DENDROCHRONOLOGY OF BRISTLECONE PINE

by

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A Final Technical Report

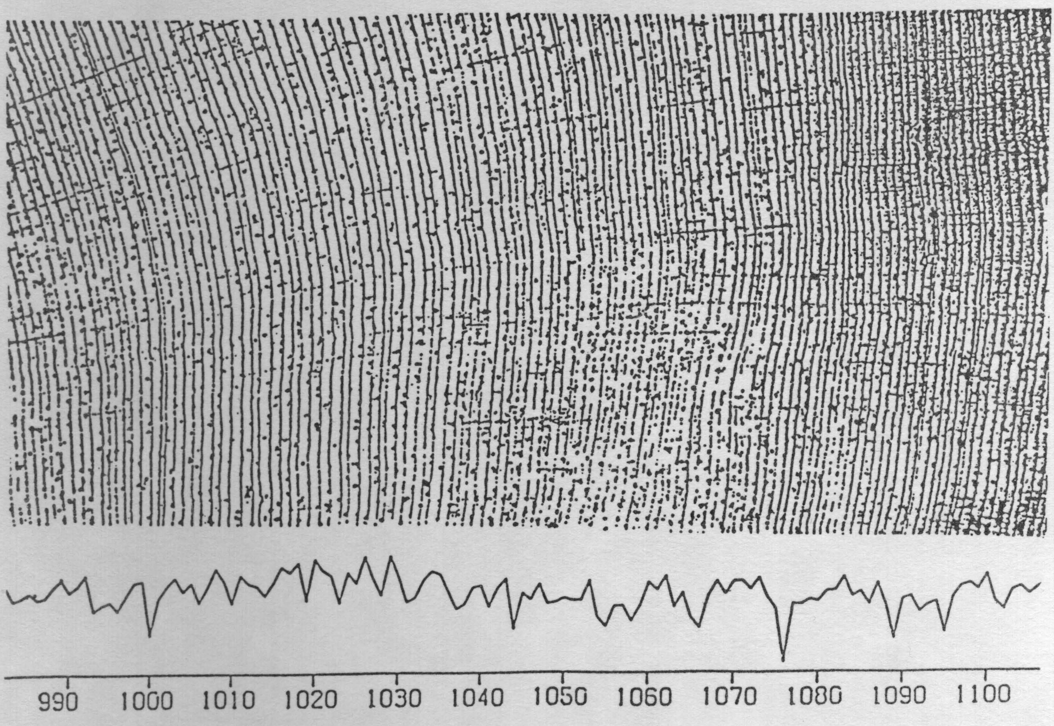
Submitted 31 May 1985

on the National Science Foundation grant EAR-8018687

for the period 1 April 1981 to 31 October 1984

with the assistance of the Department of Energy contract no. DE-AC02-81EV10680

covering the period 1 May 1981 to 31 October 1982



A floating sequence at 10,000 B.P.

DENDROCHRONOLOGY OF BRISTLECONE PINE

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. The focus of this report relates to the support by the Geology and Anthropology sections in the National Science Foundation under grant EAR-8018687 for the period 1 April 1981 to 31 October 1984 with the assistance of the Department of Energy contract no. DE-AC02-81EV10680 covering the period 1 May 1981 to 31 October 1982.

A summary of this research was recently published in *Radiocarbon* (Ferguson and Graybill 1983). In most cases various facets of the work were related to projects sponsored by all agencies. Therefore the full range of activities during that period is described herein. The primary project goals were:

(1) To extend the bristlecone pine chronology from the White Mountains of California beyond 6700 B.C. and strengthen it by incorporating additional specimens.

(2) To develop bristlecone pine chronologies in new areas for applications in archaeology, isotopic studies, and other earth sciences.

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

WHITE MOUNTAIN CHRONOLOGY DEVELOPMENT

Methuselah Walk Locality

Lat. 37°12'N., long. 118°10'W., el. 2900 m.

Field work led to the collection of 130 specimens. About 76% of these were small cross-sections taken in hopes of chronology extension. One series collected in 1981 that is about 500 years in length is over 10,000 radiocarbon years old (H. N. Michael, personal communication, 1982). It is one of three different series that date in the 2000 or so calendar years that lie just beyond the continuous chronology that reaches 6700 B.C. The remaining 24% of the collections were used to strengthen various intervals of the master chronology where specimen numbers were limited.

Cooperative studies by Henry N. Michael, University of Pennsylvania:

Dr. Michael's continued search for old wood resulted in the location and radiocarbon dating of the following sample specimens, from his 1983 collection, in the range of 6000 B.C.:

Field No.	Lab. No.	Calibrated Age, B.C.
H-83-55B	P-3433	4550-4380
H-83-55A	P-3428	4960-4565
H-83-36B	P-3408	6045-5530

The calibrated date, itself, is only a primary indicator of old wood. Equally important is the position of the sample in relation to the total radius. Resampling and, ultimately, collecting of bulk samples may take a year or two.

Chronology extension:

There has been no extension to the chronology beyond 6700 B.C. However, the collection and dating of many new specimens in the past nearly four years has not provided even a single-year change. Contrary-wise, each newly dated specimen has served to verify and strengthen the master chronology.

Collections and Specimen depth:

As of October, 1981, the number of specimens predating 4000 B.C. was 47; 5000 B.C., 35; and 6000 B.C., 13, totaling 95 individual remnants. Now, three years later, the total is about 150, with 25-30 predating 6000 B.C.

The 1983 collections were rather limited due to the shortness of the field season and the amount of rain encountered during this interval. Eight samples were collected solely for dating on the TAMS facility and other specimens were collected for possible tree-ring dating. Those that could not be readily dated, due to poor quality, shortness of the series, etc., were submitted for conventional C-14 dating or to the TAMS facility.

The 1984 collections included three bulk samples:

TRL 77-122	3000-2700 B.C.	52 lb.
TRL 80-101	5800-5500 B.C.	80 lb.
TRL 63-53	2400-2000 B.C.	50 lb.

This added material has been intensely utilized in the preparation of decade samples for the calibration program (see tables 3, 4, and 5).

An updated version of the master chronology was developed. Its primary utility is for dating control. A magnetic tape with a copy of this was furnished to the Carbon Dioxide Information Center Library at Oak Ridge National Laboratory late in 1982.

GREAT BASIN CHRONOLOGY DEVELOPMENT

Indian Garden, Nevada

Lat. 39° N., long. 115°20' W., el. 2800 m.

This site in the White Pine Range of east-central Nevada was intensively collected in 1981 and subsequently processed. All data are bristlecone pine except four cores from limber pine.

Table 1. Tree-ring samples from Indian Garden, Nevada

	Cores	Cross sections
Collected	169	64
Dated	142	61
Measured	73	57

The final chronology is continuous from 3259 B.C.-A.D. 1980. This is the second longest chronology at the lower elevational range of the species and has several potential applications. First, some wood from the sections could be used for isotope studies that concern either paleoclimate or C-14 calibration. Second, the chronology can serve as a 5240 year control for dating tree-ring series derived from archaeological or geological contexts in the region.

Mt. Jefferson, Nevada

Collections were made in 1981 at two localities from living limber pine.

Mt. Jefferson West	Lat. 38°47'30" N., long. 116°57'30" w., el. 3245 m
Mt. Jefferson East	Lat. 38°46'30" N., long. 116°56' W., el. 3360 m

Table 2. Tree-ring series from Mt. Jefferson, Nevada

	East	West
Collected	34	12
Dated	28	12
Measured	22	12

The final averaged chronology for the two sites dates from A.D. 905-1981. It was developed for two purposes. First, to serve as a dating control for tree-ring series that might be obtained from archaeological excavations on the mountain by the American Museum of Natural History (under direction of D. H. Thomas). Second, to update and expand records of paleoclimatic variation at upper treeline for limber pine and for the region.

Mammoth Creek, Utah

Lat. 37°37'30" N., long. 112°40' W., el. 3620 m.

Final collections in 1982 supplemented earlier work here. Essentially all trees older than *ca*. 100 years have now been cored at this small site. All series are bristlecone pine.

Table 3. Tree-ring series from Mammoth Creek, Utah

	No. of cores
Collected	66
Dated	61
Measured	58

The final chronology spans the period of A.D. 747-1981. It is currently in use as a control in attempts to date tree-ring series from Fremont Virgin Branch Anasazi sites in southwest Utah. It will also potentially be useful in long-term paleoclimatic studies of the region.

Panamint Mountains

A manuscript, in preparation, on cutting dates for bristlecone pine stumps in conjunction with mining history at Panamint City, Death Valley National Monument has been accepted for publication in Keepsake, published by the committee of the annual Death Valley Encampment.

