Climate Dynamics (1993) 9:107–116

Climate Dynamics

AMS radiocarbon dating and varve chronology of Lake Soppensee: 6000 to 12000 ^{14}C years BP

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Received: 13 November 1992/Accepted: 31 March 1993

Abstract. For the extension of the radiocarbon calibration curve beyond 10000 ^{14}C y BP, laminated sediment from Lake Soppensee (central Switzerland) was dated. The radiocarbon time scale was obtained using accelarator mass spectrometry (AMS) dating of terrestrial macrofossils selected from the Soppensee sediment. Because of an unlaminated sediment section during the Younger Dryas (10000–11000 ^{14}C y BP), the absolute time scale, based on counting annual layers (varves), had to be corrected for missing varves. The Soppensee radiocarbon-varve chronology covers the time period from 6000 to 12000 ^{14}C y BP on the radiocarbon time scale and 7000 to 13000 calendar y BP on the absolute time scale. The good agreement with the tree ring curve in the interval from 7000 to 11450 cal y BP (cal y indicates calendar year) proves the annual character of the laminations. The ash layer of the Vasset/Killian Tephra (Massif Central, France) is dated at 8230 ± 140 ^{14}C y BP and 9407 ± 44 cal y BP. The boundaries of the Younger Dryas biozone are placed at 10986 ± 69 cal y BP (Younger Dryas/Preboreal) and 12125 ± 86 cal y BP (Alleröd/Younger Dryas) on the absolute time scale. The absolute age of the Laacher See Tephra layer, dated with the radiocarbon method at 10800 to 11200 ^{14}C y BP, is estimated at 12350 ± 135 cal y BP. The oldest radiocarbon age of 14190 ± 120 ^{14}C y BP was obtained on macrofossils of pioneer vegetation which were found in the lowermost part of the sediment profile. For the late Glacial, the offset between the radiocarbon (10000–12000 ^{14}C y BP) and the absolute time scale (11400–13000 cal y BP) in the Soppensee chronology is not greater than 1000 years, which differs from the trend of the U/Th-radiocarbon curve derived from corals.

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Introduction

^{14}C conventional age versus absolute time scale

Although radiocarbon dating is a widely used and very convenient dating method, applicable to the last 40000–50000 y, it is known that the conventional radiocarbon time scale is not equivalent to the calendar (absolute) time scale (Stuiver and Polach 1977). Variations in the atmospheric $^{14}C/^{12}C$ ratio due to changes in the production rate of ^{14}C atoms (Lal and Peters 1967) and changes in the distribution of carbon between the various global reservoirs (Stuiver et al. 1991) result in offsets between both time scales. Experimental tracing of these changes by ^{14}C dating of tree rings (Stuiver et al. 1986) has resulted in a calibration curve which extended back to 9200 cal y BP[1] and has just recently been extended back to almost 11450 cal y BP (Kromer and Becker 1993). Further extension of the calibration curve is difficult, since as yet a continuous tree ring chronology which is older than 11450 cal y BP is lacking (Kromer and Becker 1991). Therefore, efforts are made to explore archives, other than trees, which preserve past changes in the atmospheric $^{14}C/^{12}C$ ratio.

Recent investigations have focused on two of these archives: corals and laminated lake sediments. Because of sample size limitations, it has often been difficult to obtain unambiguous radiocarbon dates on lake sediment. Bulk sediment dating often yielded ages that were too old [hard-water effect (Olsson 1986; Olsson 1991)]. With the advent of accelerator mass spectrometry (AMS), this reservoir effect is avoided by ^{14}C dating of terrestrial macrofossils selected from lake sediment (Andrée et al. 1986; Vogel et al. 1989; Zbinden et al. 1989). This provides a radiocarbon time scale for the sediment profile. By counting annual layers (varves), an absolute time scale for the sediment can

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[1] In this study the absolute age is expressed in 'calendar y BP' (0 cal y BP = 1950 AD); radiocarbon age is given in '^{14}C y BP' (0 ^{14}C y BP = 1950 AD)

also be constructed. Both time scales can then be compared in order to reconstruct changes in the atmospheric $^{14}C/^{12}C$ ratio.

Since U/Th ages can be measured on small samples by a new mass-spectrometric method (Edwards et al. 1987), the precise dating of corals is now possible. The U/Th ages of radiocarbon dated samples from Barbados corals were measured by Bard and his colleagues (Bard et al. 1990). The offset between the radiocarbon and U/Th time scales, which they found, suggests that during the last glacial maximum (LGM) and the subsequent deglaciation (10000 to 20000 ^{14}C y BP) the atmospheric $^{14}C/^{12}C$ ratio was significantly higher (30 to 50%) than it is now (i.e. the atmospheric $^{14}C/^{12}C$ ratio at 1890 AD). In contrast, results obtained on macrofossils gleaned from sediments of Swiss lakes (Zbinden et al. 1989; Lotter et al. 1991; Lotter 1991b) suggest that during the period between 12800 and 10000 ^{14}C y BP the deviation of the atmospheric $^{14}C/^{12}C$ ratio from the present value varied between 0 and 10%.

Laminated lake sediments

Laminated lake sediments have received much attention since De Geer (1912) first used annually deposited glacial clayey laminae, varves, to construct the Swedish varve chronology for the last deglaciation. Since that time, laminated sediments of lakes in various regions have been intensively studied e.g. Canada (Anthony 1977; Boyko-Diakonow 1979), E. Africa, Turkey (Kempe and Degens 1979), Great Britain (Peglar et al. 1984), Scandinavia (Saarnisto et al. 1977; Simola 1977; Tolonen 1978; Strömberg 1985), Germany (Merkt 1971; Zolitschka 1990), Switzerland (Nipkow 1921; Welten 1944; Lotter 1989) and Poland (Ralska-Jasiewiczowa et al. 1987; Rozanski et al. 1991). An absolute time scale for the sediment is of great interest for all paleoclimate studies. Such a time frame in which to view the climate changes recorded in lake sediments, can be constructed when certain conditions in the lake (e.g. water column stagnation, anoxic bottom waters) allow the preservation of the annual periodicity of the sediment layers.

