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HIGH-PRECISION BIDECADAL CALIBRATION OF THE RADIOCARBON TIME SCALE, AD 1950–500 BC AND 2500–6000 BC

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INTRODUCTION

The radiocarbon ages of dendrochronologically dated wood spanning the AD 1950–6000 BC interval are now available for Seattle (10-yr samples, Stuiver & Becker 1993) and Belfast (20-yr samples, Pearson, Becker & Qua 1993; Pearson & Qua 1993). The results of both laboratories were previously combined to generate a bidecadal calibration curve spanning nearly 4500 years (Stuiver & Pearson 1986; Pearson & Stuiver 1986). We now find that minor corrections must be applied to the published data sets, and therefore, give new bidecadal radiocarbon age information for 2500–6000 BC, as well as corrected radiocarbon age averages for AD 1950–500 BC. Corrected average ^{14}C ages for the 500–2500 BC interval are given separately (Pearson & Stuiver 1993). The Seattle corrections (in the 10–30 ^{14}C-yr range) are discussed in Stuiver and Becker (1993), whereas Pearson and Qua (1993) provide information on Belfast corrections (averaging 16 yr). All dates reported here are conventional radiocarbon dates, as defined in Stuiver and Polach (1977). Belfast ^{14}C ages back to 5210 BC were obtained on wood from the Irish oak chronology (Pearson *et al.* 1986). Wood from the German oak chronology (Becker 1993) was used by Belfast for the 5000–6000 BC interval. For the overlapping interval (5000–5210 BC), Belfast reports weighted Irish wood/German wood ^{14}C age averages. The Seattle ^{14}C ages for the AD interval were either on Douglas fir wood from the US Pacific Northwest, or Sequoia wood from California (Stuiver 1982). The BC materials measured in Seattle were mostly part of the German oak chronology. Thirteen samples (5680–5810 BC) from the US bristlecone pine chronology (Ferguson & Graybill 1983) were measured in Seattle as well. Here, the final Seattle decadal ^{14}C ages resulted from averaging German oak and bristlecone pine ages.

Several factors contribute to the uncertainty in the calibration curve for bidecadal cellulose samples. The precision and accuracy of the ^{14}C measuring process is limited, and dendrochronological errors (if any) may result in ^{14}C age differences when materials of different chronologies (and "identical" AD or BC age) are used. And although relatively fast transport in the troposphere causes atmospheric $^{14}CO_2$ to be fairly uniformly mixed near the earth surface, small regional differences remain. General circulation and carbon reservoir model calculations (Braziunas, Fung & Stuiver 1991) predict regional "age" differences of maximally 20 ^{14}C years within the northern hemisphere.

Such inhomogeneity in atmospheric $^{14}CO_2$ alone can induce ^{14}C age offsets on the order of a decade between individual northern hemisphere dendrochronologies.

The Seattle and Belfast results on wood of the same calibrated (cal) age, but not necessarily of the same region, give consistent replication for most of the 8000-yr record. Marginal replication is only encountered for the 5180–5500 BC interval. We first discuss the aspects of replication; detailed calibration curves follow.

SAMPLE AVAILABILITY AND PRETREATMENT

During the earlier phases of the Seattle calibration project, many of the wood samples of AD age were treated with dilute NaOH and HCl solutions to remove resins, sugars and a portion of the lignin (de Vries method, Stuiver & Quay 1980). The samples from the German chronology (and part of our single-year AD Pacific Northwest chronology) were subjected to a more rigorous extraction, yielding alpha cellulose. The cellulose preparation procedure is similar to the ^{13}C sample treatment given in Stuiver, Burk & Quay (1984), with slight modifications due to the bulk of the ^{14}C samples. The de Vries method is less efficient in removing components added after the year of growth, but the influence of the incomplete removal on the ^{14}C ages of the Seattle samples is limited to 2 or 3 ^{14}C years (Stuiver & Quay 1981). All Belfast samples were pretreated to reduce the wood to cellulose (Pearson & Stuiver 1986).

To cover identical bidecades for Belfast and Seattle, we combined pairs of Seattle decadal ^{14}C (weighted mean) to produce appropriate bidecadal results. The sequence is not entirely a rhythmic flow of numbers because there are a few 10-yr gaps in the Belfast bidecadal sequence, some overlapping bidecadal measurements with a 10-yr difference at midpoint, and some missing Seattle and Belfast measurements. Many samples had to be processed, and occasionally, wood was either not available in sufficient quantities (thin rings) for the high-precision ^{14}C measurement, or was lost during sample processing. There are also small differences in midpoint age of the "contemporaneous" 20-yr blocks used for ^{14}C age averaging of up to 2 cal yr. Thus, the listed midpoint cal ages (which are multiples of 10, with exceptions listed below) can differ by up to 1 cal yr from the actual cal age. The following exceptions apply (dates given are midpoints):

AD 1940–1860	Seattle bidecadal data only
AD 1825/AD 1275/AD 1245	Seattle decadal points inserted in Belfast data gaps
AD 1212/AD 1192/AD 952	Averages of bidecades with midpoints 5 yr apart
2450 BC/4150 BC/5150 BC	Belfast data only, as in each case one of the Seattle decadal measurements was missing.

TECHNIQUE AND LABORATORY REPRODUCIBILITY

The radiocarbon community tends to under-report the standard error in a ^{14}C age determination (International Study Group 1982; Scott, Long & Kra 1990). Age errors solely based on the Poisson error in the number of counts accumulated during the ^{14}C activity measurement are lower limits only, and an "error multiplier" K (defined as the actual standard error/quoted standard error) must be applied (*e.g.*, Stuiver 1982). The error multiplier of a specific laboratory may range from 1 to 2 (Scott, Long & Kra 1990). Although the sources of variance are additive (causing K to increase with sample age), K is a convenient expression of the degree to which the quoted error is representative of the overall error in a ^{14}C date.

The quoted standard errors of the Belfast laboratory are based on a study of the parameters contributing to the error in ^{14}C measurements of the liquid scintillation counting system employed (Pearson *et al.* 1986), whereas for Seattle's CO_2 gas counting system, the quoted errors are based on the Poisson standard deviation in the sample count and the largest of 1) the Poisson deviation in the average of multiple standard runs, and 2) the standard deviation from the observed scatter in these multiple runs. Previous replicate analysis of 55 determinations on pairs of wood of the same age yielded $K_{Belfast} = 1.23$ (Pearson *et al.* 1986), whereas the upper limit for $K_{Seattle}$ was estimated at 1.6 (Stuiver & Pearson 1986; Stuiver & Becker 1993).

SYSTEMATIC DIFFERENCES BETWEEN LABORATORIES

Interlaboratory comparisons are needed to identify any offsets, and these lead to independent K information as well. We compared the ^{14}C age results (Kromer *et al.* 1986; Kromer & Becker 1993; de Jong, Becker & Mook 1986; Linick *et al.* 1986; Pearson, Becker & Qua 1993; Pearson & Qua 1993; Stuiver & Becker 1993, Vogel *et al.* 1993) of dendrochronologically dated wood of the same age and different origin, as well as those of the same age and same chronology.

Of the six laboratories involved, three measured either decadal (Tucson and Seattle) or bidecadal samples (Belfast). Groningen, Heidelberg and La Jolla measured samples grown over shorter time intervals (usually 1–3 yr). For comparison purposes, we choose to average the published results over decades or bidecades. Usually only part of the 10 or 20 years will have been measured, and the "decadal" or "bidecadal" ^{14}C ages calculated in this manner need not be identical to the ^{14}C ages that would have been obtained by measuring decadal or bidecadal samples directly. An error multiplier, $K_{Lab\ A-Lab\ B}$, for interlaboratory comparisons was derived by taking the quotient of the standard deviation, σ_{tot}, in the observed differences and the average standard deviation, σ, of the differences calculated from the quoted errors in the ^{14}C determinations.

A test of internal consistency of ^{14}C data of laboratories measuring wood of the same tree chronology provides insight into the sum total uncertainty tied to procedures of wood allocation, dendro-age determination, sample pretreatment, laboratory ^{14}C determination, regional ^{14}C distribution and ^{14}C differences between individual trees of the same chronology. Often the splitting of samples from wood sections in the dendrochronology laboratories took place several years apart, and wood from identical trees was not necessarily supplied for the same chronology to different ^{14}C laboratories. Here, even the region may be uncertain, because the area of original growth is not well defined for trees collected from alluvial sediments.

Good interlaboratory ^{14}C age agreement (n = number of comparisons, offset = "a" with positive values when Lab A dates are older) is found, *e.g.*, for decadal or bidecadal wood (in some instances, "decadal" or "bidecadal", see above) of the German chronology (Becker 1993) with $K_{Seattle-Groningen} = 1.8$ and $a = -4 \pm 2$ yr (3210–3910 BC, n = 36), $K_{Seattle-Pretoria} = 1.2$ and $a = 4 \pm 2$ yr (1930–3350 BC, n = 72), $K_{Seattle-La\ Jolla} = 1.3$ and $a = -4 \pm 3$ yr (2500–5000 BC, n = 97), and $K_{Seattle-Belfast} = 1.5$ and $a = -15 \pm 4$ yr (5500–6000 BC, n = 24). Less satisfactory agreement is found in $K_{Seattle-Belfast} = 1.3$ and $a = -54 \pm 5$ yr (5180–5500 BC, n = 16) and $K_{Seattle-Heidelberg} = 1.8$ and $a = -41 \pm 4$ yr (4075–5265 BC and 5805–5995 BC, n = 65). The reasons for the larger offsets are, as yet, not well understood.

Comparing decadal or bidecadal ^{14}C dates from the German (measured in Seattle and Belfast) and bristlecone pine (measured in Tucson and Seattle) chronologies for the 5680–5810 BC interval yields excellent agreement with $K_{Seattle-Seattle} = 1.3$ and $a = -6 \pm 7$ yr (n = 13), $K_{Seattle-Tucson} = 1.8$ and $a = -3 \pm 7$ yr (n = 15; the 2 additional points are at 6475 and 6360 BC), and $K_{Belfast-Tucson} = 1.8$ and $a = 6 \pm 7$ (n = 7). A comparison of the joint Northwest Pacific and German chronology measured in Seattle, and the Irish chronology measured in Belfast, yielded, for bidecadal samples covering the AD 1840–5180 BC interval $K_{\text{Seattle-Belfast}} = 1.56$ and a = 2 ± 1 (n = 344). The majority of offsets are in the decade (or less) range, and error multipliers for the age differences are 1.8 maximally.

Of crucial importance for the construction of the bidecadal calibration curve are the systematic differences between Seattle and Belfast results for the AD 1840–6000 BC interval. The systematic difference, averaging only −0.8 ± 0.9 yr (K = 1.7, n = 386) for the full AD 1840–6000 BC interval, can be substantially larger for shorter time units. Systematic differences for successive millennia (first "millennium" is AD 1840–1000, last one 5001–6000 BC) are −0.4 ± 2.3 yr (K = 1.4), 0.9 ± 2.6 (K = 1.4), 9.9 ± 2.5 (K = 1.3), 16.6 ± 2.6 (K = 1.4), 2.4 ± 2.4 (K = 1.8), −4.3 ± 2.6 (K = 1.4), −12.1 ± 2.8 (K = 1.9) and −25.2 ± 2.7 (K = 1.7). These offsets (applying the corresponding K value) equal, respectively, 0.1, 0.2, 3.0, 4.6, 0.1, 1.2, 2.3 and 5.3 times the standard deviation in the mean. Clearly, the 9.9 (3.0 σ), 16.6 (4.6 σ) and −25.2 (5.3 σ) ^{14}C year offsets are too large to be accounted for solely by statistical considerations of the reproducibility of the measurements. Measurements on four duplicate samples (3130 BC, 3190 BC, 3210 BC and 3230 BC) of the Irish chronology also yielded a substantial offset of 52 ± 8 yr, with Belfast results being older.