Miscellaneous sites

Four other sites were investigated in 1982 for their potential:

	Cores Collected	Cores Dated	Cores Measured	Date Span
Bryce Point, Utah Lat. 37°36' N., 112°10'W., el. 2500 m.	27	11	0	A.D.1303-1982
Badger Creek, Utah Lat. 37°36'30" N., 112°17'30"W. el. 2635 m.	37	17	11	A.D.1226-1982
Twisted Forest, Utah Lat. 37°41'N., long. 112°52'W. el. 3050 m.	37	29	29	A.D. 311-1980
Highland Peak, Nevada Lat. 37°54'N., long. 114°35'W. el. 2750 m.	21	21	21	A.D.1347-1980

No further work is planned at the Bryce Point, Badger Creek and Twisted Forest sites. The chronologies can serve as controls for dating other tree-ring series but are not suitable for paleoclimatic analysis. The Highland Peak site can serve for chronology control and paleoclimatic analysis.

SHEEP RANGE

Modern chronologies for five species, Douglas-fir, white fir, and bristlecone, pinyon, and ponderosa pines, have been developed for the Sheep Range, north of Las Vegas, Nevada. In addition, a study has been made of debris flow in the Hidden Forest drainage of the Sheep Range. Selected remnants of bristlecone and pinyon pines have been collected and examined, but no chronologies have been developed.

An apparent reason for the difficulty in chronology building was indicated by radiocarbon dates of five of the bristlecone pine remnants (Table 1); they are earlier than the modern controls and are somewhat spaced in time. This, however, indicates a potential for the development of a three-to-four thousand year chronology for the Sheep Range. A long-term chronology from this area may provide a basis for the dating of tree-ring material from early archaeological sites in the Southwest. One such potential would be the Cave DuPont site.

Table 1. Radiocarbon age of five Sheep Range bristlecone pine remnants

LJ No.	Description	Age (Years B.P.)
3801	921, Rings 362-372	1750 ± 50
3802	931, Rings 106-116	3260 ± 40
3803	991, Rings 170-180	1040 ± 50
3853	870, Rings 40-50	1560 ± 60
3854	880, Rings 77-87	1640 ± 60

Prospects for the Extension of the Bristlecone Pine Chronology:

The bristlecone pine tree-ring chronology for Methuselah Walk extends to 6700 B.C. Three remnants, dated only by radiocarbon, exist beyond the present limit. The three have 500, 600, and 500 rings and raise the total number of rings to about 10,280. Correspondingly, the three gaps total perhaps 1300 to 1400 years. Two of the remnants, each with 500 rings, are too small for decade samples to be prepared for conventional radiocarbon analysis. The third, about midway between the other two, has 600 rings and decade samples have been prepared. In a preliminary report by Ferguson, Lawn and Michael (1985, in press), five dates, with ^{13}C corrections, in the range of 9,000 B.P. are presented. Thirteen samples have been burned; the remaining eight are being processed. Ultimately, about 40 contiguous decade samples will be dated. The constancy of the ever-lengthening time range covered by the dendrochronologically dated remnants, combined with the presence of even earlier wood, indicate a strong possibility for the extension of the year-to-year tree-ring chronology and for its use in the calibration program.

Prepared Decade Samples on Hand:

A tabular summary, in 1000-year intervals, of dated decade specimens on hand was presented by Ferguson (1979). Then, there were 1138 decade samples on hand with a total weight of 15,758 grams; now, the stockpile has grown by an estimated 20-30 percent. In the preparation of samples for either routine or special requests, it is more convenient to prepare the wood in a "broadside," where a unit of wood is processed on a systematic basis, decade by decade, from the inside to the outside. If alternate decades are requested, the intervening decade samples are also prepared and will be "on the shelf" along with the overages (clean material above the gram-weight requirement) and immediately available for other studies. For example, a 240-year interval, A.D. 1380 to 1620, was processed to provide seven replacement samples. The distributed samples totaled 285 grams and the prepared "on-the-shelf" decade samples total 977 grams, a total of 1262 grams. The reserve supply is of value for requests, such as for a series of samples for calibration studies at new laboratories or for problem oriented research.

Distribution of Prepared Decade Samples:

The data in Table 1 represent the utilization of a single specimen, TRL 80-101, in the preparation and distribution of dendrochronologically dated decade samples for the calibration of the radiocarbon time scale. The time span represented is from 5820 to 5350 B.C. Weight requirements are 40 grams for Arizona (A), 25 for Pennsylvania (P), and 75 for Washington (QL). The total number of decade samples prepared was 165; distributed 118. The total gram weight prepared was 9736; distributed 5296. The material on hand constitutes a handy reserve supply for replacement samples and for new calibration sample requests. Since these data were completed, there has been more sample preparation, particularly between 5650 and 5350 B.C.

The dates are given in terms of our computer-oriented time scale. The year '0' was added at the A.D./B.C. break in terms of the Christian calendar. The unsigned positive dates are equivalent to A.D. calendar dates.

Abbreviations:

PILO = *Pinus longaeva*, Great Basin bristlecone pine

PIMO = *Pinus monophylla*, singleleaf piñon

Samples provided for C-14 research

Dated wood provided to P. E. Damon, University of Arizona

Date range			Grams	Genus and Species
-6570	TO	-6560	1.0	PILO
-6460	TO	-6450	40.0	PILO
-6440	TO	-6430	40.0	PILO
-6410	TO	-6400	40.0	PILO
-6400	TO	-6390	40.0	PILO
-6390	TO	-6380	40.0	PILO
-6380	TO	-6370	40.0	PILO
-6370	TO	-6360	40.0	PILO
-6360	TO	-6350	40.0	PILO
-6350	TO	-6340	40.0	PILO
-6340	TO	-6330	40.0	PILO
-6330	TO	-6320	40.0	PILO
-6320	TO	-6310	40.0	PILO
-6310	TO	-6300	40.0	PILO
-6300	TO	-6290	40.0	PILO
-6290	TO	-6280	40.0	PILO
-6280	TO	-6270	40.0	PILO
-6270	TO	-6260	40.0	PILO
-6260	TO	-6250	40.0	PILO
-6250	TO	-6240	40.0	PILO
-6240	TO	-6230	40.0	PILO
-6230	TO	-6220	40.0	PILO
-6220	TO	-6210	40.0	PILO
-6210	TO	-6200	40.0	PILO
-5820	TO	-5810	41.0	PILO
-5810	TO	-5800	40.0	PILO
-5800	TO	-5790	40.0	PILO
-5790	TO	-5780	40.0	PILO
-5780	TO	-5770	40.0	PILO
-5770	TO	-5760	41.0	PILO
-5760	TO	-5750	40.0	PILO
-5750	TO	-5740	41.5	PILO
-5740	TO	-5730	40.0	PILO
-5730	TO	-5720	40.5	PILO
-5720	TO	-5710	40.0	PILO
-5710	TO	-5700	40.0	PILO
-5700	TO	-5690	40.0	PILO
-5690	TO	-5680	40.0	PILO
-5680	TO	-5670	40.5	PILO
-5670	TO	-5660	40.0	PILO
-5660	TO	-5650	40.0	PILO
-5650	TO	-5640	41.5	PILO
-5640	TO	-5630	40.0	PILO
-5630	TO	-5620	40.0	PILO
-5620	TO	-5610	40.0	PILO
-5610	TO	-5600	40.0	PILO
-5600	TO	-5590	40.5	PILO
-5590	TO	-5580	41.0	PILO
-5580	TO	-5570	41.0	PILO
-5570	TO	-5560	40.5	PILO
-5560	TO	-5550	40.5	PILO
-5550	TO	-5540	40.0	PILO

(continued)

-5540	TO	-5530	40.5	PILO
-5530	TO	-5520	40.0	PILO
-5520	TO	-5510	40.0	PILO
-5510	TO	-5500	40.0	PILO
-5500	TO	-5490	40.5	PILO
-5490	TO	-5480	40.0	PILO
-5480	TO	-5470	40.0	PILO
-5470	TO	-5460	40.0	PILO
-5460	TO	-5450	40.0	PILO
-5450	TO	-5440	40.0	PILO
-5440	TO	-5430	40.0	PILO
-5430	TO	-5420	40.0	PILO
-5420	TO	-5410	40.0	PILO
-5410	TO	-5400	40.0	PILO
-5400	TO	-5390	40.0	PILO
-5390	TO	-5380	40.0	PILO
-5380	TO	-5370	40.0	PILO
-5370	TO	-5360	39.5	PILO
-5360	TO	-5350	40.0	PILO
-750	TO	-740	50.0	PILO
-750	TO	-740	50.0	PIMO
-660	TO	-650	50.0	PIMO
1835	TO	1855	27.0	PILO

Dated wood provided to M. Stuiver, University of Washington

Date range			Grams	Genus and Species
-5810	TO	-5800	75.0	PILO
-5800	TO	-5790	75.0	PILO
-5790	TO	-5780	75.0	PILO
-5780	TO	-5770	72.5	PILO
-5770	TO	-5760	75.0	PILO
-5770	TO	-5760	75.5	PILO
-5760	TO	-5750	20.0	PILO
-5760	TO	-5750	50.5	PILO
-5750	TO	-5740	50.0	PILO
-5750	TO	-5740	20.5	PILO
-5740	TO	-5730	20.0	PILO
-5740	TO	-5730	51.5	PILO
-5730	TO	-5720	76.0	PILO
-5720	TO	-5710	50.0	PILO
-5720	TO	-5710	67.5	PILO
-5720	TO	-5710	11.0	PILO
-5710	TO	-5700	75.0	PILO
-5700	TO	-5690	75.0	PILO
-5690	TO	-5680	75.5	PILO
-5630	TO	-5620	75.0	PILO
-5620	TO	-5610	75.0	PILO

