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PROBLEMS IN THE EXTENSION OF THE RADIOCARBON CALIBRATION CURVE (10–13 KYR BP)

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ABSTRACT. Radiocarbon dating of varved lake sediments shows that, during the Late Glacial (10–12 kyr BP), the offset between the ^{14}C and the absolute time scales was *ca.* 1 kyr. Varve counting and accelerator mass spectrometry (AMS) dating were used to build absolute and ^{14}C time scales of sediments from two lakes—Soppensee, Switzerland and Holzmaar, Germany. The resulting chronologies extend back to *ca.* 12.9 kyr cal BP (12.1 kyr BP) in the case of Soppensee and to *ca.* 13.8 kyr cal BP (12.6 kyr BP) in the Holzmaar record. They compare well with each other but differ significantly from the ^{14}C-U/Th chronology of corals (Bard *et al.* 1993; Edwards *et al.* 1993).

EXTENSION OF THE RADIOCARBON CALIBRATION CURVE

The radiocarbon time scale is affected by variations in the ^{14}C production rate and changes in the global carbon cycle. The differences between ^{14}C age and absolute/calendar age can be traced by ^{14}C dating of material of known absolute age such as trees (calibration curve). Although the continuous tree-ring calibration curve, which is the most precise ^{14}C calibration method, is available only for the last 11.5 kyr (calendar) (Kromer and Becker 1993), many studies have recently focused on archives alternative to tree rings. Using mass spectrometry (Edwards, Chen and Wasserburg 1987) for precise U/Th dating of small coral samples, Bard *et al.* (1993) and Edwards *et al.* (1993) constructed the ^{14}C-U/Th curve for the last 20 kyr BP. Another option for studies of variations in the atmospheric ^{14}C/^{12}C ratio is provided by dating of laminated sediments. The accelerator mass spectrometry (AMS) ^{14}C dating of terrestrial macrofossils deposited in annually laminated (varved) sediments from lakes can be compared with absolute time derived from varve counting. However, as the method is quite often limited by the quality of laminations or the lack of a continuous record, studies of many independent records are required. Two sites, Soppensee (Hajdas *et al.* 1993) and Holzmaar (Hajdas *et al.* 1995b), have been studied for the extension of the calibration curve.

VARVE CHRONOLOGIES – RESULTS FROM SOPPENSEE AND HOLZMAAR

Coupled ^{14}C/varve time scales were built for Soppensee and Holzmaar. In each case, the ^{14}C scale is based on AMS measurements on terrestrial macrofossils and the absolute time scale consisted of varve counting. The annual varves (Lotter 1989) in Soppensee are alternating calcite (pale) and organic material (dark) layers, whereas the varves in Holzmaar are clastic (Zolitschka 1991). In both cases, complications in the varve chronologies required corrections. The corrections to each varve chronology were made independently, by statistically matching the younger part to the established tree-ring calibration curve (for details, see Hajdas *et al.* 1993; Hajdas *et al.* 1995b). The ^{14}C/varve chronology of Soppensee sediments extends to 12.1 kyr BP, which corresponds to *ca.* 13 kyr cal BP (Table 1, Fig. 1). The ^{14}C record of Lake Holzmaar extends to *ca.* 12.6 kyr BP. On the varve time scale, this corresponds to *ca.* 14 kyr cal BP (Table 1, Fig. 1).

The agreement we obtained between both varve chronologies is best illustrated by the absolute dating of the Laacher See tephra (LST). The Laacher See volcano (West Eifel, G) erupted *ca.* 11.2 kyr BP (Hajdas *et al.* 1995a), and the layer of ash can be found, as an excellent time marker, in sediments

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of many European lakes and bogs. The Soppensee varve chronology dates the LST layer at 12,350 ± 150 yr cal BP, whereas the varve chronology of the Holzmaar record yields an age of 12,201 ± 224 yr. The agreement between the chronologies is exemplified by the absolute age of the LST from the two independent records (Fig. 2).

