ELSEVIER
Palaeogeography, Palaeoclimatology, Palaeoecology 159 (2000) 203–214
PALAEO
www.elsevier.nl/locate/palaeo

Oxygen isotopes of lake marl at Gerzensee and Leysin (Switzerland), covering the Younger Dryas and two minor oscillations, and their correlation to the GRIP ice core

Jakob Schwander [a,*], Ueli Eicher [a], Brigitta Ammann [b]

[a] *University of Bern, Physics Institute, Sidlerstrasse 5, CH-3012 Bern, Switzerland*
[b] *University of Bern, Geobotanical Institute, Altenbergrain 21, CH-3013 Bern, Switzerland*

Abstract

The ratio of oxygen isotopes is a temperature proxy both in precipitation and in the calcite of lacustrine sediments. The very similar oxygen-isotope records from Greenland ice cores and European lake sediments during the Last Glacial Termination suggest that the drastic climatic changes occurred quasi-simultaneously on an extra-regional, probably hemispheric scale. In order to study temporal relations of the different parameters recorded in lake sediments, for example biotic response times to rapid climatic changes, a precise chronology is required. In unlaminated lake sediments there is not yet available a method to provide a high-resolution chronology, especially for periods with radiocarbon plateaux. Alternatively, an indirect time scale can be constructed by linking the lake stratigraphy with other well-dated climate records. New oxygen-isotope records from Gerzensee and Leysin, with an estimated sampling resolution of between 15 and 40 years, match the Greenlandic isotope record in many details. Under the assumption that the main variations in temperature and thus in oxygen isotopes occurred about simultaneously in Greenland and Switzerland, we have assigned a time scale to the lake sediments of Gerzensee and Leysin by wiggle-matching their stable-isotope records with those of Greenland ice cores, which are among the best dated climatic archives. We estimate a precision of 20 to 100 years during the Last Glacial Termination. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: chronology; climate change; ice core; lake sediment; oxygen isotopes; Younger Dryas

---

1. Introduction

The Last Glacial Termination was characterised by a series of rapid climatic oscillations that are manifested in many terrestrial, glacial, and marine proxy records, especially around the North Atlantic region. The sites of Gerzensee and Leysin were among the first studied for stable-isotope ratios in fresh-water marls, and they showed a characteristic Late Glacial and Early Holocene sequence that correlated with vegetational changes, implying shifts in temperature (Eicher and Siegenthaler, 1976). During the Oldest Dryas regional pollen zone after the ice retreat, very strongly negative values indicate cool temperatures. Around 12,700 radiocarbon years B.P. a very rapid positive shift in the $^{18}O/^{16}O$ ratio of about 2.5–4‰ occurred at the beginning of the Bølling (BØ) regional pollen zone, characterised by reforestation of the Swiss lowlands, pointing to

---

* Corresponding author. Fax: +41-31-631-87-42.

E-mail addresses: schwander@climate.unibe.ch (J. Schwander), ammann@sgi.unibe.ch (B. Ammann)

PII: S0031-0182(00)00085-7

a rapid climatic warming. After a rather stable period [during the pollen zones of BØ, Older Dryas, and Allerød (AL)], an interval with stronger negative values coincides with the Younger Dryas (YD) pollen zone, the end of which is marked by a sharp rise towards less negative values. This general picture is now found at many sites in Europe (Ahlberg et al., 1996; Eicher, 1987, 1995; Schwalb et al., 1994; von Grafenstein et al., 1994) and has been correlated with the oxygen-isotope record of the Dye 3 ice core (Oeschger et al., 1984; Siegenthaler et al., 1984).

Superimposed on this very distinct pattern of three major shifts are minor oscillations, termed Aegelsee, Gerzensee, and Preboreal (PB) (Eicher and Siegenthaler, 1976; Lotter et al., 1992). The Gerzensee oscillation was recognised in lake sediments of Europe (Eicher, 1979, 1980, 1994; Goslar et al., 1995; Lotter et al., 1992) as well as in the GRIP (Greenland Ice Core Project) ice core (Björck et al., 1996, 1998; Johnsen et al., 1995). In the following, where applicable, we will indicate in parentheses the names according to the event stratigraphy for the Last Termination in the North Atlantic region (based on the GRIP ice-core isotope record) as proposed by the INTIMATE group (INTegration of Ice-core, MArine and TErrestrial records is a core programme of the INQUA Commission) (Björck et al., 1998). In this nomenclature the oscillation in the GRIP isotope record that most likely corresponds to the Gerzensee oscillation is termed Greenland Interstadial 1b (GI-1b). In maritime Canada it is indicated by pollen and chironomid analysis and is termed the Killarney oscillation (Levesque et al., 1994, 1997, 1993a,b; Mayle and Cwynar, 1995). In Greenland it is estimated to have started about 500 years before the onset of the YD (Greenland Stadial 1 or GS-1) and to have lasted about 400 years (see Fig. 4). Minor negative oscillations before and after the YD were recently also found in Ontario (Yu and Eicher, 1998).

The PB oscillation, sometimes called 'Youngest Dryas', has long been recognised in European pollen records (Behre, 1978; Björck et al., 1997; Goslar et al., 1995; Schneider and Tobolski, 1985) and seems to occur also in parts of North America (Yu et al., 1997). The GRIP ice core shows low values of δ^{18}O [expressed as the per mille deviations δ^{18}O relative to standard mean ocean water (SMOW)] and methane and high values of Ca (Blunier et al., 1995; Chappellaz et al., 1993; Fuhrer et al., 1993; Johnsen et al., 1995), indicating cooler and drier conditions.

The relation between climate and stable-isotope records from ice cores is rather direct. δ^{18}O in ice cores from dry accumulation areas reflects directly the isotopic ratio of the local precipitation, except for relatively minor post-depositional modifications from sublimation and drifting snow. The difference between the δ^{18}O of precipitation and the sea-surface water of the vapour source area is primarily a function of the condensation temperature of the precipitation. The relation between the mean annual temperature at the precipitation site and the mean δ^{18}O is thus also affected by the δ^{18}O of the vapour source, the seasonal distribution of the precipitation, and the size of the inversion layer. Although these parameters, and thus the δ^{18}O/temperature sensitivity, were generally not constant in the past (Johnsen et al., 1995), δ^{18}O is predominantly affected by the condensation temperature, which is closely related to the surface temperature.