There are generally three types of laminations present in non-glacial laminated sediments; those of physical, biological and chemical origin (Ludlam 1979). Layers of gradually deposited inorganic allochthanous material form clayey or clastic laminations. The distinction between chemical and biological varves is often gradational. Light and dark layers, found in many eutrophic lakes, may result from seasonal lake mixing (Anthony 1977) or seasonal changes in the productivity and/or the water temperature of the lake (Kelts and Hsü 1978). Sequences of layers which are deposited during one year form annual laminations or varves (originally thought to contain only a couplet made up of a pale and a dark layer) (O'Sullivan 1983 and references therein).

Usually, the annual periodicity of laminations is established by microscopic/palynological examination of each laminae (Welten 1944; Peglar et al. 1984; Lotter 1989). Although this method is very important, comparison with results of independent dating is necessary to prove the integrity of the varve chronology. The possibility of either a hiatus in the sediment record (e.g. sediment lost during sampling) or in the varve chronology (changes in the character of the laminations) must be estimated by means of independent dating methods, e.g. radiocarbon dating (Stuiver 1971; Pazdur et al. 1987).

Laminated sediment from the Swiss Lake Soppensee, represented material with potential use for the extension of the calibration curve to 12000 ^{14}C y BP (Lotter 1991a). However, as radiocarbon dating and varve counting proceeded, it became clear that the laminations present in the Soppensee profile are not continuous. In this study, we show how the intervals of unlaminated sediment affect the previous varve chronology (Lotter et al. 1991). That chronology was constructed by taking into account only the clearly identifiable varves, i.e. unlaminated intervals were treated as instantaneous deposits and neglected in counting. In the next step, we estimate a correction for the previous varve chronology and discuss the implications this correction represents for the radiocarbon calibration curve.

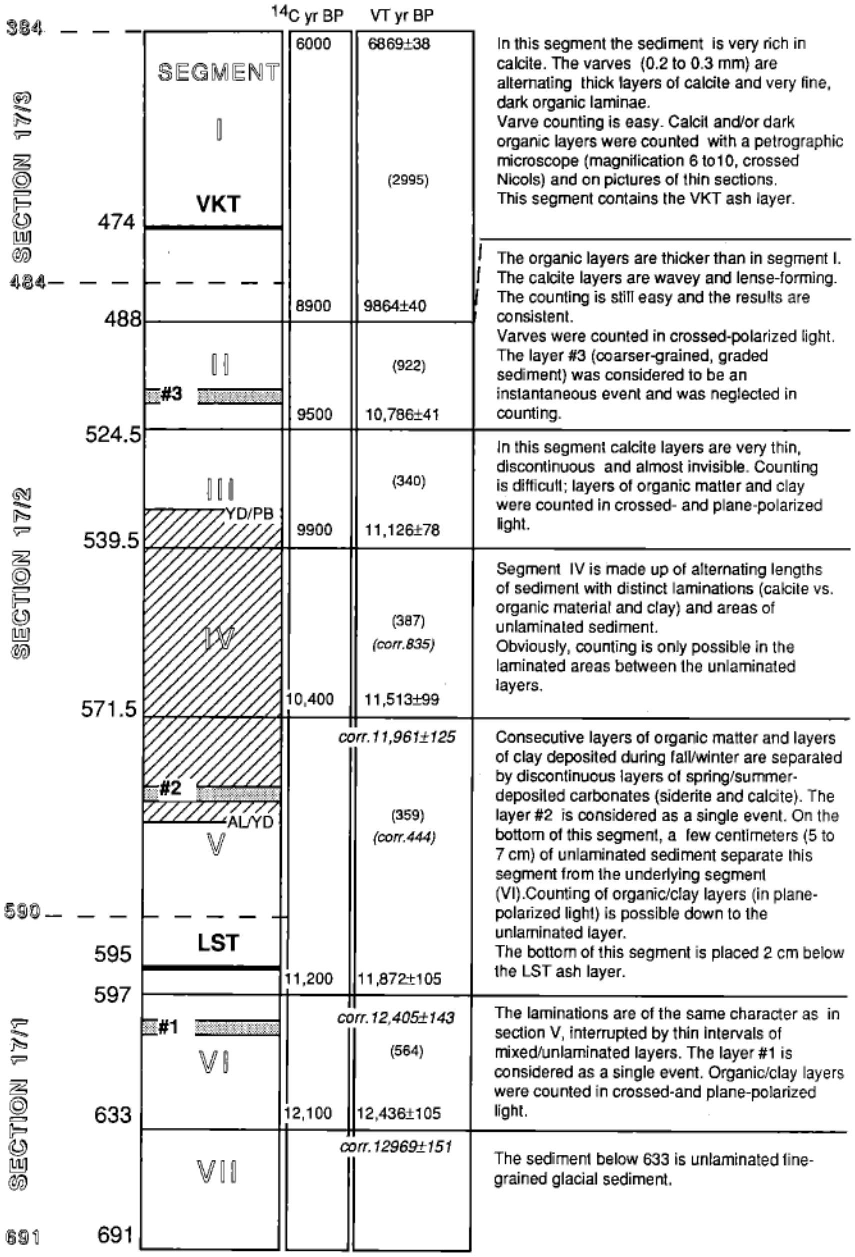
Experimental methods

The Lake cores and varves

Soppensee is a small, eutrophic lake located in the central Swiss plateau about 30 km north of the Alps (600 m a.s.l., 8° 20′ E, 47° 5′ 30″ N). It is a kettle-lake that formed at the end of the LGM, after the retreat of the western arm of the Reuss Glacier. The lake has no major inlets and receives only seasonal surface run-off.