Dated wood provided to H. N. Michael and E. K. Ralph,

University of Pennsylvania

Date range			Grams	Genus and Species
-6410	TO	-6400	20.0	PILO
-6400	TO	-6390	20.0	PILO
-6390	TO	-6380	20.0	PILO
-6380	TO	-6370	20.0	PILO
-6370	TO	-6360	20.0	PILO
-6360	TO	-6350	20.0	PILO
-5810	TO	-5800	25.0	PILO
-5800	TO	-5790	26.0	PILO
-5790	TO	-5780	25.0	PILO
-5780	TO	-5770	26.5	PILO
-5770	TO	-5760	25.0	PILO
-5760	TO	-5750	28.0	PILO
-5750	TO	-5740	25.0	PILO
-5740	TO	-5730	25.5	PILO
-5730	TO	-5720	25.0	PILO
-5720	TO	-5710	25.0	PILO
-5710	TO	-5700	25.0	PILO
-5700	TO	-5690	25.0	PILO
-5670	TO	-5660	25.0	PILO
-5650	TO	-5640	25.0	PILO
-5570	TO	-5560	25.0	PILO

Dated wood provided to H. E. Seuss at La Jolla, California

Date range			Grams	Genus and Species
-5284	TO	-5273	30.5	PILO
-5263	TO	-5253	23.5	PILO
-5253	TO	-5243	23.5	PILO
-5243	TO	-5233	24.5	PILO
-5233	TO	-5223	30.5	PILO
-5223	TO	-5213	23.5	PILO
-5193	TO	-5181	22.5	PILO
-5181	TO	-5171	20.5	PILO

Additional distribution of calibration samples:

Dated wood has been provided for J. C. Vogel, Pretoria, South Africa to aid in his calibration of some European features. Initially, he was sent the following set of bristlecone pine samples:

Age, -A.D.		Weight, grams
2950	to 2945	5.5
2950	2945	17.0
2945	2940	25.5
2945	2940	6.5
2840	2830	32.0
2840	2835	6.5
2835	2830	7.0

The project with Dr. Vogel is a continuing one. Material in the range of 2400 to 2000 B.C. has been prepared as decade samples. He has submitted a poster title "Radiocarbon calibration of the 3rd millennium B.C." for the 12th International Radiocarbon Conference, Trondheim, Norway, June 1985.

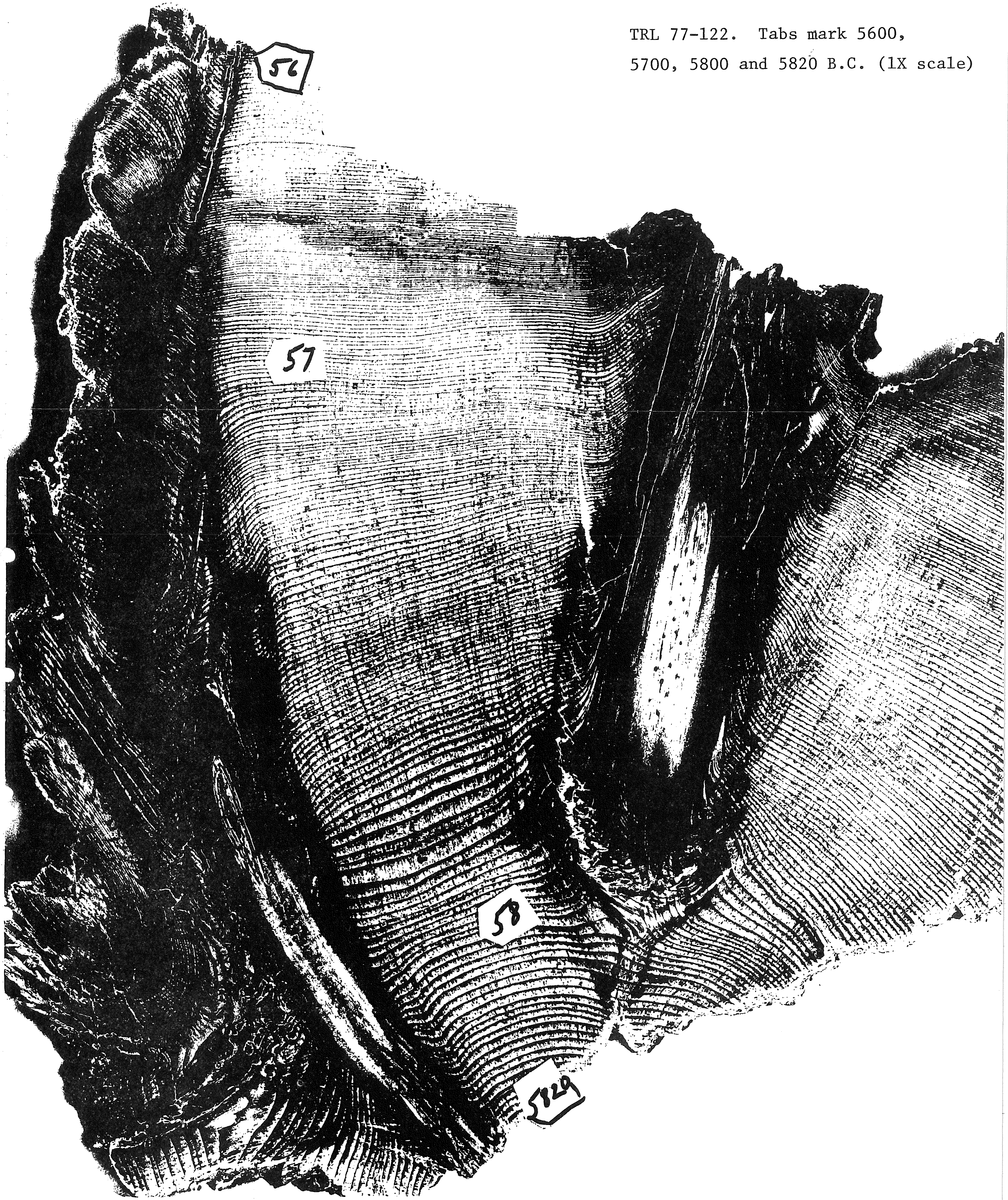
Three contiguous decade 200-gram samples -5760 to -5730, have been sent to Dr. Gordon W. Pearson in Belfast, Ireland, as a control for European chronology development in this time period.

A series of samples for internal calibration has been sent to the radiocarbon laboratory at the Alberta Environmental Centre, in Vegreville, Alberta, Canada, and a similar series is being prepared for the laboratory at the University of California at Riverside. Two samples were sent to the University of Wisconsin at Madison.

Table 1. Gram weight of samples on hand and distributed from a single remnant, TRL 80-101.

Midpoint, B.C.	on hand	Total	A	P	QL	Other	Total grams
5815	21		41				62
5805	34		40	25	75		174
5795	53		40	26	75	40 1/ 40 2/	274
5785	43		40	25	75		183
5775	158		40	26	72		296
5765	88		41	25	75		229
5755	36		40	28	70	201 3/	375
5745	83		41	25,26	70	202	447
5735	15		40	25	71	201	352
5725	151		40	25	76		292
5715	93		40	25	78		236
5705	93		40	25	75		233
5695	57		40	25	75	5	197
5685	5		40		75		120
5675	25		40	25			90
5665	25		40	25		684	90
5655	-		40	26			66
5645	117		41	25			183
5635	158		40	25			223
5625	188		40		75		303
5615	170		40	25	75		310
5605	198		40	25	-		263
5595	97		40	25	-		162
5585	89		41	25	-		155
5575	141		41	25	-		207
5565	175		40	25	(possible)		240
5555	121		40	25	-		186
5545	140		40	25	(possible)		205
5535	110		40	25	76.0		251
5525	145		40	25	-		210
5515	88		40	25	-		153
5505	137		40	25	-		202
5495	111		40	25	-		176
5485	118		40	25	-		183
5475	98		40	25	76.5		239
5465	84		40	25	77.5		226
5455	141		40	25	-		206
5445	82		40	25	75.5		222
5435	103		40	25	75.5		243
5425	113		40	25	76.0		254
5415	134		40	25			199
5405	92		40	25			157
5395	90		40	25	21		155
5385	76		40	25			141
5375	62		40	25	1567		127
5365	54		40	25			119
5355	55		40	25			120
						Distributed: Prepared	
Total samples	47 decades		47	45	118	Total number	165
Total grams	4467		1886	1132	5296	Total grams	9736

TRL 77-122. Tabs mark 5600, 5700, 5800 and 5820 B.C. (1X scale)



Results of the calibration program:

Klein, et al (1980) in their "Radiocarbon Concentration in the Atmosphere: 8000-year Record of Variations in Tree Rings: First Results of a USA Workshop" say, under acknowledgments, that "We thank C. W. Ferguson for his efforts in the collection, dendrochronologic dating and distribution of bristlecone pine samples, without which this work would not be possible." They continue, "We would like to thank the National Science Foundation for its generous support of this work through the following grants: EAR-78-23584 (Workshop), EAR-78-21813 (Arizona-Radiocarbon fluctuations), EAR-78-15183 (La Jolla), EAR-78-23837 and DES-22233 (Pennsylvania), and EAR-78-04436 (dendrochronology of bristlecone pine, Tree-Ring Laboratory)."

