Determination of the Age of Swiss Lake Dwellings as an Example of Dendrochronologically-Calibrated Radiocarbon Dating

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Dedicated to Professor Dr. W. Gentner *on the occasion of his 60th birthday*

Comparison of the radiocarbon content of a series of samples of dendrochronologically dated bristlecone pine wood with that from trees for which a so-called floating tree-ring chronology has been established makes it possible to determine an empirical age for this floating tree-ring series based upon the age of the wood used for comparison. For the case of the Swiss Lake Dwellers, the difference between conventional radiocarbon dates and the age values determined in this manner amounts to about 800 years. The age of the floating chronology was determined within a standard error of less than 40 years. The measurements indicate that the dwellings were constructed during the 38th century B. C.

For many methods of radioisotope dating the exact definition of the age of a sample represents a difficulty [1]. This difficulty does not exist in the case of the dating of wood by radiocarbon [2]. The age of wood is precisely defined as the time elapsed since the year in which the tree grew. This is true even for differences in the age of wood from one and the same tree, because radial migration of radiocarbon, and hence the transfer of organic matter from tree ring to tree ring has never, even in sapwood, been observed to occur to an extent that could affect radiocarbon measurements [3]. The accuracy, however, with which this well-defined age can be determined is limited by the fact that the carbon-14 level in the atmospheric carbon dioxide has not been completely constant during the past. It may have been somewhat different from the present at the time when the wood grew. In such a case, the radiocarbon age of the wood sample will differ from its true age. The existence of such differences was first demonstrated by De Vries [4]. Advanced techniques of radiocarbon determinations have now made it possible to determine these deviations accurately [3]. Variations of the carbon-14 level in the atmospheric carbon dioxide are undoubtedly world-wide phenomena. Local carbon-14 variations cannot be important, because the terrestrial atmosphere mixes within less than two years. Although Willard Libby's radiocarbon clock does not always show the exact age, it is possible to calibrate this clock for periods of time for which samples of precisely known age are available. Measurements of radiocarbon in such samples of known age have been carried out by many laboratories [5] and the results are essentially in agreement. For the last 2,000 years, one of us [6] has published a calibration curve based on about 150 individual measurements. In general, for the A. D. time period, the fluctuations in the carbon-14 level of the order of one or two per cent. Larger deviations were observed for samples from the B. C. time period [7].

1 W. Gentner, Nova Acta Leopoldina **21,** 57 [1959].
2 W. F. Libby, Radiocarbon Dating, University of Chicago Press, Chicago 1952.
3 H. E. Suess, J. Geophys. Res. **70,** 5937 [1965].
4 H. De Vries, Koninkl. Ned. Akad. Wetenschap. Proc. **B 61,** 94 [1958].
5 E. H. Willis, M. Tauber, and K. O. Münnich, Am. J. Sci. Radiocarbon Suppl. **2,** 1 [1960].
6 H. E. Suess, J. Geophys. Res. **70,** 5937 [1965]. Fig. 4; M. Stuiver and H. E. Suess, Am. J. Sci. Radiocarbon Suppl., in press.
7 H. E. Suess, Proc. Highland Park, Ill. Conf., Publication 845, NAS-NRC Washington, D.C. 1960.

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Dendrochronologically determined ages of wood:

Wood for which the time of growth can be determined by the study of its tree rings is the ideal material for the determination of the differences between radiocarbon age and true age. The study of the annual tree rings of long-lived trees, especially, has led to reliable tree-ring chronologies. The 3,200-year record for the giant sequoia, *Sequoia gigantea,* established by DOUGLASS [8], has been exceeded by ages of well over 4,000 years for bristlecone pine, *Pinus aristata,* as reported by SCHULMAN and FERGUSON [9], SCHULMAN [10], and CURREY [11]. Recently, one of us [12] has succeeded in establishing a continuous, 6,600-year tree-ring chronology for bristlecone pine by incorporating the records from long-dead trees.

