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RADIOCARBON AGE CALIBRATION BACK TO 13,300 YEARS BP AND THE ^{14}C AGE MATCHING OF THE GERMAN OAK AND US BRISTLECONE PINE CHRONOLOGIES

MINZE STUIVER*, BERND KROMER**, BERND BECKER† and C W FERGUSON‡

INTRODUCTION

With the recent establishment of an unbroken West European tree-ring sequence spanning the past 7272 years (Pilcher *et al,* 1984) the calibration of the ^{14}C time scale was advanced considerably. It is now possible to use this chronology as an independent cross-check on the 8681-year US Bristlecone Pine series (Ferguson & Graybill, 1983). There also are opportunities for ^{14}C matching (wiggle matching) between the older portion of the Bristlecone Pine series and floating (not tied to the present) parts of the South German Oak sequence. Linick, Suess and Becker (1985) used this approach in matching the earliest part of the Bristlecone Pine series with the Donau 6 Main 4/11 (Becker, 1983) series and thus established a D6M4/11 "zero" point (tree-ring no. 1) of 7215 BC.

We report here 49 high-precision measurements of the D6M4/11 series (Table 1). Fifteen Bristlecone Pine samples with dendrochronologically determined ages (6480–6470, 6370–6350, and 5805–5685 BC) also were measured (Table 2). ^{14}C age matching of the new results confirms the D6M4/11 ring 1 age of 7215 BC within a few decades.

Having anchored the available 750 years of the D6M4/11 series to the calendric scale in this manner results in the ^{14}C age calibration curve (from 6470 to 7200 yr BC) given in Figures 3 and 4. A comparison of the D6M4/11 results with the Lake of Clouds varve series (Stuiver, 1970, 1971) proves the reliability of this varve sequence for ^{14}C age calibration. This leads, in combination with adjusted Swedish varve dates, to tentative age calibration results back to 13,300 cal BP (Fig 7).

TECHNIQUE AND INTERCALIBRATION

Cellulose was prepared from all wood samples. The analytical procedures involving sample preparation and CO_2 gas counting were discussed previously (Stuiver, Robinson & Yang, 1979; Stuiver & Quay, 1980, 1981). Standard deviations, as well as off-sets, need to be considered for an assessment of the reliability of the calibration curve.

Standard Deviation

The reported standard deviation σ_c in a ^{14}C age determination is traditionally calculated from the Poisson statistics of the accumulated sample and standard counts. This procedure can only underestimate the statistical error in the laboratory determinations because other factors (ao sample purity and counting voltage variability) also play a role. To account for the additional variance σ_a^2 an error multiplier K can be used for well-defined cases (Stuiver, 1982; International Study Group, 1982). The use of K values, however is not a simple matter because K depends on counting time and sample age.

The following relationship applies:

$$K\sigma_c = \sqrt{\sigma_c^2 + \sigma_a^2} \qquad (1)$$

or

$$K = \sqrt{1 + \left(\frac{\sigma_a}{\sigma_c}\right)^2} \qquad (2)$$

Standard errors σ_c for Seattle 4-day-counts are ca 17 years for ^{14}C ages in the 2000–4000 yr range. An analysis of reproducibility of duplicate runs leads to an upper limit for K of 1.5 to 1.6 (Stuiver & Pearson, 1986). Substitution of K = 1.5 in equation (1) yields a σ_a of 19 years, or

$$K = \sqrt{1 + \left(\frac{19}{\sigma_c}\right)^2} \qquad (3)$$

The dependence of K on counting time or age is illustrated by the following examples:

1) Counting the sample twice as long reduces σ_c by a factor of 1.4. Here the K value (Eq 3) is 1.9.

2) Having an older sample with half the ^{14}C activity increases σ_c by an approximate factor of 1.4. The K value for samples this old is nearly 1.3.

Clearly, K values can be used only within the confines of defined counting conditions.

The errors in the ^{14}C ages listed in this paper are all based on counting statistics alone. According to Eq 3, the error "multiplier" for samples of the age range given (and for 4-day counts) would be 1.3.

Off-sets

The variance σ_a^2 accounts for the degree of reproducibility of the measurements made within a single laboratory. It does not account for systematic errors. Such errors may reflect a simple off-set (caused, eg, by a wrong activity level of the standard), or they may reflect age-dependent anomalies (eg, if the "dead" time in counting, which depends on sample activity, would be important and uncorrected for).

The ^{14}C timescale calibration requires independent determination of the ^{14}C activities by two or more laboratories. The magnitude of the off-sets between different laboratories can be estimated from the differences in measured ^{14}C ages of duplicate samples.

A comparison of 214 sample pairs of wood of identical age, but of different geographic regions gave an age difference of 0.6 yr between Belfast

*University of Washington, Seattle
**Universität Heidelberg
†Universität Hohenheim, Stuttgart
‡University of Arizona, Tucson; deceased March 24, 1986.

and Seattle (Stuiver & Pearson, 1986). These 214 samples were all <4500 yr old.

The Seattle laboratory also participated in the Glasgow international calibration project (International Study Group, 1982). The six measured samples, with approximate age of 5000 ^{14}C yr BP, differed from the group average by 17 yr (average of three estimates), with the Seattle ages being older.

A comparison of data with three other laboratories of samples in the 7000–8000 yr BP range yields somewhat larger differences. The ^{14}C ages of 19 samples of the German Oak chronology (Table 1) differ 29 ± 10 yr from their La Jolla counterparts which are wood samples with mid-point ages up to 3.5 yr different from the Seattle set (Linick, Suess & Becker, 1985). Six sample pairs (Table 3) yield an age difference of 27 ± 12 between the Seattle and Heidelberg laboratories. The largest difference is between Seattle and Tucson, where the ^{14}C ages of 13 Bristlecone Pine sample pairs (5805–5685 BC, Table 2 & Linick *et al*, 1986) differ by 52 ± 8 yr. For the latter three comparisons, the Seattle ^{14}C ages are on average all on the younger side.

The standard deviations in the off-sets are based on counting statistics of the laboratory results alone. The application of K values of ca 1.5 to the results of all laboratories involved would bring the off-sets, with the exception of Tucson-Seattle, within 2 σ of the quoted error.