A series of 23 long cores (cut into one metre sections) was recovered from Soppensee in fall/winter 1989. The cores from the deepest (27 m), flat-bottomed part of the lake were used for pollen analysis (cores SO89-23 and SO89-17), sedimentological and geochemical analysis (core SO89-23) and high-resolution AMS ^{14}C dating (core SO89-17). Varve counting for this study was performed primarily on thin sections from core SO89-17 and cross-checked by counting on portions of cores SO89-23 and SO89-19. Laminations in the Soppensee sediment are clearly visible only from depth 362 to 633 cm in core SO89-17. We focused on the sediment between depth 384 and 633 cm which corresponds to 6000 to 12000 ^{14}C y BP (Fig. 1). Additionally, radiocarbon ages were obtained on some samples from the correlated cores SO89-12 and SO89-19 and from core SO86-14, which was studied earlier for pollen stratigraphy (Lotter 1991a).

Precise correlation between the various cores was possible using the depths of marker beds (which are layers of specific colour or centimetre-thick homogeneous layers) and sequences of laminae which are present in all cores. Clearly visible in thin sections, ash layers



In this segment the sediment is very rich in calcite. The varves (0.2 to 0.3 mm) are alternating thick layers of calcite and very fine, dark organic laminae. Varve counting is easy. Calcit and/or dark organic layers were counted with a petrographic microscope (magnification 6 to10, crossed Nicols) and on pictures of thin sections. This segment contains the VKT ash layer.

The organic layers are thicker than in segment I. The calcite layers are wavey and lense-forming. The counting is still easy and the results are consistent. Varves were counted in crossed-polarized light. The layer #3 (coarser-grained, graded sediment) was considered to be an instantaneous event and was neglected in counting.

In this segment calcite layers are very thin, discontinuous and almost invisible. Counting is difficult; layers of organic matter and clay were counted in crossed- and plane-polarized light.

Segment IV is made up of alternating lengths of sediment with distinct laminations (calcite vs. organic material and clay) and areas of unlaminated sediment. Obviously, counting is only possible in the laminated areas between the unlaminated layers.

Consecutive layers of organic matter and layers of clay deposited during fall/winter are separated by discontinuous layers of spring/summer-deposited carbonates (siderite and calcite). The layer #2 is considered as a single event. On the bottom of this segment, a few centimeters (5 to 7 cm) of unlaminated sediment separate this segment from the underlying segment (VI).Counting of organic/clay layers (in plane-polarized light) is possible down to the unlaminated layer. The bottom of this segment is placed 2 cm below the LST ash layer.

The laminations are of the same character as in section V, interrupted by thin intervals of mixed/unlaminated layers. The layer #1 is considered as a single event. Organic/clay layers were counted in crossed-and plane-polarized light.

The sediment below 633 is unlaminated fine-grained glacial sediment.

Fig. 1. The studied part of core SO89-17 (not to scale) is divided into sediment segments (I to VII). Radiocarbon ages and varve time (*VT*) age are shown for the boundaries between the segments. The Younger Dryas is indicated by the *cross-hatched* area. The number of varves counted in each segment is written in *parentheses.* In segment IV and V, a corrected number of varves counted in that segment is written in italics (*corr.*) and the corrected absolute ages of the bottom of segments IV, V and VI (*corr. VT*) are also shown. In the *right panel,* the sediment and the varve (laminae) quality, the feasibility of counting the varves and the method of counting are described.

of the Laacher See Tephra (LST) and the Vasset/Killian Tephra (VKT) (Juvigné 1991) (known as the Boreal Tuff or the Puy Lacroix tephra) also aided correlation.

The biogenetic varves or microlaminations in Soppensee are mostly made up of alternating calcareous and carbonaceous layers (Holocene varves, present between 362 and 525 cm). Detailed investigations with a microscope show that a couplet, i.e. the pale calcareous layer (calcite with or without siderite/diatoms) corresponding to summer deposition and the black organic-rich layer to fall/winter, represents material from a single year (Lotter 1989). Where calcite layers are very thin and discontinuous or disappear altogether (late Glacial varves, present between 525 and 633 cm), the spring/summer layers consisting of diatoms and chrysophyte cysts alternate with layers of organic fine-detritus deposited in fall/winter (Lotter 1991b).

AMS ^{14}C dating

To select macrofossils needed for radiocarbon dating, consecutive sediment slices, 1-cm thick, were cut from core SO89-17 between depth 384 to 633 cm. The sediment samples were submerged in acid (10% HCl) and then sieved under running water. The procedure was repeated with base (10% KOH). Organic material retained on the sieve was examined under a binocular microscope. Clearly identifiable macrofossils of land plants were chosen for sample material. The macrofossils were then pretreated with the standard A-B-A method (Olsson 1986); HCl (0.5 M), NaOH (0.1 M) followed by HCl (0.5 M) all at 60°C. The first two steps removed encrusted carbonate and humic substance contamination, respectively. The final acid step freed any modern CO_2 absorbed from the air during the base step. Rinsing to neutral pH followed each step. Of the

Table 1. Results of AMS radiocarbon dating (with one sigma error) on terrestrial macrofossil samples selected from the sediment of lake Soppensee.

