^{14}C CALIBRATION IN THE SOUTHERN HEMISPHERE AND THE DATE OF THE LAST TAUPO ERUPTION: EVIDENCE FROM TREE-RING SEQUENCES

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ABSTRACT. Tree rings from a section of *Prumnopitys taxifolia* (matai) covering the period AD 1335–1745 have been radiocarbon dated and used to generate a ^{14}C calibration curve for southern hemisphere wood. Comparison of this curve with calibration data for northern hemisphere wood does not show a systematic difference between ^{14}C ages measured in the northern and southern hemispheres. A floating chronology covering 270 yr and terminating at the last Taupo (New Zealand) eruption, derived from a sequence of 10-yr samples of tree rings from *Phyllocladus trichomanoides* (celery pine, or tanekaha), is also consistent with the absence of a systematic north-south difference, and together with the matai data, fixes the date of the Taupo eruption at AD 232 ± 15.

INTRODUCTION

This paper forms part of an investigation into the relation between the ^{14}C calibration curves applicable to the northern and southern hemispheres. Based on measurements on paired tree samples from the two hemispheres (Vogel *et al.* 1986), the convention was adopted of decreasing terrestrial ^{14}C ages measured in the southern hemisphere by 30 yr before calibration with curves derived for the northern hemisphere (Mook 1986). Further measurements on European oak and Cape pine gave a higher offset of 41 yr (Vogel *et al.* 1993). While a case can be made on plausibility grounds for expecting the offset to exist, due to the large oceanic area of the southern hemisphere, we do not consider the magnitude of the offset to be well established for two reasons:

1. The time interval covered by the data of Vogel *et al.* (1993) supporting the offset is relatively small (AD 1835–1900), and it is not obvious that an effect determined for such a limited period can be extrapolated back over many hundreds of years.
2. Within that interval, the observed deviation between northern and southern hemisphere wood is not constant, but fluctuates, further calling into question the validity of applying a constant offset over long periods of time.

Two approaches are presented here. One is based on the ^{14}C dating of decadal samples of tree rings constituting a floating chronology covering 270 yr whose endpoint is known to coincide with the last Taupo eruption (central North Island, New Zealand). The other uses a tree-ring sequence from a section of *Prumnopitys taxifolia* (matai) that was felled in 1971 and for which measurements from AD 1335–1745 have been obtained. We compare these ^{14}C ages with the published decadal calibration curves (Stuiver and Becker 1993). We also emphasize that the intention is not to produce a southern hemisphere calibration curve in its own right, which would require at least the same effort and resources that went into determining the northern hemisphere curves. Our objective was to decide whether or not an offset should be applied to southern hemisphere dates before using the northern hemisphere calibration curves.

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Proceedings of the 15th International ^{14}C Conference, edited by G. T. Cook, D. D. Harkness, B. F. Miller and E. M. Scott. RADIOCARBON, Vol. 37, No. 2, 1995, P. 155–163

METHODS

Wood Specimens

Prumnopitys taxifolia (Podocarpaceae)

The *Prumnopitys* samples were taken from a tree growing at an altitude of 310 m in the Dennistoun Bush, Peel Forest Park, near the east coast of the South Island of New Zealand. The tree was felled in 1971. It had been progressively killed by ground application of herbicide in 1965, but was not completely dead when it was felled. The tree was very uniform in cross-section, with symmetric growth rings, and the bark was intact when ring counting was carried out in 1971. A complete section of the trunk, 50 mm thick, was planed and sanded smooth, and the rings counted along four radii separated by *ca.* 90°. The rings along three of the radii were distinct and continuous; only along the fourth radius did some of the rings become indistinguishable. When we commenced this work we recounted rings, cross-checking them to the two best radii before marking them in 10-yr groups. Blocks of wood 10 rings thick were removed for ^{14}C dating, the central years of the groups spanning the period AD 1335 to 1745.