δ^{18}O in biogenically precipitated carbonates [δ ^{18}O relative to the Peedee Belemnite standard (PDB)] such as lake marl is less directly related to temperature. Besides the temperature of precipitation in the catchment area (Siegenthaler and Eicher, 1986; Siegenthaler et al., 1984), it is mainly affected by the moisture source (McKenzie and Hollander, 1993), the water balance of the lake (Schwalb et al., 1995), and the lake temperature. δ^{18}O of precipitation is modified by evaporation in the catchment area and from the lake surface, as well as fractionation during the carbonate formation. However, the different fractionation steps of δ^{18}O still depend primarily on the local temperature. While a quantitative interpretation is rather complex (Siegenthaler and Eicher, 1986), the temperature tends to be positively correlated with δ^{18} O of carbonate sediments in lakes.

Nevertheless, δ^{18}O in Greenland precipitation as well as in lake sediments seems to respond to changes in local temperature without delay

(Ammann, 1989; Wright, 1984). The very similar pattern of the isotopic signal at both locations suggests that corresponding variations are caused by the same climatic event (Björck et al., 1998).

The radiocarbon dates support the assumption that the isotopic signal registers climatic change without time lag. We can thus assume that the three major shifts, namely the beginning of the BØ (GI-1e) and the beginning and end of the YD (GS-1), represent nearly synchronous events of hemispheric or even global extent (Björck et al., 1996; Broecker, 1992; Hughen et al., 1998; Peteet, 1992, 1993, 1995; Siegenthaler and Eicher, 1986; Thompson et al., 1998; Walker et al., 1991; Wright, 1989). The underlying mechanism of these fast climatic variations is probably a change in the thermohaline circulation (Stocker and Wright, 1996). Björck et al. (1996) suggest a weakening of the thermohaline circulation also for the two minor oscillations. A change in ocean circulation most likely affects the climate of large areas quasi-simultaneously. But we must still be aware that the reactions to general climatic changes could be time-transgressive, e.g. by a gradual change in the position of the polar front, and that therefore events recorded in Swiss lakes and Greenland may not have happened exactly simultaneously, although they were causally linked. However, if significant time lags had occurred the signal would probably have been attenuated.

We thus attempt to construct a common time scale for the Greenland ice-core records and Swiss lake-sediment records by matching the isotopic records. The goal of the present study is threefold. First, to produce the high-resolution records of oxygen isotopes at Gerzensee and Leysin, necessary to provide a baseline of rapid climatic changes for the coordinated project (Ammann, 2000), the aim of which is to assess the biotic responses of vegetation and both terrestrial and aquatic invertebrates to rapid climatic changes. Second, the correlation of these high-resolution oxygen-isotope records with those of the GRIP ice core provides a time scale for the period in which a plateau of constant radiocarbon ages prevents direct dating. Third, this high-resolution record provides the basis for the time scale of lower-resolution oxygen-isotope analyses of the six parallel cores of lake marl from Gerzensee that were necessary to combine large enough samples for plant macrofossils (Tobolski and Ammann, 2000) and Coleoptera (Lemdahl, 2000).

2. Materials and methods

2.1. The stable-isotope measurements

Sampling resolution of the lake-marl cores was between 0.5 and 1.0 cm. Gerzensee samples from 169 to 201 cm are from the core GEA, and those from 203 to 300 cm from core GEB. Leysin samples from 304 to 350 cm are from core LEB, and those from 352 to 388 cm from core LEA. Both records were thus compiled from two different cores with staggered core segments, drilled close to each other in order to avoid the tops of segments, which are subject to contamination during the drilling process with the Streif piston corer. Core sections were matched by their isotopic records. Treatments and measurements were performed as described by Siegenthaler and Eicher (1986).

2.2. Age scale based on the correlation of $\delta^{18}O$ records (Gerzensee–GRIP–Leysin)

For the investigation of the temporal and geographical evolution of climatic variations and their interactions with the land biosphere based on proxy data from natural archives, these should ideally be absolutely dated with a precision of one year, or at least a precise common relative age scale should exist for the period of interest. Neither exists yet, because even annually layered archives appear to have missing layers or layers that cannot be identified unambiguously as clear annual deposits. Dating with radioisotopes is not precise enough for the investigation of climatic variations on an annual or decadal scale. In addition, radiocarbon records show plateaux of constant ^{14}C, preventing the assignment of calendar ages within these layers.

The alternative to an absolute dating of each archive is their matching by time horizons. Such horizons are, for example, created by the deposition of tephra layers after large volcanic eruptions.

Distinct 'horizons' are also defined by abrupt climatic changes of hemispheric extent that are believed to have occurred quasi-simultaneously in the investigated areas. A near-simultaneous occurrence is suggested for the fast variations during and at the end of the Glacial Age by the very similar shape of the climatic signals recorded in various distant archives (Hughen et al., 1996; Siegenthaler et al., 1984). This similarity is used here to establish a time scale for the Gerzensee and Leysin sediments, with the preliminary GRIP time scale as a basis (Johnsen et al., 1992). We recognise that this matching yields an accuracy that is limited by possible time lags between corresponding climate events in Greenland and Central Europe, and that any information on such lags is therefore lost a priori. However, this method provides the densest set of 'time horizons', and the Greenland ice cores are among the best absolutely dated archives. This method therefore yields probably the most reliable time scale presently available for these lake sediments.

We have adjusted the $\delta^{18}O$ record from Gerzensee and Leysin to overlie the $\delta^{18}O$ record of GRIP. In order to perform the matching as objectively as possible, we have used a Monte Carlo method (Schwander et al., 1997). We have removed most of the 'local noise' by slightly smoothing the records before the matching. By 'local noise' we mean the part of the signal that seems to be independent of a regional climate signal. 'Local noise' levels were estimated by comparing the GRIP and GISP2 parallel cores (GISP2: Greenland Ice Sheet Project 2) and separately five Gerzensee cores. The correlation was performed in a two-pass procedure. In the first pass, a coarse match was calculated by maximising the overall correlation coefficient between the smoothed records. In the second pass, the records were locally matched with a windowing technique. Random noise of natural stochastic variations was added to the isotope records in order to assess the range of solutions.

