VOL. 78, NO. 36 JOURNAL OF GEOPHYSICAL RESEARCH DECEMBER 20, 1973

7

Accuracy of Tree Ring Dating of Bristlecone Pine for Calibration of the Radiocarbon Time Scale

V. C. LaMarche, Jr., and T. P. Harlan

Laboratory of Tree-Ring Research, University of Arizona, Tucson, Arizona 85721

An independently developed tree ring chronology for bristlecone pine in the White Mountains, California, provides a basis for testing the accuracy of dendrochronological calibration of the radiocarbon time scale. Several lines of evidence show that the growth rings in this species are true annual rings. Internal evidence and cross-chronology comparison indicate that there is no error in calendar dates assigned to wood specimens for comparative radiocarbon analysis, at least back to 3535 B.C.

Large discrepancies have been found between radiocarbon and tree ring ages of wood from bristlecone pine (*Pinus longaeva* Bailey). These findings [*Olsson,* 1970] not only affect the interpretation of radiocarbon dates of geological and archaeological material but also have important geophysical implications. The dendrochronologically dated wood on which these results are based has come from the White Mountains of eastern California, where studies initiated by *Schulman* [1956, 1958; *Schulman and Ferguson,* 1956] and continued by *Ferguson* [1968, 1969, 1970*a*, *b*, *c*, 1972] have resulted in a painstakingly constructed annual tree ring chronology over 8200 years long. During a recent investigation in the White Mountains we had the opportunity to develop a long bristlecone pine chronology independently. In this report we evaluate some of the basic premises of dendrochronology and the potential sources of error in tree ring dates and test the reproducibility of tree ring dating methods as applied to bristlecone pine.

Study Area and Methods

This study is based on wood specimens from living trees, standing snags, logs, and weathered remnants from a limited area on Campito Mountain (Figure 1) in the southern White Mountains. Our main objective was to locate and date past levels of the upper tree line, which has retreated about 150 meters vertically within the past several thousand years [*LaMarche and Mooney,* 1967]. The tree ring dates for the wood indicate times of past tree line fluctuations, which may in turn be linked to climatic variations [*LaMarche,* 1973]. Subsample 1, which provides chronological control for the period A.D. 600 to A.D. 1971, is drawn from increment cores that were collected from all the living trees on the northwest slope of the mountain over a 3380-meter elevation. Although 40 trees were sampled, only 37 yielded tree ring records that could be incorporated into the chronology. A total of 81 series representing 75 radii was used. Subsample 2 consists of increment cores and cross sections collected from dead trees, logs, and remnants and was selected from a total sample of all wood remains in a transect extending from the present upper tree line to the summit of the mountain. The remains of 94 dead trees were identified in the transect, and wood from 70 trees was dated in whole or in part by tree ring methods [*Stokes and Smiley,* 1968]. From these, 118 ring width series representing 106 radii from 51 trees were measured and transformed to tree ring indices [*Fritts et al.,* 1969] for inclusion in the mean chronology (Figures 2 and 3). The final chronology contains 5403 annual values and begins about 3433 B.C. (as will be shown subsequently, the probable beginning date is 3435 B.C.). The last annual value is for A.D. 1970. Ring formation was not complete in all trees at the time of sampling in late August 1971, and therefore the width of the ring for 1971 was not measured.

Potential Sources of Error

Intraannual rings. The basic premises underlying tree ring dating of bristlecone pine are

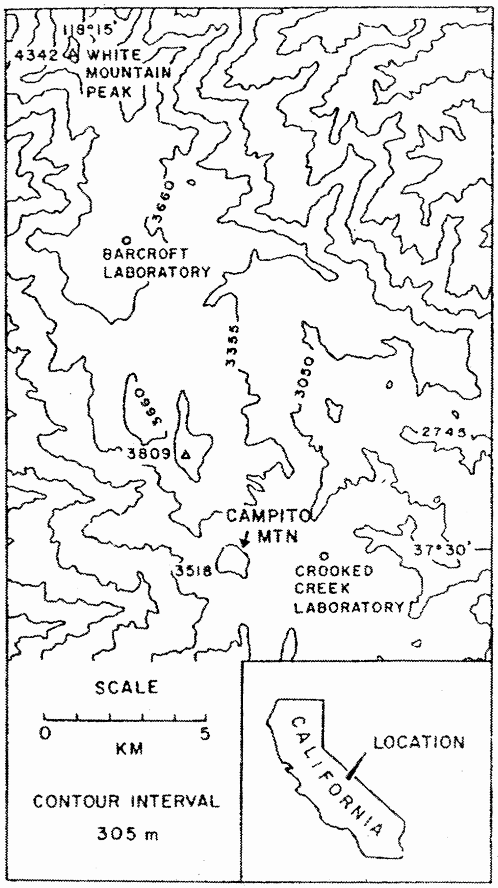

Fig. 1. Index map.