The building of a tree-ring chronology, in which each consecutive annual ring is assigned to the calendar year in which it was formed, is based upon crossdating of the pattern of large and small rings between wood specimens from different trees. What difficulties there are for bristlecone pine are due not to multiple rings, but to "missing" rings associated with the extremely slow growth rate of this species. In one specimen, over 1,100 annual rings occurred in five inches (12.7 cm.) of radius; hence, in a tree such as this where the average ring width is only a few hundredths of a millimeter, there is often no evidence of growth in a large portion of the stem during a year of environmental stress. In some instances, 5% or more of the annual rings may be absent along a given radius that spans many centuries. The location of such "missing" rings in one specimen can be determined by crossdating with other specimens where the ring is present [13].

In certain species of conifers at lower elevations or in southern latitudes, one season's growth increment may be composed of two or more flushes of growth that give the appearance of annual rings [14]. Multiple growth rings are extremely infrequent in bristlecone pine, however, and especially infrequent at the elevation (10,000 to 11,000 feet above sea level) and latitude (37° 23′) of the bristlecone pine sites being studied. In fact, in the growth-ring analyses of approximately 1,000 trees in this area, no evidence of multiple growth layers has been found.

A growth-environment study of bristlecone pine trees was made by FRITTS [15] of the laboratory of tree-ring research. Measurement and analysis of ring growth during three growing seasons indicate a sharply-defined period of growth which starts about June 26 and ends about August 8. Periodic cambial samples and recordings of stem growth by both dendrometers and dendrographs indicate a single continuous unit of growth for one season. While a mid-season dry period may reduce the rate of stem increment, it appears that once cambial activity has reached a critically low rate, it will not again increase and form larger cells even though there may again be very favorable growing conditions.

The precisely dated tree-ring chronology for bristlecone pine is based upon collections made by the Laboratory of Tree-Ring Research in the especially designated Ancient Bristlecone Pine Forest within the Inyo National Forest in east-central California.

The bristlecone pine chronology has been established primarily upon the study of the radial growth-ring sequence of core samples extracted with the Swedish increment borer. The record from living trees, which reaches ages up to 4,600 years in this area, has been strengthened and extended by the comparative study of cores and sequences of cross sections from dead trees and eroded remnants of trees. The incorporation of this millenia-old wood has made possible the construction of a continuous tree-ring chronology of over 6,600 years. At present, the chronology for the earliest centuries is based upon the crossdating of only three specimens. However, these are of good quality and in sufficient volume to make possible a thorough study and a high degree of confidence in the dating. It is this material that provided the dated wood for the comparative radiocarbon analysis reported below.

[8] A. E. DOUGLASS, Climatic Cycles and Tree Growth, Carnegie Institution of Washington Publication **1**, 289 [1919].

[9] Appendix C, Millenia-old pine trees sampled in 1954 and 1955: in E. SCHULMAN, Dendroclimatic Changes in Semiarid America, The University of Arizona Press, Tucson, Arizona 1956.

[10] E. SCHULMAN, Bristlecone Pine, Oldest Known Living Thing, National Geographic **113**, (No. 3), 354 [1958].

[11] D. R. CURREY, Ecology **46**, (No. 4), 564 [1965].

[12] C. W. FERGUSON, Longevity of Bristlecone Pine, *Pinus aristata.* Paper presented at the AAAS meeting, Berkeley, Calif., Dec. 30, 1965.

[13] According to W. ELLING (Flora **156**, 1966, in press) up to 40% of the rings can be missing in suppressed trees of alder *(Alnus glutinosa)*.

[14] W. S. GLOCK, R. A. STUDHALTER, and S. R. AGERTER, Publ. Smithsonian Institution No. 4421, Washington 1960.

[15] Personal communication, March 2, 1966.

Previously, radiocarbon measurements on samples from this chronology have been carried out by several laboratories [16]. Their results show that radiocarbon dates of more than 2,000 years before the present become increasingly too recent [7]. The results are consistent with those obtained with wood from *Sequoia gigantea.* Analogous discrepancies between radiocarbon ages and true ages had been observed for historically dated wood from Egypt.

