AGE-DEPTH MODEL OF LAKE SOPPENSEE (SWITZERLAND) BASED ON THE HIGH-RESOLUTION ^{14}C CHRONOLOGY COMPARED WITH VARVE CHRONOLOGY

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ABSTRACT. An age-depth model for laminated sediments of Lake Soppensee is constructed using radiocarbon ages of macrofossils and a depositional model of the OxCal v 4.1 program with the updated IntCal09 data set. The resulting calendar chronology is compared with the varve chronology that was built for this record in a previous study (Hajdas 1993); there is a very good agreement between the 2 approaches. This illustrates the potential of high-resolution ^{14}C dating for construction of reliable, high-resolution calendar timescales for sedimentary records. Based on the age-depth model of this study, the Vasset/Killian tephra found in sediment of Soppensee dates to a calendar age of 9291–9412 cal BP (2-σ range) while the Lachersee tephra dates to 12,735–12,871 cal BP (2-σ range). Precise dating of the Late Glacial boundaries is possible with this chronology but requires more precise correlation between proxies and records than typically practiced.

INTRODUCTION

The quest for high-resolution records of past climate changes was initiated by ice-core studies more than 2 decades ago. Discovery of abrupt changes in temperature recorded in layers of ice from the Greenland ice cap (Dansgaard et al. 1993) called for research and comparison with continental and deep-sea records. The annual or nearly annual resolution of ice-core records provides a high-resolution chronological frame for these archives. Tree rings have comparable or better resolution to ice-core records; however, most of the archives that are typically researched for past environmental and climate changes are lake or deep-sea sediments. Therefore, development of high-resolution chronologies for many sedimentary records would enhance the potential of those studies.

Laminations in sedimentary deposits might be of annual or seasonal frequency, and therefore, can provide high-resolution chronologies. Numerous sites have been studied, the most famous being the annual laminations deposited at the edge of the Fenno-Scandinavian Ice Sheet, used by the Swede G De Geer (1912) to establish a chronology of deglaciation in this region. Consequently, the Swedish word "varve" is used to describe the annual deposits of sediments or annual laminations. The search for laminated sediments continues, and research on the already discovered ones is being intensified for reasons stated above.

Despite the impressive number of sites discovered around the world that are known to have laminated or even annually laminated sediments, most archives are not laminated but are equally vital to past climate research. For these records, reliable chronologies are needed and are usually based on radiocarbon ages of deposits selected at various depths. However, it is often argued that chronologies are impaired by the complicated nature of the ^{14}C timescale and calibration of ^{14}C ages. A reliable age-depth model of the records is then the next step in building a chronology needed for comparison with historical records or with ice-core data. As discussed in the literature (Telford et al. 2004a,b; Heegaard et al. 2005), the reliability of such models must be tested.

Recently developed calibration programs that incorporate a Bayesian approach (Buck et al. 1996) alleviate this problem to a certain degree and provide tools for building reliable age-depth models of sedimentary records dated using ^{14}C (Buck et al. 1999; Bronk Ramsey 1995, 2001, 2008; Bronk

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Ramsey et al. 2001; Blockley et al. 2004, 2007). Such models incorporate independent information about the samples such as their stratigraphic order, which combined with the calibration of ^{14}C ages, give the most probable calendar age range for the sample (Bronk Ramsey 2008).

In this study, we present the potential of ^{14}C dating to construct high-resolution chronologies of sedimentary records that are comparable to counting annual laminations (i.e. varves). To demonstrate this, we applied the *P_Sequence* model that is implemented in OxCal v 4.1 (Bronk Ramsey 2008) to obtain a calendar chronology based on ^{14}C ages of macrofossils from Soppensee sediments and compare this with the varve chronology of the sediment core that was previously sampled for ^{14}C dating (Hajdas 1993; Hajdas et al. 1993).

THE SITE

Soppensee is a small lake that was formed on the central Swiss Plateau (8°05′E, 47°05′30″N) immediately after retreat of the Reuss Glacier from the Swiss Alpine foreland at the end of last glaciation ~17–18 ka cal BP. The lake's small area and relatively great depth (0.227 km^2 and 27 m [central part], respectively) may be responsible for creating anoxic conditions that preserved the lake sediment from bioturbation that would have destroyed the laminations. The lake sediment is annually laminated for the most part of the early-mid Holocene. The annual laminations are made of light, carbonate (spring/summer) and dark, organic matter (fall/winter) layers (Lotter 1989). The laminations allowed high-resolution reconstruction of the past environmental conditions (Fischer 1996; Lotter 1999, 2001) and provided an opportunity for comparison with ^{14}C dating (Hajdas et al. 1993).

^{14}C CHRONOLOGY OF SOPPENSEE SEDIMENTARY RECORD

High-resolution sampling (1-cm slices) of sediment and selection of terrestrial macrofossils was possible for most of the Holocene section. A total of 103 samples were dated using accelerator mass spectrometry (AMS) by Hajdas et al. (1993) and this study (Table 1). Most of the samples contained 2 mg of carbon and were made of small (short-lived) remains of plants: seeds of trees, leaves, needles, fragments of flowers, etc., which were very well preserved in the anoxic conditions of the laminated sediment layers. Selection of terrestrial macrofossils assured that material used for dating was free of "hardwater effect." Because of the bedrock, this lake is known to contain dissolved old carbonates that could affect the ^{14}C ages of total organic carbon (TOC). Three ^{14}C ages date the deepest non-laminated section of the sediment core SO89-17 (Figure 1). The oldest ^{14}C age of 14,190 ± 120 BP is one of the oldest ^{14}C ages known for lakes formed by retreating glaciers during the deglaciation in Switzerland (see Ivy-Ochs et al. 2008). The next 20 ages were obtained from the partly laminated sediment between 640 and 540 cm. The first 3000 yr of Holocene sediment were annually laminated with well-preserved laminations. High-resolution sampling was performed and 70 macrofossil samples were dated between 488 and 362 cm (Hajdas 1993). The top 360 cm of sediment do not show distinct laminations. Only 10 samples were measured for the upper sediments between 190 and 370 cm (Table 1). The uppermost sediment has not been ^{14}C dated.