Phyllocladus trichomanoides (Phyllocladaceae)

The *Phyllocladus* samples came from logs recovered from a subfossil forest discovered in 1983 near Pureora, west of Lake Taupo on the North Island of New Zealand (Clarkson, Patel and Clarkson 1988). The forest was buried in the Taupo volcanic eruption that took place approximately 2 ka ago. This eruption is regarded as one of the most violent to have occurred within the last 5 ka, and deposited a layer of ignimbrite spreading across 160 km; ash has been found on the seafloor up to 100 km from the east coast of the North Island (Wilson *et al.* 1980). The pumice and ash layers form an important stratigraphic marker. Thus, establishing the best possible estimate of the eruption date is significant for New Zealand geology.

We cross-matched 18 cross-sections of different *Phyllocladus* trees to provide a floating chronology spanning 426 yr, with the incomplete outer ring grown in the year of the eruption (Palmer 1988). From three trees included in this chronology, 21 contiguous samples, starting 5 yr before the eruption, were selected for ^{14}C dating. This produced a sequence of ^{14}C ages corresponding to precisely known calendar year intervals whose endpoint, the sequence base year, is the year of the eruption.

SAMPLE PREPARATION AND COUNTING

The wood was milled into fragments of < 0.5 mm and treated with 0.1N NaOH at 80°C for 15 h, followed by a hot water wash. The cellulose obtained from this process was then bleached with alkaline hydrogen peroxide at 80°C for 1 h, washed with water and treated with 0.1N HCl at 80°C for 1 h, followed by a final wash with hot water. When dry, the cellulose was burned in a quartz combustion tube using excess secondary oxygen to ensure complete combustion.

The resulting CO_2 was purified and passed though a charcoal column at 0°C into the gas proportional counter. At the same time, a sample of the purified gas was taken for $\delta^{13}C$ measurement using conventional mass spectrometry. The *Prumnopitys* samples were sufficient to allow the 10-yr blocks to be counted individually. In the case of *Phyllocladus,* we used some samples that spanned a longer period to obtain enough material for counting. All samples were counted at least twice, and duplicate samples from the same ring groups were counted for the *Prumnopitys.* ^{14}C ages were calculated relative to the HOxI international standard and are expressed as the conventional radiocarbon age

(CRA) according to the recommendations of Stuiver and Polach (1977). Uncertainties in the measured CRAs include a multiplier of 1.3 based on repeated measurements on the oxalic standard.

As a check on the accuracy of the counting system employed for this investigation, a series of measurements were made on samples of Belfast pine used in the Glasgow University laboratory intercomparison exercise, and IAEA cellulose C (Scott *et al.* 1992). Table 1 shows a comparison of the results obtained with the sample consensus values. For both samples, the measured values with their standard errors overlap the consensus values, indicating no significant systematic bias in the ages measured on our counting system.

TABLE 1. Comparison of Measurements on Belfast Pine and IAEA Cellulose C with Consensus Values

Material	n	Mean measured value	Consensus value*
Belfast pine	6	4518 ± 22 BP	4503 ± 6 BP
IAEA C cellulose	4	130.0 ± 0.3 pMC	129.70 ± 0.08 pMC

*(E. M. Scott, personal communication)

RESULTS AND DISCUSSION

Prumnopitys Results

Table 2 summarizes the results of the measurements on the *Prumnopitys* samples.

TABLE 2. Mean ^{14}C Ages of 10-yr Tree-Ring Samples from the *Prumnopitys taxifolia* Section

Central Ring (cal AD)	^{14}C age (yr BP)	Central Ring (cal AD)	^{14}C age (yr BP)
1335	617 ± 22	1545	324 ± 14
1345	635 ± 19	1555	322 ± 18
1355	639 ± 20	1565	307 ± 22
1365	683 ± 20	1575	377 ± 25
1375	637 ± 22	1585	385 ± 26
1385	618 ± 17	1595	396 ± 21
1395	593 ± 19	1605	361 ± 12
1405	599 ± 19	1615	367 ± 17
1415	530 ± 20	1625	360 ± 21
1425	471 ± 21	1635	286 ± 18
1435	484 ± 21	1645	288 ± 20
1445	422 ± 21	1655	290 ± 16
1455	453 ± 17	1665	220 ± 20
1465	450 ± 19	1675	163 ± 22
1475	420 ± 22	1685	163 ± 20
1485	417 ± 17	1695	182 ± 23
1495	380 ± 23	1705	167 ± 21
1505	380 ± 21	1715	157 ± 17
1515	372 ± 15	1725	167 ± 20
1525	334 ± 21	1735	176 ± 21
1535	323 ± 15	1745	206 ± 17

Figure 1 shows a plot of CRA *vs.* calendar year superimposed on the decadal calibration curve of Stuiver and Becker (1993).