Calibration of radiocarbon dates by comparison with results from bristlecone pine wood. In many cases, a comparison of the carbon-14 content of a single sample of unknown age with the contents of several samples of ages determined through tree-ring studies will lead to a very accurate and reliable value for the unknown age. During certain periods of the past, however, the carbon-14 content of the atmosphere changed at a rate comparable to, or greater than the rate of radioactive decay. For such periods of rapid change of the atmospheric carbon-14 level, a single radiocarbon determination, even when an identical result is derived from a sample of known age, may not reveal a defined age, in that material of two or three different ages spanning several centuries could provide the same radiocarbon date. Radiocarbon determinations of a number of samples with a known difference in age, or from a tree-ring series within a single timber of sufficient age range may delineate the true age by relating the resultant series of fluctuations in the delta value (derived from the relationship of the radiocarbon years to the true years) with those of an established pattern.

An ideal situation for applying the method of calibrated radiocarbon dating exists for the case of oak timbers from settlements of Swiss Lake Dwellers. It is possible there to compare not only the absolute carbon-14 contents of the individual samples with those of samples of known age, but also the general trends of the carbon-14 level, viz. its time derivative for several hundred years. This is possible because Huber and Merz [17] were able to integrate the tree-ring sequences in oak pilings from the late neolithic settlement, Thayngen (Michelsberger Kultur), with those from Burgäschisee-Süd and Südwest into one single consistent tree-ring sequence containing a total of 311 annual rings. The wood from this sequence has previously been dated by the Bern Laboratory [18] and the results have been discussed by Müller-Beck [19]. We have concentrated on the investigation of two sections of timber of the Thayngen Settlement because of a possibility that samples from Burgäschisee-Süd had been treated with an organic wood preservative. Only one sample from Burgäschisee-Süd was, therefore, measured. This sample gave the same carbon-14 content as the Thayngen samples of the same time of ring growth. This agreement is further proof of a correct correlation of tree rings in wood from the two settlements. (See Table 1.)

LJ No.	Tree No.	Rings Arbitrary Scale	Average	C^{14} Content Relative to 1884 Standard	δC^{13}	Conventional C^{14} Age ($T_{1/2} = 5568$ yrs. Zero = 1950)
1265	276	90—70	80	0.5415	— 0.6	4982
1279	276	110—90	100	0.5425	— 2.2	4938
1261	276	170—150	160	0.5343	— 3.0	5060
1277	266	180—160	170	0.5435	— 0.3	4960
1278	266	210—200	205	0.5375	— 1.4	5033
1262	276	270—230	250	0.5314	— 6.1	5043
1266	266	292—280	286	0.5347	— 1.3	5070
1293	2030	200—160	180	0.5238	—10.2	5060

Table 1. Conventional radiocarbon ages of samples from a floating tree-ring series in wood from Thayngen (Trees No. 276 and 266) and Burgäschisee-Süd (Tree No. 2030).

[16] P. E. Damon, A. Long, and D. C. Grey, J. Geophys. Res. **71**, 1055 [1966]. — E. K. Ralph, H. N. Michael, and J. Gruninger, Jr., Am. J. Sci., Radiocarbon **7**, 179 [1965].

[17] B. Huber and W. Merz, Jahrringchronologische Synchronisierung der jungsteinzeitlichen Siedlungen Thayngen-Weier und Burgäschisee-Süd und -Südwest. Germania **41**, 1 [1963]. — B. Huber, Dendrochronologie in Seeberg/Burgäschisee-Süd. V. Acta Bernensia (in press). — U. Guyan, Die steinzeitlichen Moordörfer im „Weier" bei Thayngen, Hegau **9**, 191 [1964] and further publication in press.

[18] C. Gfeller, H. Oeschger, and U. Schwarz, Bern Radiocarbon Dates II. Am. J. Sci., Radiocarbon **3**, 15 [1961].