New results from the Swedish varves (Wohlfarth *et al.* 1995) and Japanese laminated Lake Suigetsu (Kitagawa *et al.* 1995) agree with the Soppensee and Holzmaar varve chronologies up to 12 kyr BP. However, in their reconstruction, ^{14}C ages become close to calendar ages beyond 12 kyr BP. In the Holzmaar chronology, an offset between the ^{14}C and the calendar age is *ca.* 1.4 kyr (see Fig. 1, Table 1) at 12.6 kyr BP. This shows that the atmospheric $^{14}C/^{12}C$ ratio was higher at the beginning of the Late Glacial than during the Younger Dryas (YD) and the early Holocene (~10 kyr). The ^{14}C–U/Th curve (Bard *et al.* 1993; Edwards *et al.* 1993) shows an even larger (up to 2 kyr) offset between ^{14}C

TABLE 1. AMS ^{14}C Ages of Terrestrial Macrofossils Selected from Sediments of Soppensee and Holzmaar and the Corresponding Varve Ages

Site	ETH-no.	Sample, depth (cm)	^{14}C age (yr BP)	Varve age (cal yr BP)
*Holzmaar**				
	7246	HZM9	9515 ± 75	10,904
	7241-1	HZM10.1	10,085 ± 80	11,245
	7248-3	HZM11.3	10,195 ± 85	11,510
	7249	HZM12	10,520 ± 90	11,786
	7250	HZM13-a	11,210 ± 95	12,101
	7250	HZM13-b	11,380 ± 90	12,101
	12471+2†	HZM30.1+2	11,250 ± 110	12,236
	12475	HZM32.1	11,600 ± 140	12,737
	12476	HZM32.2	11,940 ± 130	12,750
	7254	HZM17	12,100 ± 110	12,781
	12481+2	HZM35.1+2	12,570 ± 130	13,571
	7255	HZM18	12,430 ± 110	13,752
	7256	HZM19-a	12,590 ± 110	13,757
	7256	HZM19-b	12,520 ± 110	13,757
Soppensee‡				
	7701	540.5–544.5	9970 ± 100	11,204 ± 104
	7710	544.5–549.5	10,135 ± 100	11,335 ± 118
	6803	549.5–551.5	9965 ± 75	11,413 ± 102
	6828	568.5–569.5	10,400 ± 70	11,909 ± 123
	7703	573.5–580.5	10,440 ± 100	12,088 ± 157
	5290	593–595	10,760 ± 105	12,329 ± 139
	6930	596.5–598.5	11,190 ± 80	12,412 ± 146
	6932	599.5–601.5	11,160 ± 60	12,488 ± 154
	6804	603.5–605.5	11,050 ± 80	12,604 ± 153
	6933	605.5–606.5	11,470 ± 70	12,668 ± 153
	5305	606–808	11,380 ± 105	12,668 ± 152
	6805	609.5–610.5	11,300 ± 90	12,668 ± 152
	6806	610.5–611.5	11,385 ± 90	12,681 ± 152
	6807	628.5–630.5	12,040 ± 90	12,904 ± 152
	6808	631–632	11,930 ± 90	12,940 ± 151
	6809	633–634	12,150 ± 90	12,977 ± 151

*Hajdas *et al.* (1993)
†Hajdas *et al.* (1995a)
‡Hajdas *et al.* (1995b)