that each growth ring represents wood formed during a single calendar year and that no more than one ring is formed in any year. Some authorities have questioned the annual character of the growth ring in this species. For example, in referring to White Mountain bristlecone pines, *Mirov* [1967] writes that 'Apparently a semblance of annual rings is formed after every rather infrequent cloudburst.' *Libby* [1963] also suggested that the discrepancy between radiocarbon and tree ring ages of the oldest dendrochronologically dated bristlecone pine samples then available (about 3600 years old) might be explained by these trees' having added more than one ring per year. However, there are several lines of evidence showing that growth rings in bristlecone pines are true annual rings.

The growth rings of bristlecone pine do not resemble the 'false' rings found in some other species. Such intraannual growth bands, which could be misidentified and counted as annual rings, are generally seen to have diffuse or gradational boundaries upon close inspection under the microscope [*Glock*, 1937; *Glock et al.*, 1960; *Stokes and Smiley*, 1968]. The small, thick-walled cells of the false 'latewood' of one intraannual band are followed by progressively larger and thinner-walled cells that merge with the false 'earlywood' of the next band. In bristlecone pine the boundary between latewood of one ring and earlywood of the next is almost invariably sharp (Figure 4), with no evidence of gradation in cell size or wall thickness. The rare exceptions occur where extremely low average growth rates have produced sequences of rings only two or three cells in width. However, because growth rings are difficult to identify in such intervals, they are normally discarded for dating purposes and do not represent an important source of uncertainty in tree ring dates.

Further evidence of the nature of the growth ring comes from the study of ring development during the growing season. Dendrographic measurements of tree diameter and cambial samples for cell study were obtained from bristlecone pines in the White Mountains during three consecutive summers [*Fritts*, 1969]. Cambial activity and resultant ring growth were found to occur in a relatively brief and well-defined growing season. At the elevation of Fritts' study area (3100 meters), ring growth began in mid-June to late June and ended in late July or early August. Cell size decreased more or less regularly from the beginning to the end of the growing season, and there was no pronounced response to the soil moisture replenishment that resulted from a midseason storm during one of the summers. That is, the trees studied formed only one growth ring in each year and did not form intraannual bands, even under presumably favorable conditions.

Another argument for the annual character of growth rings in bristlecone pine depends on recognition of time-synchronous internal markers in growth ring sequences. These include 'critical' rings, which are much narrower than average, and frost damage zones within certain rings. The identification and matching of growth rings constitute a well-established technique known as cross dating. Introduced by A. E. Douglass in the early 1900's [*Douglass*, 1914],

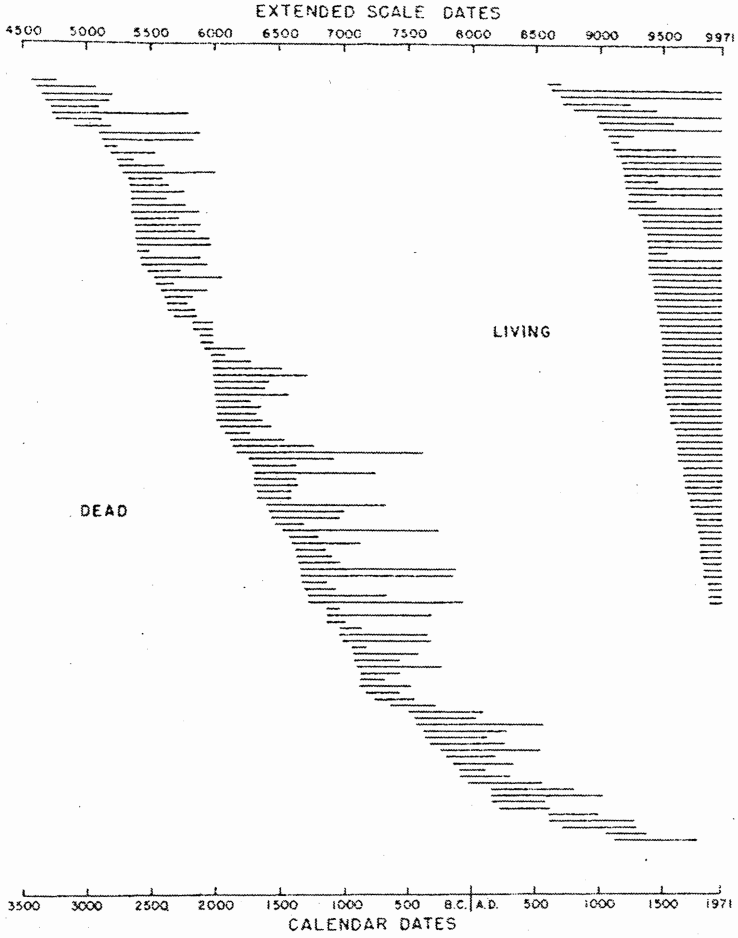

Fig. 2. Time spans of tree ring index series included in Campito chronology.