Table 1 All ^{14}C ages (including outliers) of macrofossils selected from Soppensee sediments (different cores). Ages marked with asterisks (*) are this study; the remaining were published by Hajdas (1993). Shaded cells mark unlaminated section of the core.

Sample nr (ETH-)	Core/depth in core (cm)	Depth in core SO89-17 (cm)	^{14}C age (BP)	δ^{13}C (‰)	Notes^a
10973	23/218–220	188–190	1495 ± 55	–24.5 ± 1.2	(*)
10972	23/244–245	214–215	2145 ± 55	–24.7 ± 1.2	(*)
12339	23/260–261	230–231	2365 ± 55	–28.6 ± 1.2	(*)

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Sample nr (ETH-)	Core/depth in core (cm)	Depth in core SO89-17 (cm)	^{14}C age (BP)	δ^{13}C (‰)	Notes[a]
10971	23/292–293.5	267–268.5	3310 ± 70	–17.8 ± 1.2	(*)
7404	23/310–311	285–286	3810 ± 60	–28.4 ± 1.6	(*)
10970	23/330–332	306–308	4435 ± 60	–27.0 ± 1.2	(*)
10968	23/345–347	320–322	4445 ± 80	–18.0 ± 1.2	(*)
10969	23/349–351	324–326	4845 ± 75	–28.6 ± 1.4	(*)
12338	23/362.5–364	340–343	4910 ± 60	–26.9 ± 1.2	(*)
10967	23/390.5–393	370–373	5660 ± 75	–28.2 ± 1.4	(*)
7210/7352		390–391	6190 ± 40	–27.6 ± 1.0	
7353		391–392	6180 ± 55	–30.4 ± 0.8	
7386		397–398	6170 ± 50	–28.5 ± 1.0	
7211		398–399	6325 ± 50	–31.5 ± 1.1	
7387		399–400	6425 ± 55	–30.0 ± 1.0	
7388		403–404	6405 ± 55	–26.7 ± 1.0	
7212/7354		404–405	6620 ± 40	–28.6 ± 1.0	
7213		408–409	6640 ± 55	–30.9 ± 1.2	
7214		411–412	6850 ± 55	–31.7 ± 1.2	
7215		412–413	6930 ± 50	–31.3 ± 1.2	
7216		418–419	6945 ± 55	–31.3 ± 1.2	
7217		419–420	6990 ± 55	–32.6 ± 1.2	
6239	14/320–321	422–423	7300 ± 90	–31.5 ± 1.6	excl
7218		422–423	7080 ± 50	–29.2 ± 1.2	
7621		423–424	7405 ± 85	–26.3 ± 1.6	s/excl
6238	14/321–323	423–425	7075 ± 90	–30.0 ± 1.6	
7586		424–425	7010 ± 50	–29.7 ± 1.1	
7389		424–425	6965 ± 65	–15.7 ± 1.0	
7587		425–426	6900 ± 55	–31.5 ± 1.1	excl
6237	14/323–324	424.5–42.5	7300 ± 85	–27.7 ± 1.7	
7588		426–427	7195 ± 80	–28.9 ± 1.1	
6236	14/324–325	426.5–427.5	7315 ± 90	–30.8 ± 1.8	
6235	14/325–326	427.5–428.5	7405 ± 90	–27.4 ± 1.6	
7390		428–429	7215 ± 55	–28.7 ± 1.0	
7589		429–430	7245 ± 55	–23.6 ± 1.1	
7590		430–431	7230 ± 110	–32.1 ± 1.1	
7622		431–432	7310 ± 85	–28.8 ± 1.7	s
7391		432–433	7335 ± 80	–25.7 ± 1.0	
7591		434–435	7285 ± 70	–31.1 ± 1.1	
6233	14/331–336	433.5–438.5	7205 ± 95	–25.4 ± 1.6	
7592		436–437	7360 ± 90	–27.1 ± 1.1	
7593		437–438	7425 ± 55	–32.4 ± 1.1	
7392		438–439	7550 ± 75	–22.1 ± 1.0	
6232	14//336–339.5	439–442.5	7885 ± 95	–28.9 ± 1.7	excl
6231	14/339.5–344	443–447.5	7710 ± 100	–31.9 ± 1.6	
7393		445–446	7620 ± 60	–28.8 ± 1.0	
5296	14/343	447	7710 ± 80	–27.4 ± 1.2	
6230	14/344–347	448–451	7800 ± 95	–37.8 ± 1.6	
5295/6103	14/347	451	8060 ± 60	–24.6 ± 1.0	
5292	14/348–351	453–455.5	7615 ± 80	–30.0 ± 1.2	s/out