Closer inspection of the distribution of the actual ^{14}C age differences of the 3 millennia with statistically unacceptable systematic offsets shows one interval (5180–5500 BC) with substantial Seattle and Belfast ^{14}C age differences (a = −54 ± 5 yr). The offset for the remaining portion of the millennium (5001–5180 BC and 5500–6000 BC) is now −12.2 ± 3.3 yr (K = 1.5). This offset equals 2.4 standard deviations of the mean, which is not an abnormally large value. Significant systematic Seattle-Belfast differences are then 9.9 yr (1–1000 BC), 16.6 yr (1001–2000 BC) and −54 yr (5180–5500 BC). The standard deviation given with the calibration curve does not account for offsets. Therefore, for the above intervals, the calibration curve ^{14}C age averages could be subject to systematic errors of, respectively, 5.0, 8.3 and 27 yr. The first two systematic errors are rather insignificant, as they are less than a decade and only a fraction of the curve standard deviation (which averages 12.9 yr). The 27-yr systematic error contribution to the radiocarbon ages of the 5180–5500 BC interval, however, is unacceptably large and warrants further calibration efforts.

CONSTRUCTION OF THE RADIOCARBON AGE CALIBRATION CURVES

When calculating the Seattle-Belfast bidecadal ^{14}C age averages, and their errors, an error multiplier must be assigned to the quoted laboratory error. In our previous papers, we took $K_{\text{Belfast}} = 1.23$ and $K_{\text{Seattle}} = 1.6$ for results going back to 2500 BC. K tends to increase with sample age (*e.g.*, for the AD 1840–2500 BC interval, $K_{\text{Seattle-Belfast}} = 1.44$ (n = 212, a = 7 ± 1.2 yr), whereas for the 2500–5000 BC interval, $K_{\text{Seattle-Belfast}} = 1.75$ (n = 124, a = −7 ± 1.6)). Thus, we selected a larger K value of 1.7 for both Seattle and Belfast for samples older than 2500 BC. A more detailed discussion of this choice can be found elsewhere (Stuiver & Pearson 1992).

The above K values, multiplied with the quoted standard deviation, yield corrected standard deviations (σ) for the individual Belfast and Seattle ^{14}C ages. Using these standard deviations, we find that the calculated standard deviations of the ^{14}C age differences of contemporaneous bidecadal sample pairs of Seattle and Belfast account for 90–100% of the demonstrated standard deviations in ^{14}C age differences of both laboratories for the AD 1940–5180 BC and 5500–6000 BC intervals. The standard deviations of the weighted average ^{14}C ages (Table 1) of sample pairs that form the basis of the ^{14}C calibration curve are based on the above K-corrected standard deviations.

The mean standard deviation of the bidecadal averages of Seattle and Belfast is 12.9 (± 1.6‰ for Δ^{14}C) ^{14}C yr for the AD 1950–6000 BC interval. The standard deviations of the ^{14}C ages associated with the 5180–5500 BC interval do not fully account for the total uncertainty, as systematic error contributions play a role for this part of the calibration curve (see previous section).

CALIBRATION INSTRUCTIONS

We recommend that users of ^{14}C dates obtain additional information on reproducibility (and systematic error, if any) from the laboratory reporting the ^{14}C date. This information should lead to a realistic standard deviation in the reported age. A systematic error has to be deducted from, or added to, the reported radiocarbon age prior to age calibration.

Only the calibration curve is given in Figure 1; the one-sigma (1σ; standard deviation) uncertainty in the curve is not given. The actual standard deviation (averaging 12.9 ^{14}C yr for the nearly 8000 cal yr bidecadal calibration curve of Seattle-Belfast ^{14}C age averages) is tabulated in Table 1 for each bidecadal midpoint.

Cal BP ages are relative to the year AD 1950, with 0 cal BP equal to AD 1950. The relationship between cal AD/BC and cal BP ages is cal BP = 1950–cal AD, and cal BP = 1949 + cal BC. The switch from 1950 to 1949 when converting BC ages is caused by the absence of the year zero in the AD/BC chronology.

The conversion of a ^{14}C age to a cal age is as follows: 1) draw line A parallel to the bottom axis through the ^{14}C age to be converted; 2) draw vertical line(s) through the intercept(s) of line A and the calibration curve. The cal AD/BC ages can be read at the bottom axis, the cal BP ages at the top.

To convert the standard error in the ^{14}C age into a range of cal AD/BC (BP) ages, determine the sample standard deviation, σ, by multiplying the quoted laboratory standard deviation with the "error multiplier." Unfortunately, information on error multipliers is often lacking. Here, the ^{14}C age user should refer to K values given above, or to Scott, Long & Kra (1990).

Once the sample σ is known, the curve σ should be read from Table 1. The curve σ and sample σ should then be used to calculate total $\sigma = ((\text{sample }\sigma)^2 + (\text{curve }\sigma)^2)^{1/2}$ (Stuiver 1982). Lines parallel to A should now be drawn through the ^{14}C age + total σ, and ^{14}C age − total σ value. The vertical lines drawn through the intercepts now yield the outer limits of possible cal AD/BC (cal BP) ages that are compatible with the sample standard deviation.

The conversion procedure yields 1) single or multiple cal AD/BC (BP) ages that are compatible with a certain ^{14}C age, and 2) the range(s) of cal ages that correspond(s) to the standard deviation in the ^{14}C age (and calibration curve). Here, the user must determine the calibrated ages from Figure 1 graphs by drawing lines, whereas an alternate approach would be to use the computerized calibration (CALIB) program discussed elsewhere in this issue (Stuiver & Reimer 1993).

The probability that a certain cal age is the actual sample age may be quite variable within the cal age range. Higher probabilities are encountered around the intercept ages. The non-linear transform of a near-Gaussian distribution around a ^{14}C age into cal AD/BC (cal BP) age is not a simple matter, and computer programs are needed to derive the complex probability distribution. The CALIB program incorporates such probability distributions.

The calibration data presented here are valid for northern hemispheric samples that were formed in equilibrium with atmospheric $^{14}CO_2$. Systematic age differences are possible for the southern hemisphere, where ^{14}C ages of wood samples tend to be about 40 yr older (Vogel *et al.* 1993). Thus, ^{14}C ages of southern hemispheric samples preceding our era of fossil-fuel combustion should be reduced by 40 yr before conversion into cal AD/BC (BP) ages.

The Figure 1 calibration points are the midpoints of wood samples spanning 20 yr. Samples submitted for dating may cover shorter or longer intervals. The decadal calibration results of the Seattle laboratory (Stuiver & Becker 1993; Stuiver & Reimer 1993) provide a better time resolution, whereas the CALIB program also has an option to use Figure 1 moving averages (*e.g.*, a 5-point or 100-yr moving average of the bidecadal curve). The latter should be used for a sample grown over a 100-yr interval. Samples formed over intervals longer than a decade or bidecade are very desirable, as the ^{14}C "wiggles" of the calibration curve have lesser influence on the (midpoint) cal age when a smoothed (moving average) calibration curve is used (Stuiver 1992).

The calibration curve is only valid for age conversion of samples that were formed in equilibrium with atmospheric CO_2. Conventional ^{14}C ages of materials not in equilibrium with atmospheric reservoirs do not take into account the offset in ^{14}C age that may occur (Stuiver & Polach 1977). An offset, or reservoir deficiency, must be deducted from the reported ^{14}C age before any attempt can be made to convert to cal AD/BC (BP) ages.

The reservoir deficiency is time dependent for the mixed (and deep) layer of the ocean. For the calibration of marine samples, the reader is referred to Stuiver and Braziunas (1993) and, of course, the CALIB program.

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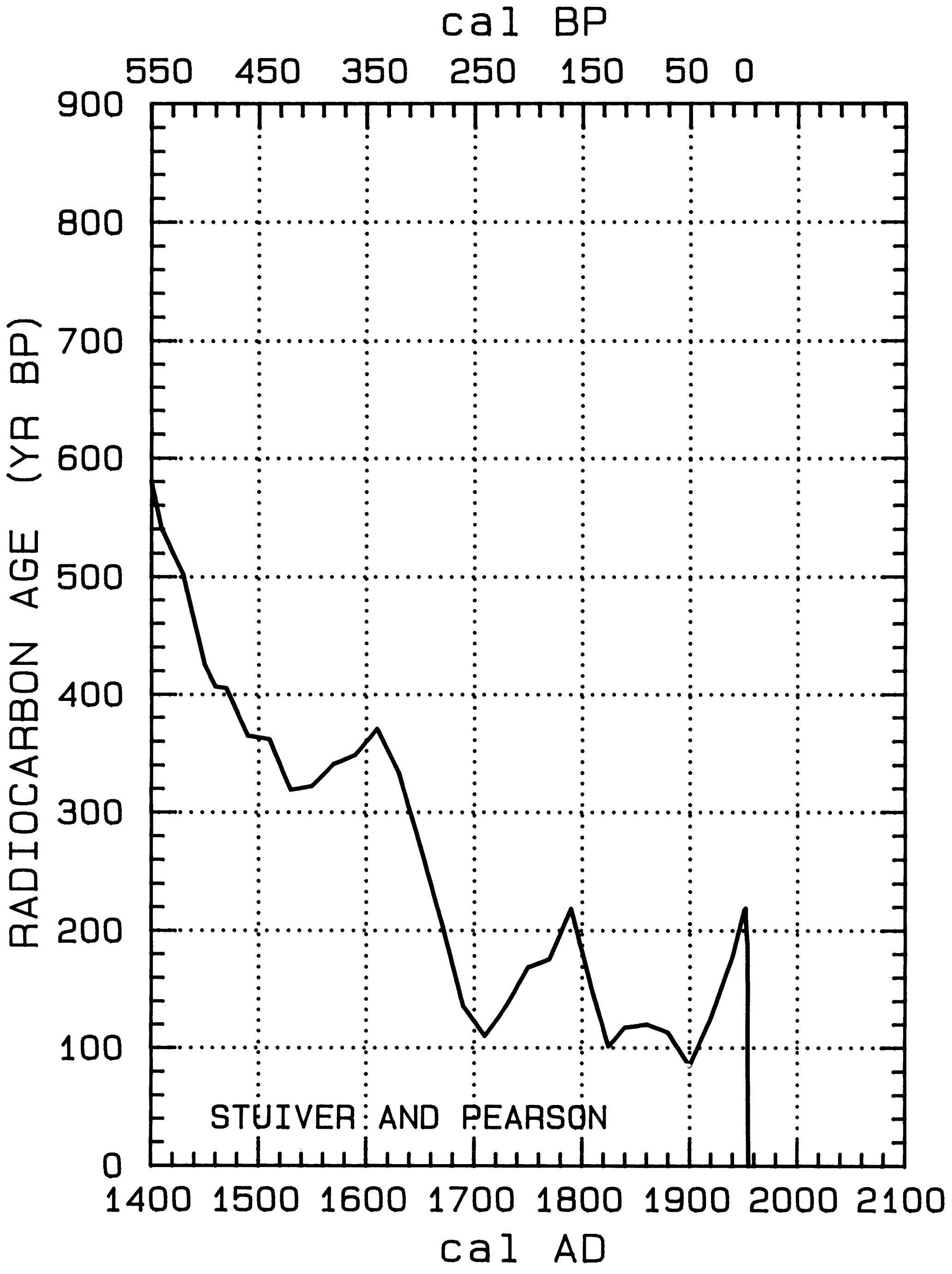

