DENDROCHRONOLOGY OF BRISTLECONE PINE

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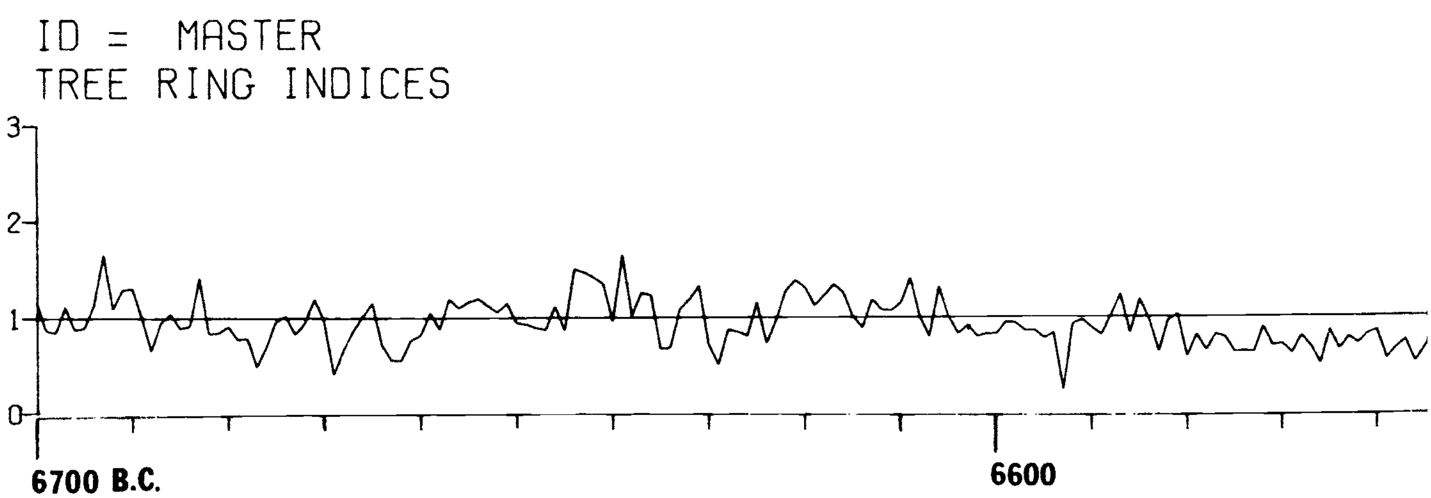

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C. W. Ferguson and D. A. Graybill

Introduction

Since Edmund Schulman's initial interest in 1953, the Laboratory of Tree-Ring Research has conducted dendrochronological studies of bristlecone pine (*Pinus longaeva* D. K. Bailey, sp, nov.) in the White Mountains of east-central California where living trees reach ages in excess of 4,000 years. Sponsorship by the National Science Foundation began in 1956 and continued through grants in 1961, 1962, 1965, 1969, 1976 to the one in 1978. In this report, we are summarizing the project status as of October, 1981, incorporating data secured under the 1978 grant.

The primary objectives of the project were:

(1) To extend and strengthen the 8253-year bristlecone pine tree-ring chronology from the White Mountains of California.

(2) To furnish dendrochronologically dated wood to researchers engaged in the study of past variations in carbon isotope ratios and climate.

(3) To develop bristlecone pine chronologies in new areas.

(4) To develop computerized files and appropriate software for storage, retrieval and analysis of most bristlecone pine data.

(5) To evaluate all ring-width series from the Methuselah Walk site for potential inclusion in a master chronology used for dating purposes and for potential inclusion in a chronology used for climatic reconstruction.

Substantial progress was made in meeting each of the objectives. The White Mountain bristlecone pine chronology was extended from 6278 to 6700 B.C. Collection of large amounts of bulk wood covering most of that chronology will permit extensive new research on past variability in carbon isotopes.