The report "Calibration of Radiocarbon Dates: Tables Based on the Consensus Data of the Workshop on Calibrating The Radiocarbon Time Scale," by Klein, Jeffrey, J. S. Lerman, P. E. Damon, and E. K. Ralph (1982), was published in Radiocarbon 24(2)103-50 and reprints were handed out at the 11th International Radiocarbon Conference in Seattle in June 1982. However, additional reprints were not released to me (anticipating the addition of an errata supplement) until 28 May 1985. The bristlecone pine project provided most of the wood for the calibration. This contribution is acknowledged (p. 119). A photocopy of a portion of the title page (103) and the acknowledgments (page 119) is included in the appendix and the full reprint is presented as a separate attachment to this report.

Analysis:

Sonett and Suess (n.d.) show the LaJolla and Belfast $\Delta^{14}C$ sequences superimposed on a common time scale. They say that "although differences exist, the close agreement between these two sequences, one determined over a period of years beginning about 1955 and carried out on White Mountain bristlecone pines, and the other done later in Belfast using Irish peat bog wood, is striking." Then, they say that this "confirms the validity of the two dendrochronologically established annual tree ring sequences and shows that, as expected on geochemical grounds, a close global relation exists, and that these two laboratories have obtained data in which the similarities outweigh differences. This correlation between the two strongly reinforces the statistical view that the $\Delta^{14}C$ record is that of real interplanetary modulation of the cosmic ray source leading to the generation of atmospheric ^{14}C."

Spörer Minimum Study:

Dendrochronologically dated decade samples were provided to the University of Arizona ^{14}C Laboratory to supplement earlier data in a study of the Spörer Minimum (A.D. 1380 to 1620). The second suite of samples, from TRL 67-3, is summarized below:

Interval, A.D.	Wt., grams	Date Delivered
1590 to 1600	40.0	2-2-84
1570 1580	40.0	1-26-84
1540 1550	45.0	1-18-84
1520 1530	40.0	1-26-84
1420 1430	40.0	2-3-84
1400 1410	40.0	2-3-84
1380 1390	40.0	2-3-84

Exploratory Tests for Berillium-10

At the request of Dr. James R. Arnold, University of California, San Diego; bulk samples were provided for exploratory tests for the presence of Berillium-10.

Four old samples and a modern control were submitted December 1984:

Specimen	Interval, A.D.	Weight, grams
TRL 74-101	1855 to 1875	138.0
TRL 63-53	-2370 -2340	120.0
TRL 77-122	-2950 -2750	140.0
TRL 80-101	-5780 -5770	105.0
H-83-29 with H-84-1	(ca 10,000 B.P.)	126.0

The 10,000-year-old sample was from a specimen (in two pieces) and containing 600 rings that was dated by radiocarbon. Decade samples are being analyzed for a study of the fluctuations in this time period.

Lal, Arnold, and Nishiizumi (1985, in press) discuss briefly the geophysical records of a tree, and suggest that the ^{10}Be content of tree samples may also permit measuring changes in the cosmic ray flux reaching them during the past $\leq 10^4$ years, which should allow one to deduce maximum changes in the geomagnetic dipole field and solar activity during this period.

Tandem Accelerator Mass Spectrometer (TAMS)

The current project has provided duplicate samples of dated wood to the TAMS facilities at Arizona and Oxford, England so that a direct inter-laboratory comparison of dating results can be made. The samples listed below have been supplied to those facilities:

Dated wood provided to D. Donahue, University of Arizona

Date range			Grams	Genus and Species
-6570	TO	-6560	1.0	PILO
-5051	TO	-5047	2.0	PILO
-4000	TO	-3990	2.0	PILO
-3010	TO	-3000	2.0	PILO
-1980	TO	-1970	2.0	PILO
-1000	TO	-990	2.0	PILO
00	TO	10	2.0	PILO
280	TO	290	2.0	PILO
480	TO	490	2.5	PILO
700	TO	710	2.5	PILO
890	TO	900	2.5	PILO
1000	TO	1010	2.0	PILO
1120	TO	1130	2.0	PILO
1880	TO	1885	2.0	PILO
1885	TO	1890	2.0	PILO

Dated wood provided to R. Gillespie, Oxford

Date range			Grams	Genus and Species
-5051	TO	-5047	2.0	PILO
-4000	TO	-3990	2.0	PILO
-3010	TO	-3000	2.0	PILO
-1980	TO	-1970	2.0	PILO
-1000	TO	-990	2.0	PILO
00	TO	10	2.0	PILO
1000	TO	1010	2.0	PILO
1885	TO	1890	2.0	PILO
1880	TO	1885	2.0	PILO

The dates are given in terms of our computer-oriented time scale. The year '0' was added at the A.D./B.C. break in terms of the Christian calendar. The unsigned positive dates are equivalent to A.D. calendar dates.

Abbreviations:

PILO = Pinus longaeva, Great Basin bristlecone pine

PIMO = Pinus monophylla, singleleaf piñon

We are continuing to cooperate with the accelerator group in the Department of Physics at the University of Arizona. Initially, dated material was provided to aid in the calibration of their facility. Now, they are assisting us in the dating of remnants of unknown age. The latest (TRL 84-213; AA-1036), submitted 7 January 1985, was from a long radial section of a highly eroded stump. The exploratory sample consisted of a fragment with a span of about 25 years. With the guidance of the TAMS date, 3870± 80 B.C., and the calibration (Klein et al, sigma = 20 years) of -2540 to -2180, the tree-ring dating was picked up (our difficulty was evident when we found the specimen to have 6-7% missing rings). The mid-point of the calibration, -2360, was 45 years earlier than the mid-mass, -2405, of the sample, a figure well within the ±80 of the 20-year sigma.

The TAMS facility at the University of Arizona has improved their precision from the initially promised precision of plus-or-minus 5% (for commercial users) to about 2% on current tests. Thus, they are now in the same range as the best of the conventional C-14 dating laboratories. And there is the promise of even further improvement. This means that the newer method may supplant the conventional method in the calibration studies.

We have been supplying three laboratories with decade samples of 25, 40, and 75 grams -- 140 grams of sound wood per decade -- in the range of 6550 to 5350 B.C. The availability of wood prior to 6550 B.C. (the dendrochronologically dated wood extends to 6700 B.C.) decreases rapidly and 6550 B.C. is about the ultimate limit for even 20-gram decade samples. Three "floating" sequences are in hand that would provide an extension to more than 10,000 B.P. when the corresponding three gaps are bridged. These remnants, however, are of limited volume and would not provide the quantity of wood presently being used for conventional radiocarbon dating. The new method, requiring only milligram samples, would be able to continue the calibration studies beyond the limit of the present conventional procedure. Thus, the next few years may see an increased need for dated bristlecone pine material, predating the present, well established chronology. Conversely, the TAMS facility, in exploratory studies, is running "quickie" dates in the search for earlier material.

Samples of bristlecone pine were cited by Taylor *et al* (1983) in the dating of the Sunnyvale skeleton. With this new approach, the tandem accelerator dating facility, we have the prospect of dating one-year (as opposed to the present 10-year) samples for more detailed studies of sunspot cycles, etc.

The TAMS facility at the University of Arizona provided eight radiocarbon dates for exploratory samples from the 1982 collections in Methuselah Walk (1890 control; Klein calibration; Donahue, 8-18-82):

TRL No.	Age, B.P.	Form
82-53	5000 ± 800	pith area
82-54	4500 ± 800	pith area
82-55	5000 ± 800	small frag.
82-59	6000 ± 800	small frag.
82-64	3500 ± 1000	?
82-68	4500 ± 1000	pith area
82-70	5200 ± 800	pith area
82-72	6300 ± 800	pith area?

None of these predated 6300 B.P., but did serve to identify specimens of possible use.

A later run provided eight additional dates (Donahue, 12-5-83):

AA-Number	TRL Number	5568 date (no ^{13}C normalization)
254	82-51	6210 ± 250
255	82-56	1940 ± 190
256	82-58	5200 ± 310
*257 or 258	82-60 or 61	3080 ± 190
*257 or 258	82-60 or 61	2300 ± 210
259	82-66	3870 ± 190
260	82-73	4370 ± 360
261	82-80	3880 ± 220

*Both of these samples were labeled the same during the target-mounting process, thus the ambiguity.

Donahue (7-6-84) gave the results of seven "quickie" samples:

TRL	C-No.	Radiocarbon Age years (B.P.)
83-113	C-1323	2380 ± 200
83-115	C-1324	3360 ± 200
83-123	C-1325	5925 ± 320
83-124	C-1326	2670 ± 240
83-125	C-1327	6950 ± 300
83-126	C-1328	5425 ± 240
83-127	C-1329	4470 ± 280

The oldest of these, TRL 83-125, was calibrated as 5400 B.C.