Sample number ETH[a]	Depth core SO89-17 (cm)	^{14}C age (y BP)	Relative VT[b] (y)	VT (y BP)	Remarks[d]
7210/7352	390–391	6190± 40	127	6996± 40	
7353	391–392	6180± 55	151	7020± 40	
7386	397–398	6170± 50	305	7174± 40	
7211	398–399	6325± 50	331	7200± 43	
7387	399–400	6425± 55	369	7238± 41	
7388	403–404	6405± 55	484	7353± 40	
7212/7354	404–405	6620± 40	509	7378± 40	
7213	408–409	6640± 55	606	7475± 40	
7214	411–412	6850± 55	688	7557± 41	
7215	412–413	6930± 50	719	7588± 41	
7216	418–419	6945± 55	878	7747± 40	
7271	419–420	6990± 55	903	7772± 40	
6239	422–423	7300± 90	981	7850± 41	14
7218	422–423	7080± 50	981	7850± 41	
7631	423–424	7405± 85	1012	7881± 41	s
6238	423–425	7075± 90	1022	7891± 49	14
7586	424–425	7010± 50	1041	7910± 42	
7389	424–425	6965± 65	1041	7910± 42	
7587	425–426	6900± 55	1070	7939± 41	
6237	424.5–425.5	7300± 85	1081	7950± 41	14
7588	426–427	7195± 80	1103	7972± 42	
6236	426.5–427.5	7315± 90	1114	7983± 42	14
6235	427.5–428.5	7405± 90	1146	8015± 42	14
7390	428–429	7215± 55	1165	8034± 42	
7589	429–430	7245± 55	1193	8062± 42	
7590	430–431	7230±110	1216	8085± 43	
7622	431–432	7310± 85	1240	8109± 42	s
7391	432–433	7335± 80	1267	8136± 41	
7591	434–435	7285± 70	1318	8187± 41	
6233	433.5–438.5	7205± 95	1374	8243± 83	14
7592	436–437	7360± 90	1374	8243± 41	
7593	437–438	7425± 55	1402	8271± 41	
7392	438–439	7550± 75	1432	8301± 42	
6232	439–442.5	7885± 95	1504	8373± 57	14
6231	443–447.5	7710±100	1628	8497± 67	14
7393	445–446	7620± 60	1628	8497± 42	
5296	447	7710± 80	1665	8534± 39	14
6230	448–451	7800± 95	1740	8609± 61	14
5295/6103	451	8060± 60	1793	8662± 39	14
5292	453–455.5	7615± 80	1900	8769± 62	*s/14
7394	454–455	7600± 60	1900	8769± 42	*
7594	456–457	7470±100	1970	8839± 44	*s
7623	458–459	7880± 90	2035	8904± 43	s
6144/6152	459.5	8080± 65	2073	8942± 40	14
6143	460.5–464.5	8120± 95	2202	9071± 88	14
7395	462–463	8180± 60	2187	9056± 45	
5291	463–465	8165± 75	2244	9113± 53	14
7355	464–465	8115± 65	2274	9143± 42	
6142	464.5–467.5	8140±100	2326	9195± 56	14
6141	467.5–470.5	7880±100	2405	9274± 55	*s/14
6139	471.4–474.5	8110±100	2450	9319± 49	s/14/VKT
8246	472–475	7705±100	2480	9349± 73	*s
9641	473–475	8230±140	2538	9407± 62	s/12/VKT
9505	475–479	8970± 95	2615	9484± 75	12
9504	476–481	8820±100	2670	9539± 53	19
6614	494.5–496.5	9020± 75	3185	10054± 47	s
6615	496.5–497.5	8990± 70	3240	10109± 43	s
6616	500.5–501.5	9020± 65	3350	10219± 44	
6936	504.5–506.5	9115± 95	3475	10344± 51	s
6617	506.5–507.5	9255± 60	3525	10394± 43	
6618	507.5–508.5	9495± 70	3548	10417± 42	
6619	508.5–509.5	9475± 85	3567	10436± 42	
6620	512.5–514.5	9440± 70	3656	10525± 47	s

Table 1. (continued)

Sample number ETH[a]	Depth core SO89-17 (cm)	^{14}C age (y BP)	Relative VT[b] (y)	VT (y BP)	Remarks[d]
7699	514.5–516.5	9620 ± 100	3705	10574 ± 48	s
6621	516.5–518.5	9320 ± 75	3725	10594 ± 44	s
7700	518.5–520.5	9530 ± 95	3784	10653 ± 50	s
6622	523–524	9625 ± 65	3893	10762 ± 43	
6623	524–525	9595 ± 70	3916	10785 ± 44	s
7709	534.5–537.5	9665 ± 95	4171	11040 ± 81	s
6802	537.5–539.5	9620 ± 80	4231	11100 ± 79	s
7701	540.5–544.5	9970 ± 100	4309	11178 ± 104	
7710	544.5–549.5	10135 ± 100	4366	11235 ± 117	
6803	549.5–551.5	9965 ± 75	4401	11270 ± 99	
7702	558.5–563.5	9740 ± 100	4525	11394 ± 120	*s
6929	568.5–569.5	10400 ± 70	4621	11490 ± 101	
7703	573.5–580.5	10440 ± 100	4765	11634 ± 137	
7704	584.5–590.5	10020 ± 110	4877	11746 ± 129	*s
5303	589–592	10070 ± 155	4950	11784 ± 112	*s/14
5290	593–595	10760 ± 105	4932	11828 ± 108	s/14/LST
6930	596.5–598.5	11190 ± 80	5003	11872 ± 109	LST
5304	596–600	10540 ± 150	4994	11890 ± 118	*s/14
6932	599.5–601.5	11160 ± 60	5069	11938 ± 110	
6804	603.5–605.5	11050 ± 85	5185	12054 ± 108	
6933	605.5–606.5	11470 ± 70	5249	12118 ± 108	
5305	606–808	11380 ± 105	5249	12118 ± 107	s/14
6805	609.5–610.5	11300 ± 85	5249	12118 ± 107	
6806	610.5–611.5	11385 ± 90	5262	12131 ± 108	s
6807	628.5–630.5	12040 ± 90	5485	12354 ± 107	
6808	631–632	11930 ± 90	5521	12390 ± 106	s
6809	633–634	12150 ± 90	5558	12427 ± 106	s
8726	644.5–645.5	12190 ± 120			*unlaminated/s
8725	679.5–680.5	13280 ± 115			*unlaminated/s
8727	681.5–682.5	14190 ± 120			*unlaminated/s

