} is around 0.70 above the tephra, suggesting a higher concentration of haematite. The ratio $\chi_{IRM}/IRM_{1000}$ indicates if variation in susceptibility is due to variable content of ferromagnetic minerals. Fig. 7b shows that much of the variation in susceptibility can be attributed to the concentration of ferromagnetic phases. The two susceptibility peaks between 17.00 and 18.00 m, however, still remain, which indicates that the higher susceptibility is not due to the ferromagnetic mineralogy for these peaks. The ratio of ARM/IRM_{150} is high in the gyttja and in the tephra layer (Fig. 7d), but otherwise relatively constant between 13.80 and 18.00 m depth. The low constant ratio in the clastic section suggests that the grain size of the ferromagnetic mineralogy is relatively constant in these sediments. The increase in the tephra layer is largely due to finer grain size of magnetite/maghaemite. Finer ferrimagnetic grains are also found in the lower part of the gyttja, which may reflect reductive dissolution of originally coarser clastic grains.

3.6. Palynostratigraphy

Core BL 3.1 was used for pollen analysis in order to answer the following questions: (1) How did the vegetation change under major climatic shifts

Fig. 7. Results of magnetic measurements on the lower core sections of BL1.2 and BL3.1: a) mass susceptibility of core BL1.2 (filled circles) and BL3.1 (open diamond); b) coercivity ratio from the IRM measurements in core BL3.1, which indicates the relatively constant composition of the ferromagnetic fraction below 1350 cm, c) mass susceptibility normalized by the IRM in core BL3.1, which indicates susceptibility peaks at depth are due to ferromagnetic fraction; and d) ratio of ARM to IRM imparted at 150 mT in core BL3.1, which is an indicator of constant ferromagnetic grain size below 1350 cm.
Fig. 8. Palynostratigraphy of core Bergsee BL3.1 for the Late Pleistocene and Early Holocene. Betula, Pinus, Juniperus, Salix, Ephedra, Gramineae, Artemisia, Chenopodiaceae, Helianthemum, Rubiaceae, Rumex/Oxyst, Caryophyllaceae, Brassicaceae, Ranunculaceae, Thalictrum, Apiaceae, Corylus, Quercus, Ulmus.

Fig. 9. Palynostratigraphy of core Bergsee BL3.1 for the Holocene. Pollen percentages are based on a pollen sum excluding alder. Additional taxa compared with Fig. 8: Tilia, Fraxinus, Taxus, Fagus, Hedera, Cyperaceae, Plantago lanceolata, Urtica.
between 29,000 BP and the early Holocene? (2) Can prehistoric human impact on the vegetation be recorded? Therefore entailed pollen analysis was done in two different sections of the core. A lower section was analysed to provide an overview about the general evolution of the vegetation during Late Würm. A detailed pollen study was done in the upper part of the core to answer the second question.

For the older section (20.70 – 10.40 m) of the core the pollen diagram (Fig. 8) provides an overview over four major pollen zones (Berg A to D) representing four vegetation types:

Berg-A: This zone is characterized by a clear decrease of pollen grains from shrubs and a significant increase of non-arboreal pollen. However, the full-glacial vegetation characteristic for a cold and dry steppe-tundra was still not established.

Berg-B: The full-glacial vegetation was a steppe-tundra, which means it was a treeless landscape with possibly a few shrubs of Salix, probably species that show today an arctic-alpine range. High percentage values of Artemisia, Chenopodiaceae, Helianthemum and Gramineae indicate steppic conditions. The low percentages of Betula and Pinus, both strong pollen producers, are best interpreted as long-distance transport and not as local presence. Compared to La Grande Pile and Les Échets the tree-pollen percentages are extremely low, another argument for the absence of trees around Bärsegge during this full-glacial phase. Towards the end of this pollen zone the Betula curve shows a significant increase. On the neighbouring Swiss plateau this could be a consistent wide-spread phenomenon: the vegetation of the last third of the Olden Dryas is often a shrub-tundra where dwarf birch (Betula

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**Table 2. Palynostratigraphy and its interpretation in Bärsegge.**

