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EXTENDED ^{14}C DATA BASE AND REVISED CALIB 3.0 ^{14}C AGE CALIBRATION PROGRAM

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INTRODUCTION

The age calibration program, CALIB (Stuiver & Reimer 1986), first made available in 1986 and subsequently modified in 1987 (revision 2.0 and 2.1), has been amended anew. The 1993 program (revision 3.0) incorporates further refinements and a new calibration data set covering nearly 22,000 cal yr (~18,400 ^{14}C yr). The new data, and corrections to the previously used data set, derive from a 6-yr (1986–1992) time-scale calibration effort of several laboratories.

One purpose of this paper is to introduce the reader to some features of the IBM-compatible CALIB 3.0 program. As such, it supplements the 26-page CALIB User's Guide (Stuiver & Reimer 1993), which gives the ultimate CALIB details. A Macintosh version of CALIB 3.0 is available upon request.

The CALIB 3.0 program is menu-driven to calibrate ^{14}C ages, provide Δ^{14}C series and display results. CALIB, the User's Guide, and the calibration data are compressed on the floppy disk enclosed with this *RADIOCARBON* issue; this information should be copied following the instructions printed on the diskette label and in the file, README. The program can also be obtained separately from the Quaternary Isotope Laboratory. Δ^{14}C series include the data for Figures 2 and 11 of Stuiver and Braziunas (1993).

Although the basic tree-ring calibration data are either decadal or bidecadal, smoothed versions of the calibration curves can be obtained for multiyear samples using the moving average option. These smoothed versions are desirable, as the ^{14}C "wiggles" of the calibration curve play a lesser role in creating cal age uncertainty. Such smoothed versions should be used when samples have grown over intervals longer than 20 yr (*e.g.*, 100 yr for a 5-point moving average of the bidecadal curve).

In the following sections, we evaluate the selection of the calibration (and Δ^{14}C) data, and discuss new CALIB program features.

THE DATA

The ^{14}C data sets used for the CALIB program are given in Table 1. These data sets were constructed from four main categories, as listed below:

A. Bidecadal Data Set (AD 1950–9440 BC; 0–11,390 Cal Yr BP)

The data set utilized in the 1993 CALIB version came from several sources. The entire AD 1950–6000 BC interval is based on averages of ^{14}C ages obtained by the Seattle and Belfast laboratories on 20-yr samples. In the 1987 CALIB version 2.1, we utilized the published bidecadal data of Stuiver and Pearson (1986) and Pearson and Stuiver (1986) for the AD 1950–2500 BC interval. Some minor corrections in the 10–30 ^{14}C yr range (*e.g.*, a radon correction for Quaternary Isotope Laboratory results (Stuiver & Becker 1993)) have since been applied to the published Seattle and Belfast ^{14}C ages. The 1993 program incorporates 1) cor-

TABLE 1. ^{14}C data sets used for the 1993 calibration program. A, B, C and D refer to the subdivisions in the data section.

For atmospheric samples:	
Set 1.	Limited to 0–18,360 ^{14}C yr BP
	Bidecadal tree ring data set A (AD 1955–9440 BC, 0–11,390 cal yr BP)
	+ inferred atmospheric spline from D (9450 BC–20,000 BC, 11,400–21,950 cal yr BP)
Set 2.	Limited to 0–7210 ^{14}C yr BP:
	Decadal tree-ring data set B (AD 1955–6000 BC; 0–7950 cal yr BP)
For marine samples:	
Set 3.	Limited to 18,760 ^{14}C yr BP
	Marine bidecadal model data set C (0–11,400 cal yr BP)
	+ marine coral data spline from D (11,400–21,950 cal yr BP), slightly adjusted between 11,400 and 11,750 cal yr BP (Stuiver & Braziunas 1993)

rected averaged bidecadal data of both laboratories for the AD 1950–2500 BC interval, and 2) a new averaged bidecadal data set for the 2500–6000 BC interval (Stuiver & Pearson 1993; Pearson & Stuiver 1993).

The bidecadal ^{14}C age averages of the AD 1950–5000 BC interval are based on separate dendrochronologies (Irish oak for Belfast, and German oak/Northwest Pacific sequoia or Douglas fir for Seattle), which yield ^{14}C results with negligible systematic differences (Stuiver & Pearson 1993). The degree of coherence with other data sets also is discussed in the above paper. Between 5000–5160 BC, a mixture of Irish and German oak is used; for the 5180–6000 BC interval, calibration results are tied solely to the German chronology, with the exception of the 5680–5810 BC interval, where bristlecone pine data (Table 2) were added to the Seattle data set. There is minimal systematic difference between the ^{14}C results of both laboratories between 5500 BC and 6000 BC. For the 5180–5500 BC interval, however, the bidecadal calibration curve may be liable to a 27 ^{14}C-yr offset (see Stuiver & Pearson 1993).

TABLE 2. Radon-corrected ^{14}C ages of Ferguson bristlecone pine samples (Stuiver *et al.* 1986). Standard deviations are based on counting statistics only.

Year (BC)	Year (BP)	No. of rings	^{14}C age	Δ^{14}C
6475	8424	11	7733 ± 26	+57.9 ± 3.4
6360	8309	21	7472 ± 25	+77.9 ± 3.3
5805	7754	11	6968 ± 16	+73.1 ± 2.1
5795	7744	11	6974 ± 22	+71.0 ± 3.0
5785	7734	11	6994 ± 21	+67.0 ± 2.8
5775	7724	11	6976 ± 23	+68.2 ± 3.1
5765	7714	11	6930 ± 17	+73.0 ± 2.3
5755	7704	11	6933 ± 18	+71.3 ± 2.4
5745	7694	11	6946 ± 22	+68.3 ± 2.9
5735	7684	11	6909 ± 22	+71.9 ± 3.0
5725	7674	11	6861 ± 21	+77.0 ± 2.9
5715	7664	11	6895 ± 22	+71.3 ± 3.0
5705	7654	11	6840 ± 21	+77.2 ± 2.9
5695	7644	11	6843 ± 21	+75.6 ± 2.8
5685	7634	11	6844 ± 21	+74.1 ± 2.8

The 6000–8000 BC interval is covered in several data sets. Available intervals are 6016–7885 BC for Heidelberg (Kromer *et al.* 1986; Kromer & Becker 1993), 6436–7160 BC for Seattle (Table 3), 6000–7890 BC for Belfast (Pearson, Becker & Qua 1993), 6393–7199 BC for La Jolla (Linick *et al.* 1985) and 6089–6549 BC for Tucson (Linick, Suess & Becker 1986). Whereas the Tucson laboratory measured samples from the bristlecone pine chronology, all other laboratories worked with samples from the German chronology. Two data sets (Belfast and Tucson) were based on measurements of bidecadal (or decadal) wood samples (indicated below as true bidecadal wood); the other laboratories (Heidelberg, Seattle, La Jolla) measured samples grown over shorter time intervals (usually 1–3 yr).

To compare results from different laboratories, we define an error multiplier, $K_{\text{Lab A-Lab B}}$ (*e.g.*, Stuiver & Pearson 1992, 1993) as the ratio of the actual standard error in the age differences to the average standard deviation of the differences calculated from the quoted errors in the ^{14}C determinations. We define n = number of comparisons, and a = systematic difference with positive values when Lab A dates are older. Comparing Belfast and available Tucson data prior to 6000 BC (6090–6550 BC), $K_{\text{Belfast-Tucson}} = 1.8$, a = 15.8 ± 5.0 yr and n = 24. Application of an error multiplier of 1.8 to both data sets increases the error term in the offset to 9 yr. As the 15.8-yr offset (1.7 σ) is statistically insignificant, we averaged the Belfast and Tucson data over the 6090–6500 BC interval. Our true bidecadal (trueBD) curve for the 6000–8000 BC interval is identical to the Belfast bidecadal data set, except for the 6090–6550 BC interval, where the Belfast and Tucson data averages were used. For comparison with the Heidelberg, Seattle and La Jolla results, we also calculated "bidecadal" data points by averaging the available ^{14}C dates over 20-yr intervals. Often, only part of the bidecade was measured, and the "bidecadal" ^{14}C ages calculated in this manner need not be identical to the ^{14}C ages that would have been obtained by measuring bidecadal wood samples directly. However, the ^{14}C age differences between bidecadal and "bidecadal" samples should, in most instances, be $< \sim 10$ yr, as the scatter of single-year Δ^{14}C data usually is restricted to a few per mil (*e.g.*, Stuiver 1982).

Comparisons of the trueBD calibration curve to the Heidelberg, Seattle and La Jolla "bidecadal" data reveal some offsets, with $K_{\text{Heidelberg-TrueBD}} = 1.5$, a = 32 ± 4.1 yr, n = 47 (6020–7130 BC), $K_{\text{Heidelberg-TrueBD}} = 1.8$, a = 52 ± 4.8 yr, n = 34 (7190–7870 BC), $K_{\text{Seattle-TrueBD}} = 1.4$, a = 51 ± 4.5 yr, n = 34 (6430–7130 BC) and $K_{\text{LaJolla-TrueBD}} = 1.2$, a = −5 ± 7.8 yr, n = 36 (6390–7190 BC).