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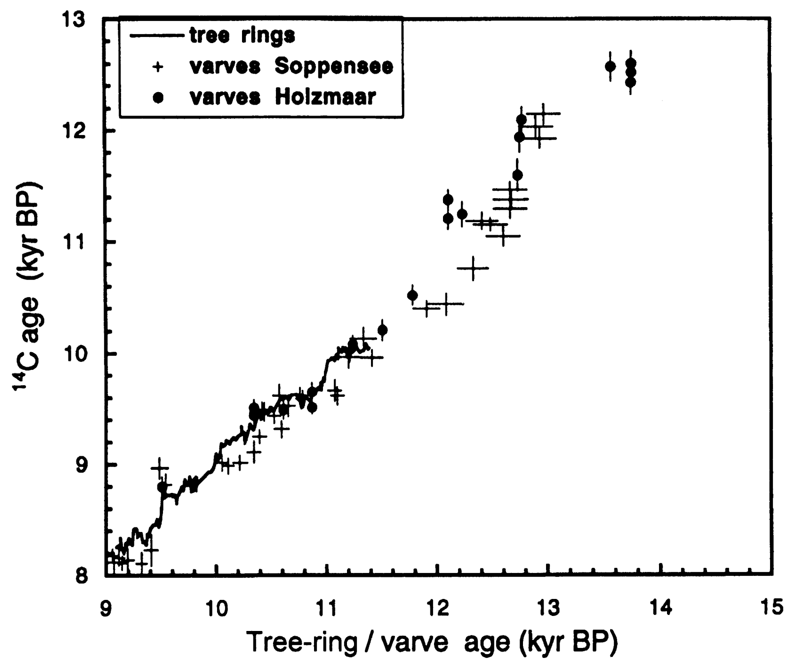

Fig. 1. Comparison between Soppensee and Holzmaar ^{14}C/varve chronologies. The AMS ^{14}C ages (plotted with 1-σ uncertainty) obtained on terrestrial macrofossils selected from sediment of Soppensee, Holzmaar are plotted *vs.* calendar years (tree rings and varve years). Both ^{14}C/varve chronologies show features of the tree-ring curve, *e.g.*, plateaus in ^{14}C age at 9.6 and 10 kyr BP.

and calendar years during this period (Fig. 2). A lack of agreement exists between all the methods and an extension of the ^{14}C calibration curve beyond tree-ring data, *i.e.,* 10 kyr BP is still problematic. Because the differences first appear beyond the tree-ring curve (Fig. 2), dating of the Late Glacial is very important for this discussion.

Recently, the duration of the YD, the calendar age of the onset and the end of the event have been determined by studies of various high-resolution records, *e.g.,* ice cores, laminated sediments and tree rings. A comparison between them shows certain similarities but also differences, which cannot yet be explained. There is an offset between the absolute age of the YD/PB (Preboreal) transition in ice cores and the Soppensee record. Although ice cores place it at 11,580 BP (GRIP (Johnsen *et al.* 1992)) and 11,640 BP (GISP 2 (Taylor *et al.* 1993)), *i.e.*, just at the beginning of the 10-kyr ^{14}C age plateau, the Soppensee varve chronology dates the transition at *ca.* 11 kyr cal BP (Fig. 3), which is at the end of the age plateau. A similar age of *ca.* 11 kyr cal BP is also indicated by the tree-ring data (Kromer and Becker 1993), although the transition in this record is based on variations of δD and $\delta^{13}C$ in wood (Becker, Kromer and Trimborn 1991). In sediments of Lake Gościąż, the end of the YD was dated at 11,200 (+500/−200) yr cal BP (Goslar *et al.* 1993). It must be noted that a discrepancy exists between the length of the YD in Soppensee (1140 yr) and Holzmaar (450 yr) (Hajdas *et al.* 1995b). The length and the boundaries of the YD in Holzmaar are currently being more closely studied on new cores (B. Zolitschka, personal communication).

Recently reported ^{14}C dating results from the Norwegian Lake Kråkenes (Gulliksen *et al.* 1994) show that most of the 10-kyr plateau belongs within the YD. Also new data from Gościąż (Goslar *et*