The differences in age determinations of different laboratories need further investigation, and the user of calibration curves should realize that off-sets of a couple of decades are possible when calibration curves of a single laboratory are used. These small differences are, of course, relatively unimportant for the preliminary calibration back to 13,300 yr BP.

^{14}C MATCHING OF THE BRISTLECONE PINE AND DONAU 6 MAINE 4/11 SERIES

The German Oak ^{14}C ages of the 750-yr section of the floating D6M4/11 chronology are listed in Table 1 and plotted in Figure 1 to the left. Also plotted in the same graph are the ^{14}C ages of two Bristlecone Pine samples. The ring numbers of the 6480–6470 and 6370–6350 BC Bristlecone Pine samples on the D6M4/11 scale were obtained by ^{14}C matching. The matching is imprecise for two samples, and the resulting zero point (year 1) fixing of the D6M4/11 series at 7190 BC may be off by a few decades. There is also good agreement of the above Bristlecone Pine ^{14}C ages with Heidelberg and La Jolla (Linick, Suess & Becker, 1985) results on the D6M4/11 series (Fig 1, right side). This confirms the ca 7190 BC start of the German Oak sequence.

The ^{14}C ages of the two Bristlecone Pine samples also agree with Bristlecone Pine dates obtained previously at La Jolla (Bruns *et al*, 1983). Seattle and La Jolla results are compared with each other on the left side of Figure 2. To the right is a comparison of the absolutely dated Seattle Bristlecone Pine dates (Table 2) of the 5805–5685 BC interval and the La Jolla D6M4/11 results calibrated on a 7215 BC zero point (Linick, Suess & Becker, 1985). The unweighted averages of the data sets would have been equal if the D6M4/11 series had started at 7234 BC.

The above analysis of Bristlecone Pine and German Oak dates gives a zero point ^{14}C age determination of the D6M4/11 series in the 7190–7234 year BC range. The new results are entirely compatible with the 7215 BC determination of Linick *et al* (1986), and this date for the start of the D6M4/11 has therefore been adapted for the calculations of the Δ^{14}C values given in Table 1. Similarly, adoption of the 7215 BC start gives the Figures 3 and 4 ^{14}C age calibration curves. The sudden departure from a rather smooth ^{14}C age trend at 7014 BC is based on a single age determination. Independent confirmation is needed before too much significance is attached to this anomaly.

The uncertainty in the starting date of the D6M4/11 chronology caused by ^{14}C age matching may add a systematic uncertainty of a few decades to the standard deviations already given in the graphs.

THE LAKE OF THE CLOUDS VARVE CHRONOLOGY

The ^{14}C matching of the Oak and Bristlecone Pine series makes it possible to compare tree-ring-derived Δ^{14}C values (back to 7215 BC) with varve-derived Δ^{14}C values from Lake of the Clouds sediment back to 10,200 yr BP (Stuiver, 1970, 1971). The Seattle measurements of the D6M4/11 series (with 7215 BC calibration), and the Lake of the Clouds Δ^{14}C data are in good agreement for the 8400–9200 yr BP interval (Fig 5). The more extensive varve data set also agrees with the La Jolla results of the Donau series (Linick, Suess & Becker, 1985) (averaged over centuries in Fig 6, 6000–9200 yr BP interval). Clearly, the Lake of the Clouds varve series has been shown to be a reliable indicator of atmospheric Δ^{14}C change.

The older portion of the Lake of the Clouds varve chronology can be ^{14}C matched with floating varve chronologies in a similar manner as tree rings. A suitable candidate is the Swedish varve chronology. The younger portion of this chronology, as used by Tauber (1970), was derived from varves studied at a single site (Fromm, 1971). This part of the chronology appears less reliable than the older part of the sequence where the chronology has been derived from several closely overlapping varve deposits. For the purposes of extending the Lake of the Clouds chronology, we considered the Swedish varve segment with Tauber's (1970) ^{14}C ages between 8600 and 12,350 yr BP to be "floating," and matched the older part of the Lake of the Clouds chronology with the younger part of the floating Swedish segment. This yields the varve-derived Δ^{14}C values back to 13,300 yr BP given in Figure 6.

The ^{14}C matching of the Lake of the Clouds ^{14}C ages with the corresponding ones of the Swedish chronology points towards a shortage in the Swedish varve count. The off-set was previously estimated at 800 varves (Stuiver, 1970), and is 1000 varves when the two oldest ^{14}C ages of the Lake of the Clouds chronology are matched. A part of the discrepancy has been solved by a re-evaluation of the varved sediment in the Ångermanälven valley which resulted in an additional 365 varves (Cato, 1985). An anomaly of 400 to 600 varves may still exist near 10,000 cal BP.

The anomaly appears smaller for the revised Swedish chronology near 10,700 BP. The end of the Younger Dryas has a revised date of 10,700 ± 50 varves (Stromberg, 1985), which is in good agreement with the annual ice layer count of the same event of 10,720 ± 75 yr (Hammer *et al*, 1986).

The ^{14}C age of the end of the Younger Dryas was estimated at 10,000 ± 75 yr by Hammer, Clausen and Tauber (1986). According to our ^{14}C matching with the Lake of the Clouds chronology, and using Tauber's (1970) evaluation of Swedish ^{14}C dates, the corresponding cal BP date is 10,970 ± 110 yr (the standard deviation is based on the fact that 1) the age conversion does not take into account the century type ^{14}C oscillations, and 2) the standard deviation in the ^{14}C age is 75 yr).

The three methods, varve counting, ice stratigraphy, and a mixture of ^{14}C matching and varve counting lead to a cal BP age for the end of the Younger Dryas of, respectively, 10,700 ± 50, 10,720 ± 75, and 10,970 ± 110 yr. It is possible that the matching method overestimates the cal BP age by a few hundred years, which would correspond for the pre-10,500 cal BP interval to a reduction in $\Delta^{14}C$ values of 3% (Fig 6) and a reduction in age anomalies of ca 250 yr (Fig 7).