The ^{14}C ages of these imperfect "bidecades" can be used to construct a bidecadal data set incorporating all true bidecadal and "bidecadal" data (AllBD). Comparing AllBD with TrueBD, we find a 300-yr interval of substantial offset (6740–7040 BC). Here the mean difference is 43.3 ± 5.7 yr (n = 15, K = 0.84). The minimum proven offset is 43.3 ± 11.4 (2 σ), or $\sim$ 32 yr. Assuming that the average of the Seattle, Heidelberg, Belfast and La Jolla data is more representative of the average trend than the TrueBD data alone, which, for this interval, is Belfast data only, we elected to adjust the TrueBD curve by adding 32 ^{14}C yr to the ^{14}C dates of the 6740–7040 BC interval (the actual midpoints bracket 6750–7030 BC). We also took the trends in the AllBD curve to generate two missing data points in the TrueBD curve, at 7150 and 7170 BC (dashed line in Fig. 1). The resulting bidecadal calibration data set used in CALIB 3.0 for the 6000–7890 BC interval is the Adjusted TrueBD set, with K = 1.7 applied to the quoted standard deviations. The Adjusted TrueBD set is compared to the AllBD set in Figure 1 (offset a = 9.3 ± 2.1 yr, K is only 0.9 and n = 86). The systematic difference averages less than a decade, and is fairly randomly distributed (Fig. 1).

TABLE 3. Corrected data set of previously published (Stuiver *et al.* 1986) cal BC and ^{14}C ages of the unified Donau 6/Main 4/11 German chronology. Ring 1 of this chronology is now matched at 7177 BC and a radon correction (Stuiver & Becker 1993) was applied to the ^{14}C dates. Standard deviations are based on counting statistics only.

Ring no.	Year (BC)	Year (BP)	No. of Rings	^{14}C age	Δ^{14}C
18.5	7159.5	9108.5	2	8306 ± 41	+70.2 ± 5.1
28.5	7149.5	9098.5	4	8236 ± 24	+78.3 ± 3.0
42.0	7136	9085	5	8199 ± 25	+81.5 ± 3.1
52.0	7126	9075	5	8201 ± 25	+80.0 ± 3.1
72.0	7106	9055	5	8238 ± 24	+72.4 ± 3.0
82.5	7095.5	9044.5	6	8168 ± 23	+80.3 ± 2.9
107.0	7071	9020	5	8234 ± 24	+68.4 ± 3.0
132.0	7046	8995	5	8178 ± 23	+72.6 ± 2.8
157.0	7021	8970	5	8151 ± 24	+73.0 ± 3.0
167.0	7011	8960	5	8070 ± 24	+82.5 ± 3.0
187.0	6991	8940	5	8085 ± 24	+77.9 ± 3.0
202.0	6976	8925	5	7908 ± 25	+99.9 ± 3.1
205.0	6973	8922	11	8017 ± 14	+84.7 ± 1.7
217.0	6961	8910	5	7983 ± 32	+87.6 ± 4.0
232.0	6946	8895	5	8048 ± 27	+77.0 ± 3.4
255.0	6923	8872	11	8027 ± 17	+76.8 ± 2.2
257.0	6921	8870	5	8010 ± 26	+78.8 ± 3.3
278.5	6899.5	8848.5	6	8001 ± 24	+77.2 ± 3.0
285.0	6893	8842	11	7994 ± 36	+77.2 ± 4.4
297.0	6881	8830	5	8016 ± 24	+72.8 ± 3.0
317.0	6861	8810	5	8030 ± 24	+68.4 ± 3.0
322.0	6856	8805	5	7973 ± 50	+75.3 ± 6.2
342.0	6836	8785	5	8036 ± 20	+64.3 ± 2.5
347.0	6831	8780	5	8090 ± 25	+56.6 ± 3.1
365.5	6812.5	8761.5	4	8060 ± 26	+58.1 ± 3.2
387.5	6790.5	8739.5	4	8065 ± 26	+54.6 ± 3.2
402.0	6776	8725	5	8008 ± 23	+60.3 ± 2.8
414.0	6764	8713	3	7967 ± 26	+64.1 ± 3.2
431.0	6747	8696	3	7981 ± 26	+60.1 ± 3.2
451.0	6727	8676	3	7982 ± 25	+57.5 ± 3.1
457.0	6721	8670	5	7956 ± 23	+60.2 ± 2.8
462.0	6716	8665	5	7951 ± 25	+60.1 ± 3.1
462.5	6715.5	8664.5	6	7976 ± 24	+56.8 ± 3.0
477.0	6701	8650	5	7940 ± 23	+59.7 ± 2.8
497.0	6681	8630	5	7969 ± 24	+53.3 ± 3.0
502.5	6675.5	8624.5	6	7945 ± 24	+55.8 ± 3.0
517.0	6661	8610	5	7964 ± 23	+51.5 ± 2.8
525.0	6653	8602	11	7938 ± 24	+53.8 ± 3.0
542.5	6635.5	8584.5	6	7872 ± 17	+60.3 ± 2.2
556.5	6621.5	8570.5	6	7928 ± 25	+51.1 ± 3.1
572.0	6606	8555	5	7861 ± 23	+57.9 ± 2.8
589.5	6588.5	8537.5	10	7851 ± 21	+57.0 ± 2.7
618.5	6559.5	8508.5	4	7806 ± 24	+59.2 ± 3.0
641.5	6536.5	8485.5	6	7824 ± 24	+53.9 ± 3.0
663.5	6514.5	8463.5	8	7705 ± 16	+66.8 ± 2.0
680.5	6497.5	8446.5	8	7793 ± 24	+53.0 ± 3.0
704.0	6474	8423	5	7781 ± 17	+51.6 ± 2.1
719.5	6458.5	8407.5	4	7706 ± 17	+59.4 ± 2.1
742.0	6436	8385	5	7640 ± 18	+65.4 ± 2.3

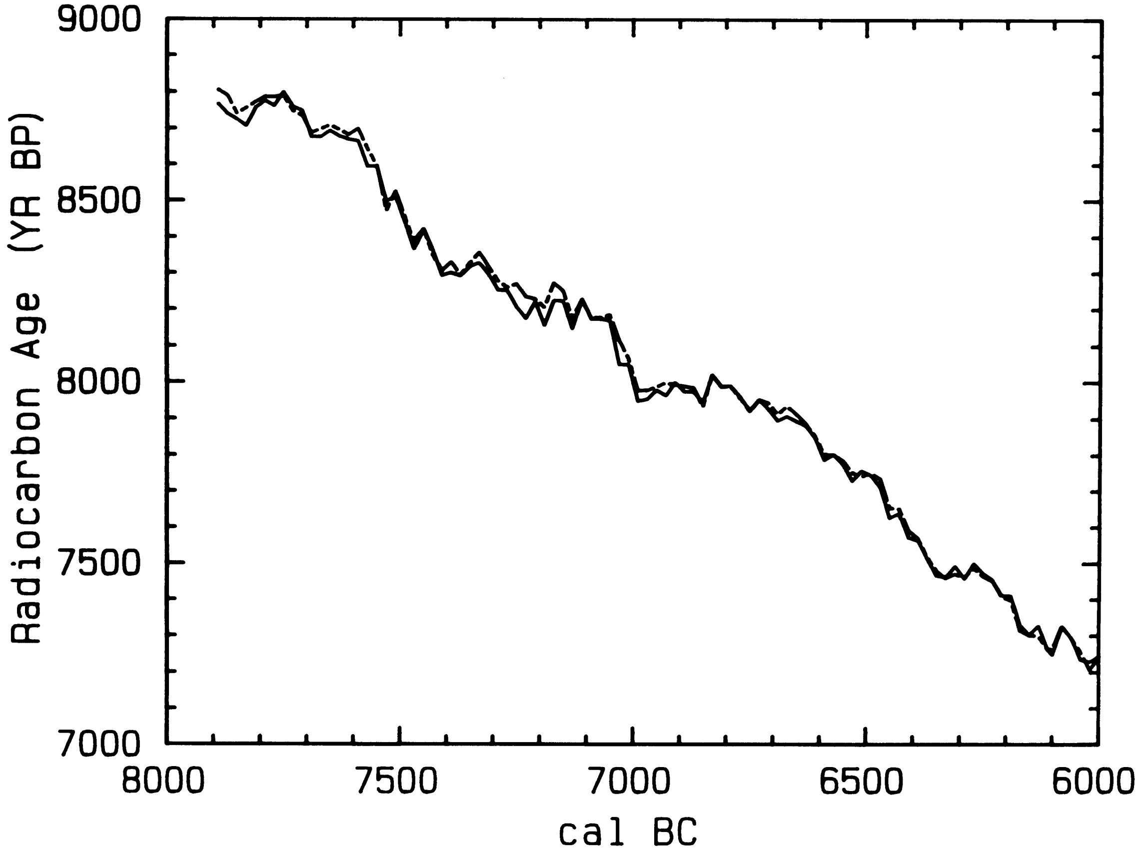


Fig. 1. A comparison of the CALIB 3.0 bidecadal data set (——) and ^{14}C age averages of available data from the Belfast, La Jolla, Heidelberg, Seattle and Tucson laboratories (– –). The CALIB set of the 8000–6000 BC interval derived from Pearson, Becker & Qua (1993) and Linick *et al.* (1986) with adjustments discussed in the text.