Several new chronologies were developed in the Great Basin. One site appears to have a potential chronology length of almost 5500 years and could provide extensive material for isotopic analysis. Three other sites have the potential of each providing about 2000 years of bristlecone pine chronology.

Most of our data in the laboratory are now computerized. Numerous programs have been written for a variety of data management and analytical applications. These procedures facilitate the process of evaluating ring-width data to be used in a revised crossdating chronology and in the development of a climatic chronology for the White Mountains of California.

Isotopic Relationships

Field work during 1978-1981 led to the collection of about 600 kg of bulk wood. Some has been processed for specific projects described below and the remainder is stockpiled in anticipation of future requests.

A substantial amount of processed wood has also accumulated in the laboratory as a result of overages that occurred. These units, normally ten years, weigh from a few to about 100 grams and span the past 7500 years. These samples are available to qualified investigators. Table 1 summarizes this material by millennia (Ferguson 1979). A detailed inventory of each piece is available upon request.

TABLE 1. Dated samples available for isotopic analysis.

Interval		Number of Samples	Grams
A.D. 1974-1001		85	1931
A.D. 1000-1		75	1160
1-1000 B.C.		147	1079
1001-2000 B.C.		115	1121
2001-3000 B.C.		304	4270
3001-4000 B.C.		264	3916
4001-5000 B.C.		128	2192
5001-5500 B.C.		20	89
	Total	1138	15758

Radiocarbon Studies

Dendrochronologically dated 10-year samples submitted to various radiocarbon laboratories have been used in the calibration of the C-14 time scale. The major objective of the workshop on the calibration of the radiocarbon time scale, held in Tucson January 28 to February 2, 1979 (Klein, et al. 1980) was the ultimate publication of a cooperative calibration project, incorporating results derived from dendrochronologically dated wood back to 5400 B.C. This will include 1132 samples provided by the bristlecone pine project (250 analyzed at the University of Arizona; 252 at the University of Pennsylvania; and 630 at the University of California, San Diego). The samples were primarily 10-year units, some were 4-year units, and a few were 20-year units.

At the workshop, an agreement was reached (by the radiocarbon laboratories at the universities of Arizona, California, Pennsylvania, and Washington) to publish an inter-laboratory collaboration on the calibration for the period 6000 to 5400 B.C. This study is still incomplete due in part to extended down time for two of the four collaborating laboratories and a request from one laboratory for samples of greater weight. Since the analysis of this time interval was proposed, the quality and quantity of wood has increased; thus the increased gram weight requirements, rendering unusable the initially prepared samples, can be met only by the complete preparation of the total time span from a new and more open specimen.

Dated decade samples continue to be sent to various radiocarbon laboratories. Current cooperative work will extend the calibration to 6000 B.C., and wood is now being prepared which will extend it to 6600 B.C. Individual laboratories are investigating anomalies in specific periods and the relationships of early European tree-ring chronologies to dendrochronologically dated bristlecone pine wood.

Consecutive 40-gram decade samples were provided to the C-14 laboratory at the University of Arizona for detailed studies of two 200-year intervals. A similar series is being prepared for the 600-year period from 6000 back to 6600 B.C., the present limit of available wood (only a token amount of wood carries the chronology back to 6700 B.C.)

The singleleaf pinyon, *Pinus monophylla*, occasionally has very open rings and from one specimen dating 1000-600 B.C., 40-gram decade samples are being prepared for study at the universities of Arizona and Washington. This will put a second species into the calibration for the B.C. period and will serve as a verification-comparison for the bristlecone pine.

Isotopic Ratios

Dated sections for Minze Stuiver's study of isotopic ratios at the University of Washington are being processed and sent to him. To provide the maximum continuity, the series from the present back to 6600 B.C. will be based upon only four specimens:

Specimen	Interval
79-68	A.D. 1953 - 200
63-43	A.D. 975 - 2200 B.C.
H-79-26	2000 - 6100 B.C.
79-138	5900 - 6600 B.C.