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Sample nr (ETH-)	Core/depth in core (cm)	Depth in core SO89-17 (cm)	^{14}C age (BP)	δ^{13}C (‰)	Notes[a]
7394		454–455	7600 ± 60	–29.9 ± 1.0	out
7594		456–457	7470 ± 100	–31.5 ± 1.1	s/out
7623		458–459	7880 ± 90	–21.9 ± 1.6	s
6144/6152	14/355	459.5	8080 ± 65	–33.3 ± 1.0	
6143	14/356–360	460.5–464.5	8120 ± 95	–27.8 ± 1.0	
7395		462–463	8180 ± 60	–28.3 ± 1.1	
5291	14/358–360	463–465	8165 ± 75	–24.3 ± 1.2	
7355		464–465	8115 ± 65	–29.7 ± 0.9	
6142	14/360–363	464.5–467.5	8140 ± 100	–34.8 ± 1.0	
6141	14/363–366	467.5–470.5	7880 ± 100	–32.1 ± 1.2	s/out
6139	14/367–370	471.5–474.5	8110 ± 100	–30.7 ± 1.0	s/VKT
8246		472–475	7705 ± 100	–23.0 ± 1.0	s/out
9641	12/VKT	473–475	8230 ± 140	–25.1 ± 1.3	s/VKT
9505	12/1–3 cm below VKT	475–479	8970 ± 95	–20.5 ± 1.0	excl
9504	19/1–5 cm below VKT	476–481	8820 ± 100	–20.5 ± 1.4	
6614		494.5–496.5	9020 ± 75	–24.8 ± 2.1	s
6615		496.5–497.5	8990 ± 70	–32.9 ± 2.0	s
6616		500.5–501.5	9020 ± 65	–28.4 ± 1.9	
6936		504.5–506.5	9115 ± 95	–22.8 ± 1.4	s
6617		506.5–507.5	9255 ± 60	–33.5 ± 0.9	
6618		507.5–508.5	9495 ± 70	–28.2 ± 1.1	excl
6619		508.5–509.5	9475 ± 85	–30.5 ± 3.8	
6620		512.5–514.5	9440 ± 70	–22.4 ± 1.5	s
7699		514.5–516.5	9620 ± 100	–25.6 ± 1.0	s
6621		516.5–518.5	9320 ± 75	–17.8 ± 2.0	s
7700		518.5–520.5	9530 ± 95	–24.4 ± 1.3	s
6622		523–524	9625 ± 65	–29.0 ± 0.9	
6623		524–525	9595 ± 70	–13.5 ± 1.9	s
7709		534.5–537.5	9665 ± 95	–26.1 ± 1.0	s
6802		537.5–539.5	9620 ± 80	–30.4 ± 2.1	s
7701		540.5–544.5	9970 ± 100	–22.6 ± 1.0	
7710		544.5–549.5	10,135 ± 100	–26.0 ± 1.0	
6803		549.5–551.5	9965 ± 75	–22.3 ± 2.0	
7702		558.5–563.5	9740 ± 100	–21.6 ± 1.0	s/out
6929		568.5–569.5	10,400 ± 70	–30.0 ± 2.1	
7703		573.5–580.5	10,440 ± 100	–22.0 ± 1.0	
7704		584.5–590.5	10,020 ± 110	–21.1 ± 1.0	s/out
5303	14/476–479	589–592	10.070 ± 155	–22.0 ± 1.2	s/out
5290	14/479–482	593–595	10.760 ± 105	–31.4 ± 1.2	s/LST
6930		596.5–598.5	11,190 ± 80	–30.1 ± 1.1	LST
5304	14/482–485	596–600	10,540 ± 150	–20.7 ± 1.2	s/out
6932		599.5–601.5	11,160 ± 60	–27.2 ± 1.0	
6804		603.5–605.5	11,050 ± 85	–21.1 ± 1.8	
6933		605.5–606.5	11,470 ± 70	–26.4 ± 1.1	
5305	14/491–493	606–808	11,380 ± 105	–28.1 ± 1.6	s
6805		609.5–610.5	11,300 ± 85	–32.4 ± 1.8	
6806		610.5–611.5	11,385 ± 90	–22.6 ± 1.8	s

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Sample nr (ETH-)	Core/depth in core (cm)	Depth in core SO89-17 (cm)	^{14}C age (BP)	δ^{13}C (‰)	Notes[a]
6807		628.5–630.5	12,040 ± 90	–31.8 ± 2.0	
6808		631–632	11,930 ± 90	–32.3 ± 1.8	s
6809		633–634	12,150 ± 90	–41.6 ± 1.9	s
8726		644.5–645.5	12,190 ± 120	–26.3 ± 1.2	s
8725		679.5–680.5	13,280 ± 150	–19.4 ± 2.0	s
8727		681.5–682.5	14,190 ± 120	–27.1 ± 1.0	s

[a] In Notes column, samples <1 mg are marked by "s." If the age was an outlier identified by Hajdas (1993), it is marked as by "out"; if the age was excluded from the present age-depth model, it is labeled "excl."

VARVE CHRONOLOGY OF SOPPENSEE

The quality of the laminations in the Soppensee record changed depending on the environmental conditions (Figure 1). The early deposits shortly after the lake was formed were not laminated. The first laminations appear during the Bølling-Allerød (BO/AL) warm period. The layer of Laacher See tephra (LST) that was identified in all Soppensee cores was deposited at the end of the BO/AL and followed by the Younger Dryas cold reversal (Hajdas et al. 1993; Fischer 1996; Lotter 1999). During this cold period, laminations occurred sporadically, resulting in discontinuous sections of varves. Even when present, the laminations are of poor quality in the whole of the Late Glacial. It is only at the beginning of the Holocene that the laminae become distinct and provide a continuous high-resolution record.

Counting the distinct varves of Holocene section has been done on thin sections and pictures of thin sections. The resulting floating varve chronology had to be anchored to the calendar timescale, i.e. the top of the chronology had to be dated.

In a previous study (Hajdas 1993), ^{14}C ages of macrofossils were paired with relative varve counts and such floating varve chronology was fitted (χ^2 fit) to the first international dendro-calibration curve published by Stuiver et al. (1986). The first ^{14}C age in the section with counted varves (ETH-7210/7352; 6190 ± 40 BP) was then placed at 6996 ± 34 cal BP and the floating varve chronology was anchored to the calibration curve. Because the Soppensee varve chronology begins 127 yr earlier than the anchor point, the top of the section with counted varves was dated at 6869 ± 34 BP (Figure 1). This provided a high-resolution age-depth model for the Holocene laminated sediments but not for the upper unlaminated section and the Late Glacial sections. There the age must rely on the ^{14}C dating, which would be difficult if only calibration of ^{14}C ages is considered without information about the sequence of ^{14}C ages.