<table>
<thead>
<tr>
<th>Regional</th>
<th>Local Pollen zones</th>
<th>14C age BP (years)</th>
<th>Cubit ratio</th>
<th>Local Pollen</th>
<th>Criteria for limits of PAZ</th>
<th>Stratigraphic position</th>
<th>Rise</th>
<th>Fall</th>
<th>Rise</th>
<th>Fall</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>at 2900 m</td>
<td>1350 BP to 1400 BP</td>
<td>3.0</td>
<td>Berg A</td>
<td></td>
<td></td>
<td>V</td>
<td>V</td>
<td>V</td>
<td>V</td>
</tr>
<tr>
<td></td>
<td>at 2600 m</td>
<td>1400 BP to 1500 BP</td>
<td>2.5</td>
<td>Berg B</td>
<td></td>
<td></td>
<td>V</td>
<td>V</td>
<td>V</td>
<td>V</td>
</tr>
<tr>
<td></td>
<td>at 2300 m</td>
<td>1500 BP to 1600 BP</td>
<td>2.0</td>
<td>Berg C</td>
<td></td>
<td></td>
<td>V</td>
<td>V</td>
<td>V</td>
<td>V</td>
</tr>
<tr>
<td></td>
<td>at 1800 m</td>
<td>1600 BP to 1700 BP</td>
<td>1.5</td>
<td>Berg D</td>
<td></td>
<td></td>
<td>V</td>
<td>V</td>
<td>V</td>
<td>V</td>
</tr>
</tbody>
</table>

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**Legend:**
- PAZ: Pollen Accumulation Zone
- V: Vegetable zone
- A: Algal zone
- F: Faunal zone
- R: Rock zone
- M: Mineral zone
- C: Cobble zone
- R: River zone
- S: Soil zone
- D: Desert zone
- T: Tundra zone
- B: Boreal zone
- N: Narural zone
- H: Humid zone
- D: Dry zone

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**Additional Information:**
- Berg A: This subzone refers to the lowest part of BL3.1 up to a depth of 20.30 m. A few trees and shrubs were growing in the pollen-source area, mainly Betula, Pinus, Juniperus and Salix. Non-arboreal pollen dominates the spectra. A correlation of the interstadial to Denekamp is primarily based on its position below the pleniglacial (Hammen et al. 1967, Ran 1990) and on one radiocarbon date. However, fluctuations in these pleniglacial sequences are extremely strong and difficult to correlate as can be shown with pollen spectra of similar age at La Grande Pile only about 100 km W of Bärsegge (Woillard 1975, 1978, Beaulieu & Reille 1992) and Les Échets about 260 km to the southwest (Beaulieu & Reille 1984, see also discussion in Behre & Flöh 1992).

Berg-A: The upper subzone is characterized by a clear decrease of pollen grains from trees and shrubs and an increase of non-arboreal pollen. However, the full-glacial vegetation characteristic for a cold and dry steppe-tundra was still not established.

Berg-B: The full-glacial vegetation was a steppe-tundra, which means it was a treeless landscape with possibly a few shrubs of Salix, probably species that show today an arctic-alpine range. High percentage values of Artemisia, Chenopodiaceae, Helianthemum and Gramineae indicate steppic conditions. The low percentages of Betula and Pinus, both strong pollen producers, are best interpreted as long-distance transport and not as local presence. Compared to La Grande Pile and Les Échets the tree-pollen percentages are extremely low, another argument for the absence of trees around Bärsegge during this full-glacial phase. Towards the end of this pollen zone the Betula curve shows a significant increase. On the neighbouring Swiss plateau this could be a consistent wide-spread phenomenon: the vegetation of the last third of the Olden Dryas is often a shrub-tundra where dwarf birch (Betula
nana, also found as macrofossils) played a major role together with Juniperus and Salix (AMMANN & TOBOLSKI 1983).

Berg-C, Würm Late-Glacial: At the transition from pollen zone Berg-B to Berg-C the ecologically so important event of the afforestation occurs. The zone Berg-C represents the forested Late-Glacial (Bolling, Allerød, Younger Dryas), dominated by birch and pine woods.