Between 7890 and 9440 BC, the CALIB 3.0 program uses Heidelberg measurements (Kromer & Becker 1993) of an early Holocene pine chronology from south-central Europe. The oldest part of the absolute German oak chronology and the youngest portion of the pine chronology have not yet been absolutely matched. The connection by Becker, Kromer and Trimborn (1991) assigns minimum absolute ages to the pine chronology. Bard *et al.* (1993) and Stuiver *et al.* (1991) suggest a shift of 150 and 300 yr, respectively. A very tentative match of overlapping tree-ring patterns by Becker (1993), equivalent to a 74-yr increase in cal ages, leads to the absolute BC ages of Kromer and Becker (1993). These tentative BC dates were adopted for the CALIB 3.0 program. A "bidecadal" record was generated for the 7890–9450 BC interval by taking 20-yr averages of ^{14}C ages reported for shorter-lived samples, with an error multiplier of 1.7 applied to the quoted errors. The CALIB 3.0 tree-ring bidecadal calibration set ends at 11,390 cal yr BP (*ca.* 10,000 ^{14}C yr BP). The corresponding bidecadal Δ^{14}C profile is given in Figure 2.

Uncertainties and fluctuations in the calibration curve cause the discrete cal ages to broaden into ranges, even for a ^{14}C age with (hypothetical) zero error. The spreads of the cal-yr ranges, obtained from the age calibration of ^{14}C dates between 0 and 10,000 ^{14}C yr BP (bidecadal data set) are given in Figure 3. To generate the graph, the youngest calibrated age of each range

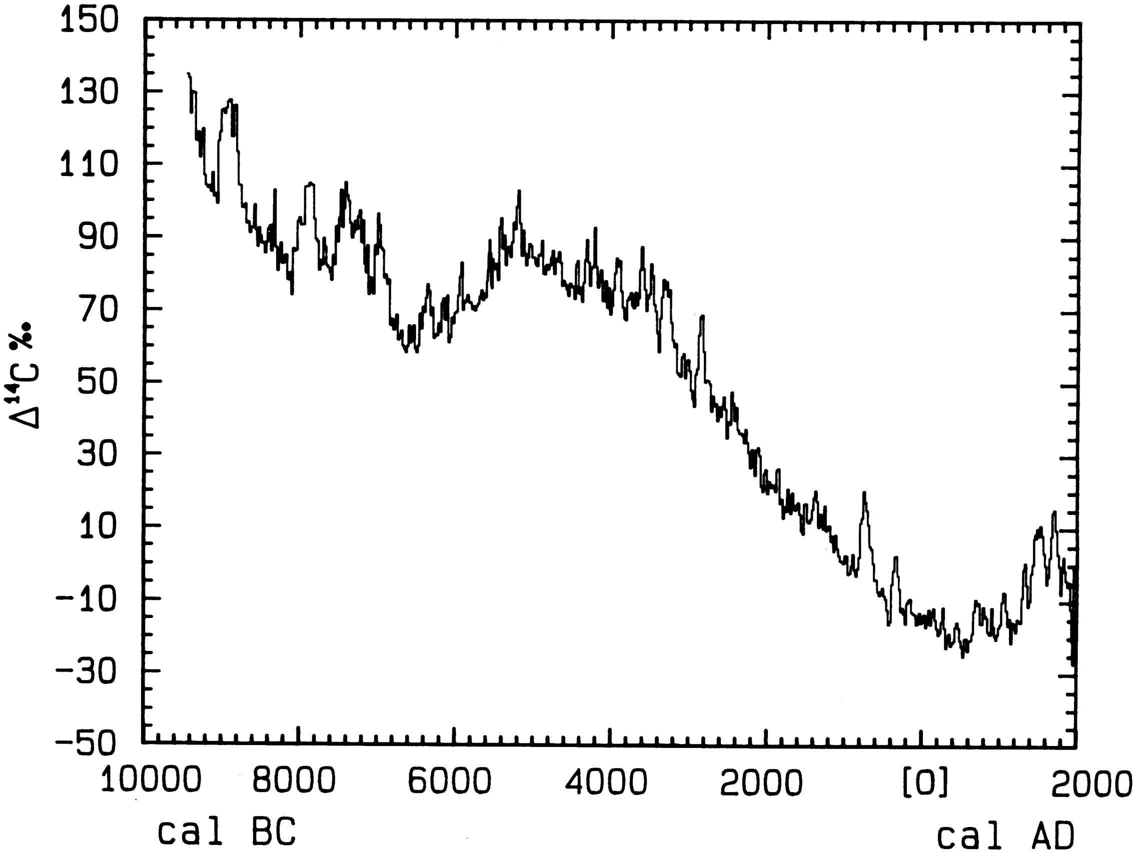


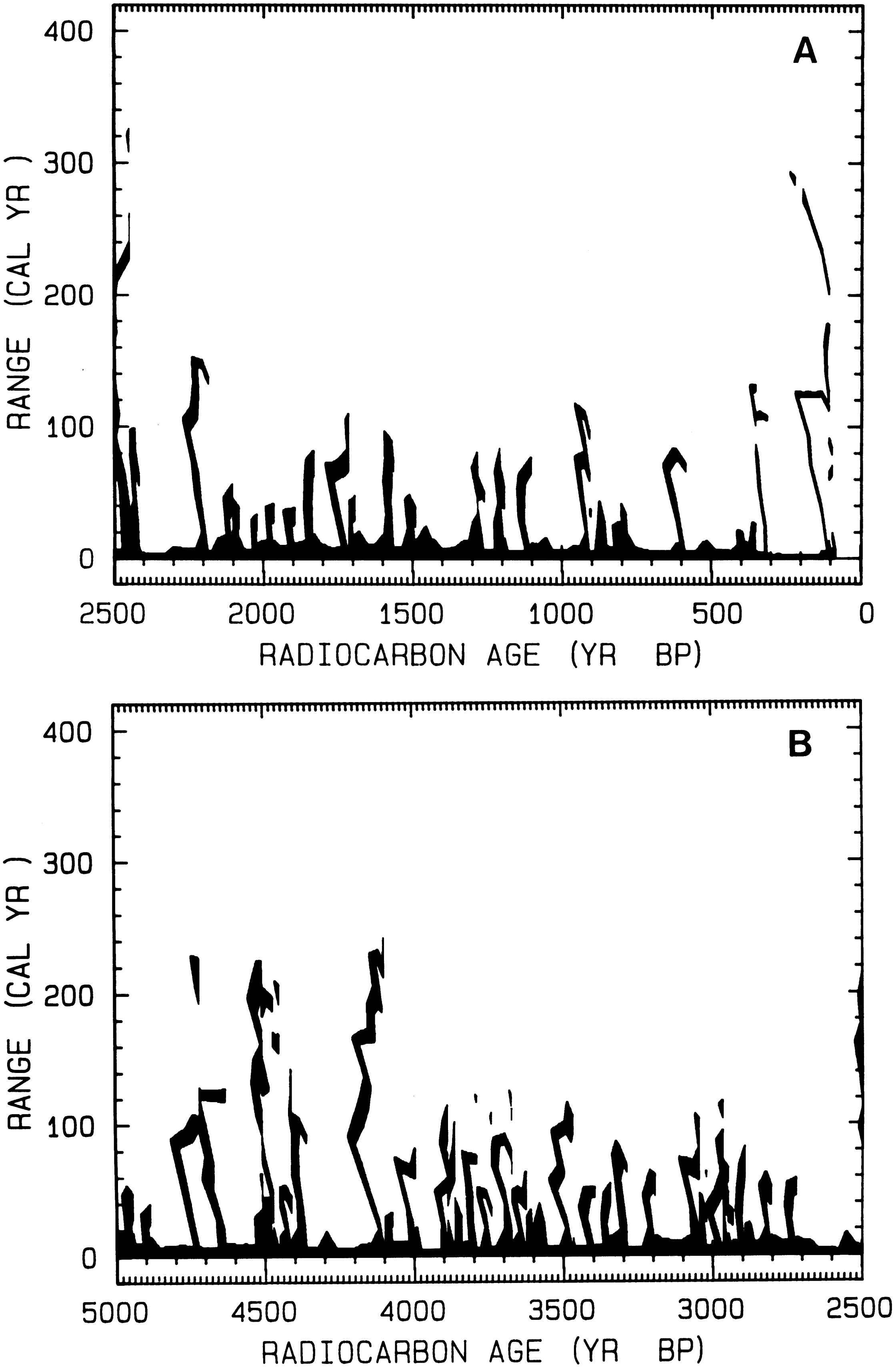
Fig. 2. Bidecadal $\Delta^{14}C$ values (‰) of the CALIB 3.0 data set

of cal ages obtained for each ^{14}C age was set at zero. Each section of the range is represented by a black vertical bar; plotting these vertical bars for each ^{14}C year results in the black shaded areas of Figure 3, which can be used to canvas the ^{14}C ages corresponding to limited cal age ranges. Cal ages will be relatively less precise for ^{14}C dates in the 7500–10,000 ^{14}C yr range, as here the "time warps" (in cal yr) increase in magnitude (Fig. 3).

