

Seasonal variability of Holocene climate: a palaeolimnological study on varved sediments in Lake Jues (Harz Mountains, Germany)

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Abstract Studies combining sedimentological and biological evidence to reconstruct Holocene climate beyond the major changes, and especially seasonality, are rare in Europe, and are nearly completely absent in Germany. The present study tries to reconstruct changes of seasonality from evidence of annual algal successions within the framework of well-established pollen zonation and ¹⁴C-AMS dates from terrestrial plants. Laminated Holocene sediments in Lake Jues (10°20.7' E, 51°39.3' N, 241 m a.s.l.), located at the SW margin of the Harz Mountains, central Germany, were studied for sediment characteristics, pollen, diatoms and coccal green algae. An age model is based on 21 calibrated AMS radiocarbon dates from terrestrial plants. The sedimentary record covers the entire Holocene period. Trophic status and circulation/stagnation patterns of the lake were inferred from algal

assemblages, the subannual structure of varves and the physico-chemical properties of the sediment. During the Holocene, mixing conditions alternated between di-, oligo- and meromictic depending on length and variability of spring and fall periods, and the stability of winter and summer weather. The trophic state was controlled by nutrient input, circulation patterns and the temperature-dependent rates of organic production and mineralization. Climate shifts, mainly in phase with those recorded from other European regions, are inferred from changing limnological conditions and terrestrial vegetation. Significant changes occurred at 11,600 cal. yr. BP (Preboreal warming), between 10,600 and 10,100 cal. yr. BP (Boreal cooling), and between 8,400 and 4,550 cal. yr. BP (warm and dry interval of the Atlantic). Since 4,550 cal. yr. BP the climate became gradually cooler, wetter and more oceanic. This trend was interrupted by warmer and dryer phases between 3,440 and 2,850 cal. yr. BP and, likely, between 2,500 and 2,250 cal. yr. BP.

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Introduction

Despite decades of research, there are still many open questions concerning the variability of the Holocene climate in Central Europe. Reasons are uncertain chronologies, large distances between investigated

sites, and lack of understanding of the regional effects of climate change, especially of changing seasonality.

The climate of Central Europe is grossly transitional between four major, neighbouring regimes: (i) Maritime or Oceanic (North Atlantic), (ii) Continental (Eurasian), (iii) Sub-arctic and (iv) Mediterranean:

	Warm	Cool
Wet	Oceanic	Subarctic
	Central European	
Dry	Mediterranean	Continental

The actual Central European climate is highly variable regionally and temporally. As is typical for the temperate zone, four seasons are generally expressed. Usually, summer and winter have more stable, higher atmospheric pressure weather, whereas the transitional seasons are changeable. Due to the disrupted topography of the continent, lasting changes of the hemispheric circulation do not simply result in latitudinal shifts of the climate zones, but may have different effects even in neighbouring regions. This constrains the correlation of different palaeoclimatic reconstructions over great distances.

Further, reliable chronologies are essential for precise reconstruction of environmental changes and are prerequisites for the distinction between climatic and local environmental effects, when compared to other palaeo-archives. Many otherwise detailed palaeo-reconstructions suffer from uncertain chronologies (e.g. Nesje et al. 2000; Seppä and Birks 2001; Wennrich 2005) and are therefore not readily available for exact comparison. Radiocarbon dating should preferably be done on terrestrial macrofossils. Bulk sediment ages remain questionable as locally and temporally changeable reservoir effects can be compensated for by wiggle matching at best (van Geel et al. 1996).

Especially in Germany, reliably dated palaeoclimate reconstructions are still rare with the exception of studies of vegetation history. Pollen data allow researchers to reconstruct former types of vegetation from which some climatic conditions can be derived. More detailed information about the former climate, however, can only be gained by combined analysis of additional proxies. In Germany, only five palaeoecological reconstructions—covering the entire Holocene—are well dated, four of them on

varved sediment sequences and one on oak tree-ring chronologies (Holzmaar: Baier et al. 2004; Brauer et al. 2001; Lücke et al. 2003; Zolitschka 1998; Zolitschka et al. 2000; Meerfelder Maar: Brauer et al. 2001; Lake Steisslingen: Eusterhues et al. 2002, 2005; Hämelsee: Kleinmann et al. 2000a, b; River Main: Spurk et al. 2002).

Hence, there is an urgent need for a closer-meshed net of well-dated studies in Germany to distinguish not only between warmer and cooler but also between drier and wetter phases. Moreover, the effects of climate change on the seasonality, especially on the transitional seasons, should be considered. So far, only a few palaeolimnological studies have addressed seasonal changes (e.g. Baier et al. 2003; Bradbury and Dieterich-Rurup 1993; Köster and Pienitz 2006; Lotter and Bigler 2000; Schmidt et al. 2007; Rautio et al. 2000).

With the present study, we try to fill the gap between the better investigated regions of Switzerland, France and Scandinavia (Berglund 2001; Eronen et al. 1999; Haas et al. 1998; Hammarlund et al. 2005; Hormes et al. 2001; Magny 2004; Tinner et al. 2003). This paper focuses on aquatic vegetation, including diatoms, green algae, and hydrophytes, on sediment characteristics and on the former terrestrial vegetation to derive, from their changes, limnological and climatic shifts.

The sediments in Lake Jues, situated in the Harz forelands, a region already well investigated in pollen-analytical respects (Beug 1992; Beug et al. 1999; Chen 1988), were chosen for this study. The record from this lake is especially suitable for environmental reconstructions because of its high and constant sedimentation rates throughout the entire Holocene, the annual laminations, the very sensitive climate-controlled circulation pattern, and the excellent preservation of biological indicators in the sediment. Sediment characteristics and accumulation rates are determined by climate and human impact only, because the catchment of the lake is small and has not changed during the Holocene except for the last few centuries. Sufficient amounts of macrofossils from terrestrial plants allow excellent AMS radiocarbon dating.

Organic annual laminations in lake sediments (varves) can only develop when there are seasonal climatic differences, and when nutrients and temperatures are sufficient for lacustrine biogenic production (Saarnisto 1986). Varves are preserved

when bioturbation is prevented due to at least temporary anoxia in the hypolimnion. The latter is favoured by oligo- or meromixis, but can also develop in eutrophic holomictic lakes (Zolitschka 1998). Annual climate, especially the length and variability of spring and fall periods, determines the circulation pattern and, in turn, the development of plankton and the trophic status of a lake. As biogenic varves consist of the seasonal succession of algal—mainly diatom—blooms (spring, summer and autumn layers) and a detritus layer (late autumn and winter), they reflect variations of the seasonal climate. Diatoms are highly sensitive to changes in nutrients, pH and salinity (Smol and Cumming 2000) and, thus are reliable tools for long-term environmental reconstructions, including annual and subannual varve analysis. Annually varved lake sediments sensitively reflect environmental changes at high time resolution and are ideal subjects for palaeo-reconstructions beyond the mere registration of wetter/dryer or warmer/cooler phases.

Study site

Physiography, geology and climate

Lake Jues is situated at the SW-margin of the Harz Mountains (Central Germany, Figs. 1, 2). The Harz Mountains, rising to 1,142 m a.s.l., form a natural barrier to the north and to the east. They consist of Palaeozoic greywacke, shale and chert folded during the Hercynian orogeny. Upper Permian Zechstein formations lapping onto the folded basement consist of several hundred metres of alternating dolomite and anhydrite. The Permian rocks extend along the margin of the Hercynian basement in a kilometre-wide depression (Fig. 2). The evaporitic rocks are heavily karsted and pierced by thousands of sinkholes.

Lake Jues fills two overlapping sinkholes, which formed after the collapse of a cave in the 40 m thick Z1 (“Werra”)-anhydrite, at the end of the last glaciation (Fig. 3). With an original volume of more than 2.5 M m³ the Jues sinkholes rank among the biggest of this kind in Germany (Teichmann 1986).

The environs of Lake Jues are dominated by Quaternary erosion and accumulation of gravel terraces by the rivers Sieber and Oder, in turn overlain by loess and post-glacial soils (Mohr 1982; Priesnitz 1969). The Lower Triassic Rotenberg sandstone hills

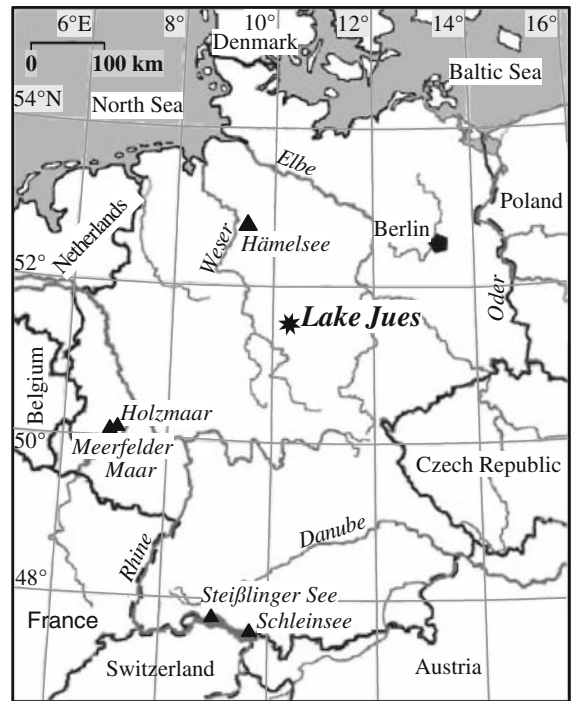


Fig. 1 Map of Germany, locations of Lake Jues and other sites with known Holocene varved sediments

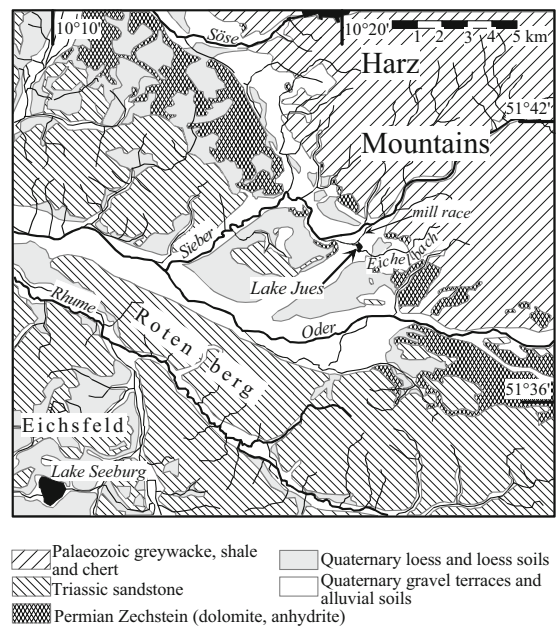
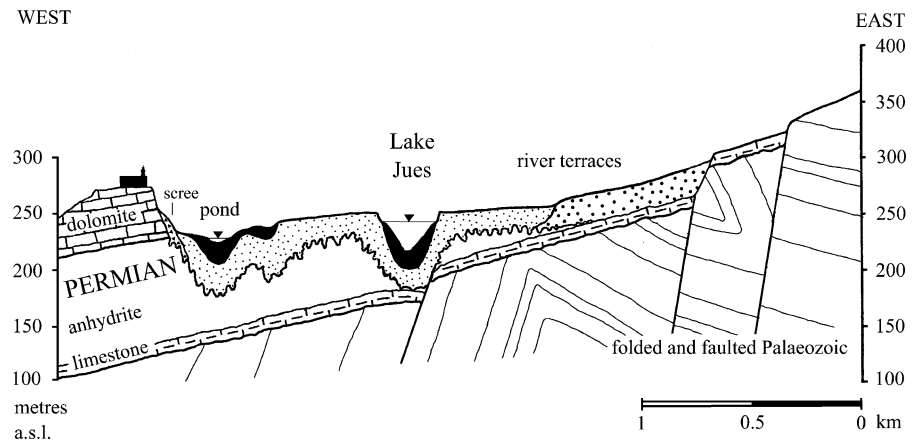


Fig. 2 Geological map of the study area (source: Geologische Übersichtskarte der Bundesrepublik Deutschland 1:200,000/ CC 4726 Goslar)

Fig. 3 Geological section across Lake Jues. Note section is 5 times exaggerated; black: Holocene limnic sediments (modified after Teichmann 1986)



and the rivers Oder and Sieber separate the Jues area from the extended, loess-covered region of the Lower Eichsfeld in the southwest (Fig. 2).

Lake Jues lies amidst the residential town of Herzberg (10,600 inhabitants). Land use around the town is mainly agricultural while Harz Mts. and Rotenberg are wooded.

The area south of the Harz Mts. is situated about the transition between Middle-European oceanic and continental climates. Due to the nearby mountain chain, the local climate is humid with 840 mm annual precipitation and a slight maximum (90 mm/month) during summer. The mean annual temperature is 6–7°C with monthly averages of 15–17°C in summer and –1°C in January and February. The mean snow-cover period (>1 cm) is 41 days (Glässer 1994).

Current hydrography and limnology (Table 1, Figs. 4–6)

Lake Jues fills two sinkholes connected through a 50 m wide passage (Fig. 4). The smaller basin has a surface area of 1.2 ha and a maximum depth of 6.5 m, the large one is 28.5 m deep and covers an area of 5.6 ha. Today, Lake Jues has one, intermittent inflow, the 5 km long Eichelbach brook which springs from the folded Palaeozoic (Fig. 2). Passing the karsted Permian rocks, most of this creek's water recedes underground to feed the Rhume spring 10 km south (Thürnau 1913). The lower end of the Eichelbach is a drainage ditch that was dug to divert the waters of the brook away from two sinkholes, and into the lake (according land-registry office, Osterode). Water from the river Sieber can be supplied to

Table 1 Morphometrical and chemical characteristics of Lake Jues (main basin)

Coordinates	10°20.7' E, 51°39.3' N
Altitude	241 m a.s.l.
Lake surface	56,600 m ²
Lake volume	521,000 m ³
Average depth	9.2 m
Maximum depth	28.5 m
Catchment area	3.5 km ² (present)
Mean pH	7–8
Mean conductivity	190 µS/cm
Mean total phosphorus (TP)	<30 µg/l*
Mean total nitrogen	309 µg/l
Mean sulphate	42 mg/l

The mean values are based on the monthly measurements between November, 1983 and February, 1985, each time at ten different water depths (Teichmann 1986)

* For seasonal distribution and changes see Fig. 6

the lake through the Mühlengraben (mill race) since ca. 1034 AD (according to our sedimentological and AMS-data). A weir-regulated outlet is located at the NW edge of the main basin, leading the water back via the mill race into the river Sieber. During preindustrial times, Lake Jues existed as a groundwater pond, the level changing with that of the surrounding groundwater.

The main sinkhole of Lake Jues has a relatively small surface area, is fairly deep, and has steep sides. Because of this morphometry, the circulation depends strongly on the length and the nature of the spring and fall periods. As a result, Lake Jues is oligomictic with a temporarily anoxic hypolimnion that can reach up to 10 m or less water depth in summer (Fig. 5).