it has since been applied to the dating of a large number of tree ring specimens. Comparison of tree ring sequences obtained from living trees in the same area in different years gives a measure of the number of rings formed per year, provided that the sequences can be cross-dated. In a sample obtained during the growing season the outermost ring will be incomplete and must therefore have been formed during the current calendar year. Regardless of the time of sampling the outermost complete ring will normally have been formed in the previous growing season. Thus the calendar year date of at least the outermost ring in a sequence is known exactly, regardless of assumptions about the annual or nonannual nature of the growth rings. *Schulman* [1956] collected bristlecone pine samples in 1954 and presented ring width measurements for dated series ending in 1953. Plotted ring width measurements from samples obtained in 1971 can easily be matched with Schulman's series, the indication being that most trees have formed exactly 18 rings in the period 1954–1971. In a few cases only 17 rings were formed, this result being attributable to the local absence of the ring for 1960 on some of the sampled radii. However, in no case has any of the sampled trees formed more than one ring per year since 1953.

Frost damage zones (frost rings) provide a time-equivalent internal marker that can also be used for relative dating of tree ring sequences [*Bailey*, 1925] and, in some circumstances, for absolute dating of growth layers [*Glock*, 1951; *Glock et al.*, 1960]. Frost damage is caused by the occurrence of temperatures well below

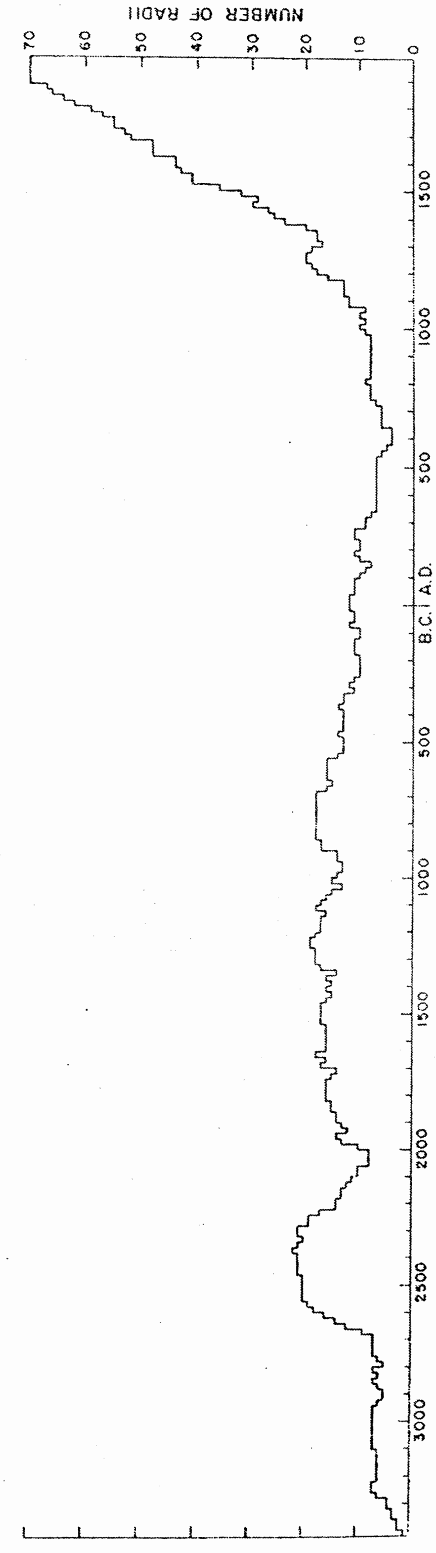

Fig. 3. Number of radii represented in the Campito chronology.