The first step of this study was to match the floating varve chronology of Soppensee to the present calibration curve IntCal09 (Reimer et al. 2009). The same 65 ^{14}C dates from the distinctly laminated part of the core (depth 390–537 cm), which were used in the previous fit to the 1986 calibration curve (see above and Hajdas 1993), were now fitted using the OxCal v 4.1 wiggle-matching procedure, function *D_Sequence* (Bronk Ramsey 2001). The first ^{14}C date in the laminated section was placed at a calendar age (mean) of 7055 ± 7 cal BP, which is 59 yr older than the anchor found by Hajdas (1993). However, the quality of the agreement was rather poor (A_{comb}<0.1%, $\chi^2/df = 2.78$) because as many as 11 dates were outliers, with an agreement index smaller than 10%. In the next step, these outliers were removed and a fit to the IntCal09 calibration curve using the OxCal *D_Sequence* pro-

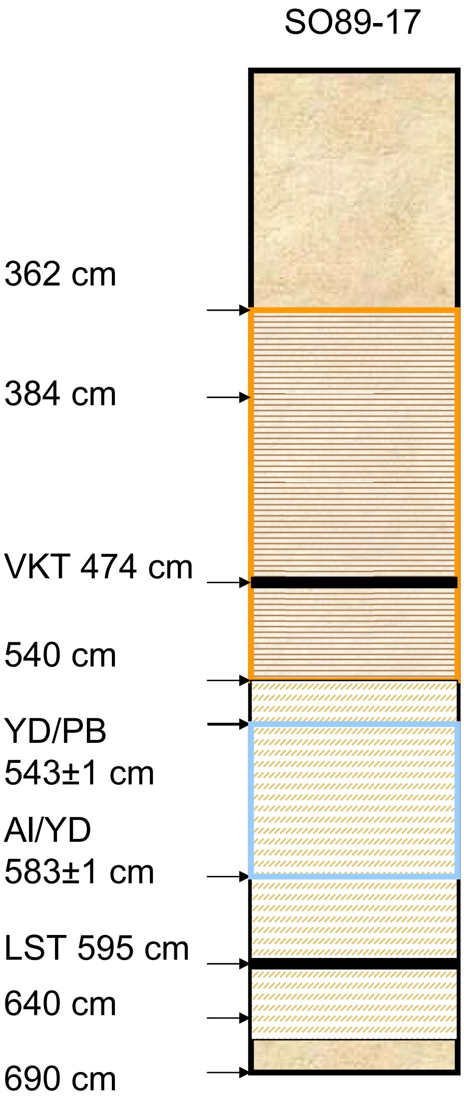

Figure 1 Sedimentary record of the core SO98-17 (not to scale) showing the non-laminated sediments sections (690–640 cm), poorly laminated sediments of the Late Glacial (640–540 cm), and very well laminated Holocene sediments (540–362 cm). The top 362 cm of the core are not laminated or poorly laminated. The top of the varve chronology is marked at 384 cm; the tephra layers Vasset/Killian tephra (VKT; 474 cm) and Laacher See Tephra LST (595 cm) are shown as lines. The YD cold period is marked between 583 and 543 cm.

cedure was performed using a group of only 54 dates. In this case, the final fit did not change considerably: the first ^{14}C date (ETH-7210/7352) corresponds to the calendar date (mean) 7057 ± 7 cal BP, but significance of the fit improved substantially (A_{comb} = 15.6%, $\chi^2/df = 1.27$). Therefore, this calendar age, which is shifted by 61 yr towards the older ages in comparison to the anchor obtained in 1993, was chosen as the new calendar age for the floating ^{14}C-varve chronology.

COMPARISON OF VARVE CHRONOLOGY WITH AGE-DEPTH MODEL

The age-depth model was constructed based on 65 ^{14}C dates from the distinctly laminated part of the Soppensee core; 16 dates from the bottom, poorly laminated section; and 10 dates from the upper, non-laminated sediment section (Figure 1). We decided not to include ^{14}C dates that were identified as outliers in previous study (Hajdas 1993): 5 dates from the laminated part of the core and 4 dates from the bottom, unlaminated part. All came from small samples that contained <1 mg of carbon (note that the AMS measurements were performed in the early 1990s). The age-depth model was developed with the aid of the OxCal 4.1 *P_Sequence* function (Bronk Ramsey 2008), in which calendar ages for a sequence of ^{14}C ages are calculated. This function requires estimation of the k parameter, which describes a magnitude of random variation from a constant sedimentation rate. Bronk Ramsey (2008) and Blockley et al. (2008) used $k = 3$ cm^{-1} for the Soppensee chronology. We decided to test the agreement between the varve chronology and the age-depth model for 3 different values of k (0.5, 3, and 10 cm^{-1}).

Another problem to deal with was the treatment of outliers. The first approach was to point out ^{14}C dates from small samples (<1 mg of C) that were suspected to be outliers, using the OxCal v 4.1 *Outlier* command (Bronk Ramsey 2009). However, the first calculations showed that in most cases, the dates suspected to be outliers were consistent with the model (with the values of the agreement index greater than 60%), whereas many "unsuspected" dates were inconsistent. Therefore, similarly to the approach used to calculated the new anchor of the varve chronology, dates with very low values of the agreement index between "prior" and "posterior" (modeled) likelihood distribution (<10% for $k = 10$ cm^{-1} and at the same time <60% for $k = 0.5$ and 3 cm^{-1}) were excluded from the model. Such low values of the agreement were found for 7 dates: 6 dates from the laminated part of Soppensee core and 1 date from the bottom part. Finally, the age-depth model was constructed using 59 ^{14}C dates from the laminated part, 15 dates from the bottom, and 10 dates from the upper part of the Soppensee core.