Currently, we are completing preparation of the second specimen, which extends to about 2200 B.C. The third specimen contains a 4000-year series from a tree that died about 2000 B.C. and will provide an adequate overlap with the adjacent specimens. The fourth and last specimen will carry the study to 6600 B.C., the present limit of the dated wood that can be used in destructive analysis.

Tandem Accelerator Mass Spectrometer

The tandem accelerator mass spectrometer (TAMS) C-14 dating facility, operated jointly by the departments of geosciences and physics (N.S.F. grant CHE78-18576), was delivered to the University of Arizona in September, 1981. Tests are anticipated by January, 1982, and dendrochronologically dated samples will be provided for the calibration of the instrument. Samples of unknown age will progressively be integrated into the testing program to aid in the detection of material to extend the chronology. As the TAMS instrument becomes more functional, an increasing number of unknowns will be submitted, perhaps 50 or 100 a year, in an effort to identify specimens of great age that would make possible the extension of the chronology.

The bristlecone pine project will provide duplicate samples at 1000-year intervals back to 5000 B.C. to the Oxford group (Donahue, personal conversation, 22 Oct. 81; Gillespie, personal corres., 14 Oct. 81) so that a direct inter-laboratory comparison can be made between the TAMS C-14 dating facilities at the University of Arizona and at Oxford.

Chronology development - White Mountains, California

Field work devoted to chronology development resulted in the collection of 381 specimens. Nearly 65 percent of these were exploratory samples taken in attempts to extend the chronology. The remainder were cores from living trees used to update the modern portion of the chronology. Most of the data has been fully processed.

On hand from the 1981 collections in the White Mountains are approximately 25 undated exploratory samples. These have been surfaced and visually examined and will be measured and plotted as time permits. Those that cannot easily be dendrochronologically dated because of tightness of the ring sequence or other problems or because they are earlier than the master chronology will be submitted for "quickie" C-14 dating (Michael and Ralph, 1981). Each of the samples represents only a portion of the bulk material. Should a C-14 date indicate an early specimen, a more complete collection would be made. The two specimens most recently tree-ring dated were ca. 5300 and 6200 B.C., providing some hope that others may be in the same or earlier time range. The earlier of these two represents a large remnant that will not be collected en toto until the summer of 1982. This sequence of collecting and re-collecting illustrates the value of a continuing program.

Chronology extension

Prior to the onset of funding for the current grant, the chronology reached 6278 B.C. The discovery of one specimen (TRL #79-138) extended the continuous chronology to 6700 B.C. In addition, the specimen depth prior to 4000 B.C. has gone from 69 to 95, an increase of 38%. The number of dated specimens prior to 4000, 5000, and 6000 B.C. is shown in Table 2. Parallel with this numerical increase is the opportunity, through selection, to improve the quality of the resultant master chronology.

Since 1967, we have had in hand a 500-year series dated by four radiocarbon laboratories as being between 9,000 and 10,000 years B.P. There is a gap of a few centuries between the present limit of the chronology and this "floating" sequence. An obvious goal is to cross this gap and have a chronology nearly 10,000 years in length.

TABLE 2. The number of specimens predating 4000, 5000, and 6000 B.C.

	Dec. 1978	Dec. 1979	Oct. 1981
Pre-4000 B.C.	24	32	47
Pre-5000 B.C.	14	27	35
Pre-6000 B.C.	3	10	13
Total	41	69	95

Chronology Development

One project objective was to strengthen the chronology in terms of the number and quality of ring-width series that it contained. Another objective was to determine which series might be used in climatic reconstruction. A major laboratory effort was made to evaluate more than 400 measured ring-width series for those purposes. A computerized data storage and retrieval system was developed for all ring-widths that had been keypunched through the history of the bristlecone project. Approximately 200,000 cards were converted to disk or tape files. Substantial software was developed for data manipulation and analysis.