Berg-D: In the early Holocene the vegetation changed from birch-pine forests to a mixed deciduous, rather thermophilous forest made of Corylus, Ulmus and Quercus.

For the younger portion of the section (8.80 – 2.80 m) Fig. 9 shows selected taxa and Table 2 summarizes the major changes in the pollen assemblage. Alnus was excluded from the pollen sum because this riparian and very local tree dominates the spectra after about 6300 uncal. BP and compresses all other pollen curves. The zones Berg-1 to Berg-3 are dominated by mixed oak forests with decreasing amounts of Corylus and significant amounts of Hedera and Viscum. In Berg-3 the immigration of Abies and Fagus into the area occurs around ca 6600 uncal BP. Berg-4 is suddenly dominated by Alnus and the immigration of Taxus. The most marked change in forest composition is found at the transition to Berg-5: Ulmus and Tilia decline markedly while the expansion of Fagus and then Abies occur; it is here that the first evidence for human impact on the vegetation is found: findings of Plantago lanceolata co-occur with a first peak of Taxus at ca 5800 uncal BP and somewhat later Urtica dioica (an indicator for eutrophication) appears. Only in the following zone Berg-6 are Cerealia found. These increases of apophytes, such as Plantago and Urtica, and the first appearance of anthropochores, such as Cerealia, can probably be attributed to the occupation of Middle Neolithic populations in the surroundings.

In the zones Berg-5 to Berg-7 an interesting interplay between the two late-successional taxa of Abies and Fagus and of the early-successional taxa of Betula and Corylus related to phases with higher non-arboreal pollen was found. These phases correspond to Late Neolithic, Bronze Age and Iron Age occupations around the lake.

Berg-8 is characterized by the first occurrences of Juglans, Buxus and Secale. Because of the somewhat too old radiocarbon age we can relate this zone to the Iron Age and to the beginning of the Roman period and thus the transition to historic times.

3.7. Chironomids

Studies in the early 1990s showed strong statistical correlations between the summer water temperature and the chironomid species occurring in freshwater lakes (WALKER 1991). The temperature can be considered to be a key factor affecting chironomid fauna directly as for instance by the reproduction success and the growth rates of larvae but also indirectly by the lake’s nutrient status, the mixing regime and the oxygen availability. Thus, the analyses of chironomid remains in lake sediments provide information allowing the reconstruction of past climate conditions (e.g. WALKER et al. 1997). Chironomid assemblages were studied in Bergsee, firstly to assess long-term changes in climate during the Würm interstadial ‘possibly Dene- kamp’, the last Würm maximum LGM, and the Late Würm independently of other proxies, and secondly to reveal rapid climate changes possibly unmatched by other proxies like pollen assemblages during periods where the plant cover might be in a disequilibrium with climate conditions (COOPE 2002). In Europe, only two low resolution chironomid stratigraphies covering this time interval were previously published by HOFMANN (1991) from Lac du Bouchet (France) and MANCA et al. (1996) from Lago Albano (Italy).

Chironomid assemblages were analysed in 104 samples in a depth between 11.80 m and the base of core BL3.1. Chironomid head capsules were extracted from the sediment following the procedure described by HOFMANN (1986). The sediment was deflocculated in hot 10 % KOH for about 20 minutes and then passed through 200 µm and 100 µm mesh sieves. The sieving was transferred to a Petri dish from where head capsules were hand sorted under a 10X to 50X binocular microscope. Each head capsule was slide mounted in Gurr Aquamount mountant. Identification of specimens according to HOFMANN (1971) and WIEDERHOLM (1983) was performed in most cases to genus or species group level. The number of head capsules in samples (mean: 108 head capsules per sample) was sufficient to deduce statistically valuable assemblages according to HEIRI & LOTTER (2001) and LAROCQUE (2001).