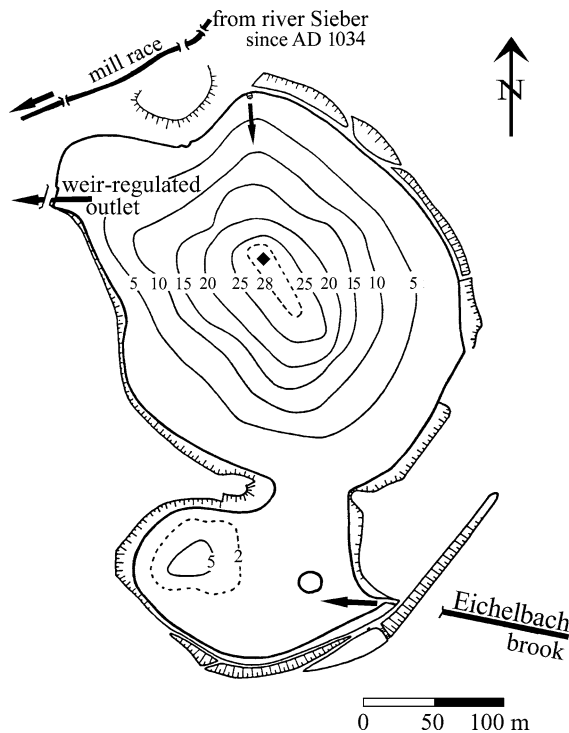


Fig. 4 Bathymetric map of Lake Jues, contours: metres (Teichmann 1986). Diamond: coring stations

Teichmann (1986) surveyed two years of autumnal monomixis between November 1983 and February 1985 at monthly intervals (Figs. 5, 6). At mean phosphorus concentrations lower than $30 \mu\text{g/l}$ (Table 1), Lake Jues appears to be mesotrophic. However, total phosphorus concentrations vary considerably during the course of one year. Very high epilimnic concentrations (max. $240 \mu\text{g/l}$) were measured during and after circulation periods, whereas the epilimnion was nearly depleted of phosphorus ($<10 \mu\text{g/l}$) during summer and autumn. Shortly after deep circulation, hypolimnic phosphorus concentrations reach extremes of $1,900 \mu\text{g/l}$ due to re-dissolution from the sediment. Two temporary superficial phosphorus peaks result from agricultural discharge (October 1984 and February 1985). With secchi-depths of less than 2 m, mass-development of plankton, and epilimnic over-saturation of oxygen, the lake is more appropriately classified as meso- to eutrophic.

Nitrogen concentrations are rather low (Table 1), although nitrogen is not a factor limiting plankton growth in this lake. Sulphate concentrations are quite low, too. At present time, the water body of Lake Jues has apparently little exchange with the groundwater

in the surrounding Permian anhydrite and gypsum. However, ammonium and hydrogen sulphide still heavily accumulate in the hypolimnion during long anoxic phases.

The lake is circumneutral with average pH values of 7.2 during circulation periods, but summer plankton growth results in a strong pH increase in the epilimnion reaching pH 9.4.

Methods

Fieldwork and sampling

Five sediment cores were taken from the profundal of Lake Jues in April and June 1995 by means of aluminium tubes on a pneumatic vibration corer (Meischner et al. 1981). The sediment surface was lost in cores JUES 95/4 and JUES 95/7 but is included in the shorter cores which are not compacted by coring. Cores JUES 95/4 and JUES 95/7 (85 mm diameter) were combined to a composite profile for this study using the distinct laminations of the sediments for precise correlation (Fig. 7). All cores were used for studying macroscopic sediment characteristics.

Subsamples for pollen-analytical and diatomological studies were taken with PVC-syringes. Additionally, continuous sampling for high-resolution pollen analyses was done using sample corers with a square cross section of $11 \times 11 \text{ mm}^2$. One centimeter thick sediment slices were taken for macrofossil analysis. Further samples ($10 \text{ cm} \times 2 \text{ cm}$) were taken for thin sections (Table 2).

Cores are stored in Geowissenschaftliches Zentrum, University of Göttingen, Department of Sedimentology, Germany.

Radiocarbon dating

Terrestrial macrofossils and a deer bone were radiometrically dated (AMS method) at the Leibniz-Laboratory for Radiometric Dating and Isotope Research of the University of Kiel/Germany (Table 3, Fig. 8). The bone (kia 11824) from core JUES 95/4 plotted about 1,000 years younger than the host sediment. It was probably displaced by the coring process. Another very small sample (kia 3818, 2.8 mg of leaf and wood fragments) obviously dated too old. The age model is based on inter- and extrapolation of

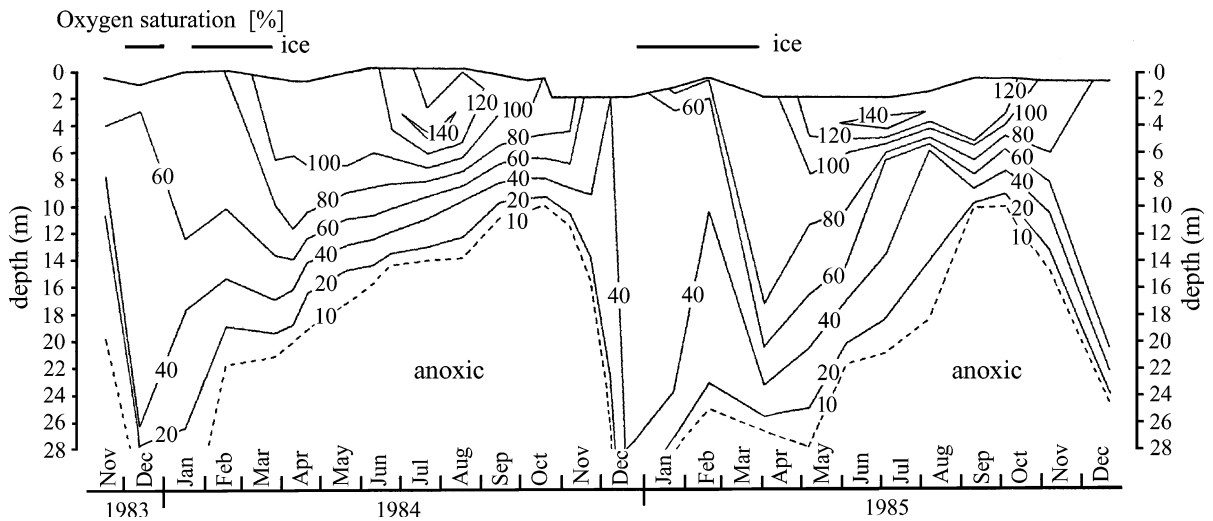


Fig. 5 Oxygen saturation (%) in Lake Jues, November 1983 through December 1985, iodometric titration acc. to Winkler (1888), isopleths calculated by linear interpolation (Teichmann

1986). Dashed line: not equidistant. Water depth zero denotes the mean water-level (241 m a.s.l.). Note: Spring circulations are incomplete due to late ice covers

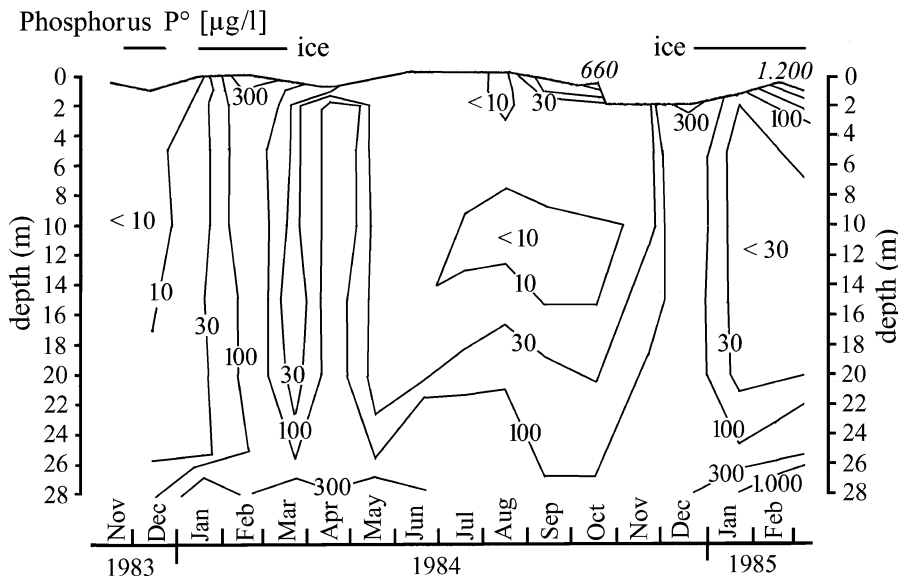


Fig. 6 Total phosphorus concentrations ($\mu\text{g/l}$) in Lake Jues, November 1983 through December 1985, vanadium-blue photospectrometric method, data recalculated from Teichmann (1986), logarithmic interpolation. Water depth zero corresponds to the mean water-level (241 m a.s.l.). Note high

P-concentrations in the whole water column subsequent to more or less complete circulation and oxygenation events (cf. Fig. 5) become consumed within short time. Excessively high concentrations in the epilimnion (slant figures) are caused by pollution from local sources

21 reliable ^{14}C -measurements (calibration according to Stuiver et al. 1998). Extrapolation was not done for the Younger Dryas because of the change in sediment type at the transition from Younger Dryas to Preboreal. When the calibration curve yielded more than one fit

due to a fluctuation in atmospheric ^{14}C , the arithmetic mean was used. For the chronological presentation of the results the thick minerogenic layers are excluded, because these are considered to be deposited during very short episodes (extreme weather events).

Fig. 7 Correlation of cores, sediment types and inter-/extrapolated radiocarbon ages (cal. yr. BP). Depths below sediment surface not corrected for compaction by coring. Vertical lines show the sediment slices used for the composite profile. Stars indicate dated levels. LST = Laacher See Tephra

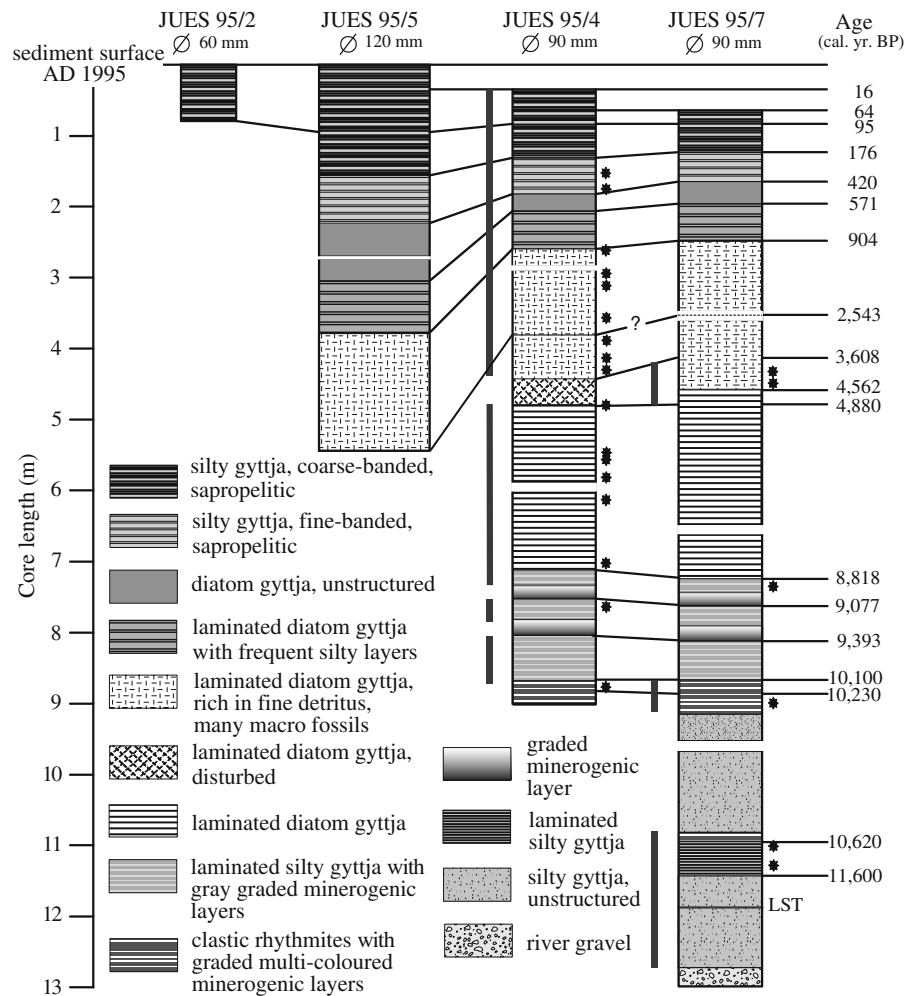


Table 2 Location of thin sections in core JUES 95/7

Thin section (no.)	Sediment depth (cm)	Age (cal. yr. BP)	Pollen zone
1	995.5–985.5	10,630–10,560	Va
2	824–813.3	10,400–10,340	Va
3	692–682	9,245–9,120	Vb/VI
4	641–631	8,920–8,690	VI
5	535–525	7,430–6,880	VI
6	409–399	4,910–4,760	VIIIa
7	241–231	1,630–1,490	IX

Pollen analysis

Pollen samples (0.6–2 cm³ of sediment) were treated with hot potassium hydroxide (KOH), with hydrochloric and hydrofluoric acids (HCl and HF, respectively), then acetolysed (Beug 1957) and

sieved in a water bath (ultrasonic sieving) to remove particles <10 μm.