Fig. 1A–L. ^{14}C calibration curve derived from bidecadal samples, with single-year AD 1951–1954 data added to complete the pre-nuclear bomb era

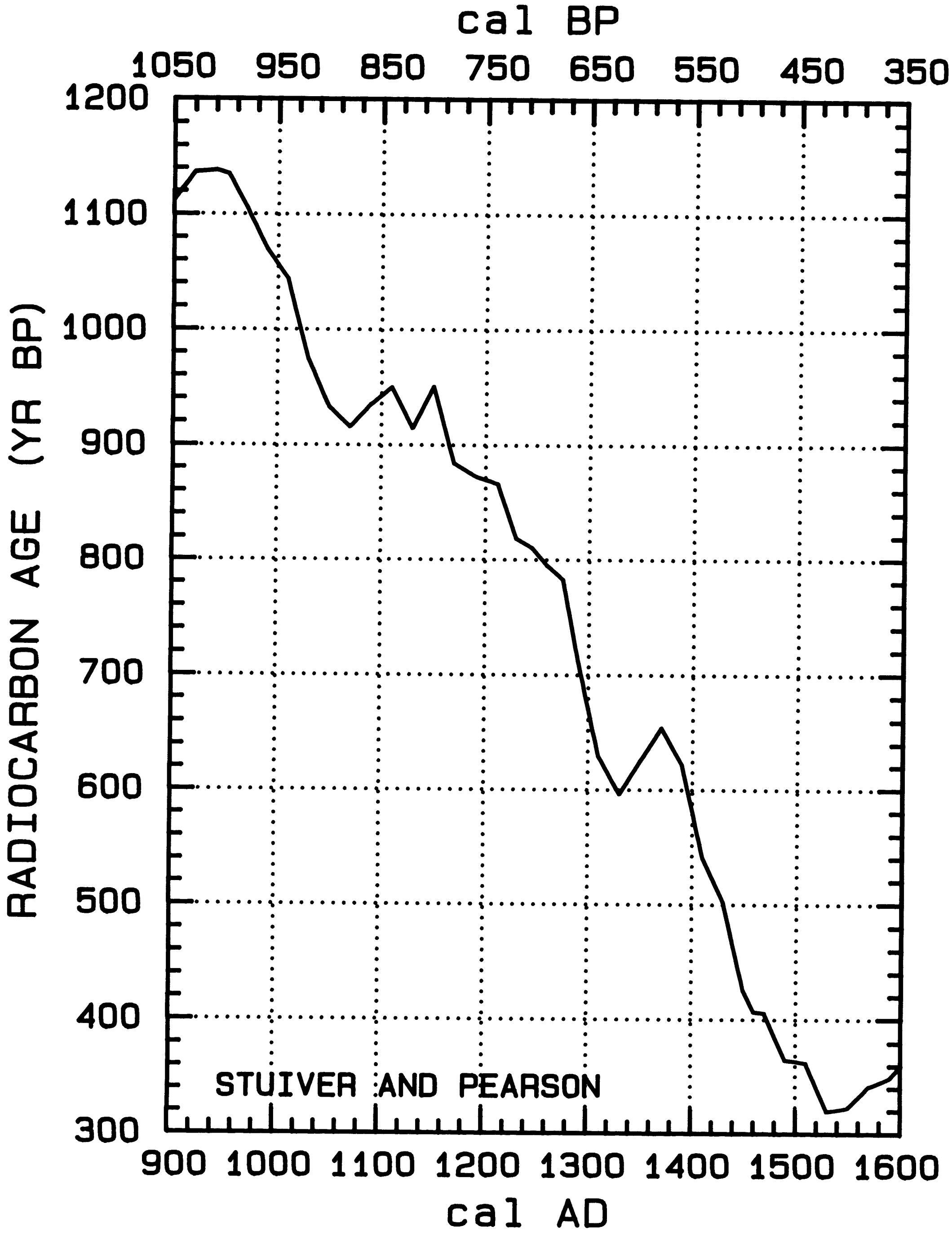
cal BP
1050
950
850
750
650
550
450
350
RADIOCARBON AGE (YR BP)
1200
1100
1000
900
800
700
600
500
400
300
STUIVER AND PEARSON
900
1000
1100
1200
1300
1400
1500
1600
cal AD

Fig. 1B

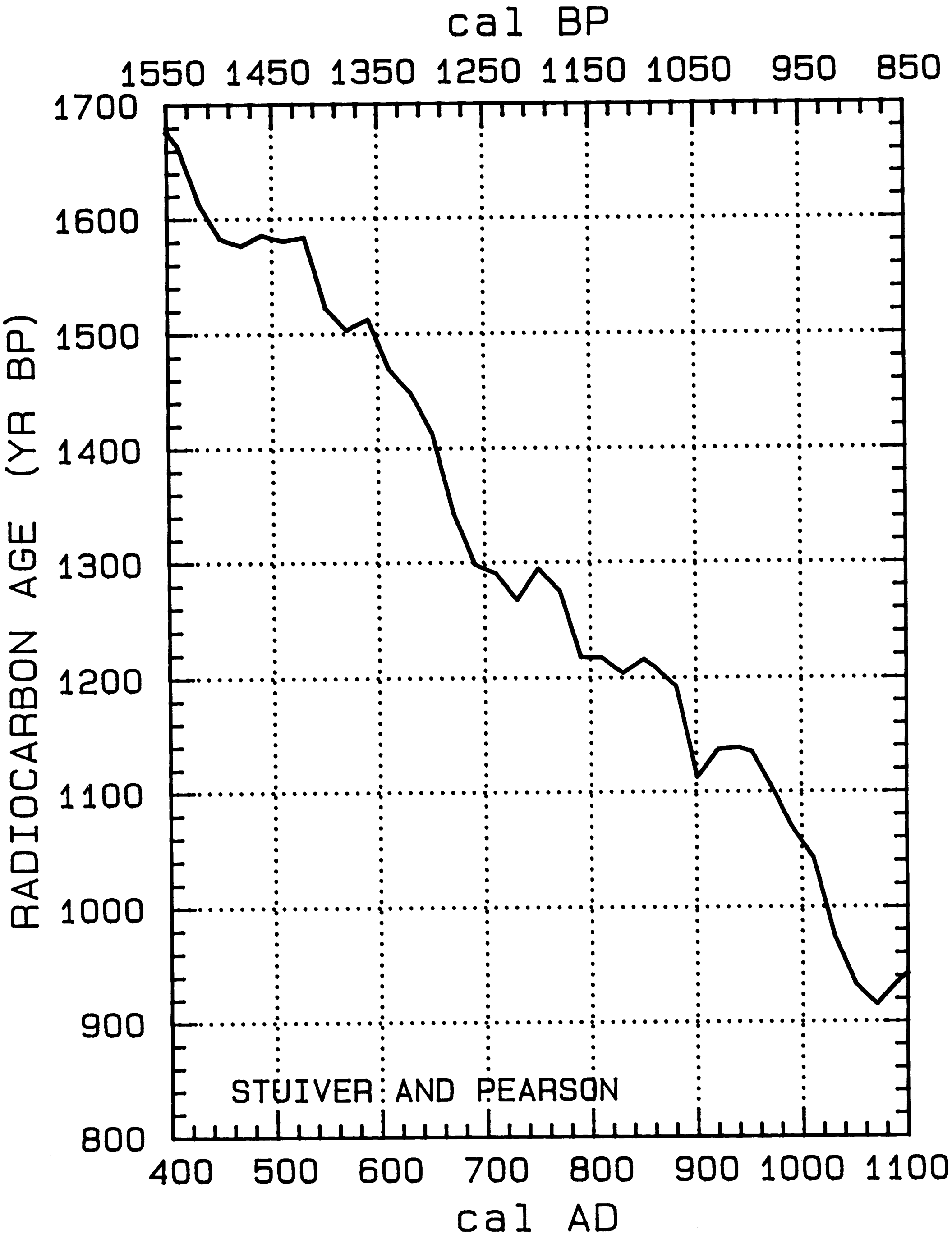
cal BP
1550
1450
1350
1250
1150
1050
950
850
RADIOCARBON AGE (YR BP)
1700
1600
1500
1400
1300
1200
1100
1000
900
800
STUIVER AND PEARSON
400
500
600
700
800
900
1000
1100
cal AD

Fig. 1C

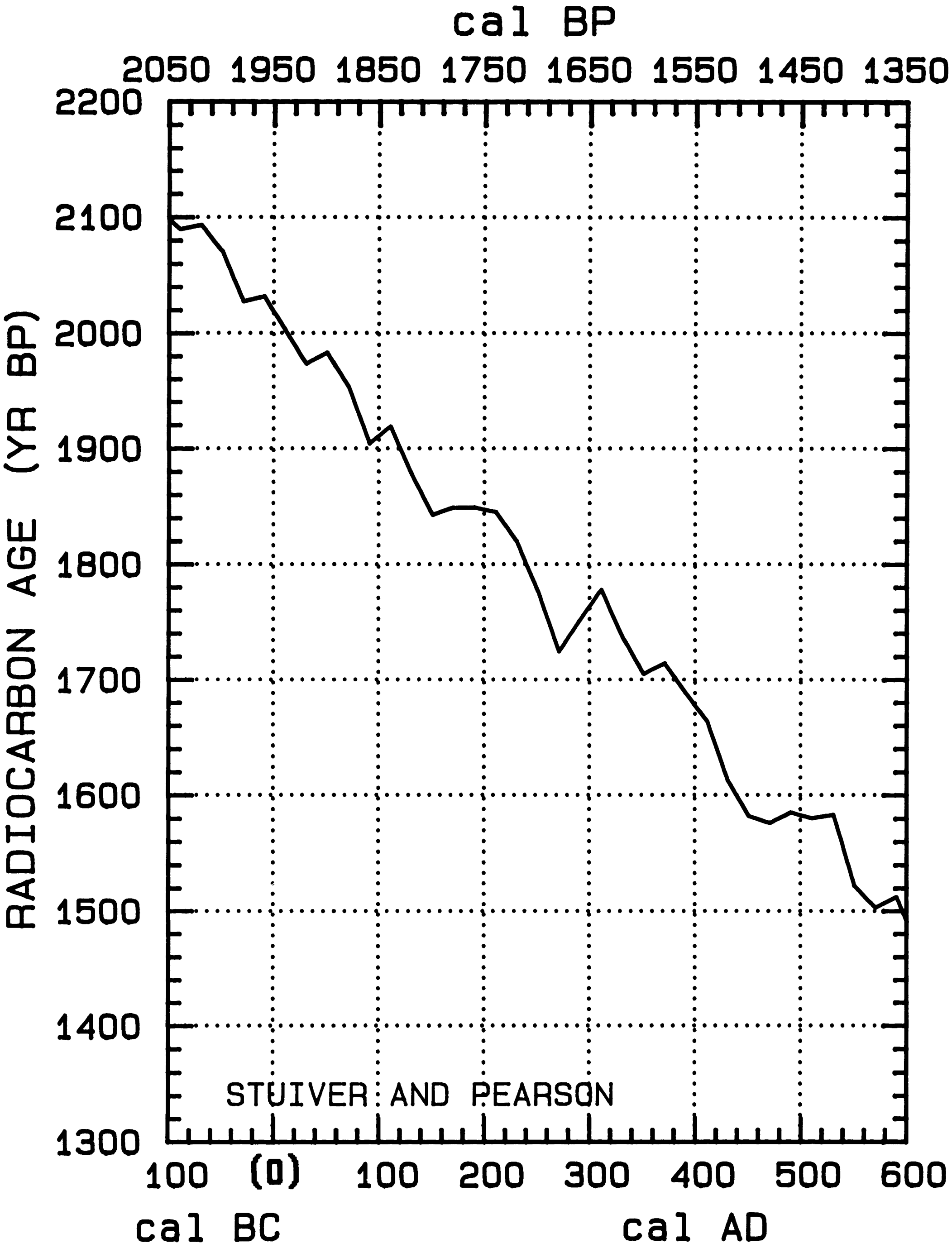
cal BP
2050 1950 1850 1750 1650 1550 1450 1350
RADIOCARBON AGE (YR BP)
2200
2100
2000
1900
1800
1700
1600
1500
1400
1300
STUIVER AND PEARSON
100 (0) 100 200 300 400 500 600
cal BC
cal AD