We start with the preliminary time scale for the lake records as obtained from the first pass. We consider time windows with n $\delta^{18}O$ values of the lake record and search for the best correlations of this subrecord with the corresponding part of the GRIP $\delta^{18}O$ record ($n=20$ for this study). The maximum correlation is searched by varying each of the n age values randomly and within meaningful limits. The matching procedure is started with the subrecord window placed at one end of the lake record. After the age values yielding the best correlation are saved, the window is shifted by one data point, and the random variations are repeated with the first age point fixed at the value of the best correlation from the previous window position. The window is shifted until it reaches the other end of the record. Ages of the new time scale are then computed by averaging the values from the best correlations of each window position. Age values were only considered significant if the local correlation between lake records and GRIP was above a certain threshold value, and if the subrecord contained a distinct structure.

The inferred sedimentation rate in the two lakes showed some sharp spikes. This is a result from averaging a set of Monte Carlo runs and has no climatic explanation. Therefore we have slightly smoothed the sedimentation record to remove the spikes and have calculated the definitive chronology (Tables 1 and 2) from this smoothed sedimentation record. In the vicinity of the Laachersee tephra layer (LST) the matching was tuned in order to obtain the same age for Gerzensee and Leysin (independent matching of the two cores resulted in a difference of 69 years for the LST level).

How well features in the two records can be linked depends strongly on their uniqueness and distinctness. Very distinct features like the beginning and end of YD (GS-1) can be matched as closely as the sample resolution. Matching of less distinct features is more subject to fortuitous coincidence, and the confidence level is accordingly lower, as in the middle of YD.

3. Oxygen-isotope records of lake marl and the GRIP chronology

3.1. The high-resolution record of oxygen isotopes at Gerzensee and Leysin

Fig. 1 shows the high-resolution record of $\delta^{18}O$ at Gerzensee covering the period from late AL

Table 1
GRIP scale ages for Gerzensee sediment records obtained by wiggle-matching of stable-isotope records. Ages are calendar years before 1950 A.D. NV: no value obtained from matching procedure

Depth (cm)	Age	Depth (cm)	Age	Depth (cm)	Age	Depth (cm)	Age
169	NV	195	11,501	235	12,305	273	12,855
170	NV	195.5	11,508	237	12,331	274	12,875
171	11,154	196	11,516	241	12,379	275	12,896
172	11,165	196.5	11,526	243	12,406	276	12,919
173	11,176	197	11,536	245	12,438	277	12,949
174	11,187	197.5	11,546	247	12,473	278	12,982
175	11,199	198	11,557	249	12,503	279	13,016
176	11,214	198.5	11,567	250	12,517	280	13,051
177	11,228	199	11,578	251	12,532	281	13,081
178	11,240	199.5	11,588	252	12,545	282	13,106
179	11,251	200	11,597	253	12,557	283	13,126
180	11,264	200.5	11,605	254	12,568	284	13,145
181	11,278	201	11,613	255	12,581	285	13,163
182	11,292	203	11,647	256	12,598	286	13,181
183	11,307	205	11,687	257	12,616	287	13,199
184	11,326	207	11,732	258	12,633	288	13,217
185	11,346	209	11,777	259	12,650	289	13,231
186	11,362	211	11,823	260	12,666	290	13,244
187	11,376	213	11,869	261	12,681	291	13,255
188	11,391	215	11,912	262	12,694	292	13,268
189	11,407			263	12,708	293	13,305
190	11,422	217	11,953	264	12,720	294	13,365
191	11,437	219	11,995	265	12,730	295	13,405
191.5	11,445	221	12,037	266	12,740	296	13,424
192	11,455	223	12,075	267	12,752	297	13,438
192.5	11,465	225	12,110	268	12,769	298	NV
193	11,473	227	12,151	269	12,787	299	NV
193.5	11,480	229	12,193	270	12,805	300	NV
194	11,487	231	12,235	271	12,823		
194.5	11,494	233	12,273	272	12,836		

(LST at 272 cm) to the PB. Fig. 2 presents the results from Leysin.

Both the major shifts at the onset and at the end of the YD (GS-1) as well as the two minor oscillations, Gerzensee–Killarney (GI-1b) and the PB oscillation, are visible. The differences between the two sites may have several causes: (1) differences may exist in $\delta^{18}O$ of precipitation and/or modification after precipitation; (2) the usual 1 cm sample contains roughly sediment of 10 to 50 years, so we measure different groups of years in different cores, and this may produce differences especially during periods of rapid change; (3) errors of measurement, which are about 0.05‰; (4) various amounts of erosional input of carbonates from the catchment may exist. For two reasons we can consider detrital input as unimportant: the loss-on-ignition curve at Leysin is very stable, and the curves of stable isotopes measured on *Pseudocandona marchica* and *Pisidium* ssp. at Gerzensee (von Grafenstein et al., 2000) resemble the values measured on bulk sediment. But a method to separate biogenically precipitated from detrital carbonates would be useful.

At Gerzensee the shifts at both ends of the YD are about 3‰, and at Leysin about 2.5‰. The two minor oscillations at both sites have an amplitude of about 1 to 1.5‰.

In order to define the beginning and end of each climatic period, we should use an objective, reproducible method. We applied the same mathematical method to Gerzensee, Leysin, and GRIP.

Table 2
GRIP scale ages for Leysin sediment records obtained by wiggle-matching of stable-isotope records. Ages are calendar years before 1950 A.D. NV: no value obtained from matching procedure

Depth (cm)	Age	Depth (cm)	Age	Depth (cm)	Age	Depth (cm)	Age
304	NV	330	11,244	344.5	11,849	364.5	12,684
306	NV	330.5	11,260	345	11,871	365	12,699
308	NV	331	11,276	345.5	11,892	366	12,733
310	10,542	331.5	11,291	346	11,911	367	12,766
312	10,612	332	11,304	346.5	11,931	368	12,798
314	10,667	333	11,327	347	11,952	369	12,836
316	10,734	333.5	11,341	347.5	11,972	370	12,869
318	10,811	334	11,356	348	11,989	371	12,898
320	10,881	334.5	11,371	348.5	12,003	372	12,932
320.5	10,901	335	11,386	349	12,021	373	12,975
321	10,926	335.5	11,404	349.5	12,040	374	13,020
321.5	10,948	336	11,421	350	12,063	375	13,061
322	10,967	336.5	11,437	352	12,166	376	13,100
322.5	10,987	337	11,456	354	12,278	377	13,136
323	11,011	337.5	11,478	356	12,374	378	13,173
323.5	11,033	338	11,503	358	12,456	379	13,218
324	11,050	338.5	11,533	358.5	12,477	380	13,267
324.5	11,068	339	11,567	359	12,497	381	13,312
325	11,089	339.5	11,602	359.5	12,512	382	13,346
325.5	11,110	340	11,634	360	12,532	383	13,383
326	11,128	340.5	11,659	360.5	12,552	384	13,428
326.5	11,144	341	11,681	361	12,566	385	13,469
327	11,161	341.5	11,706	361.5	12,578	386	13,508
327.5	11,176	342	11,732	362	12,591	387	NV
328	11,188	342.5	11,756	362.5	12,608	388	NV
328.5	11,201	343	11,778	363	12,628		
329	11,216	343.5	11,803	363.5	12,648		
329.5	11,230	344	11,826	364	12,667		