A minimum of 1,000 arboreal pollen grains, excluding *Corylus*, was counted in each of close to 300 samples, except for a few late-glacial samples, which were very poor in pollen. The mean

Table 3 AMS radiocarbon dates, calibrated age ranges (one sigma) obtained from intercepts (method A) according to Stuiver et al. (1998)

Lab-codes (Univ. Kiel)	Core/sediment depths (cm) (uncorrected)	Conventional uncalibrated radiocarbon ages (BP)	Calibrated ranges (1 σ), years before present (cal. yr. BP)	Calibrated ages used in diagrams (cal. yr. BP)	Dated material
kia 1667	JUES 95-4, part 1/119–120.5	230 \pm 30	303–0	216	Leaf fragments (<i>Fagus</i> and <i>Quercus</i>), wood of <i>Picea</i>
kia 1666	JUES 95-4, part 1/140.5–141.5	360 \pm 30	476–323	382	Leaf fragments of <i>Quercus</i> , wood of <i>Picea</i>
kia 1665	JUES 95-4, part 1/228–229	1,020 \pm 30	954–927	932	Leaf fragment and bud scale of <i>Fagus</i>
kia 1664	JUES 95-4, part 2/252–253	1,330 \pm 30	1,289–1,260	1,276	Leaf and wood fragments, <i>Alnus</i> fruit, <i>Fagus</i> bud scale
kia 3816	JUES 95-4, part 2/274–275	1,690 \pm 30	1,687–1,541	1,580	Leaf fragments, <i>Tilia</i> fruit, <i>Fagus</i> bud scale
kia 1663	JUES 95-4, part 2/317–319	2,220 \pm 30	2,312–2,152	2,208	Twig wood of <i>Alnus</i>
kia 1662	JUES 95-4, part 2/348.5–351	2,480 \pm 30	2,712–2,468	2,586	Leaf fragments, <i>Fagus</i> bud scales
kia 3817	JUES 95-4, part 2/375–377	2,930 \pm 30	3,204–2,995	3,115	Leaf fragments, bark, <i>Alnus</i> fruit, <i>Quercus</i> bud scale
kia 1661	JUES 95-4, part 2/391.5–392.5	3,140 \pm 30	3,382–3,346	3,361	Leaf fragments
kia 3815	JUES 95-7/811–812	3,740 \pm 30	4,147–3,998	4,090	Leaf fragments of <i>Alnus glutinosa</i> and others, <i>Quercus</i> bud scales
kia 3814	JUES 95-7/793.5–794.5	3,980 \pm 30	4,507–4,415	4,421	Leaf fragments, <i>Alnus</i> fruit, bud and bud scales of <i>Quercus</i>
kia 1660	JUES 95-4, part 2/442–443	4,330 \pm 30	5,025–4,834	4,865	Leaf fragments
kia 11824*	JUES 95-4, part 2/506–510	3,623 \pm 31	3,979–3,874	3,946	Humeral bone of red deer
kia 3818*	JUES 95-4, part 2/518–519	5,980 \pm 60	6,887–6,730	6,802	Small leaf and wood fragments
kia 3819	JUES 95-4, part 2/544–546	6,030 \pm 40	6,902–6,760	6,830	Leaf fragments, bud and bud scale of <i>Quercus</i>
kia 3820	JUES 95-4, part 3/549–550	6,400 \pm 40	7,416–7,268	7,315	Leaf fragments of <i>Quercus</i> and others
kia 1659	JUES 95-4, part 3/638–639	7,770 \pm 30	8,625–8,426	8,569	Leaf fragments, bark
kia 1657	JUES 95-7/521	8,090 \pm 50	9,057–9,003	9,012	<i>Corylus</i> wood
kia 3821	JUES 95-4, part 3/700–701	8,190 \pm 50	9,263–9,029	9,163	Leaf fragments, bud scales of Coniferae and <i>Quercus</i> , bark
kia 1658	JUES 95-4, part 3/826.5–827.7	9,050 \pm 70	10,239–10,185	10,216	Bark, wood, fertile scale of <i>Betula</i>
kia 3813	JUES 95-7/357–358	9,200 \pm 90	10,497–10,237	10,333	Needles and short shoot of <i>Pinus</i>
kia 3812	JUES 95-7/170.5–171.5	9,400 \pm 60	10,725–10,514	10,621	<i>Pinus</i> needles and short shoots, bark, bud scales of Coniferae
kia 3811	JUES 95-7/144–145	9,730 \pm 60	11,198–11,142	11,171	<i>Pinus</i> needles and short shoots, bark, fruits of <i>Betula pendula</i>

* Not used for the age model (Fig. 8)

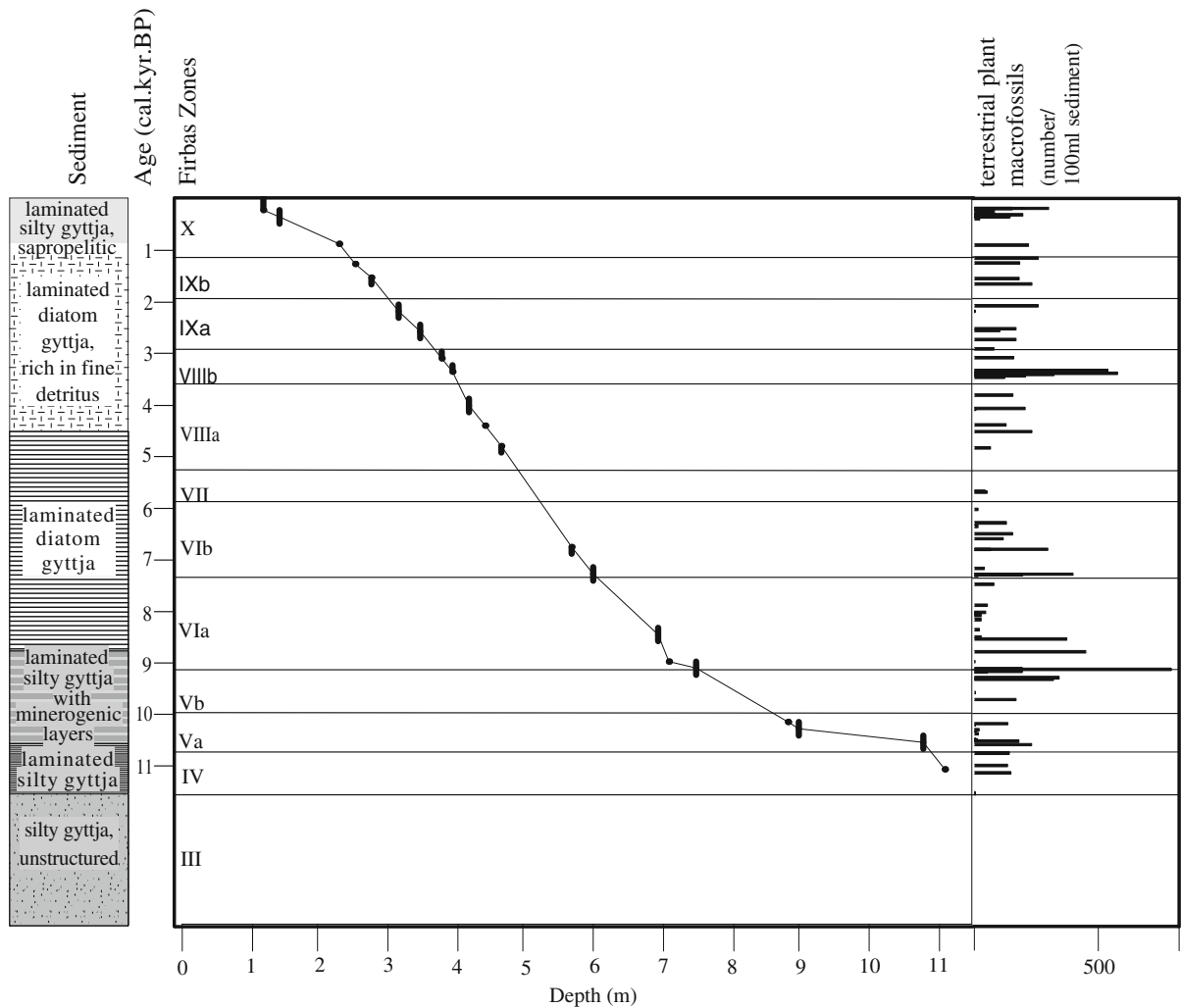


Fig. 8 AMS radiocarbon dates (with standard deviation) versus sediment depth. Additionally, sediment stratigraphy, Firas zones and terrestrial macrofossil abundances are shown.

Note two apparently false AMS-dates were not used for the Age-Depth-Model (for discussion see text)

temporal resolution is 32 calendric years for phases of human settlement and 47 years for the entire sequence.

In addition to a reference pollen collection, pollen keys were used to determine unknown pollen grains and spores (Beug 1961; Fægri et al. 1989; Moore et al. 1991). Remains of green algae were determined using Komárek and Fott (1983). The pollen diagram (Fig. 9) is subdivided into pollen zones according to Firas (1949, 1952), Beug (1992), Bartens (1990), and Chen (1982). The criteria on which the zonation is based are listed in Table 4. The pollen content of the minerogenic layers is shown in Table 9. The

counts are accessible via the Pangaia database (<http://www.pangaia.de/PangaVista>).

Macrofossils

The samples for macrofossil analysis were wet-sieved (mesh size 0.3 mm) and then analysed under a stereomicroscope and an additional transmission-light-microscope for high enlargements. Seeds and bud scales were determined by use of reference collections. Leaves were determined by the characteristic epidermal cell pattern. The identification key of Haas (1994) was used for charophyte oospores.

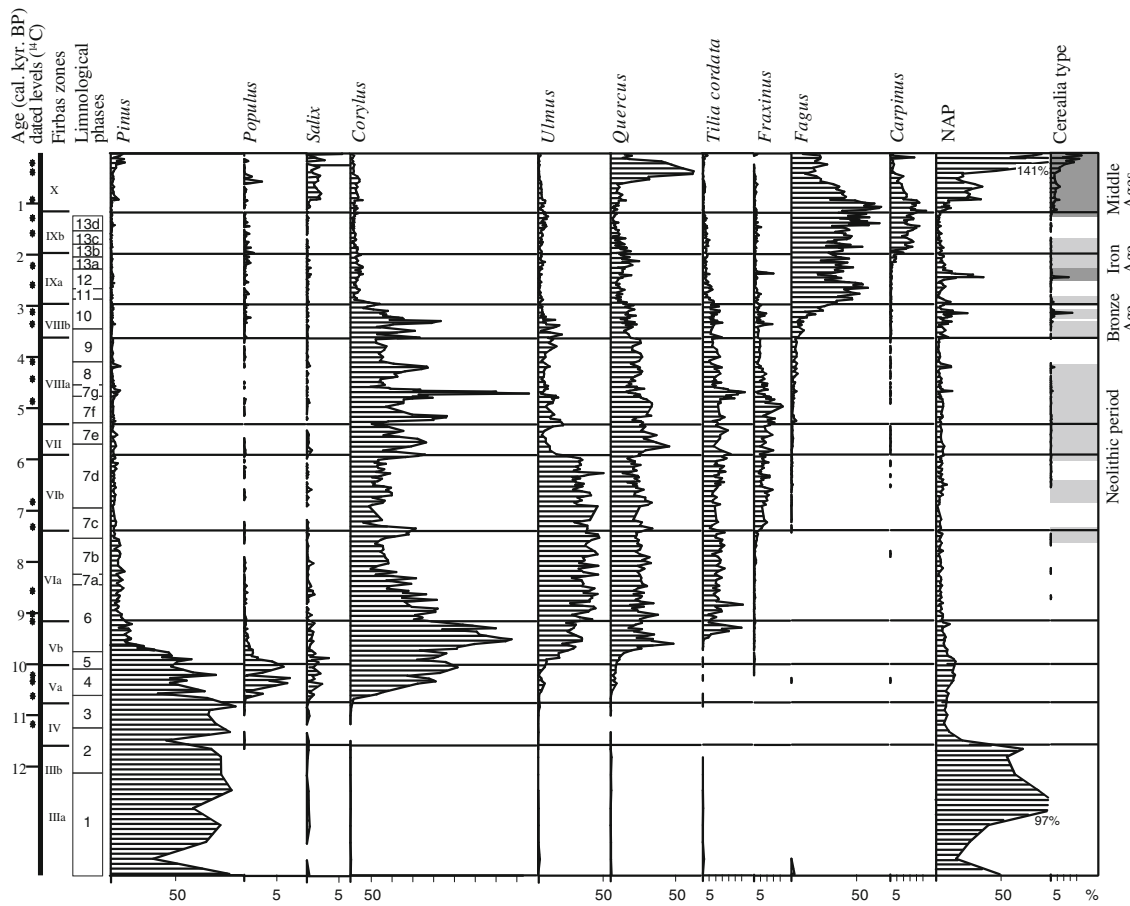


Fig. 9 Frequency diagram of significant pollen types. Percentages are based on the sum of arboreal pollen types (AP) excluding *Corylus*. Zonation according to Firbas (1949, 1952).

Human settlement phases are indicated by different grey shades according to their intensity (darker grey = more intensive land use)

Table 4 Criteria for zonation of the Lake Jues pollen stratigraphy according to Firbas (1949, 1952), Beug (1992), Bartens (1990) and Chen (1982), and ages of zone boundaries (cal. yr. BP) at Lake Jues

Firbas pollen zones (biozones)	Age	Criteria for zonation
Older Subatlantic, part b/Younger Subatlantic	IXb/X	1,160 Cerealia > 1%
Older Subatlantic, part a/part b	IXa/IXb	1,970 <i>Carpinus</i> > 5%
Younger Subboreal/Older Subatlantic	VIIIb/IXa	2,960 <i>Fagus</i> becomes dominant
Older Subboreal/Younger Subboreal	VIIIa/VIIIb	3,620 <i>Fagus</i> > 5%
Younger Atlantic/Older Subboreal	VII/VIIIa	5,300 <i>Fagus</i> > 1%
Older Atlantic/Younger Atlantic	VIb/VII	5,910 <i>Ulmus</i> percentages decrease (elm decline)
Older Atlantic, part a/part b	VIa/VIb	7,390 <i>Fraxinus</i> percentages increase, first <i>Fagus</i> pollen grain
Younger Boreal/Older Atlantic	Vb/VIa	9,160 <i>Pinus</i> < 10%
Older Boreal/Younger Boreal	Va/Vb	10,020 <i>Quercus</i> , <i>Ulmus</i> , <i>Tilia</i> , <i>Fraxinus</i> > 10%
Preboreal/Older Boreal	IV/Va	10,770 <i>Corylus</i> > 5%
Younger Dryas/Preboreal	III/IV	11,600 NAP percentages decrease

Diatom analysis and thin sections

Wet sediment samples of ca. 0.5 ml, were treated with hot hydrogen peroxide (30%) for at least 24 h. After complete evaporation the samples were re-suspended in water and conserved with formaldehyde for storage. Diluted subsamples of 10 µl volumes were mounted in Naphrax[®]. All diatom valves and chrysophyte cysts in this 10-µl drop or of an aliquot were identified and counted. Valve concentrations were calculated following the aliquot method by Battarbee (1986). Mean diatom concentrations as high as 470,000,000 valves/cm³ sediment required several dilution steps. As the error increases with dilution, this method yields rough estimates only (Wolfe 1997). The diatom influx (valves × cm⁻² × a⁻¹) was calculated using concentration and sedimentation rates.

Altogether, 178 diatom samples were counted and taxonomically analysed. The mean temporal resolution is 100 years. A minimum of 1,000 valves, on average 2,700 valves per sample, were counted using a Leica DMLS microscope with oil immersion and phase contrast at 1,000× magnification. The taxonomy follows Krammer and Lange-Bertalot (1986–1991). In addition the following publications were used for identification: Reichardt and Lange-Bertalot (1991) for *Gomphonema*, Witkowski et al. (1995/96) for *Fragilaria martyi*, Lange-Bertalot and Moser (1994) for the genus *Brachysira*, Lange-Bertalot (1993) and Lange-Bertalot and Metzeltin (1996) for several *Navicula* and *Gomphonema* species. New genus names such as *Sellaphora* are used for newly described species only, not for renamed ones. This allows easier access to published ecological information. *C. pseudocomensis* according to Scheffler (1994) and *Cyclotella comensis* were not differentiated, because the intraspecific variation seems to be too large and overlapping.