Fig. 1D

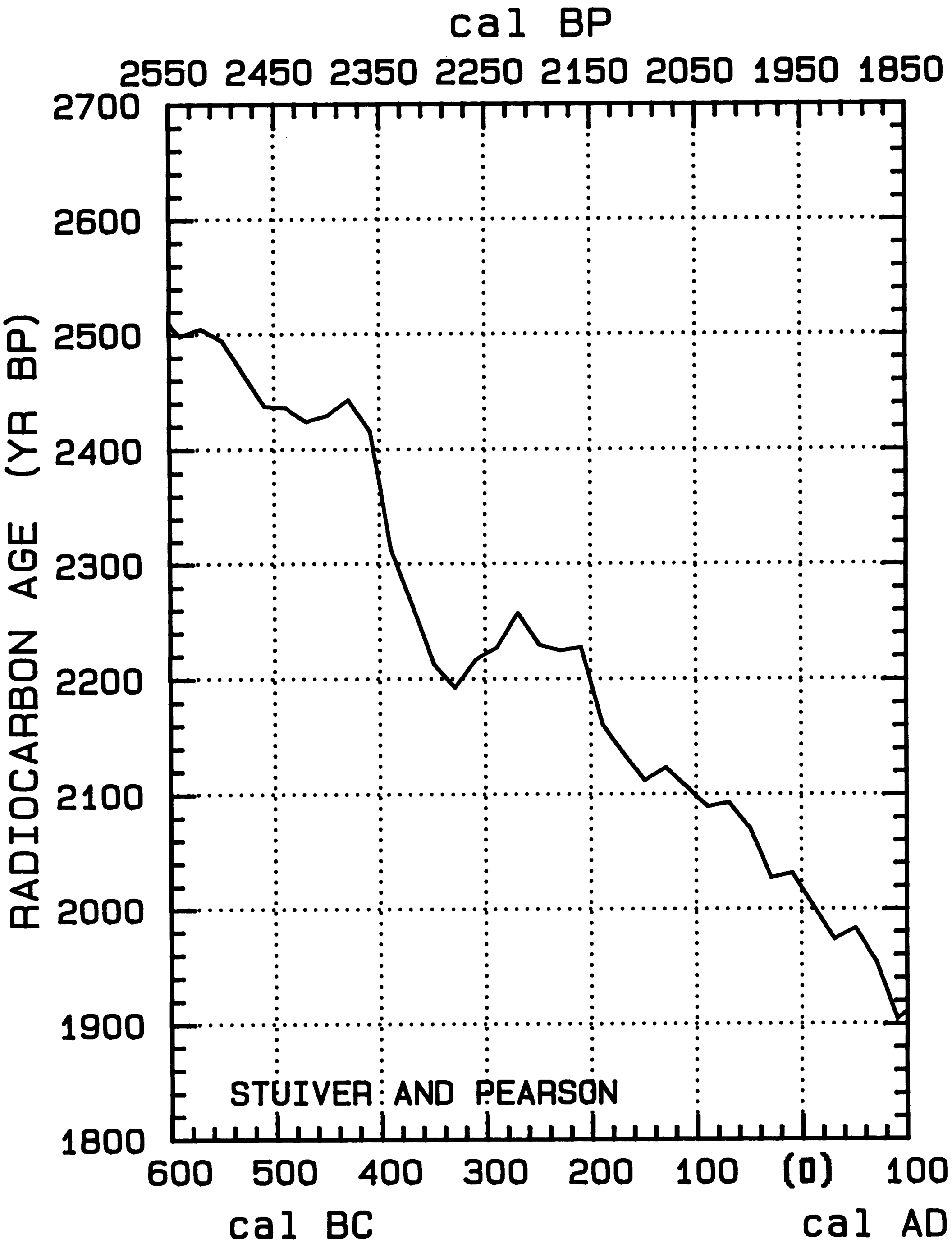
cal BP
2550
2450
2350
2250
2150
2050
1950
1850
2700
2600
2500
2400
2300
2200
2100
2000
1900
1800
RADIOCARBON AGE (YR BP)
STUIVER AND PEARSON
600
500
400
300
200
100
(0)
100
cal BC
cal AD

Fig. 1E

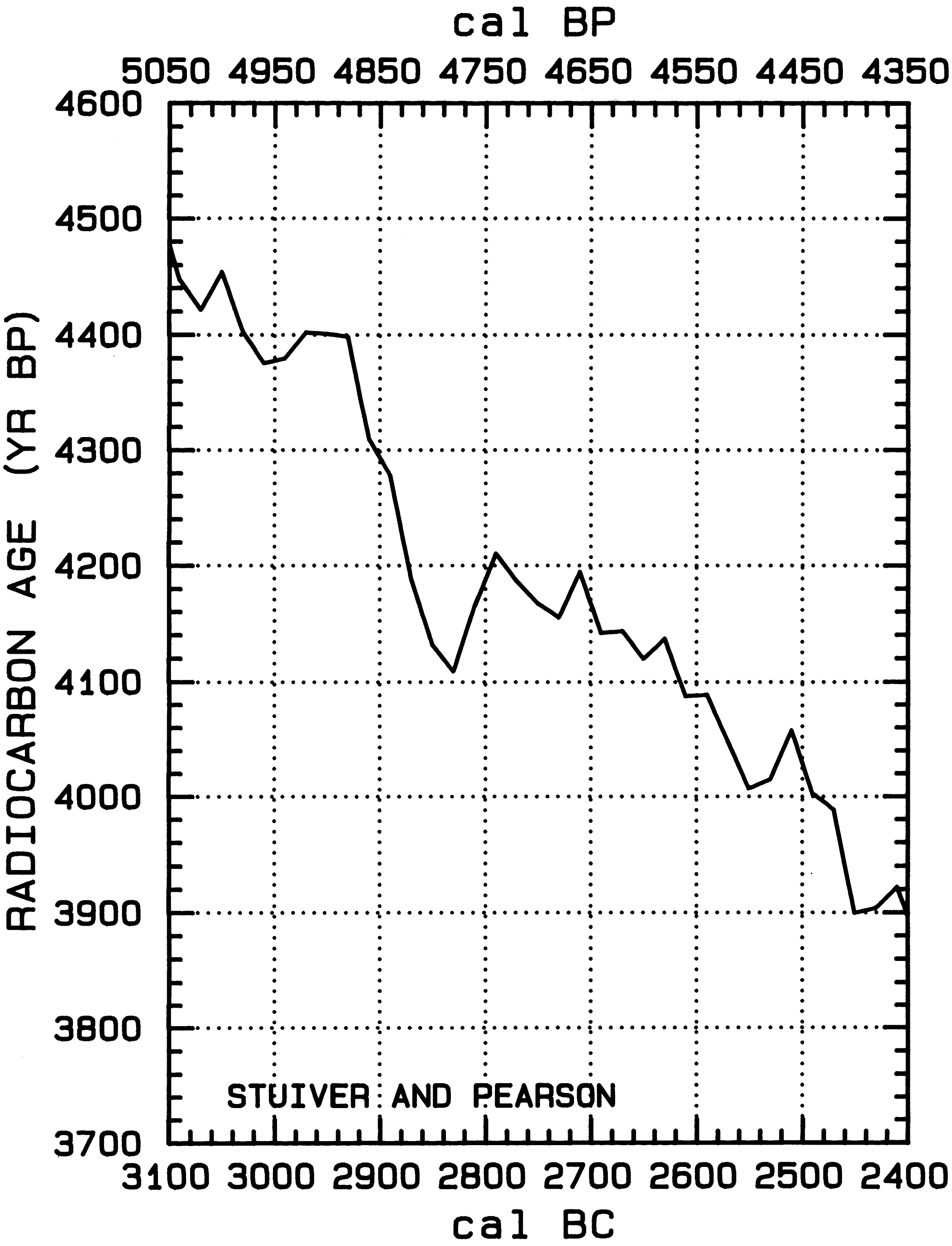
cal BP
5050
4950
4850
4750
4650
4550
4450
4350
RADIOCARBON AGE (YR BP)
4600
4500
4400
4300
4200
4100
4000
3900
3800
3700
STUIVER AND PEARSON
3100
3000
2900
2800
2700
2600
2500
2400
cal BC

Fig. 1F

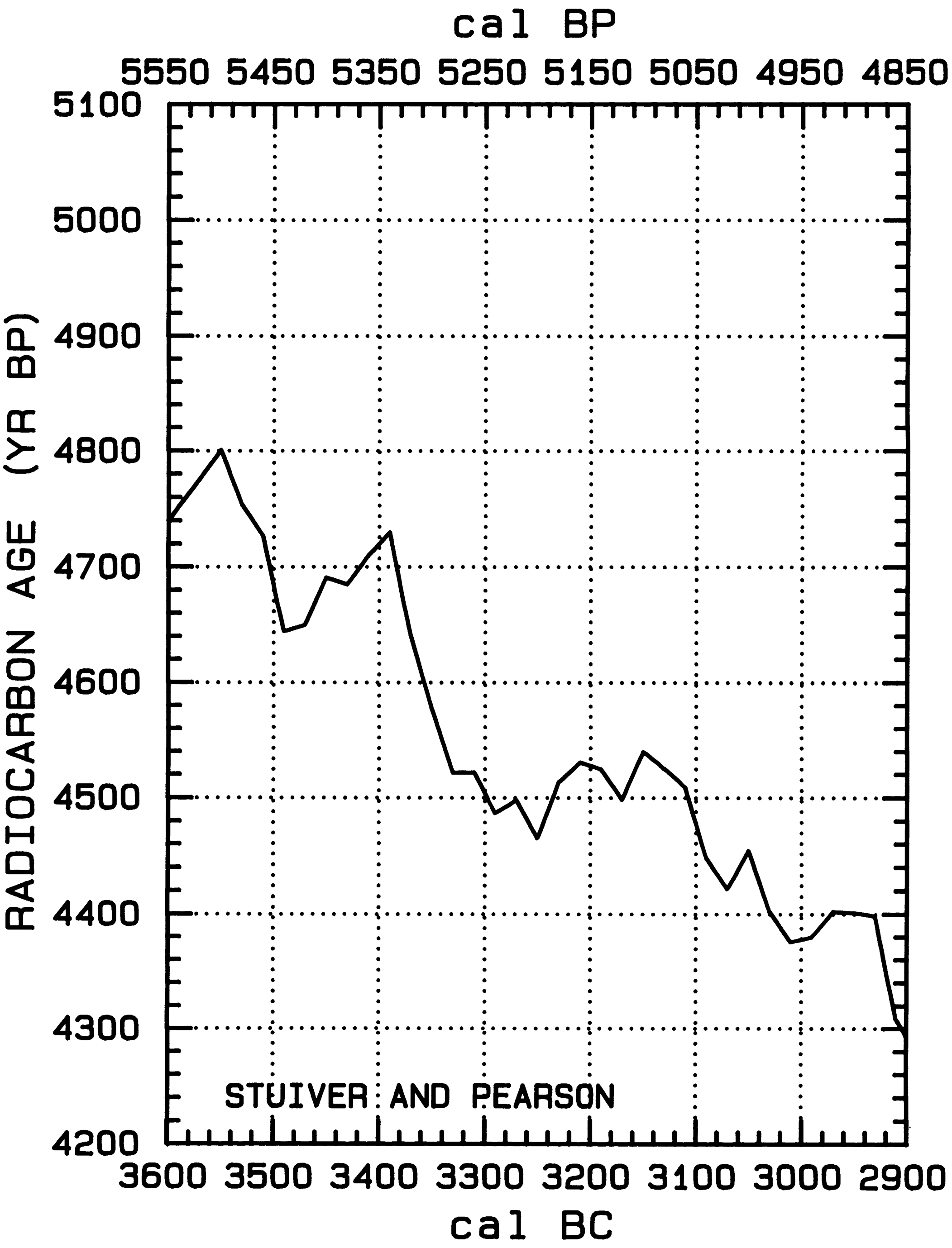
cal BP
5550
5450
5350
5250
5150
5050
4950
4850
RADIOCARBON AGE (YR BP)
5100
5000
4900
4800
4700
4600
4500
4400
4300
4200
STUIVER AND PEARSON
3600
3500
3400
3300
3200
3100
3000
2900
cal BC