A final evaluation awaits a more precise assessment of the ^{14}C ages and varve counts of the first 2000 years of the Swedish chronology. The Figure 7 calibration curve is only approximate in the pre-10,500 cal BP portion where errors of a few hundred years certainly are a possibility.

TIME-SCALE CALIBRATION BEYOND 10,000 YEARS BP

Following the reasoning given in the previous section, the age calibration based on tree rings (averaged over centuries) and Lake of the Clouds varves can be extended to 13,300 cal BP using the earlier portion of the Swedish varve chronology. The Figure 7 data prior to 10,500 BP are based on ^{14}C matching with the Swedish varve chronology.

The older part of the Figure 7 calibration curve, where conventional ^{14}C ages appear at least 1000 yr too young, may need future adjustment when other chronologies become available. As discussed in the previous section, the pre-10,500 cal BP age anomalies may be over-estimated in Figure 7 by a few hundred years. It also should be noted that at 10,000 yr BP the first 300 years of the age anomaly are due to the use of the "short" 5568-yr half-life for a conventional ^{14}C date. The Figure 7 data set, of course, also neglects the details of the century type oscillations. An excellent approximation of the Figure 7 data is $X = 1.05R + 470$, where X is the cal BP age and R the ^{14}C age BP.

ACKNOWLEDGMENTS

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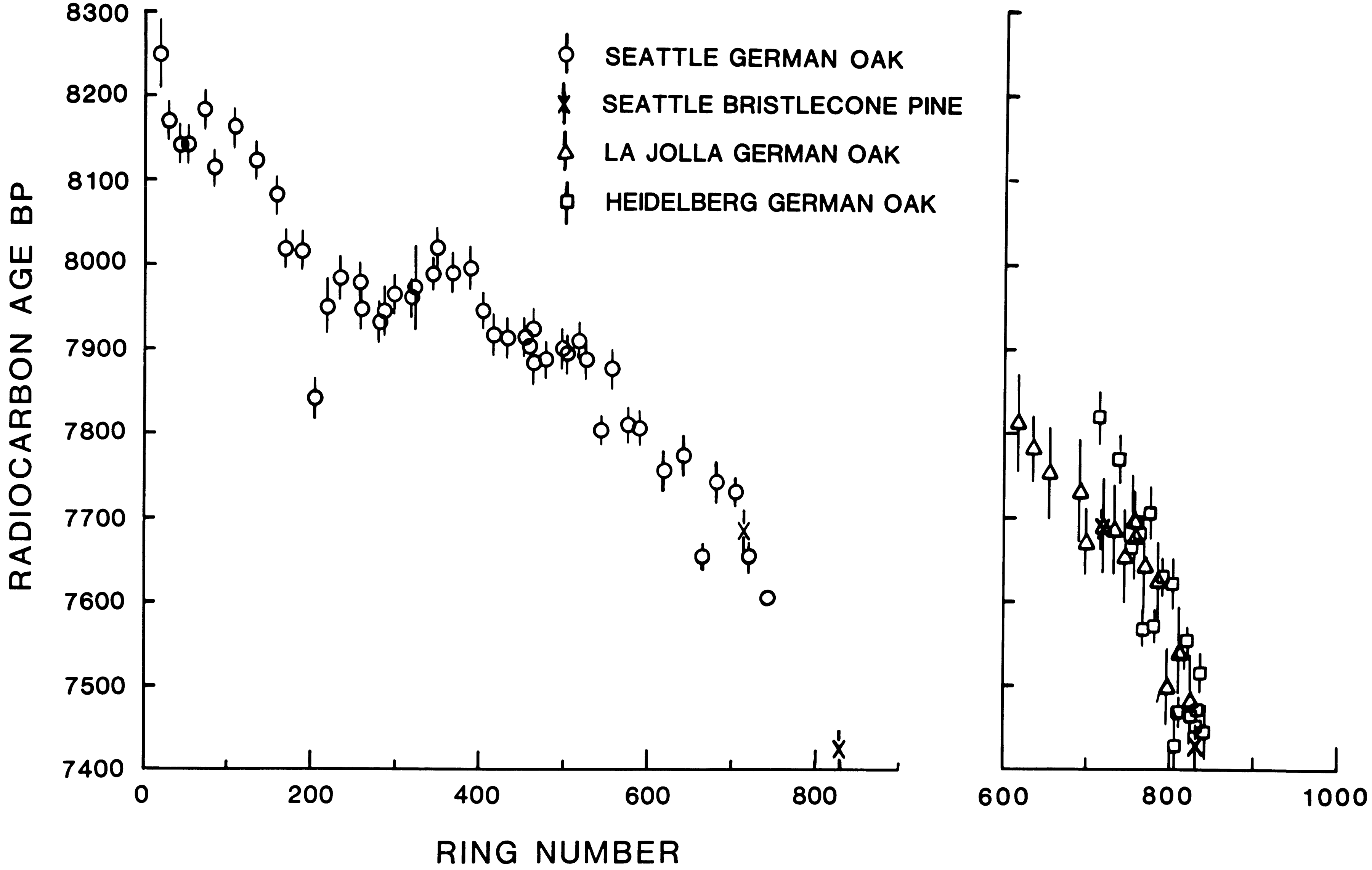


Fig 1. *Left:* ^{14}C ages, with standard deviations derived from counting statistics only, *vs* ring number of the D6M4/11 German Oak series. The two Bristlecone Pine data points assume an age of 7190 yr BC for ring number 1. *Right:* Heidelberg, La Jolla, and Seattle ^{14}C ages *vs* ring number of the D6M4/11 series.