The results of the diatom analysis, calculated as percents (100% = sum of counted valves), total concentration, and total influx, are shown in Figs. 10 and 11 and Table 9. The counts are available in the database PANGAEA (<http://www.pangaea.de/PangaVista>). The diatom diagram is subdivided into Firbas pollen zones and limnological phases (Table 8).

Thin sections for annual and subannual varve analysis were prepared according to Merkt (1971) and microscopically examined at 250×, 400× and 1,000× magnification with linear and crossed

polarised light. Annual lamination is documented by photography in Baier (1997).

Numerical reconstruction of trophic status

The distribution of diatom species is highly controlled by total phosphorus (TP) concentrations (Hofmann 1994; Kelly and Whitton 1995; Lotter et al. 1998; Wunsam et al. 1995). Trophic preference and tolerance of a species can be calculated from its relative frequencies and the accompanying measured TP-concentrations by using the methods of weighted averaging (ter Braak and van Dam 1989; ter Braak and Juggins 1993). However, preference and tolerance can also be determined empirically from the frequency distribution along a TP-gradient by assigning the species to defined trophic classes (Hofmann 1994). For both methods TP-concentrations should cover a wide range and should be distributed as evenly as possible along the gradient. Based on optima and tolerances, TP-concentrations or trophic conditions during past time periods can be reconstructed using diatom assemblages in a sediment core.

In this study we performed a TP-reconstruction (Fig. 11) using the method described by Hofmann (1994, also compare Kelly and Whitton 1995) in combination with ecological information from the TP-data sets of the European Diatom Database (EDDI, Bennion et al. 1996; Lotter et al. 1998; Rioual 2000), excluding the Central European data set CEURO (Wunsam and Schmidt 1995). CEURO was not used, because here *Stephanodiscus minutulus* was not always distinguished from *S. alpinus*. In contrast to Kelly and Whitton (1995), who worked on rivers with a very wide TP-range, Hofmann investigated periphyton communities of 44 circumneutral and alkaline lakes in Southern and Western Germany (TP-gradient from 6 to 64 µg/l). Based on these TP-concentrations and on published information, Hofmann assigned a trophic status to every lake following Vollenweider (1979). She distinguished five groups of lakes: oligotrophic = 1, oligo-/mesotrophic = 2, mesotrophic = 3, meso- to eutrophic = 4 and eutrophic = 5. Hofmann then calculated the trophic state value of the species by weighted averaging (Zelinka and Marvan 1961; ter Braak and van Dam 1989), using the figure of the trophic status as the variable. In a second step, the trophic state tolerances of every species were empirically determined from their distribution along

Table 5 Characterization of the diatom tolerance groups according to Hofmann (1994)

Tolerance group	Weighting	Milieu of occurrence	TP-conc. ($\mu\text{g/l}$) acc. to Vollenweider (1979)
Oligotrophic species	3	Restricted to oligotrophic	<11.8
Oligo- β -mesotrophic species	2	From oligotrophic to moderately mesotrophic	<19
Oligo- α -mesotrophic species	1	From oligotrophic to strongly mesotrophic, not tolerating eutrophic conditions	<26.8
α -Meso-eutrophic species	2	From moderately mesotrophic to eutrophic	≥ 26.8
Eutrophic species	3	Restricted to eutrophic	>46.5
Tolerant species	0	No clear relation to trophic status discernible	

the TP-gradient. Six tolerance groups were distinguished according to the criteria listed in Table 5. The tolerance groups are overlapping and limited on one side only, because the frequencies of most species are not symmetrically distributed along the TP-gradient. Weightings depend upon the tolerance ranges (stenoeious = 3, euryoeious = 0). This classification of species was then scrutinized and in some cases corrected by comparison with diatom assemblages from 155 additional European lakes (slides from Coll. Lange-Bertalot) and published information. Hofmann's classification was confirmed by experiments (Reimann 1998).

Using these autecological data, the unknown trophic status of a lake can be inferred by weighted averaging, using the species' abundances, trophic state values and weightings:

$$TI = \frac{\sum_{i=1}^n H_i \times G_i \times T_i}{\sum_{i=1}^n H_i \times G_i} \quad (1)$$

TI = trophic state index, H_i = relative abundance of species i , G_i = weighting of species i , T_i = trophic state value of species i .

Table 6 shows the relation between trophic state index TI and trophic status. This method was successfully used in many lake monitoring programs

Table 6 Relation between trophic state index and trophic status, according to Hofmann (1994)

Trophic state index	Trophic status
1.00–1.99	Oligotrophic
2.00–2.49	Oligo- to mesotrophic
2.50–3.49	Mesotrophic
3.50–3.99	Meso- to eutrophic
4.00–5.00	Eutrophic

on Bavarian lakes (Hofmann, 1999; Hofmann and Schaumburg 2005a–d).

To date, this data set comprises 448 species and their trophic state classification (Hofmann 1999). In the fossil samples of Lake Jues, 439 diatom taxa were identified (71 species per sample on average). Thereof, 160 taxa are not classified by Hofmann, but comprise the most dominant planktonic species. Trophic state values of these species were estimated by their distribution in the combined TP-data set from EDDI, but also by compiling published references (Table 7). 77 species remained unclassified, of those only three constitute more than 1% in the Lake Jues profile (*Fragilaria capucina* Desmazières 1925, *F. pseudoconstruens* Marciniak 1982 and *F. microstriata* Marciniak 1982).

A diversity of indicator species is required to make accurate paleoenvironmental inferences. Hofmann (1994, 1999) recommends that at least 10 indicator species per sample should be present, which do not necessarily have to occur at high abundances. Good indicator taxa often are quite rare, while tolerant species can be very abundant. Amongst the latter are many small opportunistic taxa with fast reproduction and immigration rates, e.g. *Achnanthes minutissima* Kützing 1833 and *Fragilaria construens* (Ehrenberg) Grunow 1862. The mean number of indicator species is 31, with abundances between 1.7 and 96% (59% on average). Only one of the samples contains less than 10 indicator species.

Results and discussion

Lithology and laminations

The predominant sediments of Lake Jues are annually laminated silty gyttjas with changing proportions of

fine and coarse detritus (Fig. 7). The laminations show characteristic patterns allowing a precise correlation of the cores. Several macroscopic and microscopic features of the record provide evidence of the limnological conditions during the time of deposition.

Lamination

Dark and light laminae, 0.04–1.4 mm thick, alternate in the record. During spring and summer, a sequence of algae blooms, mainly diatoms, but also cysts of Chrysophyceae, contribute to one or a few light sublaminae. Pollen grains of *Corylus*, *Alnus*, *Betula*, *Quercus* and *Pinus* in the light layers indicate spring and early summer as the time of deposition. The dark layers, consisting mainly of inorganic and organic fine detritus, i.e. material derived from the lake's littoral and the catchment area, represent fall and winter. Planktonic diatoms are usually rare in the dark layers because of the low phytoplankton production during winter (Baier 1997).

Annual laminations are mainly preserved in small (surface < 100 ha) and deep lake basins. This topography favours anoxic conditions in the hypolimnion depending upon circulation pattern, length of stagnation periods, and the amount of organic production. Lasting stagnation results in accumulation of organic matter at more or less reducing conditions in the hypolimnion and, at the same time, nutrient depletion in the epilimnion. High concentrations of dissolved and suspended substances in the hypolimnion can prevent deep mixing and thus cause biogenic meromixis (Sommer 1994). Meromixis is also favoured by a more continental climate with stable winter and summer weather and short transitional seasons.

Sediment colours

Before 8,300 cal. yr. BP and after 2,500 cal. yr. BP, the sediments in Lake Jues are mainly grey or greenish. The long section in between is nearly exclusively black (Fig. 11). Reddish colours, due to the Fe³⁺-minerals hematite and goethite, occur in minerogenic layers between 10,620 and 10,100 cal. yr. BP and between 4,300 and 3,440 cal. yr. BP. Fe-Oxides are only preserved under oxic conditions in the hypolimnion and at low organic production. With increasing temperature and organic production, Fe-oxides are reduced during the diagenesis of the sediments

resulting in first greenish and, finally, grey and black sediments (Hinze and Meischner, 1968). The black stain indicates reduction of sulphate and formation of iron sulphides in the pore waters or, in extreme cases, already above the sediment surface. The grade of reduction of iron may be taken as an indication of increased organic production and reduced circulation, a trend generally favoured by rising temperatures in a temperate climate. However, a direct reference to seasonal circulation patterns is not possible.

Vivianite

Bright-blue clusters of vivianite crystals (Fe₃(PO₄)₂ · 8 H₂O) occur at the base of the limnic sediments, and become frequent with the increasing burial of undecomposed organics, finally forming nodules and crusts parallel to the bedding. The precipitation of vivianite clearly precedes the formation of sulphides in the course of eutrophication (Gächter and Müller 2003). In Lake Jues, vivianite formation ceased about 9,900 cal. yr. BP, and was replaced by black sulphides (Fig. 11).

Orthophosphate is provided by the oxic decay of organics while the iron is delivered as Fe²⁺-ions from already reduced sediments. Thus vivianite forms at a high redox-gradient close to or at the sediment surface, and at high phosphate concentrations and availability of reduced pore fluids, most likely due to expulsion of pore water by compaction of the deeper sediment. Oxic decay in the hypolimnion is indicated by complete dissolution of carbonate by the resulting CO₂ (Emerson and Bender 1981). Phosphorus may also be provided by carbonate dissolution as carbonate lattices can contain up to 600 ppm phosphorus (Morse and Mackenzie 1990).

Vivianite therefore is an indicator of at least temporary deep circulation at high organic production. The accumulation of massive vivianite may have prevented the cycling of phosphorus and, hence, hampered the establishment of a rich trophic system during the early stages of Lake Jues.

Diatom stratigraphy and ecology

The stratigraphy of the common diatoms is shown in Figs. 10 and 11 and in Table 8. Their trophic state values, used for the diatom-inferred trophic state index, are given in Table 7.

Table 7 Trophic state values of frequent planktonic species of ancient Lake Jues

Species	Trophic state value	Weighting	Reference
<i>Asterionella formosa</i> Hasall 1850	4	1	EDDI TP-data sets, van Dam et al. (1994), Denys (1991)
<i>Aulacoseira granulata</i> (Ehrenberg) Simonsen 1979	4	2	EDDI TP-data sets, Whitmore (1989)
<i>Cyclotella comensis/pseudocomensis</i> (<i>Cyclotella comensis</i> Grunow in Van Heurck 1882, <i>Cyclotella pseudocomensis</i> Scheffler 1994)	2.5	1	EDDI TP-data sets
<i>Cyclotella ocellata</i> Pantocsek 1901	Tol	0	EDDI TP-data sets
<i>Cyclotella radiosa</i> (Grunow) Lemmermann 1900	2.5	1	EDDI TP-data sets
<i>Fragilaria crotonensis</i> Kitton 1869	Tol	0	EDDI TP-data sets, Hofmann (1999)
<i>Fragilaria capucina</i> var. <i>gracilis</i> (Oestrup) Hustedt 1950	Tol	0	Hofmann (1999)
<i>Fragilaria delicatissima</i> (W. Smith) Lange-Bertalot 1980	2	2	Hofmann (1999)
<i>Fragilaria tenera</i> (W. Smith) Lange-Bertalot 1980	2.5	1	Hofmann (1999)
<i>Nitzschia paleacea</i> (Grunow) Grunow in Van Heurck 1881	5	3	Hofmann (1999), van Dam et al. (1994)
<i>Stephanodiscus alpinus</i> Hustedt in Huber-Pestalozzi 1942	Tol	0	Stoermer (1984, 1993), Hickel and Håkansson (1993)
<i>Stephanodiscus parvus/minutululus</i> (<i>S. parvus</i> Stoermer and Håkansson 1984, <i>S. minutulus</i> (Kützing) Cleve and Möller 1878)	4.3	2	EDDI TP-data sets

Asterionella formosa is the most abundant species of the record, only becoming rare between 12,000 and 11,000 cal. yr. BP, 4,000 and 2,900 cal. yr. BP and between 2,600 and 2,000 cal. yr. BP. While some authors describe *Asterionella formosa* as tolerant (Round 1981; Round and Brook 1959; Bradbury 1975; Dixit and Dickman 1986), the EDDI TP-data sets clearly show its meso- to eutrophic distribution, and thereby confirms the classification of van Dam et al. (1994) and Denys (1991). *Cyclotella comensis*, frequent in Lake Jues throughout the Holocene except for parts of the Atlantic period and the last 2,000 years, usually occurs at oligotrophic to α -mesotrophic conditions (Hofmann 1994, 1999; TP-data sets of EDDI). This agrees with observations that show increasing abundances of *C. comensis* following a modest nutrient enrichment (Fritz et al. 1993; Stoermer 1993). *Cyclotella ocellata* mainly occurred during the Atlantic and between 2,000 and 1,000 cal. yr. BP. The species is classified as oligotraphentic (Stoermer and Yang 1970; Denys 1991) as well as meso- to eutraphentic (van Dam et al. 1994). According to the combined TP-data set, this species is not indicative of lower trophic state conditions,

although it shows decreasing vitality at TP-concentrations $>100 \mu\text{g/l}$. For *Fragilaria crotonensis*, found in Lake Jues during the Subatlantic, the combined TP-data set shows no clear relation to TP-concentrations and confirms the estimate of Hofmann (1994, 1999). *Nitzschia paleacea*, common in Lake Jues only during the Older Subatlantic, is an eutraphentic species (Hofmann 1994, 1999), that additionally indicates high NH_4 -concentrations (Hürlimann and Schanz 1993) and becomes more abundant with increasing organic pollution (α -mesosaprobic, Krammer and Lange-Bertalot 1986–1991). *Stephanodiscus alpinus* occurred nearly exclusively during the Preboreal and Boreal. The species seems to be distributed in oligo- to mesotraphentic conditions according to the combined TP-data. However, other studies describe its morphological adaptations to changing nutrient concentrations and classify the species as tolerant (Stoermer 1984, 1993; Hickel and Håkansson 1993). The high P-requirement of *Stephanodiscus parvus/minutululus* is well-known (e.g. van Dam et al. 1994; Kilham et al. 1986), its vitality under mesotrophic conditions, however, is only shown by the EDDI TP-data set (excluding the

CEURO data set). Hence, this species has similar P-demands as *Asterionella formosa*, but was not as abundant in Lake Jues as the latter.