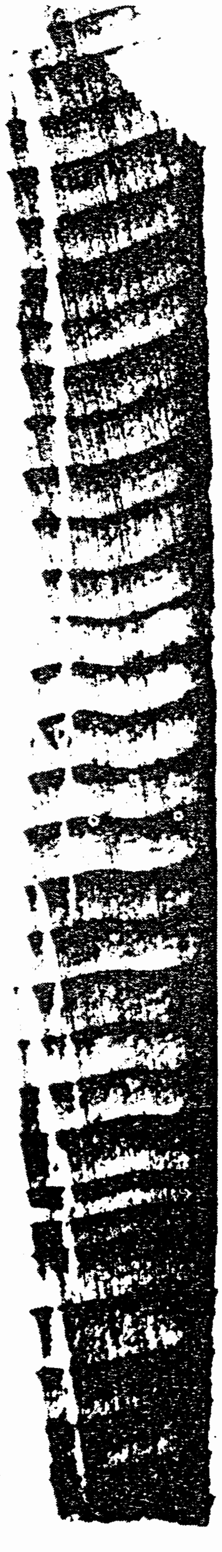

Fig. 4. Ring structure in bristlecone pine, print of X radiograph.

freezing at some time during the growing season. Under such conditions, extracellular ice formation causes dehydration and physical disruption of immature xylem cells, leaving a permanent record in the wood [*Glerum and Farrar*, 1966]. In bristlecone pines, frost rings are virtually restricted to upper-elevation trees and occur more frequently in young trees than in old ones [*LaMarche*, 1970].

The circumstances leading to late-season frost damage in bristlecone pine are illustrated by the events in autumn 1965, when extensive frost damage occurred in trees in the Snake Range in Nevada [*LaMarche*, 1970]. This date is well documented because increment cores were obtained in this area in the summers of both 1965 and 1966 and show that damage occurred after mid-August but prior to the end of the growing season in 1965. Temperatures throughout the period May–September 1965 were much below normal, probably delaying the completion of cambial activity and xylem cell maturation by several weeks. A record cold spell occurred on September 17–19, when the trees were still susceptible to frost damage because of the delayed growing season. The temperatures required to produce frost damage are not excessively low. *Glock* [1951] found that two successive nights with minimums of −5° and −2°C, respectively, and temperatures just above freezing during the intervening day were sufficient to produce frost damage in trees of several different species near Lubbock, Texas. In bristlecone pine the prolongation of the growing season into early autumn, when subfreezing temperatures are likely to occur, seems most important as a contributing factor.

Frost rings were studied in increment cores obtained in 1971 from living trees on Campito Mountain (subsample 1). Cores from nine trees showed no frost damage, but at least one frost ring occurred in each of 45 cores from the remaining 31 trees. A count was made of the number of growth rings in each core, back to and including the ring containing the first frost zone encountered. In all but four cases the first evidence of frost damage occurs in the eighty-fifth to eighty-eighth ring, the eighty-eighth ring containing the frost zone in 26 of the cases. Because of the low average frequency of occurrence of frost rings, this concentration in the eighty-eighth ring is unlikely to have resulted by chance. Rather it must reflect the occurrence of an unusual sequence of meteorological events that caused the simultaneous freezing of the stems of a large number of bristlecone pines at a time when they were susceptible to frost damage. Because only the outer part of the ring was affected, freezing must have occurred in late summer or in early autumn.

If the growth rings in bristlecone pine are annual rings, then a simple count shows that an eighty-eighth ring prior to 1971 would have formed in 1884. Weather records [*U.S. War Department*, 1884] show that the summer of 1884 was unusually cool in the western United States. June temperatures were below normal and were associated with unseasonally heavy rain in northern California. July was noted as 'remarkably cool' in this region, and 'notably low mean temperatures' were also recorded in August. September was particularly cold in the Great Basin, with Salt Lake City, Utah, reporting a monthly mean temperature about 3°C below normal. A cold wave that could have caused freezing of high-altitude bristlecone pines occurred in early September, associated with a high-pressure area extending from California to Manitoba. Red Bluff, California (elevation 104 meters, 440 km northwest of the White Mountains) registered a minimum of 18°C, the low for the month, on September 9. The lowest minimum for September 1884 at Salt Lake City, Utah (elevation 1281 meters, 645 km northeast) was 3°C on September 10. It seems safe to assume that minimum temperatures at the upper tree line in Nevada and eastern California were well below freezing during this period. Although it cannot be demonstrated conclusively that the frost damage in the eighty-eighth ring prior to 1971 did in fact take place in 1884, it is clear that antecedent conditions were highly favorable to such damage and that a cold wave did occur in early September of that year. The phenomenon was of wide geographic extent, since frost rings in bristlecone pines in the Snake Range have also been dated to 1884.

The annual nature of the growth rings in bristlecone pine is thus indicated by their structure by observations of ring growth, by comparison of ring sequences in samples obtained in different years, and by the probable correspondence of frost damage zones with known meteorological events. Although the annual character is demonstrable with certainty only for the last few decades, the growth rings of the oldest wood studied in this work do not differ qualitatively from those forming at the present time. Therefore the basic premises that each ring represents a 1-year growth and that no more than one ring is formed in any given year appear correct.