Fig. 1G

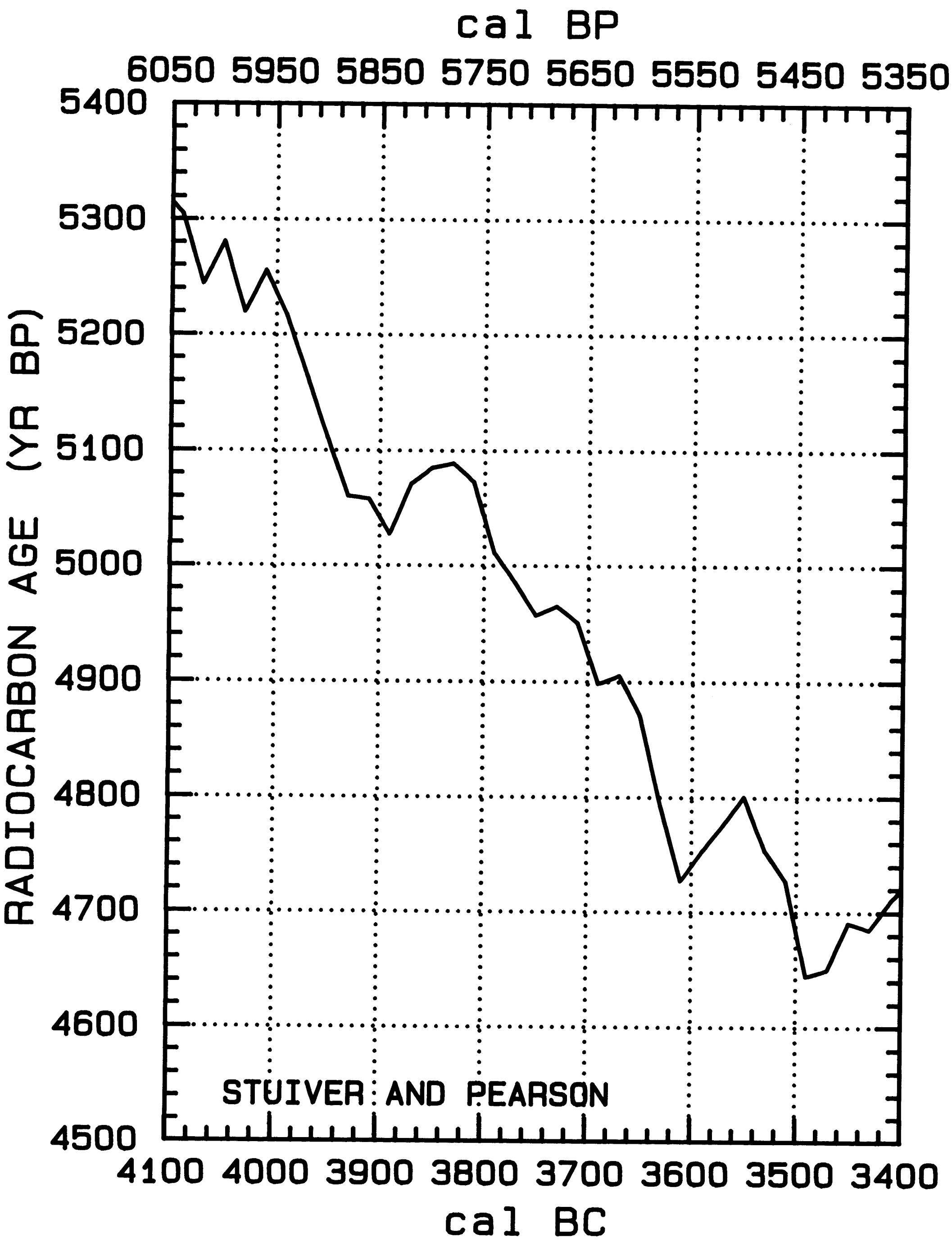
cal BP
6050 5950 5850 5750 5650 5550 5450 5350
5400
5300
5200
5100
5000
4900
4800
4700
4600
4500
RADIOCARBON AGE (YR BP)
STUIVER AND PEARSON
4100 4000 3900 3800 3700 3600 3500 3400
cal BC

Fig. 1H

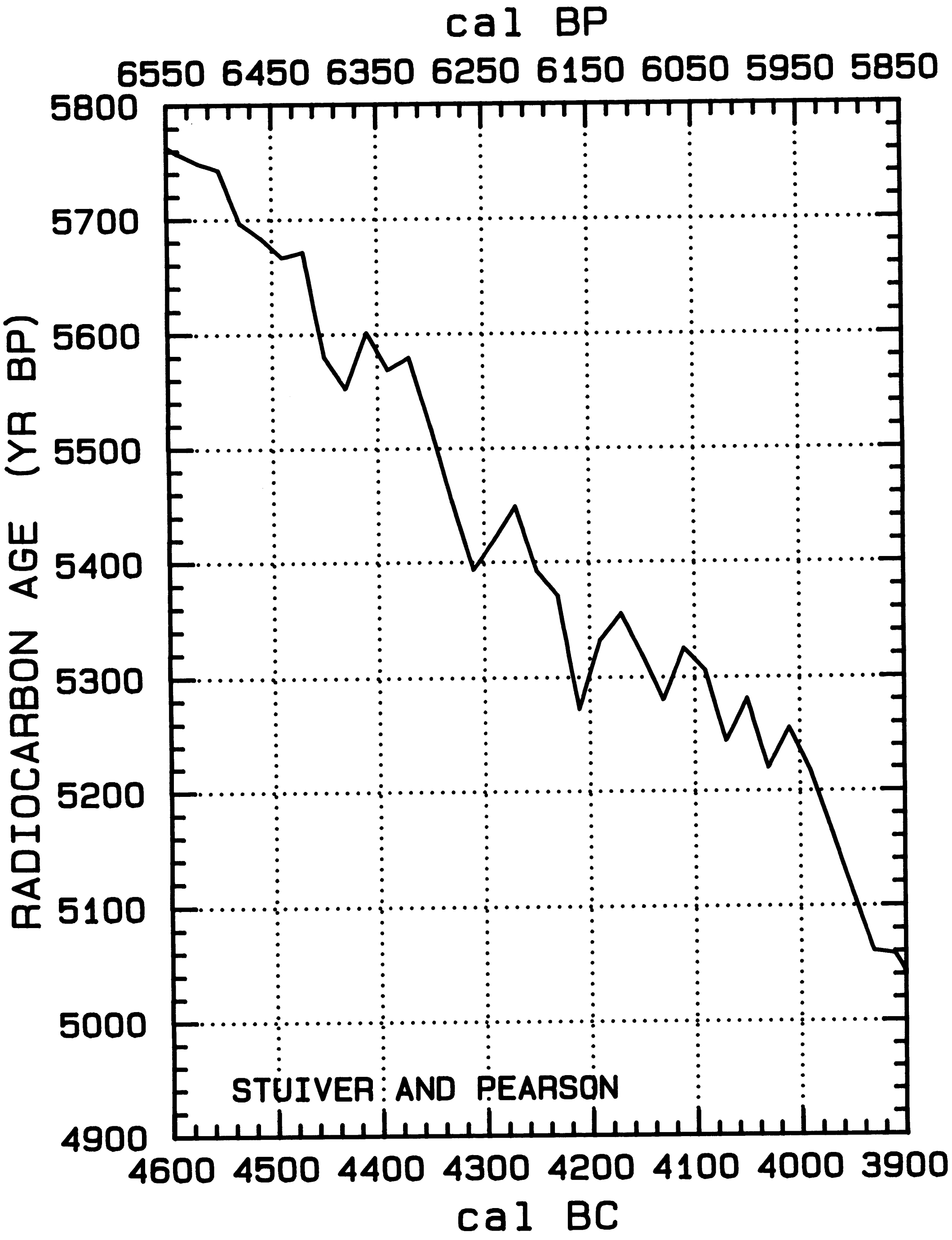
cal BP
6550 6450 6350 6250 6150 6050 5950 5850
RADIOCARBON AGE (YR BP)
5800
5700
5600
5500
5400
5300
5200
5100
5000
4900
STUIVER AND PEARSON
4600 4500 4400 4300 4200 4100 4000 3900
cal BC