B. Decadal Data Set (AD 1950–6000 BC; 0–7950 Cal Yr BP)

For users interested in a decade subdivision of time, we have included the decade results of the Seattle laboratory back to 6000 BC (Stuiver & Becker 1993). As discussed above, there is good agreement between the Belfast and Seattle ^{14}C ages for the entire interval, except for 5180–5500 BC, where Seattle ages are, on average, 54 ^{14}C yr younger than Belfast ages. Because the origin of the offset between the laboratories is not known, it is impossible to decide which data set is correct. The decadal cal age calculations of the CALIB 3.0 program do not include offset corrections for the 5180–5500 BC interval, and, therefore, differ from the bidecadal curve by 27 yr.

Fig. 3A–D. The time warps, or ranges, in cal years, obtained from the calibration of ^{14}C ages (for sections covering 0–10,000 ^{14}C BP) when using the CALIB 3.0 bidecadal record. The ranges were produced for an ideal hypothetical case with zero ^{14}C sample standard deviations. The youngest cal age obtained for each ^{14}C age was set at zero. The sample was assumed to have been formed during a 20-yr (or shorter) interval. ⟶

A
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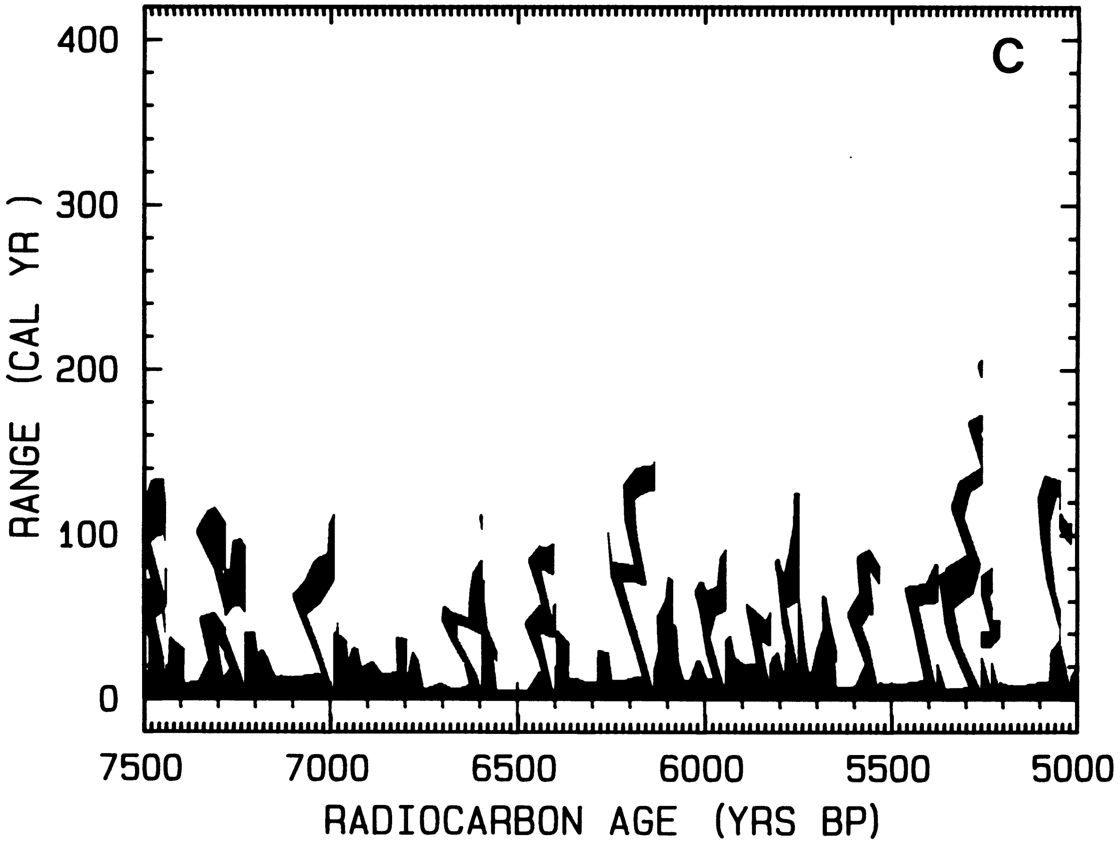
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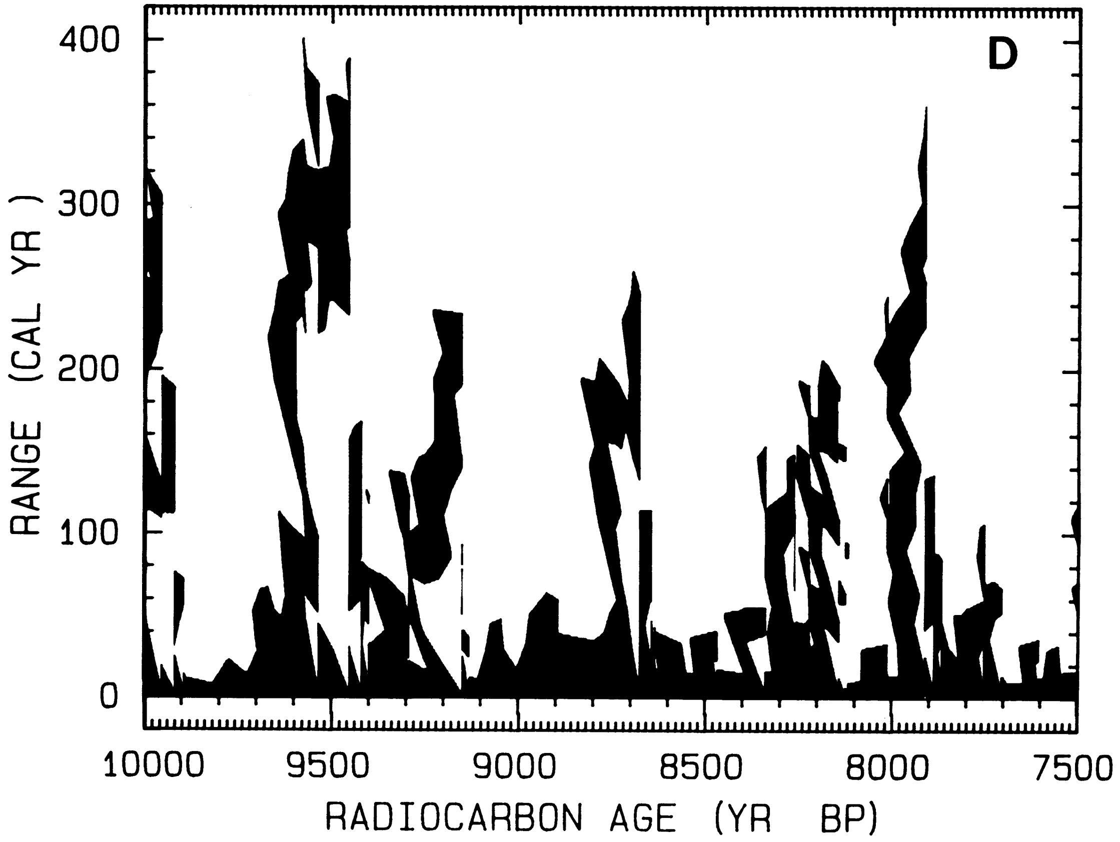
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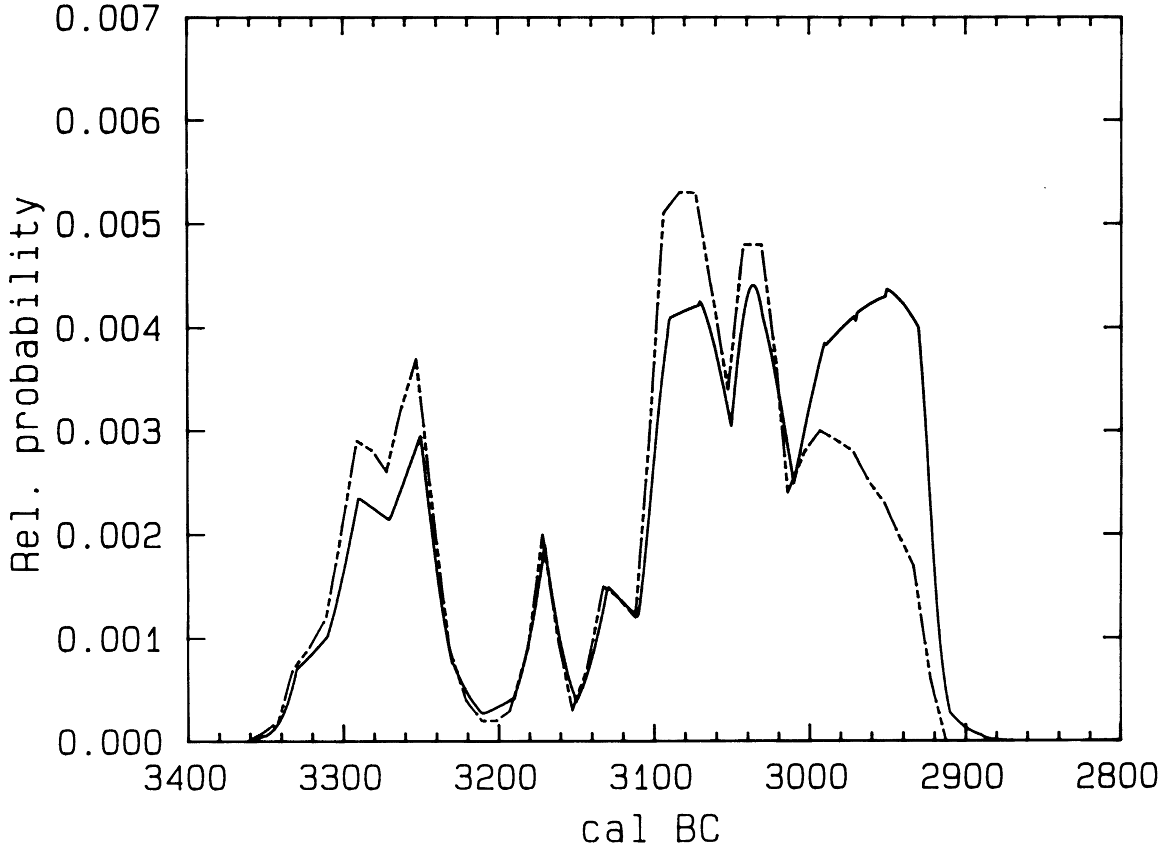