[a] The samples with two ETH numbers are weighted means of two samples made from different macrofossil material selected from the same depth

[b] Relative varve time represents the number of varves counted from the beginning of the floating varve chronology (depth 384.5 cm on Fig. 1)

[c] Varve time (absolute time scale) was obtained by adding 6869 years to the relative varve time (fit of the floating varve chronology to the radiocarbon calibration curve – see text)

[d] In the remarks column the outlying samples (triangles on Fig. 2) are marked with the stars and all samples of ≤1 mg of C with 's'. Core numbers are given for the samples taken from correlated cores SO86-14, SO89-19 and SO89-12 (correlation between cores on the basis of marker beds, e.g. ash layers). The ages obtained on the samples stratigraphically close to the ash layers are shown as VKT and LST, respectively

250 sediment slices from core SO89-17 that were prepared, only 69 contained sufficient material, because a minimum of about 1 mg carbon was used for AMS dating. When necessary, samples from adjacent slices were combined to form one sample.

The pretreated macrofossils were placed in preheated quartz tubes (950°C) together with preheated CuO (950°C) and silver wire (450°C). The tubes were then evacuated and sealed. The material in the tubes was combusted in a muffle furnace for 2 h at 950°C. The CO_2 was reduced catalytically to graphite over cobalt in the presence of hydrogen by the method described by Vogel et al. (Vogel et al. 1984; Vogel et al. 1987). The resulting graphite-cobalt mixture was pressed onto copper discs for the AMS analysis.

Samples were measured along with standards (NBS oxalic acid I, ANU sucrose) and blanks. Blanks of size similar to that of the macrofossil samples were made of combusted and then graphitized coal and natural graphite. At the ETH Zürich/PSI (Paul Scherrer Institute) AMS facility, $^{14}C/^{12}C$ and $^{13}C/^{12}C$ ratios were measured quasi-simultaneously (Bonani et al. 1987). The procedure suggested by Stuiver and Polach (1977) was followed for the calculation of the conventional radiocarbon ages. The errors are at the one sigma level and represent both the statistical error and the scatter of results for both standards and blanks. The results are listed in Table 1.

On Fig. 2, the conventional radiocarbon ages of the macrofossils are plotted against sediment depth in core SO89-17. A number of the small samples (less than 1 mg of carbon) and two of the samples, which contained more than 1 mg C, are significantly younger than expected (indicated by a star in Table 1). Because this problem does not appear for data obtained on other small samples, it seems that the blank correction may not have been sufficient for these few samples. Presumably, they were contaminated by modern carbon

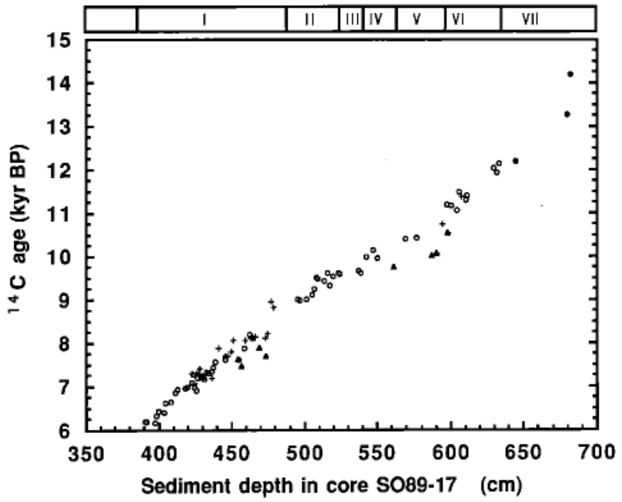


Fig. 2. Radiocarbon ages of macrofossils selected from the Soppensee sediment are plotted against sediment depth in core SO89-17. The corresponding sediment segments (see Fig. 1) are shown *in the upper part* of the graph. *Open circles* represent data points obtained on the core SO89-17, *crosses* are the ages of macrofossil samples from the cores SO86-14, SO89-19 and SO89-12 (see Table 1). Outlying ages are plotted as *triangles* (see Table 1 and text). *Solid circles* represent ages of the macrofossils selected from the deepest, unlaminated sediment (segment VII)

during preparation, e.g. cleaning, weighing of the macrofossils, and/or transfer of the CO_2 to the reaction chamber. The problems associated with the preparation of small samples will be discussed elsewhere (Hajdas, in preparation). Three radiocarbon ages were obtained on macrofossils selected from the lowermost, unlaminated part of the sediment core. The possibility that some of these macrofossils were reworked from older deposits and washed into the lake cannot be excluded and these results are only considered as oldest ages obtained on Soppensee sediment. The outlying data points and three oldest ages, are neglected in further discussion.

Varve counting

Photographs were taken of the fresh sediment in the core sections (sections 17/1, 17/2 and 17/3). Potential loss of sediment between the core sections (due to cutting the 7-m long core into one metre-long sections) was excluded after photographs and thin sections of core SO89-17 were compared with photographs and thin sections of correlated cores SO89-19 and SO89-23. Correlation between 1-cm overlapping thin sections was accomplished by painstakingly comparing the sediment structure and the marker beds (including the two ash layers of the VKT and LST) in the thin sections and on the photographs of the fresh sediment for each core. Wax impregnated thin cuts of sediment, 15–30 μm thick, were also examined.

The varve counting results presented later were obtained on core SO89-17. The counting proceeded at 1 cm intervals, and was recorded with respect to sediment depth in that core. Sections 17/1 and 17/2 (633 to 484 cm) were counted twice under the microscope. The sediment of section 17/3 (484 to 384 cm) was counted twice on photographs of thin sections taken under the microscope and counted once directly on the thin sections with the polarizing microscope.