Locally absent rings. In years of severe environmental stress the cambium may fail to lay down a growth ring over part of the circumference of a tree. Seen in cross section, such rings 'wedge out' in the tangential direction, and the rings of the preceding and following years come into direct contact. The ring will thus be absent from an increment core taken at this location. The local absence of the ring for a particular year in the sample is usually indicated by cross dating with other samples that do contain a ring for that year. In this case the sequence from which the ring is absent will contain one too few rings in comparison with other sequences. The exact position in which the ring should be located can often be determined because the ring will usually be much narrower than average in the specimens in which it does occur. However, locally absent rings do represent a potential source of error in tree ring dating because of the possibility that the ring for a particular year may not appear in any of the samples covering that time period. In this case the master chronology will be in error by 1 year. Because chronology building normally proceeds from the present into the past, frequent occurrence of such unaccounted for annual rings could produce serious underestimation of the true calendar age of a wood specimen in the early part of the time range covered by a chronology. To evaluate this source of error, an analysis was made of the frequency of occurrence of locally absent rings in the Campito Mountain sample. A ring was locally absent from one or more of the sampled radii in 164 of the 5403 years represented in the chronology. In each of these 164 years the number of radii from which the ring was locally absent was expressed as a percentage of the total number of radii included in the chronology for that year. The percentages were tallied by 10% frequency classes and plotted as a function of the number of occurrences (Figure 5). There is an approximately linear inverse relationship between the percentage of radii from which a ring for a given year is locally absent and the logarithm of the number of occurrences of such years. In 95 of the years a ring was absent in about 5% of the radii, but only in 1 year was a ring absent from as many as 65% of the radii. Simple extrapolation suggests that absence of an annual ring from all the sample radii would occur less than once in 5400 years. However, this projection may be too optimistic, since the probability of missing a ring entirely depends heavily on sample size. For example, if we assume that locally absent rings are randomly distributed among radii in any particular year and that the average frequency in the population is, say, 0.35, then the probability of the ring being absent from all of 10 randomly selected radii is 0.35^{10} (about 0.00003). But, if only two radii were sampled, the chance of the ring being absent from both would be 0.3^2 or about 0.1. Even though the rate of occurrence of years in which rings are locally absent for as many as 35% of the radii is very low (four occurrences in 5403 years), there is a possibility of a few annual rings being unaccounted for in the chronology, particularly in the earliest period, for which the sample size is relatively small (Figure 4). However, if the relationship shown in Figure 5 is even approximately valid, the error in the chronology for this source can only be of the order of 1 year.

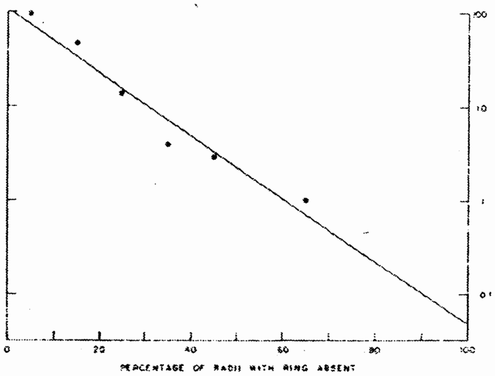

Fig. 5. Frequency of locally absent rings in the Campito sample.

Cross dating error. Large dating errors could occur when a long tree ring chronology is developed through the cross dating of overlapping series that are relatively short. For example, two series, each 1000 years long and representing the same time period, could conceivably be mismatched in such a way as to result in an erroneous 'chronology' nearly 2000 years long. Such gross errors are most unlikely to have occurred in the development of the Campito Mountain chronology. The manner in which the component series are overlapped is shown in Figure 2. Throughout most of the time period there is a regular progressive increase in ages of the earliest rings and a substantial degree of overlap with other series. There is only one discontinuity of the sort that would be expected to occur in this diagram if a major transposition and duplication had been made. The cause is not a gross dating error but rather the occurrence of severe frost damage. This unique event, which is dated at 2035 B.C., caused the complete disruption of the physical continuity of the wood in the radial direction in nearly all the specimens. As a result, specimens fall apart along this surface, which has also been an avenue for weathering and decay. Most measured ring width series thus end a few years prior to 2035 B.C. and are continued a few years afterward. The fact that this traumatic frost damage is not repeated anywhere in the record strongly supports the conclusion that no gross duplications have been made that would result in large chronology errors and that might yield erroneous tree ring ages substantially greater than the true age of the wood.