In addition to phosphorus, silicon is important for growth and vitality of diatoms with Si:P-ratios as a factor for dominance and seasonal succession of the planktonic species. Several diatom species prefer specific Si:P-ratios. According to Kilham et al. (1986), Sommer (1987) and Tilman et al. (1982), *Fragilaria* and *Asterionella* and probably also the needlelike *Nitzschia* spp. are good competitors for P and relatively poor competitors for Si and hence prefer high Si:P-ratios. *Fragilaria delicatissima* is even more Si-demanding than *Asterionella*. In contrast *Stephanodiscus minutulus* has high demands for P, but only low Si-requirements. *Cyclotella comensis* and *Cyclotella radiosa* grow well at low Si- and P-concentrations (Raeder 1990; Wolin et al. 1988). The changing dominance of species with different Si- and P-preferences can be shown more clearly by assigning the long *Fragilaria* spp. and *Asterionella* to a high Si:P-ratio taxon group. *Stephanodiscus minutulus* represents the low Si:P-ratio group.

Limnological reconstructions through time (Figs. 10 and 11, Table 8)

Younger Dryas (pollen zone III)

The limnic sediments are underlain by strongly weathered gravel. After the formation of the sinkhole lake, 124 cm of unstructured silty gyttja with sand and gravel layers and vivianite concretions were deposited upon the gravel.

Low pollen concentrations combined with high percentages of nonarctic pollen (NAP), *Pinus* and *Betula* allow us to conclude that the oldest lake sediments date from the Younger Dryas at least. The sand and gravel layers, numerous reworked pollen grains, pre-Quaternary sporomorphs, and rheophilous and aerophilous diatoms, such as *Meridion circulare* (Greville) C.A. Agardh 1831, *Diatoma mesodon* (Ehrenberg) Kützing 1844, *Fragilaria arcus* (Ehrenberg) Cleve 1898, *Navicula gallica* var. *perpusilla* (Grunow) Lange-Bertalot 1985, *N. contenta* Grunow in Van Heurck 1880, and *Pinnularia borealis* Ehrenberg 1843, indicate strong erosive processes (pollen zone IIIa). The terrestrial plant cover was apparently fragmentary, but became gradually

denser so that the inflow of minerogenic detritus decreased (pollen zone IIIb).

Limnological phase 1 (Table 8): The aquatic and telmatic vegetation of Lake Jues was still rather sparse at this time. *Typha latifolia* type, *Typha angustifolia* type, and *Potamogeton* (proved by a few pollen grains) as well as algae, mainly diatoms and Chrysophyceae, were present (Figs. 10, 11). Diatom concentrations were relatively low (mean 13×10^7 valves/cm³). The high percentages of planktonic diatoms show that not only pollen of thermophilous species from older interglacials, but also an unknown quantity of diatom valves were redeposited during the time of zone IIIa.

Limnological phase 2: Starting with pollen zone IIIb, the diatom associations reflect ecological conditions no longer influenced by redeposition. At that time Lake Jues was mesotrophic (Fig. 11). The absence of varves and the occurrence of vivianite concretions indicate holomixis which must have occurred during the short ice-free periods (cold monomictic).

Simultaneously with reduced terrigenous inflow, the portions of the planktonic diatom species (mainly *Asterionella formosa* and *Cyclotella comensis*) decreased from 30% to 10%, while diatom concentrations increased (mean 20×10^7 valves/cm³). Small, probably tycho-planktonic *Fragilaria* spp. and periphytic species dominated the diatom assemblages, a phenomenon typical of the late glacial and the early Post-glacial, and a characteristic of modern Arctic lakes (Haworth 1976; Lotter and Bigler 2000; Marciniak 1986; Smol 1983, 1988). Diatom plankton bloomed during the short ice-free periods. In the littoral zone, where the ice disappeared earlier in the year, a pioneer association of periphytic and tycho-planktonic diatoms (mainly *Fragilaria robusta* (Fusey) Manguin and *F. martyi* (Heribaud) Lange-Bertalot 1993) developed (Lotter and Bigler 2000; Smol 1983, 1988). Species which are now common in the cold nordic-alpine, arctic-boreal, and alpine regions (Krammer and Lange-Bertalot 1986–1991) were part of these assemblages (“cold water diatoms”): *Achnanthes bioretii* Germain 1957, *A. flexella* (Kützing) Brun 1880, *A. gracillima* Hustedt 1927, *A. laevis* Oestrup, *A. levanderi* Hustedt 1933, *Amphora fagediana* Krammer 1985, *Cymbella reichardtii* Krammer 1985, *Gomphonema ventricosum* Gregory 1856, and *Nitzschia alpina* Hustedt 1943 emend. Lange-Bertalot 1980 (Fig. 11). These species

Table 8 Characterization of limnological phases in Lake Jues

Limnolog. phases	Age	Characteristic features	Circulation
1		Redeposited diatoms abundant, “cold-water diatoms” present	Monomictic
2		Small <i>Fragilaria</i> spp. and periphytic species dominant, “cold-water diatoms” decreasing, <i>Stephanodiscus alpinus</i> present	Monomictic
3	11,200–10,620	Increase of planktonic species (<i>Cyclotella comensis/pseudocomensis</i> , <i>Asterionella formosa</i> , <i>Stephanodiscus minutulus</i>), <i>Stephanodiscus alpinus</i> common	Dimictic
4	10,620–10,100	Dominance of small <i>Fragilaria</i> spp. and periphytic species, “cold-water diatoms” more frequent again, sedimentation of clastic rhythmites	Dimictic
5	10,100–9,500	Dominance of planktonic species (<i>Cyclotella comensis/pseudocomensis</i> , <i>Asterionella formosa</i> , <i>Stephanodiscus minutulus</i>), “cold-water diatoms”, and <i>Stephanodiscus alpinus</i> still present	Alternating holo- and meromictic
6	9,500–8,400	Disappearance of “cold-water diatoms” and <i>Stephanodiscus alpinus</i> , planktonic diatom assemblages more diverse	Alternating holo- and meromictic
7	8,400–4,550	Coccal green algae (<i>Botryococcus</i> , <i>Tetraedron</i>) abundant	Meromictic
a	8,400–8,200	Increase of coccal green algae	Meromictic
b	8,200–7,530	High abundance of <i>Asterionella formosa</i>	Meromictic
c	7,530–6,750	Dominance of <i>Cyclotella</i> spp.	Meromictic
d	6,750–5,700	Dominance of <i>Cyclotella</i> spp. continues, higher values of <i>Myriophyllum spicatum</i> pollen grains as well as of tychoplanktonic and periphytic diatoms, low diatom influx	Oligomictic
e	5,700–5,250	Low values of coccal green algae and <i>Myriophyllum spicatum</i> , high percentages of <i>Stephanodiscus minutulus</i> and <i>Cyclotella radiosa</i>	Oligomictic
f	5,250–4,770	High abundances of coccal green algae, more diverse diatom assemblages, high pollen values of <i>Myriophyllum spicatum</i>	Meromictic and oligomictic
g	4,770–4,550	Still higher abundances of coccal green algae, decreasing values of <i>Myriophyllum spicatum</i> , <i>Cyclotella radiosa</i> and <i>Asterionella formosa</i> dominant	Meromictic
8	4,550–4,100	<i>Asterionella formosa</i> dominant, decreasing values of coccal green algae	Oligomictic
9	4,100–3,450	<i>Fragilaria capucina</i> var. <i>gracilis</i> , <i>F. delicatissima</i> and <i>Cyclotella</i> spp. dominant, reddish sediment colours	Holomictic phases more frequent
10	3,450–2,850	<i>Cyclotella</i> spp. dominant, Characeae present	Oligo- or meromictic
11	2,850–2,650	<i>Asterionella formosa</i> , <i>Fragilaria capucina</i> var. <i>gracilis</i> , and <i>F. delicatissima</i> dominant	Oligomictic
12	2,650–2,280	Settlement phase (Iron Age), alternating dominances of <i>Stephanodiscus minutulus</i> , <i>Cyclotella comensis/pseudocomensis</i> and <i>Nitzschia paleacea</i>	Oligomictic and dimictic
13	2,280–1,240	<i>Asterionella formosa</i> , <i>Fragilaria capucina</i> var. <i>gracilis</i> , and <i>F. delicatissima</i> abundant	Dimictic
a	2,280–2,050	Si-preferring diatoms dominant, reddish sediment colours	Dimictic
b	2,050–1,800	<i>Cyclotella ocellata</i> dominant, Si-preferring diatoms subdominant	Dimictic
c	1,800–1,500	Si-preferring diatoms dominant	Dimictic
d	1,500–1,240	<i>Cyclotella</i> spp. dominant, Si-preferring diatoms subdominant	Dimictic

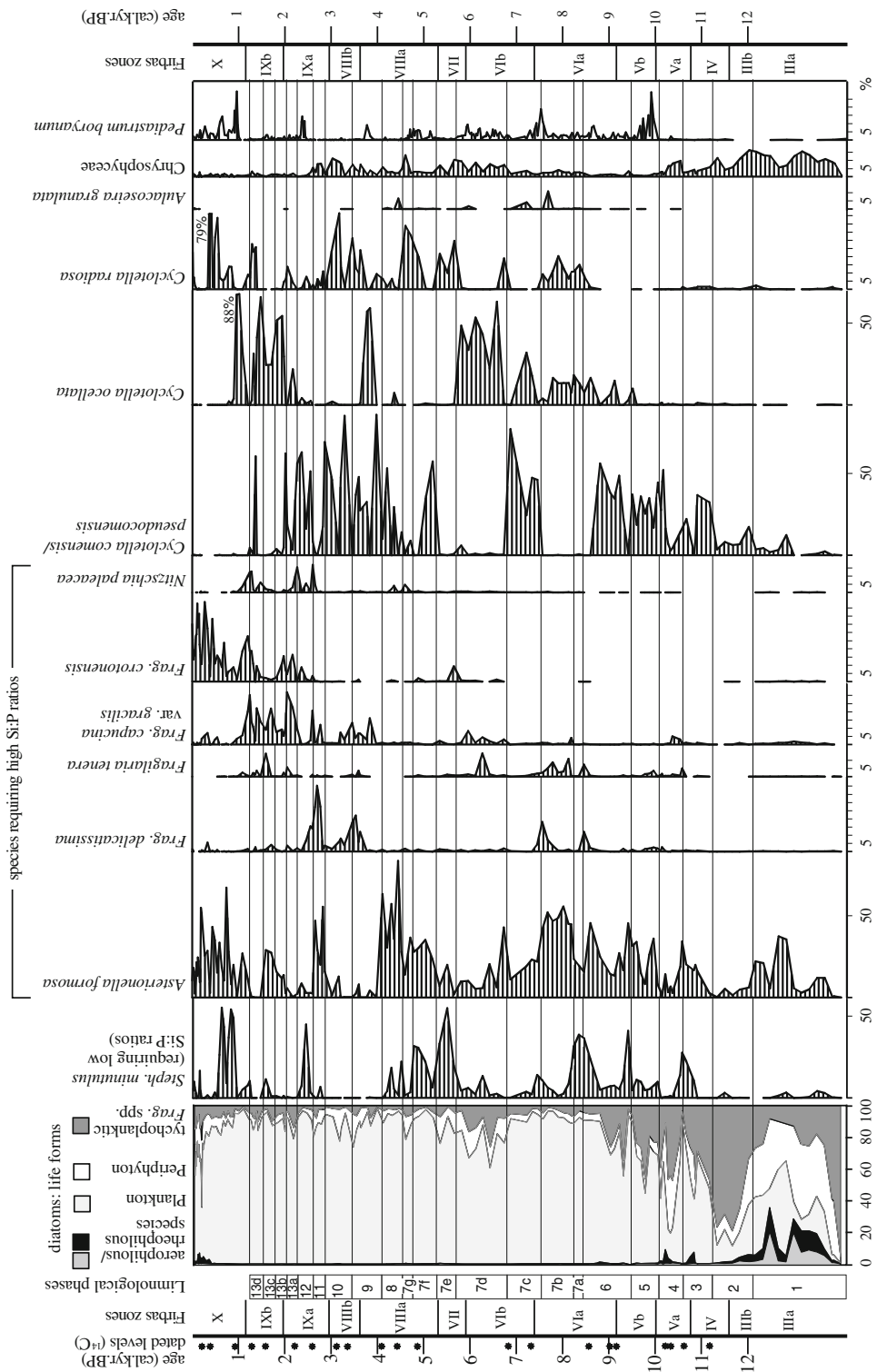


Fig. 10 Percentage diagram of diatom life forms and of the most important planktonic diatoms, chrysophyte cysts and *Pediastrum boryanum*. Percentages are based on the total of

diatom valves or the tree pollen sum (in the case of *Pediastrum boryanum*), respectively

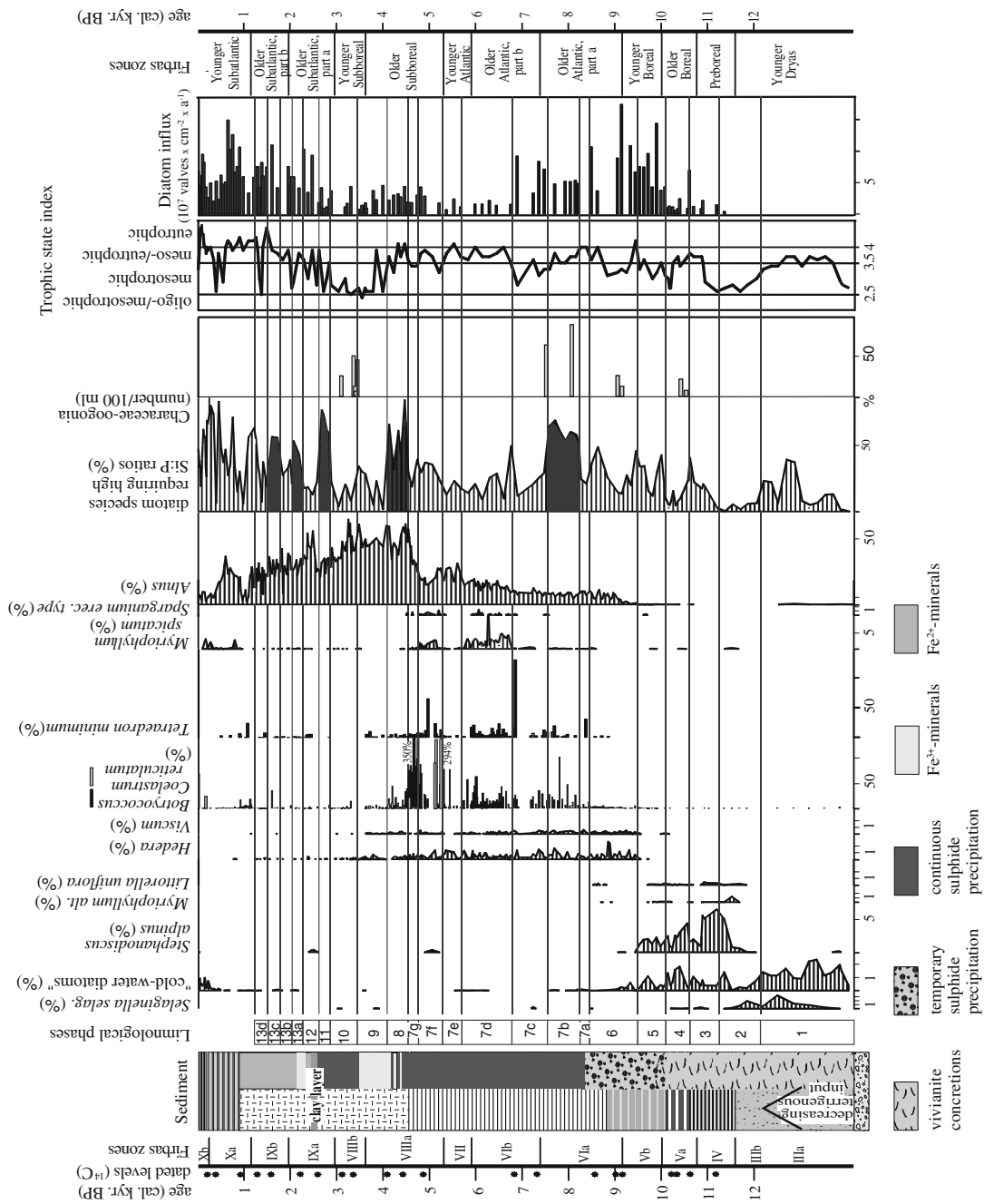


Fig. 11 Diagram of selected pollen, diatom and algae taxa, diatom-inferred trophic level and diatom influx. Diatoms, green algae, water- and land plants are ordered from left to right according to their significance in the course of time. Signatures of the sediment column see Fig. 7. Percentages are based on

the tree pollen sum (water- and land plants and green algae) or the total of diatom valves, respectively. Characeae oogonia are given as number per 100 ml sediment. Darker hatching in the curve of diatoms requiring high Si:P-ratios indicates periods of inferred higher precipitation

are no true temperature indicators, but weak competitors which colonize extreme sites. Despite their low frequencies (0.2–2.4%) they can, however, be

considered to indicate cold conditions like the cold-resistant lesser clubmoss *Selaginella selaginoides* which occurred at the same time.