For discussion, the sediment between 633 and 384 cm in core SO89-17 (sections 17/1, 17/2 and 17/3) was subdivided into segments. As shown in more detail in Fig. 1, the various segments were differentiated from each other by the nature of the varves and the ease with which the varves could be counted. It may be noted that a comparison of the thin sections from other Soppensee cores, e.g. SO86-14, SO89-23, SO89-19 showed that when the sediment is unlaminated at a certain depth in core SO89-17, these conditions prevented the formation and/or preservation of varves anywhere in the lake at that time.

In segment VII, below a depth of 633 cm, unlaminated very fine-grained glaciolacustrine sediments occur. Rhythmic deposits are first seen in the sediment above depth 633 cm. Between 633 and 597 cm (segment VI), the organic matter/clay layers are distinct and were counted in crossed- and plane-polarized light. Infrequent thin microturbidite layers and/or intervals of unlaminated sediment are also present. In this segment, a coarser-grained homogeneous layer # 1 which occurs at 609–605 cm has been interpreted to represent a single depositional event (Sturm and Matter 1978). This layer as well as layers # 2 and # 3 (see text later) were neglected in counting.

The LST ash layer lies at depth 595 cm in segment V (597 to 571.5 cm). On the bottom of this segment a few centimetres of sediment (2 cm below and 5 cm above LST) are unlaminated. The sediment in the following segment (590 to 571.5) is laminated and layers of organic matter/clay were counted. A marker bed # 2 occurs between 582–577.5 cm. Segment IV (571.5 to 539.5 cm) consists of approximately 30 cm of sediment which is made up of short, laminated intervals (about 5 to 20 varves) alternating with unlaminated deposits. The varves visible between the unlaminated intervals were counted.

Segment III (539.5 to 524.5) is very poor in calcite. Close examination of the thin cuts for this segment showed that the best preserved and most continuous rhythmic deposits are made up of a thin layer of organic matter overlain by a clay layer which is followed by an irregular layer of calcite. Layers or organic matter/clay were counted but with difficulty. Between 524.5 and 488 cm (segment II) the calcite layers are still well preserved and could be counted almost as easily as the varves in segment I, where the carbonate content is very high. Segment II contains marker bed # 3 between 517.5–516.5 cm. The Holocene varves of segment I (488 to 384 cm) represent the best laminated part of the whole sediment profile. The calcite layers, which were distinct, were counted in crossed-polarized light. The VKT ash layer lies in this segment at depth 474 cm.

After completion of the varve counting on the thin sections and photographs of the thin sections, a mean value of all counting was taken and the total number of varves counted between 633 and 384 cm, for each centimetre of sediment, was determined.

The error is represented by maximal deviations between the total number of varves counted in a single counting and the mean value of all the counting; a larger error value indicates that the counting in that segment was more difficult. The number of varves counted for each segment and the absolute (varve) age of the segment boundaries, with the associated error, are shown in the VT (varve time) column of Fig. 1.

Results and discussion

Varve chronology of core SO89-17

The described varve-counting results were used to build a floating radiocarbon-varve chronology for Soppensee. This was done by matching the varve counts at a certain depth to the appropriate macrofossil ^{14}C dates for that depth (Table 1). The part of the Soppensee chronology corresponding to the first 2900 varve years has a high resolution of radiocarbon dating and a varve time scale based on continuous varve counting (segment I on Fig. 1). We compared this part of our radiocarbon/varve chronology with the tree ring curve (Stuiver et al. 1986) in order to place the floating varve chronology on the absolute time scale. A best fit to the calibration curve, based on a least square minimizing method, located the beginning of the Soppensee chronology at 6869 ± 38 cal y BP on the absolute time scale (Fig. 3).

In comparing the two chronologies (Fig. 3), it is apparent that, throughout more than 4000 calendar years (7000 to 11 000 cal y BP), the Soppensee chronology follows the dendro-calib curve very closely. Notably, a characteristic feature of the dendro curve, e.g. the ^{14}C plateau at 9500 ^{14}C y BP (Kromer and Becker 1993), is reconstructed in the Soppensee curve (Fig. 3).

At a depth of 539.5 cm in core SO89-17 (9900 ^{14}C y BP and 11 120 cal y BP) the laminations are no longer continuous, i.e. intervals of unlaminated sediment alternate with intervals of laminated sediment in segment IV (Fig. 1). Thus, the absolute ages obtained by varve counting may be too low and the resulting absolute time scale becomes problematic. Because of the presence of the 10 000 ^{14}C plateau at the end of the dendrocalibration curve, it is impossible to see or estimate the effect of the intervals of unlaminated sediment on the absolute dating in this time range. Three data points in the Soppensee chronology from segment IV (see Fig. 3) appear to lie on this 10 000 ^{14}C plateau (on the dendro curve between ~11 100–11 450 cal y BP) but their varve ages may be slightly underestimated. Moreover, the number of years which are missing in our uncorrected varve chronology (Fig. 3) increases with depth as only the visible varves in segment IV are counted. Finally, a lack of varves in segment IV shifts all of the data points of this segment and the segments below (older than 10 000 ^{14}C y BP) towards younger ages on the (absolute) varve time scale. Note that segment IV, containing intervals of unlaminated sediment, corresponds entirely to the Younger Dryas biozone (see Fig. 1 and 4). Thus, the varve-years which are missing affect the determination of the length of this period. Additionally, a number of years are also missing due to the presence of a short, unlaminated interval in segment V (sediment surrounding the LST).