Construction of the *P_Sequence* age-depth model was repeated for $k = 0.5$, 3, and 10 cm^{-1} and the results of these 3 versions of the model were compared with the varve chronology. The section between 380–540 cm with good laminations and varve chronology was chosen for this comparison. The comparison was done by calculation of the agreement index between the modeled (posterior) calibrated ^{14}C age probability distribution and the varve age distribution for each pair of the ^{14}C and varve ages and then the overall agreement index of the analyzed section of the chronology. In order to quantitatively estimate a degree of agreement between the results of the *P_Sequence* age-depth model and the varve chronology, we used agreement indices defined similarly as the indices calculated in the OxCal program when "prior" and "posterior" distributions are compared (Bronk Ramsey 1995, 2001). For the individual varve that was dated by ^{14}C, the modeled (posterior) likelihood distribution $p_m(t)$ was compared with the likelihood distribution of the varve time $p_v(t)$. The individual agreement index A was thus calculated as follows:

$$A = \frac{\int p_v(t) \cdot p_m(t)}{\int p_v(t) \cdot p_v(t)}$$

where $p_v(t)$ is the likelihood distribution of varve age and $p_m(t)$ is the modeled (posterior) likelihood distribution of the date, obtained as a result of the OxCal *P_Sequence* age-depth model.

The likelihood distribution of the varve age $p_v(t)$ was assumed to have a Gaussian distribution. To check the agreement of a group of n pairs—the modeled likelihood distribution and the varve time likelihood distribution—for a given time (depth) interval, the overall agreement index A_{overall} was determined. It was defined by the following formula:

$$A_{overall} = \left\{ \prod_{i=1}^{n} A_i \right\}^{1/\sqrt{n}}$$

where A_i is the individual agreement index calculated for the pair number i. The overall agreement index, which is identically defined, in the OxCal program is calculated to test model consistency (Bronk Ramsey 1995). Both the overall and individual agreement indexes are expressed in percent.

RESULTS AND DISCUSSION

Results of the age-depth model with various *k* parameters are presented in Figures 2a–c. This comparison shows that the number of ^{14}C-varve age pairs with an individual agreement index <60% decrease and the overall agreement index increases for higher *k* values. The best agreement between varve chronology and the OxCal *P_Sequence* age-depth model ($A_{overall} = 54.5\%$) is observed for $k = 10$ cm^{-1}. The overall agreement index of the *P_Sequence* age-depth model for $k = 10$ cm^{-1} has a value slightly lower than 60%, but when only 1 date with the lowest individual agreement index (ETH-6142, A = 33.0%) is removed from the model the overall agreement index increases to 62.9%. Such a good agreement demonstrates the effectiveness of the age-depth construction; at the same time it shows the precision and accuracy of the Soppensee varve chronology. It is worth noting that the value of the *k* parameter, for which the agreement between the varve chronology and the age-depth model is the best, corresponds to varve thickness that are <1 mm thick. A high value of the *k* parameter means that the age-depth model is closer to linear and shows that fluctuations of deposition process were small and that conditions at the Lake Soppensee were rather stable during the time period 6700–11,275 cal BP (depth 380–540 cm). Therefore, the parameter $k = 10$ cm^{-1} was chosen for the whole Soppensee chronology.

In Figures 3 and 4, the final age-depth model constructed with assumed value of the *P_Sequence* parameter $k = 10$ cm^{-1} is presented. The same results of the model (gray strip: 95% confidence intervals of the posterior likelihood distributions; *P_Sequence* parameter $k = 10$ cm^{-1}) are plotted in Figure 5 together with the varve chronology (black line). This figure illustrates the importance of the quality of the laminations for construction of varve chronologies. In the distinctly laminated part of the core (depth 380–540 cm), the *P_Sequence* age-depth model and the varve chronology are in a very good agreement. However, from the onset of the poorly laminated part (depth 540 cm), an offset between these 2 chronologies can be observed. Years appear to be missing in the Varve Time (VT) of the 1993 study in comparison to the age-depth model due to the poor preservation of varves, which caused erroneous counting, as well as a total lack of laminations. For this part of the Soppensee record, the age-depth model provides the only reliable chronology.

CHRONOLOGY OF SOPPENSEE BASED ON AGE-DEPTH MODEL

To verify the reliability of the ^{14}C-based chronology of Soppensee, we studied the ages for climatic changes observed in this sediment. The set of distinct markers identified in Soppensee sediments (Hajdas 1993; Fischer 1996) allows correlation between ^{14}C-dated cores and other cores studied for pollen (Lotter 2001) and stable isotopes (Fischer 1996). The age-depth model for the Holocene sediments is also of interest for the upper, not laminated sediment section. Although events of the Late Glacial section can be dated, it must be kept in mind that the age-depth model relies on ^{14}C ages of the record, the applied *P_Sequence*, but also on the calibration curve. This study uses the IntCal09 data set; thus, it is important to note that especially for the Younger Dryas period, the changes introduced to the calibration curve slightly affected the age-depth model of the Soppensee Late Glacial sediments when compared with calculations performed with the IntCal04 data set (Reimer et al. 2004). At this point, we would like to emphasize the importance of quoting original ^{14}C data in publications because these data remain unchanged and can always be recalibrated to improve the chronology as soon as the updated calibrations sets are available.