Two more were given by Jull (1-21-85):

Date no. (target no)		^{14}C age (BP)
AA-992 (V1712)	Tree-ring TRL 84-237	2330±110
AA-1036 (V1835)	Tree-ring TRL 84-213	3870±80

Relationships to European dendrochronology:

In the La Jolla laboratory, 575 European oak tree-ring samples have been radiocarbon dated (Suess, Linick, and Becker, 1985). Several previously separate tree-ring series have been reduced to one absolutely dendro-dated chronology spanning the period from 4075 B.C. to the present and one still-floating chronology which spans the approximate period 7225 to 4125 B.C. Tentative dating of the floating sequence was determined by wiggle matching with the bristlecone pine chronology. Ferguson is acknowledged as furnishing the wood samples from the bristlecone pine chronology for the La Jolla laboratory.

A 7272-year European tree-ring chronology is reported by Pilcher et al (1984). They say that "the construction of over 7,000 yr. of European tree-ring chronology means that all of the radiocarbon calibration measurements on European oak are now anchored to a calendrical time scale and can be compared directly with measurements on bristlecone pine."

There may be a possibility of extending the calibrated radiocarbon dates beyond 6000 B.C. for Achilleon, a Neolithic site in Greece (Gimbutas, personal correspondence, Dec. 21, 1984) as was done for sites in southwest Europe (Ferguson, Gimbutas, and Suess, 1976).

A paper to be presented at the White Mountain Symposium, Aug. 23-25, 1985 on the "Old Bristlecone Pine and the European Connection" will relate the current developments, as in Ferguson, Lawn, and Michael (1985), to research activities both here and in Europe as presented at the 12th International Radiocarbon Conference to be held in Trondheim, Norway in June, 1985.

Five of the nine contributors to "Archaeology, Dendrochronology, and the Radiocarbon Curve" (Ottaway, ed., 1983; the results of a Workshop held in Edinburgh 22 October 1982) refer to our bristlecone pine studies. In regard to the hypothesis that there is a 71-year difference between the German and Irish chronologies Pilcher (ob. cit.) says "that the possibilities are:

(a) the tentative dating of the end of GB2 at 229 BC is wrong; or,

(b) the German-Ireland link in the 2nd millennium BC is wrong; or,

(c) the wiggle-matching is wrong; or,

(d) the bristlecone chronology is wrong; or,

(e) the German chronology is wrong.

For the sake of this discussion (a) and (b) are not going to be considered as it is these tentative observations which suggest that the 71 year difference exists. Of the remaining 3 possibilities we have to exclude (d). The bristlecone chronology would have to be proven to be wrong and this would only arise if the European oak chronologies were absolutely secure, i.e. the German and Irish chronologies were in agreement and the calibration relationship were observed to go out of phase between the old/new worlds. As regards (c) it is already known that the same wiggles are observed in both the Irish oak and the American pine calibrations for the whole of the last two millennia (Pearson, 1980; Pearson and Baillie, 1983). We are left, therefore, with a circumstantial case for asking whether anything can be wrong with the German oaks chronology complex?"

Archaeological potentials:

From the Cave DuPont archaeological site, near Kanab, Utah, two wood cross sections of Juniperus sp. with 203 and 255 annual rings and a common (within two years) bark date, crossdate quite well, and give a composite chronology of 257 years. This has been undatable (Dean, personal communication,13 Dec. '83).

Comparable Basketmaker II sites on Black Mesa, AZ, have uncalibrated radiocarbon dates back to 600 B.C. (Euler, personal communication,13 Dec. '83). Considering that the present tree-ring chronologies go back only to 322 B.C. and that the calibrated C-14 dates would go back to about 7-800 B.C., it is entirely possible that the DuPont material would predate the existent tree-ring chronology. The Sheep Range bristlecone pine, with a potential chronology length of 4000 years may serve to date this and other early sites.

Upper timberline archaeology in the White Mountains has been investidated by Robert Bettinger of the University of California. He has just received a major National Science Foundation grant to intensify and continue these studies. The potential for dendrochronological dating of sites at upper timberline was indicated by Ferguson and Graybill (1968) in their study of charcoal and wood fragments of Crooked Creek Cave. They reported intermittent occupancy of this small cave at 10,000 feet over a period of 2000 years. Bettinger has written in C. W. Ferguson as a consultant for three seasons starting (tentatively) July 1, 1985. Dating controls consist of the upper timberline bristlecone pine chronology developed by LaMarche; the low elevation bristlecone pine chronology (Ferguson and Graybill, 1983), and units of a chronology of singleleaf pinyon developed by Ferguson (these consist of unpublished data spanning nearly 3,000 years).

Aspects of the 12th International Radiocarbon Conference:

Results of many years of work on the bristlecone pine project will be presented at the 12th International Radiocarbon Conference in Trondheim, Norway in June 1985. Many of the papers to be presented by our European colleagues will relate directly or indirectly to the bristlecone pine studies.

The three bristlecone pine remnants reported by Ferguson, Lawn, and Michael (1985) have a total of 1100 annual rings, all within the range reported by Becker (in a submitted title) on a "Subfossil pine tree-ring series 8850 to 10100 BP (6900-8150 B.C.), a chance for early Holocene radiocarbon calibration." A comparison of these two data sets will relate one to another and may make it possible to more precisely estimate the number of years in the gap separating TRL 68-40 and H-84-1.

Brackenredge will report on the "Atmospheric ^{14}C activities, 14,000-8,000 yr BP (12050-6050 B.C.) as expressed in vertical sample profiles: Upper limits on the effect of the Vela Supernova." Thus, it seems possible that the date of the Vela Supernova may fall within the range of the three remnants.

Another time overlap will be presented by Kromer, Rhein, Bruns, Schoch-Fischer, and Münich in their report on "Radiocarbon calibration data for the 6th to the 8th millennium BC."

Sonett (1984; see abstract in the Appendix) has related very long solar periods and the radiocarbon record. Sonett and Suess will present a related paper asking "Are the '200' year periods in radiocarbon and bristlecone pine ring growth correlated?"

Abstracts submitted to The 12th International Radiocarbon Conference, Trondheim-NTH NORWAY, June 1985:

Damon, P. E., T. W. Linick, Austin Long, and C. W. Ferguson*

Extension of the high precision C-14 calibration curve to 6520 B.C. using decadal, dendrochronologically dated bristlecone pine samples

Ferguson, C. W., Barbara Lawn, and H. N. Michael*

Prospects for the Extension of the Bristlecone Pine Chronology: Radiocarbon analysis of H-84-1

Stuiver, M., B. Kromer, B. Becker, and C. W. Ferguson

^{14}C age matching of the German oak and bristlecone pine tree-ring series in the sixth and seventh millennium B.C.

Ferguson, C. W.*

Bristlecone Pine: that Rare American Species with its Head above the Clouds: A Photographic Essay (poster)

* abstracts included in the appendix

CO_2 related research:

Tree-ring series collected near 3500 m in the White Mountains of California were used in conjunction with others collected from Mt. Jefferson, Nevada to provide initial support for the hypothesis that subalpine conifers in the Great Basin may now evidence a CO_2 fertilization effect. This work was reported in Science (LaMarche, Graybill, Fritts, and Rose 1984). Under current DOE support Graybill is attempting to refine this hypothesis with an increased data base and intensive analysis.

Plans for the Future:

Unfulfilled commitments include supplying wood for the interval roughly 6000-5800 B.C., for which adequate wood is not in hand, and the possibility of providing replacement decade samples in intervals where wood is available.

Damon (personal communication) suggested a study of geographical variations in ^{14}C (using the high-precision gas counters) and a new search for the 11-year solar cycle (using TAMS analysis of graphite prepared from single-year wood samples). It would require less than 1/100 as much wood/year for the TAMS analysis as it would for conventional high-precision counting.

When final results of the 1984 field season are known, an evaluation will be made in terms of continued work. Based upon present knowledge, it would seem that the presence of three remnants, floating in time (but dated by radiocarbon), would indicate a strong possibility that the associated three gaps could be crossed. Any extension of the master chronology or of the floaters (in either direction) would be of value.

Acknowledgments:

We are indebted to the Geology and Anthropology program of the National Science Foundation for their continued support over the years and to the Department of Energy for their recent support.

Field work has been in cooperation with divisions of the U. S. Forest Service, especially the Inyo National Forest, Bishop, California; the Humboldt National Forest, Elko, Nevada; and the Toiyabe National Forest, Reno, Nevada. We want to acknowledge the interest and cooperation of Gene Murphy, Supervisor, Dennis Orbus, District Ranger, and Brian Miller, Forest Information Officer, in Bishop; Jack Wilcox, District Ranger, Ely, Nevada; Robert Wize, District Ranger, Las Vegas, Nevada; and Mr. Glade Quilter, District Ranger, Tonopah, Nevada.