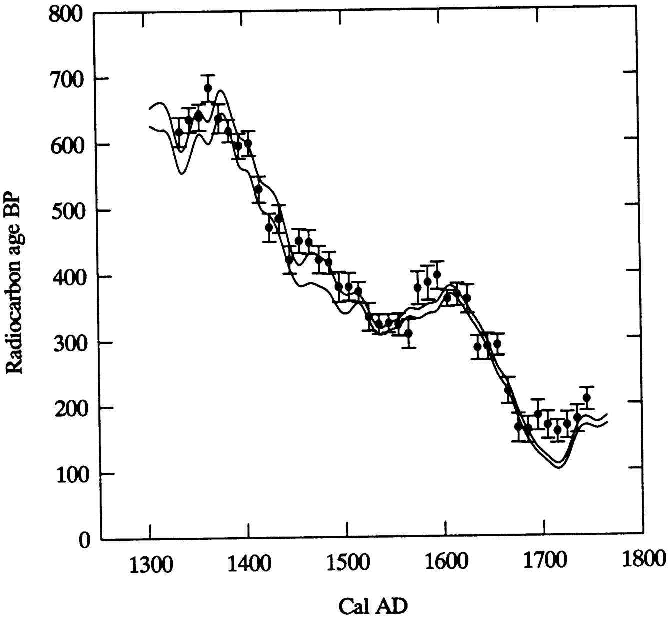


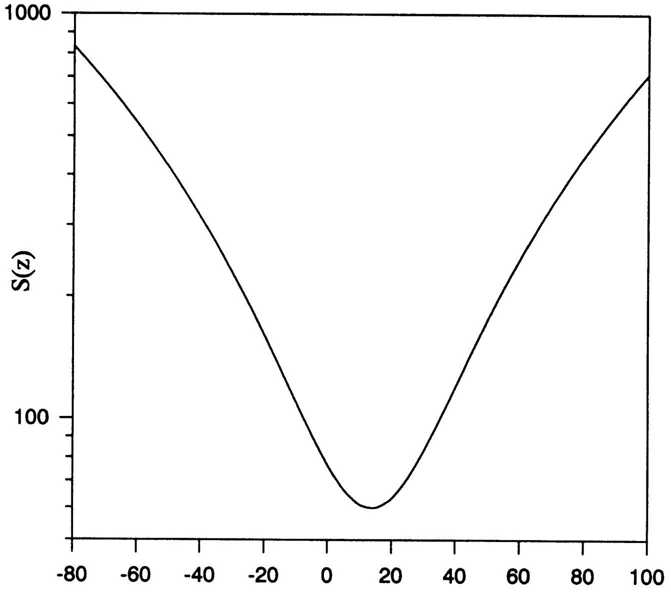
Fig. 1. Measured ^{14}C ages of 10-yr samples of *Prumnopitys taxifolia* plotted *vs.* the calendar age derived from tree-ring counting. The continuous band is the calibration curve of Stuiver and Becker (1993) over the same period.

The curve is shown as an envelope obtained by fitting a smooth curve through the extremes of the ± 1 σ uncertainty limits of the calibration data. The quality of the fit between the tree-ring data and the calibration curve is given by the function

$$S(z) = \sum \frac{(R-z-C)^2}{e^2} \tag{1}$$

where R is the measured CRA, C is the corresponding value of the calibration curve, e is the quadratic sum of the uncertainties in the two quantities and z is the offset to be applied to southern hemisphere CRA measurements relative to sorthern hemisphere measurements. Figure 2 is a plot of S(z) *vs.* z using the data of Table 2. The minimum occurs at the offset value of 13.5 yr. If the data points correspond to the calibration curve, but are displaced by a uniform amount z, then S(z) will have a χ^2 distribution with n–1 degrees of freedom, where n is the number of data points. The minimum of S(z) in Figure 2 corresponds to the 3% significance level for 41 degrees of freedom, indicating that the hypothesis of a simple displacement of the data may not be correct. Examination of Figure 1 shows that the data points are not all uniformly displaced from, or distributed around, the northern hemisphere calibration curve, but that significant deviations occur in the ranges AD 1575–1595 and AD 1695–1745. If the deviations are accepted as real, their effect will be to shift the minimum in S to higher z for the whole curve. Omitting these points results in a minimum S at z = 5.8 yr, with a range of –2.5 to 14.1 yr at the 10% significance level. In terms of the consequences for calibrating

^{14}C ages, such an offset value is less than the standard deviation of a typical high-precision measurement, and applying it as a correction does not contribute significantly to the accuracy of the result.