Fig. 1I

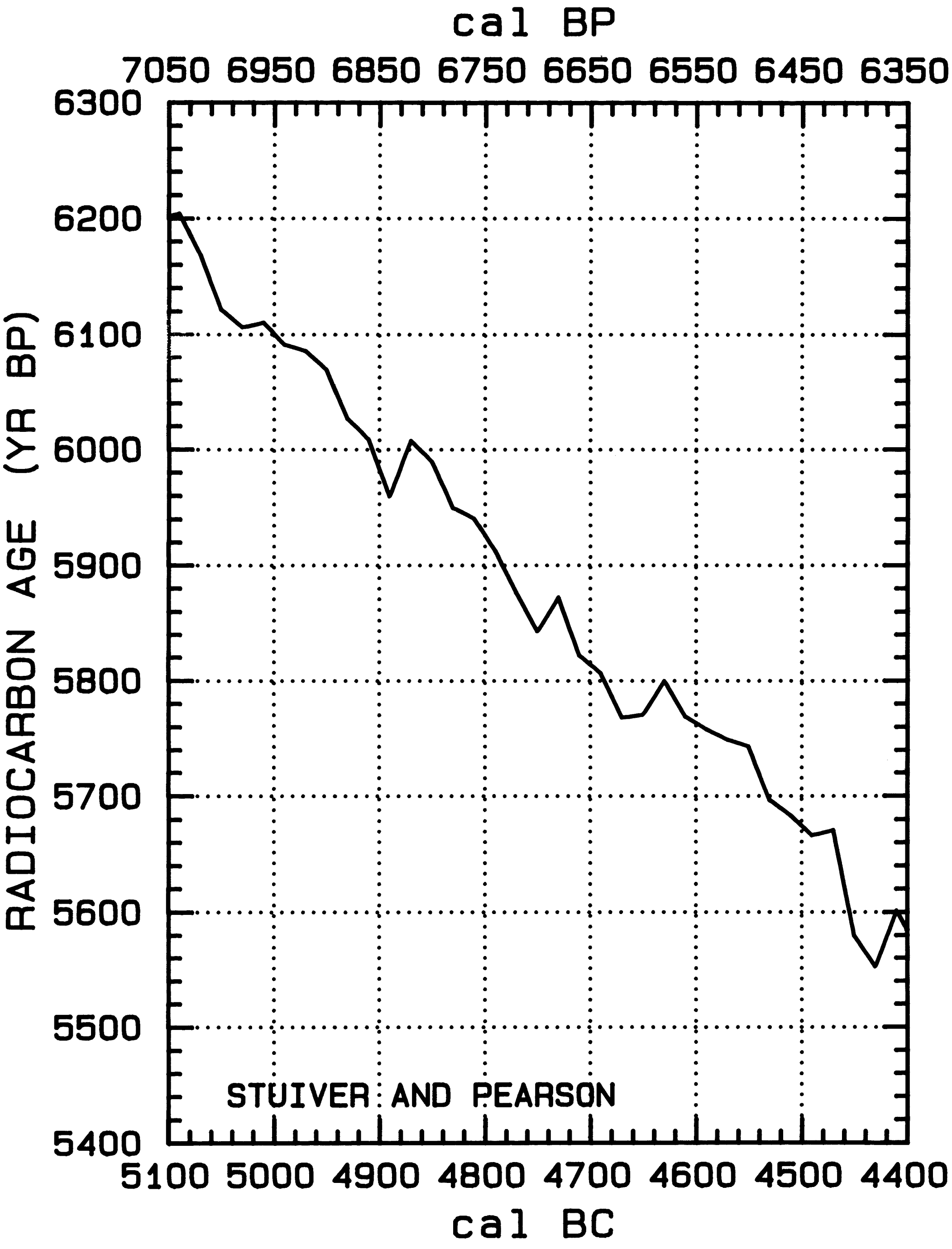
cal BP
7050
6950
6850
6750
6650
6550
6450
6350
6300
6200
6100
6000
5900
5800
5700
5600
5500
5400
RADIOCARBON AGE (YR BP)
STUIVER AND PEARSON
5100
5000
4900
4800
4700
4600
4500
4400
cal BC

Fig. 1J

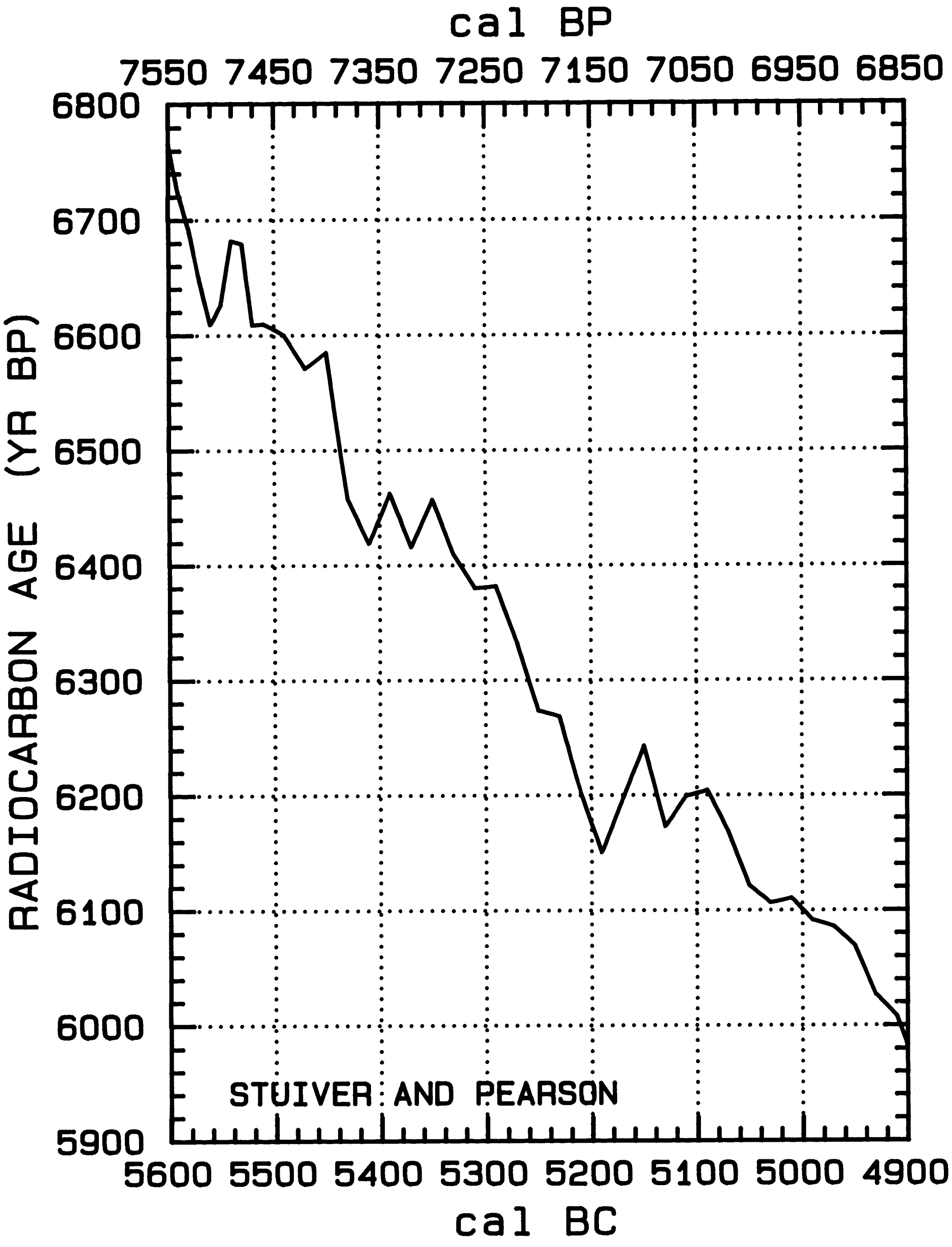
cal BP
7550
7450
7350
7250
7150
7050
6950
6850
RADIOCARBON AGE (YR BP)
6800
6700
6600
6500
6400
6300
6200
6100
6000
5900
STUIVER AND PEARSON
5600
5500
5400
5300
5200
5100
5000
4900
cal BC

Fig. 1K

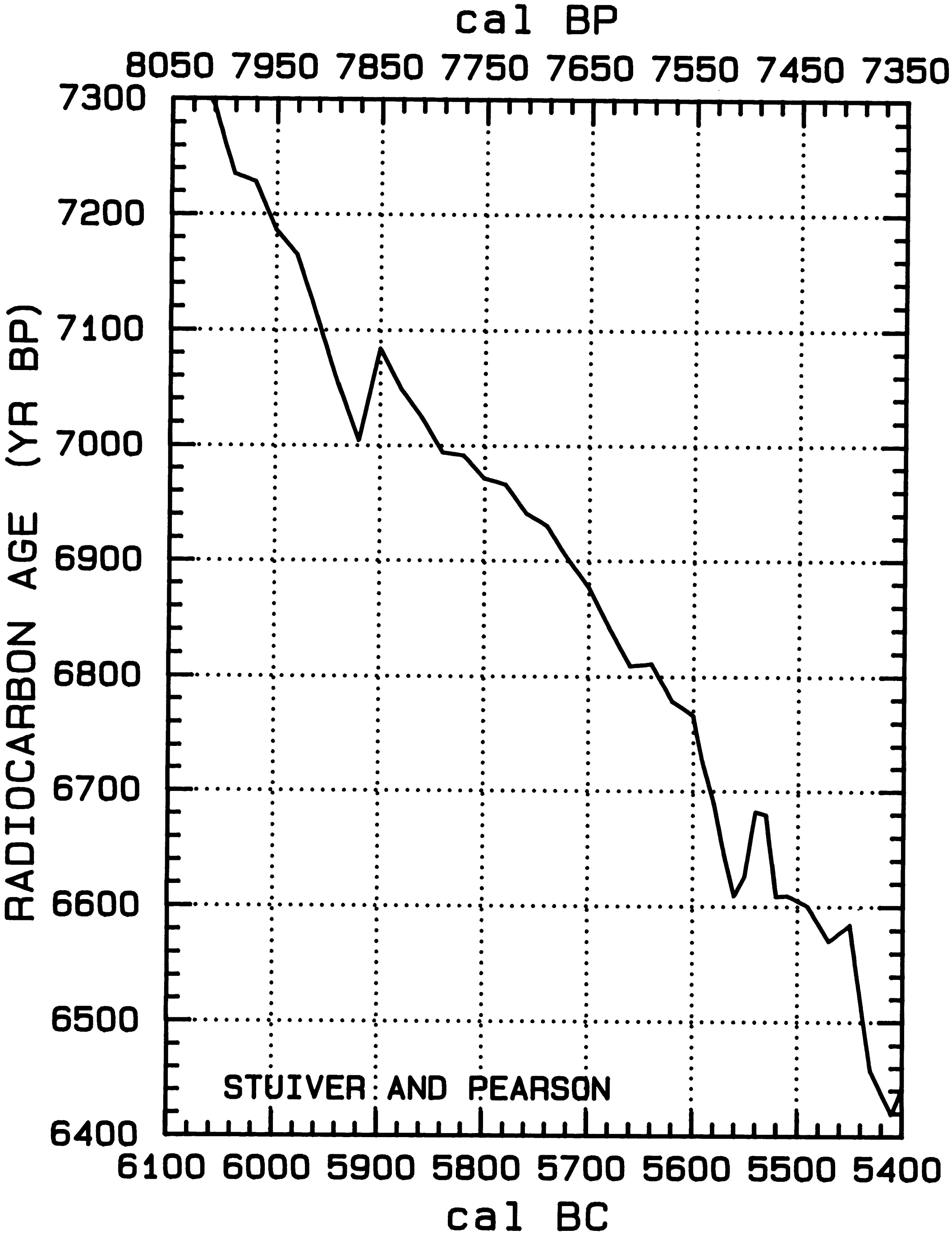
cal BP
8050 7950 7850 7750 7650 7550 7450 7350
7300
7200
7100
7000
6900
6800
6700
6600
6500
6400
RADIOCARBON AGE (YR BP)
STUIVER AND PEARSON
6100 6000 5900 5800 5700 5600 5500 5400
cal BC

Fig. 1L

TABLE 1. Weighted averages of University of Washington (Seattle) and the University of Belfast ^{14}C age determinations. The cal AD/BC (or cal BP) ages represent the midpoints of bidecadal wood sections, except as noted in the text. The standard deviation in the ages and Δ^{14}C (defined in Stuiver and Polach (1977)) values includes lab error multipliers of 1.23 for Belfast and 1.6 for Seattle after 2500 BC, and 1.7 for both labs prior to 2500 BC.