The Bureau of Land Management, in the Ely, Las Vegas, and Tonopah districts, has been of assistance.

In the field of radiocarbon studies, we have had the continued interest and cooperation of Dr. Minze Stuiver, at the University of Washington; Dr. Hans Suess, at the University of California, San Diego; Drs. Beth Ralph and Henry Michael, at the University of Pennsylvania; and Drs. Paul Damon and Austin Long, at the University of Arizona. We would especially like to acknowledge the continued support from the University of Pennsylvania in the collection and analysis of exploratory radiocarbon dates.

Staff members, many of whom have made major contributions over the years, are too numerous to list, but of our present staff we are grateful of the skill and devotion provided over the years by Mr. James Burns in the routine dating and measuring of our samples. Mr. Martin R. Rose and Mr. Michael S. McCarthy have been particularly helpful in sample collection efforts. Recently, Mr. Michael McComas and Mrs. Elizabeth Barlow have assisted in the various laboratory activities.

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APPENDIX

List of Titles

(no pagination)

Dendrochronology of Bristlecone Pine: A Progress Report (2 pp.)

Increasing Atmospheric Carbon Dioxide: Tree Ring Evidence for Growth Enhancement in Natural Vegetation (3 pp.)

Calibration of Radiocarbon Dates

Very Long Solar Periods and the Radiocarbon Record

Prospects for the Extension of the Bristlecone Pine Chronology: Radiocarbon Analysis of H-84-1

Extension of High Precision Radiocarbon to 6,550 B.C.

Bristlecone Pine: That Rare American Species with its Head Above the Clouds: A Photographic Essay

[Radiocarbon, Vol 25, No. 2, 1983, P 287-288]

DENDROCHRONOLOGY OF BRISTLECONE PINE: A PROGRESS REPORT

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ABSTRACT. Dendrochronological studies of bristlecone pine, *Pinus longaeva*, have produced a continuous tree-ring sequence back to 6700 BC for the White Mountains of California and to 3258 BC for east-central Nevada.

Dendrochronological studies of bristlecone pine, *Pinus longaeva*, at 10,000 feet in the White Mountains of east-central California, have resulted in the establishment of a continuous tree-ring sequence back to 6700 BC, a total of 8681 years. This represents a 1576-year extension of the chronology since it was last published (Ferguson, 1969;1970).

Given the quality and length of series of specimens that have recently been dated in the 5500-6500 BC range, we are cautiously optimistic that the chronology may eventually reach back at least 10,000 years. This thought is buttressed by the presence of a 500-year "floating" sequence in the range of 9000 years BP (Ferguson, 1968). Current ^{14}C analysis seems to indicate that another remnant, collected in 1981, again with ca 500 rings, may be over 10,000 years old (H N Michael, pers commun, 1982). Continuing tree-ring and ^{14}C studies will further define the temporal relationship of these two specimens.

One other long bristlecone-pine chronology was recently developed. Collections at a site in the White Pine Range, east-central Nevada, have provided excellent material for a chronology back to 3258 BC, a total of 5238 years. This provides the second longest continuous record of isotopic and paleoclimatic variation at the lower, rainfall dependent range of the species.

The historic development of the bristlecone-pine project, a general overview of its relation to other scientific activity and a summary of the inventory of prepared samples was recently presented by Ferguson (1979). The primary focus of the project -- to provide dendrochronologically-dated decade samples for an interlaboratory calibration of the ^{14}C time scale (Klein *et al*, 1982) -- continues as bulk material for selected time periods becomes available.

Another focus of the project is to attempt paleoclimatic inference with the long bristlecone-pine tree-ring series (Ferguson and Graybill, 1981). The primary climatic signal that can be isolated in both the California and Nevada series is annual moisture variability. Current efforts are directed at calibration of the tree-ring series with instrumented climatic series.

ACKNOWLEDGMENTS

We would like to thank the National Science Foundation for their support, since 1956, of the bristlecone-pine project through various grants, most recently EAR 78-04436 and EAR-8018687. The US Department of Energy should also be acknowledged for their recent support of the bristlecone-pine project with Contracts EE-78-A-28-3274 and DEC-AC02-81EV10680.

Field work has been in cooperation with divisions of the US Forest Service, especially the Inyo National Forest, Bishop, California, the Humboldt National Forest, Elko, Nevada, and the Toiyabe National Forest, Reno, Nevada.

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Increasing Atmospheric Carbon Dioxide: Tree Ring Evidence for Growth Enhancement in Natural Vegetation

Abstract. *A response of plant growth to increased atmospheric carbon dioxide, which has been anticipated from laboratory data, may now have been detected in the annual rings of subalpine conifers growing in the western United States. Experimental evidence shows that carbon dioxide can be an important limiting factor in the growth of plants in this high-altitude environment. The greatly increased tree growth rates observed since the mid-19th century exceed those expected from climatic trends but are consistent in magnitude with global trends in carbon dioxide, especially in recent decades. If correctly interpreted, these findings have important implications for climate studies involving tree ring observations and for models of the global carbon dioxide budget.*

The amount of CO_2 in the earth's atmosphere has been increasing steadily over the past century because of human activities that release stored CO_2 from terrestrial reservoirs (*1–3*). The increase in CO_2 and other minor or trace gases may affect the radiation balance of the earth, with possible climatic consequences (*4*). In addition, rising atmospheric CO_2 may directly influence net photosynthesis, plant growth, and productivity (*5*). Termed the fertilization effect, enhanced growth in response to artificially elevated CO_2 has been observed in greenhouses and in limited field experiments (*6*). Large-scale effects may now be taking place in nature (*7*). In this report we present what appears to be the first direct evidence of CO_2-related growth enhancement in natural vegetation: increased widths of annual rings of trees in subalpine habitats in the western United States during recent decades.

Ring widths in subalpine bristlecone pines (*Pinus longaeva* D. K. Bailey and *Pinus aristata* Engelm.) at high-altitude sites from New Mexico and Colorado to California show increases from about 1840 to 1970. Physiological considerations and temperature records suggested that this positive growth trend was due to rising warm-season temperatures until about 1960 (*8*). Its persistence through the late 1960's without continuation of this climatic trend was originally interpreted as a lagging biological response to temporarily increased leaf area related to rising temperatures in the first half of the century because bristlecone pines commonly retain needles for 15 years or more (*9*). The increase in photosynthetic biomass could have resulted in higher growth rates despite stable or even cooling temperatures. However, more recent sampling of another subalpine conifer, *Pinus flexilis* James, in central Nevada (*10*), showed that the growth trend had continued or even accelerated during the 1970's (Fig. 1). Mechanisms other than, or in addition to, climatic factors must be invoked to explain this apparent anomalous regional trend.

In order to determine whether the recent growth increase in Nevada is a local phenomenon, or part of a regional or larger trend, and to clarify the role of climate we recently resampled bristlecone pines at two upper tree-line sites (3400 to 3500 m) in the White Mountains of eastern California (*11*). The sites lie between two high-altitude meteorological observatories (*12*). Ring width data on these samples were used to supplement existing ring width index chronologies (*13*) through the early 1980's, and are shown in Fig. 2 (*14*). Growth rates have remained very high through the early 1980's. Figure 3 shows climatic records combining data for the two stations for the period 1949 to 1980. No climatic trends are apparent that might explain the positive trends in tree growth, nor are such trends apparent in longer series of regional data (*15*).

In the absence of strong climatic forcing, alternative explanations for this positive regional growth anomaly must be considered. We believe, from the evidence now available, that subalpine vegetation generally, and upper tree-line conifers in particular, could now be exhibiting enhanced growth as a direct response to increasing concentrations of atmospheric CO_2. The basis for this hypothesis is the important effect that CO_2 concentration would be expected to have on net photosynthesis in this high-altitude environment.

Although there are systematic regional differences and regular seasonal fluctuations in CO_2 concentration of a few parts per million, as well as longer term global trends (*16*), the proportion of CO_2 in the atmosphere remains constant over a vertical range of at least 80 km (*17*). However, because the atmospheric pressure and thus the density of air decrease with increasing altitude, the partial pressure, or concentration of CO_2 per unit volume of air, also drops. For the standard atmosphere in July at 30°N (*18*), the density of air decreases from 1.159 kg/m^3 at sea level to 0.835 kg/m^3, or 72 percent of its sea-level value, at an altitude of 3500 m. As pointed out by Tranquillini (*19*), the change in CO_2 concentration reduces the diffusion gradient from atmosphere to plant leaf and thus could substantially reduce CO_2 uptake. Although theoretical calculations by Gale (*20*) suggested that there might be some compensating effects of lower partial pressure, such as increased diffusion coefficients, his own research did not demonstrate a major counteracting effect. Also, Tranquillini (*19*) estimated that the photosynthetic performance of trees at timberline in the Alps (1900 to 2600 m) may fall 10 to 20 percent below that at lower altitudes because of decreased availability of CO_2.