In Bergsee the chironomid fauna is dominated by shallow lake taxa, such as Tanytarsus (HOFMANN 1986), throughout the whole record (Fig. 10), indicating shallow lake conditions during the late Pleniglacial and the Late Glacial. This makes the Bergsee chironomid record particularly suitable for climate reconstructions since the temperature has a strong effect on chironomid communities living in shallow lakes (WALKER et al. 1991). From major changes in chironomid assemblage composition, five biozones were distinguished (Fig. 10):
Chz-1, 20.66 m – 18.82 m. The dominant taxa of Chz-1 are Tanytarsus (mainly Tanytarsus type pallidicornis, not shown), Parakiefferiella bathophila-type and Procladius. In Europe, these taxa are common in warm to temperate lakes. Furthermore, the high taxonomic richness of this biozone suggests favourable environmental conditions for the development of well diversified aquatic biota. The high relative abundance of Procladius indicates that the lake was productive enough to support a large population of these predatory chironomids (Berg 1985). This interpretation is corroborated by the presence of Chironomus frequently found in mesoeutrophic lakes with high organic accumulation (Maitland 1979, Pinder & Reiss 1983, Wolfram 1996). Temperature preferences of taxa suggest a mild climate during Chz-1. Changes in relative abundances of the different taxonomic group show, however, a climate variability within this biozone (Fig. 10). At 20.05 m a brief peak of Sergentia (most probably Sergentia coracina) occurred. Sergentia coracina is widely distributed over Europe, and is a typical member of the profundal community of deep oligo-mesotrophic lakes in temperate regions. In shallow lakes like Bergsee, Sergentia coracina is found in the sub-arctic zone and can be considered as a cold stenothermal taxa (Brundin 1949). Thus, the peak of Sergentia at 20.05 m suggests an abrupt and short cold oscillation.

Chz-2, 18.82 m – 16.20 m. The onset of this biozone corresponds with an abrupt major change in chironomid community. Constraining environmental conditions limiting aquatic biota could be inferred from the very low taxa richness. The assemblages of the biozone were strongly dominated by Sergentia (most probably Sergentia coracina) with relative abundance reaching 80 % in several samples. Assuming that Bergsee was still shallow during Chz-2, strong dominance of the cold stenothermal Sergentia coracina implies very cold climate conditions. Sergentia coracina as the larger member of the Tanytarsus lugens community typical of ultra-oligotrophic lakes (Brinkhurst 1974), tolerates less oxic water than the other taxa of this group (Brundin 1958). During Chz-2, the food content in the sediment was probably so low that only taxa belonging to the Tanytarsus lugens community were able to develop. A water desoxygenation seemed to take place since only Sergentia remained in the assemblages. This desoxygenation of water might be produced by a longer ice-cover on the lake surface probably linked with the very cold climate. Several very short episodes of drop in relative abundance of Sergentia consequently replaced by Parakiefferiella bathophila-type were detected at depth 18.35 m, 18.10 m, 17.65 m and 17.25 m. Because the temperature optimum of Parakiefferiella bathophila-type is much higher than the thermal optimum of Sergentia (e.g.

Fig. 10. Chironomid diagram of core BL3.1 showing changes in relative abundance of selected taxa and taxa richness with depth.
Walker et al. 1997), the five peaks of Parakiefferiella bathophila-type should be interpreted as short warm events which interrupted a long cold phase.

Chz-3, 16.20 m – 13.90 m. This biozone is characterised by an increase in the taxa richness and the sudden and complete disappearance of the cold stenothermal Sergentia. Assemblages are dominated by Tanytarsus and Parakiefferiella bathophila-type. Based on these observations a shift in climate conditions marked by an increase in temperature can be concluded. The warming in Chz-3 probably reached a level similar to Chz-1 since both biozones have similar dominant taxa.

Chz-4, 13.90 – 13.07 m. The biozone is marked by the appearance and the strong dominance of Corynocera ambigua, a species of the phylum Tanytarsini. Modern distribution of this taxon suggests a high benthic primary production, clear water and development of large benthic hydrophytes beds similar to those of charophytes (Brodersen & Lindegaard 1999). The temperature preference of Corynocera ambiguа remains unclear. Whereas this taxon is often considered to be a cold water indicator, C. ambiguа has never been found in warm lakes with water temperature reaching 20°C in summer (Brodersen & Lindegaard 1999).