The broader rationale for some of the analyses described here can be found in Fritts (1976) while some of the terminology, specific procedures, and software are from Graybill (1979a, 1979b, no date a). Descriptively, it is useful to conceive of tree-ring chronologies as time series with certain frequency domain properties. This domain is composed of four different kinds of signals that are recognizable and are germane to the goals of analysis. For any individual specimen let

$R_t = C + B + D + E$

where R_t = the measured ring width in year t

C = the macro-climatic signal common to trees at a site

B = the biological growth curve that is a function of increasing tree age

D = the tree disturbance signal that may be:

1. Unique to a single specimen or tree due to random events that affected its growth.
2. Common to most or all specimens due to fire, insect damage, etc. that affected an entire site.

E = the random growth signal unique to each specimen

In the development of a dating or a climatic chronology it is necessary to recognize and remove or control the B, D and E signals. Failure to do so would obscure the climatic signal at most frequencies, including short term variation of 1-2 years that is important for crossdating purposes.

Recognition of the presence and form of biological growth trends was accomplished by visual inspection of a plot of 20-year averages shifted by 10-year increments for each series. Consideration of the tree disturbance signal, D1, was accomplished by comparison of the running mean plots for all specimens covering any particular time period. Occurrence of this signal is shown by a surge or depression in growth in one series that is not apparent in others. The second type of tree disturbance signal, D2, is more commonly found in dense stands or mesic sites and is not considered a problem with the bristlecone in the White Mountain area.

Either part or all of series that exhibited the D1 disturbance signal was removed from further consideration. Two data files were then developed: one for the dating chronology and one for use in climatic reconstruction.

Crossdating chronology

Eighty of the 375 series in the file exhibited biological growth trend. This was removed from each series by fitting an appropriate line and converting the ring-widths to indices. In all cases either a negative exponential or a straight line that took the slope of the apparent trend was used. The remaining series were fit with a straight line through the mean. The conversion of ring-widths to indices has the effect of scaling the mean of each series to about 1.0 and distributing the variance more uniformly through each series (Fritts 1976).

The annual indices of each specimen were then plotted with the aid of Calcomp graphic routines. These plots were used for final independent visual checks on the crossdating of each series against the current master chronology by at least two different members of the project.

One further attempt was made to ascertain the representativeness and quality of each series for the time period that it spanned. Given the period defined by a series length, a variety of descriptive statistics were computed both for that series and for the average of all others falling partially or wholly in the same period. The statistics included mean index value, standard deviation, mean sensitivity, first order autocorrelation, simple correlation between a single series and the average of others and the significanve level of that coefficient corrected for autocorrelation effects. Evaluation of these figures led to the removal of 12 series that exhibited relatively low mean sensitivity of less than .20 or relatively low correlation with the averaged series of less than .30. Initially it was suspected that series with such low correlations might contain dating errors, but this was not the case. Inspection of each original ring-width series indicated that mean ring width was very small (ca. .08-.10 mm) and there was almost no high frequency variance in the 2-8 year range.

The sample depth for the Methuselah Walk master chronology averages about 25, with maximum of 45. Prior to 6000 B.C., the sample depth per year drops to below 15. In the period from 944 to 1290 B.C., the numbers dropped below 15, probably because this interval represented the transition from core sampling to the collection of bulk material from remnants. To improve the specimen depth in this interval, a concerted attempt was made during the 1981 field season to collect additional series in the 1000 B.C. time period. Twelve new specimens are being processed and will be added to the data base.

Final processing of the new master chronology will include the addition of the 12 series noted above as well as other usable material from the 1981 field season. It is estimated that about 300-325 series will be used. Given the rigorous evaluation and selection and the large number of series available, the final averaging process should adequately minimize the random growth signal (E) described earlier. A more detailed description of the chronology characteristics and the final chronology will be published during the next year (Ferguson, Graybill and Burns, manuscript).