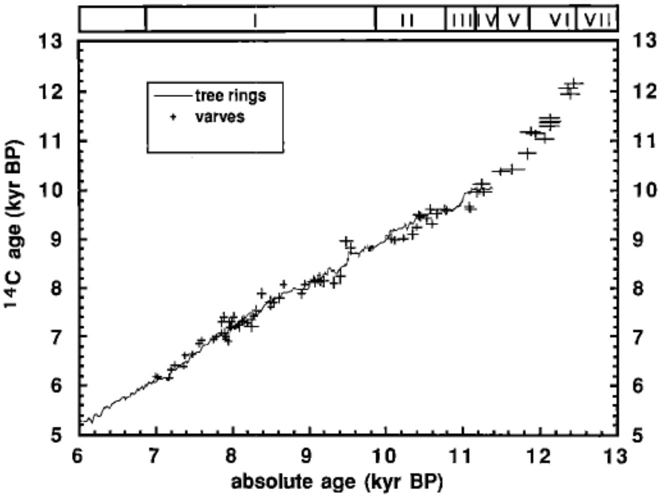


Fig. 3. The floating varve-radiocarbon chronology, which was constructed on the basis of varve counting and dated with the radiocarbon dating method (see text) was fitted to the dendrocalibration curve (Kromer and Becker 1992; Stuiver et al. 1986). Radiocarbon ages are plotted with one sigma (Table 1). The errors plotted on the varve time scale include maximal deviation between VT and results of each counting. The number of varves corresponding to the size of sediment samples taken for radiocarbon dating is included in the error of varve counting

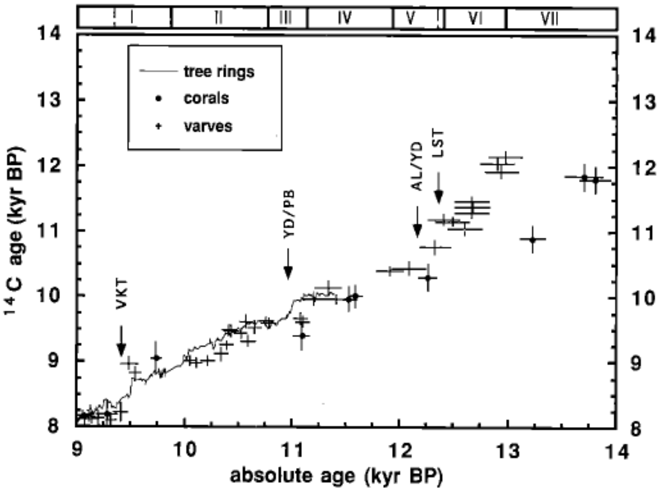


Fig. 4. The Soppensee radiocarbon-varve chronology corrected for unlaminated sediment is plotted together with the tree curve (Kromer and Becker 1992; Stuiver et al. 1986) and results from dating on corals (Bard et al. 1991; Bard et al. 1990). The correction of varve time in Soppensee for samples below 539.5 cm is shown in Table 2. *Arrows* indicate the VKT and the LST ash layers. The boundaries of the Younger Dryas biozone were found on the base of pollen stratigraphy on core SO89-17

Correction for missing varves

In order to estimate the number of missing varve-years, we assume that the sedimentation rate of unlaminated sediment is the same as that in the immediately surrounding laminated sediment. The sedimentation rate in segment IV was interpolated from the sedimentation rates of segments II, III and the parts of V which are well laminated. In segment II and III (above the sediment with unlaminated intervals), approximately 28 varves per centimetre were counted (mean value from 40 cm). In the sediment below (segment V, laminated part), 24 varves per centimetre were estimated (mean value from 16 cm). The mean value of 26±2 varves/cm was used to calculate a corrected number of varves for segment IV.

The same procedure was applied to the layer of unlaminated sediment, which is present on the bottom of segment V. In this case, the values of 24 varve/cm and 30 varve/cm in segments V and VI, respectively, were considered and the mean value of 27±3 varve/cm was used for an estimation of the missing varves. Corrections for both intervals were then added to the varve time of the varve chronology. The deviation from the minimal and maximal corrections is included in the total error of the corrected varve chronology (Table 2).

Implications of the corrected Soppensee chronology

The final Soppensee varve chronology consisting of two parts, the continuously counted Holocene (6000 to 10000 ^{14}C y BP) and the corrected varve chronology of the late Glacial (10000 to 12000 ^{14}C y BP), yields a number of interesting results (Fig. 4).

The VKT ash layer, present in the Holocene part of the chronology (474 cm, Fig. 1), is a biotite- and amphibole-bearing trachytic tephra thought to have originated from the Vasset or the Killian volcano in the Chaine des Puys volcanic district of the Massif Central region, France (Juvigné 1991; Juvigné et al. in press). Macrofossils selected from the sediment sample at the same level as the VKT ash layer were radiocarbon dated at 8230±140 ^{14}C y BP and the sample selected just above the VKT ash layer (i.e. 90 cal y) yielded a radiocarbon age of 8110±100 ^{14}C y BP (see Table 1 and Fig. 4). The results of varve counting place the VKT at 9407±44 y BP calendar age which corresponds to a radiocarbon age of 8300 to 8500 ^{14}C y BP. In lake and bog deposits of the Massif Central region, the Chopine, the Vasset and the Killian tephra deposits are located at the same stratigraphic horizon. Juvigné et al. (in press), give an age of around 8500 ^{14}C y BP, which is an average of ten radiocarbon ages for these deposits. Only the V/K tephra fall extended into Switzerland (Juvigné 1991), thus our ^{14}C chronology dates this eruption uniquely.

In the Soppensee sedimentary record, the transition between the Younger Dryas and the Preboreal biozones is defined on the basis of pollen analyses (Lotter et al. 1991; Lotter 1991b). In core SO89-17, this boundary is placed at the depth 534±0.5 cm. The radiocarbon age obtained on macrofossils from depth 537 cm is 9665±95 ^{14}C y BP and the age of the sample from depth 542.5 cm is 9970±100 ^{14}C y BP. The corresponding absolute age of 10986±69 cal y BP for 534±0.5 cm was determined by continuous varve counting. These results agree well with results of the German pine chronology, i.e. a radiocarbon age around 9700 ^{14}C y BP and the calendar age of 11050 cal y BP, which were found by Kromer and Becker from an isotopic study (δ^{13}C and δD) of the wood (Kromer and Becker 1991; Kromer and Becker 1993). However, the preliminary results of dating for the δ^{18}O profile of the Greenland ice cores, which were just recently published, place the isotopic transition from the

Table 2. Varve time (Table 1) of samples below depth 539.5 cm was corrected for the presence of unlaminated sediment.