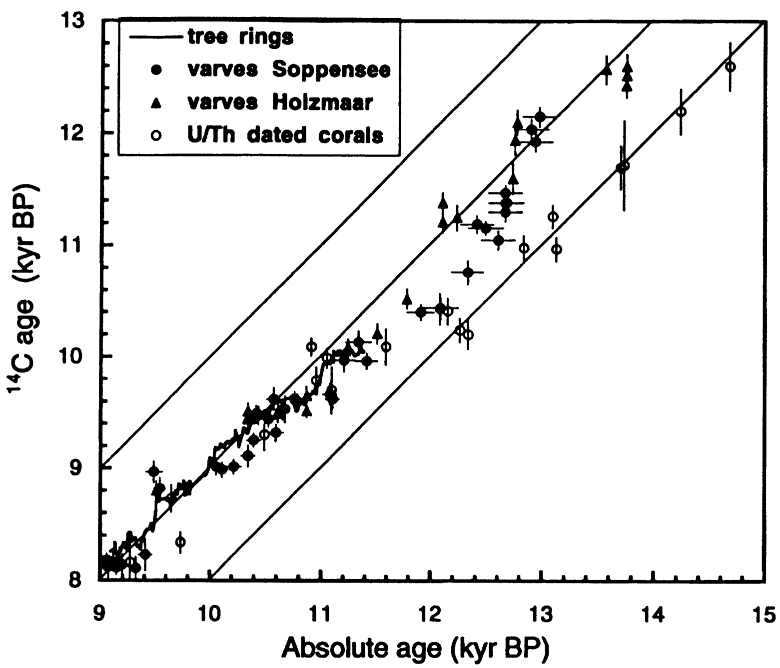

Fig. 2. Extension of the ^{14}C calibration curve beyond 10 kyr BP. Good agreement between tree ring data, varve chronologies (Fig. 1) and the ^{14}C-U/Th chronologies from corals can be seen for the last 10 kyr BP (*ca.* 11 kyr cal BP). An offset of *ca.* 1 kyr between the ^{14}C time scale and the calendar time scale of the tree-ring calibration curve is observed at the beginning of the Holocene (10 kyr BP). In the Late Glacial period (10–12.5 kyr BP), varve data indicate the same trend of the ^{14}C calibration curve, *i.e.*, varve ages are *ca.* 1 kyr older than ^{14}C ages of macrofossils. In contrast, the U/Th ages of corals are *ca.* 2 kyr older than their corresponding ^{14}C ages.

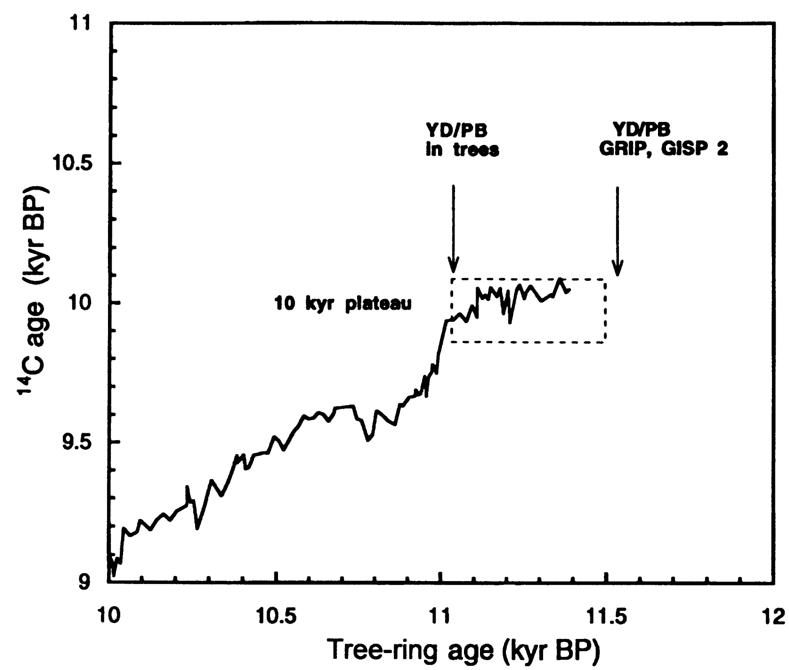

Fig. 3. Dating of the YD/PB boundary. The arrows indicate the location of the beginning of the YD as determined from the absolute time scale of ice cores and tree rings with respect to the 10-kyr plateau.

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al. 1994) do not place the transition at the beginning of the plateau (Fig. 3) as the ice core records do. Assuming that the event was felt simultaneously over the North Atlantic region or even the whole world (Alley *et al.* 1993), differences of up to 500 yr in dating of such dramatic changes seem to be unlikely. Resolving this problem is critical for dating the Late Glacial as well as for the extension of the ^{14}C calibration curve.

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