North-south calibration offset, z

Fig. 2. Plot of the fit of the *Prumnopitys* data to the calibration curve as a function of the offset between the northern and southern hemisphere ^{14}C ages.

Phyllocladus Results and the Taupo Eruption

The *Phyllocladus* data consist of a sequence of ^{14}C ages corresponding to known relative calendar ages (Table 3). Comparing these data to the calibration curve involves two unknowns: the value of the north-south offset as before and the base year of the sequence of calendar ages, *i.e.*, the year of the Taupo eruption that killed the trees. The eruption is known to have occurred somewhere *ca.* AD 200 from numerous dates obtained from charcoal and wood fragments found in the ash layers. This information can be used to constrain the range of possible values. As with the *Prumnopitys* data, the fit with the calibration curve can be expressed with the function

$$S(z, B) = \sum_{\alpha} \frac{[R - z - C(B - \alpha)]^2}{e^2} . \tag{2}$$

This function S has two parameters, the offset z and the sequence base year B. The mean age of each of the tree-ring samples relative to B is α, and $C(B - \alpha)$ is the calibration curve at year $B - \alpha$. Figure 3 shows S(z, B) as a family of curves labeled by B and plotted against offset z. The function has a minimum corresponding to an offset of *ca.* 8 yr and a base year between AD 230 and 240. At the 10% significance level, the range around the optimum values is relatively wide and asymmetric. This occurs because, with two free parameters, one may obtain a tolerable fit by sliding the data along the curve over a range of values for both the offset and the base year. Nevertheless, the *Phyllocladus* data are consistent with those for the *Prumnopitys*, and favor a low value for the north-south offset.

TABLE 3. Mean ^{14}C Ages of *Phyllocladus trichomanoides* Samples

Central ring (years before eruption)	^{14}C age (yr BP)	Central ring (years before eruption)	^{14}C age (yr BP)
10	1801 ± 28	150	1907 ± 28
20	1862 ± 30	160	1977 ± 105
30	1844 ± 30	170	1972 ± 53
50	1852 ± 29	180	1977 ± 46
60	1868 ± 31	205	1940 ± 34
70	1876 ± 31	220	2005 ± 33
90	1831 ± 28	240	2021 ± 38
100	1846 ± 30	250	2043 ± 40
110	1897 ± 31	260	2053 ± 29
120	1927 ± 30	270	2072 ± 36
135	1901 ± 29		

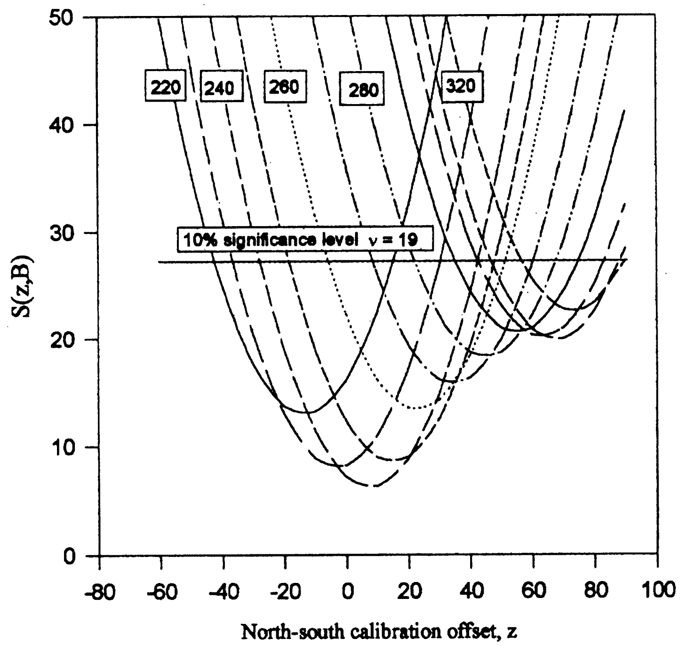


Fig. 3. Family of curves of the fit of the *Phyllocladus trichomanoides* samples to the calibration curves as a function of the north-south ^{14}C age offset. Curves are labeled by the base year of the *Phyllocladus* sequence, *i.e.*, the year of the Taupo eruption.