Field and laboratory experiments were

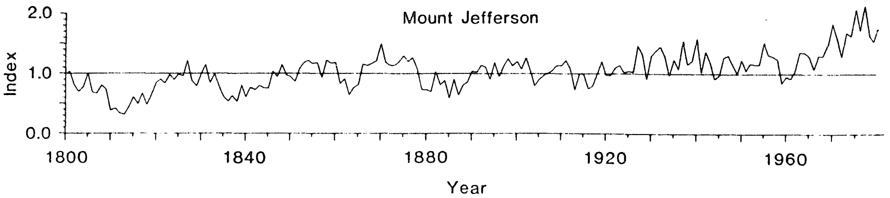

Fig. 1. Ring width indices for limber pine, Mount Jefferson, Nevada, showing rapidly increasing growth since the 1960's.

conducted at reduced CO_2 concentrations on herbaceous plants, woody perennials, and shrubs native to the White Mountains near sea level and at about 3100 m by Mooney and co-workers (*21*). They estimated that photosynthetic rates for these species in the field at 3900 m, somewhat above the local tree line, average about 70 percent of those under standard laboratory conditions near sea level because of differences in the concentration of CO_2. Although data are not available for the photosynthetic performance of bristlecone pine at reduced CO_2 concentrations, the CO_2 response seems to be shared by a broad range of subalpine taxa. For example, measurements made at lower altitudes on another subalpine conifer (*Abies alba*) by Koch (*22*) also showed a nearly linear decrease in net assimilation with decreasing CO_2 concentration in the range 50 to 350 ppm under moderate light (1×10^4 lux). Thus an atmosphere like that of the early 1960's, containing 310 to 320 ppm CO_2 at sea level (*16*), would have had volumetric concentrations in the July standard atmosphere at 3500 m equivalent to 223 to 230 ppm, which is well within the linear portion of the net assimilation versus CO_2 response curve for *Abies* and probably for *P. longaeva* as well.

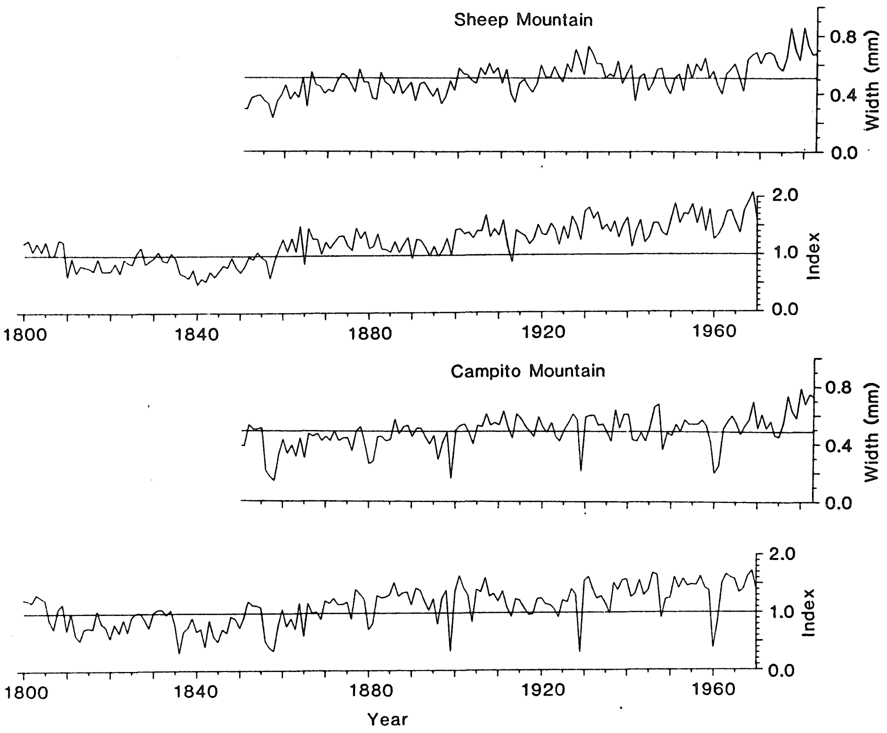

Fig. 2. Bristlecone pine growth records, White Mountains, California. Width index series for 1800 to 1970 are supplemented by average ring width data from recent sampling (*14*). Growth rates increased from 0.34 to 0.70 mm/year (106 percent) between 1850 to 1859 and 1974 to 1983 at the Sheep Mountain site and from 0.37 to 0.64 mm/year (73 percent) during the same interval at the Campito Mountain site.

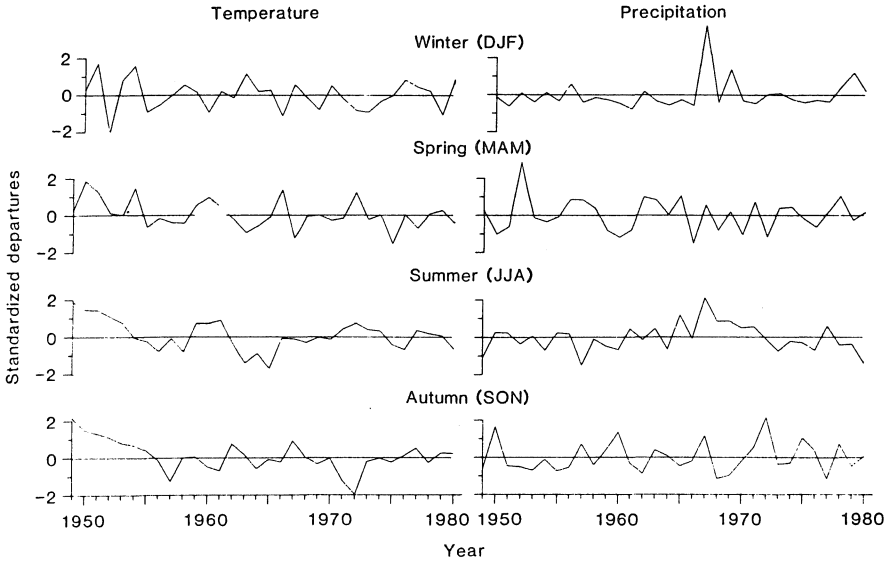

Fig. 3. Seasonal climatic data, White Mountains, California, 1949 to 1980. The data are seasonally averaged monthly mean daily average temperatures and total monthly precipitation values. The values in each series were reduced to standard scores or *Z* scores before being combined in order to eliminate the effects of differences in means and variances between the two stations. Only Crooked Creek Station is represented before 1953 and only Barcroft Station after 1977 (*12*).

The reduction in photosynthetic efficiency would thus be directly proportional to the decrease in the partial pressure of CO_2 with increasing altitude if the proportion of CO_2 remained constant. Therefore, whether due directly to higher CO_2 concentrations or to less direct physiological effects, photosynthetic efficiency in high-altitude plants could be increasing with time as the concentration of CO_2 in the atmosphere increases.

If we use a value for the preindustrial CO_2 concentration of about 270 ppm (*23*) and a modern value of 340 ppm (*24*), we find a 26 percent increase in the concentration of CO_2 from 1850 to 1983. A corresponding increase in the average growth rate of high-altitude bristlecone and limber pine would be consistent with an increase in CO_2 of this magnitude.

In addition to the direct effects on net photosynthesis that would be expected at high altitudes because of increased assimilation rates, increasing CO_2 might have longer term effects on radial growth by influencing plant growth and development, anatomical features, and flowering and fruiting patterns (*25*). For example, in bristlecone and limber pine the number of needle primordia and the rate of needle elongation might be positively influenced by CO_2, leading to large long-term gains in exposed photosynthetic surface and in biomass that could reinforce the direct effects of CO_2 (*26*).

Although high-altitude subalpine forests constitute only a small fraction of the earth's standing biomass, increased CO_2 uptake and storage could now be occurring in these habitats. This could modify projected future increases in atmospheric CO_2. Estimates of the "beta factor" (*2*) in some global carbon-balance models reflecting growth enhancement by elevated CO_2 concentrations may now need to be reconsidered.

Our findings also have important implications for paleoclimatic reconstructions involving certain kinds of tree ring data. Changing atmospheric CO_2 could introduce nonclimatic growth fluctuations that could interfere with calibration of climate and its reconstruction. Techniques like those now applied to remove biological age trends or effects of ecological factors (*27*) would have to be developed to separate such effects from the climate signal in tree ring data. Conversely, the climatic and ecological information in tree rings could be applied to isolate and enhance the apparent CO_2 signal. Such enhanced proxy records of atmospheric CO_2 might be developed at different localities from the beginning of the industrial era.

It will be necessary to determine the geographic extent of the postulated fertilization effect and to test high-altitude growth trends against longer and geographically more representative sets of climatic data. In addition, the effects of changing CO_2 concentrations on productivity, growth, and development of conifers growing under high-altitude conditions should be determined experimentally.