Chz-5, 13.07 m – 11.85 m. This biozone shows the highest taxonomic richness of the whole biostratigraphy. This implies that environmental and climatic conditions became favourable for the development of a more diversified aquatic biota. The biozone is dominated by Tanytarsus, Procladius and Polyplectum, which are warm adapted taxa (Walker et al. 1997). A general enrichment of the lake system is suggested by the return in high relative abundances of the predatory chironomids Procladius. Reappearance of Polyplectum and Chironomus could be interpreted as revealing an organic matter accumulation in the sediment and a beginning of the subsequent water desoxygenation. These changes could result from an increase in water nutrient concentration and allochthonous organic inputs caused by a strong climate warming as indicated by the dominance of warm adapted taxa.

3.8. Geochemistry

In order to assess geochemical variation due to anthropogenic land use within the catchment area, five core intervals were investigated for carbon, nitrogen, phosphorus and calcium content (CNPCa) in cores BL1.1 and BS1 (Fig. 11). The deepest interval is from the Late Pleistocene and the next four

Fig. 11. Carbon-, nitrogen-, phosphorus and calcium contents of selected core sections from Bergsee sediments after the Late Würm.
intervals from the Holocene, whereby the uppermost section covers a time period where the catchment area was enlarged by the opening of the canal.

Every core interval was cut in 5 cm thick slices. Each sample was oven-dried at 105°C for 24 hours. The dry sediment material was roughly homogenized using a mortar. After homogenization of the dry samples in a rotation mill for 10 minutes, the total and organic carbon as well as total nitrogen was measured using an Elemental Analyzer (Leco; CHN 1000). Available phosphorus and calcium were extracted with ammonium-lactate-acetic-acid solution (EGNER et al. 1960). Phosphorus was analysed photo-
metrically after VOGEL (1978), calcium was analysed using Atomic Absorption Spectrometry (AAS) after CARTER (1993).

The Late Pleistocene Laachersee Tephra is clearly recognizable in the very low carbon, nitrogen and calcium contents of BL 1.1 at about 12.85 m depth. In Holocene segments carbon, nitrogen and phosphorus content increased reaching a maximum in a depth around 4 m, where for instance phosphorus content in the sediment was even higher than in recent times of hyper-
trophication. Carbon content in the sediment was highest (30-40 %) in the samples from the Middle Holocene and in the 18th century. Lower carbon content (about 20 %) is typical for the oldest core section from Late Pleistocene, i.e. Younger Dryas and Alleröd (Fig. 11). The nitrogen content also follows this trend, showing the lowest values in the sediments from Younger Dryas and Alleröd (~12.25 m depth), and the highest values in the sediments from the Middle Holocene (~4.9 m depth, Fig. 11). Calcium content in the sediment remained very stable at 4500 mg/kg DW in the Holocene segments and was nearly bisected in 65 cm depth.

Phosphorus content, however, showed remarkable variations. Phosphorus can be dissolved from the surface layer of the lake sediment under anoxic conditions which could explain short-term fluctuations of the phosphorus content. However, large-scale changes are more likely related to changes of the phosphorus input and thus reflect changes of the landscape in the small natural catchment. High phosphorus contents in the sediments were typical for the whole Middle Holocene (Fig. 11). In the cores of Late Pleistocene, phosphorus content was low but showed high variations. We correlate this to a high variability of the biogeochemical environment in the catchment or in the lake itself. The existence of vivianite patches (indicated with ‘V’ in Fig. 4) points to a reducing environment (NRIAGU & DELL 1974). Such patches are often quoted in the literature as remnants of bones, leaf nerves or animal excrements (THEWALT & GREGOR 2001). If precipitation and dissolution of iron phosphates was a dominant regulation mechanism for Lake Bergsee over the whole period, we would expect a widespread occurrence of small nodules of vivianite in the core samples which we did not find in the Bergsee sediments.