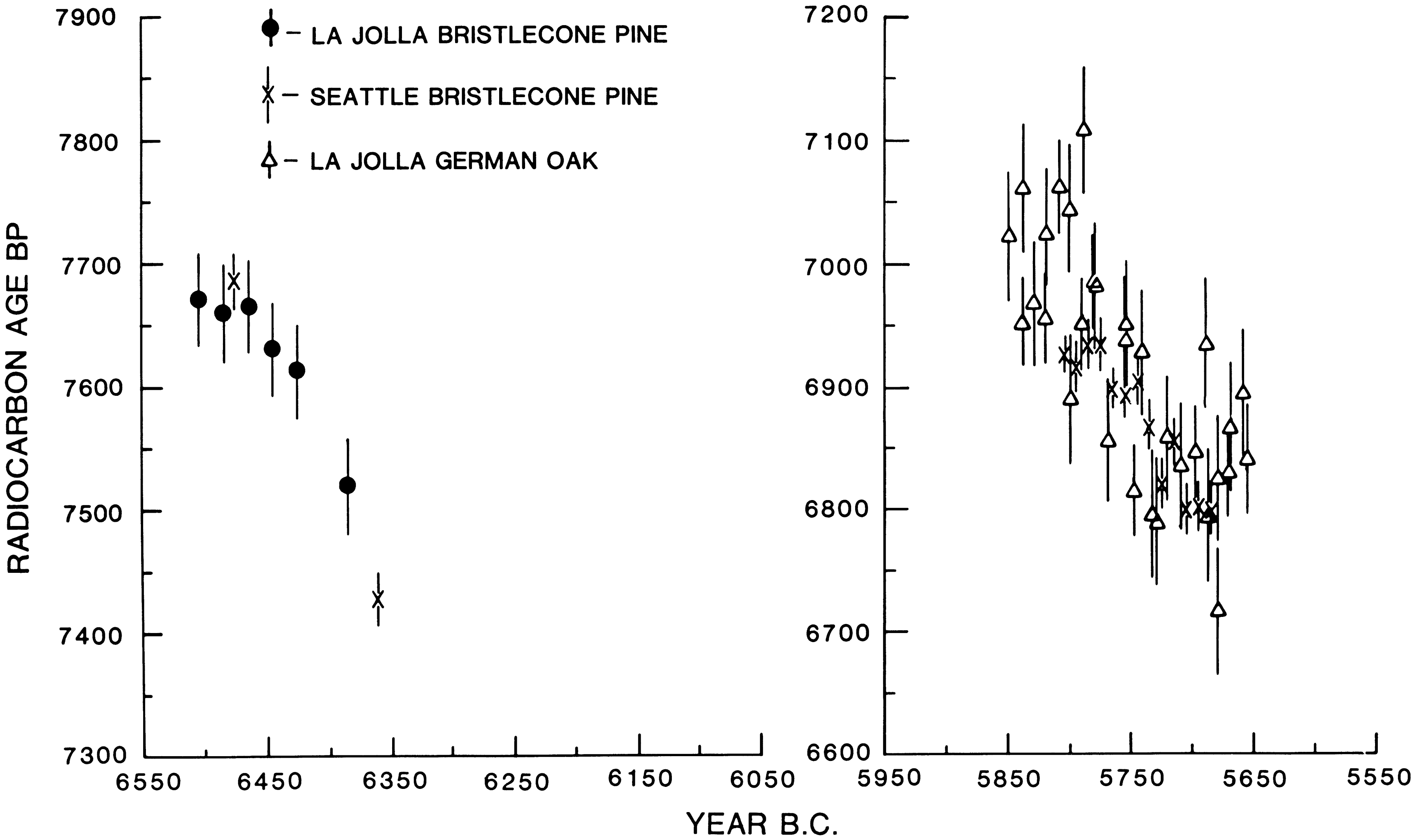
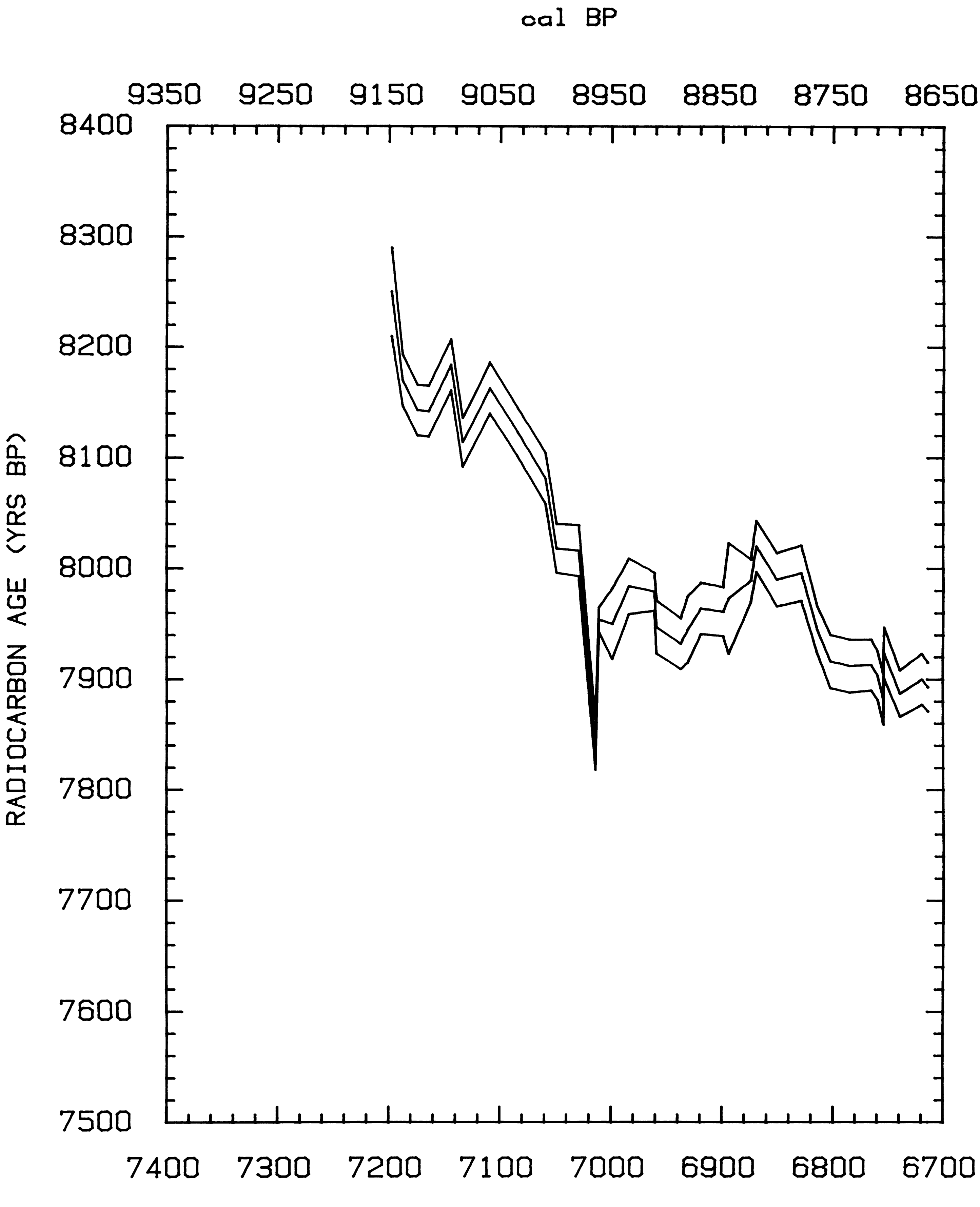