Preboreal (pollen zone IV, 11,600–10,770 cal. yr. BP)

The gradual transition from unstructured to laminated mud as well as shifts in the pollen and diatom spectra indicate the start of the Preboreal. The age of the zone III to IV boundary—between 11,600 and 11,555 cal. yr. BP, extrapolated from radiocarbon dates—is in good agreement with the results of the varve counts from Lake Steisslingen (11,580 cal. yr. BP; Lechterbeck 2000) and Holzmaar (11,600 cal. yr. BP; Zolitschka 1998).

Lamination became distinct since 11,470 cal. yr. BP. The lamination is often slightly disturbed (in most cases by sliding for a few millimetres). A marked disturbance (11 cm) occurred between 11,015 and 10,830 cal. yr. BP. Ground unrest due to newly forming sinkholes in the area might have caused these disturbances.

The onset of lamination indicates stagnation phases during the summer with temporary anaerobic conditions in the hypolimnion due to gradually increasing temperatures. Lasting anaerobic conditions in the hypolimnion can be ruled out as vivianite formation continued. Apparently the lake was dimictic now.

The pollen spectra indicate closed forests with mainly *Betula* and *Pinus* (Fig. 9) which reduced erosion. *Littorella uniflora* and *Myriophyllum alterniflorum*, both characteristic of the shoreweed communities (Littorelletea), grew along the shore of Lake Jues during the Preboreal (Fig. 11). They indicate clear and weakly acid, nutrient-poor water (Ellenberg 1996). This agrees with the calculated trophic state index (mesotrophic at the lower end). The warming was not yet sufficient to support a temperature-induced increase of bioproduction and strong development of plankton. Tycho planktonic *Fragilaria* spp. (mainly *F. brevistriata* Grunow in van Heurck 1885 and *F. robusta*) continued to dominate the diatom spectra (limnological phase 2, Fig. 10, Table 8). However, cold water-adapted species decreased, but did not totally disappear. The presence of *Myriophyllum alterniflorum*, too, points to still relatively low water temperatures. Today this species occurs in cool waters of nordic-subatlantic regions (Oberdorfer 1994). Increasing abundances of *Stephanodiscus alpinus* indicate that the ice cover during winter still lasted for a long time. *Stephanodiscus alpinus* can survive long dark periods (Stoermer

1993), and therefore has a competitive advantage after periods of lasting ice cover (Hickel and Håkansson 1993). Hickel and Håkansson (1993) emphasize that *Stephanodiscus alpinus* is not a cold-water species, but rather a poor competitor for P and Si.

Limnological phase 3: The increase of diatom concentrations (mean 32×10^7 valves/cm³) and of plankton species such as *Cyclotella comensis/pseudocomensis* and *Asterionella formosa* points to further rising summer temperatures since ca. 11,200 cal. yr. BP. The mean diatom influx was 2.4×10^7 valves \times cm⁻² \times a⁻¹. Meso- to eutrophic conditions since 10,900 cal. yr. BP indicate improved nutrient supply due to temperature-induced higher bioproduction and intensified remineralization. The warmer climate allowed a first, but limited expansion of elm.

Older Boreal (pollen zone Va, 10,770–10,020 cal. yr. BP)

The early part of the Boreal is characterized by the spread of hazel. Hazel invaded the existing birch-pine-forests forming a dense undergrowth. Elm and oak trees remained rare (Fig. 9). Three different limnological phases (3, 4, 5, Table 8) are distinguished:

Limnological phase 3 had already begun at the end of the Preboreal, and continued during the first ~150 years of the Boreal. *Stephanodiscus minutulus* became a frequent member of the planktonic diatom assemblages (Figs. 10, 11). Thin section no. 1 (Table 2) proves the annual character of the lamination. Above the detrital winter layer there follows a layer of Chrysophyceae cysts with pollen of *Betula* and *Pinus*, occasionally a layer of *Stephanodiscus minutulus* (main bloom in spring), and an autumnal layer rich in phytoplankton and detritus.

Limnological phase 4: Between 10,620 and 10,100 cal. yr. BP, clastic rhythmites with reddish, grey, and yellow, partially graded minerogenic layers (1–65 mm thick) were deposited. Diatom and pollen content of the minerogenic layers differ much from that of the older sediment (Table 9). Littoral (periphyton, tycho plankton) and allochthonous (aerophilous and rheophilous) diatoms prevail in the minerogenic layers, fern spores are unusually frequent. These layers were probably deposited during episodes of thawing and/or heavy rainfall accompanied by floods. The colours of the minerogenic layers reflect the conditions

Table 9 Pollen, spore and diatom percentages of various sediment types in time section 11,600–8,820 cal. yr. BP (unusual percentages are bold)

Age (cal. yr. BP)	Laminated silty gyttja	Laminated silty gyttja	Clastic rhythmites	Coloured minerogenic layers	Laminated silty gyttja	Grey minerogenic layers	Unstructured silty gyttja
	11,600–10,770 (Preboreal)	10,770–10,620 (Boreal)	10,620–10,100 (Boreal)		10,100–8,820 (Boreal, Older Atlantic)		ca. 10,450 Boreal
Plankton	35	70	42	13	71	61	15
Periphyton/ Tychoplankton	56	26	48	62	27	30	69
Aerophilous diatoms	0.31	0	0.34	2.9	0.09	0.84	0.25
Rheophilous diatoms	1.4	0.57	2	11	0.35	3.7	0.2
Polypodiaceae	5.5	12	7.9	227	2	41	7.5
<i>Corylus</i>	0.6	7.7	171	810	236	464	35

Percentages are based on the tree pollen sum (*Corylus*, Polypodiaceae) or the total of diatom valves, respectively

after the time of inflow of the washed-in components (Lambert and Hsü 1979). The reddish (oxidized) layers must have been deposited during phases of circulation (see preceding chapter). Thin section no. 1 shows that since 10,620 cal. yr. BP the laminated sequence is—with increasing frequency—interrupted by minerogenic layers intercalated between the winterly detritus and the Chrysophyceae. The annual lamination is no longer distinct in thin section no. 2. Generally, however, the multicoloured minerogenic layers are followed by a diatom-Chrysophyceae layer and detritus above. Therefore the minerogenic layers are most likely the result of floods during winter and springtime, and thus are caused by thawing. At the same time and until 9,900 cal. yr. BP, birch, poplar and willow spread (Fig. 9), most likely indicating greater discharge and frequent shifts of the bed of the river Sieber which favoured softwood riparian forests. The planktonic species, except *Stephanodiscus alpinus*, diminished while tychoplankton and periphyton became dominant again. “Cold-water species” as well as rheophilous and aerophilous diatom species became more frequent since ca. 10,400 cal. yr. BP. A general warming started after 10,230 cal. yr. BP, but the indicators of less favourable climatic conditions did not vanish until 9,800 cal. yr. BP.

Lamination and the presence of vivianite concretions prove that the ecological conditions in the lake (dimictic, temporarily anaerobic hypolimnion) had not changed since the end of the Preboreal.

A 154-cm-thick layer of unstructured silty gyttja with a special pollen and diatom content interrupts

the clastic rhythmites of limnological phase 4 at ca. 10,450 cal. yr. BP (Fig. 7). *Corylus* pollen is much less frequent (mean 35%) than in the sediments above and below (236%). The diatom spectra are dominated by littoral species, the plankton values are low (Table 9). These changes were probably caused by a slump of older sediments with little or no pollen of *Corylus* into the deep of the lake basin.

Limnological phase 5 started during the last years of the older Boreal and continued during the beginning of the younger Boreal. Above the rhythmites (limnological phase 4), laminated silty gyttja with numerous, merely grey, graded minerogenic layers (1–220 mm thick) follows, containing similar pollen and diatom floras as the clastic rhythmites of phase 2. The diatom influx increased distinctly (Fig. 11). The increase of the coccal green alga *Pediastrum boryanum* indicates warmer summers (Raeder 1990). The grey (reduced) minerogenic layers were probably deposited during stagnation phases. Although dating from limnological phase 6, thin section no. 3 resembles this sediment type. The two- to three-layered varves consist of a detritus layer deposited in winter, a phytoplankton layer formed in spring or summer (mainly *Asterionella formosa*, *Cyclotella comensis/pseudocomensis*, *C. ocellata*), and sometimes an additional layer with fragments of benthic diatoms and detritus. These littoral species were most likely washed into the lake by heavy summer or autumn rainfall like in the other, thicker grey minerogenic layers.

The spotty occurrence of (black) sulphides in the sediments indicates that deep circulation was

temporarily hindered, possibly caused by decreasing wind exposure resulting from the formation of a sheltering broad-leaved forest belt around the lake. Now holomictic and meromictic phases alternated.

Younger Boreal (pollen zone Vb, 10,020–9,160 cal. yr. BP) and Older Atlantic (pollen zone VI, 9,160–5,910 cal. yr. BP)

During the Younger Boreal closed deciduous forests replaced the birch-pine-woods in the vicinity of Lake Jues (Fig. 9). In addition to oak and elm, small-leaved lime (*Tilia cordata*), a species adapted to summer-warm sites, gained in importance since 9,700 cal. yr. BP. From ca. 9,500 cal. yr. BP mistletoe (*Viscum*) indicating warm summers and ivy (*Hedera*) sensitive to strong frost and therefore indicating mild winters became more frequent in the forests (Fig. 11).

Farming spread in Central Europe since about 7,650 cal. yr. BP (Linear Pottery; Behre 1995). At about the same time, the forests around Lake Jues were affected for the first time by human activity (Fig. 9). Human influence remained weak, however, during all of the Neolithic period (Voigt 2006).

The sediments deposited during the Younger Boreal and the Older Atlantic are laminated throughout. As before—since 10,100 cal. yr. BP and until 8,820 cal. yr. BP—a silty gyttja rich in plant-macrofossils and with numerous grey minerogenic layers was deposited (Table 9) indicating that heavy summer or autumn rainfall continued to occur. Subsequently the sedimentation of minerogenic layers ended. Diatom gyttja with less macrofossils follows above the silty gyttja.

The increasing importance of the thermophilous woody taxa (*Tilia cordata*, *Hedera*, *Viscum*) since 9,700 cal. yr. BP coincides with changes of the water plant and diatom floras (Figs. 10, 11, Table 8) at the transition from limnological phase 5 to 6. Around 9,700 cal. yr. BP *Myriophyllum alterniflorum* and *Littorella uniflora* disappeared from Lake Jues. About 200 years later, with the beginning of limnological phase 6, the “cold water diatoms” mentioned before, and *Stephanodiscus alpinus* decreased significantly. Planktonic diatoms became more frequent again and more diverse at the same time. Since 9,500 cal. yr. BP *Cyclotella ocellata*, and since 8,600 cal. yr. BP also *Cyclotella radiosa*, *Fragilaria delicatissima*, and

F. tenera became more common, while *Asterionella formosa*, *Cyclotella comensis/pseudocomensis*, and *Stephanodiscus minutulus* were still present.

Limnological phase 6 is represented by thin sections nos. 3 and 4. In thin section no. 3 (9,245–9,120 cal. yr. BP) only one diatom bloom with *Asterionella*, *Stephanodiscus minutulus*, and *Cyclotella* spp. occurred in spring and early summer layers. In summer probably other algae thrived, among them *Pediastrum* colonies. In thin section no. 4 (8,920–8,690 cal. yr. BP) two annual diatom blooms can be distinguished: *Asterionella* (Si-demanding) and/or *Stephanodiscus minutulus* (requiring much P) reached a springtime maximum depending on the Si:P-ratio. The Si:P-ratio is determined by the circulation pattern (P-reflux from the hypolimnion) and the amount of precipitation (Si-input). Extended periods of deep circulation and/or low winter and spring precipitation provide high phosphorus concentrations and a low Si:P-ratio. Under opposite conditions, the phosphorus flux decreases and/or silicon concentrations increase so that a high Si:P-ratio results (Bradbury and Dieterich-Rurup 1993). Subsequent to the following clear water phase a *Cyclotella* bloom occurred. *Cyclotella* species tolerate low Si- and P-concentrations and typically occur during summer stratification because they are favoured by stable light and temperature conditions (Fahnenstiel and Glime 1983; Stoermer 1993). The autumnal diatom phase could not be identified in the thin section and is probably obscured by the detritus layer.

Limnological phase 7: A distinct change of the summer algae assemblages started ca. 8,400 cal. yr. BP with the proliferation of the coccal green algae *Botryococcus* and *Tetraedron minimum* (Fig. 11). Coccal Chlorophyceae prosper in small eutrophic lakes during periods of high insolation favouring stable summer stratification (Reynolds 1984). During long lasting periods of fine weather Raeder (1990) observed blooms of *Tetraedron*, *Coelastrum*, *Pediastrum* and other coccal green algae. This green-algae-phase lasted until 4,550 cal. yr. BP and is divided into 7 subphases.