Besides the Laachersee Tephra event there is another clear incident visible in the sediment record at a depth of 0.65-0.7 m, interpreted as the opening of the canal and the enlargement of the catchment area of Bergsee. Several parameters change dramatically afterwards. While bulk density increases from 0.1 to 0.25 g cm⁻³ (data not shown), carbon and nitrogen content decrease from 40 % C to 10 % C and from 2 % N to 0.8 % N. The C/N ratio decreases from 14-16 to less than 13, which suggests a better degradation of the organic material. Phosphorus content however increased strongly from 75 to 30 cm depth, where the maximum of recent phosphorus accumulation occurred (Fig. 11).

The geochemical data provide some information on the stability and constancy of the Bergsee catchment. While carbon and nitrogen content of the sediment show a continuous increase from Late Pleistocene to the present, especially phosphorus fluctuates strongly from period to period and therefore seems to be an important indicator for landscape changes especially since it has surface related triggering mechanisms (e.g. vegetation changes, forest clearing, tillage). The most striking feature of the present sediment quality is the relatively low carbon and nitrogen content, and the generally high nutrient content, which is caused by the high proportion of clastic material from the artificially increased catchment.

4. Discussion

4.1. Interstadial, possibly 'Denekamp'

The grey colour of the weakly bedded silty clayey deposits in BL 3.1 deeper than 20.20 m suggests a slightly higher organic content. This organic material should have originated mainly from allochthonous input of soil and plant remains. This interpretation is corroborated by the pollen assemblages, which point to a denser plant cover in the watershed of the lake with a sparse birch and pine forest together with juniper and dwarf willow between 20.20-20.60 m. A higher autochthonous production is also possible, but as the chironomid assemblages point to a shallow lake environment, allo-

chthonous organic input should be dominant compared with lacustrine pro-
duction. Optimal climate conditions are also corroborated by the chironomid assemblages and the clear drop in the susceptibility curve (Fig. 4), which reflects the increase of the organic content in the sediments. All these data sets are indicative of a warmer, interstadial-like climate during this period. The radiocarbon date (29,110 uncal. 14C yr BP at depth 20.46 m) indicates that this period of relative warm climate could be tentatively correlated to
the late "Denekamp complex" (Ran 1990). The Bergsee record suggests a short-term variability of environment and climate, which seems to be characteristic during this period. At Tolsta Head (Scotland), for example, Whittington & Hall (2002) could also show large climate variability during the Denekamp Interstadial, which was correlated with the GI-5 to GI-8 interval of the GRIP record.

4.2. Würm Maximum

This period can be divided into four phases, which are represented by the core sections 20.20 m – 18.80 m, 18.80 m – 16.20 m, 16.20 m – 13.90 m, 13.90 m – 13.10 m in BL 3.1 that characterise different environmental and climatic conditions.

A cold event can be recognized, as indicated by a drop in the pollen percentages of Pinus, Betula and Juniperus and the sharp peak of the cold stenothermal taxon Sergentia in the chironomid assemblages at a depth around 20.05 m; and this immediately follows the relative warm phase in the deepest part of BL 3.1. Characteristic park tundra developed possibly with single birch and pine trees, some juniper and willow scrub, but mainly grasses and herbs such as Artemisia and Helianthemum.

Around 18.80 m a rapid and strong deterioration of the climate can be inferred from the pollen and chironomid assemblages which are characterized by steppe tundra vegetation without any trees and a cold adapted aquatic biota. The Rhine glacier of the Würm Maximum did not reach the Bergsee area, nor did the glaciers of the Black Forest. Bergsee lay in a Periglacial area characterized by an open landscape covered with tundra vegetation in a dry and very cold climate. The lake was seasonally covered by ice; however, it was not covered by ice permanently, which would have led to the disappearance of chironomids like Sergentia with a long larval

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**Fig. 12.** Average particle size distributions of clastic samples from Bergsee BL 3.1 from depth between 14.50-17.50 m compared with loess samples (Löss I-IV) from Hügelheim (Zollinger 1985) and Möhlin (Seeliboden, -345 cm) (Egli 1995). The samples from Bergsee, Löss I and Seeliboden refer to the Würm period.
development. In addition, the chironomid record suggests that this very cold episode could have been interrupted by very short-term climatic ameliorations (Fig. 10). Between 16.20 m and 13.90 m chironomid assemblages suggest a climate warming, which, however, is not detected by the pollen assemblages possibly reflecting the shortness and/or the degree of climatic ameliorations and/or unfavourable soil conditions (Coope 2002).