Depth in core SO89-17 (cm)	^{14}C age (y BP)	VT (y BP)	Correction (y)	Corrected VT (y BP)
540.5–544.5	9970±100	11178±104	26± 8	11204±104
544.5–549.5	10135±100	11235±117	100± 16	11335±118
549.5–551.5	9965± 75	11270± 99	143± 25	11413±102
568.5–569.5	10400± 70	11490±101	419± 69	11909±123
573.5–580.5	10440±100	11634±137	454± 76	12088±157
593–595	10760±105	11828±108	498± 87	12329±139
596.5–598.5	11190± 80	11872±109	540± 97	12412±146
599.5–601.5	11160± 60	11938±110	550±108	12488±154
603.5–605.5	11050± 80	12054±108	550±108	12604±153
605.5–606.5	11470± 70	12118±108	550±108	12668±153
606–808	11380±105	12118±108	550±108	12668±152
609.5–610.5	11300± 90	12118±107	550±108	12668±152
610.5–611.5	11385± 90	12131±108	550±108	12681±152
628.5–630.5	11040± 90	12354±107	550±108	12904±152
631–632	11930± 90	12390±106	550±108	12940±151
633–634	12150± 90	12427±106	550±108	12977±151

The number of varves ion segment IV and in a short unlaminated layer of segment V (Fig. 1) was estimated using the sedimentation rate calculated for laminated sediment. The error of the correlation is included in the total error of the VT

Younger Dryas to the Preboreal at 11550±70 cal y BP (GRIP) (Johnsen et al. 1992) and 11680±250 cal y BP (GISP2) (Taylor et al. 1993).

The beginning of the Younger Dryas biozone was located using pollen stratigraphy at a depth of 584±0.5 cm in core SO89-17. The absolute age is estimated by the corrected varve chronology at 12125±86 cal y BP. Thus, the estimated length of the Younger Dryas biozone is 1140 y. Dating of the Greenland ice cores yields 1150 y (Johnsen et al. 1992) and 1300±70 y (Taylor et al. 1993) for the duration of the Younger Dryas period.

The radiocarbon ages of 11190±80 ^{14}C y BP and 10760±105 ^{14}C y BP of a sample taken two centimetres below and one taken one centimetre above the LST ash layer, respectively, agree with the average of 11000 ^{14}C y BP quoted by Bogaard and Schminke (1985). From the corrected varve chronology, an absolute age of the LST eruption is estimated at 12350±135 cal y BP.

A sample made of fruits of dwarf birch *(Betula nana)* and fragments of a twig, recovered 50 cm below the onset of rhythmic sedimentation in core SO89-17, yielded the oldest radiocarbon age of 14190±120 ^{14}C y BP. This sample was found in clay deposits which, in shoreline Soppensee cores, overlie the coarse-grained fluvioglacial sediments. The data agrees well with other dates from northern Switzerland (e.g. Zurichsee 14600 ^{14}C y BP (Lister 1988)) which imply an ice-free foreland of the Alps by 14000–15000 ^{14}C y BP (Schlüchter 1988).

In Fig. 4, the corrected Soppensee chronology and the results of radiocarbon and U/Th dating on corals are compared. The existing dendro curve is also included on this graph for reference. Both chronologies, varve counting and recently published new data from corals (Bard et al. 1991), place the 10000 ^{14}C plateau between 11200 and 11500 cal y BP on the absolute time scale. However, beyond the ^{14}C plateau at 10000 ^{14}C y BP, the varve chronology and the U/Th time scale begin to deviate from each other and the difference reaches 800 to 1000 ^{14}C y at the end of the Soppensee chronology (12000 ^{14}C y BP). In order to prove whether the correction for the years missing in the Soppensee record was sufficient, radiocarbon-varve chronologies reaching beyond 10000 ^{14}C y BP from other lakes are needed. In this way, the varve-chronology dating method might help the extension of the radiocarbon calibration curve.

Summary

The results presented in this study confirm the utility of laminated sediment for dating, despite all the discussed limitations of varve counting. The agreement between the Soppensee varve-radiocarbon curve with the dendro-curve over the period where laminations are well preserved is striking. This proves that the counted varves were deposited annually. The difficulty arises when rhythmic deposits are not present in the sediment. From the Soppensee sediment we learned that the highest probability of losing years, counting too low number of varves, is connected with specific sediment layers. Such layers of unlaminated/mixed sediment should be carefully considered to avoid possible errors in varve chronology.

The remaining discrepancy between the Soppensee varve chronology and the results of the radiocarbon and U/Th dating on corals requires more studies on different lakes with laminated sediment. For the final establishment of the radiocarbon-varve chronology, local problems with varves must be overcome. Radiocarbon dating on Lake Holzmaar (Germany), currently in progress, may provide first results for the discussion of radiocarbon and varve time scales extending back to 12500 ^{14}C y BP (Hajdas, in preparation). Also, construction of a radiocarbon time scale for laminated Lake Gosciaz in Poland would be helpful, as the varve chronology and results of isotope studies (Rozanski et al. 1991) provide absolute timing for the termination of the last deglaciation, i.e. the Younger Dryas.

Although the duration of the Younger Dryas biozone in Soppensee agrees with the length of the Younger Dryas which is seen in the δ^{18}O and the dust records of the newest ice cores from Greenland summit, the absolute chronologies of the last deglaciation are not synchronous. Thus, the problem with the correlation and timing of climatic signals obtained from pollen stratigraphy and those from ice cores remains open.

Acknowledgements. We would like to thank Bernd Kromer and Bernd Becker for providing us with the extension of the dendrocalibration curve prior to its publication. This project was supported by the Swiss National Science Foundation.

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