Fig. 4. Alteration of CALIB 3.0 probability diagram (——) when relative position of the sample is taken into account (– –)(Buck *et al.* 1990). Maximum modification is represented by the above example.

C. Marine Bidecadal Data Set (0–11,400 Cal Yr BP)

This calibration for marine samples (Table 1, Stuiver & Braziunas 1993) is based on carbon-reservoir calculations that utilize the bidecadal atmospheric data set as an input. The calculated calibration curve is applicable to the world ocean only, and regional offsets should be accounted for by a ΔR term (see Stuiver & Braziunas 1993). The 1 σ uncertainties assigned to the calculated marine values correspond to the atmospheric bidecadal standard deviations discussed in Section A and below.

D. Atmospheric (Marine) ^{14}C Data for Samples Older Than 10,100 (10,500) ^{14}C Yr BP

U/Th and ^{14}C dating of corals provide ^{14}C age calibration beyond 10,000 ^{14}C yr BP (Bard *et al.* 1993). These data provide measured marine ^{14}C ages. Atmospheric ^{14}C ages are inferred by deducting a 400-yr reservoir age (Bard *et al.* 1993) from the coral ^{14}C ages. Thus, the character of the marine calibration curve changes when moving beyond the Holocene; older samples are calibrated against a curve based on direct measurements, whereas younger samples are calibrated against a model-calculated curve. For atmospheric samples, the situation is the reverse; we use an inferred atmospheric curve for older samples (based on the assumption of a constant 400-yr reservoir age) and a detailed measured calibration curve for the last 11,400 cal yr.

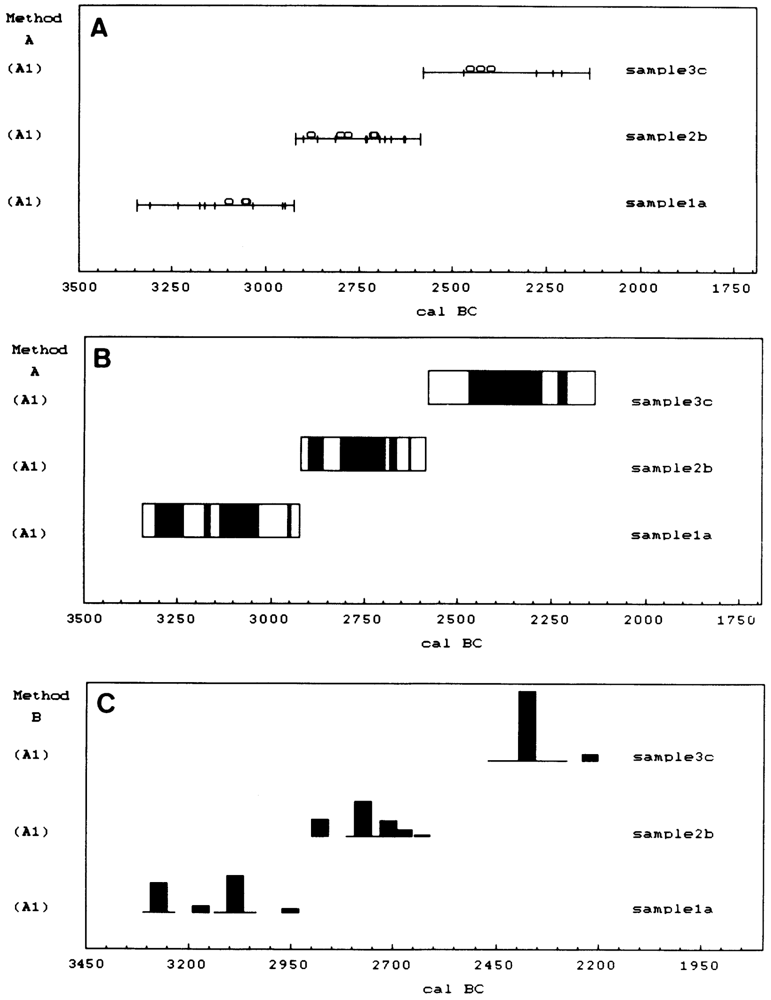

Fig. 5. Calibrated age range plot from CALIB 3.0. The calibration data set used for each sample is indicated in parentheses in the left margin (*e.g.* (A1) = atmospheric Set 1). A. Short, vertical bars indicating the 1 σ ranges, longer vertical bars, the 2 σ ranges, and circles, the calibrated ages. B. Solid blocks representing the 1 σ cal age ranges, and outlined blocks, the 2 σ cal age ranges. C. Cal age ranges represented by horizontal line, and the relative probability, by a column proportional in height to the relative area under the probability curve.

For the CALIB program, the inferred atmospheric data set (11,400–21,950 cal yr BP) is approximated by a smoothing spline (Reinsch 1967) with smoothing parameter = 4. The 1 σ uncertainties assigned to the spline values (one calculated data point for every 50 cal yr) were derived from an interpolation of the reported uncertainties in the ^{14}C ages of the corals. The assigned ^{14}C age errors are an upper limit, as the spline itself is more representative of a moving average. U/Th age errors (about 1/2 the ^{14}C age errors), on the other hand, have not been taken into account. More definite calibration errors, based on the expectation of a much larger future data set, will be assigned in the next CALIB version.

For a smooth connection between the splined curve of inferred atmospheric data and the bidecadal atmospheric data set, we included in the spline derivation a single point (at 11,390 cal BP) of the tree-ring calibration curve. The two marine segments, a pre-11,750 cal yr BP smoothing spline through coral measurements and a post-11,650 cal yr BP model-calculated part, are connected by a short linear interpolation.