Basically, a polyline with 13 segments was fitted to the records by the method of least squares, and eight of the 12 intersection points were used to define the zone boundaries (Fig. 3). For the lake sediments the fits were made on the depth scale as well as on the correlated time scale, but the differences are insignificant. The average of the resulting ages of the intersection points for the GRIP and the lake records has been used to define consistent zone boundaries on the common GRIP time scale. These values are summarised in Table 3 and also shown in Figs. 1, 2 and 4. Corresponding sampling resolutions are also given in Table 3. Taking the average of the different records to define consistent zone limits on the common time scale makes some of these limits appear slightly off the position where one would place them intuitively (for example Gib-4/5 in Fig. 1). These shifts arise from differences between wiggle-matching and polyline fitting. Both the intuitive 'eye-fit' and the mathematical techniques may be biased. Our eyes probably tend to overestimate the correlation of optically striking patterns, which may in some cases only be the result of coincident stochastic variations. For this reason we have slightly smoothed the records before the wiggle-matching, as described earlier. However, by smoothing we attenuate the high frequency end of the climatic signal, possibly leading to a slight misalignment of 'sharp' features contained in the original records. This clearly demonstrates the limits of the matching techniques and means that we must accept uncertainties of a few centimetres in the positions of the zone boundaries.

A minor but still unresolved stratigraphic problem is the following discrepancy: both in the six

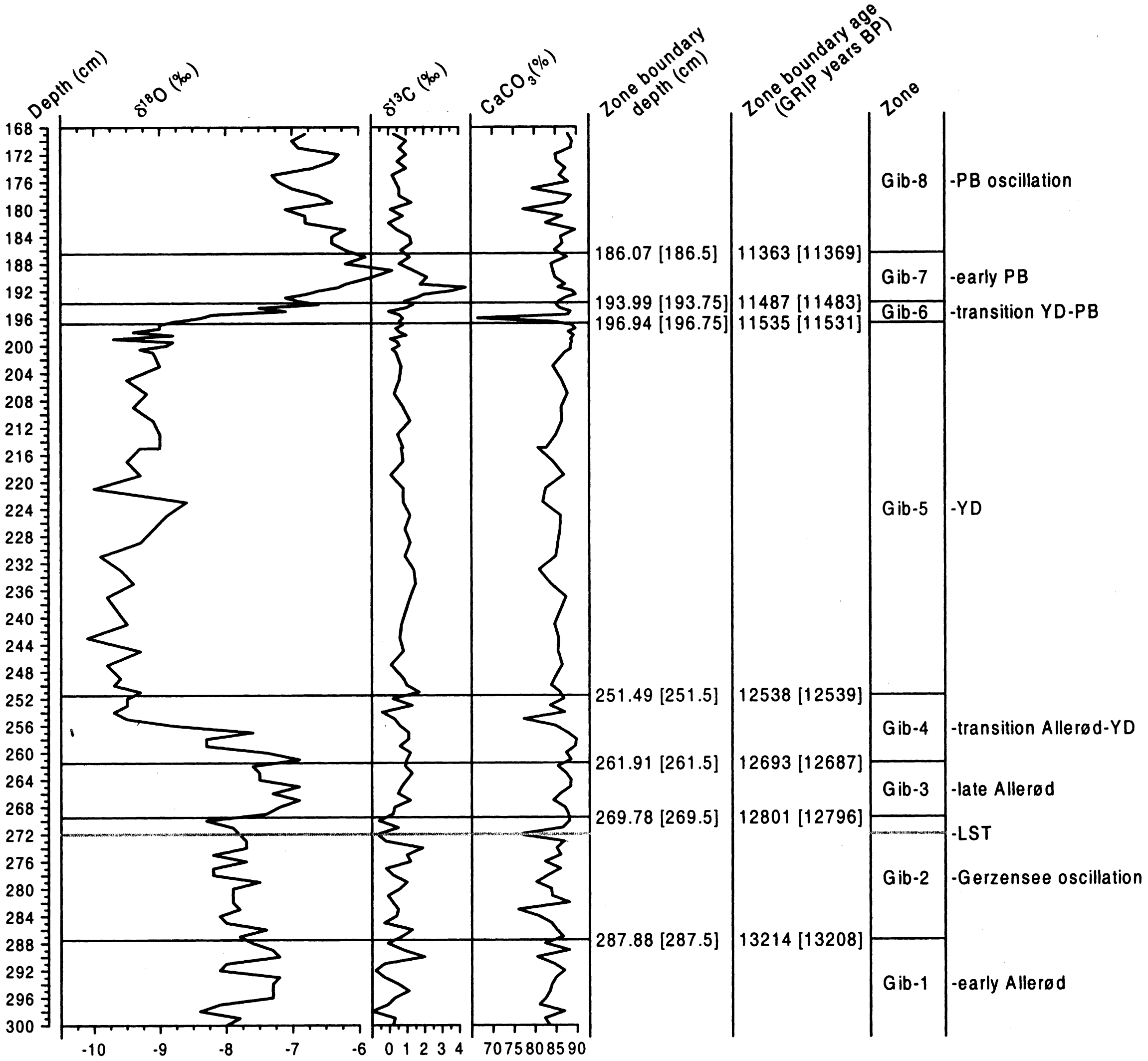

Fig. 1. Oxygen and carbonate isotopes and carbonate content of bulk-sediment samples from Gerzensee cores GEA and GEB. Values in brackets correspond to sample boundary closest to calculated zone limits.

sites compiled by Lotter et al. (1992) and in our two sites of Gerzensee and Leysin, the relative position of the LST to the Gerzensee oscillation (GI-1b) seems slightly inconsistent. In Gerzensee (Fig. 1 and Lotter et al., 1992) the LST lies in the upper third of the Gerzensee oscillation, whereas in Leysin (Fig. 2 and Lotter et al., 1992) the LST coincides with the very end of the oscillation. Uneven sampling resolution may only solve part of the problem. Our sediment description that recorded the position of the LST only to the nearest centimetre may have caused another part of the problem. Unfortunately, the LST layer has not yet been clearly identified in the Greenland ice cores.