Because the relative ages of the tree rings are known, a more precise estimate for the year of the eruption can be found by calibrating independently the ^{14}C ages of the samples. Calibrated ^{14}C ages should correspond to calendar ages, so a plot of the sample calendar ages against their relative ages should lie along a line of unit slope whose intercept with the calendar axis represents the year of the eruption (Fig. 4).

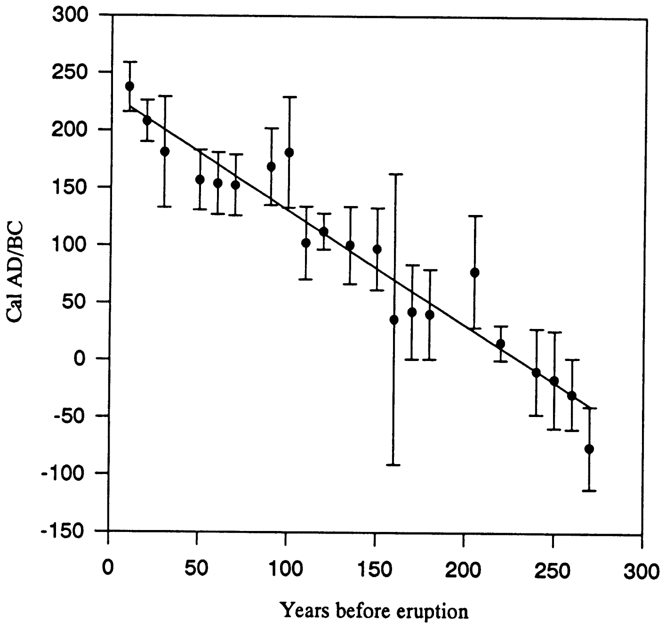


Fig. 4. Calibrated *Phyllocladus* ages plotted *vs.* their relative ages. Straight line is a linear least squares fit to the data (see text).

The line through the tree-ring age data (marked with error bars) is the result of a weighted linear least squares fit with parameters

Intercept	230 ± 15
Slope	−1.00 ± 0.07
$\chi^2(\nu = 19)$	7.1 .

Error bars on the calibrated ages represent 1-σ intervals given by Method B of Stuiver and Reimer (1989). We applied no offset in performing the calibrations, as discussed above. A further correction must be applied to these results to obtain the year of eruption. The outermost growth ring of the *Phyllocladus* section was incomplete with little or no late wood, indicating that the trees were buried in the southern late summer or autumn (Palmer, Ogden and Patel 1988). The accepted convention is to ascribe a tree-ring year to the year in which the season's growth commenced (Norton and Ogden 1987). Consequently, in the southern hemisphere, the growth period includes two calendar years. As growth apparently ceased during the second calendar year of the growing season, 2 yr must be added to the intercept of the fitted line in Figure 4, giving the year of the eruption as AD 232 ± 15 yr. Figure 5 shows the *Phyllocladus* ages converted to cal AD/BC ages superimposed on the decadal calibration curve of Stuiver and Becker (1993).

Healy (1964) reviewed early estimates of the date of the Taupo eruption based on ^{14}C ages of wood and charcoal recovered from the Taupo Pumice and obtained a weighted mean of 1819 ± 17 BP, corresponding to a calendar date of AD 131. In a later review, Froggatt (1981) re-assessed the dates used by Healy and included later data, obtaining a mean age of 1820 ± 80 BP. Froggatt and Lowe (1990) presented a comprehensive review of ^{14}C age measurements on New Zealand tephras, including Taupo, and obtained a weighted mean CRA for the Taupo Tephra (Pumice) of 1810 ± 10 BP. Wilson *et al.* (1980) postulated a date of AD 186, based on ancient Chinese and Roman records of unusual