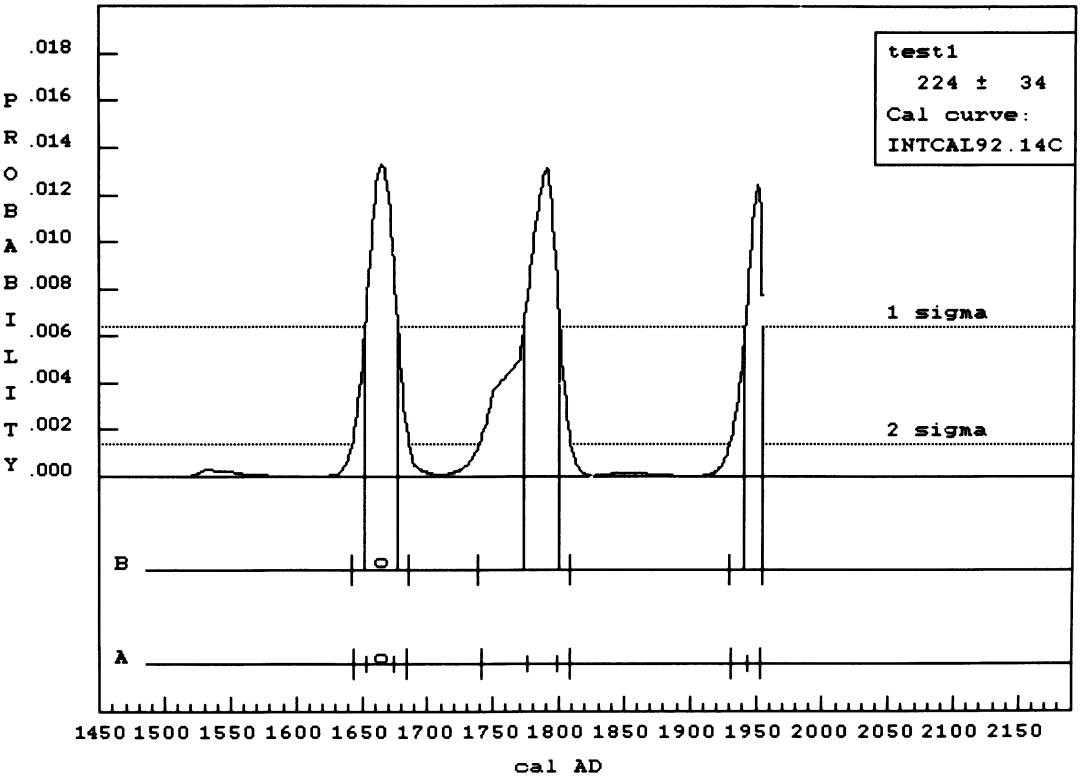

Fig. 6. The probability distribution from CALIB 3.0 for a test sample with Methods A and B cal age ranges marked by vertical lines (see Fig. 5) and cal ages denoted by circles

THE CALIB PROGRAM

CALIB 3.0 runs on any IBM-compatible computer with 640 kb available memory; a hard disk is recommended. The graphics are compatible with VGA, EGA, CGA and HGC (Hercules graphics) cards. To use the program in EGA or VGA mode, MS-DOS 4.0 is required. For older DOS versions, the program will set the mode to CGA or HGC as appropriate. A simplified Macintosh version (requiring >1.5 mb memory) of the IBM program can be obtained from the Quaternary Isotope Laboratory.

The 1993 program (revision 3.0) provides the integrated data (^{14}C age, $\Delta^{14}C$ and standard deviations) for sets 1-3, summarized in Table 1. CALIB 3.0 makes the conversion from a conventional ^{14}C age to calibrated calendar years, and will calculate the probability distribution of the sample's true age. A conventional ^{14}C age implies correction for isotope fractionation through normalization on $\delta^{13}C = -25$ ‰ (Stuiver & Polach 1977). Substantial errors may result if a "radiocarbon date" is not corrected for isotope fractionation. Quite a few commercial "dates" lack $\delta^{13}C$ corrections, and here, the user must estimate $\delta^{13}C$ values based on the type of material. The program will accept an input of either uncorrected "radiocarbon dates", together with an estimated $\delta^{13}C$ value, or conventional ^{14}C ages. Of course, for the latter case, $\delta^{13}C$ should not be entered. Table 1 in Stuiver and Polach (1977) (see also Stuiver & Reimer 1993) illustrates estimated average $\delta^{13}C$ values for various materials.

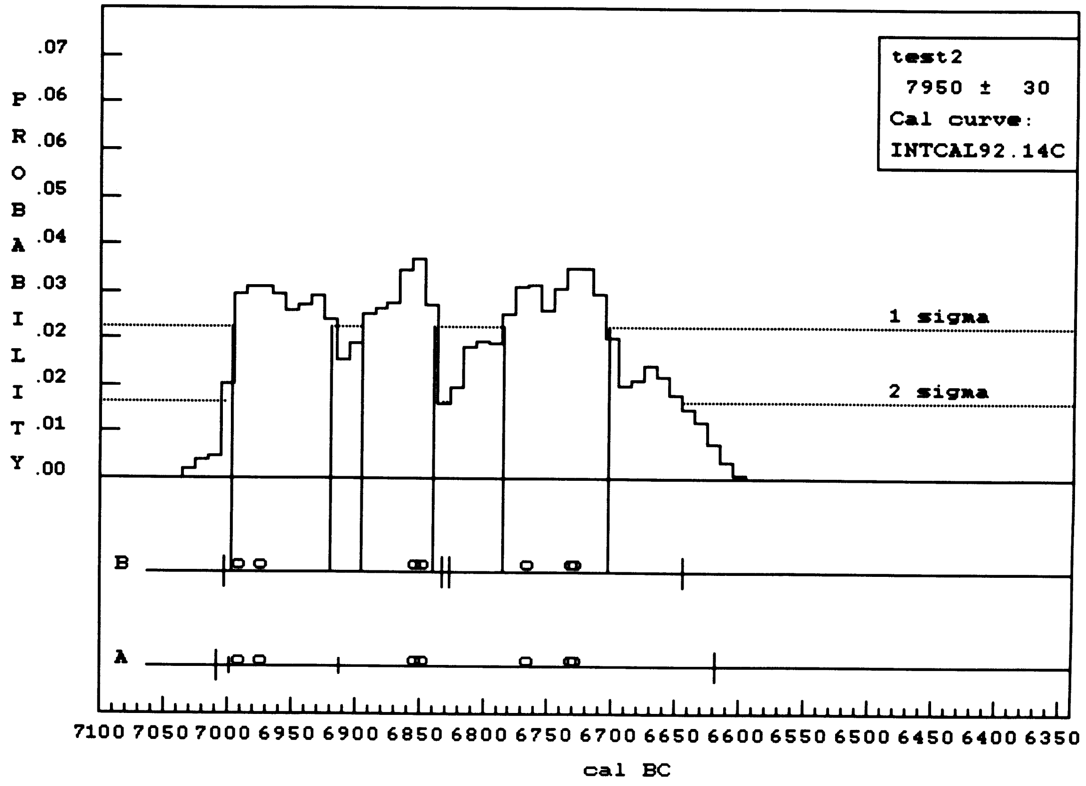

Fig. 7. The probability distribution from CALIB 3.0 for a test sample plotted as a histogram with Methods A and B cal age ranges marked by vertical lines (see Fig. 5) and cal ages represented by circles

An enlargement of the ^{14}C age error will accompany a δ^{13}C estimate, due to the spread of δ^{13}C values in nature. The δ^{13}C uncertainty may differ somewhat for various sample types (Stuiver & Polach 1977). The program assigns, as a first-order approximation, a 2.5 ‰ error to the estimated δ^{13}C value. This enlarges the reported standard deviation (σ) of the ^{14}C age determination to $(\sigma^2 + 40^2)^{\frac{1}{2}}$. The fixed 2.5 ‰ δ^{13}C error can be avoided by entering an estimated δ^{13}C. Of course, those using the conventional ^{14}C age option should avoid the δ^{13}C error estimate. In this case, only conventional ^{14}C age and error should be entered.

CALIB's Method A yields calibrated ages (intercepts) and age ranges; Method B generates a cal age probability distribution compatible with the ^{14}C age and its Gaussian age distribution (formulation as given in Stuiver & Reimer 1989). In the 1987 version 2.1, the average curve σ of the cal age intercepts was used to calculate the total σ for the range calculations; the 1993 revision 3.0 (Stuiver & Reimer 1993) uses more detailed curve σs found over the full range.

In the 1993 revision, the user can increase the reported standard deviation, σ, by either applying a lab error multiplier, K, or adding variance, f^2 (year^2). The latter approach may be more desirable to some users, as adding sources of variance conforms with standard statistical methods. The sample standard deviation σ increases to either $K\sigma$, or $(\sigma^2 + f^2)$. The curve sigma, σ_c, is added in both cases, so that the total σ of the ^{14}C age prior to its cal age transformation can be either $((K\sigma)^2 + \sigma_c^2)^{\frac{1}{2}}$ or $(\sigma^2 + \sigma_c^2 + f^2)^{\frac{1}{2}}$. K values should be available from the laboratory that provides the ^{14}C