The lacustrine sediments are very homogeneous, hardly showing any bedding at all, and with a maximum of the particle size distribution in the coarse silt fraction (Fig. 5). This suggests that a significant amount of the sediments in Bergsee were of aeolian origin. Aeolian deposits are widespread in the area, for instance, 5 km W of Bergsee in the Mühlin Field and in the Upper Rhine Graben area (Zollinger 1985, 1991). A comparison with particle size distributions of typical loess from Britzingen-Hügelheim (Zollinger 1985), 40 km NW of Bergsee, and the Mühlin Field (Egli 1995) is given in Fig. 12. Obviously the four samples between 14.50 and 17.50 m depth (Fig. 12) agree well, whereas the deepest (18.50 m) and shallowest samples (13.50 m) have higher clay and reduced coarse silt contents compared with a characteristic loess particle size distribution. The magnetic data also suggests that the ferromagnetic minerals have a constant grain size and composition in this time interval (Fig. 7), which suggests that the sediment source is stable. The clay content is always above 15 % in Bergsee samples, which is above ‘normal’ for loess deposits. A source for the higher clay content could be from the weathering of gneisses and granites in the surroundings of Bergsee under periglacial conditions (Zollinger, pers. comm.). Thus, a significant ‘autochthonous loess’ input from the weathering of surrounding crystalline rocks adds to the allochthonous loess input from the Upper Rhine valley. In contrast, the deepest and the shallowest samples (18.50 and 13.50 m) indicate conditions for the deposition of finer grained sediments in the deepest lake basin that most likely originated from the input of clastic sediments by run off from the surrounding valley flanks.

At 13.90 m chironomid assemblages show a change in lake functioning. An increase in benthic production linked to clear water conditions is hypothesised. This palaeolimnological change might be related to a drop in the minerogenic allochthonous (aeolian) input. The enhanced benthic productivity in the lake can be linked to a higher organic input caused by a developing plant cover in the watershed as shown by pollen assemblages with slightly higher percentages of Betula. In the Swiss Plateau, a slight increase in Betula pollen percentages, confirmed by macro-remains, mark the final stage of the Oldest Dryas (Ammann et al. 1994). In Lake Lautrey in the neighbouring French Jura, large percentages of C. ambiguus characterised the last part of the Oldest Dryas (Millot et al. 2003). Thus, compared with the chironomid and the pollen record in Bergsee the onset of this last subzone was probably contemporaneous with the latest part of the Oldest Dryas.

4.3. Late Würm

Based on the pollen and chironomid assemblages in BL3.1 the Late Würm interstadial starts at a depth of about 13.10 m. The sediments show the gradual transition from the yellow brown clayey silt deposits of the Würm Maximum to the grey and black organic lake mud deposits (gyttja), which correlates well with the re-establishing of forest vegetation, first dominated by birch and later supplemented by pine. This is further supported by the magnetic measurements which show a gradual change. The decrease in susceptibility and ferromagnetic content, due to reductive dissolution of iron minerals, supports an increase in organic content. The denser vegetation in the surroundings prevented the input of large quantities of clastic sediments washed into the lake. The general amelioration of the climate, the development of a denser vegetation cover and the increase of nutrients in the lake finally transferred the lake environment stepwise to conditions, which are common for most of the Holocene period. Weak layering can be seen in some sections of the clastic and the organic-rich deposits.