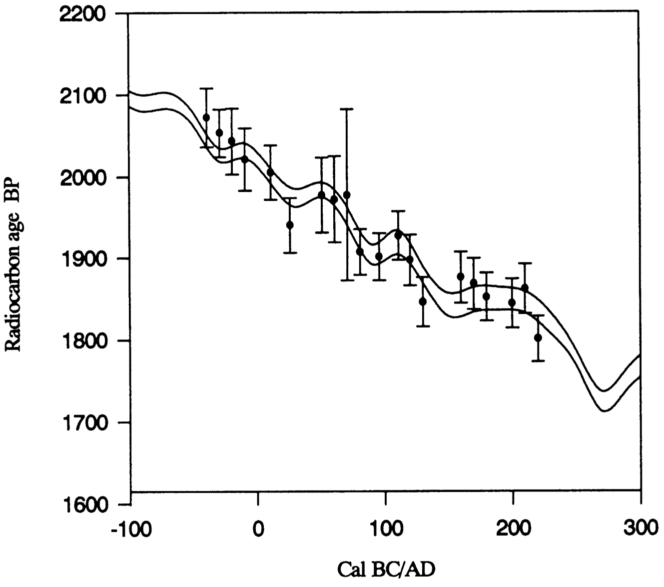


Fig. 5. *Phyllocladus* data, calibrated with zero north-south offset and with sequence base year of AD 232, superimposed on the calibration curve of Stuiver and Becker (1993).

atmospheric phenomena in about this year. Apart from Wilson's date, all these estimates were in terms of uncalibrated ^{14}C ages. When they are calibrated with the curves of Stuiver and Becker (1993) they yield 1-σ calendar intervals (Table 4). When calibrated, the estimates of Healy (1964) and Froggatt (1981) cover the range of dates derived from the *Phyllocladus* data. The value obtained by Froggatt and Lowe (1990) is based on a total of 41 individual measurements that very likely include some wood whose time of growth significantly predated the eruption, and so the mean CRA represents a maximum age. The date obtained in this work does not agree with the suggestion of Wilson *et al.* (1980), but as there is no necessary connection between the Chinese and Roman observations, on the one hand, and the Taupo eruption, on the other, this disagreement does not constitute a conflict of evidence. It may be noted in passing that the uncalibrated date AD 131 of Healy (1964) and the suggested date AD 186 of Wilson *et al.* (1980) are the most frequently quoted dates in discussions of the last Taupo eruption.

TABLE 4. Calibrated Age Intervals of Earlier Estimates of the Taupo Eruption

Source	Mean ^{14}C age (yr BP)	Calendar interval (AD) (1 σ)
Healy (1964)	1819 ± 17	161–202 215–244 305–316
Froggatt (1980)	1820 ± 80	88–100 127–262 278–325
Froggatt and Lowe (1990)	1850 ± 10	142–150 162–213

CONCLUSION

^{14}C ages of tree rings from the *Prumnopitys* specimen, covering the interval AD 1335–1745, do not indicate a systematic offset with respect to the northern hemisphere calibration curve of Stuiver and Becker (1993), although larger shifts may occur within relatively short (<50-yr) intervals. The data provided by the *Phyllocladus* measurements, while less precise in constraining the magnitude of the offset, are fully consistent with the *Prumnopitys* results. From this evidence, we conclude that there is presently no basis for applying a constant correction, prior to calibration, to ^{14}C ages measured on terrestrial samples from the southern hemisphere. The *Prumnopitys* data indicate the possibility of significant deviations between northern and southern ^{14}C ages over relatively short time intervals, as discussed above. Independent measurements are needed to confirm the existence of such deviations. If they are real, then high-precision southern hemisphere calibrations will require the development of a separate calibration curve as was done for the northern hemisphere. This conclusion is not contradicted by the data presented by Vogel *et al.* (1993), since the north-south difference shown in their measurements has a similar structure to the deviations discussed in the present work and may represent confirmation of the suggestion that significant *short-term* deviations may occur at certain times.

ACKNOWLEDGMENT

We gratefully acknowledge the cooperation of the Peel Forest Park Board in making available the *Prumnopitys taxifolia* section.

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