Chronology Comparison

An important test of the reproducibility of tree ring dating methods is provided by comparison of two independently constructed chronologies for bristlecone pine. One is the Methuselah chronology, which has been the standard used in dating wood samples for comparative radiocarbon analysis. It is based largely on wood samples from the relatively low elevation Methuselah Walk area, about 10 miles south of the Campito Mountain study site described in this paper. The 7104-year segment of the Methuselah chronology, published by *Ferguson* [1969] will serve as a basis for comparison with the 5403-year Campito chronology. The dates referred to here will be in the extended time scale, adopted for convenience in data processing, in which 8001 equals A.D. 1 and 8000 equals 1 B.C. The suffix M designates Methuselah chronology dates, and C designates Campito chronology dates.

The Campito chronology contains 5403 annual values beginning in 4568 C (about 3433 B.C.) and ending in 9970 C (A.D. 1970). Cross dating shows that 4568 C represents the same annual ring as 4566 M. Thus the Methuselah chronology contains two more annual values than the Campito chronology does between 4566 M and 9962 M (A.D. 1962, the date of the last ring represented in the published Methuselah series). There appear to be no years for which a ring is present in the Campito chronology but absent from the Methuselah chronology. Thus the discrepancy seems to be explained by the absence of annual rings for 2 calendar years in all the Campito samples, rings that are present in at least some of the Methuselah samples. Year-by-year comparison indicates that the rings dated at 5859 M and 5320 M are absent from the Campito chronology. Insertion of a nominal value of '0' for the ring width index for each of these years (Figure 6) brings the chronologies into exact synchrony. The error of 2 years due to locally absent rings is in excellent agreement with the estimated error of about 1 year on the basis of the evaluation of the frequency of locally absent rings within the Campito sample.

Cross dating of the two chronologies can be demonstrated objectively by means of cross-correlation analysis. Low-frequency variations in both series were first removed by using a high-pass digital filter containing 13 weights, which has a 50% response at a frequency of 1/10 years. The published Methuselah series [*Ferguson*, 1969] represents similarly filtered tree ring indices. Such 'prewhitening' is recommended [*Jenkins and Watts*, 1968] when a test of nonzero correlation between two time series is required. Linear product-moment cross-correlation coefficients were computed for 100-year subperiods beginning with the subperiod centered at 4700 M. The analysis was first carried out by using the dates originally assigned to the Campito chronology. The resulting coefficients (Figure 7) are negative or have low positive values prior to the most recent sub-

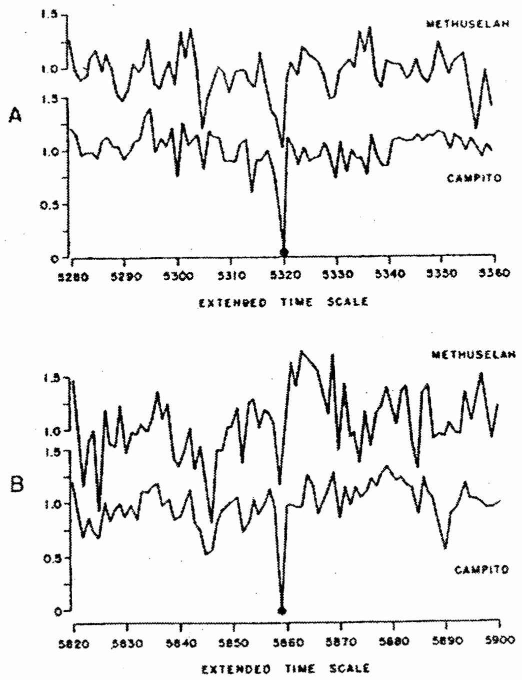

Fig. 6. Plots of Methuselah and Campito indices showing insertion of zero value (circled) for years in which the ring is totally absent from the Campito sample.

period (5850 M to 5949 M) from which a ring is missing from the Campito chronology (5859 M). All subsequent coefficients are positive and greatly exceed the values expected for samples drawn from a population in which the true cross-correlation coefficient is zero. Thus the chronologies are significantly correlated after 5859 M but are clearly mismatched prior to that date. When the Campito dates are adjusted by insertion of the two 'missing' rings, the cross-correlation coefficients for the entire period are positive and highly significant (Figure 7). Correlation analysis thus verifies the adjustments made in the Campito chronology on the basis of visual comparison of the plotted series of tree ring indices.

The nearly perfect agreement between two independently developed chronologies shows that dendrochronological techniques give highly reproducible results upon their application to bristlecone pine. This agreement is further evidence that gross cross dating errors have not been made in the development of either of the two chronologies.