Clearly visible in three drill cores between 12.60 and 13.20 m is the LST (Fig. 4), which is a sequence of whitish and greenish blurred layers and patches of silty and clayey sediments containing pumices, amphiboles and pyroxites. It is also visible in the susceptibility curve (Fig. 4) by a peak caused by an increase in fine-grained magnetite. Geochemically, the material is characterized by very low carbon, nitrogen and calcium content (Fig. 11) which points at a strong outwash of silt and tepha in the catchment during that period. Radiocarbon dates in cores BL1.1 and BL1.2 approximately 1 cm above the latest occurrence of pumices and ferromagnetic minerals give ages of 11290±80 uncal. BP and 11340±80 uncal. BP which is in good agreement with given ages for the LST (Friedrich et al. 1999, Hajas et al. 1995). Different is the radiocarbon date from BL3.1 about 6 cm above the last occurrence of ferromagnetic minerals enriched in a silt layer: 11700±80 BP. This age seems to be too old compared with the aforementioned results to be compatible with the LST. Also the pollen sample at a depth of 12.66 m is unusual, showing an assemblage with Betula and Juniperus without Pinus which is not typical for this period and, thus, would indicate an older age for this sample. The vertical distribution of volcanic fragments and minerals in the cores in the range of a few centimetres is astonishing as it is one order larger than in many occurrences of the LST in Switzerland and the southern Black Forest with thicknesses of the LST in the range of a few millimetres only (Wegmüller & Welten 1973,
4.4. Early Holocene (Preboreal – Atlantic)

The Early Holocene lake sediments consist of very homogeneous organic lake mud (gyttja), indicative of deep-water conditions in the lake. Mixed deciduous forests of hazel, oak, elm and linden replaced the late-glacial forests of birch and pine. A progressive shallowing of the lake is first seen in BL3.1 with the first occurrence of detritic gyttja at the end of the early Holocene.

4.5. Late Holocene (Subboreal – Subatlantic)

The progressive shallowing of the lake due to infilling of the lake basin can be seen in the change of the sediments from fine-detritus gyttja to coarse-detritus gyttja and final to organic detritus with large plant remains like leaves, seeds, roots of reed plants, twigs and lumps of moss. This points to the fact that the lake has progressively filled in and was transformed into a mire, which may have been partly dry. For example, the use of Bergsee as a fishpond in historical times was always under threat by over vegetation of the lake as indicated in historical chronicles (Metz 1980).

Human impact is recorded in the region since the Neolithic and increases stepwise during the Bronze Age, Iron Age and Roman Times. The very high phosphorus content in sediments of the Late Holocene (4-5 m depth), which was temporarily even higher than in recent times of hypertrophication, is probably an expression of increased soil erosion combined with mire formation in parts of the lake. This period most likely corresponds to the onset of human clearing of forests in the catchment. This interpretation is supported by the clear increase of phosphorus in the most recent sediments, which were deposited after the canal construction in the 19th century. The additional inflow from the Schöpfesch-Heidenruhr-System, which drains agricultural land, led to an increase in suspended and particulate matter to Bergsee.

A dramatic change in the lake evolution, which is clearly seen in the sudden change in the type of sediments and the geochemistry from organic deposits to predominantly clastic deposits, took place with the use of the lake as a water reservoir. Based on the distribution of these youngest sediments with the greatest thickness in the NE of the lake basin and smallest in the SE it is clear that the sediment input comes from the NE from the canal.

Artificial increase in the lake level with water from the Schöpfesch-Heidenruhr system changed the lake ecology from a low productive dystrophic lake to a higher productive mesotrophic lake. Maximum phosphorus contents in sediments of 0.2-0.3 m depth are consistent with the maximum eutrophication of the hypertrophic Bergsee in the late 1960ies (Wüthrich & Leser 1999, Wüthrich 2003). Lower phosphorus contents in the youngest sediments may be a consequence of the improved wastewater management in the catchment area. One important conclusion for the future lake management is that the building of the canal in 1802/03 has changed the biogeochemistry of the lake more than all the climatic oscillations from Late Würm to the 19th century.

5. Conclusions

The interdisciplinary approach that used information from sedimentology, geochemistry, biology (pollen and chironomid analyses), and magneto-mineralogy has brought new insights in environmental change over the past 30,000 years in Bergsee region. Pollen, chironomid, sedimentological and geomagnetic data complemented one another in reflecting changes in climate. Geochemical together with pollen data are particularly sensitive to record changes in the lake environment and land use in the catchment area, reflecting the human activity in the late Holocene.

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References