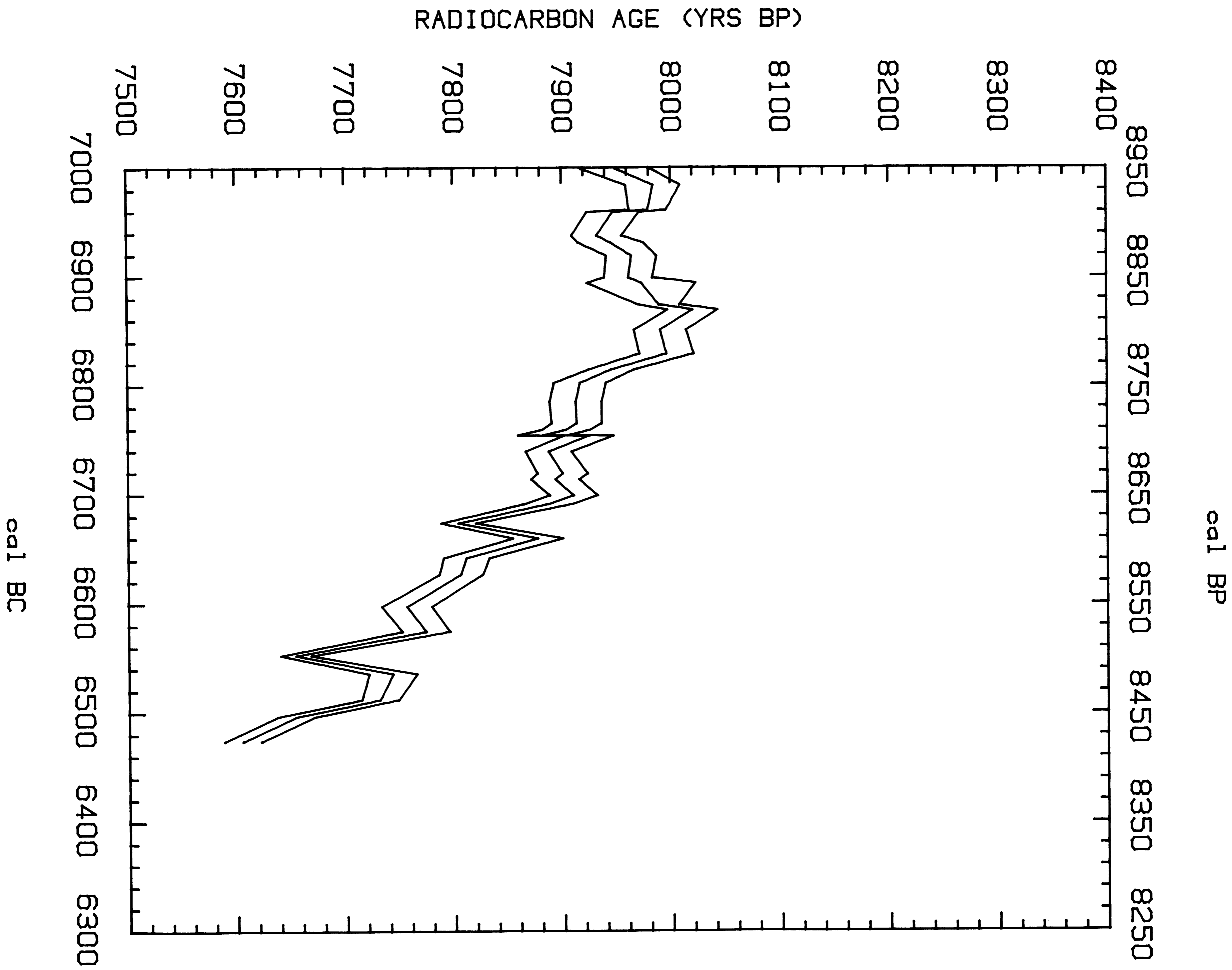