Uncertainty in Tree Ring Dates

The calendar dates assigned to annual rings of trees have traditionally been given in absolute terms with no explicit recognition of any uncertainty in the date. The reasoning is [*Douglass*, 1946] that, if cross dating is carefully done and if a large number of tree ring specimens are studied, the possible error is nil. This may not strictly apply in the present case because of the relatively small sample sizes involved and the unusually great length

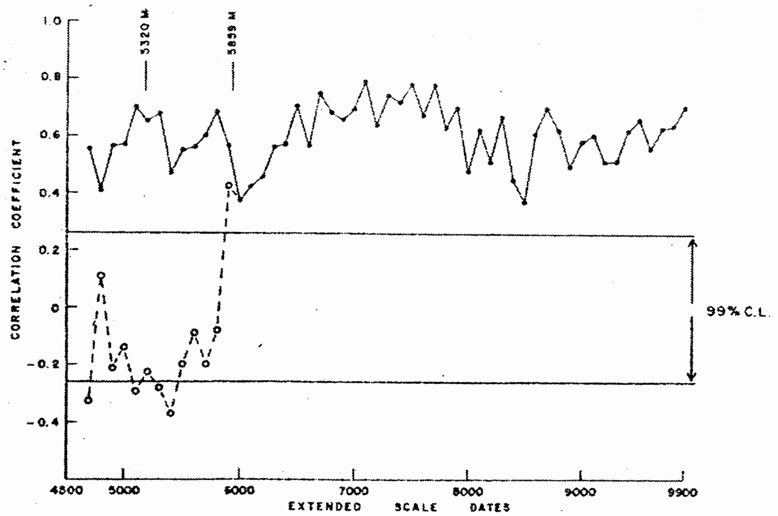

Fig. 7. Correlation coefficients between Campito and Methuselah chronologies before (open circles) and after (closed circles) insertion of missing rings in Campito chronology.

of the bristlecone pine chronologies. One approach to estimating the uncertainty of tree ring dates assigned to annual rings of White Mountain bristlecone pine is to consider the dates assigned by the two chronologies to the same annual ring as repeated observations of the same quantity. Thus the first annual ring represented in the Campito chronology would be assigned a date of 3433 B.C. according to the Campito chronology but a date of 3435 B.C. according to the Methuselah chronology. Thus it has a mean date of 3434 B.C. ± 1.4 years, in which the uncertainty is expressed as plus or minus one standard deviation. However, this assumes that additive and subtractive errors are equally probable. In fact, the incidence of false rings that might erroneously increase the age is so small as to preclude explicit evaluation. The only important potential source of error seems to be locally absent rings. On the basis of the close agreement of the estimated number of rings absent from the Campito chronology with the observed discrepancy between the Campito and the Methuselah chronologies, it is highly probable that the absolute error of the Methuselah chronology at 3435 B.C. is, in fact, zero.

Summary and Conclusions

A long tree ring chronology for bristlecone pine has been developed independently of previous work. Several lines of evidence show that the growth rings are true annual rings. Evaluation of several potential sources of error in tree ring dates indicates that any uncertainty in calendar dates assigned to annual rings in this series is due to annual rings that may be absent from all samples for a particular year or years. Internal evidence and intrachronology comparison suggest that there are only two such occurrences in the 5403-year Campito record developed in this work. Annual rings for these years are represented in the Methuselah chronology, which has served as the standard for most radiocarbon calibration studies. The Methuselah chronology very probably contains no dating error, at least back to 3435 B.C.

Tree ring dates for bristlecone pine are accurate and are reproducible with high precision. Therefore the large discrepancies observed between dendrochronological and radiocarbon ages of bristlecone pine wood samples, especially prior to about 2000 B.C., cannot be explained by major systematic errors in tree ring dating.

Acknowledgments. This research was carried out under U.S. Atomic Energy Commission contract AT 11-1 (2056) and National Science Foundation grant GA-4128. The facilities of the University of Arizona Computer Center were used in the data analysis. We gratefully acknowledge the cooperation of C. W. Ferguson, who supplied previously unpublished tree ring indices used in Figure 6.

References

Bailey, I. W., The 'spruce budworm' biocoenose, 1, Frost rings as indicators of the chronology of specific biological events, *Bot. Gaz. 80*(1), 93–101, 1925.

Douglass, A. E., A method of estimating rainfall by the growth of trees, in *The Climatic Factor as Illustrated in Arid America, Carnegie Inst. Wash. Publ. 192,* edited by E. Huntington, pp. 101–138, Carnegie Institute of Washington, Washington, D.C., 1914.

Douglass, A. E., Precision of ring dating in tree-ring chronologies, *Univ. Ariz. Bull., 17*(3), 5–21, 1946.