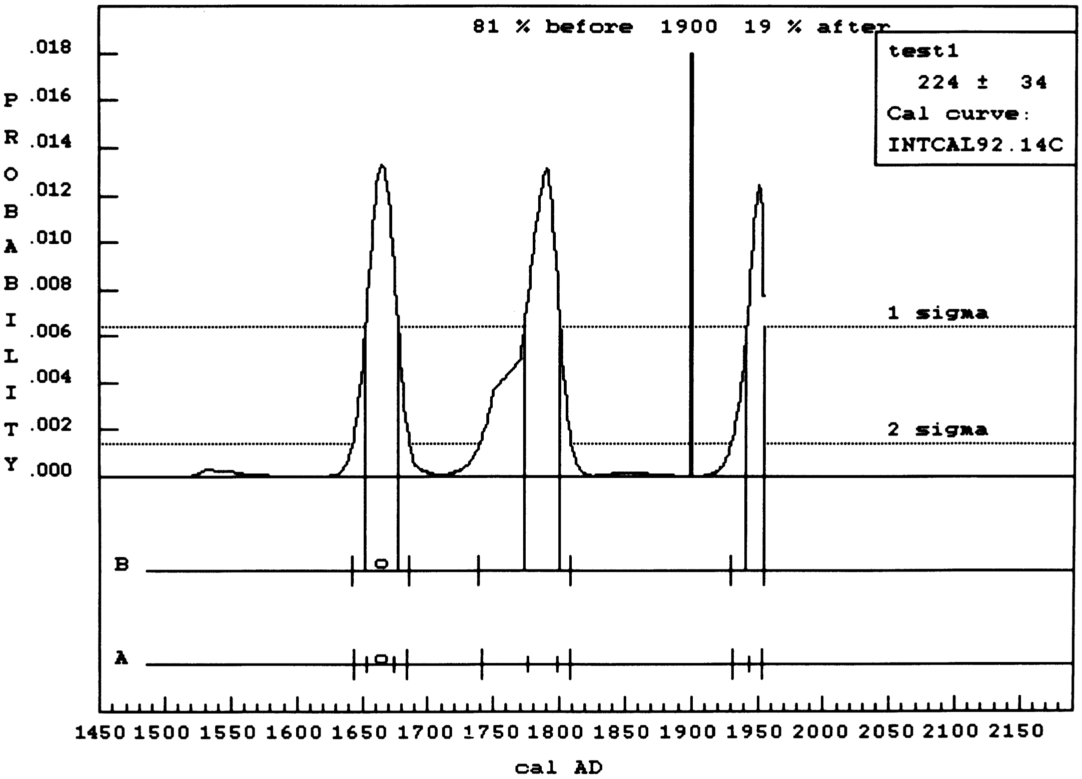

Fig. 8. The probability distribution from CALIB 3.0 for a test sample with a calendar/time marker. The relative area under the probability distribution above and below the marker is labeled.

age determination. A value for f suggested by Clark (1975) for routine ^{14}C dating is 50 yr for samples less than 2700 BP, or 60 yr for samples older than 2700 BP.

CALIB 3.0 allows a series of ^{14}C ages to be checked for consistency through a χ^2 test (Ward & Wilson 1978). If the ^{14}C age differences are judged as insignificant, and if geological, archaeological or other evidence corroborates sample contemporaneity, a pooled ^{14}C age (weighted average) can be used for the age calibration.

When the χ^2 test disproves contemporaneity, the individual probability distributions derived for the sample ages may be summed, if desired. All dates are considered equal, in that the user assumes no *a priori* knowledge of the relative position of the samples. Additional information on sample stratigraphy modifies the summed probability distribution of the group samples to some extent. CALIB does not give information on such modification, but a specific case was discussed by Buck *et al.* (1990), where a series of samples was subdivided into four groups in chronological order. Figure 4 compares the Buck *et al.* (1990) calculated posterior probability with the CALIB probability summation for the sample group experiencing maximum modification of the CALIB distribution. Additional information on estimating the duration of archaeological phenomena is available in Aitchison *et al.* (1991).

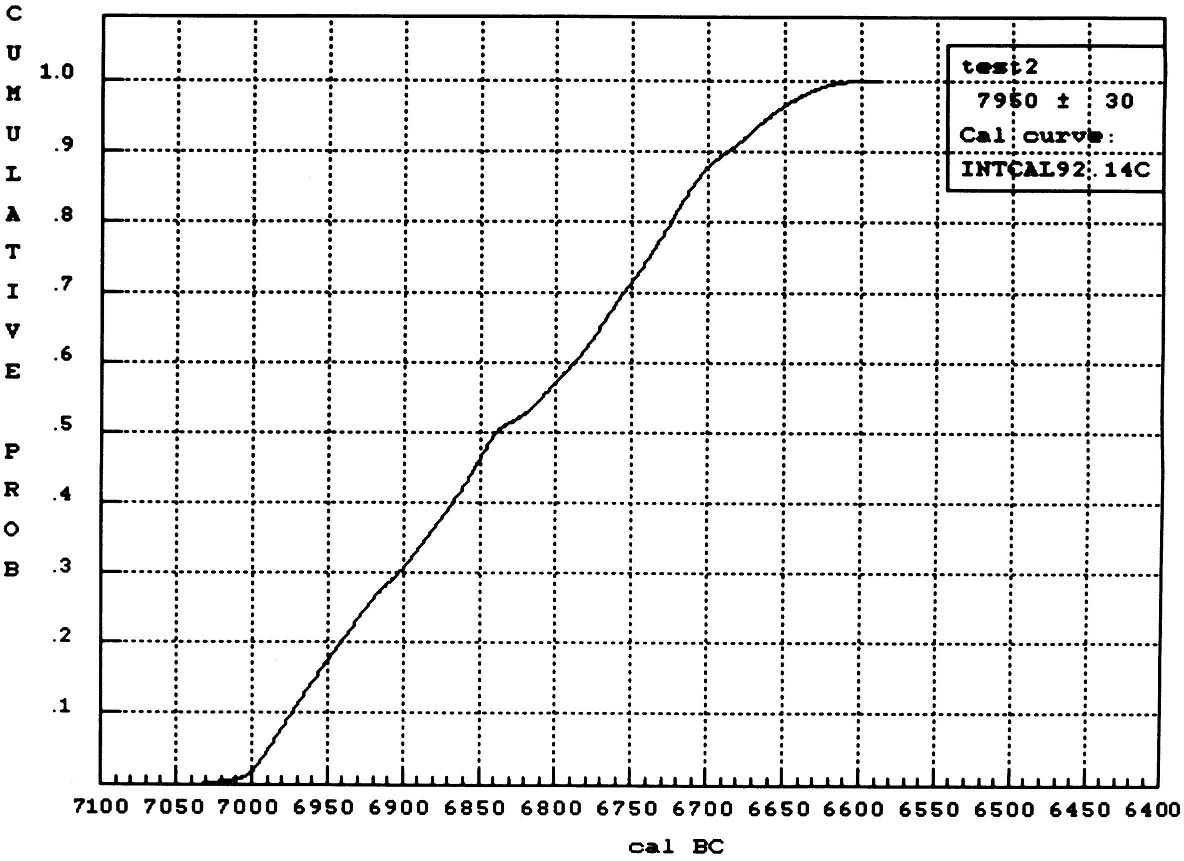

Fig. 9. The cumulative probability plot for a test sample from CALIB 3.0

In the 1987 revision, we did not calculate the ^{14}C ages of any Gaussian distribution (representing the sample σ) falling outside the range of the calibration curve. For the 1993 version, the end of the calibration curve is either extended by a straight-line interpolation between coral data (Sets 1 and 3) or a straight-line estimate (1 ^{14}C yr = 1 cal yr, Set 2). The cal ages exceeding the curve limit are reported as older than the curve limit. The cal age ranges and the probability distribution associated with estimated (beyond the curve limit) cal years are shown as dashed lines in the plots. Plots are displayed in graphics mode, rather than character mode, as in the old version. Three types of plots are available: calibrated age ranges, probability distributions and the calibration curves. The plots may be printed to an IBM-compatible graphics printer or an HP-series printer; for HP, the HPSCREEN driver is required for MS-DOS versions prior to DOS 5.0.

Cal ages and their ranges can be displayed graphically (Figs. 5A and 5B), as can probabilities derived from the age conversion (Figs. 5C–9). Calibrated age ranges may be plotted as: 1) horizontal lines on which circles depict the cal ages, and vertical bars depict the magnitude of 1 (short bars) and/or 2 σ (longer bars) ranges (Fig. 5A); 2) as solid blocks for 1 σ ranges and outlined blocks for 2 σ ranges (Fig. 5B), or 3) as horizontal lines with the relative area under the probability curve for each range, as described in the Fig. 5C legend. The number of samples per plot is set by the user, and samples may be ordered by ^{14}C age.