Fig 2. *Left:* La Jolla and Seattle Bristlecone Pine ^{14}C ages. *Right:* Seattle Bristlecone Pine ^{14}C ages compared to La Jolla ages of the German Oak chronology (with ring 1 of the D6M4/11 series at 7215 yr BC). Vertical bars denote 1σ in the measurement.



Figs 3, 4. ^{14}C time-scale calibration derived from the German Oak chronology (with ring 1 of the D6M4/11 series at 7215 yr BC). The width of the calibration curve is based on standard deviations derived from counting statistics only (see text).


RADIOCARBON AGE (YRS BP)
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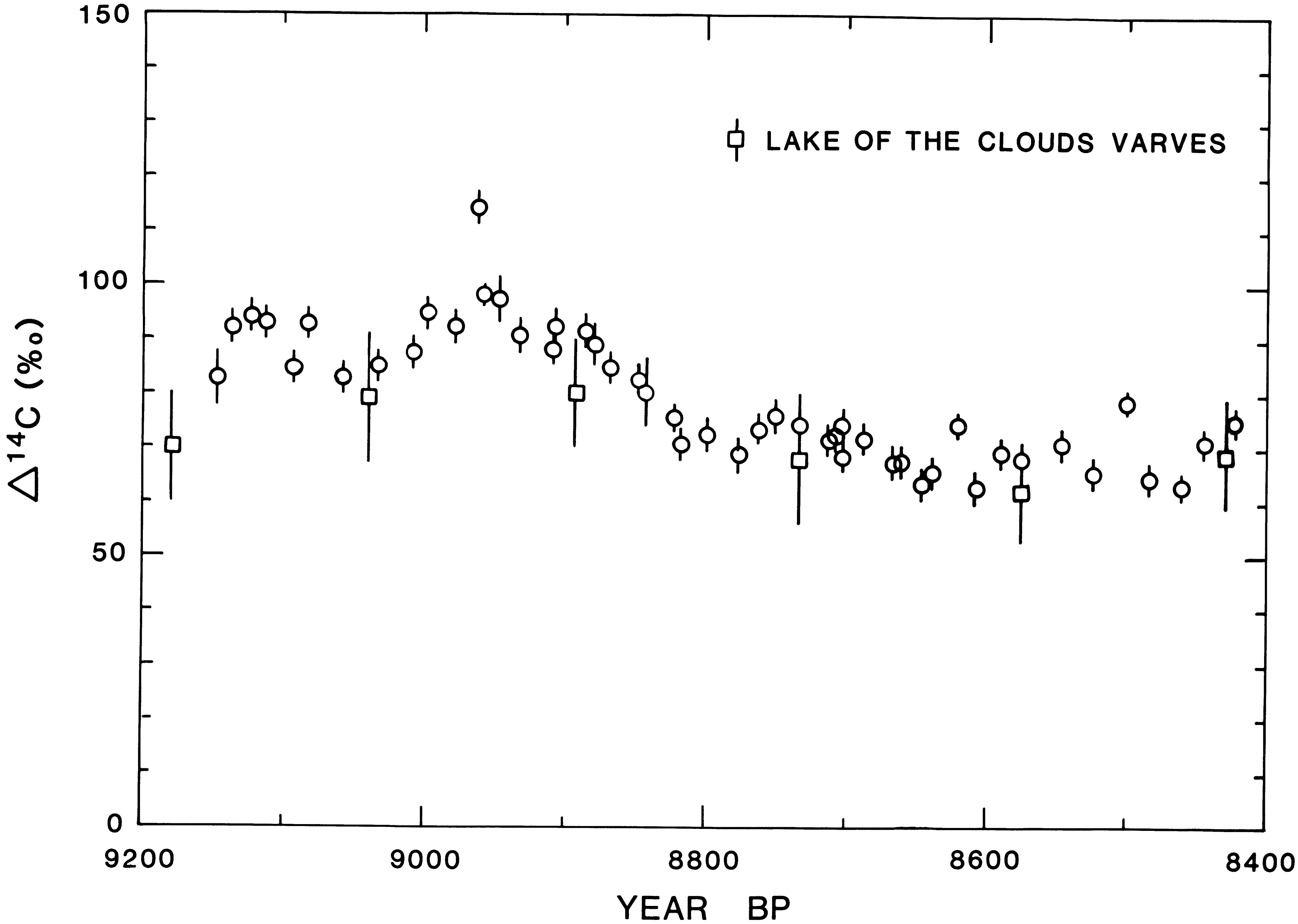

Fig 5. A comparison of $\Delta^{14}C$ values derived from Lake of the Clouds varves and South German Oak tree-ring samples. ^{14}C age errors are 1σ, based on counting statistics only.