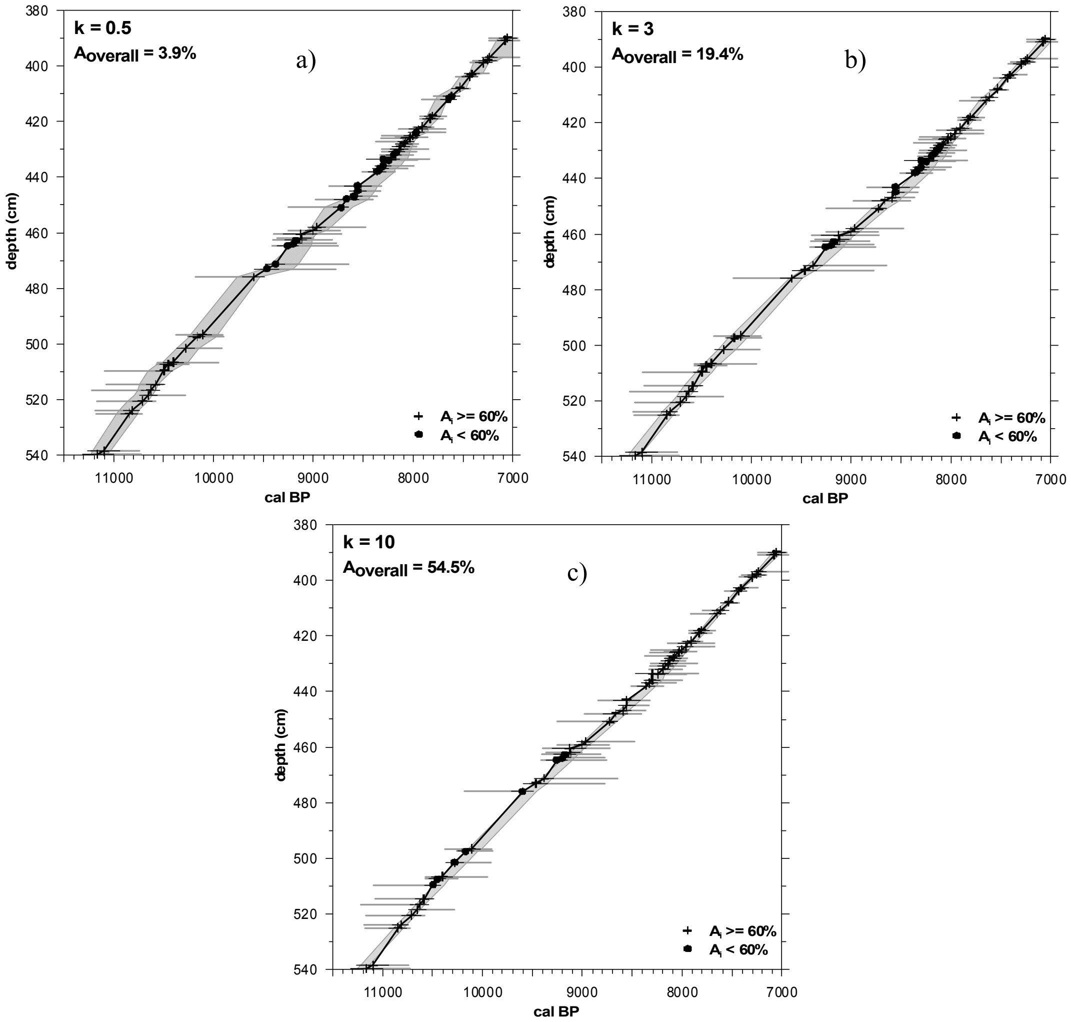

Figure 2a–c Comparison of the age-depth model of OxCal v 4.1 (Bronk Ramsey 2008) with the varve chronology for different values of the parameter *k*: 0.5, 3, and 10 for a), b), and c), respectively. Dark gray horizontal bars mark 95% confidence intervals of the prior likelihood distributions; gray strips indicate 95% confidence intervals of modeled (posterior) likelihood distributions. The varve chronology is presented by the black line, with 2-σ errors marked by black dashes. Different symbols indicate different values of individual agreement indices (see legend on the graphs).

The calendar ages obtained for 2 ash layers and the Late Glacial changes in Soppensee sediment are listed in Table 2. The Varve Time (VT) in Soppensee provided the first very precise dating of the Holocene tephra identified as the Vasset/Killian tephra from France (Hajdas et al. 1993). As mentioned, the depth-age model of this study compares very favorably with the Varve Time of the Holocene record. The model places the tephra between 9291 and 9412 cal BP, whereas the Varve Time (corrected for the fit to the IntCal09) dates this tephra between 9424 and 9502 cal BP. Another ash layer present in the sediment is the Laacher See tephra, which stems from an eruption from the Eifel region (Germany) that took place at the end of the warm Allerød period. The age of this tephra is of great importance as a chronostratigraphic marker for Late Glacial records in Europe because it preceded the onset of the Younger Dryas by 200 yr (Brauer et al. 2008). Our age-depth model returns the calendar age of 12,735–12,878 cal BP, which again compares very favorably with the