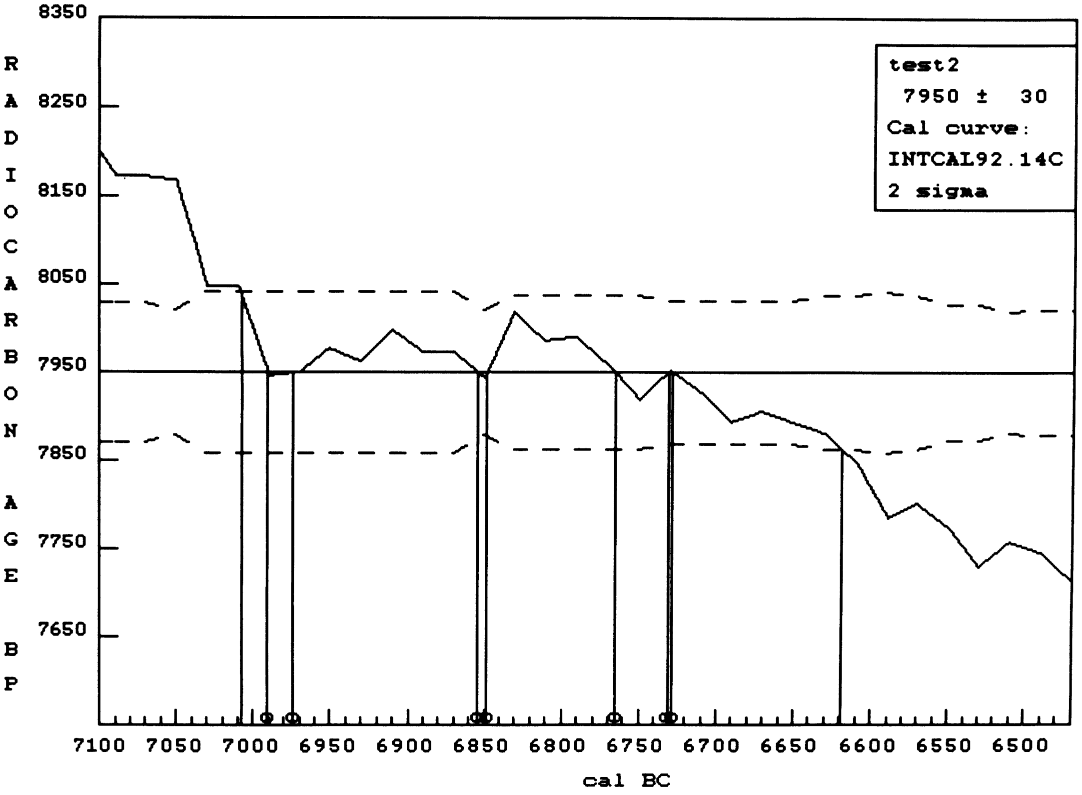

Fig. 10. Bidecadal ^{14}C age BP *vs.* calendar year in the cal age range of the sample. The intersections of the ^{14}C age and ^{14}C age ± total σ (– –) with the calibration curve are marked with vertical lines drawn to the cal yr axis. The calibrated ages are marked with circles.

CALIB 3.0 allows normalization of the probability distributions (Fig. 6), so that total area or the maximum = 1 for the plot. The distribution may be plotted as a histogram (Fig. 7) or a smooth line. The plot may include the Method A and/or Method B cal age ranges. A stratigraphic/calendar marker may be drawn, with the relative area under the probability distribution above and below the marker labeled (Fig. 8). Plotting the cumulative probability (Fig. 9) is another option.

Another CALIB 3.0 feature focuses on the calibration curve, which may be plotted as ^{14}C age BP *vs.* calendar year (Fig. 10), with or without the age ranges for a selected sample, or as $\Delta^{14}C$ ‰ *vs.* calendar year (*e.g.*, Fig. 2). In Figure 10, vertical distance between the dashed lines (representing ^{14}C age ± total σ) varies with cal age, as the σ associated with the calibration curve is not constant.

For additional information, the reader is referred to the CALIB User's Guide (Stuiver & Reimer 1993).

REFERENCES

Aitchison, T., Ottaway, B. and Al-Ruzaiza, A. S. 1991 Summarizing a group of ^{14}C dates on the historical time scale: With a worked example from the Late Neolithic of Bavaria. *Antiquity* 65(246): 108–116.

Bard, E., Arnold, M., Fairbanks, R. G. and Hamelin, B. 1993 ^{230}Th-^{234}U and ^{14}C ages obtained by mass spectrometry on corals. *Radiocarbon*, this issue.

Becker, B. 1993 An 11,000-year German oak and pine dendrochronology for radiocarbon calibration. *Radiocarbon*, this issue.

Becker, B., Kromer, B. and Trimborn P. 1991 A stable isotope tree-ring timescale of the Late Glacial/Holocene boundary. *Nature* 353: 647–649.

Buck, C. E., Kenworthy, J. B., Litton, C. D. and Smith A. F. M. 1990 *Combining Archaeological and Radiocarbon Information: The Betting Man's Guide to Skara Brae.* Nottingham Statistics Group, Department of Mathematics, University of Nottingham, England: 20 p.

Clark, R. M. 1975 A calibration curve for radiocarbon dates. *Antiquity* 49: 251–266.

Kromer, B. and Becker, B. 1993 German oak and pine ^{14}C calibration, 7200–9400 BC. *Radiocarbon*, this issue.

Kromer, B., Rhein, M., Bruns, M., Schoch-Fischer, H., Münnich, K. O., Stuiver, M. and Becker, B. 1986 Radiocarbon calibration data for the 6th to the 8th Millennia BC. *In* Stuiver, M. and Kra, R. S., eds., Proceedings of the 12th International ^{14}C Conference. *Radiocarbon* 28(2B): 954–960.

Linick, T. W., Long, A., Damon, P. E. and Ferguson, C. W. 1986 High-precision radiocarbon dating of bristlecone pine from 6554 to 5350 BC. *In* Stuiver, M. and Kra, R. S., eds., Proceedings of the 12th International ^{14}C Conference. *Radiocarbon* 28(2B): 943–953.

Linick, T. W., Suess, H. E. and Becker, B. 1985 La Jolla measurements of radiocarbon in South German oak tree-ring chronologies. *Radiocarbon* 27(1): 20–32.

Pearson, G. W., Becker, B. and Qua, F. 1993 High-precision ^{14}C measurement of German and Irish oaks to show the natural ^{14}C variations from 7890 to 5000 BC. *Radiocarbon*, this issue.

Pearson, G. W. and Stuiver, M. 1986 High-precision calibration of the radiocarbon time scale, 500–2500 BC. *In* Stuiver, M. and Kra, R. S., eds., Proceedings of the 12th International ^{14}C Conference. *Radiocarbon* 28(2B): 839–862.

_____1993 High-precision bidecadal calibration of the radiocarbon time scale, 500–2500 BC. *Radiocarbon*, this issue.

Reinsch, C. H. 1967 Smoothing by spline functions. *Numerische Mathematik* 10: 177–183.

Stuiver, M. 1982 A high-precision calibration of the AD radiocarbon time scale. *Radiocarbon* 24(1): 1–26.

Stuiver, M. and Becker, B. 1993 High-precision decadal calibration of the radiocarbon time scale, AD 1950–6000 BC. *Radiocarbon*, this issue.

Stuiver, M. and Braziunas, T. F. 1993 Modeling atmospheric ^{14}C influences and radiocarbon ages of marine samples back to 10,000 BC. *Radiocarbon*, this issue.

Stuiver, M., Braziunas, T. F., Becker, B. and Kromer, B. 1991 Climatic, solar, oceanic and geomagnetic influences on Late-Glacial and Holocene atmospheric $^{14}C/^{12}C$ change. *Quaternary Research* 35: 1–24.

Stuiver, M., Kromer B., Becker B. and Ferguson, C. W. 1986 Radiocarbon age calibration back to 13,300 years BP and the ^{14}C age matching of the German oak and US bristlecone pine chronologies. *In* Stuiver, M. and Kra, R. S., eds., Proceedings of the 12th International ^{14}C Conference. *Radiocarbon* 28(2B): 969–979.

Stuiver, M. and Pearson, G. W. 1986 High-precision calibration of the radiocarbon time scale, AD 1950–500 BC. *In* Stuiver, M. and Kra, R. S., eds., Proceedings of the 12th International ^{14}C Conference. *Radiocarbon* 28(2B): 805–838.

_____1992 Calibration of the radiocarbon time scale 2500-5000 BC. In Taylor, R. E., Long, A. and Kra, R. S., eds., *Radiocarbon After Four Decades: An Interdisciplinary Perspective.* New York, Springer Verlag: 19–33.

_____1993 High-precision calibration of the radiocarbon time scale, AD 1950–500 BC and 2500–6000 BC. *Radiocarbon*, this issue.

Stuiver, M. and Polach, H. A. 1977 Discussion: Reporting of ^{14}C data. *Radiocarbon* 19(3): 355–363.

Stuiver, M. and Reimer, P. J. 1986 A computer program for radiocarbon age calibration. *In* Stuiver, M. and Kra, R. S., eds., Proceedings of the 12th International ^{14}C Conference. *Radiocarbon* 28(2B): 1022–1030.

_____1989 Histograms obtained from computerized radiocarbon age calibration. *In* Long, A. and Kra, R. S., eds., Proceedings of the 13th International ^{14}C Conference. *Radiocarbon* 31(3): 817–823.

_____1993 CALIB User's Guide Rev. 3.0. University of Washington, Quaternary Isotope Laboratory.

Ward, G. K. and Wilson S. R. 1978 Procedures for comparing and combining radiocarbon age determinations: A critique. *Archaeometry* 20(1): 19–34.