Climatic Chronology

The purpose of this sector of the bristlecone project is to merge overlapping tree-ring records from the Methuselah Walk site to create a series that can be used for climatic reconstruction in the period from A.D. 1900 to 6200 B.C. The primary climatic signal that can be isolated and reconstructed is annual moisture deficit.

The major procedures in this study include the following:

1. Evaluation and selection of individual series to be merged.
2. Evaluation and selection of climatic data.
3. Calibration and verification of the tree-ring and climate relationship during the time of instrumented climatic records.
4. Reconstruction of precipitation deficit back to 6200 B.C.
5. Determination of the areal generality of the reconstruction.

Evaluation of tree-ring series:

The overriding goal of the specimen selection and merging process will be to maintain as much of the variance spectrum as possible in order that both long and short-term climatic variation can be reconstructed. Therefore the final averaging process will utilize ring-width series instead of ring-width indices. The argument against using indices in this application has been clearly stated by LaMarche (1974:1046). If each component series is standardized to a mean of 1.0, the average values of the series will also approach 1.0 as component length decreases. This would eliminate or obscure the nature of any trends that are longer than the individual component series.

The use of ring widths still requires the removal of age trend from the series. Fortunately, the longevity and growth characteristics of bristlecone pine simplify this task. After 300-500 years of age the biological growth trend is not apparent. One can simply exclude those portions of series that exhibit age trend and retain the remainder for analysis. This procedure has been completed, leaving 265 series in the climatic data file.

One further goal of evaluation is to detect and remove series that might have radically different variance spectra from those of other series in the same time period. This should have the effect of removing noise in the final averaged series and permit more reliable reconstructions than might otherwise be obtained. The extensive computational procedures for this task have just begun. An attempt to detect the presence of outliers will be made by evaluating the results of cross-spectral analysis (Jenkins and Watts 1968). The spectrum of each series will be compared with that of other averaged series for the time period in question. One potential problem with this procedure is that if there is high persistence in the series then spurious coherences between series will be produced. Therefore it is necessary to first examine the persistence structure of each series with autoregressive-moving-average (ARMA) modelling (Box and Jenkins 1976). If statistically significant types of persistence are found then series can be prewhitened by use of an appropriate ARMA model. The residual values of the time series can then be used in cross-spectral analysis.

Evaluation of climatic data:

Instrumented climatic data has been collected for relevant stations in the Great Basin region. They are currently being analyzed for inhomogeneity and missing values have been estimated with regression methods. When these analyses are completed, averaged climatic time series for temperature and precipitation will be developed that are representative of those conditions in the west-central Great Basin.

Calibration of tree-ring-climate relationships:

The climate-growth response was qualitatively described first by Fritts (1969) in an ecological growth study of White Mountain bristlecone.

Narrow rings were associated with dry/warm conditions concurrent with the growth period and dry summer/autumn seasons preceding the growth year. The nature of this response was revised and quantified by a subsequent study (Fritts 1974) using response function analyses originally developed by Fritts et al. (1971). In general terms, the revised response analysis showed that winter and early spring temperature was inversely related to growth while there was also a positive relation to precipitation in the prior summer and autumn. The regional climatic data for this analysis were from the Decennial Census of the United States Climate for the period 1932-1962. The region used was California division 3, a narrow strip running northward from the White Mountain area. In general the temperatures are similar but the precipitation is greater than those values in the area of the tree growth.

Preliminary response function analysis recently conducted as part of the current project provides somewhat differing results from Fritts' analyses. The overall response shows more positive relationships to precipitation. With the exception of November and December, all months from May of the current growth year through July of the previous year show significant responses. Significant inverse relationships are present between growth and temperature of the current March and May and preceding August and September. The climatic data used were from Nevada division 3 for the period 1931-1980 (NOAA, 1981). This division covers roughly one fourth of the state of Nevada, running eastward across the state from the White Mountain area. The climatic values here are somewhat drier and warmer than those found in the immediate vicinity of the trees.