Ferguson, C. W., Bristlecone pine: Science and esthetics, *Science, 159,* 839–846, 1968.

Ferguson, C. W., A 7104-year annual tree-ring chronology for bristlecone pine, *Pinus aristata,* from the White Mountains, California, *Tree-Ring Bull., 29,* 1–29, 1969.

Ferguson, C. W., Aspects of research on bristlecone pine, in *The Ancient Bristlecone Pine Forest,* edited by R. Johnson and A. Johnson, pp. 47–51, Chalfant Press, Bishop, Calif., 1970*a*.

Ferguson, C. W., Dendrochronology of bristlecone pine, *Pinus aristata*: Establishment of a 7484-year chronology in the White Mountains of east-central California, U.S.A., in *Radiocarbon Variations and Absolute Chronology,* edited by I. U. Olsson, pp. 237–259, Almquist and Wiksell, Stockholm, 1970*b*.

Ferguson, C. W., Bristlecone pine chronology and calibration of the radiocarbon time scale, in *Tree-Ring Analysis with Special Reference to Northwest America, Forest. Bull. 7,* edited by J. H. G. Smith and J. Worrall, pp. 88–91, University of British Columbia, Vancouver, B. C., 1970*c*.

Ferguson, C. W., Dendrochronology of bristlecone pine prior to 4000 B.C., *Proceedings of the 8th International Conference on Radiocarbon Dating,* edited by T. A. Rafter and T. L. Grant-Taylor, pp. A1–A10, R&D Associates, Santa Monica, Calif., 1972.

Fritts, H. C., *Bristlecone Pine in the White Mountains of California: Growth and Ring-Width Characteristics,* vol. 4, pp. 13–18, University of Arizona Press, Tucson, 1969.

Fritts, H. C., J. E. Mosimann, and C. P. Bottorff, A revised computer program for standardizing tree-ring series, *Tree-Ring Bull., 29,* 15–20, 1969.

Glerum, C., and J. L. Farrar, Frost ring formation in the stems of some coniferous species, *Can. J. Bot., 44,* 879–886, 1966.

Glock, W. S., Principles and methods of tree-ring analysis, *Carnegie Inst. Wash. Publ. 486,* 1937.

Glock, W. S., Cambial frost injuries and multiple growth layers at Lubbock, Texas, *Ecology, 32* (1), 28–36, 1951.

Glock, W. S., R. A. Stuhalter, and S. R. Agerter, Classification and multiplicity of growth layers in the branches of trees (at the extreme lower forest border), *Smithson. Misc. Collect., 140*(1), 1960.

Jenkins, G. M., and G. D. Watts, *Spectral Analysis and Its Applications,* p. 340, Holden-Day, San Francisco, Calif., 1968.

La Marche, V. C., Jr., Frost-damage rings in subalpine conifers and their application to tree-ring dating problems, in *Tree-Ring Analysis with Special Reference to Northwest America, Forest. Bull. 7,* edited by J. H. G. Smith and J. Worrall, pp. 99–100, University of British Columbia, Vancouver, B. C., 1970.

LaMarche, V. C., Jr., Holocene climatic variations inferred from treeline fluctuations in the White Mountains, California, *Quarternary Res., 3*(4), 1973.

LaMarche, V. C., Jr., and H. A. Mooney, Altithermal timberline advance in western United States, *Nature, 213*(5080), 980–982, 1967.

Libby, W. F., Accuracy of radiocarbon dates, *Science, 140,* 278–280, 1963.

Mirov, N. T., *The Genus Pinus,* p. 146, Ronald Press, New York, 1967.

Olsson, I. U. (Ed.), *Radiocarbon Variations and Absolute Chronology,* pp. 233–337, Almquist and Wiksell, Stockholm, 1970.

Schulman, E. (Ed.), *Dendroclimatic Changes in Semiarid America,* p. 12, University of Arizona Press, Tucson, 1956.

Schulman, E., Bristlecone pine, oldest known living thing, *Nat. Geogr. Mag., 113*(3), 355–372, 1958.

Schulman, E., and C. W. Ferguson, Millenia-old pine trees sampled in 1954 and 1955, in *Dendroclimatic Changes in Semiarid America,* edited by E. Schulman, pp. 136–138, University of Arizona Press, Tucson, 1956.

Stokes, M. A., and T. L. Smiley, *An Introduction to Tree-Ring Dating,* University of Chicago Press, Chicago, Ill., 1968.

U.S. War Department, Signal Office, *Mon. Weather Rev., 12,* 1884.

(Received June 8, 1973;
revised August 27, 1973.)