3.2. Correlation between lake records and GRIP

The result of the best match between the lake sediment and GRIP stable-isotope records is shown

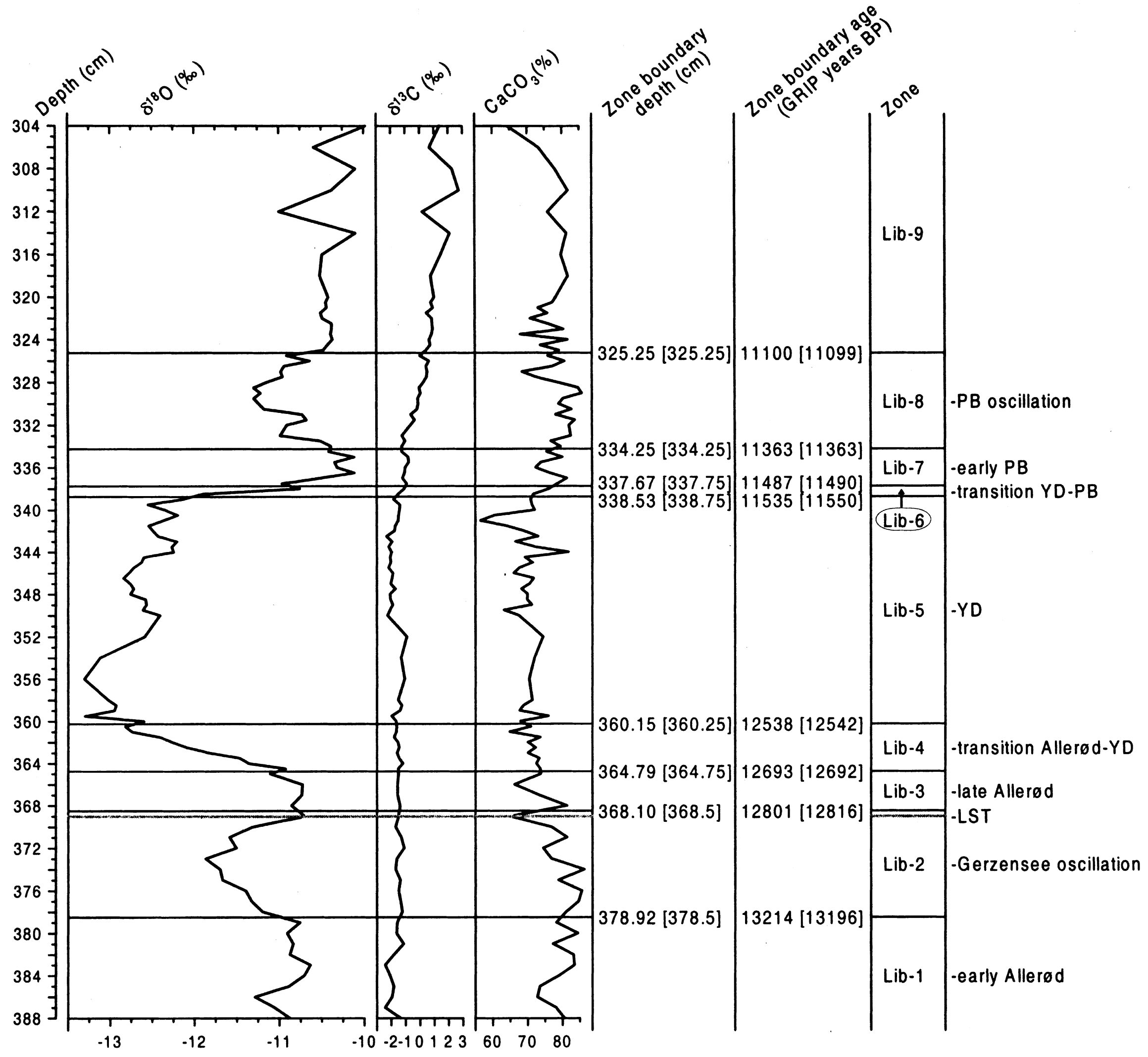

Fig. 2. Oxygen and carbonate isotopes and carbonate content of bulk-sediment samples from Leysin cores LEA and LEB. Values in brackets correspond to sample boundary closest to calculated zone limits.

in Fig. 4 on the GRIP age scale, together with the inferred carbonate sedimentation rates. The similarity of the records is striking in view of the roughly 4700 km distance between the sites: (1) the similarity in amplitudes of the two major steps; (2) the slight increase within the YD (GS-1) (with a high internal variability); (3) the slightly higher level during the PB than during the AL (GI-1a); and (4) the magnitude of the minor oscillations: about one third (at Gerzensee) to one half (at Leysin and GRIP) of the amplitude of the big shifts.

The inferred sedimentation rate varies within a factor of two of the mean value, except for the deepest part of the Gerzensee record, where the event matching is rather poor. Some of the variations could have been produced accidentally from associating wiggles in the two records that have no common climatic cause. Comparisons of further records and more unequivocal time horizons (like LST) would be required to see whether the variations would be reproducible and thus characteristic for each lake.