The diatom assemblages of subphase 7a are still similar to those of limnological phase 6.

Subphase 7b: High relative abundances of *Asterionella* and only small amounts of *Stephanodiscus minutulus*, indicate little phosphorus reflux from the sediment due to incomplete circulation and/or increased

Si-supply, likely caused by more precipitation in springtime (Bradbury and Dieterich-Rurup 1993).

Subphase 7c: The prevalence of spring diatoms decreased (thin section no. 5). Other algae, not identifiable in the thin section, and Chrysophyceae dominated the spring-bloom. A major growth of diatoms (*Cyclotella comensis/pseudocomensis* or *C. ocellata*) occurred in summer only (Fig. 10).

Subphase 7d: The sediments deposited between 6,750 and 5,820 cal. yr. BP contain greater amounts of pollen of *Myriophyllum spicatum* and *Sparganium erectum*-type, both members of the emergent vegetation (Fig. 11). This might be due to erosion of littoral deposits following a lowering of the lake level. Increasing percentages of periphyton and tycho plankton and a small diatom influx reflect a reduced growth of the planktonic diatoms. Less precipitation and, hence, reduced Si-inflow into the lake probably prevented a distinct spring diatom-bloom.

Holomictic and meromictic phases continued to alternate until about 8,300 cal. yr. BP as shown by spotty distribution of dark sulphide in the sediment (limnological phases 5 and 6, Fig. 11). However, the meromictic phases became gradually longer, so that the oxygenation at the sediment/water interface was no longer sufficient for the formation of vivianite after 9,900 cal. yr. BP. While the phosphorus concentrations in the epilimnion were high during holomictic phases (meso- to eutrophic status), phosphorus reflux from the sediment and hypolimnion was hindered during meromixis causing reduced availability of phosphorus in the epilimnion (mesotrophic status). The obvious trend towards persistent meromixis and thus towards depletion in nutrients was enforced after 8,400 cal. yr. BP (limnological phase 7), when continuous warm weather caused longer lasting stagnation periods with blooms of coccal green algae and the accumulation of great quantities of organic substances in the hypolimnion (Sommer 1994, biogenic meromixis). The now black colour of the sediment (sulphides) is indicative of anoxic conditions. The lake did not return to oligomictic conditions until about 6,660 cal. yr. BP as indicated by the then increasing trophic state. At that time (subphase 7d) circulation was probably favoured by longer spring periods and/or shorter winters. Sulphide precipitation, however, continued, indicating lasting anoxic conditions in the hypolimnion, probably due to high production of organic material and high mineralization rates.

Younger Atlantic (pollen zone VII, 5,910–5,300 cal. yr. BP) and Older Subboreal (pollen zone VIIIa, 5,300–3,620 cal. yr. BP)

Deciduous forests thrived in the area around Lake Jues during the Younger Atlantic and the Older Subboreal (Fig. 9). Mistletoe and ivy were common at that time (Fig. 11). Although beech percentages increased during zone VIIIa, this species did not reach any importance in the forests for the next 1,700 years. Forest communities were more and more affected by human impact as shown in zones VII and VIIIa comprising Middle, Young and Late Neolithic (Voigt 2006; Fig. 9). Anthropogenic influence continued around Lake Jues until about 4,170 cal. yr. BP and probably slightly increased up to this time. Between 4,170 and 3,620 cal. yr. BP, i.e. by the end of zone VIIIa, human settlement ceased at Lake Jues.

Sedimentation of laminated diatom gyttja continued during the Younger Atlantic and the Older Subboreal. In zone VII plant macrofossils are extremely rare. After about 4,550 cal. yr. BP greater quantities of fine plant detritus and macrofossils were preserved.

During pollen zones VII and VIIIa Lake Jues experienced five different floristic and limnological phases (7e, f, g, 8 and 9):

Subphase 7e: A change of the aquatic vegetation of Lake Jues occurred about 200 years after the start of the Younger Atlantic, simultaneously with the expansion of alder (*Alnus glutinosa*, Fig. 11). Lower values of *Myriophyllum spicatum* and *Sparganium erectum*-type point to less erosion of littoral material and a rise of the lake level. Though low diatom influx rates and high periphyton values still reflect a weak plankton development, higher abundances of *Stephanodiscus minutulus* indicate a spring diatom bloom, probably followed by a bloom of *Cyclotella radiosa* (lower Si- and P-requirements). Mass development of green algae became rarer due to wetter summers. Increased precipitation led to elevated water levels and to the rise of groundwater which favoured the expansion of alder. Despite the climatic change, mixing and trophic state conditions remained unchanged as shown by the trophic status (meso- to eutrophic) and the continuously black sediment.

Subphase 7f: Higher diatom influx and lower periphyton and tycho plankton percentages reflect the increased prevalence of diatoms in the plankton

assemblages. Thin section no. 6 shows that varves became more complex. The early spring succession started with the dominance of *Cyclotella radiosa*, replaced by *Stephanodiscus minutulus* or *Asterionella formosa* depending on the Si:P-ratio. This might indicate low Si- and P-concentrations due to warm and dry conditions during early spring, followed by more humid and/or cooler weather conditions, resulting in increasing P- and/or Si-concentrations. Lower Si- and P-concentrations in summer favoured *Cyclotella comensis/pseudocomensis* and *C. radiosa*. Also green algae proliferated again in summer. In addition to *Botryococcus* and *Tetraedron minimum*, *Coelastrum reticulatum* was temporarily very abundant (5,250–5,000 cal. yr. BP), a species found today more frequently in the tropical rather than in the temperate zone (L. Krienitz, pers. communication). A weak diatom bloom of *Fragilaria crotonensis* and *F. ulna* var. *acus* followed in autumn.

The distinct blooms of green algae, especially the bloom of *Coelastrum reticulatum*, indicate long lasting dry and warm summer weather. This caused a lower water level between 5,150 and 4,770 cal. yr. BP, as reflected by higher pollen percentages of *Myriophyllum spicatum* and *Sparganium erectum*-type, and lower ones of *Alnus* (Fig. 11). During the *Coelastrum*-stage of this period, mesotrophic conditions point to meromixis. Subsequently increasing nutrient concentrations indicate a shift towards oligomixis. Consequently, the hypolimnion stayed anoxic.

Subphase 7g: The mass development of green algae even increased (up to 350% *Botryococcus* relative to the AP-sum) during the warm and sunny summers, and nutrient concentrations decreased temporarily due to meromixis. Although warm conditions continued to prevail, higher precipitation, presumably during winter and spring, supported the spread of *Alnus glutinosa*. Groundwater and lake level rose again, as shown by decreasing pollen percentages of the littoral species *Myriophyllum spicatum* and *Sparganium erectum*-type.

Limnological phase 8: *Asterionella* dominated during the spring bloom, reflecting a rise of the Si/P-ratio. Summer blooms of green algae became rarer because of cooler and/or wetter summers (Fig. 11). Temporarily eutrophic conditions point to more frequent holomictic phases due to longer transitional seasons. The eutrophic conditions and the concurrent high biomass production caused anoxia in the

hypolimnion and in the pore water and favoured the continuous formation of sulphides in the sediment. The decomposition of the litter slowed down, as indicated by more well-preserved allochthonous land plant remains. Subsequently, the supply of dissolved phosphorus decreased, and the lake became mesotrophic since about 4,300 cal. yr. BP. In summer *Cyclotella comensis/pseudocomensis* increased (Fig. 10), because of low P and Si concentrations. Reddish sediment colours between 4,300 and 4,230 cal. yr. BP prove temporary oxic conditions in the hypolimnion.

Limnological phase 9: Decreasing diatom influx values indicate a weaker primary production caused by the continuous nutrient depletion. Due to the weak production and/or due to relatively short periods of stable stratification, the hypolimnion again became oxic between 4,120 and 3,440 cal. yr. BP as shown by reddish colours of the sediment. The spring succession started now with the Si-preferring species *Fragilaria delicatissima* and/or *F. capucina* var. *gracilis*. *Fragilaria delicatissima* is a species adapted to low phosphorus concentration, scant light intensity and low temperatures (Hofmann 1994). In summer *Cyclotella comensis/pseudocomensis* still dominated the plankton, sometimes accompanied by *C. radiosa* or *C. ocellata*.

Younger Subboreal (pollen zone VIIIb, 3,620–2,960 cal. yr. BP) and Older Subatlantic (pollen zone IX, 2,960–1,160 cal. yr. BP)

With the start of the Younger Subboreal beech began to proliferate (Fig. 9). Until 2,960 cal. yr. BP beech had replaced the other deciduous tree species at most of the well-drained sites and dominated the forests (Beug 1992; Beug et al. 1999; Chen 1988). In the shady beech forests flowering *Hedera* became rare. *Viscum*, an indicator of warm summers, disappeared completely, despite the fact that its prominent host trees, *Populus*, *Salix*, *Tilia*, *Betula* and *Acer* (Oberdorfer 1994), were initially not much affected by the spreading of beech. Although the spread of beech was probably influenced by human activities, beech was certainly favoured by climatic factors such as more humid summers and fewer late frosts (Voigt 1996).

Settling around Lake Jues started anew during the Early Bronze Age after the interruption at the end of the Older Subboreal (Fig. 9). Human influence continued almost uninterrupted during the following two

millennia. Scanty in the beginning, it became more distinct after 3,310 cal. yr. BP, but decreased again after 2,245 cal. yr. BP (Voigt 2006).

There are seven limnological phases (10, 11, 12, 13a–d) reflecting climatic change as well as human impact:

Limnological phase 10: The plankton communities were dominated by nearly pure *Cyclotella* blooms (Fig. 10). Increasing abundances of *Cyclotella* spp. with lower Si-requirements even during springtime points to decreased Si concentrations and lower precipitation. Strongly reducing conditions in the hypolimnion are indicated by the black colour of the sediment. Slightly warmer summers allowed stratification to last longer so that oligo- or meromictic conditions returned. The nutrient concentrations remained unchanged at a low level until around 3,200 cal. yr. BP. For the first time since zone VIa Characeae (*Chara globularis* or *Ch. delicatula*) appeared again in the littoral (Fig. 11). According to Melzer (1999) both species do not occur in eutrophic waters. Slightly increased phosphorus concentrations, presumably linked to Younger Bronze Age settlement activities, caused a decline of the Characeae, ending with their absence after 3,115 cal. yr. BP.

Limnological phase 11: An increase of total precipitation, starting at the end of the Younger Bronze Age settlement, is indicated by higher abundances of Si-demanding diatoms such as *Asterionella formosa*, *Fragilaria delicatissima* and *F. capucina* var. *gracilis* while *Cyclotella* species, characteristic of the previous assemblages, decreased probably due to unfavourable weather.

Due to more frequent deep mixing, dissolved nutrients, which had accumulated during the preceding period, were re-suspended into the epilimnion leading to a temporary rise in the trophic state. Concurrent with the higher organic production, the sediment-water-interface continued to be anoxic (black sediment) during this period. Subsequently, unfavourable climate and declining human impact at the transition from Bronze to Iron Age led to lower nutrient concentrations (Figs. 9, 11).

Limnological phase 12: From 2,700 cal. yr. BP a settlement phase began at Lake Jues, which lasted 440 years (Voigt 2006). Although until 2,500 cal. yr. BP land use was as weak as during the preceding Bronze Age settlement phase, the beginning of the

new phase coincides with eutrophication, probably caused by human activities. This assumption is supported by the temporary abundance of the pollution-tolerant *Nitzschia paleacea* between 2,700 and 2,600 cal. yr. BP (Fig. 10).

During the Iron Age a settlement probably existed in immediate vicinity of the lake. Clearings, arable farming and meadow culture led to destabilization of soils and, hence, to erosion. A 2 cm thick clay layer deposited around 2,500 cal. yr. BP reflects considerable disturbances along the shore of Lake Jues. Numerous thinner clay layers prove intensified erosive processes. Probably due to construction work on the shore of Lake Jues, the circulation pattern changed to annual holomixis which the lake retained until medieval times as indicated by the greenish colour of the sediment. Phosphorus-reflux from the sediment and anthropogenic supply of phosphorus and nitrogen caused eutrophication of the lake and an increase of primary production. The high organic production and/or lasting phases of stable summer stratification resulted in high oxygen-consumption in the hypolimnion and the reduction of Fe-oxides, but not in the reduction of sulphate. For this period it is not possible to differentiate clearly between anthropogenic influence and climate signals. The plankton assemblages reflect the strong human impact of the Iron-Age-settlement. Eutrophication favoured *Stephanodiscus minutulus* (requiring low Si:P-ratios) in spring and *Pediastrum boryanum* blooms in summer (Fig. 10). Nitrogen supply and/or organic pollution likely favoured *Nitzschia paleacea*. Although *Cyclotella comensis/pseudocomensis* does not tolerate eutrophication (Hofmann and Schaumburg 2005e, f), this species also reached high abundances, perhaps following the P-consuming blooms of *Stephanodiscus minutulus* or *Pediastrum boryanum*. *Cyclotella comensis/pseudocomensis* probably also responded to nitrogen supply. According to Wolin et al. (1988) *C. comensis* prefers somewhat higher nitrate-concentrations. Chrysophyceae, which had always been part of the algal associations until this time, became insignificant now due to eutrophication (Kristiansen 2005).

Limnological phase 13: Settlement at Lake Jues declined since 2,245 cal. yr. BP (Fig. 9). The forests regenerated, but were still used as coppiced woods (spread of *Carpinus*) and as forest pasture. During the Migration Period and the Early Middle Ages the area

around the lake was almost deserted. High abundances of Si-preferring diatoms (*Fragilaria capucina* var. *gracilis*, *Asterionella formosa*, and/or *Fragilaria crotonensis*) indicate increased Si-input caused by wetter conditions between 2,280 and 2050 (subphase 13a) and between 1,800 and 1,500 cal. yr. BP (subphase 13c). At least from 1,600 to 1,500 cal. yr. BP (the period which comprises thin section no. 7) the spring diatom layer was followed by a layer rich in humus, probably caused by heavy precipitation in late spring or early summer (during the beech bloom), and a summer/fall layer mainly with *Cyclotella ocellata*. Nutrient concentrations were no longer sufficient for *Pediastrum boryanum* to grow. In between these two wetter phases a period with probably warmer and dryer summers is indicated by high percentages of *Cyclotella* spp. (subphase 13b). From 1,500 cal. yr. BP decreasing percentages of Si-preferring diatoms reflect lower precipitation (subphase 13d).