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11. D.A.G. and M.R.R. collected samples from 13 trees at Campito Mountain (3400 m) and from 15 trees at Sheep Mountain (3500 m) on 31 October 1983.
12. Crooked Creek Station (3094 m) was established in 1948 and discontinued in 1977; Barcroft Station (3801 m) was established in 1953 and discontinued in 1981. Early observations are summarized by N. Pace, D. W. Kiepert, and E. M. Nissen [*Climatological Data Summary for the Crooked Creek Laboratory, 1949–1967, and the Barcroft Laboratory, 1953–1967* (White Mountain Research Station, University of California, Berkeley, 1968)]. Instrument relocation in 1954 may have affected minimum temperatures at the lower station [V. C. LaMarche, Jr., *Quat. Res. (N.Y.)* **3**, 632 (1973)]. From 1955 on, data for these stations were published in *Climatological Data: California* (U.S. Weather Bureau and National Oceanographic and Atmospheric Administration, Washington, D.C.).
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28. We thank M. McCarthy for aid in sampling, F. Telewski for helpful discussions, M. Harrington and A. Allen for manuscript preparation, and the National Science Foundation for partial support under grant EAR 8018687.

8 March 1984; accepted 28 June 1984

[RADIOCARBON, VOL 24, No. 2, 1982, P 103-150]

Radiocarbon

1982

CALIBRATION OF RADIOCARBON DATES:

Tables based on the consensus data of the Workshop on Calibrating the Radiocarbon Time Scale

JEFFREY KLEIN*, J C LERMAN**, P E DAMON**,
and E K RALPH*

A calibration is presented for conventional radiocarbon ages ranging from 10 to 7240 years BP and thus covering a calendric range of 8000 years from 6050 BC to AD 1950. Distinctive features of this calibration include 1) an improved data set consisting of 1154 radiocarbon measurements on samples of known age, 2) an extended range over which radiocarbon ages may be calibrated (an additional 530 years), 3) separate 95% confidence intervals (in tabular from) for six different radiocarbon uncertainties (20, 50, 100, 150, 200, 300 years), and 4) an estimate of the non-Poisson errors related to radiocarbon determinations, including an estimate of the systematic errors between laboratories.

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ACKNOWLEDGMENTS

Special thanks are due J W Tukey and R M Clark for their many suggestions that have resulted in significant improvements in the algorithms originally presented to the Workshop. Thanks are due as well to C W Ferguson and the directors and staffs of the radiocarbon laboratories responsible for the activity measurements on these known-age samples, without which this work would not have been possible. We would also like to acknowledge the assistance of the operations staff at the University of Arizona's Computer Center, especially Jackie Dombrowski and Barry Shaede for their unfailing help, particularly during the preparations of the graphs presented here. The patience of those who have waited for the final publication of this calibration, even delaying their own work in some cases, also should not be forgotten. And finally, we would like to thank the National Science Foundation for their support of this publication through their Grant BNS-8022250, and for their support, since 1956, of the bristlecone-pine project, under the direction of C W Ferguson, through various grants, most recently EAR 78-04436 and EAR-8018687 and for their support of the USA laboratories involved in calibration-related research. The US Department of Energy should also be acknowledged for their recent support of the bristlecone-pine project with Contracts EE-78-A-28-3274 and DE-AC02-81EV10680.

REVIEWS OF GEOPHYSICS AND SPACE PHYSICS, VOL. 22, NO. 3, PAGES 239–254, AUGUST 1984

Very Long Solar Periods and the Radiocarbon Record

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The ~200-year periodicity in the time variations of atmospheric radiocarbon is shown to extend over the entire 8500-year La Jolla record and appears to be associated with a longer period between about 1500 and 2000 years via amplitude, frequency, or phase modulation, or some combination of these; but the statistical certainty of the source and form of the modulation is hampered by the low signal/noise ratio of the two periods. Autocorrelations of the La Jolla sequence show that the record violates even weak stationarity; although the 200-year period is well ordered in time, the appearance of other periods may be more sporadic. Significant cross correlation between the very long period and the modulation envelope about the neighborhood of the 200-year line suggests an identity between the two manifestations of the long period, and modulation by a nonlinearity satisfying the rule that it have at least one nonvanishing derivative of odd order and $n > 2$. Commensurate segments of the La Jolla, Belfast, and Groningen radiocarbon records confirm the existence between 3900 B.C. and 3200 B.C. of other periods, particularly 150 and 300 years. A likely source of these periodic changes in the radiocarbon record is the sun because the source of the variations is time dependence of the cosmic ray flux on the atmosphere. Further evidence is the recently reported correlation of radiocarbon and bristlecone pine growth ring variations and the lack of observational evidence to support the very large change in the earth's main field required for a geomagnetic explanation, especially of the ~200-year period. If it can be confirmed that the sun is the source, the very long periods suggest as one possibility that the core of the sun is the ultimate source, though multiple convective zone dynamo eigenmodes are an equally conjectural possibility. An alternate source for the longer period is pressure variations of the local arm of the galaxy, but this model is not favored.

PROSPECTS FOR THE EXTENSION OF THE
BRISTLECONE PINE CHRONOLOGY:
RADIOCARBON ANALYSIS OF H-84-1

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Barbara Lawn — University of Pennsylvania — U.S.A.
H. N. Michael — University of Pennsylvania — U.S.A.

The tree-ring chronology for bristlecone pine, *Pinus longaeva*, in the Methuselah Walk area of the White Mountains in east-central California was reported by Ferguson and Graybill in 1983 as extending to 6700 B.C. More than one hundred remnants predating 4000 B.C. were completely dated and the longer, better series were incorporated into the master chronology. The chronology has not been extended, but it has been greatly strengthened by the verification provided by the discovery of additional specimens of higher quality and greater length of series.

Three remnants, dated only by radiocarbon, exist beyond the present limit. Two of these, both with 500 rings, are at, roughly 11,000 and 9,000 B.P. The third, with 602 rings, is the subject of this paper. Decade samples from this remnant, H-84-1 (incorporating H-83-29, a smaller component thereof), have been prepared for radiocarbon analysis. The counting of three samples has been completed. Based upon the new half-life, they are all greater than 9,000 B.P.

The constancy of the ever-lengthening time range covered by the dendrochronologically dated remnants and the presence of even earlier wood indicate a strong possibility for the extension of the year-to-year tree-ring chronology and for its use in the calibration program.

oral

EXTENSION OF HIGH PRECISION RADIOCARBON TO 6,550 B.C.

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T. W. Linick	University of Arizona	U.S.A.
A. Long	University of Arizona	U.S.A.
C. W. Ferguson	University of Arizona	U.S.A.

High precision radiocarbon and stable isotope measurements have been completed on ninety-seven dendrochronologically dated, decadal bristlecone pine samples. The tree-ring samples include the times of growth between 5,350 B.C. to 5,820 B.C. and 6,080 B.C. to 6,550 B.C. The $\Delta^{14}C$, measured at a precision of ±3 $^{o}/oo$ s.d., follow a sinusoidal trend consistent with measurements on earlier decades and with measurements on South German oak samples (Linick and Suess, 1985; Bruns et al, 1983). Our results confirm that the radiocarbon calibration of the South German oak samples is accurate to within ±20 years. The parameters of the sinusoidal trend curve are offset = +32 $^{o}/oo$, half amplitude = 51 $^{o}/oo$, period = 11,300 years, phase lag = 2.29 radians and time is measured B.P. The trend curve is modulated by DeVries-Suess "wiggles" with amplitudes that are similar to those that occurred during the Maunder and Sporer minima. Thus, the combined effect of geomagnetic field intensity and solar activity during the sixth and seventh millennia B.C. appear to be similar to that prevailing in the fifteenth through seventeenth centuries A.D. Pronounced $\Delta^{14}C$ minima occur at 5,665 B.C., 5,760 B.C., 6,250 B.C. and 6,480 B.C. Pronounced maxima occur at 5,440B.C., 5,660 B.C., 5,700 B.C. and 6,385 B.C. No marked periodicity of the DeVries-Suess "wiggles" is apparent.

Our precise measurements (±1.89 $^{o}/oo$ s.d.) of $\Delta^{14}C$ for decadal bristlecone pine samples from the Sporer minimum are in excellent agreement with those of Stuiver and Quay (1980) suggesting no measureable ($< 2^{o}/oo$) geographical effect between high altitude bristlecone pine samples from the White Mountains of Southern California and low altitude Douglas-fir samples from the Pacific Northwest.

poster

BRISTLECONE PINE: THAT RARE AMERICAN SPECIES WITH ITS HEAD ABOVE THE CLOUDS: A PHOTOGRAPHIC ESSAY

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The bristlecone pine, Pinus longaeva, is, indeed, a rare species. Its habitat, especially at upper timberline in the White Mountains of east-central California, and its form, described as stunted or grotesque, are not what we may consider "normal." The stress of low temperatures limits the species at its upper elevational limits, while the harshness of moisture stress guards its lower limits.

The Methuselah Walk tree-ring chronology has been developed from a low elevation site. The great age of these trees and their sensitivity to year-to-year climatic changes prompted Edmund Schulman to use the descriptive title, "Longevity Under Adversity in Conifers," in his description of several coniferous species that have exceeded their generally accepted ages. And the same harshness aids in the preservation of the tree, as a snag, and of the remnants on the ground. These environmental factors have combined to provide us with a tree-ring chronology of over 4000 years from living trees and, by crossdating older and older remnants, to extend the chronology back to 6700 B.C.