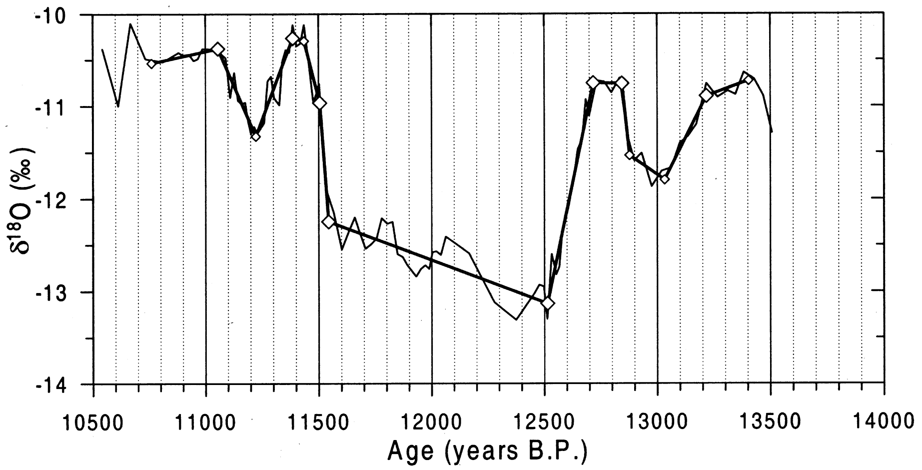

Fig. 3. Definition of isotopic zone boundaries by least-square polyline fit, as an example for the Leysin record (endpoints were held fixed in time). Zones are limited by line intersections at the large symbols.

Table 3
Limits of isotopic zones and their chronology at Gerzensee GEAB and Leysin LEAB and inferred sampling resolution

Time window		GRIP age (years B.P.)	Duration	Core depth (nearest sample boundary, cm)	GRIP age (years B.P.)	Sampling resolution (years)	Core depth (nearest sample boundary, cm)	GRIP age (years B.P.)	Sampling resolution (years)
Isotope zone[a]				Gerzensee core GEAB			Leysin core LEAB		
	End of PB oscillation	11,100					325.25	11,099	
Gib-8/Lib-8	PB oscillation		263						15
	Onset of PB oscillation	11,363		186.5	11,369		334.25	11,363	
Gib-7/Lib-7	Early PB		124			16			18
	End of transition	11,487		193.75	11,483		337.75	11,490	
Gib-6/Lib-6	Transition YD/PB		48			8			30
	Onset of transition	11,535		196.75	11,531		338.75	11,550	
Gib-5/Lib-5	YD (without its transitions)		1003			18			23
	End of transition	12,538		251.5	12,539		360.25	12,542	
Gib-4/Lib-4	Transition AL/YD		155			15			17
	Onset of transition	12,693		261.5	12,687		364.75	12,692	
Gib-3/Lib-3	Late AL		108			14			33
	End of Gerzensee oscillation	12,801		269.5	12,796		368.5	12,816	
Gib-2/Lib-2	Gerzensee oscillation		413			23			38
	Onset of Gerzensee oscillation	13,214		287.5	13,208		378.5	13,196	

[a] Gib, Gerzensee isotope bulk; Lib, Leysin isotope bulk.

Although the GRIP age scale through the YD (GS-1) is based on annual layer counting, it is subject to uncertainties because the identification of seasonal signals is not always unequivocal. For comparison, the Gerzensee record was also matched with the GISP2 $\delta^{18}O$ record (Grootes et al., 1993). The agreement with the GRIP matching is good, except for the differences in the absolute age between the two chronologies. At least one of the ice-core age scales deviates by up

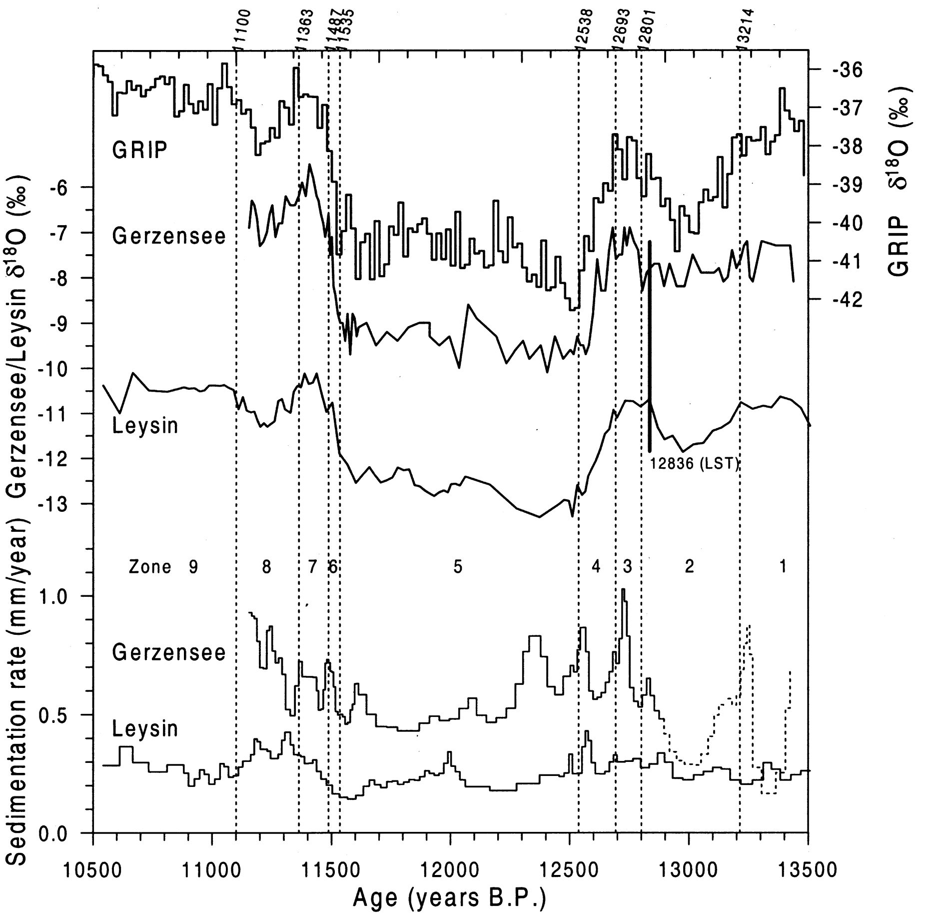

Fig. 4. Correlation between the $\delta^{18}O$ curves of Gerzensee, Leysin, and GRIP and inferred sedimentation rates for the lake cores. The age scale in calendar years before present (present is 1950 A.D.). Numbers indicated in the upper part of the figure are ages of isotopic zone boundaries. The dashed line in the Gerzensee sedimentation record indicates poor matching.

to 200 years from the true calendar age. At the termination of YD the GRIP age scale, however, does agree with the German tree-ring chronology within 20 years (Spurk et al., 1998). Based on the Monte Carlo statistics, the error in relative ages is about 20 years during the fast transitions and up to 100 years during 'quiet' times (e.g. interior of YD). However, we cannot exclude that our method matches structures in the records that look similar but had different climatic causes that did not happen at the same time. Such mismatches could only be detected by comparing more records from various sites. We would like to emphasise here that the intention was to establish the most likely chronology for the two lake records. Due to the mentioned uncertainties, details of the time scale should not be overinterpreted. In particular, care should be applied when computations of high-resolution flux records are based on the inferred sedimentation rate (Fig. 4).