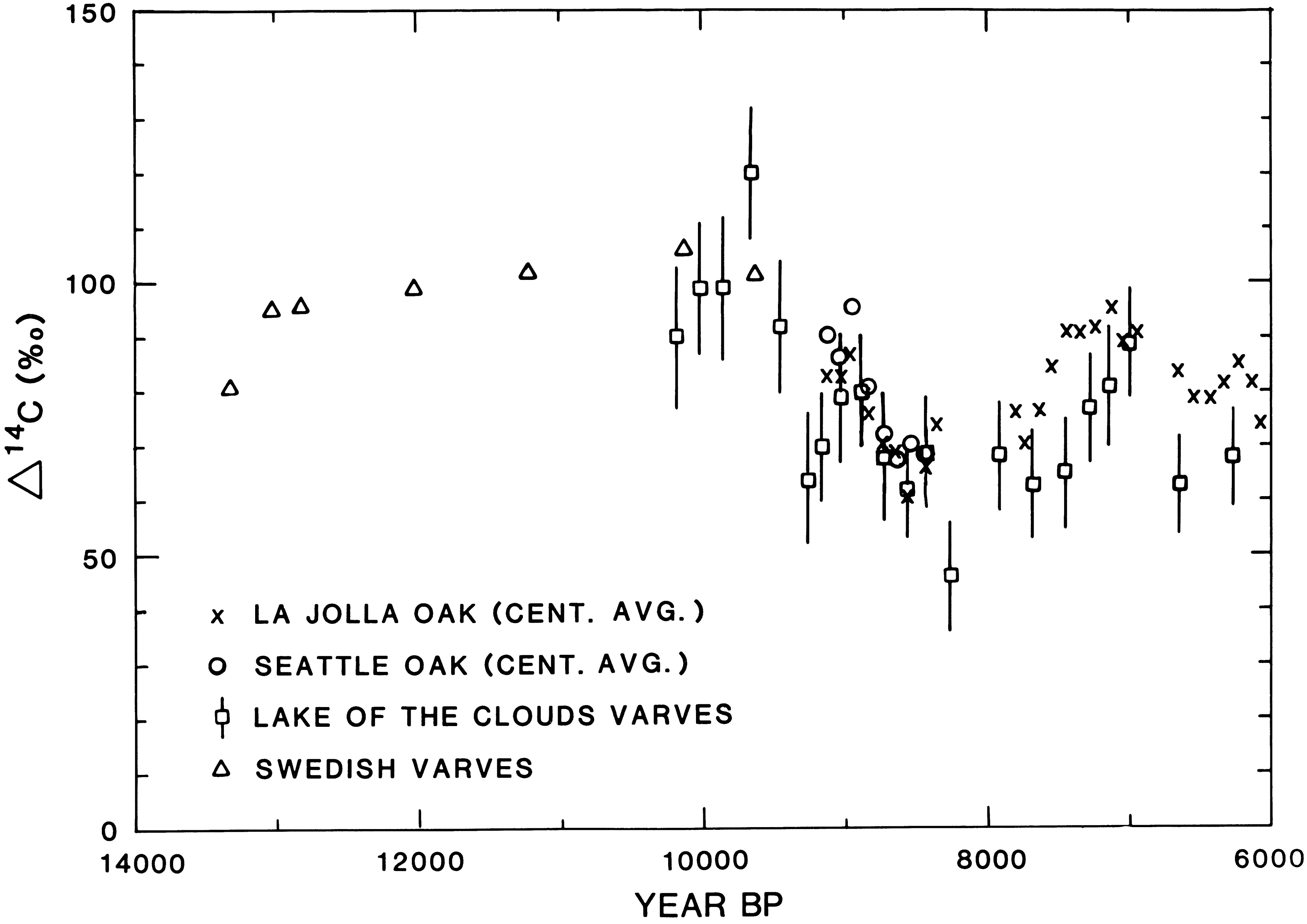

Fig 6. Century-averaged $\Delta^{14}C$ values derived from La Jolla (Linick, Suess & Becker, 1985) and Seattle measurements of the South German Oak chronology (with ring 1 of D6M4/11 at 7215 BC). Also given are $\Delta^{14}C$ values derived from the Lake of the Clouds (Stuiver, 1970, 1971) and Swedish (Tauber, 1970) varve chronology. The standard error in the century averages is a few per mil or less.

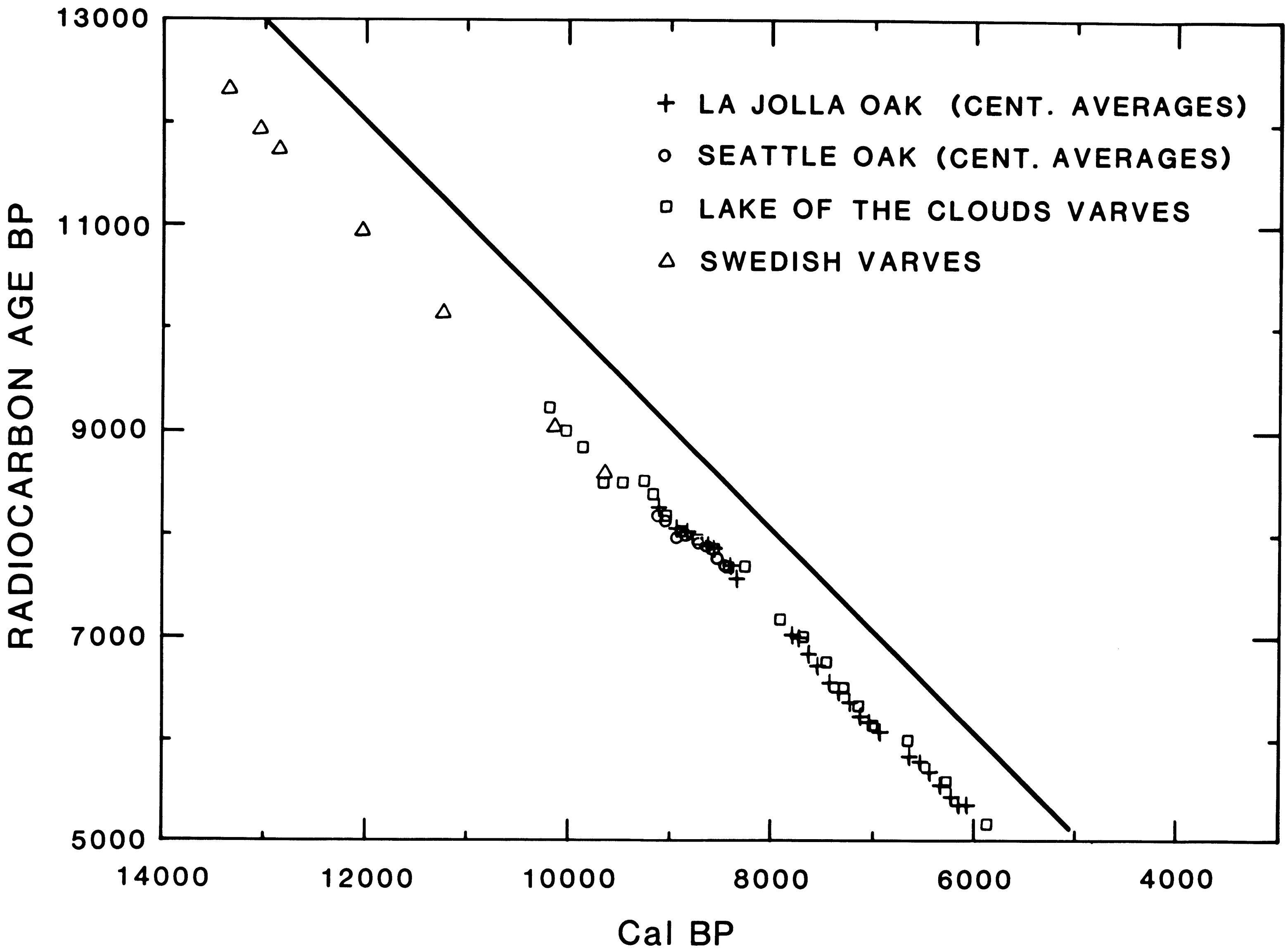

Fig 7. Century-averaged ^{14}C ages of the South German Oak chronology. The Lake of the Clouds and Swedish varve chronology data were derived from the ^{14}C ages of single samples.

TABLE 1
Becker's D6M4/11 series with ring 1 matched at 7215 BC
Standard deviations are based on counting statistics only.