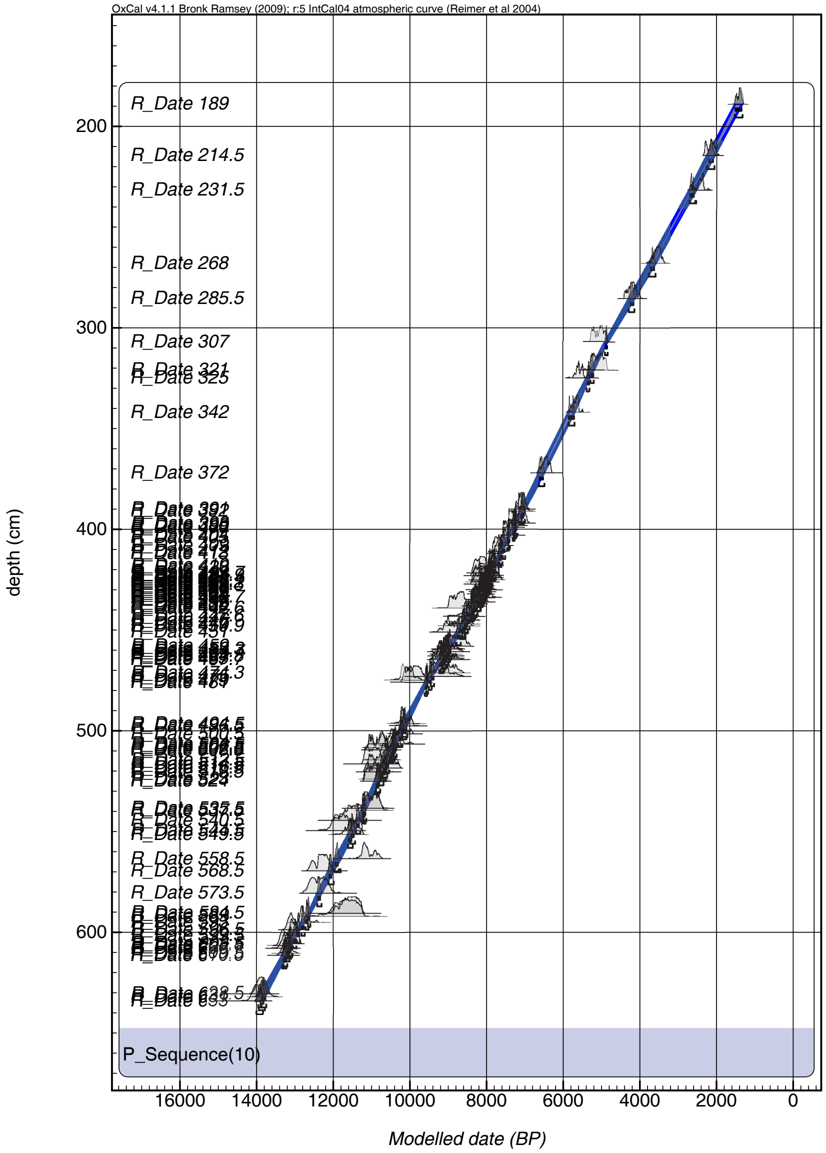

Figure 3 *P_Sequence* age-depth model of OxCal v 4.1 (Bronk Ramsey 2008) constructed using 84 radiocarbon dates.

12,880 ± 120 cal BP Varve Time determined in Meerfelder Maar sediments, a lake in the Eifel region (Brauer et al. 2008). Moreover, the onset of the Younger Dryas (12,501–12,686 cal BP) follows in about 200 yr, in agreement with ages from Meerfelder Maar (12,680 cal BP), and less so with the Greenland ice core of NGRIP (12,846 ± 138 cal BP) (Rasmussen et al. 2006). However, precise dating of the Younger Dryas boundaries might be problematic due to definition of the boundaries in different proxies and cores as well as correlation between cores. Table 2 shows the calendar ages obtained for the transitions using the age-depth model, which is based on the ^{14}C chronology. The difference in ages for the final warming (end of Younger Dryas) observed between proxies (pollen versus stable isotopes) and between correlated cores in Soppensee is evident (up to 400 yr) when

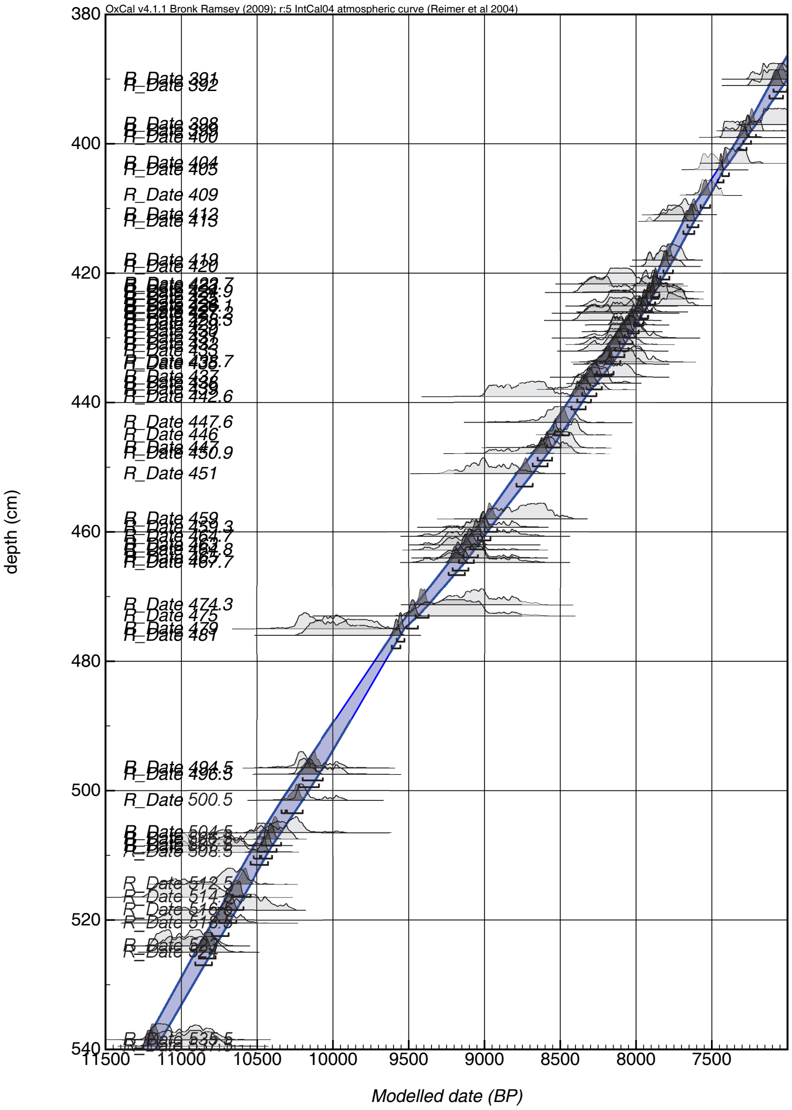

Figure 4 Fragment of the *P_Sequence* age-depth model of OxCal v 4.1 (Bronk Ramsey 2008) for the distinctly laminated part of the Soppensee core.

the age-depth model is applied. These offsets are independent of the chronology and require an explanation by paleo-studies before any further conclusions are drawn on the synchrony of the climatic changes observed in the Soppensee record versus other archives.