[19] H. Müller-Beck, Jahrringchronologische Synchronisierung der jungsteinzeitlichen Siedlungen Thayngen-Weier und Burgäschisee-Süd und -Südwest. Germania **41**, 7 [1963]. — H. Müller-Beck, Zur Altersbestimmung der Station Seeberg/Burgäschisee-Süd. Jahrbuch des Bernischen Historischen Museums in Bern **37/38**, 279—281 [1957/58].

LJ No.	Tree No.	Rings Time of Growth B. C.	Average B. C.	C^{14} Content Relative to 1884 Standard	δC^{13}	Conventional C^{14} Age ($T_{1/2} = 5568$ yrs. Zero = 1950)
1295	63–34	3600–3590	3595	0.5597	+1.4	4746
1300	63–34	3710–3690	3700	0.5435	−5.1	4881
1299	63–34	3800–3780	3790	0.5415	−1.3	4976
1304	65–F131	3830–3814	3822	0.5365	+1.3	5088
1306	65–F131	3951–3926	3938	0.5332	+0.9	5095
1305	65–F131	4018–3993	4005	0.5295	−0.6	5135
1307	65–F131	4052–4015	4035	0.5320	−2.3	5070
1302	65–F131	4103–4052	4078	0.5260	−3.7	5176

Table 2. Conventional radiocarbon ages of samples of dendrochronologically dated wood from bristlecone pine *(Pinus aristata)*.

The technical procedure of the carbon-14 determination was the same as described previously [20]. All wood samples were treated with acetone, hydroxide, and acid solutions. Acetylene was used as counting gas in two completely independent counting systems. A total of some 50,000 counts from carbon-14 decay were observed from each sample; therefore, the statistical standard error is about .4 per cent, corresponding to an uncertainty equal to ±35 years. As is always necessary when results of great precision are required, the carbon-13 content of the counting gas was measured to correct for possible isotope fractionation effects in nature or in the laboratory. These mass spectrometric measurements were carried out in the laboratory of Dr. H. Craig. The δC^{13} values shown in Tables 1 and 2 denote deviations from a standard value close to the average δC^{13} for wood and taken as −25 per mil, relative to the Chicago PDB Standard. A deviation of one per mil in the C^{13} content requires a correction of the radiocarbon age of 16 years. The carbon-13 corrections are, in general, within the statistical errors of the carbon-14 measurement, but occasional deviations require corrections of the order of 100 years or more. Carbon-13 measurements are, therefore, necessary in all cases in which results with errors of less than 150 years are required.

Table 2 shows the measured carbon-14 activities relative to an average for wood samples from a fir grown in Oregon and dating from between 1875 and 1890. The conventional radiocarbon ages given in the table are calculated with the so-called Libby half-life of 5,568 years. They are corrected for carbon-13 variations. The year 1950 is taken as the standard year of reference.

The upper part of Figure 1 shows a calibration curve for conventional radiocarbon dates based upon the carbon-14 content of dendrochronologically dated bristlecone pine wood for the period between 4100 B.C. and 3600 B.C. The calibration curve published previously [6], for the period 900 A.D. to the present, was based upon dendrochronologically dated wood from European oak trees and upon some measurements of American *Sequoia gigantea*. The fact that the eight conventional radiocarbon ages obtained for the samples from the floating tree-ring chronology do not show the expected spread, but cluster closely around the same age value of 5050 years indicates that the carbon-14 level was decreasing during the period in which the trees grew, i. e. for about two hundred years. The investigated sequence demonstrates in an excellent way the advantages of measurements of a series of samples of known relative age. The radiocarbon measurements are sufficiently accurate and consistent to assign a standard error of less than 25 years to the calibration of the floating oak chronology relative to the bristlecone pine sequence. However, local differences of the carbon-14 level have been observed, in particular for trees grown in Europe and North America, reaching values of the order of 4 or 5 per mille. Such differences cause an additional uncertainty in the age of ±30 years, so that the standard error for the age of the timber from which Swiss Lake Dwellings were built can be estimated to be about 40 years.

The conventional radiocarbon dates, determined by the La Jolla Laboratory and shown in Table 1, are considerably higher than those obtained in 1960 by the Bern Laboratory. The difference might be due either to insufficient chemical treatment of the samples, or to an error in counter calibration at

[20] H. E. Suess, Science **120**, 5 [1954] and [1965], l. c.