Ring no.	Year BC	Year BP	No. of rings	Radiocarbon age	$\Delta^{14}C$	QL* no.
18.5	7197.5	9146.5	2	8250 ± 40	+82.8 ± 5.0	10000
28.5	7187.5	9136.5	4	8170 ± 23	+92.3 ± 2.9	10001
42.0	7174	9123	5	8143 ± 23	+94.2 ± 2.9	10002
52.0	7164	9113	5	8142 ± 23	+93.0 ± 2.9	10003
72.0	7144	9093	5	8184 ± 23	+84.6 ± 2.9	10005
82.5	7133.5	9082.5	6	8114 ± 22	+92.8 ± 2.7	10006
107.0	7109	9058	5	8163 ± 23	+82.9 ± 2.9	10007
132.0	7084	9033	5	8123 ± 22	+85.0 ± 2.7	10008
157.0	7059	9008	5	8081 ± 23	+87.4 ± 2.9	10009
167.0	7049	8998	5	8018 ± 22	+94.6 ± 2.7	10010
187.0	7029	8978	5	8016 ± 23	+92.3 ± 2.9	10011
202.0	7014	8963	5	7841 ± 23	+114.3 ± 2.9	10012
205.0	7011	8960	11	7954 ± 11	+98.3 ± 1.4	10013
217.0	6999	8948	5	7950 ± 32	+97.3 ± 4.0	10014
232.0	6984	8933	5	7984 ± 25	+90.7 ± 3.1	10015
255.0	6961	8910	11	7979 ± 17	+88.3 ± 2.1	10016
257.0	6959	8908	5	7947 ± 24	+92.4 ± 3.0	10017
278.5	6937.5	8886.5	6	7932 ± 23	+91.6 ± 2.9	10018
285.0	6931	8880	11	7945 ± 30	+89.0 ± 3.7	10019
297.0	6919	8868	5	7964 ± 23	+84.8 ± 2.9	10020
317.0	6899	8848	5	7961 ± 22	+82.6 ± 2.7	10021
322.0	6894	8843	5	7973 ± 50	+80.3 ± 6.2	10022
342.0	6874	8823	5	7989 ± 19	+75.6 ± 2.4	10023
347.0	6869	8818	5	8020 ± 23	+70.8 ± 2.9	10024
365.5	6850.5	8799.5	4	7990 ± 24	+72.4 ± 3.0	10025
387.5	6828.5	8777.5	4	7996 ± 25	+68.8 ± 3.1	10026
402.0	6814	8763	5	7945 ± 21	+73.7 ± 2.6	10027
414.0	6802	8751	3	7916 ± 24	+76.0 ± 3.0	10028
431.0	6785	8734	3	7912 ± 24	+74.3 ± 3.0	10029
451.0	6765	8714	3	7913 ± 23	+71.6 ± 2.9	10030
457.0	6759	8708	5	7903 ± 22	+72.1 ± 2.7	10031
462.0	6754	8703	5	7882 ± 23	+74.3 ± 2.9	10032
462.5	6753.5	8702.5	6	7924 ± 23	+68.6 ± 2.9	10033
477.0	6739	8688	5	7887 ± 21	+71.7 ± 2.6	10034
497.0	6719	8668	5	7900 ± 23	+67.4 ± 2.9	10035
502.5	6713.5	8662.5	6	7893 ± 22	+67.6 ± 2.7	10036
517.0	6699	8648	5	7910 ± 22	+63.5 ± 2.7	10037
525.0	6691	8640	11	7887 ± 22	+65.5 ± 2.7	10038
542.5	6673.5	8622.5	6	7804 ± 16	+74.3 ± 2.0	10039
556.5	6659.5	8608.5	6	7877 ± 23	+62.7 ± 2.9	10040
574.5	6641.5	8590.5	10	7811 ± 21	+69.2 ± 2.6	10041
589.5	6626.5	8575.5	10	7806 ± 20	+67.9 ± 2.5	10042
618.5	6597.5	8546.5	4	7756 ± 23	+70.8 ± 2.9	10043
641.5	6574.5	8523.5	6	7774 ± 22	+65.5 ± 2.7	10044
663.5	6552.5	8501.5	8	7654 ± 14	+78.6 ± 1.7	10045
680.5	6535.5	8484.5	8	7743 ± 22	+64.5 ± 2.7	10046
704.0	6512	8461	5	7731 ± 17	+63.1 ± 2.1	10047
719.5	6496.5	8445.5	4	7654 ± 17	+71.3 ± 2.1	10048
742.0	6474	8423	5	7605 ± 17	+75.0 ± 2.1	10049

*Quaternary Isotope Lab (Seattle)

TABLE 2
Ferguson's Bristlecone Pine series
Standard deviations are based on counting statistics only.

Year BC	Year BP	No. of rings	Radiocarbon age	$\Delta^{14}C$	QL no.
6475	8424	10	7686 ± 23	+64.2 ± 3.1	10064
6360	8309	20	7427 ± 22	+84.1 ± 3.0	10063
5805	7754	10	6926 ± 14	+78.9 ± 2.0	10062
5795	7744	10	6915 ± 21	+79.2 ± 2.9	10061
5785	7734	10	6935 ± 20	+75.2 ± 2.7	10060
5775	7724	10	6934 ± 22	+74.0 ± 3.0	10059
5765	7714	10	6897 ± 16	+77.6 ± 2.2	10058
5755	7704	10	6893 ± 17	+76.9 ± 2.4	10057
5745	7694	10	6904 ± 20	+74.1 ± 2.7	10056
5735	7684	10	6867 ± 20	+77.7 ± 2.8	10055
5725	7674	10	6820 ± 20	+82.7 ± 2.7	10054
5715	7664	10	6853 ± 20	+77.0 ± 2.8	10053
5705	7654	10	6799 ± 20	+82.9 ± 2.7	10052
5695	7644	10	6802 ± 20	+81.2 ± 2.7	10051
5685	7634	10	6799 ± 20	+80.3 ± 2.7	10050

TABLE 3
Seattle and Heidelberg measurements of duplicate samples of Becker D6M4/11 wood. Standard deviations are based on counting statistics only.

Ring no.	Heidelberg Radiocarbon age BP	Seattle Radiocarbon age BP	Difference
556.5	7884 ± 22	7887 ± 22	-3 ± 31
502.5	7925 ± 22	7893 ± 22	32 ± 31
562.5	7959 ± 22	7924 ± 23	35 ± 32
285	7996 ± 20	7945 ± 30	51 ± 36
255	7960 ± 22	7979 ± 17	-19 ± 28
205	8010 ± 20	7954 ± 11	56 ± 23