Coinciding with the abandonment of cultivation, stable summer stratification occurred only rarely until 2,100 cal. yr. BP as shown by reddish sediment colours (subphase 13a). With a few exceptions the nutrient concentrations remained high (meso- to eutrophic), which might be the result of holomixis as well as of continued soil erosion reinforced by a wetter climate and by forest use. Following strong eutrophication the recovery of a lake from high phosphorus loads can take a long time (Hausmann et al. 2001). In the Swiss Seeburgsee oligotrophication could not take place before temperatures increased at the end of the Little Ice Age and triggered the onset of meromixis (Hausmann et al. 2001). However, the diatom-inferred eutrophy of Lake Jues around 1,480 cal. yr. BP is questionable, because in this case the trophic state index is mainly based on *Nitzschia paleacea* with a frequency of 6%, while trophic-tolerant species dominated the assemblage with 89%. In contrast, the eutrophication after 1300 cal. yr. BP (=AD 650), indicated by *Nitzschia paleacea* and *Stephanodiscus minutulus* with values >30%, may already have been caused by early medieval settlement which shows up in the pollen spectra since 1,240 cal. yr. BP. Thus this last phase is transitional to the medieval expansion of settlement during the Younger Subatlantic. Subsequently the limnological status of the lake was strongly influenced and changed by human activities.

Climatic reconstruction

The sediments of the Younger Dryas in Lake Jues were deposited under cold, arctic conditions. Diatom and pollen records provide evidence of long, cold winters that alternated with short, cool summers (limnological phases 1 and 2). Decreasing deposition of terrigenous material indicates a gradual warming which accelerated at the beginning of the Preboreal. The Preboreal temperature increase appears not as abrupt in the record of Lake Jues as it is documented in other archives (Dansgaard et al. 1989; von Grafenstein et al. 1999). Compared with the Younger Dryas, summers lasted longer in Preboreal times, but were still relatively cool. Summers did not become warmer before 11,200 cal. yr. BP (limnological phase 3). Winters continued to be cold resulting in a long-lasting ice-cover on the lake. A cooler phase lasting from 11,360 to 11,090 cal. yr. BP as suggested by Behre (1978) and Zolitschka (1998) cannot be proven in Lake Jues, due to minor sediment disturbances and insufficient temporal resolution in this part of the diatom and pollen diagrams.

The progressive warming in the late Preboreal continued during the first 150 years of the Boreal. A cooling phase (limnological phase 4) apparently started around 10,620 cal. yr. BP, culminating between ca. 10,550 and 10,230 cal. yr. BP (Fig. 12). Summers were cooler again, and long, snow-rich winters caused frequent flooding during the spring melt of snow. A cooler phase during this period is also detected in Switzerland and France (Haas et al. 1998; Lotter et al. 1992; Magny 2004) and at other places in Germany (Zolitschka 1998). The melting of the Scandinavian glaciers is assumed to have triggered the cooling process by suppression of the North Atlantic current (Björck et al. 2001, Zolitschka 1998).

Since 10,100 cal. yr. BP temperatures rose gradually while floods occurred as frequently as before, but were now caused by heavy rainfall during summer (limnological phases 5 and 6). Since 8,820 cal. yr. BP rainfall was more uniformly distributed throughout the year. Although there is no evidence for less total precipitation, this cannot be excluded. According to Kalis et al. (2003) the Boreal was a period with higher precipitation, followed by dryer conditions during the Older Atlantic. However, the start of a dryer Atlantic period is not consistently dated in German archives (Kalis et al. 2003). High

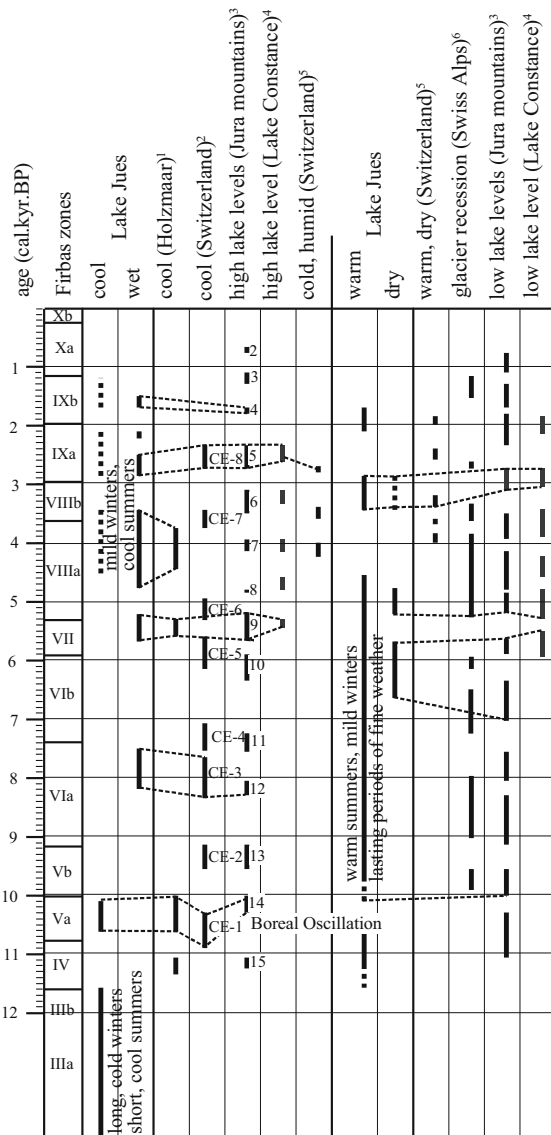


Fig. 12 Climatic changes at Lake Jues and other European sites. Coinciding changes are marked by dashed lines. ¹ Zolitschka 1998, Zolitschka and Nengendank 1997; ² Haas et al. 1998; ³ Magny 2004; ⁴ Schlichtherle et al. 2000; ⁵ Tinner et al. 2003; ⁶ Hormes et al. 2001. Episodes with high lake levels in the French and Swiss Jura mountains are numbered according to Magny (2004). Cold phases recorded from Switzerland are numbered according to Haas et al. (1998)

lake levels occurred at Hämelsee (Fig. 1) until 8,800 cal. yr. BP, only interrupted by a short phase with a low lake level between 9,340 and 9,250 y cal. BP (Kleinmann et al. 2000 b).

Warm summers (since 9,700 cal. yr. BP) and mild winters (since 9,500 cal. yr. BP) characterize the

following millennia. Long periods of fine summer weather were typical of the time between 8,400 and 4,550 cal. yr. BP (limnological phase 7). Stable warm and dry conditions between 8,000 and 4,000 cal. yr. BP were also proven for northern Europe (Eronen et al. 1999). The global cooling event around 8,200 cal. yr. BP (Alley et al. 1997; Haas et al. 1998; Magny 2004; von Grafenstein et al. 1998) is not detectable in the Lake Jues record. However, an increase of precipitation probably occurred between 8,200 and 7,500 cal. yr. BP (Fig. 12, limnological subphase 7b). For the same time a more humid phase is described from Swiss sites (CE-3, Haas et al. 1998) and from southern Sweden (around 8,200 cal. yr. BP; Hammarlund et al. 2005).

Between 6,750 and 5,700 cal. yr. BP warm summers and probably decreased precipitation caused a lowering of the water level (limnological subphase 7d). Lower levels of Hämelsee occurred between 7,000 and 6,750 cal. yr. BP and between 6,200 and 5,950 cal. yr. BP (Kleinmann et al. 2000 b). Very low lake levels were stated between ca. 7,000 and 5,650 cal. yr. BP at sites in the French and Swiss Jura Mountains, interrupted, however, by high water levels between 6,350 and 5,900 cal. yr. BP (Magny 2004, Fig. 12). In comparison, the recession phases of Alpine glaciers (Hormes et al. 2001) do not coincide exactly with this warm period (Fig. 12). A wetter phase around 6,000 cal. yr. BP could not be found in Lake Jues, while in the Upper Harz Mountains a cooler phase is indicated by increased peat growth between 6,460 and 5,810 cal. yr. BP (Beug et al. 1999). From the Alps (CE-5; Haas et al. 1998) and from northern Europe (Berglund 2001) a cool phase is known around 5,900 cal. yr. BP.

In the Lake Jues record a more humid phase is shown for the time between 5,700 and 5,250 cal. yr. BP only (limnological subphase 7e). This period lies between the two cool and humid phases CE-5 and CE-6 as known from the Alps (Haas et al. 1998). However, it begins almost simultaneously with a dendrochronologically well dated high water level in the Jura Mountains (episode 9, Magny 2004). For Lake Constance, too, a high water level is inferred around 5,400 cal. yr. BP (Schlichtherle et al. 2000). Zolitschka (1998) assumes a wetter and/or cooler phase between 5,600 and 5,300 cal. yr. BP. According to Berglund (2001) wet/cool conditions occurred around 5,500 cal. yr. BP in northern Europe.

Since 5,250 cal. yr. BP and until 4,770 cal. yr. BP summers became dryer and very warm again, causing another drop of the level in Lake Jues (limnological subphase 7f). The beginning of this warmer period coincides with the start of a period of low lake levels at Lake Constance (Schlichtherle et al. 2000) and in the Jura Mountains (Magny 2004), with the beginning of a recession phase of Alpine glaciers (Hormes et al. 2001), but also with a cool and humid phase in the Alps (CE-6; Haas et al. 1998, Fig. 12). During the following 200 years, until 4,550 cal. yr. BP, summers continued to be warm, but the climate became more humid causing a rise of the lake level (limnological subphase 7g).

Starting 4,550 cal. yr. BP lower summer temperatures, more precipitation, and less frequent late frost reflect the gradual change from a continental to a more oceanic climate (limnological phase 8 and 9). A rather wet/cool phase is reported for northern Europe around 4,500 cal. yr. BP by Berglund (2001), which coincides with a maximum of ice rafting debris (IRD event; Bond et al. 2001). According to Berglund (2001), a change from more continental to oceanic conditions began around 3,800 cal. yr. BP. At Lake Holzmaar the time between 4,450 and 3,750 cal. yr. BP was characterized by increased precipitation and/or lower temperatures (Zolitschka and Negendank 1997). In Switzerland a short cold-humid phase is reported for the period between 4,250 and 4,050 cal. yr. BP (Tinner et al. 2003). However, the time between ca. 5,000 and 3,800 cal. yr. BP is usually considered as a warm period. This is indicated, for example, by low lake levels in the Alps (Haas et al. 1998; Voigt 1996), in the Jura Mountains (Magny 2004) and in southern Sweden (Digerfeldt 1998), and by retreating glaciers in the Alps (Hormes et al. 2001; Röthlisberger 1986). Only after 3,800 cal. yr. BP (Haas et al. 1998), after 3,500 cal. yr. BP (Magny 2004; Voigt 1996), or after 3,200 cal. yr. BP (Digerfeldt 1998), respectively, the climate became cooler and/or wetter.

The trend towards a cooler and wetter, more oceanic climate continued during the Younger Subboreal (zone VIIIb) and the Older Subatlantic (zone IX), however, interrupted by dryer and warmer phases, which correspond with increased settlement intensity (Voigt 2006). A warmer and less humid period occurred between 3,450 and 2,850 cal. yr. BP (limnological phase 10). Warmer phases around 3,000 cal. yr. BP recorded from Austria (Schmidt

et al. 2007), Switzerland (Haas et al. 1998; Tinner et al. 2003) and from the Jura Mountains (Magny 2004) are in phase with these results. According to Maise (1998) there were two warm phases lasting from 3,600 to 3,400 cal. yr. BP and approximately between 3,300 and 2,800 cal. yr. BP in Central Europe.

An increase of total precipitation is indicated for the time between 2,850 and 2,650 cal. yr. BP (limnological phase 11), the transition period from the Bronze Age to the Iron Age. This wet phase corresponds well with high lake levels in the Jura Mountains (episode 5, Magny 2004) and at Lake Constance (Schlichtherle et al. 2000). Schmidt et al. (2007) assume cooler and more humid winters in the southern Austrian Alps between 2,650 and 2,350 cal. yr. BP. The century 2,800 to 2,700 cal. yr. BP is generally described as a cool phase with major consequences on the settlement structure of Central Europe (Berglund 2001; Haas et al. 1998; Kilian et al. 1995; Maise 1998; Tinner et al. 2003; van Geel et al. 1996, 1999, 2004; van Geel and Berglund 2000; Zolitschka 1998; Zolitschka et al. 2003).

During the following period (2,500–2,280 cal. yr. BP, limnological phase 12) climate signals are obscured by strong human impact. However, the extension of settlement at Lake Jues during this period was probably favoured by a warmer climate (Voigt 2006).

Changeable summers and higher precipitation are indicated by the Lake Jues record between 2,280 and 2,100 cal. yr. BP (limnological subphase 13a). According to Maise (1998) a cooler phase similar to that around 2,800 cal. yr. BP started around 2,350 cal. yr. BP. Röthlisberger (1986) described glacier advances in the Alps for this period. Tinner et al. (2003) suggest a cool, humid phase around 2,150 cal. yr. BP.

According to the sediment record of Lake Jues summers became warmer again since 2,100 cal. yr. BP. Another humid phase occurred between 1,700 and 1,500 cal. yr. BP and probably coincides with the climatic deterioration of the Migration Period (Berglund 2001; Tinner et al. 2003; Zolitschka et al. 2003). According to Magny (2004) a short phase with high lake levels occurred between 1,800 and 1,700 cal. yr. BP (episode 4). With the beginning of the Middle Ages human and climate signals cannot be separated any longer.

Conclusions

Fossil diatom assemblages can be used, as indicators of trophic status and circulation patterns of lakes. More detailed information can be gained from the study of the annual diatom succession as preserved in laminated sediments and visible in thin sections. The value of fossil diatom assemblages for reconstructions increases when combined with other proxies, e.g. pollen, other algae, sediment characteristics and ^{14}C dates.

The Lake Jues ecosystem, as well as the surrounding land vegetation, were strongly affected by climate variability, and thus enabled us to reconstruct the Holocene climate. Our results are in good agreement with those recorded from other European regions, although discrepancies exist concerning the timing of events. Events with age discrepancies within the 2σ range of our radiocarbon dates are considered contemporaneous. Larger differences exist between 4,500 and 3,500 cal. yr. BP, when low lake levels in Austria, Switzerland and France coincide with rather cool and humid conditions further north. Further detailed investigations of the sediments of Lake Jues, but also at other German sites will be necessary to resolve the underlying reasons.

According to the Lake Jues record, the Holocene is subdivided into two main climatic periods:

1. The early and middle Holocene (until about 4,550 cal. yr. BP) with a still more continental climate. This part of the Holocene is further subdivided into four periods, the warming of the Preboreal, the Boreal between 10,620 and 10,100 cal. yr. BP with a subarctic climate, the late Boreal and the early Atlantic with a warmer climate and frequent flooding events (oceanic), and the Atlantic between 8,800 and 4,550 cal. yr. BP with very warm and temporarily dry summers and mild winters (tentatively Mediterranean).
2. The late Holocene between 4,550 and 1,240 cal. yr. BP with a gradual change to a more oceanic climate with cooler and more variable summers, higher precipitation and fewer late frosts, including several phases of warmer and dryer weather.

The study of Lake Jues provided a well dated, continuous and highly sensitive environmental and climatic reconstruction of the Holocene for the

mid-latitudes in Central Europe and should serve as an important link between the better investigated neighbouring regions.

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