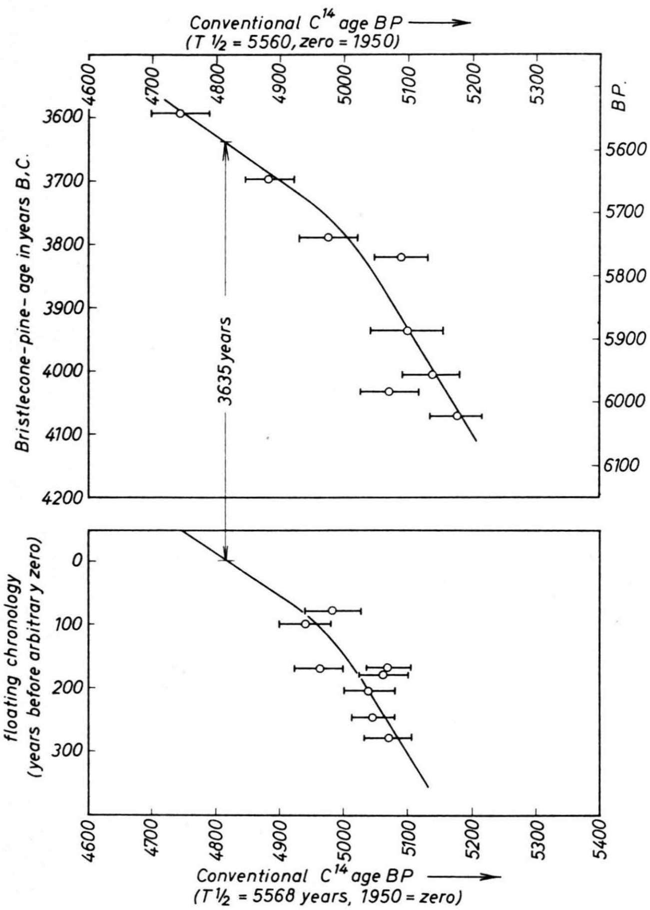

Fig. 1. *Upper portion:* Dendrochronologically determined age of wood plotted against its conventional radiocarbon age. *Lower portion:* The position of the samples from Thayngen (and one from Burgäschisee) within a floating tree-ring chronology plotted against their conventional radiocarbon ages. By comparison the zero of the arbitrary scale for the floating chronology is found to be 3670 B.C. Both parts of the figure show the same smooth line which indicates a calibration curve for the period 4100 to 3600 B.C. Future measurements may well lead to a less regular curve for this time range.

Bern [21]. The values are compatible, however, with two earlier measurements by Levi and Tauber [22] if the relatively large uncertainties of these early measurements are considered. The comparison with bristlecone pine wood increases the conventional carbon-14 age by an additional 800 years. Trees used for the construction of the Thayngen and Burgäschisee Settlements grew during the thirty-ninth und fortieth centuries B.C. The construction of the middle Thayngen Settlement was carried out around 3700 B.C. and that of the lower one occurred around 3760 B.C. These numbers have a standard error of about ± 40 years. This is about one thousand years earlier than had been previously concluded from radiocarbon measurements. According to Milojčić [23] the higher age of the Swiss Lake dwellings is in much better agreement with historical evidence, in particular with correlations between Middle European and Near East chronologies, than was the previously assumed age. A discussion of the great variety of implications of this tree-ring-calibrated radiocarbon date upon prehistorical and archaeological questions cannot be included in this note and will be given elsewhere.

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[21] C. Gfeller, H. Oeschger, and U. Schwarz, Bern Radiocarbon Dates II, Radiocarbon [1961].

[22] H. Levi and H. Tauber, Das Pfahlbauproblem, Verlag Birkhäuser, Basel 1955.

[23] V. Milojčić, Germania **35**, 102 [1957]; **36**, 409 [1958]; **39**, 434 [1961]; a further publication in press [1966].