This comparison illustrates problems observed when chronologies of climatic records are constructed. Obtaining the precise ages for changes observed in proxies is difficult and we have shown here that it can be successfully resolved with the help of high-resolution ^{14}C dating and an age-depth model. However, comparison between records and locations such as Europe/Greenland or proxies such as pollen and stable isotopes might become problematic as soon as the precise chronologies are available.

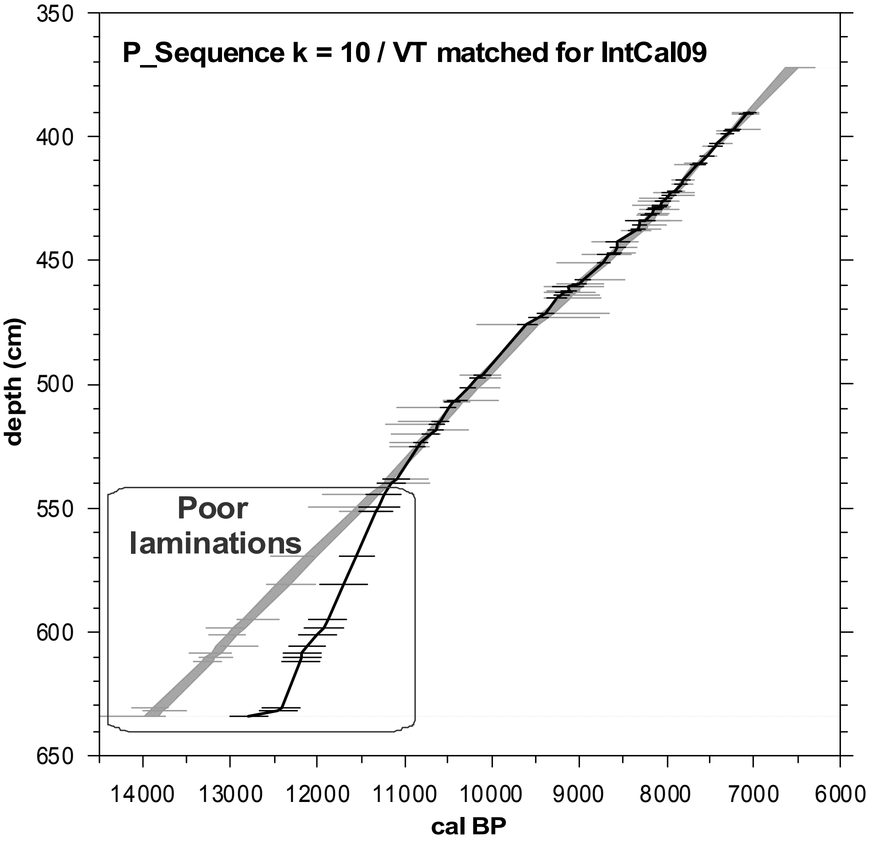

Figure 5 Comparison of the age-depth model (dark gray horizontal bars = 95% confidence intervals of the prior likelihood distributions; gray strip = 95% confidence intervals of modeled likelihood distributions) and the varve chronology (black line).

Table 2 Calendar ages of Late Glacial events and tephra layers based on the age-depth chronology of Soppensee. The timing for changes observed in pollen and stable isotopes from core SO89-23 correlated to ^{14}C-dated core SO89-17 is compared to chronologies of NGRIP (Rasmussen et al. 2006) and Meerfelder Maar (MFM) (Brauer et al. 2008).

Event	Proxy	Depth S089-17	Depth SO89-23	Age-depth model cal BP (2-σ ranges)	VT/other records cal BP
Vasset/Killian tephra VKT	Tephra layer	474 cm		9291–9412	9468 ± 44 Soppensee[a]
End of Younger Dryas	Pollen	533–535 cm[b]		11,060–11,207	11,653 ± 99 NGRIP[c] 11,590 MFM
	Stable isotopes	539 cm[d]	534 cm	11,229–11,325	
	Pollen	540 cm[e]	535 cm	11,275–11,378	
	Pollen	543 cm[d]	538 cm	11,385–11,498	
Onset of Younger Dryas	Pollen	582–584 cm[b]		12,501–12,686	12,846 ± 138 NGRIP 12,680 MFM
Laacher See tephra LST	Tephra layer	593 cm		12,735–12,871	12,880 ± 120 MFM

[a] Varve Time (VT; Hajdas et.al. 1993) +61 cal yr (see text).
[b] Hajdas et al. (1993).
[c] NGRIP time (b2k) was scaled to cal BP for comparison.
[d] Correlated to core S089-23 (Figure 7.11 in Fischer 1996).
[e] Correlation to pollen record of core S089-23 (Lotter 2001; Blockley et al. 2008).

CONCLUSIONS

Our results can be summarized in the following points:

- As a result of wiggle-matching to the IntCal09 data set, the floating varve chronology of the Soppensee record was shifted by 61 yr towards an older calendar age in comparison to the 1993 chronology.
- A very good agreement between the varve chronology and the OxCal *P_Sequence* age-depth model observed for the whole sediment interval with distinct lamination (depth 390–540 cm) shows the effectiveness of the age-depth construction using the statistical tools of OxCal and confirms the precision and accuracy of the Holocene varve chronology.
- Our analysis of the dependence of the agreement between the varve chronology and the OxCal *P_Sequence* age-depth model on the *k* parameter may help to estimate a value of this parameter in other lake sediments.
- This study shows that depositional conditions of Lake Soppensee were rather stable during the early Holocene time period between 7060 and 11,160 cal BP.
- The chronology based on the age-depth model provides precise calendar ages for tephra layers: the Vasset/Killian tephra was dated to 9291–9412 cal BP, while the Laacher See tephra dated to 12,735–12,871 cal BP.
- Climatic transitions (e.g. that of the Younger Dryas) can be more precisely dated using the age-depth model; however, definition of the boundaries and correlation between cores and proxies must be improved as well.

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