4. Conclusions

The new high-resolution stable-isotope records of Swiss lake sediments show many close similarities to the Greenland stable-isotope record, suggesting that past climatic changes caused an almost simultaneous signature at both locations. This allows us to estimate an age scale for the lake sediments based on the Greenland ice-core chronology. Considering the good agreement between the GRIP age scale and the dendrochronology, and under the premise that matched structures in the two records reflect the same age, the derived Gerzensee and Leysin age scale across the BØ/AL–YD–PB era should be on average within 100 years of the true calendar age, with superimposed fluctuations of less than 100 years, depending on the distance to the next well-defined time horizon. In the vicinity of these time markers the relative dating should be about as good as the sample resolution.

Acknowledgements

This study was supported by the Swiss National Science Foundation (SPPU-CLEAR2, NFP 31). We thank S. Björck and K. Hughen for their reviews and helpful comments and H. Wright for revising the manuscript.

References

Ahlberg, K., Almgren, E., Wright, H.E., Ito, E., Hobbie, S., 1996. Oxygen-isotope record of Late Glacial climatic change in western Ireland. Boreas 25, 257–267.

Ammann, B., 1989. Response times in bio- and isotope-stratigraphies to Late Glacial climatic shifts — an example from lake deposits. Eclog. geol. Helv. 82, 183–190.

Ammann, B., 2000. Biotic responses to rapid climatic changes, introduction to a multidisciplinary study of the Younger Dryas and minor climatic oscillations on an altitudinal transect in the Swiss Alps. Palaeogeogr., Palaeoclimatol., Palaeoecol. 159, 191–201 (this issue).

Behre, K.-E., 1978. Die Klimaschwankungen im europäischen Präboreal. Petermanns geogr. Mitt. 2, 97–102.

Björck, S., et al., 1996. Synchronized terrestrial–atmospheric deglacial records around the North Atlantic. Science 274, 1155–1160.

Björck, S., Rundgren, M., Ingølfsson, Ø., Funder, S., 1997. The Preboreal oscillation around the Nordic Seas: terrestrial and lacustrine responses. J. Quat. Sci. 12 (6), 455–465.

Björck, S., et al., 1998. An event stratigraphy for the Last Termination in the North Atlantic region based on the Greenland ice-core record: a proposal by the INTIMATE group. J. Quat. Sci. 13 (4), 283–292.

Blunier, T., Chappellaz, J., Schwander, J., Stauffer, B., Raynaud, D., 1995. Variations in atmospheric methane concentration during the Holocene epoch. Nature 374, 46–49.

Broecker, W.S., 1992. Defining the boundaries of the Late Glacial isotope episodes. Quat. Res. 38, 135–138.

Chappellaz, J., et al., 1993. Synchronous changes in atmospheric CH_4 and Greenland climate between 40 and 8 kyr B.P.. Nature 366, 443–445.

Eicher, U., 1979. Die $^{18}O/^{16}O$- und $^{13}C/^{12}C$-Isotopenverhältnisse in sptäglazialen Süsswasserkarbonaten und ihr Zusammenhang mit den Ergebnissen der Pollenanalyse. Ph.D. Thesis, Bern.

Eicher, U., 1980. Pollen- und Sauerstoffisotopenanalysen an spätglazialen Profilen vom Gerzensee, Faulenseemoos und vom Regenmoos ob Boltigen. Mitt. Naturforsch. Ges. Bern N.F. 37, 65–80.

Eicher, U., 1987. Die spätglazialen sowie die frühpostglazialen Klimaverhältnisse im Bereich der Alpen: Sauerstoffisotopenkurven kalkhaltiger Sedimente. Geogr. Helv. 42, 99–104.

Eicher, U., 1994. Sauerstoffisotopenanalysen durchgeführt an spät- sowie frühpostglazialen Seekreiden. Diss. Bot. 234, 277–286.

Eicher, U., 1995. Stable oxygen and carbon isotope analyses on lacustrine carbonate sediments. In: Frenzel, B., Stauffer, B., Weiss, M.M. (Eds.), Problems of Stable Isotopes in Tree-rings, Lake Sediments and Peat-bogs as Climatic Evidence for the Holocene. Paläoklimaforschung. G. Fischer, Stuttgart, pp. 29–38.

Eicher, U., Siegenthaler, U., 1976. Palynological and oxygen isotope investigations on Late Glacial sediment cores from Swiss lakes. Boreas 5, 109–117.

Fuhrer, K., Neftel, A., Anklin, M., Maggi, V., 1993. Continuous measurements of hydrogen peroxide, formaldehyde, calcium and ammonium concentrations along the new GRIP ice core from Summit, Central Greenland. Atmos. Environ. 27A, 1873–1880.

Goslar, T., et al., 1995. High concentration of atmospheric ^{14}C during the Younger Dryas cold episode. Nature 377, 414–417.

Grootes, P.M., Stuiver, M., White, J.W.C., Johnsen, S., Jouzel, J., 1993. Comparison of oxygen isotope records from the GISP2 and GRIP Greenland ice cores. Nature 366, 552–554.

Hughen, K.A., Overpeck, J.T., Peterson, L.C., Trumbore, S., 1996. Rapid climate changes in the tropical Atlantic region during the last deglaciation. Nature 380, 51–54.

Hughen, K.A., et al., 1998. Deglacial changes in ocean circulation from an extended radiocarbon calibration. Nature 391, 65–68.

Johnsen, S.J., et al., 1992. Irregular glacial interstadials recorded in a new Greenland ice core. Nature 359, 311–313.

Johnsen, S., Dahl-Jensen, D., Dansgaard, W., Gundestrup, N., 1995. Greenland palaeotemperatures derived from GRIP bore hole temperature and ice core isotope profiles. Tellus 47B, 624–629.