The apparent conflicts between the two analyses can only be better resolved when we have developed climatic series that are more representative of conditions in the western Great Basin near the growth site, than those that have been used. When the single station climatic data evaluations are complete, further response function analysis will ensue. This will permit final decisions on precisely what type of values can be reconstructed. One alternative to using a single series such as precipitation is an integrated value such as the Palmer Drought Severity Index (P.D.S.I.) (Palmer 1965) that has seen useful applications in tree-ring-climate reconstructions (Meko, Stockton and Boggess 1980).

Further analyses:

Given current levels of funding, the final stages of tree-ring-climate calibration and verification of reconstructions during times of instrumented climatic records will take place in 1982. The task of reconstructing moisture deficit over the past 8180 years can then proceed.

Assessment of the regional generality of the reconstruction in the past 80-100 years can be determined by relatively straightforward regression methods. The reconstructions of either precipitation or P.D.S.I. values can be used to predict those actual values at nearby and then at increasingly distant climatic stations. Another approach might be to try to predict other regional reconstructions of similar kinds of values based on a network of different tree-ring data, Fritts' (1980) reconstructions of temperature and precipitation for single stations and for the Great Basin region reach back to A.D. 1602 and would be available for that purpose.

Prior to A.D. 1602 there are no other moisture deficit reconstructions for the Great Basin that are based on independent lines of evidence, that are continuous for the past 8000+ years or have resolution close to that of the annual tree-ring values. Therefore, in order to better evaluate our own work, a second long tree-ring chronology from the eastern Great Basin is being developed. It is described in a succeeding section of this report (see p.17-18).

Chronology Development, Nevada and Utah

Several new tree-ring chronologies were developed in the Great Basin that will minimally have three kinds of utility. First, they can be used as chronology controls in attempts to date wood that is encountered in archaeological or geological contexts. Second, they provide a basis for development of a regional network of chronologies of 1000 or more years for use in climatic reconstruction. Third, some of the sites have bulk wood that can be used in either a supplementary or comparative fashion to the White Mountain wood now used for isotopic analyses.

Sheep Range, Southern Nevada

Master chronologies for four species have been completed. The species and the beginning dates are: bristlecone pine, A.D. 760; ponderosa pine, A.D. 1313; white-fir, A.D. 1606; and pinyon pine, A.D. 1681. More intensive core collections should permit an extension of the bristlecone chronology to about 2000 B.P. Exploratory C-14 dates on debris-flow wood indicate data in hand for the period 4000-2000 B.P.

Spring Mountains, Southern Nevada

Sampling in one locality has permitted the development of a bristlecone pine chronology from A.D. 1150 to 1979. A single cross-section from another locality dates back to A.D. 850. A 2000-year chronology may be possible.

White Pine Range, East-central Nevada

Bristlecone pine at one locality, referred to as the Indian Garden site, has provided the material for more than 5200 years of continuous chronology. Two segments of chronology were derived from remnants sampled in 1972 and 1978. The earliest, a 2080-year series, has been dendrochronologically dated from 3240 to 1160 B.C. The second, a 1268-year series, has a C-14 date that would place it in roughly the first 1300 years A.D.

The site contains a full spectrum of bristlecone forms: young full-bark trees, older strip barks, standing snags, and dead remnants. A concentrated effort was made in the summer of 1981 to sample as many of these as possible. Ninety eight specimens of living trees, standing snags, and large remnants were cored and sections were taken from 42 smaller remnants. These are currently being processed. The quantity and quality of material will permit us to develop the chronology as an independent unit. It can then be used for comparison with the White Mountain master chronology and with three other long chronologies from the Snake Range (about 120 km to the east): #C-114, 4862 years; #352, 3200 years; and Hill 10842, 2000 years.

None of the Nevada material will be C-14 dated until after it has been intensely studied and shown to be undatable dendrochronologically. The full surfaces provided by the cross sections are much better than cores and serious problems in dating are not anticipated. The 1981 core collection, primarily from living trees, is providing a chronology back to about A.D. 100, as of this writing.