Cal AD/BC	Δ^{14}C ‰	^{14}C age (BP)	Cal BP	Cal AD/BC	Δ^{14}C ‰	^{14}C age (BP)	Cal BP
AD 1940	−20.7 ± .6	178 ± 5	BP 10	AD 1130	−14.4 ± 1.3	914 ± 10	BP 820
AD 1920	−11.9 ± .5	126 ± 4	BP 30	AD 1110	−16.4 ± 1.1	949 ± 9	BP 840
AD 1900	−4.5 ± .7	85 ± 6	BP 50	AD 1090	−12.2 ± 1.0	935 ± 8	BP 860
AD 1880	−5.6 ± .5	113 ± 4	BP 70	AD 1070	−7.4 ± .9	915 ± 7	BP 880
AD 1860	−4.1 ± .6	120 ± 5	BP 90	AD 1050	−7.1 ± 1.1	932 ± 9	BP 900
AD 1840	−1.3 ± .5	118 ± 4	BP 110	AD 1030	−9.9 ± 1.2	974 ± 10	BP 920
AD 1825	2.5 ± .6	101 ± 5	BP 125	AD 1010	−16.0 ± 1.3	1043 ± 11	BP 940
AD 1810	−1.4 ± .5	148 ± 4	BP 140	AD 990	−16.8 ± 1.2	1069 ± 9	BP 960
AD 1790	−7.8 ± .6	219 ± 5	BP 160	AD 970	−18.9 ± 1.2	1105 ± 10	BP 980
AD 1770	−.1 ± .5	176 ± 4	BP 180	AD 952	−20.3 ± 1.5	1135 ± 12	BP 998
AD 1750	3.1 ± .5	169 ± 4	BP 200	AD 940	−19.4 ± 1.6	1139 ± 13	BP 1010
AD 1730	9.7 ± .5	136 ± 4	BP 220	AD 920	−16.8 ± 1.3	1137 ± 11	BP 1030
AD 1710	15.5 ± .4	110 ± 3	BP 240	AD 900	−11.4 ± 1.2	1112 ± 10	BP 1050
AD 1690	14.7 ± .4	136 ± 3	BP 260	AD 880	−18.9 ± 1.3	1193 ± 11	BP 1070
AD 1670	8.1 ± .5	207 ± 4	BP 280	AD 860	−18.5 ± 1.3	1210 ± 10	BP 1090
AD 1650	2.4 ± .5	272 ± 4	BP 300	AD 850	−18.2 ± 1.3	1216 ± 10	BP 1100
AD 1630	−2.8 ± .5	334 ± 4	BP 320	AD 830	−14.3 ± 1.4	1204 ± 11	BP 1120
AD 1610	−5.0 ± .5	371 ± 4	BP 340	AD 810	−13.6 ± 1.4	1218 ± 11	BP 1140
AD 1590	.1 ± .6	349 ± 5	BP 360	AD 790	−11.2 ± 1.0	1218 ± 9	BP 1160
AD 1570	3.5 ± .6	341 ± 5	BP 380	AD 770	−15.9 ± 1.2	1276 ± 10	BP 1180
AD 1550	8.3 ± .5	322 ± 4	BP 400	AD 750	−15.9 ± 1.0	1295 ± 8	BP 1200
AD 1530	11.1 ± .5	319 ± 4	BP 420	AD 730	−10.1 ± 1.0	1267 ± 8	BP 1220
AD 1510	8.2 ± .7	362 ± 5	BP 440	AD 710	−10.6 ± 1.2	1291 ± 9	BP 1240
AD 1490	10.3 ± 1.4	365 ± 11	BP 460	AD 690	−9.2 ± 1.8	1299 ± 15	BP 1260
AD 1470	7.7 ± 1.6	405 ± 13	BP 480	AD 670	−12.3 ± 1.8	1343 ± 14	BP 1280
AD 1460	8.7 ± 1.1	406 ± 9	BP 490	AD 650	−18.5 ± 1.4	1414 ± 12	BP 1300
AD 1450	7.6 ± 1.3	425 ± 11	BP 500	AD 630	−20.4 ± 1.5	1448 ± 13	BP 1320
AD 1430	.4 ± 1.6	502 ± 13	BP 520	AD 610	−20.6 ± 1.9	1469 ± 15	BP 1340
AD 1410	−1.9 ± 1.4	540 ± 12	BP 540	AD 590	−23.5 ± 1.7	1512 ± 14	BP 1360
AD 1390	−9.6 ± 1.3	622 ± 10	BP 560	AD 570	−20.0 ± 1.8	1503 ± 14	BP 1380
AD 1370	−11.2 ± 1.2	654 ± 10	BP 580	AD 550	−20.0 ± 1.5	1523 ± 13	BP 1400
AD 1350	−5.2 ± 1.4	625 ± 11	BP 600	AD 530	−25.0 ± 1.4	1584 ± 12	BP 1420
AD 1330	.8 ± 1.2	596 ± 10	BP 620	AD 510	−22.3 ± 1.6	1580 ± 13	BP 1440
AD 1310	−.9 ± 1.2	629 ± 9	BP 640	AD 490	−20.6 ± 1.6	1586 ± 13	BP 1460
AD 1290	−8.7 ± 1.4	711 ± 11	BP 660	AD 470	−17.0 ± 1.7	1576 ± 14	BP 1480
AD 1275	−15.6 ± 2.9	782 ± 24	BP 675	AD 450	−15.5 ± 1.7	1583 ± 14	BP 1500
AD 1260	−15.3 ± 1.2	794 ± 10	BP 690	AD 430	−16.8 ± 1.6	1613 ± 13	BP 1520
AD 1245	−15.4 ± 2.8	810 ± 23	BP 705	AD 410	−20.7 ± 1.6	1664 ± 14	BP 1540
AD 1230	−14.6 ± 1.1	818 ± 9	BP 720	AD 390	−21.3 ± 1.4	1689 ± 11	BP 1560
AD 1212	−18.3 ± 1.6	865 ± 13	BP 738	AD 370	−22.1 ± 1.3	1715 ± 11	BP 1580
AD 1192	−16.6 ± 1.6	871 ± 13	BP 758	AD 350	−18.5 ± 1.7	1705 ± 14	BP 1600
AD 1170	−15.5 ± 1.0	883 ± 9	BP 780	AD 330	−20.1 ± 1.7	1737 ± 14	BP 1620
AD 1150	−21.3 ± 1.0	950 ± 9	BP 800	AD 310	−22.7 ± 1.7	1778 ± 14	BP 1640

TABLE 1. (Continued)

Cal AD/BC	Δ^{14}C ‰	^{14}C age (BP)	Cal BP	Cal AD/BC	Δ^{14}C ‰	^{14}C age (BP)	Cal BP
AD 290	−17.1 ± 1.6	1752 ± 13	BP 1660	2670 BC	43.9 ± 1.6	4143 ± 12	BP 4619
AD 270	−11.4 ± 1.5	1724 ± 12	BP 1680	2690 BC	46.7 ± 1.7	4141 ± 13	BP 4639
AD 250	−15.4 ± 1.1	1777 ± 9	BP 1700	2710 BC	42.3 ± 1.6	4194 ± 12	BP 4659
AD 230	−18.3 ± 1.5	1820 ± 13	BP 1720	2730 BC	50.0 ± 1.6	4155 ± 12	BP 4679
AD 210	−19.1 ± 1.5	1846 ± 13	BP 1740	2750 BC	51.0 ± 2.0	4167 ± 15	BP 4699
AD 190	−17.2 ± 1.7	1850 ± 14	BP 1760	2770 BC	51.0 ± 2.2	4186 ± 17	BP 4719
AD 170	−14.8 ± 1.8	1849 ± 15	BP 1780	2790 BC	50.4 ± 1.6	4210 ± 13	BP 4739
AD 150	−11.6 ± 1.7	1843 ± 14	BP 1800	2810 BC	58.9 ± 1.8	4165 ± 14	BP 4759
AD 130	−13.6 ± 1.2	1879 ± 10	BP 1820	2830 BC	68.9 ± 1.5	4109 ± 12	BP 4779
AD 110	−16.2 ± 1.8	1919 ± 15	BP 1840	2850 BC	68.5 ± 1.8	4131 ± 14	BP 4799
AD 90	−12.0 ± 1.4	1904 ± 12	BP 1860	2870 BC	63.5 ± 1.8	4188 ± 13	BP 4819
AD 70	−15.7 ± 1.3	1954 ± 11	BP 1880	2890 BC	54.2 ± 2.0	4278 ± 15	BP 4839
AD 50	−16.9 ± 1.1	1984 ± 9	BP 1900	2910 BC	52.7 ± 1.9	4309 ± 15	BP 4859
AD 30	−13.3 ± 1.4	1974 ± 11	BP 1920	2930 BC	43.6 ± 2.1	4398 ± 16	BP 4879
AD 10	−14.6 ± 1.1	2003 ± 9	BP 1940	2950 BC	45.8 ± 1.7	4401 ± 13	BP 4899
10 BC	−15.8 ± 1.1	2032 ± 9	BP 1959	2970 BC	48.2 ± 2.3	4402 ± 17	BP 4919
30 BC	−12.9 ± 1.0	2027 ± 8	BP 1979	2990 BC	53.6 ± 1.8	4380 ± 14	BP 4939
50 BC	−15.9 ± 1.0	2071 ± 8	BP 1999	3010 BC	56.8 ± 2.1	4375 ± 16	BP 4959
70 BC	−16.2 ± 1.2	2093 ± 10	BP 2019	3030 BC	55.8 ± 2.0	4402 ± 15	BP 4979
90 BC	−13.4 ± 1.2	2090 ± 10	BP 2039	3050 BC	51.5 ± 1.6	4454 ± 12	BP 4999
110 BC	−13.1 ± 1.2	2107 ± 9	BP 2059	3070 BC	58.4 ± 1.6	4421 ± 12	BP 5019
130 BC	−12.8 ± 1.3	2124 ± 10	BP 2079	3090 BC	57.5 ± 2.2	4447 ± 17	BP 5039
150 BC	−9.0 ± 1.4	2112 ± 11	BP 2099	3110 BC	52.0 ± 2.1	4509 ± 16	BP 5059
170 BC	−9.5 ± 1.3	2136 ± 10	BP 2119	3130 BC	52.5 ± 2.1	4525 ± 16	BP 5079
190 BC	−10.2 ± 1.3	2161 ± 11	BP 2139	3150 BC	53.1 ± 2.1	4540 ± 16	BP 5099
210 BC	−16.0 ± 1.2	2228 ± 10	BP 2159	3170 BC	61.1 ± 2.0	4498 ± 15	BP 5119
230 BC	−13.3 ± 1.3	2225 ± 10	BP 2179	3190 BC	60.2 ± 1.7	4524 ± 13	BP 5139
250 BC	−11.6 ± 1.5	2230 ± 12	BP 2199	3210 BC	61.9 ± 1.8	4530 ± 14	BP 5159
270 BC	−12.6 ± 1.5	2258 ± 12	BP 2219	3230 BC	66.8 ± 2.0	4513 ± 15	BP 5179
290 BC	−6.4 ± 1.5	2227 ± 12	BP 2239	3250 BC	75.9 ± 2.1	4465 ± 15	BP 5199
310 BC	−2.7 ± 1.5	2217 ± 12	BP 2259	3270 BC	74.0 ± 2.3	4498 ± 17	BP 5219
330 BC	2.7 ± 1.5	2193 ± 12	BP 2279	3290 BC	78.2 ± 2.1	4486 ± 16	BP 5239
350 BC	2.6 ± 1.3	2213 ± 11	BP 2299	3310 BC	76.1 ± 1.9	4521 ± 14	BP 5259
370 BC	−1.4 ± 1.2	2264 ± 10	BP 2319	3330 BC	78.7 ± 1.7	4521 ± 12	BP 5279
390 BC	−5.0 ± 1.4	2313 ± 12	BP 2339	3350 BC	73.9 ± 1.8	4577 ± 14	BP 5299
410 BC	−15.3 ± 1.3	2416 ± 11	BP 2359	3370 BC	68.0 ± 2.4	4640 ± 18	BP 5319
430 BC	−16.2 ± 1.3	2443 ± 11	BP 2379	3390 BC	58.7 ± 2.0	4730 ± 15	BP 5339
450 BC	−12.2 ± 1.6	2430 ± 13	BP 2399	3410 BC	63.9 ± 2.4	4710 ± 18	BP 5359
470 BC	−9.1 ± 1.3	2424 ± 10	BP 2419	3430 BC	69.9 ± 1.9	4685 ± 15	BP 5379
490 BC	−8.3 ± 1.4	2437 ± 11	BP 2439	3450 BC	71.6 ± 2.5	4691 ± 19	BP 5399
2510 BC	34.9 ± 1.5	4058 ± 12	BP 4459	3470 BC	79.7 ± 1.9	4650 ± 14	BP 5419
2530 BC	42.9 ± 1.5	4015 ± 11	BP 4479	3490 BC	83.1 ± 1.9	4644 ± 14	BP 5439
2550 BC	46.5 ± 1.6	4007 ± 12	BP 4499	3510 BC	74.6 ± 1.9	4726 ± 14	BP 5459
2570 BC	43.7 ± 1.5	4048 ± 12	BP 4519	3530 BC	73.6 ± 1.9	4753 ± 14	BP 5479
2590 BC	40.9 ± 1.5	4088 ± 11	BP 4539	3550 BC	69.9 ± 1.9	4801 ± 14	BP 5499
2610 BC	43.7 ± 2.0	4087 ± 15	BP 4559	3570 BC	75.9 ± 1.9	4776 ± 14	BP 5519
2630 BC	39.7 ± 1.4	4137 ± 11	BP 4579	3590 BC	81.6 ± 1.7	4752 ± 13	BP 5539
2650 BC	44.5 ± 2.1	4119 ± 16	BP 4599	3610 BC	87.7 ± 1.6	4726 ± 12	BP 5559