Lemdahl, G., 2000. Late Glacial and Early Holocene insect assemblages from sites at different altitudes in the Swiss Alps — implications for climate and environment. Palaeogeogr., Palaeoclimatol., Palaeoecol. 159, 293–312 (this issue).

Levesque, A.J., Mayle, F.E., Walker, I.R., Cwynar, L.C., 1993a. The amphi-Atlantic oscillation: a proposed Late Glacial climatic event. Quat. Sci. Rev. 12, 629–643.

Levesque, A.J., Mayle, F.E., Walker, I.R., Cwynar, L.C., 1993b. A previously unrecognized Late Glacial cold event in eastern North America. Nature 361, 623–626.

Levesque, A.J., Cwynar, L.C., Walker, I.R., 1994. A multiproxy investigation of Late Glacial climate and vegetation change at Pine Ridge Pond, Southwest New Brunswick, Canada. Quat. Res. 42, 316–327.

Levesque, A.J., Cwynar, L.C., Walker, I.R., 1997. Exceptionally steep north–south gradients in lake temperatures during the last deglaciation. Nature 385 (30), 423–426.

Lotter, A.F., Eicher, U., Birks, H.J.B., Siegenthaler, U., 1992. Late Glacial climatic oscillations as recorded in Swiss lake sediments. J. Quat. Sci. 7, 187–204.

Mayle, F.E., Cwynar, L.C., 1995. Impact of the Younger Dryas cooling event upon lowland vegetation of maritime Canada. Ecol. Monogr. 65, 129–154.

McKenzie, J.A., Hollander, D.J., 1993. Oxygen-isotope record in recent carbonate sediments from lake Greifen Switzerland (1750–1986): application of continental isotopic indicator for evaluation of changes in climate and atmospheric circulation pattern. In: Swart, P.K., Lohmann, K.C., McKenzie, J., Savin, S. (Eds.), Climate Change in Continental Isotopic Records. American Geophysical Union, Washington, DC, pp. 101–111.

Oeschger, H., et al., 1984. Late Glacial climate history from ice cores. In: Hansen, J.E., Takahashi, T. (Eds.), Climate Processes and Climate Sensitivity, Geophysics Monographs Series Vol. 29. AGU, Washington, DC, pp. 299–306.

Peteet, D.M., 1992. The palynological expression and timing of the Younger Dryas event — Europe versus eastern North America. In: Bard, E., Broecker, W.S. (Eds.), The Last Deglaciation, NATO ASI Series. Springer, Berlin, pp. 327–344.

Peteet, D.M. (Ed.), Global Younger Dryas? Quat. Sci. Rev. 12 (5) 1993., 277–355.

Peteet, D.M. (Ed.), Global Younger Dryas 2. Quat. Sci. Rev. 14 (9) 1995., 811–949.

Schneider, R., Tobolski, K., 1985. Lago di Ganna — Late Glacial and Holocene environments of a lake in the southern Alps. Diss. Bot. 87, 229–271.

Schwalb, A., Lister, G.S., Kelts, K., 1994. Ostracode carbonate delta ^{18}O- and delta ^{13}C-signatures of hydrological and climatic changes affecting Lake Neuchâtel, Switzerland, since the latest Pleistocene. J. Paleolimnol. 11, 3–17.

Schwalb, A., Locke, S.M., Dean, W.E., 1995. Ostracode delta ^{18}O and delta ^{13}C evidence of Holocene environmental changes in the sediments of two Minnesota lakes. J. Paleolimnol. 14 (3), 281–296.

Schwander, J., et al., 1997. Age scale of the air in the summit ice: implication for glacial–interglacial temperature change. J. Geophys. Res. 102, D16, 19,483–19,494.

Siegenthaler, U., Eicher, U., 1986. Stable oxygen and carbon isotope analyses. In: Berglund, B.E. (Ed.), Handbook of Holocene Palaeoecology and Palaeohydrology. Wiley, Chichester, pp. 407–422.

Siegenthaler, U., Eicher, U., Oeschger, H., Dansgaard, W., 1984. Lake sediments as continental δ^{18}O records from the transition of glacial–interglacial. Ann. Glaciol. 5, 149–152.

Spurk, M., et al., 1998. Revision and extension of the Hohenheim oak and pine chronologies: new evidence about the timing of the Younger Dryas/Preboreal transition. Radiocarbon 40 (3), 1107–1116.

Stocker, T.F., Wright, D.G., 1996. Rapid changes in ocean circulation and atmospheric radiocarbon. Paleoceanography 11, 773–796.

Thompson, L.G., et al., 1998. A 25,000-year tropical climate history from Bolivian ice core. Science 282, 1858–1864.

Tobolski, K., Ammann, B., 2000. Macrofossils as records of plant responses to rapid Late Glacial climatic changes at three sites in the Swiss Alps. Palaeogeogr., Palaeoclimatol., Palaeoecol. 159, 251–259 (this issue).

von Grafenstein, U., Erlenkeuser, H., Müller, J., Kleinmann, A., Trimborn, P., 1994. High-frequency climatic oscillations during the last deglaciation as revealed by oxygen-isotope records of benthic organisms (Ammersee, Southern Germany). J. Paleolimnol. 11, 349–357.

von Grafenstein, U., et al., 2000. Isotope signature of the Younger Dryas and two minor oscillations at Gerzensee: Palaeoclimatic and plaeolimnologic interpretation. Palaeogeogr., Palaeoclimatol., Palaeoecol. 159, 215–229 (this issue).

Walker, I.R., Mott, R.J., Smol, J.P., 1991. Allerød–Younger Dryas lake temperatures from midge fossils in Atlantic Canada. Science 253, 1010–1012.

Wright, H.E., 1984. Sensitivity and response time of natural systems to climatic change in the late Quaternary. Quat. Sci. Rev. 3, 91–131.

Wright, H.E., 1989. The amphi-Atlantic distribution of the Younger Dryas paleoclimatic oscillation. Quat. Sci. Rev. 8, 295–306.

Yu, Z., Eicher, U., 1998. Abrupt climate oscillations during the last deglaciation in Central North America. Science 282 (5397), 2235–2238.

Yu, Z., McAndrews, J.H., Eicher, U., 1997. Middle Holocene dry climate caused by change in atmospheric circulation patterns: evidence from lake levels and stable isotopes. Geology 25 (3), 251–254.