Material from the Indian Garden site will ultimately provide the second longest continuous record of isotopic and paleoclimatic variation at the lower, rainfall dependent range of the bristlecone pine. This is valuable for several reasons. It provides a second major source of wood for isotopic and calibration work. It can be used for comparative or replicative studies that provide cross-checks on variations for corresponding time periods in the bristlecone from California. The site tends to have larger ring widths than does the Methuselah Walk wood which will facilitate preparation of C-14 samples less than ten years in length.

From the standpoint of paleoclimatic research, the data provide a second long time series that can be used for reconstruction of moisture deficit trends. Comparative analyses of the frequency domain characteristics and of climatic reconstructions from this and the White Mountain series will be particularly valuable. This will permit us to determine the generality or specificity of the frequency characteristics of each series.

Mammoth Creek, Southwest Utah

Collections at this site in 1979 and 1980 have resulted in a bristlecone pine chronology from A.D. 784 to 1980. Further collection and analysis should push the earliest date to near the 2nd century B.C. When this occurs, the master chronology may permit the temporal placement of undated wood from Basketmaker II sites in the area (e.g. Bannister, Dean and Robinson 1969:11).

Archaeological Relationships

Scientific investigations of bristlecone pine provide several types of information that are important to the worldwide archaeological community and to regional investigations in the western U.S.

Tree-ring calibration of radiocarbon dates has permitted drastic revisions of temporal sequences of cultural developments in western Europe (Renfrew, 1973, 1974, 1977; Wilson, 1975). On this side of the Atlantic, the ongoing calibration in the 7th to 9th millennium B.P. will ultimately provide North American archaeologists with a basis for refining the chronological framework of most of the Archaic period of cultural development. As the bristlecone pine chronology is extended beyond the current limit of 6700 B.C., it will be possible to extend the calibration into the period of Paleo-Indian activity in the western hemisphere. Simultaneously it will then be possible to compare C-14 activity of the bristlecone with that of oak chronologies from continental Europe (Becker, 1979; Beer, _et al_. 1979; Lambert and Orcel, 1979), and the British Isles (Pilcher, _et al_. 1977). This will permit the temporal placement of the earlier segments of the European chronologies and of archaeological materials that crossdate with them or have similar C-14 activity. This type of work has a number of precedents (Cain and Suess, 1976; Ferguson, Gimbutas and Suess, 1976) and appears to be the best procedure at this time for developing calibration of C-14 activity in the range of 9-11,000 B.P.

On a regional scale, bristlecone pine provides a unique resource for both chronology control and paleoclimatic reconstruction in the Great Basin and the northern periphery of the Southwest. Dendrochronological dating of wood from archaeological sites, using bristlecone pine, has been accomplished (Graybill and Ferguson, manuscript), and other potentials can now be explored. More than 20 bristlecone chronologies from the area are in varying stages of development. Most are continuous for the past thousand years and several can be extended to about 2000 B.P. We have found that they crossdate well among themselves and with lower elevation species such as pinyon pine (<u>Pinus monophylla</u>) and ponderosa pine (<u>Pinus ponderosa</u>). Thus the possibility of dating a variety of species of wood that might occur in archaeological sites, using a bristlecone pine chronology for a master control, is quite good.

As the number of bristlecone pine sites expands, it will be possible to develop paleoclimatic reconstructions similar to those produced by Fritts (1965, 1980) for western North America, but with much greater geographic resolution. While these data will provide a paleoclimatic record of the past 800-1000 years, there is potential for a limited number of longer term perspectives. The Methuselah Walk chronology from the western edge of the Great Basin and the chronology from the White Pine Range under development in eastern Nevada will eventually permit a two-point reconstruction of trends in moisture deficit over the past 5200 years. As climatic trends become discernible, they should permit strong inferences about changes in other natural systems. This will provide prehistorians with new bases for understanding the environmental background of human adaptations in the area.

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