TABLE 1. (Continued)

Cal AD/BC	Δ^{14}C ‰	^{14}C age (BP)	Cal BP	Cal AD/BC	Δ^{14}C ‰	^{14}C age (BP)	Cal BP
3630 BC	81.4 ± 2.1	4793 ± 16	BP 5579	4590 BC	77.1 ± 2.1	5757 ± 16	BP 6539
3650 BC	73.6 ± 1.9	4871 ± 14	BP 5599	4610 BC	78.2 ± 2.4	5769 ± 18	BP 6559
3670 BC	71.5 ± 1.7	4905 ± 13	BP 5619	4630 BC	76.7 ± 1.9	5799 ± 14	BP 6579
3690 BC	75.1 ± 1.8	4898 ± 14	BP 5639	4650 BC	83.2 ± 1.7	5770 ± 13	BP 6599
3710 BC	70.7 ± 1.8	4950 ± 14	BP 5659	4670 BC	86.2 ± 2.5	5768 ± 18	BP 6619
3730 BC	71.4 ± 2.1	4965 ± 16	BP 5679	4690 BC	83.7 ± 1.8	5806 ± 13	BP 6639
3750 BC	75.0 ± 1.8	4957 ± 13	BP 5699	4710 BC	84.2 ± 2.1	5821 ± 15	BP 6659
3770 BC	73.8 ± 1.8	4985 ± 14	BP 5719	4730 BC	80.0 ± 2.5	5872 ± 18	BP 6679
3790 BC	73.0 ± 1.7	5011 ± 13	BP 5739	4750 BC	86.6 ± 2.5	5842 ± 18	BP 6699
3810 BC	67.4 ± 2.0	5073 ± 15	BP 5759	4770 BC	84.7 ± 2.5	5876 ± 18	BP 6719
3830 BC	67.8 ± 2.2	5089 ± 16	BP 5779	4790 BC	82.5 ± 2.5	5912 ± 19	BP 6739
3850 BC	70.9 ± 1.6	5085 ± 12	BP 5799	4810 BC	81.3 ± 2.5	5940 ± 19	BP 6759
3870 BC	75.3 ± 1.4	5071 ± 10	BP 5819	4830 BC	82.7 ± 2.2	5949 ± 17	BP 6779
3890 BC	83.9 ± 1.7	5027 ± 13	BP 5839	4850 BC	80.0 ± 2.2	5989 ± 16	BP 6799
3910 BC	82.3 ± 1.6	5058 ± 12	BP 5859	4870 BC	80.1 ± 2.5	6007 ± 19	BP 6819
3930 BC	84.6 ± 1.9	5060 ± 14	BP 5879	4890 BC	89.3 ± 2.3	5959 ± 17	BP 6839
3950 BC	80.4 ± 1.7	5111 ± 13	BP 5899	4910 BC	85.3 ± 1.8	6008 ± 13	BP 6859
3970 BC	75.8 ± 1.3	5165 ± 10	BP 5919	4930 BC	85.4 ± 1.7	6026 ± 13	BP 6879
3990 BC	71.4 ± 1.7	5217 ± 13	BP 5939	4950 BC	82.3 ± 1.5	6069 ± 12	BP 6899
4010 BC	68.9 ± 1.9	5255 ± 15	BP 5959	4970 BC	82.7 ± 1.7	6085 ± 13	BP 6919
4030 BC	76.3 ± 1.7	5219 ± 13	BP 5979	4990 BC	84.6 ± 1.9	6091 ± 14	BP 6939
4050 BC	70.7 ± 2.0	5281 ± 15	BP 5999	5010 BC	84.6 ± 2.4	6110 ± 18	BP 6959
4070 BC	78.3 ± 1.9	5244 ± 15	BP 6019	5030 BC	87.8 ± 2.5	6106 ± 19	BP 6979
4090 BC	72.7 ± 1.8	5305 ± 14	BP 6039	5050 BC	88.4 ± 2.5	6121 ± 18	BP 6999
4110 BC	72.6 ± 2.1	5324 ± 16	BP 6059	5070 BC	84.6 ± 2.2	6168 ± 16	BP 7019
4130 BC	81.3 ± 2.1	5279 ± 16	BP 6079	5090 BC	82.4 ± 1.8	6204 ± 13	BP 7039
4150 BC	78.6 ± 4.8	5319 ± 36	BP 6099	5110 BC	85.7 ± 2.0	6199 ± 15	BP 7059
4170 BC	76.3 ± 2.3	5355 ± 17	BP 6119	5130 BC	91.9 ± 2.0	6172 ± 14	BP 7079
4190 BC	82.1 ± 2.1	5332 ± 16	BP 6139	5150 BC	85.0 ± 2.5	6243 ± 19	BP 7099
4210 BC	92.9 ± 2.4	5271 ± 18	BP 6159	5170 BC	93.8 ± 2.0	6197 ± 15	BP 7119
4230 BC	82.2 ± 1.8	5370 ± 14	BP 6179	5190 BC	103.0 ± 2.1	6150 ± 16	BP 7139
4250 BC	81.8 ± 2.1	5392 ± 16	BP 6199	5210 BC	98.5 ± 2.5	6202 ± 18	BP 7159
4270 BC	76.8 ± 2.2	5449 ± 16	BP 6219	5230 BC	92.2 ± 2.5	6268 ± 18	BP 7179
4290 BC	83.3 ± 2.1	5420 ± 16	BP 6239	5250 BC	94.1 ± 1.9	6273 ± 14	BP 7199
4310 BC	89.6 ± 2.3	5393 ± 17	BP 6259	5270 BC	88.7 ± 2.0	6332 ± 15	BP 7219
4330 BC	84.1 ± 2.1	5453 ± 15	BP 6279	5290 BC	84.7 ± 2.1	6381 ± 16	BP 7239
4350 BC	77.8 ± 2.0	5519 ± 15	BP 6299	5310 BC	87.6 ± 2.2	6379 ± 16	BP 7259
4370 BC	72.4 ± 1.9	5579 ± 15	BP 6319	5330 BC	86.2 ± 2.1	6409 ± 16	BP 7279
4390 BC	76.4 ± 2.4	5568 ± 18	BP 6339	5350 BC	82.4 ± 2.0	6457 ± 15	BP 7299
4410 BC	74.6 ± 2.4	5601 ± 18	BP 6359	5370 BC	90.5 ± 2.5	6416 ± 18	BP 7319
4430 BC	83.9 ± 2.4	5552 ± 18	BP 6379	5390 BC	86.9 ± 2.5	6462 ± 19	BP 7339
4450 BC	82.8 ± 2.4	5579 ± 18	BP 6399	5410 BC	95.4 ± 2.2	6419 ± 16	BP 7359
4470 BC	73.1 ± 2.0	5671 ± 15	BP 6419	5430 BC	92.8 ± 2.2	6457 ± 16	BP 7379
4490 BC	76.4 ± 2.4	5666 ± 18	BP 6439	5450 BC	78.3 ± 2.2	6585 ± 16	BP 7399
4510 BC	76.7 ± 2.4	5683 ± 18	BP 6459	5470 BC	82.8 ± 2.2	6570 ± 16	BP 7419
4530 BC	77.5 ± 2.5	5696 ± 18	BP 6479	5490 BC	81.4 ± 2.5	6600 ± 18	BP 7439
4550 BC	73.9 ± 2.5	5742 ± 18	BP 6499	5500 BC	82.1 ± 2.6	6605 ± 19	BP 7449
4570 BC	75.7 ± 1.9	5748 ± 14	BP 6519	5510 BC	82.8 ± 2.5	6609 ± 18	BP 7459

TABLE 1. (Continued)

Cal AD/BC	Δ^{14}C ‰	^{14}C age (BP)	Cal BP	Cal AD/BC	Δ^{14}C ‰	^{14}C age (BP)	Cal BP
5520 BC	84.2 ± 2.6	6608 ± 19	BP 7469	5740 BC	69.8 ± 1.6	6930 ± 12	BP 7689
5530 BC	76.0 ± 2.4	6679 ± 18	BP 7479	5760 BC	70.9 ± 1.6	6941 ± 12	BP 7709
5540 BC	76.9 ± 2.6	6682 ± 19	BP 7489	5780 BC	70.2 ± 1.7	6966 ± 12	BP 7729
5550 BC	85.8 ± 2.2	6626 ± 16	BP 7499	5800 BC	72.1 ± 1.6	6971 ± 12	BP 7749
5560 BC	89.4 ± 2.2	6609 ± 17	BP 7509	5820 BC	72.0 ± 1.6	6991 ± 12	BP 7769
5570 BC	85.7 ± 1.8	6646 ± 13	BP 7519	5840 BC	74.2 ± 1.7	6994 ± 13	BP 7789
5580 BC	81.0 ± 1.8	6691 ± 13	BP 7529	5860 BC	72.8 ± 2.5	7024 ± 19	BP 7809
5590 BC	78.1 ± 2.0	6722 ± 15	BP 7539	5880 BC	72.1 ± 2.5	7049 ± 19	BP 7829
5600 BC	73.5 ± 1.9	6766 ± 14	BP 7549	5900 BC	70.0 ± 2.3	7084 ± 17	BP 7849
5620 BC	74.4 ± 1.6	6778 ± 12	BP 7569	5920 BC	83.3 ± 2.1	7004 ± 15	BP 7869
5640 BC	72.7 ± 1.7	6811 ± 13	BP 7589	5940 BC	79.3 ± 2.7	7053 ± 20	BP 7889
5660 BC	75.6 ± 1.6	6809 ± 12	BP 7609	5960 BC	74.1 ± 2.5	7111 ± 19	BP 7909
5680 BC	73.8 ± 1.8	6842 ± 14	BP 7629	5980 BC	69.5 ± 2.3	7165 ± 17	BP 7929
5700 BC	71.7 ± 1.7	6877 ± 13	BP 7649	6000 BC	69.3 ± 2.3	7186 ± 17	BP 7949
5720 BC	71.0 ± 2.0	6901 ± 15	BP 7669				